CCANZ
concrete answers

2nd Revised Edition

THE NEW ZEALAND

GUIDE TO CONCRETE CONSTRUCTION

New Zealand Guide to

Concrete Construction

A publication of the Cement & Concrete Association of New Zealand

This publication is based on and reproduces much of the information contained in The Guide to Concrete Construction produced by the Cement and Concrete Association of Australia in conjunction with Standards Australia. The permission to do so and the assistance provided is acknowledged with gratitude.

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The Cement & Concrete Association of New Zealand is an independent industry and membership-funded organisation whose main aim is to grow the market for cement, concrete and concrete products in New Zealand.

As a technical and research-based organisation, the Cement & Concrete Association of New Zealand plays a key role in research and development (including their contribution to environmental issues), the advancement of industry standards and codes, education and training, technical information and advisory services. A significant part of its function is marketing this knowledge in a way which will most benefit decision-makers in the industry.

Preface

This publication will be of interest and value to everyone who is involved, or likely to become involved, in the specification or use of concrete in projects of any size – designers (architectural, engineering and draughting), construction companies, suppliers and contractors (both on and off the construction site).

This publication takes the place of a number of the construction-based Information Bulletins of the Cement & Concrete Association of New Zealand (CCANZ) which were based on an earlier edition of the New Zealand Standard NZS 3109 Concrete Construction.

For some readers, the guide will provide all the information they will need. For others, it will serve as a valuable introduction to the subject prior to undertaking a more in-depth study of particular aspects. Site personnel will find the guide of particular benefit, since it explains fully why various procedures – such as compacting and curing – are important, as well as making recommendations on how they should be carried out.

The contents of this guide are based on a publication originally produced by the Cement and Concrete Association of Australia with Standards Australia in 1994, Guide to Concrete Construction. The text revisions were carried out by CCANZ.

With a view to the growing move towards joint standards between the two countries, many of the Australian Standard references have been retained for possible future needs.

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Introduction

Guide to Concrete Construction

In its most basic form, concrete is a mixture of cement (portland or blended), water, and fine and coarse aggregates (sand and crushed rock or natural gravel), which is plastic when first mixed, but which then sets and hardens into a solid mass. When plastic, it can be moulded or extruded into a variety of shapes. When hardened, it is strong and durable, able to support substantial loads and, at the same time, resist the effects of fire, weather, wear, and other deteriorating influences. It is, therefore, a construction material of great versatility and wide application.

The properties of concrete in both the plastic and the hardened states are dependent on the physical characteristics, the chemical composition, and the proportions of the components used in the mixture. Hardened-state properties must be appropriate to the purpose for which the concrete is to be used; i.e. it must be strong enough to carry the loads imposed on it, and durable enough to resist the deteriorating influences of wear and weather. Plastic-state properties must also be appropriate; in this case, to the methods of handling, placing, compacting and finishing to be used in the job.

If not properly placed and compacted, concrete will not achieve its potential strength and durability. It is important, therefore, that when delivered to the construction site, concrete be sufficiently workable for it to be placed and compacted by the means available.

Workability is achieved by having sufficient cement paste (cement and water) in the mixture to lubricate the particles of aggregate and allow them to move freely as the concrete is placed and compacted.

Generally, the greater the volume of cement paste in the mixture, the more workable will be the concrete; although, as will be seen later, it is the volume of water in the paste which tends to be the dominant factor – the more fluid the paste, the more workable the concrete.

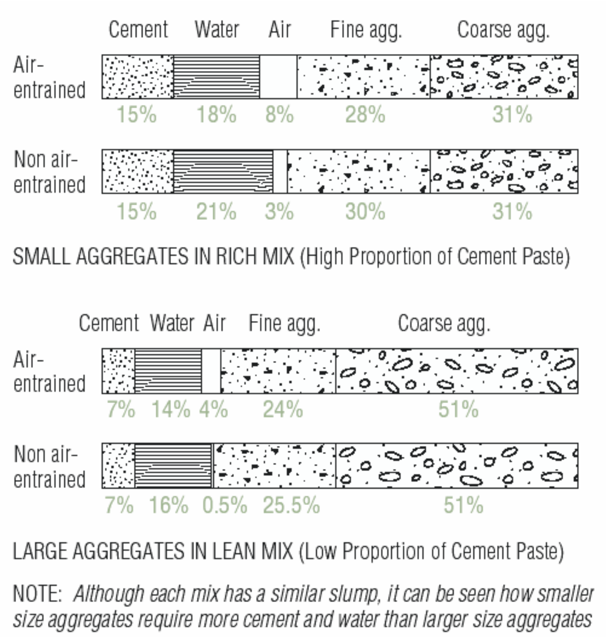


Figure 1: Typical range of concrete mix proportions.

Achievement of many of the desirable hardened-state characteristics of concrete, particularly its strength and durability, depends to a great extent on the development of physical and chemical bonds both within the cement paste as it hydrates, i.e. reacts chemically with water, and between the cement paste and the aggregate particles as the concrete hardens.

For a given mixture, maximum bond development will occur when the water content of the cement paste is at a minimum and all air is expelled from the system. In this respect, cement paste is like any other glue – excessive dilution will weaken it. The significance of the water:cement ratio cannot be overstated.

There is always present, therefore, in the proportioning of concrete mixes, something of a conflict. The addition of water tends to increase the workability of the concrete, but it also dilutes and weakens the cement paste. It is the aim of concrete mix design, or proportioning, to strike a balance between the need for concrete to be workable so that it can be placed and finished, and the need for it to be strong and durable.

To aid in achieving this aim, concrete technologists have at their disposal a range of materials other than cement, water and aggregates with which to modify the properties of concrete. These include pozzolanic and other cementitious materials, chemical admixtures, and, sometimes, special aggregates. The properties of these materials, and their effects on the properties of concrete, are discussed in subsequent chapters. At this point, their widespread use should be noted as they modify some properties of concrete in quite significant ways.

The chemical reaction between cement and water (hydration) takes time. Concrete must therefore be kept moist (i.e. cured) for a time to ensure that hydration continues and that the concrete achieves its potential strength and durability.

To summarise: good concrete, i.e. concrete which will achieve the properties specified for it, depends first of all on the selection and proportioning of its component materials, and then on the methods used to handle, place, compact, finish and cure it.

However, we seldom build using just plain concrete. Generally the structures will be constructed of reinforced or prestressed concrete and the strength, serviceability and durability of the structure will depend on the performance of the reinforced or prestressed members. The satisfactory performance of the completed structure depends on appropriate decisions being made throughout the whole design and specification process and all aspects of the construction being carried out properly. The creation of a structure that performs satisfactorily throughout its design life is complex, as illustrated overleaf.

The purpose of this Guide is to provide guidance on concrete technology and appropriate construction techniques and processes used in concrete structures. It should be emphasised at the outset that seldom is there a unique solution to achieving a satisfactory structure. Each case needs to be considered individually. The choice of materials will be influenced by local availability, while the techniques employed to carry out the various processes, e.g. curing, will be influenced by the construction processes chosen. In every case, consideration needs to be given to the ease with which the process can be carried out on site. It is a truism that designing structures to be buildable goes a long way to ensuring that the structure will achieve its design potential and perform appropriately throughout its design life. Thus designers no less than construction personnel need to understand the construction processes by which concrete structures are created.

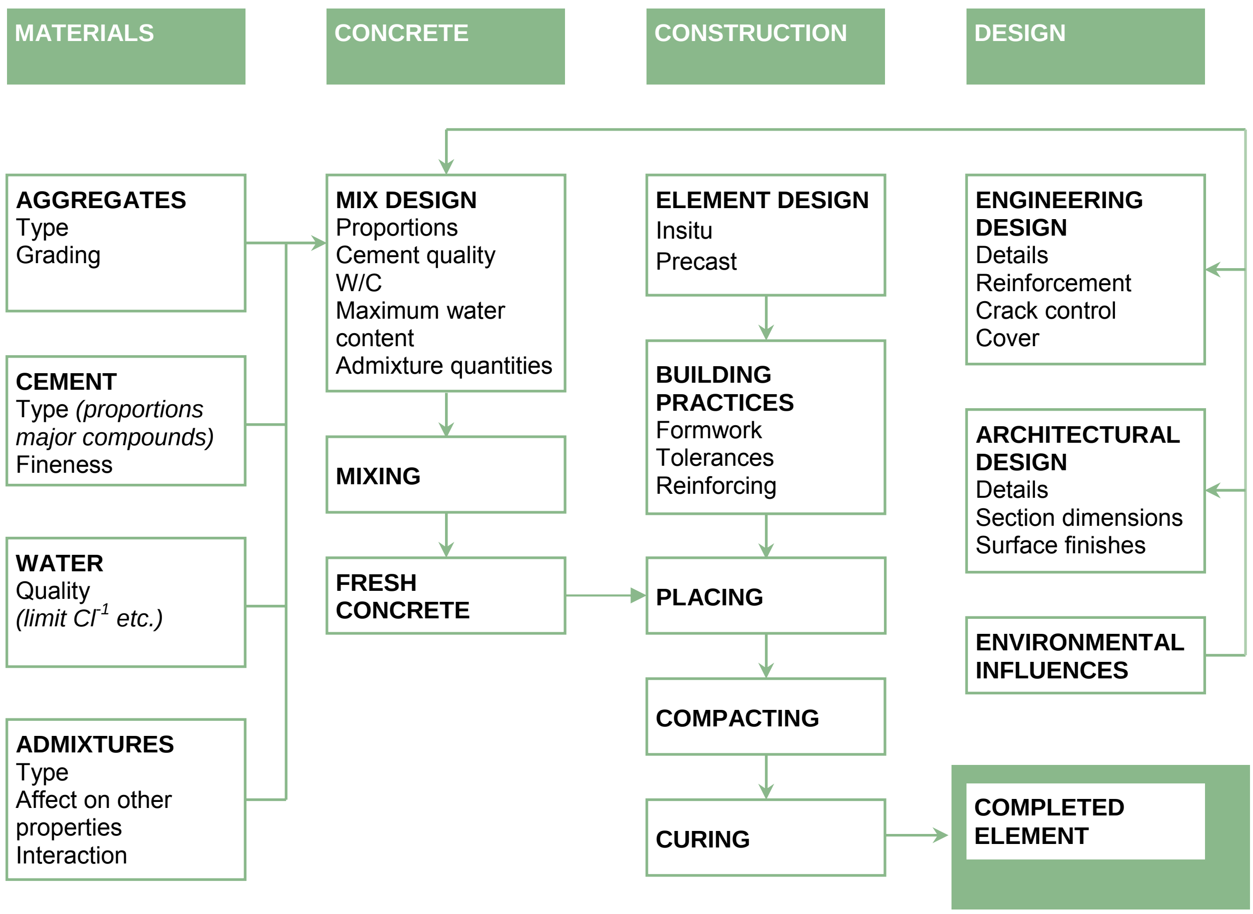


Figure 2: Factors influencing the performance of concrete structures

Principles of Reinforced and Prestressed Concrete

Chapter 1

Chapter 1

Principles of Reinforced and Prestressed Concrete

Concrete structures usually incorporate reinforced and/or prestressed concrete members. Reinforced concrete is a composite material made up of concrete and some form of reinforcement—most commonly steel bars or wires (the latter usually in the form of a mesh). In prestressed concrete members, the concrete is placed in compression (i.e. prestressed) before the member is subjected to the applied loads. The compression force is developed by stretching (tensioning) the tendons (high tensile steel wires, strands or bars) before they are bonded with the concrete and then transferring this force to the hardened concrete. Placing the concrete in compression increases its ability to withstand tensile forces.

This chapter provides basic information on the way in which steel and concrete combine to provide a versatile construction material. It also discusses the basic principles underlying the behaviour of prestressed concrete.

Information on the types of reinforcement and guidance on its handling and fixing is given in Chapter 16. Chapter 17 outlines the techniques used to tension the tendons and to bond it to the concrete and Chapter 18 covers the safety precautions which should be observed during stressing operations.

INTRODUCTION

Reinforced concrete is a material that combines concrete and some form of reinforcement into a composite whole. Whilst steel bars, wires and mesh are by far the most widely used forms of reinforcement, other materials are used in special applications, e.g. carbon-filament reinforcement and steel fibres. Other reinforcing materials are briefly mentioned in Chapter 17.

Concrete has a high compressive strength but a low tensile strength. Steel, on the other hand, has a very high tensile strength (as well as a high compressive strength) but is much more expensive than concrete relative to its load-carrying ability. By combining steel and concrete into a composite material, we are able to make use of both the high tensile strength of steel and the relatively low-cost compressive strength of concrete.

There are some other advantages to combining steel and concrete in this way which are derived from the characteristics of the materials. (These characteristics are summarised in **Table 1.1**).

Table 1.1 **Characteristics of steel and concrete**

Characteristics of Concrete	Characteristics of Steel
High compressive strength	High compressive strength
Low tensile strength	High tensile strength
Relatively high fire resistance	Relatively low fire resistance
Plastic and mouldable when fresh	Difficult to mould and shape except at high temperatures
Relatively inexpensive	Relatively expensive

For example, the plasticity of concrete enables it to be moulded readily into different shapes, whilst its relatively high fire resistance enables it to protect the steel reinforcement embedded in it.

The aim of the reinforced concrete designer is to combine the reinforcement with the concrete in such a manner that sufficient of the relatively expensive reinforcement is incorporated to resist the tensile and shear forces which may occur, whilst utilising the comparatively inexpensive concrete to resist the compressive forces.

To achieve this aim, the designer needs to determine not only the amount of reinforcement to be used, but how it is to be distributed and where it is to be positioned. These latter decisions are critical to the successful performance of reinforced concrete and it is imperative that, during construction, reinforcement be positioned exactly as specified by the designer.

It is important, therefore, that both those who supervise the fixing of reinforcement on the job-site, and those who fix it, have a basic appreciation of the principles of reinforced concrete as well as the principles and practices of fixing reinforcement.

Like reinforced concrete, prestressed concrete is a composite material in which the weakness of concrete in tension is compensated by the tensile strength of steel – in this case, steel wires, strands, or bars.

The compressive strength of the concrete is used to advantage by applying an external compressive force to it which either keeps it permanently in compression even when loads are applied to it during its service life (fully-prestressed) or limits the value of any tensile stress which arises under load (partial prestressing).

The pre-compressing or prestressing of concrete can be likened to picking up a row of books by pressing the books together **Figure 1.1**. The greater the number of books (the longer the span) the greater the force that has to be applied at either end of the row to prevent the row (the beam) collapsing under its own weight. A load applied to the top of the books would require an even greater force to be applied to prevent collapse.

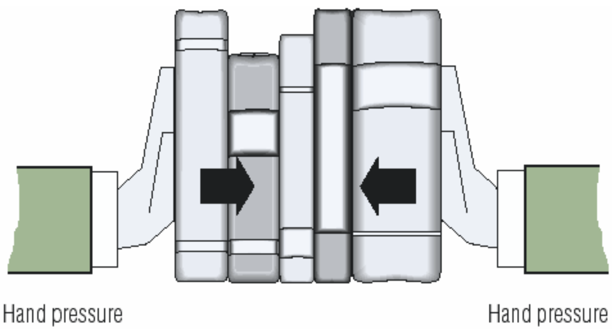


Figure 1.1 **Prestressing can be likened to picking up a row of books**

In reinforced concrete, the steel reinforcement carries all of the tensile stresses and, in some cases, even some of the compressive stresses. In prestressed concrete, the tendons are used primarily to keep the concrete in compression. The tendons are stretched (placing them in tension) and then bonded to the hardened concrete before releasing them. The force in the tendons is transferred to the concrete, compressing it.

A fully prestressed concrete member is designed to be permanently under compression, effectively eliminating most cracking. In this case, if the member is slightly overloaded, some tension cracks may form but these should close up and disappear once the overload is removed, provided always that the steel has not been overstrained beyond its elastic limit. In partially prestressed members, some tensile stresses, and therefore some cracking, is accepted at the design ultimate load.

In reinforced concrete, the steel is not designed to operate at a high level of stress, as elongation of the steel will lead to cracking of the concrete. In prestressed concrete, the steel does carry very high levels of tensile stress. Whilst it is well able to do this, there are some penalties attached. Firstly, because of the forces involved, considerable care must be exercised in stretching the tendons and securing them. Stressing operations should always be carried out, or at least supervised, by skilled personnel. Secondly, the structure must be able to compress, otherwise the beneficial prestressing forces cannot act on the concrete. The designer must detail the structure so that the necessary movements can occur.

Relevant New Zealand and Australian Standards

NZS 3101	*Concrete structures*
NZS 3109	*Concrete construction*
AS/NZS 4671	*Steel reinforcing materials*
AS/NZS 4672	*Steel wire for tendons in prestressed concrete*
AS/NZS 1314	*Prestressing anchorages*

Relevant Australian Standards

AS 1554.3	*Welding of reinforcing steel*
AS 3600	*Concrete structures*

1.1 BASIC PRINCIPLES OF REINFORCED CONCRETE

1.1.1 General

Whilst the behaviour of reinforced concrete is actually quite complex, for practical purposes we can assume that steel and concrete can combine to act compositely for the following reasons:

- Upon hardening, concrete bonds firmly to steel reinforcement so that, when loads are applied, the two act as though they are one. The tensile forces in any area are carried by the reinforcement.
- When subjected to changes in temperature, concrete and steel expand or contract by similar amounts. They therefore remain firmly bonded and continue to act compositely.
- Concrete, having a relatively high resistance to fire, and a relatively low thermal conductivity, protects steel reinforcement embedded in it, thereby substantially increasing the time taken for the temperature of the reinforcement to rise to a level where there is a substantial loss of strength.
- Concrete provides an alkaline environment to steel embedded in it. This protects the steel from rusting and, because concrete is relatively inert to chemicals other than acids, it continues to do so for long periods of time in all but very hostile environments.

The aims of a designer of reinforced concrete are threefold, viz:

- To determine the amount and the location of reinforcement so that it resists the stresses which develop in the concrete under load.
- To ensure that the steel has a sufficient thickness of concrete covering it to protect it from the environment to which it might otherwise be exposed.
- To ensure that the steel has a sufficient thickness of concrete around it to protect it against fire.

1.1.2 Types Of Stresses

The principal types of stresses that develop in structural elements or members, illustrated in **Figure 1.2** (page 1.4), are:

- compressive stresses – those which tend to cause the member to compact and crush;

- tensile stresses – those which tend to cause the member to stretch and crack; and
- shear stresses – those which tend to cause adjacent portions of the member to slide across each other.

Very rarely, however, is only one of these types of stress found in a structural member. Generally, some combination of compressive, tensile and shear stresses will be encountered and it is the job of the designer to determine these and locate the appropriate amount of reinforcement necessary to resist them.

Whilst shear stresses can be quite complex in the way in which they act and react, two principal types can be distinguished – vertical and horizontal. Vertical shear stresses occur, for example, near the ends of beams as the central portion of the beam tends to slide across the end portions which are being held in position by the supports **Figure 1.3**.

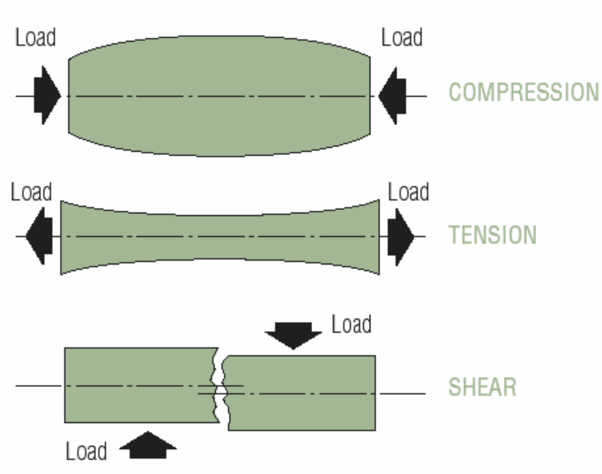


Figure 1.2 **Types of stresses**

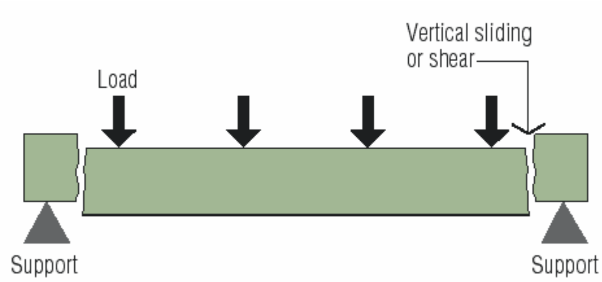


Figure 1.3 **Vertical shear stresses**

Horizontal shear stresses occur as the beam bends and the (imaginary) horizontal layers within it tend to slide over one another **Figure 1.4**.

When vertical and horizontal shear stresses react with one another, they produce what is known as diagonal tension which, in turn, tends to produce diagonal cracking. This is illustrated in **Figure 1.5** and commonly occurs near the ends of heavily loaded beams.

To resist such cracking, reinforcement must be provided. This is done commonly by providing stirrups or, on occasions, cranking the horizontal reinforcement **Figure 1.6**. Cranking steel is not used in New Zealand because it creates problems in dealing with earthquake forces which are cyclic in nature. Also open ended stirrups are not used because all the main steel needs to be confined to deal with earthquake forces. With stirrups, the spacing increases as the distance from the end of the beam increases.

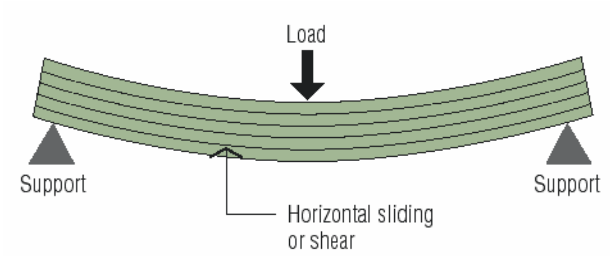


Figure 1.4 **Horizontal shear stresses**

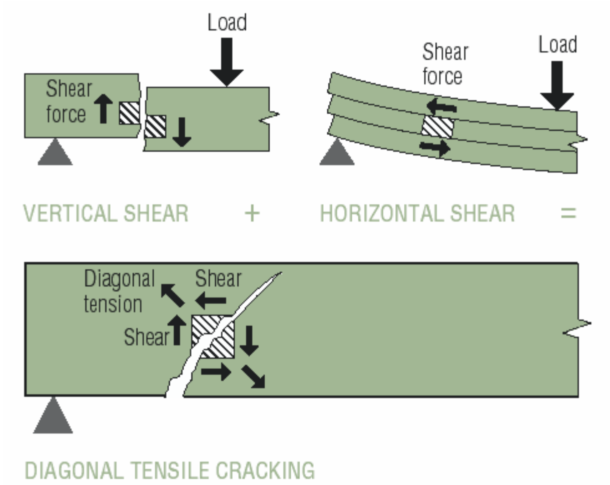


Figure 1.5 **Diagonal tension cracks**

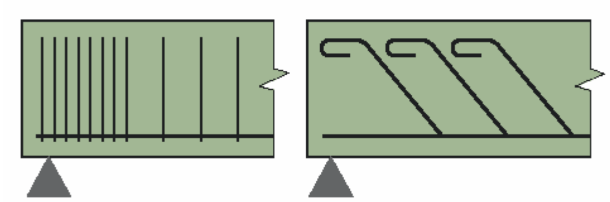


Figure 1.6 **Reinforcement to resist diagonal tension**

1.1.3 Stresses Found In Structural Members

Simply-Supported Beams and Slabs The action of a simply-supported reinforced concrete beam under load is shown in **Figure 1.7**. When such a beam is loaded, either by a central point load or a uniformly distributed load along its length, it tends to sag or deflect downwards. This causes the top of the beam to compress and the bottom of the beam to stretch. Reinforcement is placed in the bottom of the beam to resist the tensile stresses. Compressive reinforcement will not normally be required. The tensile stresses induce tension in the reinforcement and cracking in the concrete. Overloads will cause the reinforcement to elongate further and further cracking to occur, until, under severe overload, the beam will fail.

Simple Cantilevers When a simple cantilever beam or slab is loaded, it tends to droop or deflect as shown in **Figure 1.8**. Tensile stresses occur in the top of the beam or slab and compressive stresses in the bottom. In this case, therefore, the reinforcement is placed in the top of the beam.

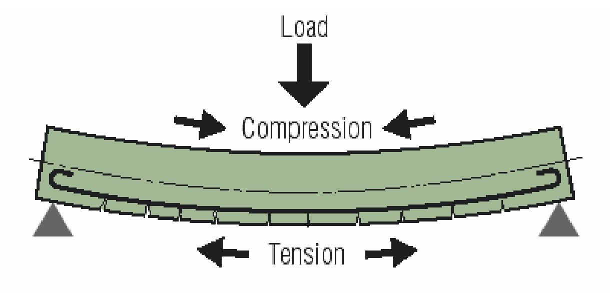


Figure 1.7 **Simply-supported beams or slabs**

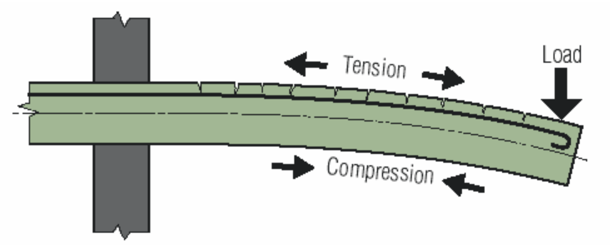


Figure 1.8 **Simple cantilevers**

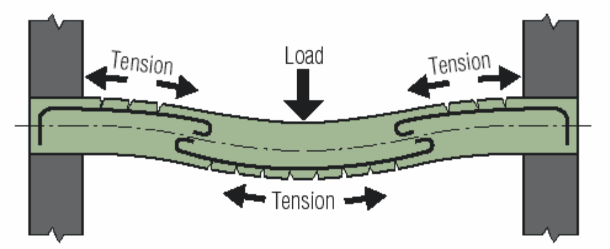


Figure 1.9 **Fixed-ended beams**

Fixed-Ended Beams When a beam which is fixed at both ends is loaded, it tends to bend as illustrated in **Figure 1.9**. Tension will again occur in the bottom of the beam and in this case also in the top of the beam close to the supports. Reinforcement must be placed in the top near the supports and in the bottom across the centre.

Multi-Span Beams and Slabs As may be seen in **Figure 1.10**, beams which span between more than two supports tend to flex or bend over the intermediate supports, necessitating reinforcement in the top of the beam at these points. They sag or deflect between supports, necessitating bottom reinforcement.

Retaining Walls Retaining walls may be likened to a vertical beam which is fixed at one end. The earth, or other material being retained, then causes the wall to act as a cantilever. However, in this case, the footing of the wall is also involved and it tends to bend or distort as load is applied. The resultant stresses are illustrated in **Figure 1.11** which also shows how the reinforcement would be distributed to resist these stresses.

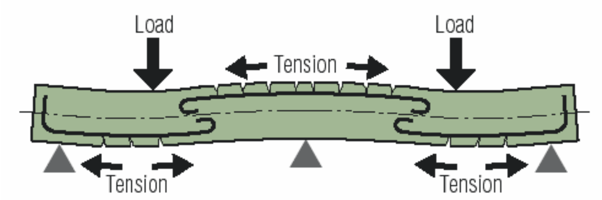


Figure 1.10 **Multi-span beams and slabs**

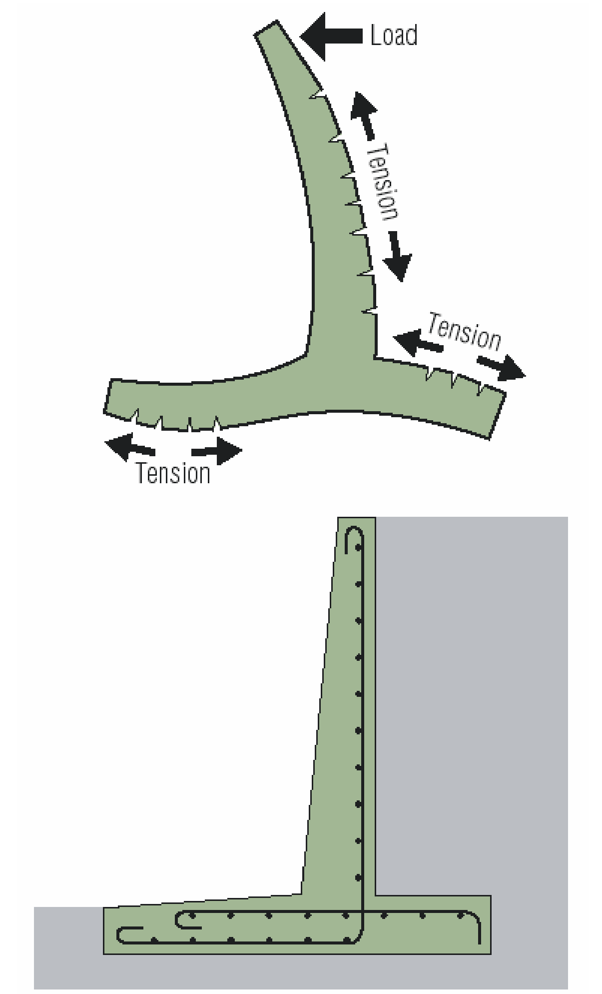


Figure 1.11 **Retaining walls**

Columns Whilst columns are designed primarily to support axial loads, bending moments are invariably introduced by uneven or eccentric distribution of the loads. Columns also tend to buckle, this tendency being a function of their slenderness. Tall, thin columns are more prone to this than are short, stocky columns.

All columns will require some reinforcement to resist these tendencies. Since, in practice, the load distribution on a column may change during its service life, it is normal to provide this reinforcement on all faces of a column to ensure that it remains safe, i.e. able to carry its loads, no matter how the distribution of these may change. This reinforcement also contributes to the ability of the column to carry axial loads.

This is illustrated in **Figure 1.12** which shows a column supporting a series of beams. As may be readily imagined, the loads on this column could change quite significantly as the loads on the beams change. Hence the column could tend to bend in any direction.

To resist the tensile stresses caused by bending in a column, vertical reinforcement is placed in the outer faces. This is illustrated in **Figure 1.13**. In addition, stirrups or ties are used to:

- help prevent lateral bursting of the column under axial loads;
- restrain the longitudinal reinforcement from buckling, and
- hold the main reinforcement firmly in place during concreting.

The prevention of steel buckling is very important in New Zealand which is why open stirrups cannot be used. Ties/links are at much closer centres than would be seen in overseas construction where earthquakes are not a risk.

1.1.4 Bond and Anchorage

As has been noted already, steel and concrete act compositely when they are firmly bonded together. The strength of this bond is an important consideration in the design of reinforced concrete. It is dependent on the concrete being thoroughly compacted around the reinforcement and on the latter being clean and free of loose scale, rust or other material. Formwork oil, for example, will destroy the bond between steel and concrete. The bond may be increased by the use of higher strength concrete or by the use of deformed reinforcing bars. These ribs or deformations rolled onto their surface which result in the bond with concrete being increased. NZS 3101/AS 3600 require that all reinforcement except that for fitments be deformed bars, see **Figure 1.14**.

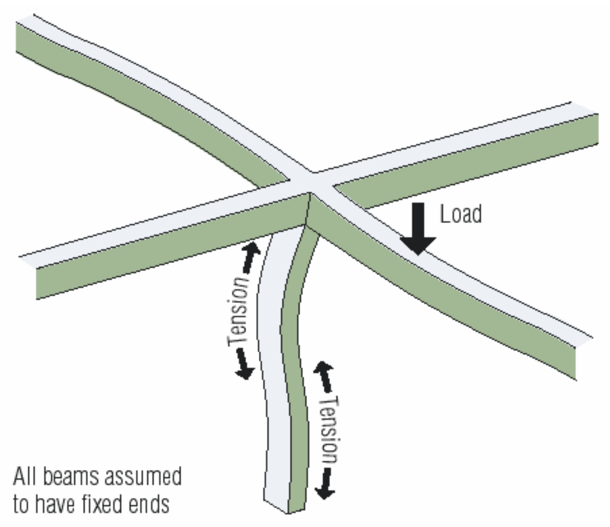


Figure 1.12 **Stresses in columns**

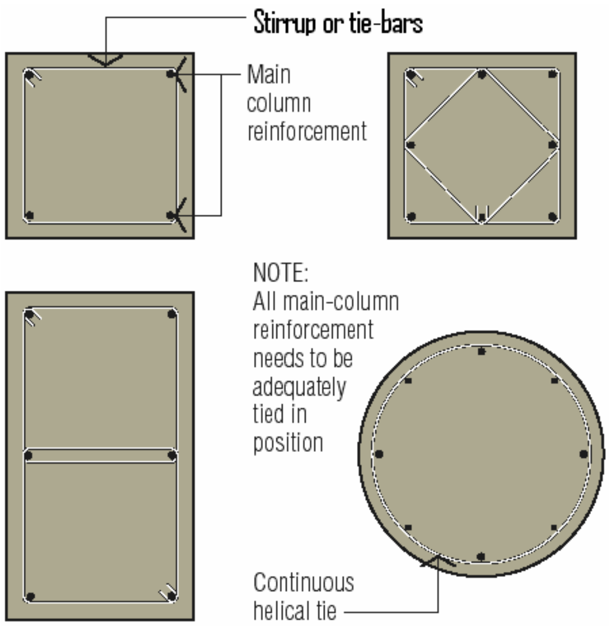


Figure 1.13 **Typical arrangement of column reinforcement**

Figure 1.14 **Typical 500-MPa deformed bar**

To ensure that adequate anchorage is achieved in the reinforcement, it is normally extended beyond the region of tensile stress for a sufficient length so that the bond between the reinforcement and the concrete can develop the tensile stress required at that point in the bar. Where this is not possible for some reason, or as an additional safety factor, bends or hooks in reinforcement are often used to provide the anchorage required.

1.2 BASIC PRINCIPLES OF PRESTRESSED CONCRETE

1.2.1 General

The action of a simply-supported reinforced concrete beam under load is described in Clause 1.1.3 and shown in **Figure 1.7**. In a simply-supported prestressed concrete beam, the application of the prestress normally results in a small upward camber or deflection of the beam as the concrete, on its underside, compresses under the action of the prestress **Figure 1.15(a)**. When an external load is then applied, the beam deflects or moves downwards, negating (or neutralising) the upwards camber **Figure 1.15(b)**. If an overload is applied, the beam will deflect still further and commence to behave in the same way as a reinforced beam. Tensile stresses will occur in the concrete and cracking will result **Figure 1.15(c)**. Severe overloads will cause the beam to fail as the steel is stretched beyond its ultimate limit.

In the context of the above, there are a number of special features about the behaviour of prestressed concrete beams (and columns) which should be noted, viz:

- The positioning of the prestressing tendons within a member is very important. Because of the magnitude of the forces involved, mislocation of tendons can have severe consequences. For example, in the beam shown in **Figures 1.15(a) and 1.15(b)**, location of the prestressing tendons closer to the bottom than was intended would cause an increased upward camber on the beam which may be unacceptable, and could even cause tension cracks to open in the top surface, which could be deleterious to the long-term durability of the beam.

- The magnitude of the stresses in a prestressed member are such that when it is precast it must be handled with considerable care. For example, the self-weight of a correctly positioned prestressed beam will tend to counteract the camber or upwards deflection **Figure 1.16(a)**. Placing a beam in an upside-down position (not unknown) will accentuate the deflection or camber and may even cause the beam to fail **Figure 1.16(b)**. Attempting to lift a beam by other than its designated lifting points may have similar consequences.

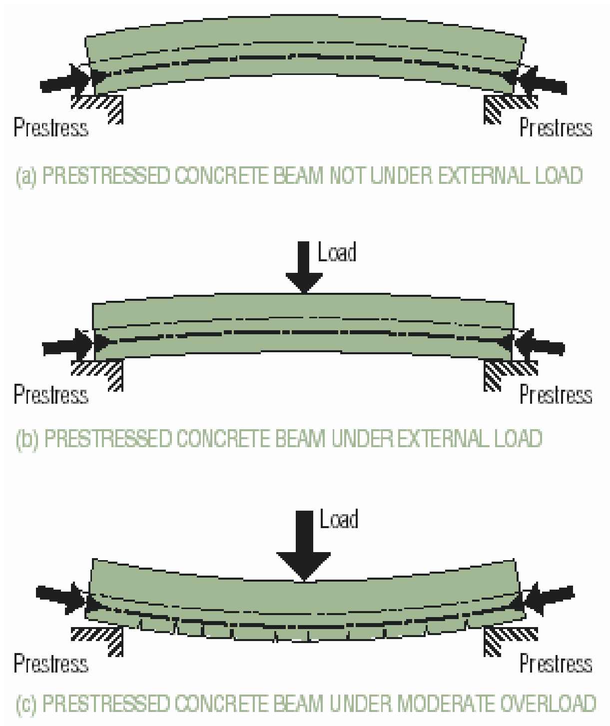


Figure 1.15 Simply-supported prestressed concrete beam under load

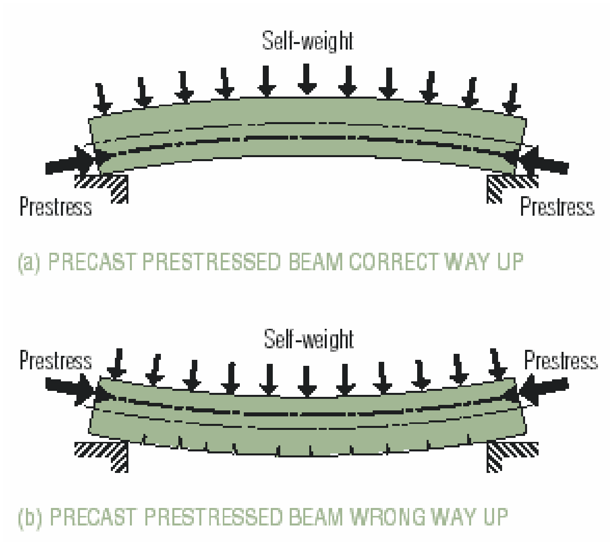


Figure 1.16 Positioning of a precast prestressed concrete beam

1.2.2 Pre-Tensioning

In a pre-tensioned member, tendons are first carefully positioned within the formwork and the design load or tension applied to them. Then, whilst tensioned, the concrete is cast around them and allowed to harden until it achieves sufficient strength (usually 40 MPa or higher) to resist the forces to be applied to it. The ends of the steel tendons are then released from their restraints and the stress in them transferred to the concrete by the bond between the two materials.

The tendons used in pretensioning are usually in the form of small-diameter wires or strands (a combination of smaller wires). The diameters of these materials are kept small to increase the surface area available for bonding with the concrete. Indented wire is also commonly used to further increase bond **Figure 1.17**.

1.2.3 Post-Tensioning

When a member is to be post-tensioned, the concrete is first allowed to harden before the steel tendons are stretched or tensioned. They cannot therefore be allowed to bond with the concrete, at least not initially. Usually they are placed in ducts or holes which have been cast in the concrete, although sometimes they are greased and encased in a plastic tube to prevent bond. In other cases, the tendons are fixed to the outside faces of the member.

After the concrete has gained sufficient strength, the wires or cables are tensioned and then fixed or anchored in special fittings cast into the ends of the concrete member. A wide variety of patented fittings and systems are available for this purpose. Typical slab and beam anchorages are shown in **Figures 1.18 and 1.19** respectively.

1.2.4 Applications

Although both pre-tensioning and post-tensioning systems are designed to apply prestress to concrete members, there are some practical differences in their fields of application. Thus, pre-tensioning is normally confined to the factory production of repetitive units where the cost of the relatively large abutments or restraints, against which the prestressing jacks operate, can be justified. Alternatively, very strong and robust formwork may be constructed and wires anchored against its ends.

Post-tensioning is more flexible in its application and may be carried out on-site. It permits the use of curved tendon profiles, and is also suited to a wide variety of construction techniques, such as 'segmental construction' and 'stage stressing'. Since stressing is not carried out until the concrete has hardened, the concrete member itself provides the restraint against which the stressing jacks operate **Figure 1.20**.

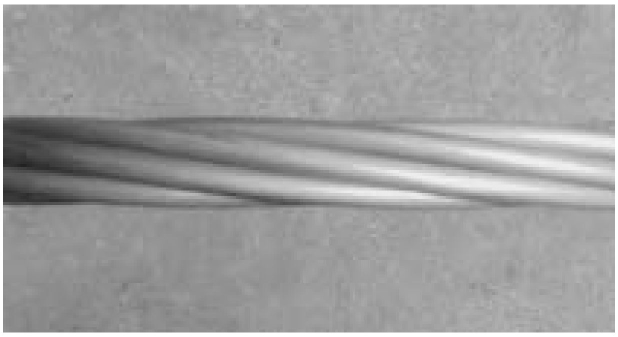


Figure 1.17 **Prestressing strand and wire**

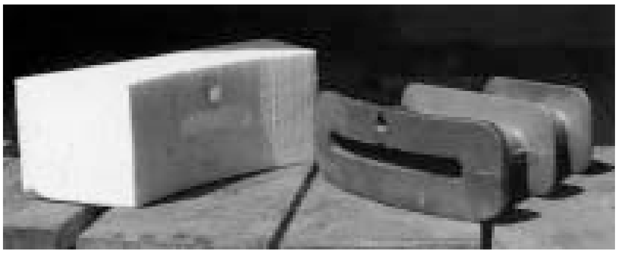


Figure 1.18 **Typical slab anchorage**

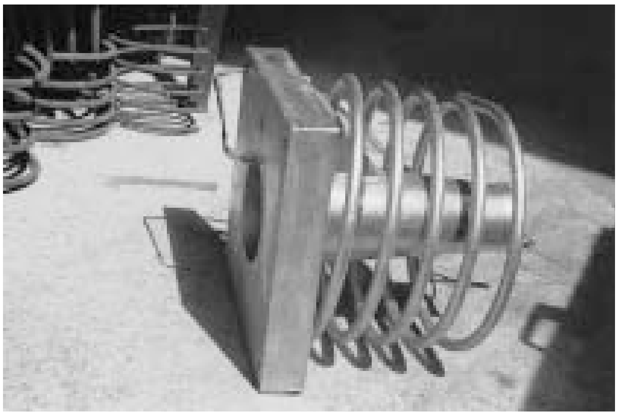


Figure 1.19 **Typical beam anchorage**

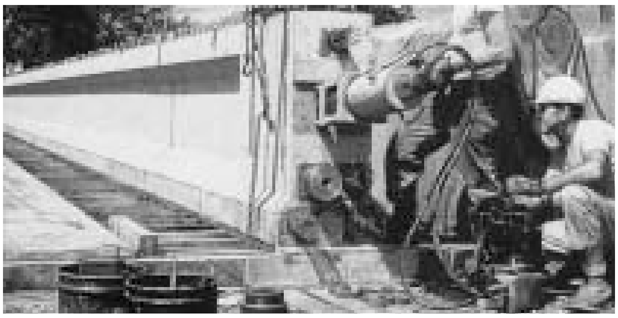


Figure 1.20 **Post-tensioning jack operating at end of concrete girder**

Hydraulic Cements

Chapter 2

Chapter 2

Hydraulic Cements

This chapter provides general information on the types of cement available in New Zealand and Australia with their characteristics, their chemical and physical properties. In addition, it supplements the information on the influence of cement on the properties of concrete given in Chapter 19 *Properties of Concrete*.

INTRODUCTION

Cement is the binding agent in concrete, normally the most active component, and usually the most costly. Its selection and proper use are important in obtaining the balance of properties required for a particular concrete mixture and in minimising the cost of that mixture. An understanding of the properties of the available cements and their influence on the properties of the concrete is important for the proper selection and use of these materials. Such understanding requires some familiarity with the chemical and physical characteristics of the cement and of their influence on cement performance.

Relevant New Zealand Standards

NZS 3122 *Specification for Portland and blended cements*

NZS 3123 *Specification for Portland pozzolan cement*

This Standard is being withdrawn and replaced by a supplementary cementitious materials in New Zealand document.

NZS 3125 *Specification for Portland limestone cement*

Note: NZS 3122 cross references to the following Australian Standards - AS 2350, AS 3582 and AS 3972.

Relevant Australian Standards

AS 1316 *Masonry cement*

AS 1379 *The specification and manufacture of concrete*

AS 2349 *Method of sampling portland and blended cements*

AS 2350 *Methods of testing portland and blended cements*

AS 2350.2 *Chemical composition of Portland cement*

AS 2350.4 *Setting time of portland and blended cements*

AS 2350.5 *Determination of soundness of Portland and blended cements*

AS 2350.7 *Determination of temperature rise during hydration of portland and blended cements*

AS 2350.11 *Compressive strength*

AS 2350.12 *Preparation of a standard mortar and moulding of specimens.*

AS 2350.13 *Determination of drying shrinkage of cement mortars*

AS 2350.14 *Length change of cement mortars exposed to sulphate solution*

AS 3582 *Supplementary cementitious materials for use with portland cement*

AS 3582.1 *Fly ash*

AS 3582.2 *Slag – Ground granulated iron blast-furnace*

AS 3582.3 *Silica fume*

AS 3972 *Portland and blended cements*

2.1 TYPES OF CEMENT AND THEIR USE

2.1.1 General

Cement is a term used to describe a wide variety of organic and inorganic binding agents. By far the most widely used are those known as hydraulic cements – finely ground inorganic materials which possess a strong hydraulic binding action, i.e. when mixed with water they harden, in the absence of air, to give a stable, durable product.

Hydraulic cements manufactured in Australia and New Zealand fall broadly into two classes, viz portland cements and blended cements. The latter are mixtures of Portland cement with other materials which either possess cementitious properties of their own, e.g. ground granulated iron blastfurnace slags (hereinafter referred to as slag), or which are pozzolanic in nature, i.e. they react with lime in the presence of water to form cementitious compounds, e.g. fly ash and silica fume.

Cements are manufactured in Australia to comply with the requirements of AS 3972. Six different types of cements are covered by this Standard, two of which are designated as 'General Purpose' and four as 'Special Purpose' cements.

In New Zealand, cements comply with NZS 3122.

The chart at the end of this chapter lists these cements and their fields of application. In addition, it covers a number of other hydraulic cements, some of which are produced locally, some of which are imported. The use of these is limited but they provide valuable additions to the range of binding agents available.

2.1.2 Portland Cements

Portland cements consist of carefully proportioned mixtures of calcium carbonate, alumina, silica, and iron oxide which, when calcined and sintered at high temperatures, give a new group of chemical compounds capable of reacting with water to form cementitious compounds. The raw materials most commonly used in making cement are calcium carbonate (in the form of limestone, coral or chalk), silica, alumina, and iron oxide (all in the form of clay and shale). Sources of silica (such as sand), of alumina (such as bauxite), and iron oxide (such as iron ore) are also used.

These materials are interground to produce the finely divided 'raw feed' for the kilns. This is then burnt in rotary kilns at temperatures from 1,300 to 1,500°C when the components partially fuse to form 'clinker' – hard balls of ceramic-like material. During burning, chemical reactions take place which convert the raw materials to new chemical compounds which are capable of reacting with water. When cool, the clinker is mixed with a small amount of gypsum (calcium sulphate) and ground to a fine powder.

In addition to gypsum, which is necessary to control the rate at which the cement hydrates when mixed with water, small quantities of other materials may be interground with the clinker in order to extend or enhance the properties of the cement. They range from very small amounts of organic compounds, which may be added to assist in grinding the clinker, to mineral additions such as limestone which may be added to assist in controlling the strength of the cement or to reduce its overall cost and/or environmental impact. The addition of such materials to portland cement is strictly controlled by NZS 3122/AS 3972 and their use should not be confused with that of the cementitious or pozzolanic materials which are used in blended cements in much larger quantities. NZS 3112/AS 3972 limits the amount of mineral addition to portland cement to no more than 5% (and this can be added only at the discretion of the cement manufacturer).

2.1.3 Blended Cements

In NZS 3122 and AS 3972, blended cements are defined as hydraulic cements containing portland cement and a quantity, greater than 5%, of slag, fly ash, or both and/or up to 10% silica fume. The materials approved by NZS 3122/AS 3972 for blending with portland cement are fly ash, slag and silica fume conforming to the requirements of the relevant parts of AS 3582. By extension, mixtures of portland cement and other active ingredients can be considered to be blended cements also, but are not presently included in the Standard.

As might be expected, the range of properties which can be achieved with blended cements is quite wide, depending on the nature of the blend and the proportions in which the constituents are mixed. In practice, however, the difference in properties between Type GP (general purpose portland cement) and Type GB (general purpose blended cement) may not be great as both are formulated to be used in general building construction.

2.1.4 Principal Cements Used in New Zealand

General

The physical and chemical properties specified in NZS 3122 are summarised in **Table 2.1** (page 2.4). As may be noted, there are few restrictions on the constituents of portland and blended cements. NZS 3122 is a performance based specification in which cements are defined in terms of their performance characteristics rather than their chemical composition.

As the raw materials used to produce portland and blended cements can vary widely from locality to locality, the chemical compositions of cements can vary quite widely also. Nevertheless, with modern technology, it is possible to produce cements from these diverse materials which have very similar physical characteristics. Hence, NZS 3122 specifies only those restrictions on chemical composition which are necessary to ensure satisfactory performance; e.g. upper limits on the MgO and SO_3 contents to guard against excessive long-term volumetric expansion of the hydrated cement paste.

Type GP – General Purpose Portland Cement

Type GP cement is intended for use in most forms of concrete construction and should be specified where the special properties of other types (such as high early strength, low heat of hydration, or resistance to sulphates (are not required.

Type GP cement may contain up to 5% of approved mineral additions. Mineral additions approved by NZS 3122 are limestone containing not less than 80% by weight of $CaCO_3$, fly ash and slag complying with the requirements of AS 3582. Such additions, in the proportions specified, are intended to assist the cement manufacturer in the production of a more economical and more uniform product. Hence, the requirement in NZS 3122 that such additions be made only at the discretion of the cement manufacturer. The limitations imposed on Type GP cement are those necessary to ensure satisfactory performance as a General Purpose cement. Thus its minimum strengths at 7 and 28 days are higher than those for the Special Purpose cements (except Type HE), but it is not required to have the special properties associated with those cements, for example low heat of hydration.

Table 2.1 **Summary of NZS 3122/AS 3972 requirements**

AS 3972 Requirement	Type of Cement GP	GB	HE	LH	SL	SR
Physical properties*						
Setting time						
Max. (h)	10	10	10	10	10	10
Min. (minutes)	45	45	45	45	45	45
Soundness						
Max. expansion (mm)	5	5	5	5	5	5
Compressive strength (MPa)						
Min. at 3 days	-	-	20	-	-	-
Min. at 7 days	25	15	30	10	20	15
Min. at 28 days	40	30	-	30	30	30
Peak temperature rise						
Max. ^{o}(C)	-	-	-	23	-	-
Drying shrinkage						
Max. (microstrain) 28 day	-	-	-	-	750	-
Sulphate expansion						
Max. (microstrain) 16 week	-	-	-	-	-	900
Chemical limitations*						
MgO in Clinker						
Less than (%)	4.5	4.5	4.5	4.5	4.5	4.5
SO_3 content						
Max. (5)	3.5	3.5	3.5	3.5	3.5	3.5

** When determined in accordance with the methods set out in AS 2350*

Type GB – General Purpose Blended Cement

Type GB cement may be seen as a companion to Type GP cement, being intended for use in most forms of concrete construction.

By varying the proportions of portland cement and fly ash, slag and silica fume in blended cements, it is possible to produce cements with a fairly wide range of characteristics. Whilst the minimum strengths specified for Type GB cements are lower than those for Type GP (in recognition of their generally lower rates of strength gain), it is not uncommon for their ultimate strengths to equal or exceed those of Type GP cement, provided moisture (e.g. through curing) is available for a sufficient length of time.

A possible exception to this is Type GB cement containing silica fume, which is often intended for use in applications where high strengths are sought.

Type HE – High Early Strength Cement

As the name implies, Type HE cement develops strength more rapidly than Type GP or Type GB cements. Rapid strength development should not be confused with rapid setting, the latter being the rate at which the cement paste loses its plasticity. Most cements have somewhat similar setting times but may have significantly different rates of strength gain.

High early strength cement lends itself to applications where rapid strength development is required; for example, where formwork has to be removed as soon as possible, for whatever reason, or where early strength is required so that further construction can proceed. The rapid strength development is usually accompanied by a higher rate of heat evolution. Hence, Type HE cement should not be used in thick concrete sections or in mass construction. On the other hand, its use for construction under cold weather conditions is beneficial.

Type LH – Low Heat Cement

Type LH cement is designed for use where limitation of the heat of hydration, and hence the temperature rise in concrete, is necessary to avoid unacceptable thermal stresses. These may occur in massive structures or in thick structural elements. Low-heat cement may be a portland or a blended cement provided it meets the requirements for temperature rise specified in NZS 3122 and AS 3972.

Low heat characteristics are achieved by reducing the content of the more rapidly hydrating compounds in cement or by blending with supplementary cementitious materials. This, generally, will result in a lower rate of strength development. Blended cements can have some inherent advantages in minimising heat evolution because of their lower rates of strength gain.

Type SL – Shrinkage Limited Cement

For many years, some major specifications in Australia have recommended chemical composition of cement as a means of controlling the shrinkage of cements to be used in concrete structures. Within the scope of NZS 3122 and AS 3972, a cement characterised in terms of its shrinkage performance was required to reflect/cover the existing practice in some areas and applications.

Type SL cement is intended for use where emphasis is placed on drying shrinkage and crack control in concrete structures (e.g. road pavements and bridge structures). Type SL cement may be a portland or a blended cement provided it meets the drying shrinkage limit specified in NZS 3122 and AS 3972 (see **Table 2.1**).

Type SR – Sulphate Resisting Cement

Type SR cement is intended primarily for use where resistance to ground waters containing sulphates in solution is required. The relationship between the sulphate resistance of portland cement and its tricalcium aluminate (C_3A) content is well established. Portland cement containing less than 5% C_3A is classified as sulphate resisting cement in many codes and standards for cement worldwide, including Australia until recently.

Studies have shown that cements potentially containing less calcium hydroxide on hydration perform well in sulphate exposure, e.g. certain blended cements. A limit on C_3A content for these cements is neither appropriate nor applicable. Therefore, as a performance based specification, NZS 3122 and AS 3972 replaced the limit on C_3A for sulphate resisting portland cement by a performance test and a performance limit (expansion limit) suitable for Type SR cement, being portland or blended cement **Table 2.1**.

Type SR cement may be a portland or a blended cement provided it meets the sulphate expansion limit specified in NZS 3122. The formulation of Type SR, as a blended cement, or as a portland cement with a low C_3A content, may produce a cement having a lower rate of strength development at early age than, say, Type GP cement. Hence, the minimum strength requirements in NZS 3122 for Type SR cement are lower than those for Type GP cement **Table 2.1**.

Portland Limestone Filler Cement and Concrete

This cement is produced in New Zealand by intergrinding cement clinker with up to 15% by total weight of mineral limestone that has a minimum calcium carbonate content of 75%.

Concretes produced from this cement generally show enhanced workability properties which is particularly useful on unformed surfaces. Some water addition savings are possible which allows for some strength adjustments. The cement is produced to comply with the provisions of NZS 3125 which also specifies limits on clay content and organic matter.

Portland Pozzolan Cement and Concrete

Pozzolan has been used with advantage in portland cement concrete in New Zealand in instances where a relatively low heat of hydration has been sought, as in mass concrete for hydraulic structures, and in sewage work where the concrete is subject to sulphate attack. The inclusion of a pozzolan has also served to inhibit harmful expansion that may result from alkali-aggregate interaction. Other characteristics of a portland pozzolan concrete include relatively high long-term strengths, reduced permeability, and in certain cases relatively low strengths at early ages. The properties of fresh concrete (before set) may also be modified, such as increased cohesiveness and resistance to segregation. The cement which could be regarded as a GB cement does have its own specification contained in NZS 3123. This standard is being withdrawn and a document covering a wider range of supplementary cementitious materials is in preparation.

Off-white and White Portland Cements

The grey colour of portland cements is due mainly to the presence of iron in the cement (the ferrite phase – tetracalcium aluminoferrite, C_4AF)). By lowering the iron content, light-coloured cements can be produced. This is achieved by using raw materials low in iron and manganese oxides. Because of more costly raw materials and special requirements in manufacturing, off-white and white cements are more expensive than the more widely used grey portland cements.

The composition of off-white and white cements is characterised by relatively high C_3A contents (9 to 14%) and low C_4AF contents (3% for off-white and 0.3 to 0.4% for white cements).

Off-white and white cements are used principally for architectural purposes. Since relatively high cement contents are normal in this application, dense concretes of low water-cement ratio, which are required properties for durability, can be obtained. However, because of the high C_3A

content of this type of cement, it should not be used in low heat or sulphate resisting applications.

There is no specific New Zealand or Australian Standard for these types of cement, but off-white cement is manufactured in Australia to meet the requirements for Type GP, GB or HE in AS 3972. Off-white and white cements imported into New Zealand are generally required to comply with NZS 3122/AS 3972 also.

Coloured Cements

Most coloured cements consist of cement and inorganic pigments interground or mixed together, although some are produced from clinkers having a characteristic colour derived from the raw materials or the manufacturing process.

In the production of coloured cements with pigments, the base is either grey cement or the more costly off-white or white cement. Grey cement is normally used to produce dark colours.

To be suitable for use with cements, pigments are required to be colour-fast under exposure to light and weather and of a chemical composition such that the pigment is neither affected by the cement, nor detrimental to its setting, hardening, and durability characteristics. Pigments should not contain salts that may cause efflorescence.

Masonry Cement

Masonry cement is intended mainly for use in mortar for brick, stone and concrete block construction. It is a finely ground mixture of portland cement clinker, gypsum (calcium sulphate) and suitable inorganic materials such as hydrated lime, limestone and pozzolans. Air-entraining agents, water-reducers (plasticisers) and water-repellent substances may also be incorporated. Masonry cement is produced in Australia to meet the requirements of AS 1316.

There is no specific New Zealand Standard and it is recommended manufacturers should follow AS 1316.

It is characterised by producing mortars of high workability and high water retentivity, but which have a lower rate of strength development than those made from portland cement. These characteristics make masonry cement especially suitable for masonry work but it is entirely unsuitable for any form of structural concrete (plain, reinforced or prestressed).

Oil-well Cement

Oil-well cement is used in the petroleum industry to grout oil and gas wells. In these applications, the cement slurry must remain sufficiently fluid (at temperatures ranging from normal to about 200°C and under pressures ranging from atmospheric to about 125 MPa) for the several hours needed to pump it into position. It should then harden fairly rapidly. It may also have to resist corrosive conditions resulting from sulfur gases or waters containing dissolved salts.

Oil-well cements are modified portland cements that are designed to serve this need. They consist of coarsely ground portland cement of low C_3A content, with or without a retarder.

The properties required of oil-well cements are set out in the American Petroleum Institute Standard STD 10A *API Specification for Oil-well Cements and Cement Additives*. They are subdivided into six classes each applicable to a specified range of well depths, temperature and corrosion conditions.

Special methods of testing oil-well cements for thickening times and strength under conditions of high temperature and pressure have been developed and are covered by the American Petroleum Institute Standard API RP-10B *Recommended Practice for Testing Oil-Well Cements and Cement Additives*.

High Alumina Cement (HAC)

HAC is entirely different from portland cement in its chemical composition and in its characteristics. The difference is derived from the raw materials from which it is made, principally bauxite and limestone. The product resulting from the chemical combination of these two materials is a cement having a high alumina (Al_2O_3) content and a low lime (CaO) content as compared with portland cement. In some literature, HAC is called 'calcium aluminate cement', but it is more commonly known as high alumina cement. It is imported into New Zealand and Australia.

HAC is characterised by a very rapid rate of strength gain which results in very high early strengths and high rates of heat evolution. The latter characteristic allows hardening to take place at relatively low temperatures but prevents its use in mass concrete or in other applications where high rates of heat evolution may cause problems. HAC is resistant to attack by sulphates and sulphate solutions, a property which, combined with its high early strength, has led to its use in factory floors and similar applications. It also finds application in refractory concrete because of its resistance to very high temperatures.

However, HAC may suffer a substantial loss of strength in conditions which are both warm (above, say, 25°C) and humid. Under these conditions, a chemical process, known as conversion, takes place during which some of the hydrated compounds of the hardened cement paste convert to other compounds of smaller volume. This results in a cement paste with reduced strength.

The rate at which conversion occurs depends on the moisture condition and temperature of the concrete. Where moisture is present and temperatures are above 25°C, the rate is fairly high. Water-cement ratio also affects the rate of conversion; the greater the original water-cement ratio, the faster the rate of conversion and the lower the converted strength. External chemical agents may also affect the rate of conversion.

The use of HAC in warm humid environments should therefore be approached with great caution because of the possibility of conversion and loss in concrete strength.

If portland cement is added to HAC, the setting time of the mixture is significantly less than that of either product used alone. The exact proportion at which the most rapid set is obtained varies with particular batches of HAC and portland cement.

Mixtures of the two cements are used neat, or in mortars and concretes, for applications requiring a quick set and the development of reasonable strength at a very early age, e.g. for sealing leaks or cementing rock. However, in general, the faster the setting time the lower the ultimate strength obtained. Caution should therefore be exercised in applications where the strength of the concrete is important to its performance.

2.2 CHEMICAL PROPERTIES

2.2.1 General

The chemical composition of portland cements, high alumina cements, slags and pozzolans is dominated by three oxides, viz: lime (CaO), silica (SiO_2) and alumina (Al_2O_3). The proportions of these oxides in these cementitious products is shown in the ternary diagram in **Figure 2.1**. Each axis of this diagram represents the percentage of the oxide present.

2.2.2 Portland Cement

Chemical Composition The chemical composition of most modern portland cement falls within the ranges given in **Table 2.2**. The composition of individual cements depends on the type of cement being manufactured and on the nature and composition of the raw materials being used. Given the wide range of raw materials found in New Zealand and Australia, it is not possible for all cements, even of the same type, to have exactly the same chemical composition.

Portland cement includes four major minerals which are formed during the clinkering process. These

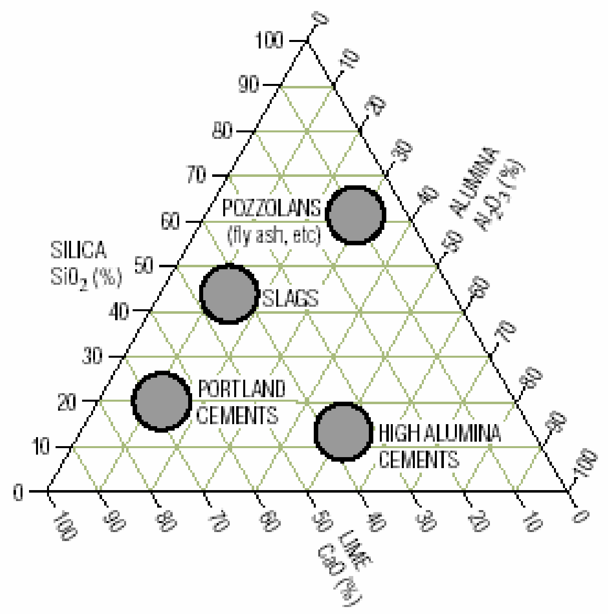


Figure 2.1 **Typical chemical compositions of cementitious materials**

Table 2.2 **Approximate oxide content limits of portland cement**

Oxide	Content (mass %)
Lime (CaO)	60 – 67
Silica (SiO_2)	17 – 25
Alumina (Al_2O_3)	3 – 8
Iron Oxide (Fe_2O_3)	0.5 – 6.0
Magnesia (MgO)	0.1 – 4.5
Alkalis (Na_2O + K_2O)	0.5 –1.3
Titania (TiO_2)	0.1 – 0.4
Phosphorus (P_2O_5)	0.1 – 0.2
Gypsum (expressed as SO_3)	1 – 3

are identified as: tricalcium silicate (C_3S), which exists in clinker in the impure form – alite; dicalcium silicate (C_2S); tricalcium aluminate (C_3A); and the ferrite phase which exists as a compound close in composition to tetracalcium aluminoferrite (C_4AF).

Each of these four minerals (phases) exists in several different crystal forms with some variation in properties. The main properties of the four phases are summarised in **Table 2.3** (page 2.8). In addition, some 'minor' constituents will be present in relatively small amounts; e.g. gypsum, alkali oxides and magnesia. Further details of these constituents are given in the Appendix to this chapter.

Reaction with Water

When portland cement is mixed with water, a series of chemical reactions take place which result in the formation of new compounds and the progressive hardening of the cement paste. Evolution of heat and the development of compressive and tensile strength within the paste occur with the passage of time.

When water is added, the resulting hydration of the tricalcium aluminate (C_3A) is affected by the gypsum included in the cement to control its setting. The immediate reaction between the C_3A and gypsum produces a needle-like crystal known as 'ettringite'. It is this ettringite layer on the surface of the C_3A grains which retards the hydration process, resulting in a dormant period in which the concrete remains plastic.

Further hydration of the C_3A, however, results in the conversion of the ettringite into a monosulphate and a hexagonal solid plate solution (C_4AH_{13}).

Figure 2.2 provides a schematic representation of these chemical reactions to a typical time scale and the resulting formation of the paste structure. Note the reduction in porosity as the setting and hardening progresses.

The rates of the reactions, and the nature and amounts of the products formed, depend on the chemical composition of the cement, on the temperatures at which the reactions take place, and on whether or not chemical admixtures are present in the mixture.

2.2.3 Blended Cements

Chemical Composition

As noted earlier, blended cements contain, in addition to portland cement, either slag, fly ash, silica fume or a combination of these. These materials are referred to as supplementary cementitious materials and are covered by AS 3582.

Slag is a non-metallic product, consisting essentially of silicates and aluminates, which is produced simultaneously with iron in a blast furnace and which is then granulated by rapid quenching. Finely ground granulated slag possesses the property of latent hydraulicity, i.e. (with some exceptions) it does not set when mixed with water alone, or does so only slowly, but will behave as hydraulic cements in the presence of activators. In a saturated solution of calcium hydroxide ($Ca(OH)_2$) hydration of the slag occurs and continues at a gradually reducing rate as the concentration of $Ca(OH)_2$ in the solution falls. Portland cement is an effective activator as it releases sufficient calcium hydroxide during hydration to activate the slag and enable it to form hydration products of its own. These are similar to those produced by portland cement.

Slag may be blended with portland cement to form a blended cement or it may be added to the

Table 2.3 Properties of the major constituents of portland cement

Mineral (phase)	**Characteristics**	**Potential heat of hydration*** (J/g)
C3S	Light in colour. Hardens quickly with evolution of heat. Gives early strength.	500
C2S	Light in colour. Hardens slowly. Gives late strength.	250
C3A	Light in colour. Sets quickly with evolution of heat. Enhances strength of the silicates.	850
C4AF	Dark in colour with little cementing value.	400

** This potential is not reached in cement hydration. The heat developed by a cement at any particular age is governed by the rate of hydration.*

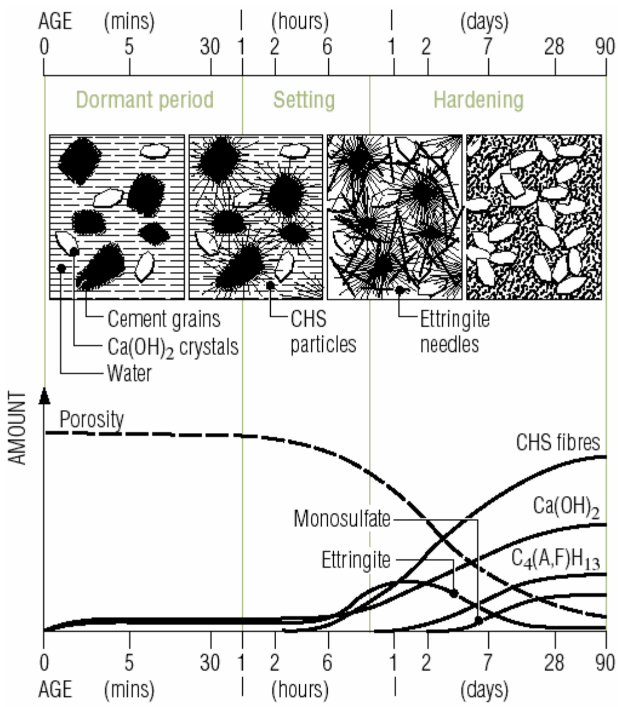


Figure 2.2 Schematic representation of chemical reactions when cement and water are mixed

ingredients of a concrete batch as a replacement for cement. Pozzolans are defined as silicious, or siliceous and aluminous, materials which in themselves possess little or no cementitious value but which will, in finely divided form and in the presence of moisture, react chemically with calcium hydroxide to form compounds possessing cementitious properties.

Not all silicious and aluminous materials are pozzolanic; for example, quartz does not react with lime solutions (calcium hydroxide) at room temperatures. It is only when the silicious and aluminous materials are present in non-crystalline form and as small particles, that they show significant pozzolanic activity.

Pozzolanic materials include natural pozzolans, some fly ashes, and silica fume. Natural pozzolans occur as silicous, or as siliceous and aluminous rocks or minerals such as volcanic ashes and diatomaceous earths. Such materials in their natural forms are often not very active and require some processing (e.g. heat treatment and/or grinding) to make them useful as pozzolans. They are not common in Australia but do occur in New Zealand.

Fly ash is finely-divided residue from the combustion of pulverised coal in power stations. It is removed from the flue gases by electrostatic precipitators. It consists mainly of aluminosilicate glassy material with inclusions of small amounts of sodium, potassium, calcium, magnesium, titanium and iron.

The chemical composition of fly ash is largely determined by the composition of the coal used. The physical and granulometric properties of the ash are a function of the fineness of grinding of the coal, the burning temperature, the rate of cooling of the ash and its method of collection. All of these may affect its pozzolanic properties.

Fly ash is used as a component of blended cement or as a separate material added to the concrete batch. The performance of the fly ash in cement and concrete, especially at early ages, depends to a greater extent upon its physical and granulometric properties than upon its chemical composition. A good quality fly ash possesses two important characteristics: water-reducing capacity, i.e. when it is used in mortar or concrete, the water required to produce a given workability is reduced; and a capability, in the long term, to contribute more to the strength of the matrix than the portland cement it replaces.

The water-reducing capability increases with the fineness of the ash and decreases with increasing carbon content. The early pozzolanic reactions are influenced by the surface area of the glassy material available to react with calcium hydroxide. The ultimate activity depends on the total silica and alumina available.

These characteristics are recognised in many national standards for fly ash which specify minimum amounts of glassy material, fineness, and maximum loss on ignition. The latter is an indication of the carbon content of the fly ash.

Silica fume is a by-product from the production of elemental silicon and ferro-silicon alloys. Fine silica is also available in New Zealand by extraction from geothermal water. Although sometimes referred to as silica dust, silica powder, silica flour or micro-silica, it consists of extremely fine spherical particles of amorphous silicon dioxide and possesses an exceedingly high specific surface area which gives it an active pozzolanic characteristic.

Silica fume is used as a component of blended cement or as a separate material added to the concrete batch. The high surface area of silica fume can increase the water demand of the concrete mix. To optimise the benefits of silica fume, high range water reducers (superplasticisers) are used to maintain mixing water requirements at an acceptable level.

Reaction with Water

When mixed with water, blended cements hydrate to produce calcium silicates and calcium aluminates in a manner analogous to that of hydrating portland cement. However, there are some important differences. Firstly, with pozzolanic materials such as fly ash and silica fume, it is the calcium hydroxide produced during the hydration of the portland cement which reacts with the silica in the pozzolan to form calcium silicate hydrates. These are similar to those produced by portland cement. The lime-silica reaction is much slower, however, than the hydration of portland cement and so cement-pozzolan mixtures tend to have lower strengths at early ages. They tend also to have lower heat of hydration.

Secondly, with slags, the calcium hydroxide acts as an activator as well as participating in the reactions. In this case also, hydrated calcium silicates and aluminates are formed. Since slags are themselves weakly cementitious, the reactions will be somewhat faster than with lime pozzolanic mixtures but, nevertheless, slower than those with portland cement alone. Blended cements made with slags can be expected to have lower rates of strength gain also. However, allowance for this can be made in the manufacture of the blended cement (e.g. by finer grinding) and in the curing of the concrete to ensure suitable strength development. At later ages, the strengths of blended cements may equal or exceed those of portland cements.

2.3 PHYSICAL PROPERTIES

2.3.1 Setting Time

When mixed with water, portland and blended cements form a plastic workable paste which progresses through setting to eventual hardening. Setting time is the period during which the cement paste loses its mobility. Arbitrarily defined initial and final setting times are used as a practical basis for ascertaining the end of the workability period and the onset of hardening.

Initial set for cement is the point at which the paste reaches a certain degree of stiffness. The time required for the paste to reach initial set is known as the 'initial setting time'. It is one of the major influences which determine the length of time for which mortar and concrete remain plastic and workable. To ensure that mortars and concretes do not stiffen or set too early, a minimum initial setting time for portland and blended cements is specified in NZS 3122/AS 3972 (see **Table 2.1**).

Final set for cement is the point at which the paste may be regarded as a rigid solid and at which it begins to develop measurable strength. The time required for the paste to reach final set is known as the 'final setting time'. A maximum value is therefore specified NZS 3122/AS 3972 (see **Table 2.1**).

The initial and final setting times are determined using the test procedure set out in AS 2350.4 which measures the penetration of a needle into a paste of specified consistency. When the needle fails to penetrate the paste by the specified amount within the specified time, the cement is said to have achieved its initial set. Final set is said to have taken place when the needle fails to penetrate the paste by 0.5 mm.

The setting times for cement paste are not, however, those which are applicable to concrete. The latter are affected by the water content of the concrete mix, the temperature, whether or not the concrete incorporates admixtures and, if so, their type and dosage.

2.3.2 Heat of Hydration/Temperature Rise

The heat of hydration of cement is the heat liberated as the cement and water react. The amount of heat liberated over time, and the rate at which this occurs, is dependent on the cement type, water-cement ratio and temperature. In general, the rate of heat liberation parallels the rate of strength increase. This rate is usually high during the first two to three days after mixing with water and then subsides appreciably.

Liberation of heat during the hydration of the cement results in rise in temperature. Temperature-rise/age relationship of various cements is shown in **Figure 2.3**. In most concrete construction, heat is dissipated from the concrete and large rises in temperature do not occur. However, in structures such as massive foundations, dams, and thick structural elements the differential temperature, between the core and the outside surface, in the large concrete sections may lead to cracking. Thus, limiting the temperature rise in concrete is important to avoid thermal cracking. Cements of low heat characteristics are produced for use in these applications.

Measurement of heat hydration using the heat of solution method has been used to characterize cements by many countries. While this method determines with good accuracy the total heat of hydration at seven days and longer, it gives no indication of the actual temperature rise under practical conditions or, more importantly, at early age when the maximum temperature rise is likely to occur. Further, the method is not suitable for blended cements for which other methods are now available, e.g. Langavant method.

AS 3972 and NZS 3122 specify/characterise low heat cement by the peak temperature rise, **Table 2.1**, measured on a standard cement mortar under semi-adiabatic conditions. **Figure 2.3** shows typical temperature rise/age curves for various types of cement.

Peak temperature rise is determined in accordance with AS 2350.7. This test method is based on a French test known as the Langavant method, but modified to put the emphasis on measurement of temperature rise allowing, as an option, the calculation of heat of hydration, if required.

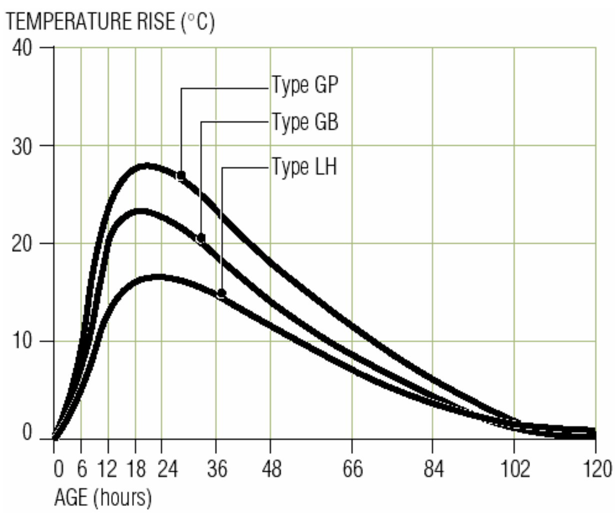


Figure 2.3 **Typical temperature rise with age of cement mortars – semi adiabatic calorimeter (AS 2350.7)**

2.3.3 Strength Development

On addition of water, the cement constituents hydrate, giving mainly hydrates of calcium silicate, calcium aluminate and calcium hydroxide. The hydration involves an increase in the volume of the solids, bringing about stiffening of the cement paste (setting). Further hydration decreases the porosity of the set paste, thereby increasing its strength. The gain in strength of the set paste (strength development) is at its maximum rate at early ages, and gradually decreases with time **Figure 2.4**. Ultimate compressive strength may take several years to achieve, but for indicators for the 'final' strength of most cements and are specified in cement Standards all over the world.

The rate of strength development of portland cement is influenced by both the chemical composition and fineness of the cement. The rate of strength development of blended cements is dependent on the nature and proportion of the component materials, i.e. the type and properties of portland cement, and the properties of the fly ash, slag and silica fume. As mentioned earlier, fly ash and slag blended cements gain strength more slowly than portland cements at early ages, but they exhibit more strength gain over a longer period, particularly if moisture is available for a sufficient time. On that basis, the ultimate strength of blended cements can be higher than that of the portland cement it incorporates **Figure 2.5**.

The compressive strength of portland and blended cements is determined by crushing tests on prisms made from the standard mortar (1:3 cement-sand mixture of 0.5 water-cement ratio). The specimens are made in accordance with AS 2350.12 and the test is conducted in accordance with AS 2350.11.

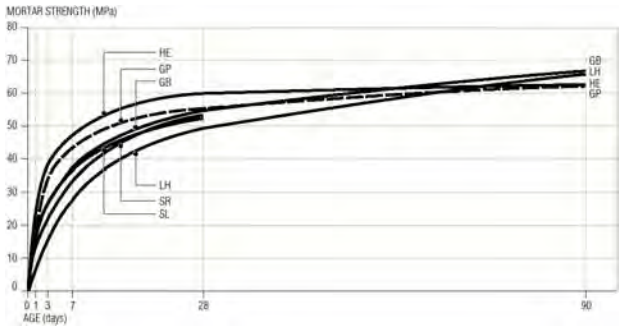


Figure 2.4 **Typical cement mortar strength development with age (AS 2350.11)**

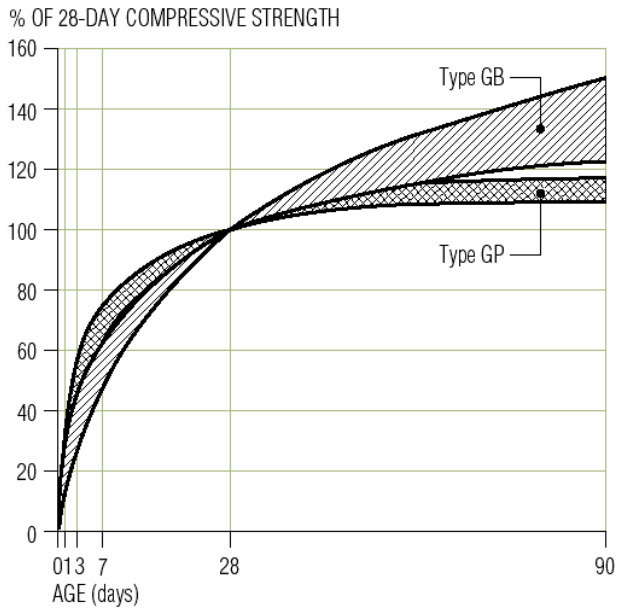


Figure 2.5 **Development of concrete strength with age**

2.3.4 Volume Change

General

A change in the volume of the hardened paste may be caused by chemical reactions, e.g. attack by aggressive solutions (see Clause 3.7); or by physical factors, such as changes in the moisture content or in the temperature of the paste.

Volume changes due to variations in moisture content (shrinkage) and to variations in temperature (thermal expansion and contraction) are discussed below.

Shrinkage

Variations in the moisture content of cement paste are accompanied by volume changes: drying causes volume decrease, i.e. drying shrinkage; while wetting causes volume increase, i.e. swelling or expansion. A schematic description of volume changes in cement paste due to alternate cycles of drying and wetting is given in **Figure 2.6**. It can be noted that maximum shrinkage occurs on the first drying of the paste and that a considerable part of this shrinkage is irreversible; part of the reduction in

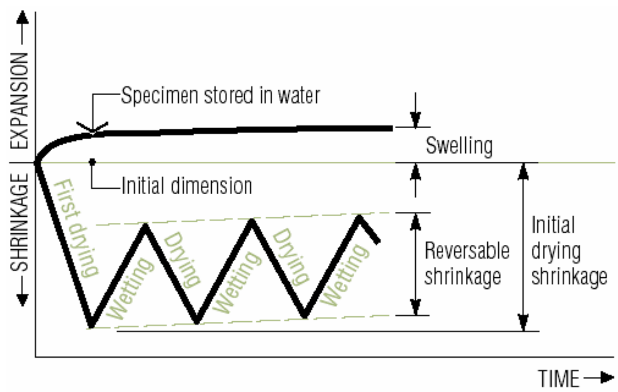


Figure 2.6 **Schematic representation of volume changes in cement paste due to alternate cycles of drying and wetting**

volume is not recovered on subsequent rewetting. During successive repetitions of wetting and drying, the process becomes reversible, depending on the structure of the paste and on the relative duration of the wetting and drying periods. Since shrinkage is caused by water loss, it is affected by external factors that affect drying, such as temperature, humidity and air movement. Shrinkage is also affected by the properties of the cement.

Although it is generally concluded that the composition of cement can affect drying shrinkage, the effect is not completely determined. The C_3A and alkali content have been observed to have a dominant effect. In turn, the effect of C_3A and alkali content on shrinkage is influenced by the gypsum content of the cement, i.e. shrinkage of cements of the same C_3A content differs for different gypsum contents.

As a result, for many years, some major project specifications in Australia have specified the chemical composition of cement as a means of controlling shrinkage of concretes to be used in structures, such as road pavements and bridges. It was recognised, however, that there are other cements outside these specifications which have performed well in low shrinkage concrete applications. This has led to the development of a cement characterised in terms of its shrinkage performance – Shrinkage Limited Cement, Type SL. An upper limit for drying shrinkage at 28 days of the standard cement mortar is set in NZS 3122/AS 3972 for Type SL cement (see **Table 2.1**).

SL cement is not commonly available in New Zealand.

Relationship Between Shrinkage of Cement and Shrinkage of Concrete

The shrinkage of cement cannot be applied directly to the shrinkage of concrete since the latter is greatly influenced by factors other than cement properties. Some of these are related to the concrete itself and others to ambient conditions – temperature and humidity. Aggregates restrain the drying shrinkage of the cement paste. The restraining effect of the aggregate, illustrated in **Figure 2.7**, is governed by its volume fraction in concrete, its modulus of elasticity and its absorption characteristics. Thus, aggregates that lack volumetric stability (such as certain volcanic breccias) will cause significantly higher drying shrinkage than those that are stable. The water content of the concrete influences its shrinkage; the higher the water content, the higher the shrinkage.

Admixtures may also affect the shrinkage of concrete in a number of ways. For example, some set-accelerating admixtures (e.g. triethanolamine) cause substantial increases in the drying shrinkage. Also, when lignosulphonate-based water-reducing admixtures are added to a concrete mix without adjusting the mix proportions, an increase in the early drying shrinkage may occur.

On the other hand, the use of an admixture which enables a net reduction in the water content of the concrete to be achieved will often result in reduced shrinkage. The complexity of modern admixtures is such that it is dangerous to generalise.

Similarly, the use of pozzolanic materials may result in either an increase or a decrease in drying shrinkage depending on their effect on the water-demand of the concrete.

Therefore, limiting the shrinkage of cement alone will not guarantee the production of low shrinkage concrete. The other factors discussed need to be considered as they may outweigh the effect of cement on the drying shrinkage of concrete.

Thermal Volume Changes

The coefficient of thermal expansion of cement paste varies between 10 x 10^{-6} and 20 x 10^{-6}/°C depending, mainly, on the moisture content of the paste. The coefficient increases with increases in the relative humidity, reaching a maximum at about 70% relative humidity.

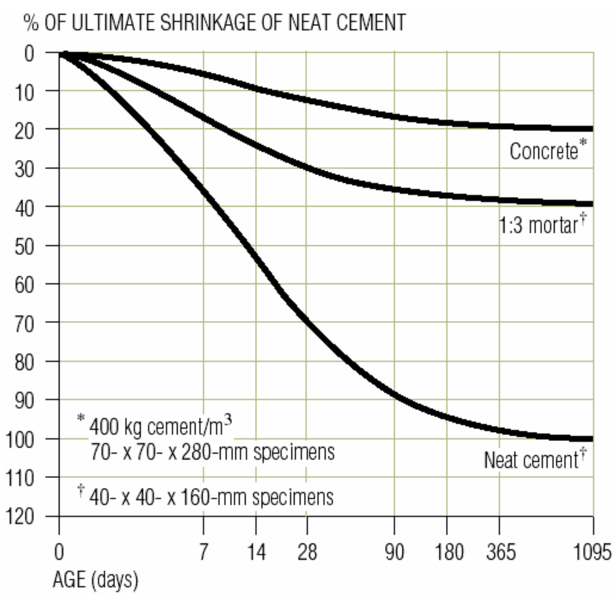


Figure 2.7 **Comparative drying shrinkage of concrete, mortar and neat cement at 50% relative humidity**

2.3.5 Permeability

Permeability of the cement paste depends not only on the porosity but also on other properties of the pore system, such as continuity and pore size distribution. These properties are affected by the water-cement ratio and the degree of hydration which in turn is affected by the amount of curing given to the paste. The effect of the water-cement ratio is illustrated in **Figure 2.8** (page 2.13) and the effect of moist curing in **Table 2.5** (page 2.13).

2.3.6 Alkalinity

Hydrated cement paste is inherently an alkaline material having a pH of approximately 12.5. It is this property which provides cement with its ability to protect steel from corrosion.

The composition of cement has little or no influence on the level of alkalinity of freshly hydrated cement paste but a reduction in alkalinity may take place as a result of the leaching of alkalis from the paste and/or the carbonation of the hydrated cement. Field and laboratory investigations have shown that the rate and extent of carbonation of blended cements tends to be higher than that of portland cements, but the permeability of the paste is likely to be a much more important factor in determining the onset of corrosion. Impermeable pastes carbonate only very slowly, no matter what the type of cement.

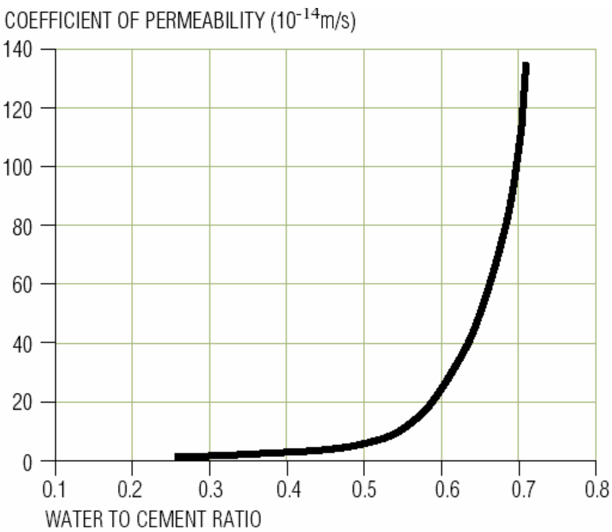


Figure 2.8 **Effect of water-cement ratio on permeability of cement paste**

2.3.7 Resistance to Chemical Attack

General

Hardened cement paste may be attacked by aggressive chemical agents. The intensity of the attack depends on the specific properties of the agent, its concentration, and on the duration and the nature of the contact with the paste, i.e. whether it is continuous or periodic. Regardless of the nature of the aggressive agent, the chemical resistance of the paste is related to its permeability, less permeable pastes being more resistant to all forms of attack.

Long term durability considerations take into account that concrete subject to external environmental conditions will be slowly attacked by CO_2 (acid) from the atmosphere and wind borne salt/seawater (chloride).

Acids

The action of acids on the hardened cement is the conversion of the calcium compounds to the calcium salts of the acid. The solubility of the resulting calcium salt determines to a large degree the aggressiveness of the acid attack. If the calcium salt is soluble, then it is readily removed by dissolution and leaching. As a result, the structure of the hardened cement is ultimately destroyed.

Hydrochloric acid and nitric acid give calcium salts which are readily soluble. Acids which result in insoluble salts, such as oxalic and hydrofluoric acid, are not expected to cause any damage.

Table 2.5 **Moist curing required to achieve capillary discontinuity**

Water-cement ratio	Duration of moist curing
0.4	3 days
0.45	7 days
0.5	14 days
0.6	6 months
0.7	1 year
>0.7	Impossible

Sulphates

All soluble sulphates attack hardened cement pastes causing the formulation of expansive products which, in severe cases, can result in complete disintegration of the paste, mortar or concrete.

Calcium, sodium and potassium sulphates attack the aluminates in the cement. The reaction, in the presence of moisture, causes expansion which may lead to cracking. Magnesium sulphate and ammonium sulphate are potentially more severe in their action since they attack not only the aluminates but also the silicates. Attack is progressive and the hardened cement can be reduced to a soft mass. The severity of the sulphate attack on cement paste, mortar and concrete depends on the type of the sulphate, its concentration, whether the sulphate solution is stagnant or flowing, and temperature.

The use of sulphate-resisting cements is recommended where the risk of sulphate attack is present.

It should be noted that resistance of concrete to sulphate attack is influenced not only by the factors affecting the chemical reactions but also, and more importantly, by the factors influencing the permeability and the overall quality of the concrete.

Chlorides

The major influence of chlorides is to increase the risk of corrosion of reinforcing steel because, if present in sufficient concentration in the vicinity of the steel, they cause a breakdown in the passive layer which normally protects steel from corrosion in alkaline conditions. Corrosion can then occur, particularly if the alkalinity of the cement paste is simultaneously reduced by carbonation.

The use of a cement relatively high in C_3A may assist in reducing the influence of chlorides by 'binding' a portion of them. Chlorides will react with calcium aluminates to form calcium chloro-aluminates. However, this measure should not be relied upon to prevent corrosion of steel by chlorides, partly because calcium aluminates combine preferentially with sulphates (to form sulfo-aluminates) before chlorides, and partly because subsequent carbonation of the paste causes breakdown of the chloro-aluminates and the release of chloride ions into the system.

Blended cements have been shown to have some advantage. The dense pore structure which results from their use reduces the mobility of the chloride ions, thus reducing the risk of high chloride concentration adjacent to the steel.

2.3.8 Resistance to Freezing and Thawing

The formation of ice involves an increase in the volume of the water frozen by about 9%. In saturated, or nearly saturated cement pastes, such volume increases will produce internal pressures which, in turn, cause dilation and cracking of the paste. Repeated cycles of freezing and thawing therefore damage cement pastes (and hence mortars and concretes) by causing internal stresses which crack the paste and eventually cause it to disintegrate.

The damaging effect of frost depends primarily, therefore, on the amount of free moisture within the pores of the paste, and this in turn depends on the permeability and/or porosity of the paste. Pastes of low water-cement ratio and, hence, low permeability, are inherently more resistant to frost action. The resistance of cement pastes to freezing and thawing may be improved dramatically by the purposeful entrainment of air within the system.

Certain types of blended cement, notably those containing fly ash with a high carbon content, tend to depress the effects of air-entraining agents and to produce a less uniform and a less stable air-void system. Otherwise, the type of cement has no inherent effect on the resistance of cement paste to freezing and thawing. In other words, for the same strength and air content the cement type has no significant effect on the resistance to cycles of freezing and thawing.

2.3.9 Resistance to High Temperature

The effect of high temperature on the hydrated cement paste will vary with the following factors:

- Rate of temperature rise.
- Length of exposure.
- The final temperature reached.
- Age of the hardened paste.
- Degree of saturation.

With a slow rise in temperature, the hardened paste progressively dries out but its properties are substantially unaffected up to about 200°C. Where the rise in temperature is rapid and the concrete is saturated, for example where it has not had the time to dry out thoroughly, significant damage may occur due to moisture trapped in the pores of the concrete turning into steam and bursting the matrix.

At temperatures between 300 and 600°C, combined water is driven off and dehydration begins to take place, resulting in a progressive loss in strength and a material which will be severely damaged by rewetting. Exposure to temperatures above 600°C will lead to complete loss of strength and, eventually, to failure. In such conditions, high-alumina cements combined with selected refractory aggregates should be used to produce a refractory concrete.

2.4 STORAGE, SAMPLING AND TESTING OF CEMENT

2.4.1 Storage

The principle underlying the proper storage of cement is that, as far as possible, moisture (or air which may contain moisture) should be excluded from contact with it. If completely protected from moisture, cement may be stored for an indefinite period of time.

Bulk cement is stored at cement plants and terminals, and at concrete batching and products plants, in steel or concrete silos. Provided moisture is excluded from the interior of such silos, cement may be stored in them for a more or less indefinite period. Satisfactory storage for several months is not unusual.

On the other hand, cement packed in multi-wall paper sacks has a more limited storage life as moisture will be absorbed from the atmosphere and cause progressive deterioration of the cement over time. In damp weather, such deterioration may be quite rapid and will be evidenced by the development of hard lumps in the cement. Such cement is likely to have reduced strength and extended setting times, even if the hard lumps are screened out. Soft lumps such as those which may occur in the lower bags in a high stack from the pressure of the bags above, and which can be broken up by rolling the bag a few times, are not a sign of deterioration.

Bagged cement storage areas must therefore be kept dry and, as far as practical, air movement restricted. Storing bags on pallets above ground, covering stacks with tarpaulins or plastic sheeting, and ensuring that the stock is used in the order in which it is received are all measures which will assist in preventing deterioration of bagged cement.

2.4.2 Sampling and Testing

Sampling and testing of cement for compliance with specifications is normally carried out in accordance with AS 2349 and AS 2350 respectively.

Testing is carried out routinely by the cement manufacturer and the results of these tests are normally available on request.

Appendix MINOR CONSTITUENTS OF CEMENT

A.1 Gypsum

Gypsum is added during grinding of the clinker in order to prevent flash setting of the cement.

The retarding action of gypsum is due mainly to the formation of coatings of ettringite (calcium sulfo-aluminate) on the surface of the aluminate (C_3A) in the cement. The gypsum content must therefore be limited as an excess may cause the formation of increased amounts of ettringite, leading to cracking and deterioration in the set cement. Consequently, cement standards specify a maximum gypsum content expressed as maximum SO_3 content. NZS 3122 and AS 3972 limits SO_3 content of cements to 3.5%.

Gypsum also has an influence on the strength and drying shrinkage properties of cement. A cement manufacturer optimises the percentage of gypsum to ensure the best combination of these properties to meet the needs of the market.

A.2 Free Lime (CaO)

The presence of free (uncombined) lime in cement may occur when the raw materials used in the manufacturing process contain more lime than can combine with the silica, alumina and iron oxides. Alternatively, free lime may occur when the amount of lime in the raw materials is not excessive, but its reaction is not completed during the burning process – the cement is underburnt. When the amount of free lime exceeds certain limits, depending on the fineness of the cement, the cement shows unsoundness. The mechanism is as follows: The free lime is intercrystallised with other minerals and is therefore not readily accessible to water. It hydrates after the cement has set and because the hydration product occupies a larger volume than the free lime it may cause expansion. This consequence is termed 'unsoundness'.

It is evident that free lime in the cement should be limited. It is difficult, however, to specify a quantitative limit for free lime in cement because its adverse effect depends not only on the amount present but also on other factors. Consequently, cement standards generally specify a test for expansion to ensure that the amount of free lime present is within safe limits. The relevant test prescribed in AS 2350.5 is the Le Chatelier Test which involves boiling a small cylinder of neat cement paste and measuring its expansion.

A.3 Magnesia (MgO)

Magnesia is introduced into cement as a minor constituent of limestone. Except for a small amount held in the crystal lattice of the cement compounds, MgO normally exists in cement as periclase, a crystalline material which can exhibit long-term expansion. Hence, most cement specifications place a limit on the amount of MgO that can be present in cement. NZS 3122 and AS 3972 limits the magnesia content of clinker to 4.5%.

A.4 Alkali Oxides (K_2O, Na_2O)

The alkali oxides, potash and soda, are introduced into cement through the raw materials. The total content of potash and soda in cement is small **Table 2.2**. A reaction may occur between these alkalis and some types of aggregates which contain reactive silica. This reaction involves expansion which may cause cracking and disruption of the concrete. Although the reaction will always occur in the presence of reactive silica, damage to the concrete may be avoided where the amount of alkali in the concrete is low. Thus, some specifications limit the amount of alkali in the cement to 0.6%, expressed as equivalent Na_2O. (Na_2O + 0.658 K_2O). This approach is not adopted in Australia but is in New Zealand. Reactive aggregates in certain regions of New Zealand and the considerable experience gathered in using them as concrete aggregates, lead specifiers to limit the level of alkali in cement to 0.6%. While the mechanism of attack is complex this measure in New Zealand has proved to be a satisfactory measure in preventing serious concrete failure. The full provisions to limit the risk of alkali aggregate reaction (AAR) are contained in the publication TR3 *Alkali Aggregate Reaction* published by the Cement & Concrete Association of New Zealand.

Alternative approaches to minimising the risk of AAR are taken in Australia where different rock types occur and this is contained in a publication T47 *Alkali Aggregate Reaction – Minimising the Risk of Damage to Concrete Structures in Australia* published by the Cement and Concrete Association of Australia.

A.5 Loss on Ignition

Loss on ignition primarily measures the presence of moisture and carbon dioxide in the cement and is determined by heating a sample to 900–1,000°C. Whilst LOI can be used to indicate whether a cement has been impaired by exposure to undue levels of moisture and/or carbon dioxide, the presence of certain mineral additions such as limestone or relatively high levels of slag can affect the result, making interpretation difficult. No limit is specified in NZS 3122 and AS 3972 for loss of ignition but is reported if required.

Summary

HYDRAULIC CEMENTS, TYPES AND APPLICATIONS

Type	**Application**
General Purpose Portland (GP)	For general use in all types of building and construction.
General Purpose Blended (GB)	For general use in all types of building and construction. *Early rates of strength gain may be lower than those of Type GP, and curing may be more critical for full strength development*.
High Early Strength (HE)	Where early strength is a critical requirement (e.g. for the early stripping of formwork). In very cold weather. In repairs to concrete structures.
Low Heat (LH)	Where rise in concrete temperature must be limited to avoid thermal stresses (e.g. in mass concrete construction or in very hot weather). Where moderate resistance to some forms of chemical attack is required.
Shrinkage Limited (SL)	Where limiting the drying shrinkage of concrete is necessary for crack control, in road pavements and bridge structures.
Sulphate Resisting (SR)	Where high resistance to sulphates is required, e.g. in sulphate-bearing soils and groundwaters.
White and Off-White	In the production of architectural concrete and concrete products. *Normally complies with the requirements of NZS 3122 and AS 3972 for Type GP, GB or HE cement.*
Coloured	In the production of concrete products, concrete paving and similar applications.
Masonry	Mortar in brick, block and stone masonry construction. Unsuitable for use in structural concrete.
Oil-well	Grouting gas, oil and other deep bore holes and wells. *Normally complies with the relevant specification of the American Petroleum Institute.*
High Alumina Cement (HAC)	Where high early strength and/or resistance to very high temperatures are required (e.g. refractory concrete and factory floors).

ACKNOWLEDGEMENTS

Permission to reproduce/adapt material from other publications is acknowledged as follows:

American Concrete Institute

Figure 2.8 Based on Figure 6 in Journal ACI 51, November 1954.

The Macmillan Press

Figure 2.2 Based on Figure 2.4 in Portland Cement Paste and Concrete 1 Soroka, 1979.

Aggregates for Concrete

Chapter 3

Chapter 3

Aggregates for Concrete

This chapter summarises information on the properties of aggregates, their sources in New Zealand, and their classification for use in concrete. It discusses their properties in some detail and their influence on the properties of the concrete. It also outlines methods of testing aggregates.

INTRODUCTION

Aggregates form up to 80% of the volume of concrete and are, therefore, an important constituent. At one time they were considered to be inert fillers but we now know that their properties can significantly affect the performance of the material in both its plastic and hardened conditions.

In this chapter New Zealand Standard references have been predominantly used except where provisions did not exist when an appropriate part of the Australian Standard, AS 1141, has been referenced.

Relevant New Zealand Standards

NZS 3101 *Concrete structures*

NZS 3104 *Specification for concrete production*

NZS 3109 *Concrete construction*

NZS 3111 *Methods of test for water and aggregates for concrete*

- Section 5 *Sampling aggregates*
- Section 6 *Sieve analysis of aggregate and calculation for fineness modulus*
- Section 7 *Moisture content of aggregate by drying*
- Section 8 *Aggregate performance in concrete*
- Section 9 *Lightweight particles in aggregate*
- Section 10 *Unit mass and voids content*
- Section 11 *Reactivity of cement and aggregate combinations*
- Section 12 *Density and absorption of coarse aggregate*
- Section 13 *Cleanness of coarse aggregate*
- Section 14 *Crushing resistance of aggregate*
- Section 15 *Weathering resistance of coarse aggregate*
- Section 16 *Density and absorption of sand*
- Section 17 *Presence of inorganic impurities*
- Section 18 *Sand equivalent value*
- Section 19 *Voids content, flowtime and percentage oversize material in sand*

NZS 3121 *Water and aggregate for concrete*

TR3 *Alkali aggregate reaction* (published by CCANZ)

Relevant Australian Standards

AS 1141 *Methods for sampling and testing aggregates*

Sections of parts:

3-6 inclusive
11-18 inclusive
22-24 inclusive
30, 31, 32, 34, 35

AS 2758 *Aggregates and rock for engineering purposes*

AS 2758.1 *Concrete aggregates*

AS 3600 *Concrete structures*

3.1 TYPES OF AGGREGATE AND THEIR USES

Concrete aggregates, regardless of their origin, are usually divided into two main classes, normal-weight (or dense) aggregates, and lightweight aggregates. Heavyweight aggregates – iron ore, barytes, or even steel shot – are also used on occasions for special purposes but these are comparatively rare.

Normal-weight aggregates are sands, natural gravels and rocks, crushed or uncrushed, and certain manufactured aggregates, such as crushed iron blast-furnace slag, all of which have a density of not less than 1,950 kg/m^3. They are by far the predominant type of aggregate employed in the production of concrete in New Zealand and should comply with the requirements of NZS 3121.

Lightweight aggregates are defined as those having a density less than 1,950 kg/m^3. They are used to produce concrete of substantially lower unit mass than that made from dense aggregates and include materials such as scoria, a porous rock of volcanic origin, and manufactured materials such as foamed iron blastfurnace slag and expanded clays and shales.

Summary TYPES OF AGGREGATES FOR CONCRETE

Weight Categories	Types of Aggregate	Uses	Indicative Concrete Density (kg/m^3)
Lightweight Particle density < 1,950 kg/m^3	Vermiculite Perlite	Thermal insulation	500 to 1,000
	Scoria Pumice Sintered pulverised fuel ash	Lightweight structural concretes	1,000 to 1,500
	Foamed iron blastfurnace slag Expanded shales Expanded clays	Lightweight structural concretes	1,500 to 1,800
Normal Weight Particle density ≥ 1,950 kg/m^3	Natural sands Natural gravels Natural rocks Air-cooled iron blastfurnace slag	Normal-weight structural concretes	2,000 to 2,600
Heavyweight Particle density > 3,000 kg/m^3	Limonite Barytes Magnetite Steel punchings	Heavyweight mass concretes Radiation-shielding	3,000 to 5,000

Concretes with densities as low as 400 kg/m^3 can be produced using materials such as vermiculite (a micaeous mineral) and perlite (a volcanic glass). The thermal insulation values of such concretes are high but their compressive strengths are low. They are not well suited, therefore, to structural applications.

Structural lightweight concretes, with densities from 1,000 kg/m^3 upwards, and compressive strengths ranging from 15 to 30 MPa and upwards, are produced with foamed slags and expanded clays and shales. Moderate-strength lightweight concretes fall midway between low-density and structural concretes with respect to unit weight and strength, the most common aggregates used in this type of concrete being scoria and pumice. Sintered pulverised fuel ash is also used.

Heavyweight aggregates include limonite, barytes, magnetite and steel punchings. They are used principally in the production of concrete for shielding against nuclear radiation, but do find application also where extremely heavy mass concrete is required for other reasons.

3.2 SOURCES OF AGGREGATES

3.2.1 General

The common types of aggregate met in practice are:

- natural sands and gravels;
- crushed rocks;
- manufactured aggregates.

The availability of aggregate types in New Zealand is summarised in **Table 3.1** (page 3.4).

3.2.2 Natural Sands and Gravels

Natural sands and gravels are found widely distributed throughout New Zealand although urban development – and the exploitation of the remaining deposits – are reducing their availability close to the major cities. Such deposits include:

- **Stream beds**, the most satisfactory source of natural aggregate. Particles are normally rounded in shape, clean and strong, all weak material having been removed by erosion. Sands tend to be deficient in fines.
- **Dunes**, formed by the action of wind. These sands tend to be single-sized and fairly fine.
- **Alluvial deposits**, formed on flood plains and in river beds. Depending on the original source of the parent rocks, such deposits may contain rocks and stones of a number of different types.
- **Marine deposits**, formed at the edges and bottom of seas and lakes. Note that marine aggregates can introduce unacceptable quantities of chlorides into concrete.

Table 3.1 **Availability of aggregates for concrete in New Zealand**

Area	Igneous	Sedimentary	Metamorphic
Northland	Basalt throughout but poorest in west	Greywacke-argillite in the east.	
Auckland, Waikato, King Country	Basalt in Auckland, andesite	Widespread greywacke-argillite quarries. Chert used for decorative purposes.	
Taranaki	Andesites predominant		
Coromandel, Bay of Plenty, Central Volcanic Region	Predominantly volcanic with andesites	Greywacke-argillite in east but often of poor quality.	
East Coast		Greywacke-argillite both quarried and as gravel. Limestone used in Gisborne area.	
Wellington		Greywacke-argillite both quarried and as river gravel.	
Marlborough, Canterbury		Principally greywacke-argillite gravels.	
Nelson, Westland	Granite	Greywacke and limestone.	Quartzite
Otago, Southland	Basalt and phonolite	Greywacke and schist gravels.	Schist

3.2.3 Crushed Rocks

Crushed rock aggregates have the advantage that they can be produced in any desired size and grading by the installation of suitable crushing and screening equipment. Rocks suitable as concrete aggregates are grouped into three major classifications according to their origin:

Igneous Rocks

They are crystalline in nature, having originated from the consolidation of magma. Crystal sizes reflect the original cooling rate. Slow cooling produced large crystals, giving coarse-grained rock such as granite. With more rapid cooling finer-grained rocks were formed. Very rapid cooling, such as of the upper surface of a lava flow, produced a volcanic glass (obsidian) with the material having been cooled too quickly for crystallisation to occur. (The term 'amorphorous' is often used to describe non-crystalline materials.)

A magma which has extruded as a lava flow and therefore cooled fast, gives rise to a rock-class known as 'volcanic'. Plutonic rocks are coarse-grained igneous rocks which have crystallised slowly in large masses at considerable depths, for example the granite in the Nelson area.

Basalts are volcanic rocks, dark in colour and of high specific gravity, with a fine texture. Some basalts are strongly vesicular. Basalts are hard and can be used to produce high strength concrete.

Rhyolite is a highly reactive volcanic rock when used in the alkali environment of concrete.

Andesites, another group of volcanic rocks, possess some large crystals in a fine matrix and are generally of less use in the aggregate industry than basalts, although their rough surface texture can lead to very strong bond in concrete and hence high strength. There is some evidence of disruptive alkali reactivity with some andesite aggregates from the Taranaki and central volcanic regions of the North Island, and this should be taken into consideration in their projected use.

Phonolite, a member of the basalt family which is found in the Dunedin area, is a more unusual variety of an intermediate-to-basic volcanic rock. The rock is very hard and particularly suitable as a concrete aggregate. Except with regard to the particular uses of scoria and pumice as lightweight aggregates, most other volcanic rocks are of doubtful value in concrete making.

Sedimentary Rocks

Sedimentary rocks are formed at the earth's surface by the accumulation and consolidation of the products of weathering and erosion of other rocks and minerals. The sediments usually harden by cementation or compaction over long periods of time. Sandstone, limestone, shales and chert are examples of sedimentary rocks.

Sandstones may be suitable as concrete

aggregates if they are composed of quartz grains cemented together with amorphous silica. Sandstones that consist of sand grains bound together by clay are unsatisfactory because they are weak and porous and may soften in water. Greywacke is the term used for sandstone rock in New Zealand although argillite which is also a sandstone is available. Some argillite may break down under the influence of weathering and therefore selective quarrying is necessary. Limestones, which are probably the most widely used as aggregates in this group, vary from very hard close-grained crystalline rocks to very soft chalk-like materials. Hard limestone is generally suitable for use in concrete but soft limestone should be avoided. Shales are generally unsatisfactory because of their soft and absorptive nature. Cherts are hard and dense but, depending on the silica minerals present, may be alkali-reactive. They should be avoided as aggregates for concrete.

Metamorphic Rocks

Metamorphic rocks are formed from pre-existing rocks by the action of heat and/or pressure from the earth's crust. They are dense but tend to break into plate-like particles. Marble, schist, quartzite and slate are examples of this type of rock.

The mineral compositions of metamorphic rocks are highly variable, depending in part on the degree of metamorphism and in part on the composition of the parent material. Certain metamorphic rocks may react with the alkalies in portland cement.

3.2.4 Manufactured Aggregates

General

Manufactured aggregates may be either by-products of an industrial process, such as blastfurnace slag, or products specially manufactured as aggregates, for example expanded clays and shales.

Iron Blastfurnace Slag

Slag is the non-metallic by-product which is produced in a metallurgical furnace. It consists, essentially, of silicates and alumino-silicates of calcium and other bases. By changing the cooling conditions and cooling rates, the molten slag can be made to solidify into a number of different forms with distinctive physical properties. By far the most common slags are those derived from iron blastfurnaces. Three types are available commercially in Australia. Currently the products are not manufactured in New Zealand.

- **Air-cooled slag** is a crystalline product produced by allowing the molten slag to cool slowly in pits or bays under atmospheric conditions. This is the usual source of slag aggregates.
- **Granulated slag** is a glassy, granular product formed when molten slag in quenched rapidly in water. It is used sometimes as a fine aggregate, but is more often ground to provide a material with cementitious properties.
- **Foamed slag** is the vesicular product formed by the controlled quenching of thin layers of molten slag in shallow pits. Water may or may not be used for quenching.
- Granulated and foamed slags are also sources of lightweight aggregate.

Expanded Clays and Shales

When certain types of clay and shale are heated to about 1,200°C, they begin to fuse and melt. At the same time, the gases generated expand the mass rapidly to form a honeycomb of small cells. The resultant material, when cooled, has a low unit weight, or bulk density, but is hard and strong.

Sintered Pulverised Fuel Ash

Fly ash is a material formed during the combustion of pulverised coal in steam boilers or similar high temperature combustion chambers. A lightweight aggregate is formed by mixing fly ash with water and coal slurry, pelletising and sintering the mixture to 1,400°C.

Polystyrene Beads

Expanded polystyrene beads represent a recent technology allowing concretes of high thermal resistance to be manufactured.

3.3 AGGREGATE PROPERTIES COVERED IN NZS 3121 AND AS 2758.1

3.3.1 General

Aggregate properties that affect the resulting concrete, and the limits placed on those properties in NZS 3121 and where appropriate AS 2758.1, are discussed in Clauses 3.2 to 3.10 below and summarised in the chart on pages 3.15 and 3.16.

3.3.2 Grading

Grading is the distribution of particle sizes in a particular batch of an aggregate. It influences the water demand of concrete and its subsequent tendency to bleed and segregate. Hence, it influences the mix proportions for a desired workability and water-cement ratio. The coarser the grading, i.e. the lower the proportion of fine aggregate, the lower the cement content required for a given workability and water-cement ratio. However, this is true within limits only, as a sufficient amount of fine material is always required to obtain a cohesive mix which can be transported, placed and compacted without segregation.

Aggregates having a continuous, relatively smooth grading curve will generally produce mixtures with fewer large voids between particles. The amount of cement paste required to fill these voids is thereby minimised. In other words, a larger volume of concrete can be made from a given amount of cement paste, and it is, therefore, a more economical mix.

If an aggregate grading is deficient in fines, i.e. there is not enough sand to fill the voids between coarse aggregate particles, or if the sand is coarse, the concrete mix will be harsh, difficult to place and finish, and will tend to bleed excessively. On the other hand, aggregate combinations with excessive amounts of sand, or excessively fine sands, may produce uneconomical concretes because of the larger surface area of the finer particles. In consequence, an excessive amount of cement may be required to produce the required strength and workability.

Whilst continuously-graded aggregates are normally specified for use in concrete, gap-graded materials (as required, for example, for exposed-aggregate concrete) can also be used to produce satisfactory mixes. However, above-average care and accuracy in adjusting the mix proportions are required to achieve optimum results. **Figure 3.1** shows typical grading curves for continuous and gap-graded aggregates.

It should be emphasised that, while there is a need for aggregates to meet specified grading curves, no ideal grading exists. Good concrete can be produced from a range of fine and coarse aggregate gradings and relatively wide ranges are permitted. Typical sand grading is shown in **Table 3.2** and **Table 3.3** (page 3.7) shows coarse aggregate grading data from NZS 3121.

The aggregate grading significantly influences the water demand and workability of the concrete, and hence affects the control of concreting operations on the job. Ultimately, it may affect the strength and other properties of the hardened concrete. Hence, it is extremely important either that aggregate gradings be uniform during the currency of a project or that the concrete mix be adjusted when changes occur in the grading.

Even when not necessary for visual reasons (e.g. for exposed 'architectural' concrete), it is often more economical to maintain uniformity in the aggregates than to adjust the mix proportions for variations in grading. Therefore, limits on variation in grading from batch to batch in the one job are specified in NZS 3121. Fine aggregate, for example, should not have variations more than ±0.20 from the average fineness modulus values of 50 samples.

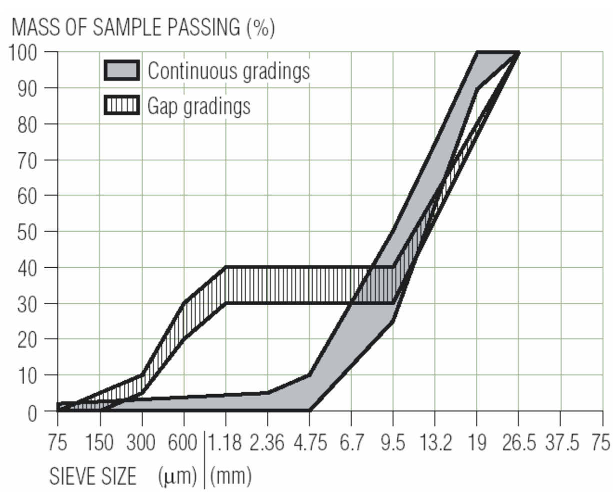
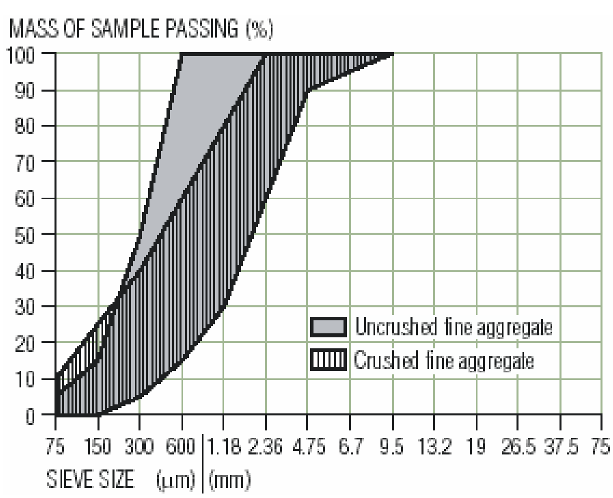


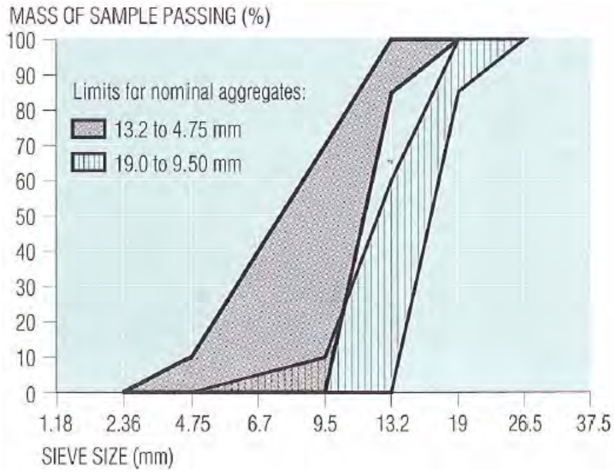
Figure 3.1 **Grading curves for 20-mm maximum size aggregate - examples only**

Table 3.2 **Typical grading requirements for fine aggregate**



Sieve Size	Mass of sample passing (%)	
	Uncrushed fine aggregate	Crushed fine aggregate
9.50 mm	100	100
4.75 mm	95-100	95-100
2.36 mm	60-100	60-100
1.18 mm	30-100	30-80
600 µm	15-100	15-60
300 µm	5-50	5-40
150 µm	0-15	0-25
75 µm	0-5	0-10

Table 3.3 NZS 3121 Grading requirements for coarse aggregate



Nominal size range (mm)	**Percentage passing test sieves having square openings**										
	106	**75.0**	**53.0**	**37.5**	**26.5**	**19.0**	**16.0**	**13.2**	**9.50**	**4.75**	**2.36**
19.0 to 9.50	–	–	–	–	100	85-100	–	0-60	0-10	0	–
16.0 to 4.75	–	–	–	–	–	100	85-100	–	0-60	0-10	–
13.2 to 4.75	–	–	–	–	–	100	–	85-100	0-70	0-10	0
9.50 to 4.75	–	–	–	–	–	–	–	100	85-100	0-10	0

Coarse aggregate consistency requirement is that the percentage material retained upon a specifically nominated sieve should not vary by ±10 from the average of the last 10 tests. The nominated sieve for each size range is shown in **Table 3.4.** An example of the Australian approach to uniformity limits is shown in **Table 3.5.**

The grading is determined by sieve analysis in accordance with NZS 3111, Section 6. In carrying out the sieve analysis, the percentage passing each sieve is determined. Usually, the coarse and fine aggregates are sieved separately.

Table 3.4 NZS 3121 Uniformity requirements for coarse aggregate

Intermediate test sieve sizes	
Nominal size range (mm)	Intermediate test sieve size (mm)
75.0 to 37.5	53.0
37.5 to 19.0	26.5
26.5 to 132	19.0
19.0 to 9.50	13.2
16.0 to 4.75	9.50
13.2 to 4.75	9.50

Table 3.5 AS 2758.1 Uniformity requirements for graded coarse aggregate (Note: For fuller details and requirements for single-size aggregate, see AS 2758.1)

	Maximum deviation (%) nominal size of graded aggregate			
Sieve size	**40**	**28**	**20**	**14**
75.00 mm	–	–	–	–
37.50 mm	±10	–	–	–
26.50 mm	±15	±10	–	–
19.00 mm	±15	±15	±10	–
13.20 mm	±10	±15	±15	±10
9.50 mm	±10	±10	±15	±15
6.70 mm	±5	±10	±10	±15
4.75 mm	–	±5	±5	±5
2.36 mm	–	–	–	–
75 µm	–	–	–	–

Maximum Size and Nominal Size

These two terms are often used in specifications for aggregates to indicate the largest size particle present in an aggregate grading. However, although they have different meanings, they are often confused and wrongly specified. The maximum size of an aggregate is the smallest sieve opening through which all the aggregate will pass.

The nominal size, on the other hand, is defined in a note in AS 2758.1 as the whole number above the sieve size through which *nearly all* the aggregate passes.

For example, in the aggregate grading shown in **Table 3.6**, the nominal size is 27 mm, i.e. the whole number just above the 26.5 sieve through which nearly all the aggregate passes. The maximum size may be as high as 37 mm, or just below the sieve size through which all the aggregate passes.

Table 3.6 **Example of Aggregate Grading**

Sieve size (mm)	**Passing** (%)
37.50	100
26.50	95-100
13.20	25-60
4.75	0-10
2.36	0-5

The nominal size of coarse aggregate used in concrete has an effect upon surface area and economy. Usually, as the nominal size of continuously graded aggregate increases, the amount of paste required to produce concrete of a given workability decreases **Figure 3.2**. On the other hand – to prevent bridging and segregation which leads to honeycombing – the nominal size of aggregate that can be used in a project will often be determined by the size and shape of the concrete member and by the clear spacing between reinforcing bars. It is recommended that the nominal size not exceed one-fifth the minimum dimension of the member, nor three-quarters the clear spacing between reinforcing bars, nor three-quarters the cover to the reinforcement **Figure 3.3**. In general, the use of the largest possible nominal size consistent with placing requirements is recommended.

3.3.3 Particle Shape and Surface Texture

The shape and texture of aggregate particles has an important influence on the workability of freshly mixed concrete, and hence may affect both the water demand and the water-cement ratio **Figure 3.4**. Smooth, rounded aggregate particles are to be preferred in achieving the maximum workability.

On the other hand, the strength of concrete is affected by the bond between coarse aggregate particles and the cement paste, and by the interlocking characteristics of the aggregate. For optimum strength, a rough-textured, cubical-shaped aggregate will generally give best results.

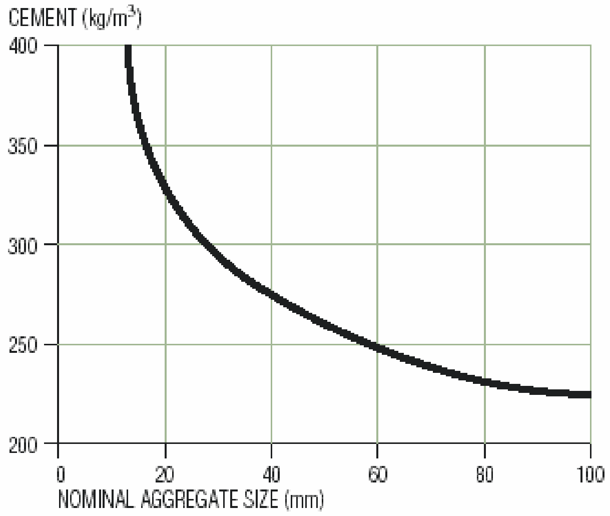


Figure 3.2 **Effect of aggregate size on cement requirement for concrete with constant W/C and slump**

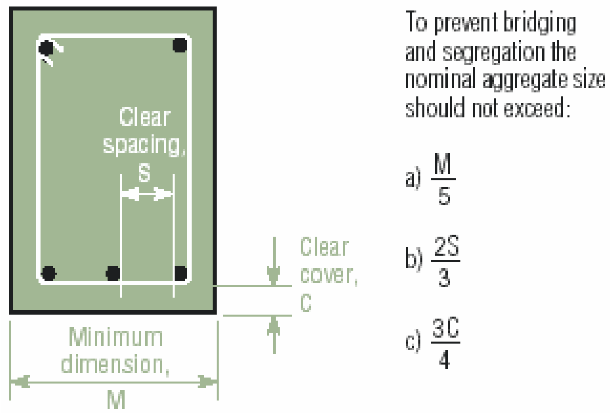


Figure 3.3 **Recommended maximum nominal**

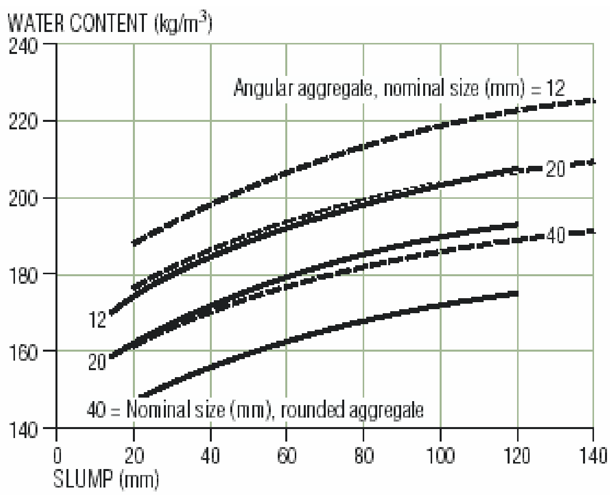


Figure 3.4 **Water requirement for concrete using aggregates of different shapes and nominal sizes**

AS 2758.1 provides guidance on the classification of aggregates according to their particle shape and surface texture. (NZS 3121 does not cover this topic.) Particle shape is described as either rounded, irregular, angular, flaky, elongated, or flaky and elongated. These fairly broad descriptions are normally sufficient to categorise aggregate particles visually **Figure 3.5**.

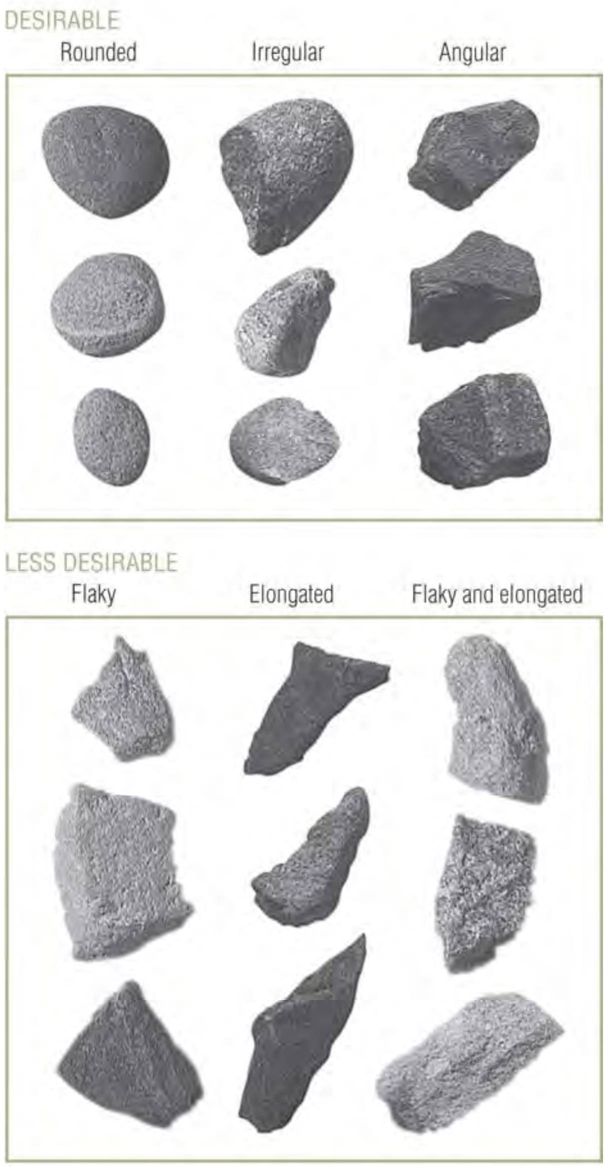


Figure 3.5 **Categorisation of aggregate particles by shape and surface texture**

Similarly, surface texture is classified as glassy, smooth, granular, rough, crystalline or honeycombed. Appendix B of AS 2758.1 gives more detailed descriptions of each of these classifications. Because flat, flaky or elongated particles not only reduce workability but may also affect adversely the strength of concrete by their tendency to selective orientation and bridging (thus forming pockets or honeycombs), aggregate specifications generally limit the allowable percentage of such misshapen particles. AS 2758.1 limits the proportion of misshapen particles in the fraction of a coarse aggregate retained on the 9.50 mm test sieve to 10%, when determined in accordance with AS 1141, Section 14 for an aspect ratio of 3:1.

The flakiness index, determined in accordance with AS 1141.15, may also be used to describe the shape of an aggregate particle. This method uses a slotted sieve or thickness gauge to determine the percentage, by volume, of flaky particles, where a flaky particle is defined as one with its least dimension (thickness) less than 0.6 of its mean dimension. The mean dimension is defined as the mean of the smallest sieve size through which the particle passes and the largest sieve on which it is retained.

The angularity number is another index of the shape of a particle and is determined in accordance with AS 1141, Section 16. It is a measure of relative angularity based on the percentage voids in an aggregate after compaction in a prescribed manner. The most-rounded aggregates have about 33% voids. The angularity number is defined as the amount by which the percentage of voids exceeds 33. In practice, it ranges from 0, for a spherical aggregate, to about 12 for very angular aggregates.

3.3.4 Density

The density of an aggregate is not, per se, a measure of its quality, although density is normally related to porosity which, in turn, is related to strength. Aggregate density is used mainly in proportioning concrete mixes. Substituting one aggregate in a concrete for another of different density will influence the yield and the unit mass of the concrete. This is undesirable, especially if a minimum mass has been specified, e.g. in concrete for nuclear radiation shielding. The determination of density is carried out in accordance with either NZS 3111, Section 12 or NZS 3111, Section 16. Unit mass is determined in accordance with NZS 3111, Section 10.

These determinations of density are based on oven-dried aggregates but, if required, they may be performed at other moisture conditions, such as damp, wet, saturated surface-dry, or air-dry. Unlike the oven-dry condition, however, achieving these conditions involves a degree of subjective judgment. The oven-dry condition is achieved by drying the aggregate to a constant mass.

3.3.5 Water Absorption

All aggregates contain minute pores which can become filled with moisture. The amount of moisture absorbed in these pores may be quite small, as is the case with dense fine-grained rocks, or quite large, as with lightweight and other porous materials. The amount of moisture so absorbed is known as the water absorption of the aggregate and may be determined by the methods set out in NZS 3111, Sections 12 and 16. Surface moisture may also be present in aggregates giving them a damp or wet appearance. The total moisture content of an aggregate is the sum of the absorbed and the surface moisture present.

It is an important parameter because it can affect, significantly, the amount of water which should be used in a concrete mix to achieve a given water-cement ratio. Variations in the moisture content of stock-piled aggregates are possibly the most common cause of variations in slump and concrete strengths. The surface moisture contents of sands, in particular, are significant.

Thus, in preparing a mix design for a particular aggregate, it is normal to determine first the moisture content of the aggregate in a saturated surface-dry condition, i.e. with the pores filled with water but without free moisture on the surface of the particles. If the aggregates used in the subsequent manufacture of the concrete have moisture contents less than this figure, additional water will need to be added to avoid a loss of workability as the aggregates absorb moisture. If greater than this figure, free moisture will be present on the surface of the aggregates and less water should be added.

Although not directly co-related, normal weight aggregates with high water absorptions are likely to produce concretes that have higher drying shrinkage and creep characteristics than those with lower values

3.3.6 Dimensional Stability

Dimensional stability, under changing moisture conditions, is an important property of aggregates intended for use in concrete. Aggregates that swell or shrink as they take up or lose water contribute to concrete shrinkage. In extreme cases, the concrete may deteriorate with cycles of wetting and drying because of the expansion and contraction of the aggregate. Dimensional instability occurs in an aggregate when the minerals comprising the rock include unstable clays, e.g. volcanic breccia.

Since there is no specific New Zealand test, the test set out in AS 1141.22 provides a useful overall guide as to the dimensional stability of a coarse aggregate. It compares the two crushing forces required to produce fines amounting to 10% of a fixed mass of the aggregate, when crushed in the oven-dry and saturated surface-dry conditions. The result is expressed as a percentage of the dry strength of the aggregate. The higher the wet/dry strength variation, the less stable is the aggregate. The test is similar to NZS 3111, Section 14 but this test does not compare a wet versus a dry result.

Clause 102 in AS 2758.1 sets limits on the maximum wet/dry strength variation – between 25 and 45% depending on the concrete exposure conditions. The high values apply to aggregates to be used in an indoor or protected position and the lower values to aggregates exposed to adverse climatic and service conditions, e.g. cycles of wetting and drying, cycles of freezing and thawing, marine environments, heavy industrial pollution, etc.

3.3.7 Abrasion Resistance

The abrasion resistance of an aggregate is its ability to resist being worn away by friction with other materials. Abrasion resistance is required in an aggregate to avoid degradation during handling, stockpiling and mixing. Breaking down, or grinding of the aggregate during concrete production, generates fines which increase mixing-water demand. This, in turn, may cause some difficulty in producing high-quality concrete.

It should, however, be pointed out that – except for concrete with an exposed-aggregate finish – the abrasion resistance of the aggregate bears no direct relationship to that of concrete. The latter is found to be directly related to concrete strength.

At the same time, weak, soft, or friable aggregates are obviously unsuitable for concrete exposed to wear, whilst strong abrasion-resistant materials do improve performance in the longer term.

The Los Angeles value determined in accordance with AS 1141.23 is the most common method of testing the abrasion resistance of coarse aggregate particles. Abrasion resistance testing is a requirement for roading aggregate in New Zealand but the Los Angeles test is not specifically requested for concrete aggregates. This test combines the effects of impact and abrasion by tumbling aggregate particles together with steel balls in a slowly revolving steel drum. A specified quantity of aggregate is placed in the drum with a charge of standard-size steel balls. The percentage of the aggregate worn away is determined by sieving and weighing. The maximum percentage loss is set by Clause 10.2 in AS 2758.1 for various types of aggregate and concrete exposure conditions.

The limits range from 25 to 40%, the higher the Los Angeles value, the more prone the aggregate to degradation, and the less suitable it is to produce high-quality concrete.

3.3.8 Soundness

The soundness of an aggregate is its ability to withstand the aggressive actions to which concrete containing it might be exposed, particularly those due to weather. If aggregate from a particular source has given satisfactory service in the past, it may be considered sound. The soundness of aggregates not having a service record can be assessed by tests as discussed below.

NZS 3111, Section 15 sets out a weathering test that gauges the aggregate's resistance in relation to wetting and drying, together with heating and cooling.

Essentially, after a period of testing the relative quality of the aggregate is considered as a percentage of fine particles becoming available from the sample. The quality index is showing in **Table 3.6**.

Finally, aggregates may be considered sound if they perform satisfactorily in concrete specimens subjected to freezing and thawing tests. In these tests (ASTM C666 *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*), concrete specimens are subjected to alternate cycles of freezing, either in air or water, and thawing in water. Deterioration is measured by the reduction in the dynamic modulus of elasticity of the specimens.

Table 3.6 **Quality index**

	Percentage retained on 4.75 mm sieve		
Cleanness Value	96 to 100	91-95	Up to 90
97-100	AA	BA	CA
71-90	AB	BB	CB
Up to 70	AC	BC	CC

3.3.9 Strength and Rigidity

The strength of aggregate will influence the strength of concrete made from it. High-strength concrete requires aggregates of high strength. However, weaker aggregates may be satisfactory if the strength of concrete is not expected to exceed that of the aggregate. The strength of aggregates is likely to vary considerably with their structure and mineral composition.

Aggregates influence the drying shrinkage of the concrete by restraining the shrinkage of the cement paste. The rigidity of the aggregate will influence its restraining effect. Thus, the higher the modulus of elasticity of the aggregate, the more effective it will be in reducing the shrinkage of the concrete.

Aggregate strength is generally gauged by a crushing test in accordance with NZS 3111, Section 14 *Crushing Resistance of Coarse Aggregate*. This test determines the crushing force which, when applied to a known mass of coarse aggregate, will produce fines amounting to 10% of the original mass. There are no specific limits set by NZS 3121.

Typical values range from 50 kN to 100 kN depending on the concrete exposure condition, the lower value being for aggregates to be used in concrete in protected conditions. Higher wet strengths are required for aggregates to be used in more adverse conditions.

3.3.10 Reactivity

General

Aggregates that are chemically stable will neither react chemically with cement in a harmful manner nor be affected chemically by normal external influences. Reactive aggregates may result in serious damage to the concrete by causing abnormal expansion, cracking and loss of strength.

Alkali-aggregate reactions

Some aggregates containing reactive silica will react with the alkalies in cement – sodium and potassium oxides – to form an alkali-silica gel which takes up water and swells. This causes abnormal expansion and map-cracking of the concrete **Figure 3.6**.

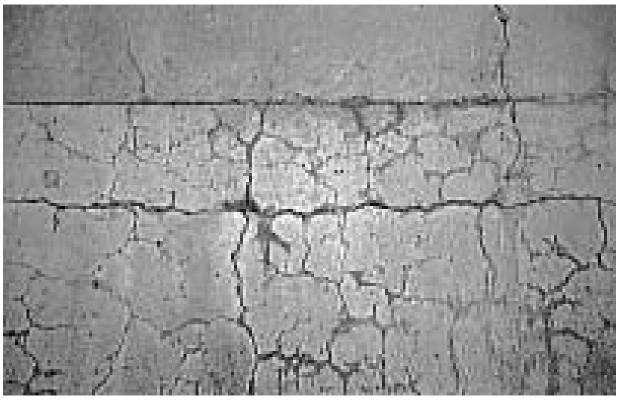


Figure 3.6 **Typical map cracking caused by alkali-aggregate reactions**

The situation in New Zealand is that considerable investigations were carried out by the DSIR (now IRL) over a long period of time to establish rock types that were prone to alkali reaction.

This work was coordinated together with other test work from other researchers into a publication TR3 *Alkali Aggregate Reaction* and **Tables 3.7 and 3.8** (page 3.12) categorise the principal rock type into non reactive and reactive types.

Table 3.7 Aggregates known to be non-reactive from field experience and testing

Greywacke	Schist
Basalt <50% SiO_2	Quartz sands
Phonolite	Rhyolitic pumice
Granite	Perlite
Vermiculite	Limestone

Table 3.8 Aggregates or minerals known to be potentially reactive either from field experience or laboratory testing

Basalt >50% SiO_2	Christobalite
Andesite	Tridymite
Dacite	Quartzite
Rhyolite	Amorphous and cryptocrystalline silicas
Volcanic glass	*(including opal and chalcedony)*

From experience gained by examining a limited number of structures that had experienced the problem, it was concluded that if the alkali content in the concrete could be kept no higher than 2.5 kg/m^3 then the risk of expansive reactions was significantly lowered when potentially reactive rocks are used. New Zealand cement manufacturers assist with this requirement by voluntarily keeping the alkali level of the cement to below 0.6%.

One key factor that has often been overlooked is that it is the sand that can be an important trigger mechanism in the reaction. This has been particularly so in New Zealand which perhaps explains why the mortar test method set out in NZS 3111, Section 11 has been successful in predicting problems. Typical traces of results for rhyolite and andesite compared with non reactive aggregates clearly demonstrates the relative reactive risks between materials, see **Figures 3.7, 3.8 and 3.9** (page 3.13). (Tests based on ASTM C289).

One topic not easily understood is that different reactive aggregates produce different amounts of expansion in concrete as their proportional content changes. **Figure 3.10** (page 3.13) shows how, for example, having just 12% of rhyolite causes 0.55% expansion yet using a concrete that has been made with 100% rhyolite materials the expansion is less than 0.1%. It is important therefore in any analysis of structural expansion to consider whether pessimum levels of reactive materials were in use.

Another kind of harmful reaction, which also results in abnormal expansion and cracking of the concrete, occurs between the alkalies in cement and dolomitic limestone. This is known as alkali-carbonate reaction but is rare in New Zealand and Australia.

Other Reactions

Other damaging chemical reactions involving aggregates include oxidation or hydration of certain unstable mineral oxides. Pyrites (ferrous sulphide), for example, can oxidise and hydrate to form brown iron hydroxide which causes unsightly stains. The presence of magnesia (MgO) or lime (CaO) in the aggregate may also cause pop-outs or cracking due to their hydration and expansion.

Tests and Testing

Field service records, when available, provide

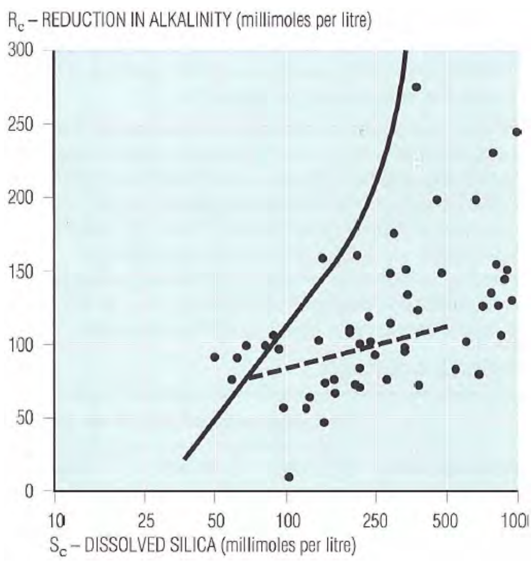


Figure 3.7 Results of testing rhyolite, dacite, and some alluvial materials containing these rocky types by ASTM C289

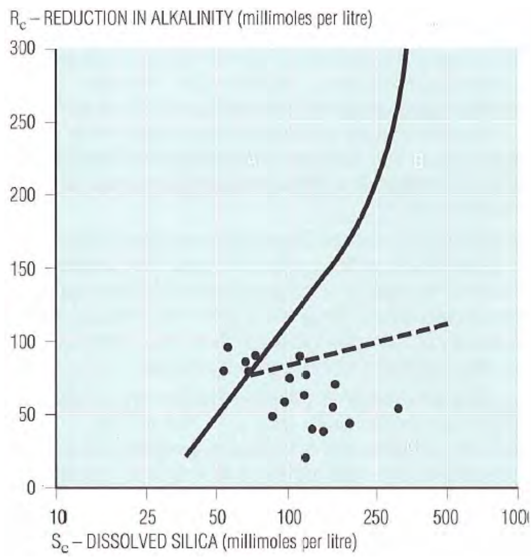


Figure 3.8 Results of testing Egmont andesite from Taranaki by ASTM C289

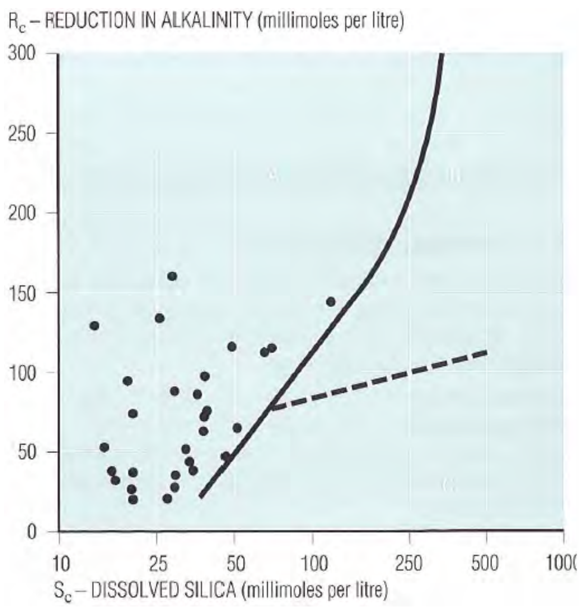


Figure 3.9 **Results of testing greywacke samples by ASTM C289**

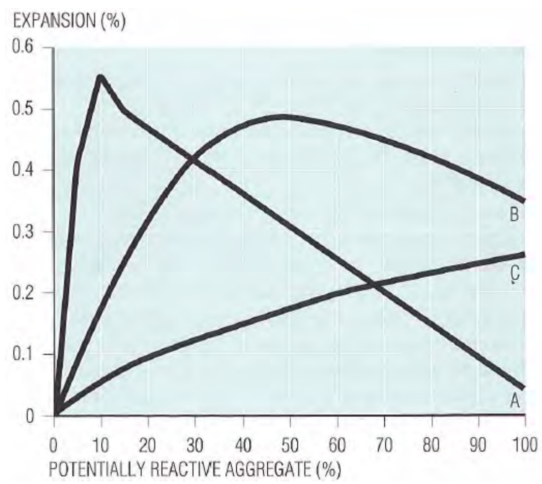


Figure 3.10 **Typical pessimum proportion curves for three New Zealand rock types (expansion at 12 months at 1.5% Na_20 equivalent)**

A Whakamaru rhyolite (Samples 80-88)
B Tongariro andesite (Sample 30)
C Egmont andesite (Sample 456)

information for the selection of non-reactive aggregates. If an aggregate has no service record, a petrographic examination can be useful by providing a description of its mineralogical and chemical constituents. It involves an examination of the aggregate particles with a microscope, together with other procedures for determining the constituents present, and in the hands of an experienced person can identify potentially reactive materials.

Physical tests are also available to measure potential reactivity. These include NZS 3111, Section 11. The potential reactivity of cement-aggregate combinations is determined by measuring the expansion of mortar bars (25 x 25 x 250 mm) during storage at 38 ± 2°C and a relative humidity not less than 90%.

Cement/aggregate combinations which show expansions greater than 0.10% at six months should usually be considered capable of harmful reactivity. When six-month results are not available, combinations should be considered potentially capable of harmful reactions if they show expansions greater than 0.05% at three months.

The chemical method described in ASTM C289 on AS 1141, Section 39 is a rapid method used to obtain in 24 hours an assessment of potential reactivity.

Because of the influence of certain minerals on the test results, the chemical test should always be accompanied by a petrographic analysis.

Indeed, the testing of aggregates for potential reactivity, and the interpretation of the results obtained, requires skill and experience. The mortar-bar test appears to give the best correlation with the behaviour of concrete, but, for improved assurance, it also should be conducted in conjunction with petrographic examination of the aggregate.

3.3.11 Impurities and Other Harmful Materials

Besides reactive minerals, aggregates may contain other impurities, such as organic matter, which are harmful to concrete.

Organic matter, such as that derived from decaying vegetation, is capable of delaying setting and hardening of concrete. It is more likely to be found in fine than in coarse aggregate and may be detected by the test set out in NZS 3111, Section 17. In this test, sand in a bottle is inundated in a sodium hydroxide solution and allowed to stand for 24 hours. The colour of the liquid above the sample is then compared with the colour of a standard reference solution. If the colour of the liquid is lighter than that of the reference solution, the amount of organic impurities present in the aggregate is not significant. If the colour of the liquid is darker than that of the reference solution, the aggregate contains organic compounds and further tests should be made to determine if these are harmful. Normally, the strength of concrete made with the sand is used as a gauge of the harmful effects of the impurities.

Sugar has a strong retarding effect on the setting and hardening of concrete. In severe cases of contamination, the resulting concrete may not set or may fail to gain appreciable strength. AS 2758.1 specifies a maximum limit on the sugar content of aggregate of one part in 10,000 determined in accordance with AS 1141, Section 35.

Silt, clay and dust may form a coating on aggregate particles, resulting in weakened bond between the aggregate and the cement paste. Excessive amounts of these fine materials may also increase unduly the water demand of the concrete, resulting in loss of concrete strength and an increase in its permeability. Cleanness in coarse aggregate can be determined by a test contained in NZS 3111, Section 13. Similarly the same Standard in Section 18 has a method of determining clay content.

Unfortunately the cleanness test does not distinguish the fine rock particles from clay and silt. Hence a supplementary test to determine the Clay Index has been agreed between the *Aggregates Association of New Zealand* and *New Zealand Ready Mixed Concrete Association*. The additional test is particularly useful in the evaluation of manufactured sands.

The presence of certain clay minerals, particularly the montmorillonites, will cause changes in volume with changing moisture conditions. Where such volumetric instability exists, the concrete may deteriorate rapidly with cycles of wetting and drying. As was mentioned in Clause 3.6 above, the wet/dry strength-variation test set out in AS 1141.22 can be used as a guide to the dimensional stability of the coarse aggregate. The amount of fine material is determined by washing a sample of the aggregate over a small sieve. Sections 12 and 13 in AS 1141 describe this type of test.

Coal, wood and other lightweight materials tend to rise to the surface during vibration of concrete, especially in pavements and floors, and produce a very poor surface finish. They also cause pop-outs and staining on vertical surfaces.

The percentage of light particles can be determined by the test set out in NZS 3111, Section 9. AS 2758.1 specifies a maximum limit on light particles of 1% by mass of aggregate (3% for slag aggregate).

There are no limits set by New Zealand Standards but as the percentage of lightweight particles increases the strength will decrease, requiring the use of NZS 3111, Section 8 Aggregate Performance in Concrete to determine an acceptable limit for supply of concrete.

Where surface appearance of the concrete is important, the amount of coal, wood and charcoal should preferably be even less.

Aggregates, particularly those dredged from the sea, or those quenched and washed with sea water, may be contaminated by sea salt which contains a high proportion of chloride ions. The amount of chlorides in concrete is of major concern because of its influence on the corrosion of embedded steel. They also increase shrinkage and reduce the sulphate resistance of concrete. Table 8 in AS 2758.1 and Clause 6.6 of NZS 3109 specify (in different ways) maximum chloride contents for concrete as placed. Adoption of the limits specified in the latter is recommended i.e. total chloride of concrete shall not exceed for:

Prestressed concrete: 0.5 kg/m^3

Reinforced concrete:

(a) Located in moist environment or exposed to chloride 0.8 kg/m^3

(b) Located in a dry or protected environment 1.6 kg/m^3

Total sulphate content shall not exceed 5% of the mass of cement.

3.4 OTHER PROPERTIES

3.4.1 Thermal Expansion

The coefficient of thermal expansion of aggregates varies from rock type to rock type and even within one type. In general, it increases with increases in the silica content of the aggregate.

The main effect of this property is to cause differential stresses between the aggregate and the cement paste – when the concrete is heated or cooled – which tend to break up the bond between the aggregate and the paste.

Concretes made with different aggregates may perform very differently, therefore, when subjected to high or low temperatures. When exposed to fire, for example, concrete made with siliceous materials is likely to spall and crack (resulting in loss of strength) to a much greater extent than concrete made with calcareous aggregates, e.g. limestone **Figure 3.7**.

3.4.2 Colour

The colour of aggregate is an important property in the production of architectural concrete, or that exposed to public scrutiny, and considerable scope exists to control concrete colour through the choice of aggregates.

There is a wide variety of colours available in aggregates, ranging from white, eg limestone and quartz aggregate, to brown and red, eg river gravel, to very dark coloured aggregates, e.g. basalt, dolerite. The colour of the fine aggregate normally has the major influence on the colour of the concrete. It is, therefore, important that the supply does not vary during the course of the work and stockpiling of special aggregate may be necessary.

Summary PROPERTIES OF AGGREGATES FOR CONCRETE

FOR COMPLIANCE WITH NZS 3121 THE FOLLOWING BASIC TESTS FROM NZS 3111 ARE REQUIRED:

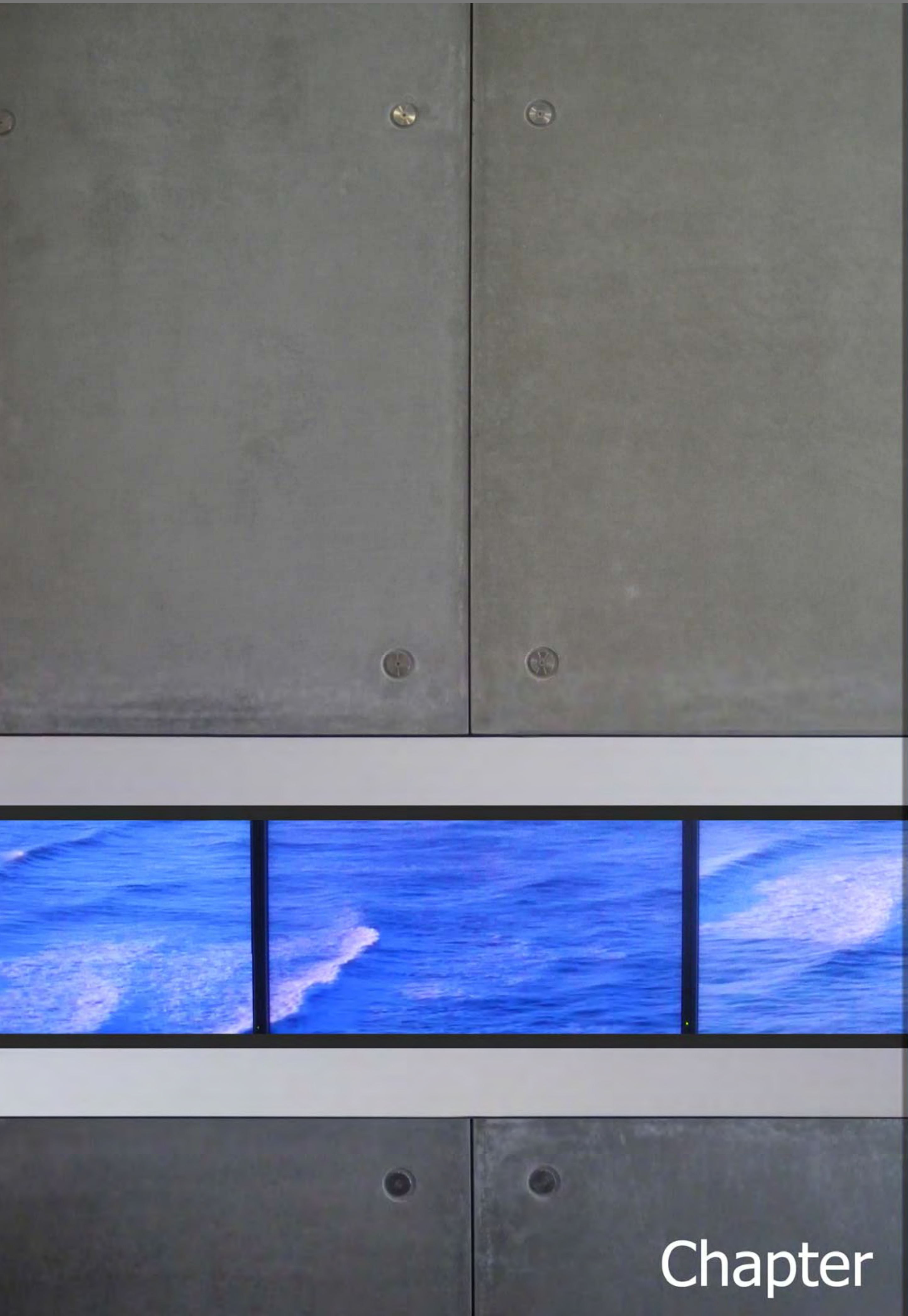
Aggregate Property	Tests	Limits specified in NZS 3121, ASTM C289, AS 2758.1 *(See Note 1)*
Grading	NZS 3111, Section 6 *Method for sieve analysis of aggregate and calculation of fineness modulus*	**Fine aggregate:** **NZS 3121, Clause 6.5.3** (a) For each sand, or a blend of sands produced, the requirements in respect of the following: (i) The amount of material retained on a 4.75 mm test sieve shall not exceed 5% by mass. (ii) The voids content of the sand passing the 4.75 mm test sieve shall not exceed 48%. (iii) The flow time shall lie within the limits set out in Table 3 of the Standard. (iv) The individual flow times obtained do not vary by more than ±0.20 from the average flow time of the 50 samples. (b) (i) The sand or resultant blend of sands, when subjected to a sieve analysis in accordance with Section 6 of NZS 3111, shall not contain more than 5% by mass retained on the 4.75 mm test sieve, and (ii) The individual fineness modulus values obtained or, in the case of blended sands, the combined fineness modulus values shall not vary by more than ±0.20 from the average fineness modulus of the 50 samples. *Note: Clause 6.5.3(b) applies to sands which have proven satisfactory concrete making service records.* **Coarse aggregate:** **NZS 3121, Clause 5.4.3** (b) Not less than 18 of the last 20 consecutive grading test results for each coarse aggregate nominal size range produced shall comply with all the appropriate individual requirements listed in Table 1 of the Standard. (c) The percentage material passing the correspond-ing intermediate sieve listed in Table 2 for nominal size range shall not vary by more than ±10 from the average of the last 10 sieve analysis tests.
Cleanness	NZS 3111, Section 13 *Method of determining the cleanness of coarse aggregate*	**NZS 3121, Clause 5.6:** Rejection if cleanness value is less than 60.
	NZS 3111, Section 18 *Method for determining the sand equivalent value*	**NZS 3121 Clause 6.3** Rejection if cleanness value is less than 60. *(See Note 2)*
Unit mass voids content	NZS 3111, Section 10 *Method for determining unit mass and voids content of aggregate*	**NZS 3121, Clause 5.4.3:** The loose poured unit mass values for the last 10 tests shall not vary by more than ±50 kg/m^3 from the average of the 10 tests.
	NZS 3111, Section 19 *Method for determining voids content flow time and percentage oversize material in sand*	**NZS 3121, Clause 6.5.3 above.**

Note 1: NZRMCA Technical Note *Water and Aggregate for Concrete* contains a number of variations to NZS 3121 agreed between the *Aggregates Association of New Zealand* and *New Zealand Ready Mixed Concrete Association* . It can be downloaded from *www.nzrmca.org.nz*.

Note 2: This restriction limit may be modified by reference to the Technical Note above and the establishment of a Clay Index value lower than 3.

Summary *(Properties of Aggregates for Concrete continued)*

Aggregate Property	Tests	Limits specified in NZS 3121, ASTM C289, NZS 3109
Deleterious materials	NZS 3111, Section 8 *Method of determining aggregate performance in concrete*	**NZS 3121, Clause 5.3** Deleterious materials Coarse aggregate providing it is of satisfactory cleanness as specified in 5.2 shall be deemed to be free of a significant quantity of the materials described in 4.2 if either: (a) It can be proven to the satisfaction of the specifying authority that the coarse aggregate has had a satisfactory concrete making service record over the previous 12 months, or (b) The coarse aggregate, when subjected to a performance test in accordance with the method set out in Section 8 of NZS 3111, gives concrete attaining a compressive strength at 28 days of not less than 33 MPa.
	NZS 3111, Section 11 *Method of determining potential reactivity of cement-aggregate combinations*	**NZS 3101 Clause 5.12** Requires precautions regarding alkali aggregate reaction.
	ASTM C289 Standard test method for potential reactivity of aggregates	**Evaluation to Figure 2 of ASTM C289**
	NZS 3111, Section 17 *Method of detecting the presence of organic impurities in sand*	**NZS 3111 Clause 17.5** Method uses a standard colour solution. Darker colour indicates high level of organic impurities.
ADDITIONAL TESTS REQUIRED FOR CONCRETE MIX DESIGN AND SPECIAL EVALUATIONS:		
Density/water absorption	NZS 3111, Section 12 *Method of determining the density of water absorption of coarse aggregate*	No specific limits set but affects mix design and workability.
	NZS 3111, Section 16 *Method of determining the density and absorption of sand*	
	NZS 3111, Section 19 *Method of determining lightweight particles in aggregate*	No specific limits set but will affect performance under NZS 3111, Section 8.
Soluble salts	ASTM C1152, *Test method for acid soluble chloride in mortar and concrete*	Prestressed concrete 0.5 kg/m3 Reinforced concrete moist/chloride 0.8 kg/m3 dry/protected 1.6 kg/m^3.
	No specific test method nominated for sulphate	Not to exceed 5% by mass of cement.
Moisture content	NZS 3111, Section 7 *Method of determining the moisture content of aggregates by drying*	No specific limits. Information required for concrete batching.
Crushing and weathering	NZS 3111, Section 14 *Method of determining the crushing resistance of coarse aggregate*	No specific limits set but affects NZS 3111, Section 8. See also AS 1141.22 details.
	NZS 3111, Section 15 *Method of determining weather resistance of coarse aggregate*	Recommended Quality Index. Table 12 of the Standard (Table 3.6 in this chapter).



Chapter 4

Water

Chapter 4

Water

This chapter discusses the effect of impurities in mixing water on the properties of concrete. It has been compiled largely from information presented by H.H. Steinour[1], supplemented by data presented by A. Samarin[2].

1 Steinour, H.H. 'Concrete mix water – how impure can it be?' *Journal of the PCA Research and Development Laboratories*, Vol. 2, No. 3, 1960, pp 32–50.

2 'Quality of mixing water', in *Australian Concrete Technology,* W.G. Ryan and A. Samarin (eds), Longman Cheshire, Melbourne, 1992.

INTRODUCTION

Most concrete specifications simply require that mixing water shall be potable, i.e. fit for drinking; or that it be clean and free from impurities harmful to concrete. NZS 3121 *Water & Aggregates for Concrete* requires that mixing water be from a source of acceptable quality, i.e. that:

- service records of concrete made with that water indicate that it is not injurious to the strength or durability of the concrete nor to the materials embedded in it; or
- the results of tests (in accordance with NZS 3111) are within the limits shown in Tables 4.1 and 4.2.

Under normal circumstances, water drawn from reticulated town-water supplies will meet these limits and be suitable for making concrete. Chloride limits specified in NZS 3101 *Concrete Structures* are not exceeded.

On projects remote from town-water supplies it may be necessary to utilise water of unknown quality or, on occasions, water which, superficially at least, is unfit to drink because of its turbidity, its smell, its taste, or even its colour. Although such water may be shown by test to be acceptable, there may be impurities present which are potentially harmful to concrete. Some knowledge of their effects will then be required.

Relevant New Zealand Standards

NZS 3101	*Concrete structures*
NZS 3104	*Specifications for concrete production*
NZS 3111	*Methods of test for water and aggregates*
NZS 3121	*Water and aggregate for concrete*

Relevant Australian Standards

AS 1379	*The specification and supply of concrete*
AS 2758	*Aggregates and rock for engineering purposes*
AS 2758.1	*Concrete aggregates*
AS 3600	*Concrete structures*

4.1 CONTAMINENTS

4.1.1 General

The solids content of water may have two components:

- solid matter, generally very finely divided, which is carried in suspension, and
- salts and/or organic matter which are dissolved in the water.

4.1.2 Solids in Suspension

Solids in suspension normally comprise finely divided silts and clays which will settle from the water if it is allowed to stand for a sufficient length of time. In any event, even quite significant amounts of finely divided silt and clay have little effect on the strength or durability of concrete as long as they are evenly distributed throughout the mix.

As a rough guide, it may be noted that AS 2758.1 permits up to 2% of material finer than 2 mm (fine silt and/or clay) in the aggregate.

Clays which coat or adhere to the aggregate particles are always objectionable because they interfere with the cement-aggregate bond. On the other hand, evenly distributed in the mixing water, they are much less objectionable.

4.1.3 Organic Matter

Organic matter can be particularly objectionable because it affects strength and, in extreme cases, can prevent the concrete from setting.

For example, even very small amounts of sugar can have this effect, (note that water containing sugar will still be potable and hence simply requiring mixing water to be potable is an insufficient specification).

More usually, however, organic matter simply retards the rate of strength gain and may be able to be compensated for by allowing additional time for the concrete to gain strength or by increasing the amount of cement in the mix.

Where organic matter is suspected, there is really no satisfactory alternative to the making of trial mixes, with the water in question, to determine its compliance with the limits set out in **Table 4.1** (page 4.3).

4.1.4 Dissolved Salts

General Steinour suggests that the salts commonly found in natural waters, that are not contaminated by industrial wastes, comprise mainly the following:

CATIONS	ANIONS
Calcium (Ca^{++})	Bicarbonate (HCO_3^-)
Magnesium (Mg^{++})	Sulphate (SO_4^{--})
Sodium (Na^+)	Chloride (Cl^-)
Potassium (K^+)	Nitrate (NO_3^-)

Other salts are normally present in such small amounts as to be negligible in their effects. Of the salts commonly found, by far the most significant are the chlorides and the sulphates.

Chlorides

Chlorides are to be found in naturally occurring waters in normally arid regions, in brackish water which has been contaminated by seawater and, of course, in seawater itself. They may also be found in some town water supplies, either as the result of treatment of the water or because it is derived from a source in which they occur.

The World Health Organisation is reported by Samarin to permit up to 350 mg/L of chloride in drinking water. A concentration as high as this would be highly unusual in drinking water in New Zealand or Australia, but even smaller amounts need to be considered in assessing the total chloride content of the concrete.

Chlorides may affect concrete in two ways. Firstly, when present in relatively large amounts, they may accelerate the setting time of the concrete, although at later ages the strength of the concrete tends to be less than might otherwise have been achieved. Calcium chloride, in amounts up to 2% by mass of cement, is sometimes used to accelerate the setting time of plain concrete in cold weather. Even seawater, which may contain up to 30,000 mg/L of chlorides, has been used to make satisfactory mass concrete when no other water has been available.

The adding of calcium chloride is a dubious practice which should be avoided. It can be added as a flake material rather than as a solution, not be evenly distributed throughout the mix and lead to unacceptably high chloride concentrations in pockets of the concrete. Further, in reinforced concrete it necessitates the testing of the concrete mix to ensure that the chloride content from all sources does not infringe the limit specified in NZS 3101.

Secondly, because even small amounts of chloride may be detrimental to the durability of reinforced concrete, NZS 3101 and NZS 3109 sets total limits on chloride in the concrete. These are 0.5 kg/m^3 for prestressed concrete, 0.80 kg/m^3 for reinforced concrete in moist exposure conditions and 1.6 kg/m^3 for other reinforced concrete applications. The contribution from chlorides in the mixing water needs to be considered with other contributors such as admixtures and aggregates. NZS 3121 specifies that the mixing water should not contain more than 500 mg/L of chlorides for reinforced concrete or 50 mg/L for prestressed concrete. The reason for the limitations is that chlorides can initiate and accelerate corrosion of reinforcing steel under certain conditions.

Table 4.1 **Limits on setting time and strength of concrete made from water from a source with no service record (determined in accordance with methods specified in AS 1379) (after Table 3 AS 1379)**

Property	Limits
Time of initial set	Within minus 60 minutes and plus 90 minutes of setting time of control sample
Compressive strength	
at 7 days	≥90% of strength of control sample at 7 days
at 28 days	≥90% of strength of control sample at 28 days

Sulphates

Sulphates may also be present in naturally occurring ground water. They can affect concrete in two ways: firstly, by affecting the setting time; secondly, by affecting later-age strengths and, in extreme cases, by exacerbating sulphate attack on the concrete should it be in continued contact with sulphate-bearing ground water. High sulphate concentrations may also cause later-age crazing and cracking.

Whilst it would be unusual for these effects to be significant, except in arid regions where sulphate soils are not uncommon, the sulphate content of natural waters should be checked to ensure that it does not exceed the limit of 800 mg/L specified by AS 1379, nor that the total suphate content of the concrete, from all sources, does not exceed 50 g/kg of cement. NZS 3121 has a maximum limit of 1,000 mg/L. NZS 3101 and NZS 3109 also restrict total suphate in the concrete to 5% of the mass of the concrete, i.e. 50 g/1 kg.

Carbonates and Bicarbonates

Sodium carbonate and sodium bicarbonate, if present in sufficient concentrations can cause set acceleration, even very rapid set, with some cements. Reduced strength may also occur.

Steinour suggests that up to 2,000 mg/L of combined sodium carbonate and bicarbonate may be safe in mixing water but that, nevertheless, it is advisable to make tests once the combined content reaches a level of 1,000 mg/L. The reason for this is the highly variable nature of these effects with some cements.

Calcium and magnesium carbonates are sufficiently insoluble as to be negligible in their effects. Whilst the bicarbonates are more soluble, it would be highly unusual for them to be present in amounts sufficiently large to cause significant problems except, perhaps, in waters highly charged with carbon dioxide (some mineral waters) where testing would be advisable in any case.

4.2 ACID AND ALKALINE WATER

4.2.1 General

While NZS 3104 does not have a pH limit, AS 1379 requires that mixing water have a pH greater than 5. Whilst the pH of water is not an entirely satisfactory measure, it nevertheless serves to alert the user to the possibility of undesirable impurities being present.

4.2.2 Acidity

Acidity in natural waters is most often caused by dissolved carbon dioxide but may also be caused by industrial wastes or by the oxidation of pyrites or other sulphides. Some mine waters, for example, become highly acidic as a result of the formation of sulphuric acid by this process. Water may also become acidic from decaying vegetable matter and the formation of humic and tannic acids. In all these cases, it is not so much the acidity itself that causes problems (cement is a highly alkaline material and the acid is soon neutralised) as the materials which have caused the acidity in the first place.

4.2.3 Alkalinity

Alkalinity in natural and treated waters may be due to the presence of sodium carbonate, which hydrolyses in solution to form hydroxyl ions, or to the presence of the alkali hydroxides, sodium and potassium. The effect of sodium carbonate on the setting and rate of strength gain of concrete has already been mentioned in Clause 4.1.4.

The alkali hydroxides are unlikely to be present in sufficient concentration to cause problems since cement itself is a highly alkaline material, although high concentrations have been shown to produce quick sets and reduced strengths with some cements. The same effect has not been noted with calcium hydroxide solutions, as the hydration of cement results in the mixing water rapidly becoming saturated with this material. In consequence, even saturated solutions of limewater have been shown to be without adverse effects on concrete made with it.

4.2.4 Recycled Water

It is almost universal practice in many parts of New Zealand and Australia for the ready-mixed concrete industry to recycle the water used to wash out truck mixers and agitators. This is one of the practices undertaken by the industry to minimise its impact on the environment. Such water is invariably alkaline and numerous tests have shown the practice to be satisfactory.

NZS 3104 permits the practice provided that the water is stored in a manner which prevents it becoming contaminated with materials deleterious to concrete and the water drawn from the storage outlet is of acceptable quality as defined, i.e. it complies with the limits set out in **Table 4.2**.

Table 4.2 **Limits on impurities in mixing water (determined in accordance with methods specified in AS 1379 (after Table 4 AS 1379) and NZS 3121)**

Impurity	**Maximum concentration** (mg/L)
Chloride as Cl–	500*
Sugar	100
pH	>5.0
Oil and grease	50
Sulphate as SO_3	1,000*

** Values from NZS 3101*

The New Zealand Ready Mixed Concrete Association has published a technical note *Use of Washwater*, downloadable from *www.nzrmca.org.nz*.

The note discusses a number of points regarding the use of recycled water (washwater):

1. Specific gravity (SG) of recycled water.
2. Initial setting time and impact on delivery/placing/slump.
3. Strength.

The significant point for use is that provided the recycled waters meets the chemical restrictions and its SG does not exceed 1.07, there would appear to be no significant changes to the concrete.

When washwater SG rises to 1.10 then 30% of total added water should be town supply. When washwater SG rises to 1.15 then town water should be increased to 50% of added water.

Essentially, by carrying out the dilution process the SG is held at 1.07 or below.

4.3 THE EFFECT ON CONCRETE DURABILITY

In considering the effect of mixing water on the durability of concrete, it is important to distinguish between short- and long-term effects. It is important also to assess the content of impurities in the mixing water in the light of their content in the other components of the concrete.

Firstly, it should be noted that mixing water which is satisfactory for plain or mass concrete may be unsuitable for reinforced concrete, and even more unsuitable for prestressed concrete. For example, water with a quite significant chloride content may be quite suitable for plain concrete but entirely unsuitable for reinforced concrete because of the danger of steel corrosion being initiated and/or accelerated. Similarly, the presence of sulphates in the mixing water may have little effect in the short term but be detrimental in the long term if the concrete is exposed to cycles of wetting and drying. The presence of chlorides and sulphates in the mixing water should always be regarded as undesirable and should always be below the limits set in NZS 3121 or AS 1379.

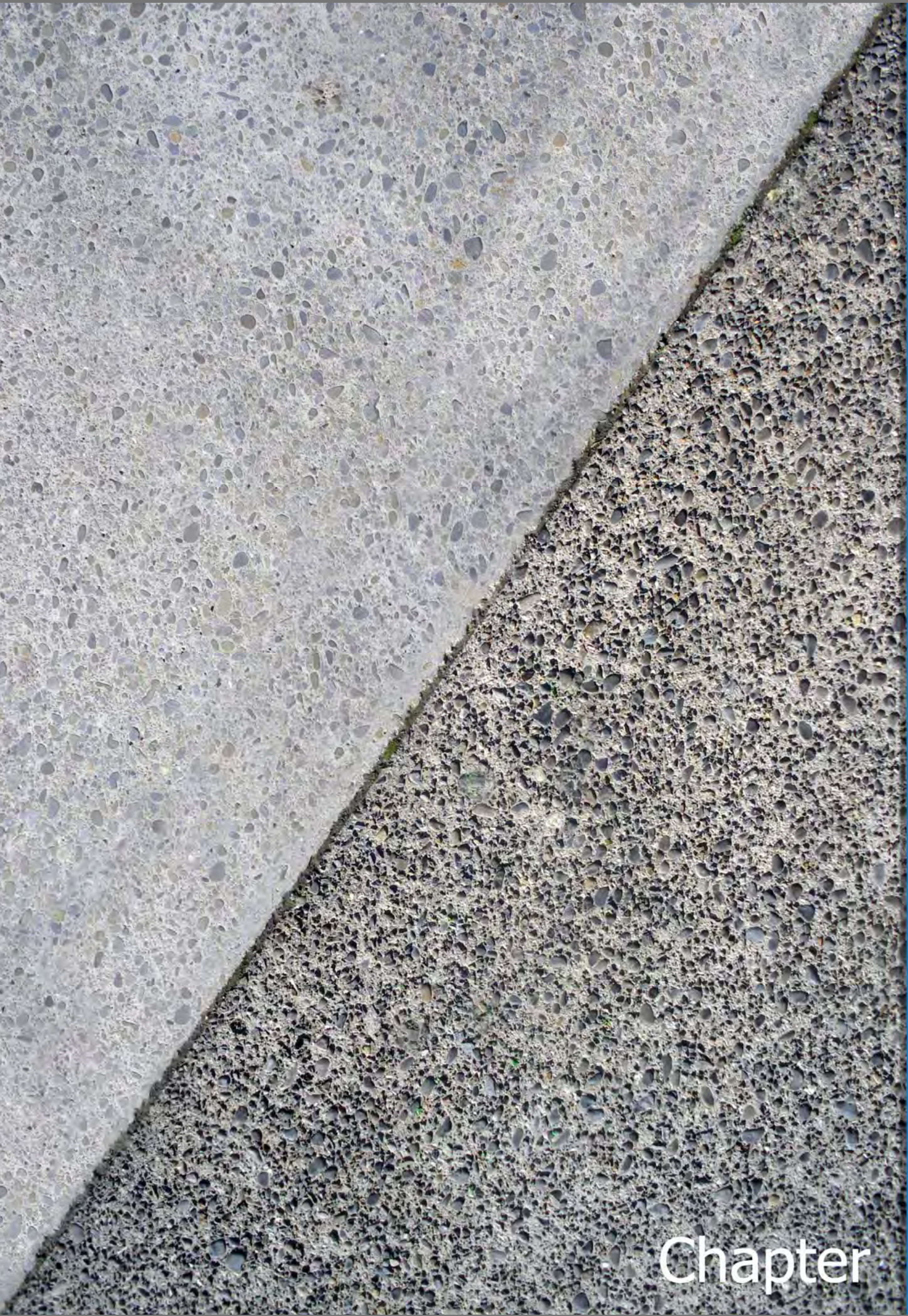
Secondly, the cumulative effect of some impurities if they are also present in some of the other components of the concrete should be noted. For example, NZS 3101 limits the total chlorides and the total sulphates in the concrete from all sources. Chlorides or sulphates in the mixing water may be sufficient to cause these limits to be exceeded. Similarly, sodium salts in the mixing water may be sufficiently low as to have little or no effect on the setting time or strength of the concrete. Nevertheless, they could be sufficient to influence the development of alkali-aggregate reaction should the aggregates be potentially reactive.

The CCANZ publication TR3 *Alkali Aggregate Reaction* also references the potential sodium equivalent contribution that water can make to the total alkali content of the concrete.

Summary WATER FOR CONCRETE

Aspect	Comment	Limits specified in AS 1379/NZS 3121
Solids in suspension	Solids evenly distributed in the mixing water have little effect.	Oil and grease, 50 mg/L
Organic matter	Adversely affects strength. Can prevent setting (sugar particularly). Where suspected, trial mixes may be required.	Sugar, 100 mg/L
Dissolved chloride salts	May accelerate setting times but reduce long-term strength. Detrimental to durability when used in reinforced or prestressed concrete.	500 mg/L*
Dissolved sulphate salts	Significant effects unusual. Natural water in arid regions requires checking.	1,000 mg/L*
Dissolved carbonates and bicarbonates	Combined sodium carbonate/bicarbonate content of up to 2,000 ppm may be safe but testing advisable when content exceeds 1,000 ppm. Calcium and magnesium carbonates usually negligible in their effects.	Sodium equivalent 300 mg/L
Acid water	Acidity itself not usually a problem (cement being highly alkaline neutralizes the acid) but the materials which caused the acidity may be a problem (e.g. sulfides, decaying vegetable matter, etc.).	pH >5.0
Recycled water	Generally satisfactory. Should comply with limits shown in Table 4.2.	
Concrete durability	Note different quality requirements for plain (unreinforced) concrete and reinforced/prestressed concrete. Note cumulative effect of some impurities if they are also present in other components of the concrete and the cumulative limits placed upon them (chlorides and sulphates).	

** are specified in NZS 3121.*



Chapter 5

Admixtures

Chapter 5

Admixtures

This chapter provides general information on admixtures used to modify the properties of concrete – in both the plastic and hardened states. Comment is included on their purpose and effects, including the influence of the other constituents of the concrete. In addition it provides some general guidance on the use of admixtures.

INTRODUCTION

The Australian Standard AS 1478 *Chemical admixtures for concrete, mortar and grout* defines an admixture as a material, other than water, aggregate and cementitious materials, used as an ingredient of concrete, and added to the batch in controlled amounts immediately before or during its mixing to produce some desired modification to the properties of the concrete.

A wide variety of materials comply with this definition but all are not recognised as admixtures. Some are used to produce special types of concrete, e.g. pigments to produce coloured concrete, fibres in fibre concrete and polymers in polymer concrete. Admixtures are used to impart certain desired characteristics to the fresh or hardened concrete. Increased workability, acceleration or retardation of the rate of hydration of cements, and added resistance to freezing and thawing are examples of these effects.

The specific effects of some admixtures may be significantly modified by factors such as type of cement, mix proportions (e.g. water content, cement content), other admixtures, aggregate type and grading, concrete temperature, and by type and duration of mixing. Many admixtures also affect more than one property of concrete, sometimes affecting desirable properties adversely. An admixture should therefore be used only after appropriate evaluation of its effects, preferably by testing with the particular materials and job conditions likely to be encountered. Whilst this is not always possible on minor work, it is of the utmost importance on major projects.

It is also particularly important when two or more admixtures are to be used in combination. It should not be assumed that the admixtures will be compatible or that the effects of admixtures used singly in concrete will be additive when they are used in combination, i.e. when two or more are added together to the concrete. In such cases, careful attention should be given to the instructions provided by the manufacturers or their guidance sought on the possible effects of interaction.

Relevant New Zealand Standards

NZS 3101	*Concrete structures*
NZS 3104	*Specification for concrete production*
NZS 3109	*Concrete construction*
NZS 3113*	*Chemical admixtures for concrete*
NZS 4210	*Masonry construction*

* This standard is being withdrawn in favour of using AS 1478.

Relevant Australian Standards

AS 1478	*Chemical admixtures for concrete, mortar and grout*
AS 1478.1	*Admixtures for concrete*
AS 2072	*Methods for the sampling of expanding admixtures for concrete, mortar and grout*
AS 2073	*Methods for the testing of expanding admixtures for concrete, mortar and grout.*

5.1 TYPES OF ADMIXTURES

5.1.1 Classification

Generally, admixtures are classified either by their characteristic or principal effect on the concrete (e.g. set-retarding) or by the type of material or chemical that is the principal constituent (e.g. polysaccharides).

Chart 1 (page 5.3) outlines the more common types of admixture used in concrete in terms of their principal effect and indicates their relationship to one another.

The summary on page 5.10 summarises their fields of application and general effects on concrete. The wide range of materials used as admixtures and the continual development of new or modified products makes it impractical to list other than the main types met in practice.

5.1.2 Air-Entraining Admixtures (AEA)

The intentional entrainment of air in concrete is a well-established means of improving the resistance of concrete to the potentially destructive effect of cycles of freezing and thawing. AS 3600 prescribes limits for the percentage of entrained air in concrete in such an environment. Air-entraining admixtures are commonly used for this purpose. They also assist in the reduction of bleedwater and tend to improve the workability of concrete mixes.

Although many materials will entrain air in concrete, not all are suitable since the size and spacing of the air bubbles is of critical importance in providing resistance to the effects of freezing and thawing. The materials used in commercially available air-entraining admixtures include salts of wood resins, salts of sulphated or sulfonated petroleum hydrocarbons, salts of petroleum acids, fatty and resinous acids and their salts.

These materials produce a void system which consists of a large number of minute air bubbles dispersed uniformly through the concrete matrix.

Chart 1 Types of Admixtures

Air entraining	(Type AEA)
Set-controlling	Set-accelerating (Type Ac) Set-retarding (Type Re)
Water-reducing	Normal (Type WR) Medium-range water-reducing – superplasticisers (Type MWR) High-range water-reducing – superplasticisers (Type HWR)
Water-reducing/set-controlling	Water-reducing/set-accelerating (Type WRAc) Water-reducing/set-retarding (Type WRRe) High-range water-reducing/set-retarding – superplasticisers (Type HWRRe)
Thickening	Pumpability aids
Shrinkage-reducing/shrinkage-compensating	
Permeability reducing	
Special purpose	Special purpose/normal setting (Type SN) Special purpose/accelerating (Type SAc) Special purpose/retarding (Type SRe)

An important aspect of the void system is the spacing of the bubbles (the spacing factor). The cement matrix in concrete is normally protected against the effects of freezing and thawing if the spacing factor, when determined in accordance with ASTM C457, is 0.2 mm or less **Figure 5.1**.

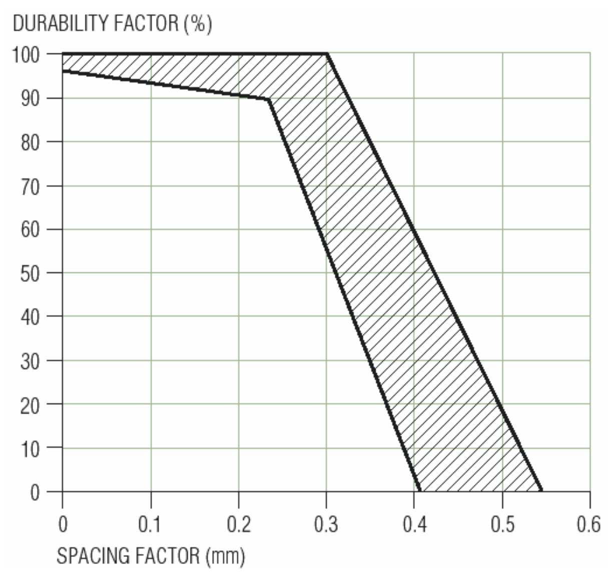


Figure 5.1 **Relationship between durability and bubble spacing factor of entrained air**

The characteristics of the air-void system produced (e.g. air content, size, spacing, etc) are influenced by many factors, the principal being:

- Type and concentration of the admixture.
- Type of cement.
- Mix proportions.
- The grading of the fine aggregate.
- Type and duration of mixing.
- Condition of transit mixer.
- Type and degree of compaction applied in placing concrete.
- Presence of other types of admixtures in the mix (e.g. water-reducers).
- Temperature of the concrete mix.

There are other advantages to intentionally entrained air in concrete and it is these which have led to its widespread use even in the more temperate regions of Australia. For example, the workability of the fresh concrete is increased, enabling a reduction in the water content of the mix. In addition, the cohesiveness of the concrete is increased, thereby reducing the danger of bleeding and segregation. These improvements in the properties of the fresh concrete, complemented by proper placing, compaction and curing, reduce the permeability of the hardened concrete.

Air-entrainment usually reduces strength, particularly in concretes with moderate to high cement contents, despite the decreased water requirement. The reduction is generally proportional to the amount of air entrained. The entrainment of excessive amounts of air should therefore be avoided and this is normally limited, by specification, to a maximum of 4-6%, or less, depending on the maximum size of aggregate **Figure 5.2** (page 5.4).

AS 1478.1 stipulates that the compressive strength, at any test age, of concrete containing an air-entraining agent shall be not less than 90% of that of the control concrete (the same concrete but without the admixture).

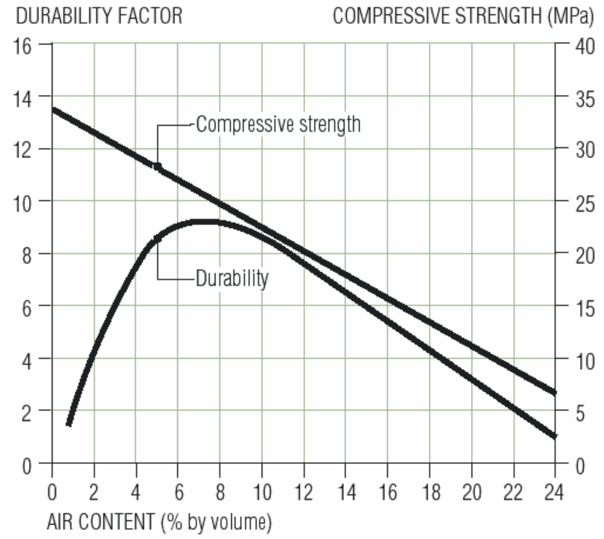


Figure 5.2 **Effect of entrained air on durability**

5.1.3 Set-Accelerating Admixtures (Type Ac)

Accelerators are used to reduce the setting time of a concrete mix particularly when concreting in cold weather. They may increase the rate of early strength development.

Formerly, the most commonly-used accelerators were calcium chloride or combinations of calcium chloride and other accelerators. Non-chloride accelerators, which impart similar concrete properties without the adverse impact of calcium chloride on the corrosion of reinforcing steel have recently been developed. These include triethanolamine, thiocyanates, nitrites and nitrates. Triethanolamine is used as a constituent of other admixtures (e.g. as a constituent of water-reducing admixtures to counteract the retarding effect of such admixtures(but is rarely used alone.

Accelerating admixtures affect the properties of concrete in both the plastic and hardened states. In the plastic state they reduce both the initial and final setting times (i.e. in practical terms the time when finishing can begin and when it is no longer possible), the amount of the reduction depending on factors such as the type and concentration of the accelerator, the temperature of the concrete, the type of cement and the cement content. Because of the reduced setting time, the tendency of concrete to bleed is also reduced.

Accelerating admixtures may increase concrete strengths at early ages, although there may be some reduction in potential strength at later ages.

Frequently, the same effects as bestowed by set-accelerating admixtures can be obtained by other means. For example, the use of high early strength cement, Type HE, the use of higher cement contents, the use of heated water and aggregates, the use of longer or different curing methods, or a combination of these means. However, in many cases, the use of an accelerator may be the most economical method of obtaining the desired results.

Calcium chloride and triethanolamine normally increase the drying shrinkage of the concrete, the increase being more pronounced the greater the dosage rate of the admixture. They also give rise to marked increases in creep, this effect being intensified by loading at an early age and in a dry environment **Figure 5.3**.

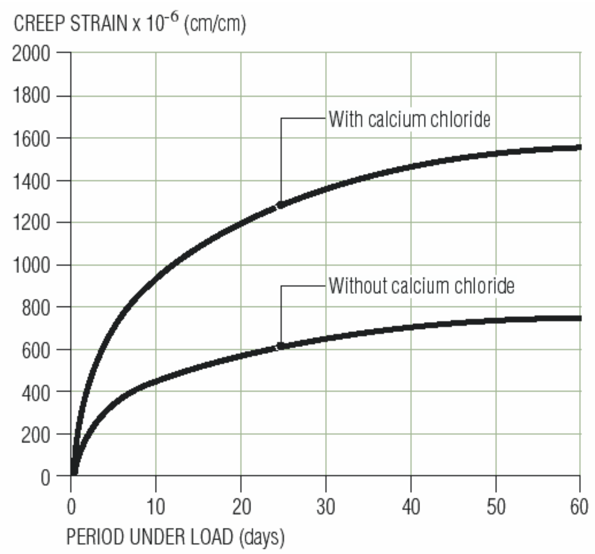


Figure 5.3 **Comparison of creep of concrete with and without calcium chloride**

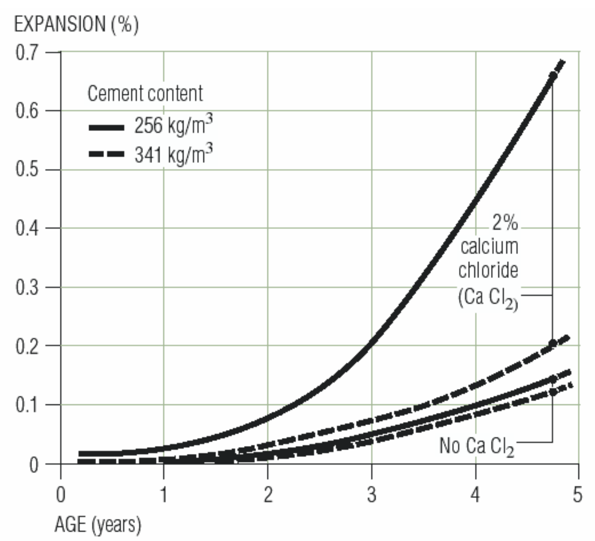


Figure 5.4 **Comparison of expansion of concrete with and without calcium chloride**

Calcium chloride's use is limited because of its undesirable side effects. A major disadvantage of calcium chloride is its tendency to promote the corrosion of embedded metals because of the presence of chloride ions. In addition to the effects previously mentioned, the use of calcium chloride reduces the resistance of concrete to sulphate attack (by increasing its expansion) **Figure 5.4** (page 5.4), and increases the rate of alkali-silica reaction if reactive aggregates are present.

Because of these problems, particularly those associated with the corrosion of reinforcing steel, calcium chloride is not recommended for use as an admixture. NZS 3101 limits the amount of acid-soluble chloride, from all sources, to 0.5 kg/m^3 for prestressed concrete, 0.8 kg/m^3 for reinforced concrete in moist exposure conditions, and 1.6 kg/m^3 for other reinforced concrete applications.

5.1.4 Set-Retarding Admixtures (Type Re)

Set-retarding admixtures slow down the setting of concrete and are widely used in hot weather to keep the concrete workable during placing. They are also used in the placing of large volumes of concrete to assist in the production of a monolithic member or structure, i.e. one free from construction joints. They are also useful when transporting concrete, mortar or grout for long distances, and may be employed for various types of delayed finishes.

The materials used to retard setting include: lignosulfonic acids and their salts, hydroxy carboxylic acids and their salts, and certain sugars and carbohydrates. Lignosulfonate-based retarders entrain air in concrete, so their use in combination with air-entraining admixtures must be carefully controlled to avoid the entrainment of excessive amounts of air. Hydroxy carboxylic groups do not entrain air but tend to increase, to varying degrees, the tendency of the concrete to bleed.

As with other chemicals, the amount to be used to produce a precise retarding effect depends on many factors, including the type of retarder, the concrete temperature, the chemical composition of the cement, and the cement content of the concrete. If setting time has to be controlled relatively accurately, the dosage of the set-retarder should be determined by preliminary trials with job materials and under job conditions.

The time in the mixing cycle at which the admixture is introduced into the concrete mix will also affect the level of retardation obtained. Delayed addition of the admixture, i.e. after the cement has been mixed with water, produces longer setting times than when the admixture is added with the mixing water.

Due to the effect of set retardation, concrete strengths at early ages may be reduced. However, no reduction (and often increases) in the 28-day and longer-term strengths may occur.

Retarders are commonly used to retard the setting time of concrete by 1 to 3 hours although longer delays can be obtained, if required. However, the dosage should be carefully controlled since overdoses can lead to excessive retardation. Extended retardation results in settlement cracking, excessive bleeding, and delays in construction schedules. In severe cases, delays in the development of measurable strength (up to several days) and reduction in later strength may occur. If high accidental over-dosages are encountered, acceptable later-age strengths will often be attained as long as the air content of the concrete is not excessive and the concrete is not allowed to dry out whilst it continues to gain strength.

5.1.5 Water-Reducing Admixtures (Types WR, WRRe, WRAc and MWR)

Water-reducing admixtures disperse the cement particles and increase the fluidity of the concrete. Hence, for a given workability, they permit a reduction in the amount of water required in the concrete. However, the chemicals used to produce water-reducing admixtures often have a natural retarding effect on the hydration of the cement, and hence on the setting times of the concrete. In proprietary products, this is normally compensated for by the addition of an appropriate amount of an accelerator such as triethanolamine. By adjustment of the amount of accelerator incorporated in the admixture, a range of setting times may be obtained. Indeed, products can be formulated to compensate for the changes in ambient temperature between summer and winter.

AS 1478.1 classifies water-reducing admixtures as follows:

- Type WR. Water-reducing (with normal setting times).
- Type WRRe. Water-reducing and set-retarding.
- Type WRAc. Water-reducing and set-accelerating.

The chemicals normally used to produce water-reducing admixtures are:

- lignosulphonic acids and their salts;
- hydroxy carboxylic acids and their salts;
- polysaccharides; and
- modifications and derivatives of the above.

The first three give water-reducing and set-retarding admixtures. The three comprises water-reducing admixtures combined with other materials to achieve varying degrees of acceleration or retardation in the rate of concrete hardening.

The lignosulfonates are less powerful than the polysaccharides and hydroxy carboxylic acid derivatives and hence are less sensitive to overdosing and excessive retardation. However, as was mentioned earlier, lignosulfonates entrain air in concrete and must be used in relatively low concentrations to avoid excessive air entrainment and correspondingly large reductions in ultimate strength.

As with other types of admixture, the specific effects of water-reducing admixtures depend on a number of factors, including the type of cement, the cement content of the concrete, and the temperature of the concrete.

Water-reducing admixtures may be used in a number of ways **Table 5.1**:

- To reduce both the water content and the cement content whilst maintaining the same nominal strength (A) and workability (B).
- To achieve increased concrete strength by reducing the water requirement whilst maintaining the same cement content and workability.
- To increase the workability without adjustment to the water and cement contents and whilst maintaining the same concrete strength.

Table 5.1 Applications of water-reducing admixtures

Equivalent Concrete Mixes		Properties	
Without water-reducer	**With water-reducer**	**28-day strength**	**Workability**
Reference mix	Reference mix + WR – water – cement	A	B
Reference mix + cement	Reference mix + WR – water	>A	B
Reference mix + cement + water	Reference mix + WR	A	>B

Investigations on lignosulfonate-based water-reducing admixtures, added to the concrete mix in the three ways mentioned above, found that they have the intrinsic effect of increasing early drying shrinkage and creep of concrete. The effect on shrinkage diminishes with time so that the long-term drying shrinkage may not be significantly different from that of plain concrete. When the use of an admixture is accompanied by a change in mix proportions, the net effect may be either an increase or a decrease in shrinkage, depending on the admixture used, the mix proportions and the drying period.

The addition of calcium chloride or triethanolamine to offset the retarding influence of lignosulfonates, increases the early drying shrinkage of the concrete more than would the lignosulfonate used alone. There is also a tendency for a permanent increase to occur in the long-term drying shrinkage. Such addition also increases creep.

Mid-range water-reducing admixtures act in a similar way but provide an increased effect compared to normal range water-reducing admixtures.

5.1.6 High-range Water-Reducing Admixtures – Superplasticisers (Types HWR and HWRRe)

Superplasticisers are admixtures which have strong water-reducing and cement dispersing capabilities and have assisted in producing many types of 'high quality' concretes over the past 15–20 years in New Zealand and Australia. They may be used to produce very highly workable concrete or to produce concrete with an extremely low water-cement ratio. When first developed, their effect on workability lasted only for a limited period of time, less than 30 minutes, so that close control had to be maintained over the time at which they were added to the concrete. More recent formulations have overcome this limitation.

AS 1478.1 classifies superplasticisers as follows:

- Type HWR. High-range water-reducing (with normal setting times).
- Type HWRRe. High-range water-reducing and set-retarding.

Superplasticisers are used in two distinct ways or in some combination of them:

- to increase greatly the workability of concrete of a predetermined water-cement ratio; or
- to increase the strength of concrete of a specified consistency by permitting significant reductions in the water content.

These are the two extremes. However, they may also be used to achieve a balance between improved workability and increased strength.

At one end of this spectrum of applications is high-slump concrete. Superplasticisers can be used to obtain slumps of 200–250 mm. Concretes with these slumps assist in concrete placing and compaction. In order to obtain flowing concrete without a marked tendency to segregation, the mix should be especially designed for the addition of superplasticisers. To avoid problems of segregation and bleeding and to maintain cohesion at the increased slump, concretes typically require increased cement contents and fine-sand percentages.

Typical applications for flowing concrete are to:

- assist the placing and compaction of concrete in areas of congested reinforcement and in areas of poor access;
- assist the production of high-class concrete surfaces;
- permit increased pumping distances and heights.

When using superplasticisers, there are several points to be noted:

- When pumping superplasticised concrete, standby pumps may be needed because of the limited time available to make repairs.
- Although high-slump concrete is almost self-levelling, adequate compaction is required to fully consolidate the concrete.
- Greater attention should be given to the formwork design and sealing of joints to prevent leakage of the fluid paste and to accommodate the increased hydraulic pressures.
- The dosage rate needs to be individually established for each particular set of conditions.

Superplasticisers may be classified according to their chemical composition:

- Naphthalene formaldehyde condensates.
- Melamine formaldehyde condensates.
- Polycarboxylic polymers.
- Modified lignosulfonates.
- Others.

Superplasticisers affect concrete fluidity only temporarily(for a period of between 20 and 240 minutes depending on the class of superplasticiser used, cement type and amount, rate of mixing, age of concrete prior to the addition, temperature and the presence of other admixtures in the mix.

Some superplasticisers have a short duration (less than an hour) effect on the workability of the concrete and are generally added on site to take full advantage of their effect. Construction procedures should be fully planned to take advantage of this behaviour of the superplasticiser, and increased site control is required **Figure 5.5**. Re-tempering of superplasticised mixes can be carried out if delays cause the slump to fall below the specified value. This should be carried out by a qualified technician. Adequate re-mixing is required to uniformly distribute the additional admixture through the concrete.

Superplasticisers, i.e. Type HWRRe, with a longer effective slump retention (two to four hours) are suitable for adding at the batching plant.

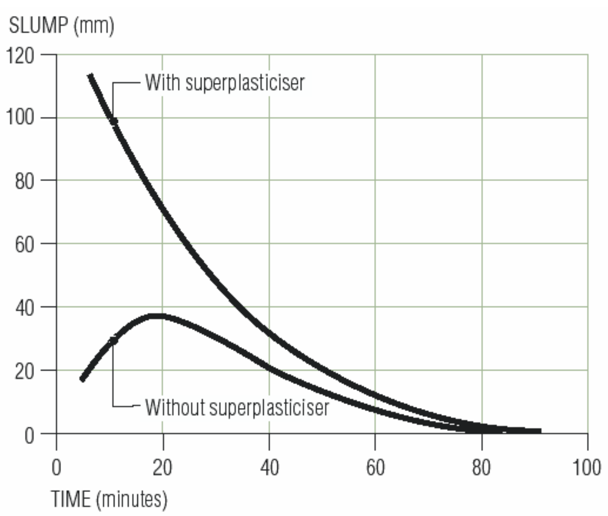


Figure 5.5 **Comparison of workability (as measured by slump) of concrete with and without superplasticiser**

5.1.7 Thickening Admixtures

Thickening admixtures are admixtures whose primary function is to improve the pumpability of concrete. Virtually all of the materials marketed as pumpability aids act to thicken or increase the viscosity of the cement paste. This inhibits forced bleeding of water from the paste and permeation of paste through the aggregate voids. In consequence, pumpability aids are not generally used in concrete that is not to be pumped or, for that matter, in concrete that can be readily pumped. The primary purpose of using admixtures to enhance pumpability of concrete is to overcome unavoidable difficulties at a reasonable cost. Whilst pumpability admixtures can improve the pumpability of some, but not all, concretes, they will not make unpumpable concrete pumpable.

AS 1478.1 classifies thickening agents according to their physical actions as follows:

Class A: Materials which dissolve in, and increase the viscosity of, the mixing water, e.g. cellulose ethers; pregelatinised starches; ethylene oxide polymers.

Class B: Soluble materials which adsorb on cement and increase the interparticle attraction between cement grains, e.g. synthetic polyelectrolytes; alginates; certain natural gums.

Class C: Materials which increase interparticle attraction and also supply additional superfine particles in cement paste, e.g. aqueous bentonite dispersions; paraffin wax emulsions which are unstable in the presence of cement.

Class D: Materials which supply additional fine particles to cement paste, e.g. kaolin; diatomite; hydrated lime; fly ash; pulverised talc; silica; pumicite; other fine mineral powders. Paraffin wax emulsions which are stable in the presence of cement may also be included in this class.

The performance of a given admixture can change dramatically with dosage rate, cement composition, mixing temperature and time. Since the main effect of a water thickener is to increase viscosity, substantial thickening can increase water requirements with the usual consequence of reduced strength.

Many of the organic thickening agents retard the setting of cement. In some cases, e.g. cellulose derivatives, the retardation can be substantial.

5.1.8 Shrinkage Reducing and Shrinkage Compensating Admixtures

Shrinkage reducing admixtures reduce the drying shrinkage of concrete by modifying the surface tension of the water in the micropores of the concrete.

Shrinkage reducing admixtures are liquids and can be added to concrete, grouts, etc. during production. They are compatible with most other admixtures. However, mix trials are desirable to fully understand the performance of the system.

Shrinkage compensating admixtures provide shrinkage compensation while the concrete is in the plastic and/or hardened state. These admixtures are materials which, during the hydration period of the cement, either expand themselves or react with other constituents of the concrete to produce expansion. The rate and the amount of expansion that results from the use of the admixture is very important. Properly timed expansion, by a suitable amount can be employed in machinery grouting, patching and the production of concrete free from shrinkage cracks. On the other hand, uncontrolled expansion may lead to cracking.

A number of materials have been reported as suitable for this purpose. They include:

- Finely divided or granulated iron with an oxidation promoter which increases the rate of oxidation. Expansion occurs in the presence of air and moisture as the iron oxidises. Control of expansion is required so that no disruption of the mortar or concrete occurs. The use of calcium chloride as an accelerator should not be permitted as it acts as an oxidation promoter and results in increased expansion. Further expansion, due to subsequent rewetting of the mortar or concrete, can occur if the exposed surfaces of the concrete or mortar are not sealed.

- Gas-generating admixtures. These are aluminium powders which react with the alkaline constituents of the cement and produce small bubbles of hydrogen throughout the mix. The reaction is affected by the temperature and type of powder used. An increased dosage or a non-uniform distribution of bubbles of hydrogen can result in an increase in porosity with consequent loss of strength.

- Lime-based admixtures. These consist of free calcium oxide. Expansion takes place as the admixture is hydrated to produce calcium hydroxide.

The satisfactory performance of expanding admixtures will depend to a significant extent on their being distributed uniformly throughout the mix. When more than one admixture is used, the compatibility of the combination is important. If a non-compatible combination is used (such as an iron-based admixture and calcium chloride as accelerator) the properties of the concrete may be adversely affected.

5.1.9 Permeability-Reducing Admixtures

A permeability-reducing admixture is defined in AS 1478.1 as an admixture that reduces the rate of transmission of moisture either in a liquid or vapour form through concrete.

Properly proportioned concrete mixtures which are handled, placed and cured with care should produce concrete with low permeability. Since the use of these admixtures is usually advocated with very good mix designs, low water-cement ratios, good compaction and curing, the increased benefit obtained is difficult to quantify.

Materials which have proved useful for this purpose include the following:

- Finely-divided materials that have some pozzolanic properties, i.e. they are able to react with the calcium hydroxide liberated by hydrating cement to produce cementitious compounds. Some naturally occurring materials, such as volcanic sands and diatomaceous earth, possess such properties but by far and away the most widely used pozzolan in Australia today is fly-ash, the byproduct of the combustion of pulverised coal in high-temperature boilers and combustion chambers. This material and its effect on the permeability of concrete are discussed in detail in Chapter 2 *Hydraulic Cements*.

- Relatively chemically inert materials such as talc, some stone powders (ground quartz) and bentonite. These materials are sometimes used in concrete mixtures which would otherwise be deficient in fines. In such cases the addition of a finely-divided material improves workability and reduces bleeding. When an appropriate quantity of the admixture is used and no increase in the water content is required the permeability of the concrete may be improved. The use of excessive amounts, or the addition of a mineral powder (unless pozzolanic or otherwise cementitious in its action) to a mixture not deficient in fines, generally increases the water demand of the mix which results in an increase in permeability and lower strengths.

- Water-repelling substances derived from soaps and fatty acids and petroleum products such as paraffin wax and bituminous emulsions. These materials depend for their efficacy on their ability to reduce the transmission of moisture and water vapour through the pores and capillaries of hardened concrete.

5.1.10 Special Purpose Admixtures

Special-purpose admixtures are those not covered by other types or classes of admixtures. They are used on a project basis to impart or enhance a specific property of plastic or hardened concrete.

Typical examples of special purpose admixtures are corrosion inhibitors and anti-washout admixtures. AS 1478.1 puts the responsibility on the supplier of these admixtures to provide verifiable data to prove their special properties.

5.2 GUIDANCE ON THE USE OF ADMIXTURES

Admixtures are used to improve one or more of the properties of fresh or hardened concrete. Among the effects sought are increased workability, variation of the natural rate of hydration or setting of the cement, added resistance to freezing and thawing, and reduced permeability. Given good basic materials and workmanship many of these improvements may be achieved without the use of admixtures. However, the use of admixtures will often produce the desired improvements more readily or economically. At the same time, their use is in no way a substitute for good concrete practice and workmanship. Indeed the careless use of admixtures may well exacerbate the very problem one is trying to resolve.

- When using admixtures consideration should be given to the following:

- The specific purpose for using an admixture should be clear.

- The basic ingredients of the admixture should be known.

- The compatibility of admixtures used in combination should be checked.

- The evaluation of the admixture should be based on trial mixes with the materials and under the conditions expected on the job.

- Supervision and site control should be increased rather than relaxed.

Summary ADMIXTURES FOR CONCRETE

Type	Application	Effect	Comment
Air-Entraining (AEA)	To enhance freeze/thaw resistance. To increase workability.	Produces a large number of small air bubbles in the concrete.	Efficiency is reduced by increases in temperature, high cement content and by the presence of fly ash.
Set-Accelerating (Ac)	For cold-weather concreting. To permit early finishing. To permit early formwork removal. To expedite completion of structure or repair.	Shortens setting time. May increase early strength of concrete. May reduce long-term strength.	Overdosing may lead to the very rapid set of concrete and to reduced ultimate strength. Those containing chloride ions (e.g. calcium chloride) have the tendency to promote the corrosion of metals embedded in, or in contact with, the concrete.
Set-Retarding (Re)	For hot-weather concreting. To facilitate the use of delayed finishes. For mass concrete. To eliminate cold joints.	Delays setting of concrete. Reduces early strength of concrete (up to 7 days).	Overdosing may lead to excessive retardation and delays in the development of concrete strength (in severe cases up to several days). Generally, later-age strengths are not affected.
Water-Reducing (WR, WRRe and WRAc) *Note: Mid-range water-reducing (Type MWR) offer greater water reduction than Type WR.*	To increase workability. To increase strength at same workability. A combination of the above two applications. To improve properties of concrete incorporating poorly-graded aggregates.	Disperses cement particles and increases the fluidity of the concrete. Reduces the water demand of the mix. May affect setting time (retard or accelerate) depending on the formulation of the admixture.	Overdoses of lignosulphonates may cause excessive retardation and excessive air entrainment with subsequent effect on strength. The chloride content should be ascertained.
High-Range Water-Reducing – Superplasticisers (HWR and HWRRe)	To facilitate placing and compacting (e.g. in heavily reinforced members). To increase strength. For the provision of high-quality formed surfaces. To facilitate pumping.	Increases the fluidity of the concrete and can be used to produce concretes with very low water-cement ratios.	Compatibility with other admixtures in the mix should be checked. Re-tempering of the concrete more than once to restore slump is not recommended.
Thickening	To facilitate pumping over greater distances at lower pressure. To improve lubrication and reduce segregation.	Increases the viscosity of the cement paste.	Will not convert unpumpable concrete into pumpable concrete – the mix must be designed specifically for pumping.
Shrinkage-Reducing	To offset volume change (in concrete, mortar and grout). For grouting of anchor bolts, prestressing ducts and prepacked-aggregate concrete. For bedding of machines and columns. For underpinning. To produce self-stressed concrete.	Some SRAs work in the plastic state and others in the hardened state.	Excessive dosage of the admix-ture, or the presence of unsuitable combinations of admixtures (or of admixture and cement) could generate excessive expansive forces that disrupt the concrete, mortar or grout. High doses of liquid SRAs may affect com-pressive strengths and consider-ation should be given to the com-bined use with a superplasticiser.
Permeability-Reducing	To reduce transmission of moisture.	Fills the pores with reactive, inert or water-repellent materials.	Will not convert poor-quality concrete into water-tight concrete. Most reduction in permeability is mainly due to improved workability and, in turn, better workmanship.

Manufacture of Concrete

Chapter 6

Chapter 6

Manufacture of Concrete

This chapter deals with the manufacture of concrete. It is described only to the extent necessary to provide the reader with some background to the selection and proportioning of materials and to the various steps in the manufacturing process.

INTRODUCTION

NZS 3104 *Specification for Concrete Production* covers site-mixed, factory-mixed, and truck-mixed concrete. In addition to specifying requirements for concrete materials, plant and equipment, the Standard read with NZS 3109 *Concrete Construction*, sets out procedures for the specification and ordering of concrete, its production and delivery, and its sampling and testing for compliance with the requirements of the specification.

Nowadays, most construction sites are supplied with concrete from a central batching plant, either operated by the contractor or by an external supplier. Whilst obviously there will be some differences in procedures in ordering and testing concrete where the contractor owns his own plant, the principles governing manufacture and delivery are essentially the same for both cases. They aim to ensure the supply of a material that meets, consistently and uniformly, the requirements of the project specification.

Relevant New Zealand Standards

NZS 3104	*Specification of concrete production*
NZS 3109	*Concrete construction*
NZS 3111	*Methods of test for water and aggregates for concrete* – parts 5-19
NZS 3112.1	*Methods of test for concrete - Tests relating to fresh concrete*
NZS 3112.2	*Methods of test for concrete - Tests relating to the determination of strength of concrete*
NZS 3112.3	*Methods of test for concrete - Tests on hardened concrete other than for strength*
NZS 3112.4	*Methods of test for concrete - Tests relating to grout*
NZS 3121	*Specification for water and aggregate for concrete*
NZS 3122	*Specification for Portland and blended cements*
NZS 3123	*Specification for Portland pozzolan cement*
NZS 3125	*Specification for portland-limestone filler cement*

Relevant Australian Standards

AS 1012	*Methods of testing concrete*
AS 1379	*The specification and supply of concrete*
AS 1478	*Chemical admixtures for concrete, mortar and grout*
AS 1478.1	*Admixtures for concrete*
AS 2758	*Aggregates and rock for engineering purposes*
AS 2758.1	*Concrete aggregates*
AS 3582	*Supplementary cementitious materials for use with Portland and blended cement*
AS 3582.1	*Fly ash*
AS 3582.2	*Slag – Ground granulated iron blastfurnace*
AS 3582.3	*Silica fume*
AS 3600	*Concrete structures*
AS 3648	*Specification and methods of test for packaged concrete mixes*
AS 3972	*Portland and blended cements*

6.1 PLANT MIXED

6.1.1 General

It is beyond the scope of this Guide to discuss, in any detail, the plant and equipment used in the manufacture of concrete. **Figure 6.1** (page 6.3) illustrates the layout of a typical concrete batching plant from which the following elements may be noted.

6.1.2 Bins and Silos

Bins and silos are used to store the various maximum size aggregates used in the manufacture of concrete as well as the cementitious materials and liquid admixtures. Some ground storage may also be provided for coarse and fine aggregates.

The following general requirements apply to all storage units:

- They should be so constructed as to prevent contamination from other materials and, in the case of aggregate bins and silos, to keep the different aggregate types and maximum-sized materials from intermingling.
- Aggregate storage units should facilitate the free drainage of the materials and be provided with a means of minimising segregation.

Figure 6.1 **Typical medium-sized concrete batching plant**

- Each storage unit should be provided with a means of actively controlling the discharge from the unit.
- Bins and silos to contain cement and other cementitious materials must be designed and constructed to keep the contents dry and to promote the complete discharge of the contents.
- Bins and silos which are used to store more than one type of constituent shall be capable of being cleaned out thoroughly and inspected internally.

6.1.3 Weighing Equipment

All weighing equipment in central batching plants should be provided with a visual weight-indicating device that is clearly visible to the operator in control of the equipment, and which should be graduated to a scale compatible with the accuracy of the production process. The weighing equipment itself should be accurate to ±0.4% of the maximum scale value when statically loaded. The equipment should also be routinely checked for accuracy, at least monthly for cement, three monthly for aggregate and six monthly for water.

6.1.4 Liquid-Dispensing Equipment

All liquid-dispensing equipment, e.g. for dispensing admixtures, should also be equipped with a visual metering device that is clearly visible to the operator. The equipment should be capable of metering the volume, or weight, of liquid to an accuracy of at least 2% of the indicated value.

As with weighing equipment, calibration of the equipment should be undertaken at least every six months, or more often if required by the equipment. Liquid-dispensing equipment should be cleaned between changes in types of liquid including changes in brands of the same type of liquid and at a frequency not less than that recommended by the manufacturer.

6.1.5 Mixers

General

A variety of mixers, ranging from the simple tilting-drum mixer, used almost universally to produce bricklaying mortar on housing sites, to the more sophisticated split-drum mixers, used on major concrete road projects, are available to mix concrete.

Although the tilting-drum mixer and its companion, the horizontal-drum mixer, were once widely used to mix concrete on construction sites, they have now largely been replaced by the inclined-drum mixer and the split-drum mixer. Indeed, the great bulk of concrete used in construction today is mixed in inclined-drum mixers mounted on trucks, the so-called truck or transit mixers.

These receive accurately batched materials from a central batching plant and, operating at mixing speed, mix the concrete en-route to the site. The complex blade and fin system operates in such a way that, when the direction of rotation of the drum is reversed, the mixed concrete discharges continuously from the drum.

Many concrete suppliers incorporate central mixers in plants, partly for the increased control over the mixing of very high strength concretes, partly for the additional pollution (dust) control which can be achieved.

The availability of split-drum mixers (a high energy, high efficiency mixer), that can mix concrete with maximum size aggregates as large as 150 mm in 60–70 seconds, has accelerated this trend.

Continuous mixers, e.g. pugmills, are also being incorporated into central plants to handle the drier mixes required for some forms of roadwork, e.g. roller-compacted concrete.

Mixers must be maintained in a clean condition, and produce a uniformly mixed batch. Mixing time is specified for stationary and truck mixers and batch volumes limited to rated capacity. Mixers must achieve results determined by the mixer performance test which checks the uniformity of mixing through a concrete batch. This is carried out annually.

New Zealand Standard Requirements

NZS 3104 sets out a number of requirements to govern the performance of both batch and continuous mixers. These include:

- A requirement that batch mixers have mounted on them an identification plate which provides information on:
  - the gross internal volume of the mixing chamber (m^3);
  - the rated mixing capacity (m^3);
  - the recommended minimum –
    - number of revolutions of the mixer required to achieve uniformity in the concrete, or
    - mixing time (in minutes) at a given rotational speed of the mixer (in revolutions per minute);
  - if the mixer is designed to be used as an agitator –
    - the recommended capacity of the mixer used as an agitator, and
    - the recommended speed of the mixer (in revolutions per minute) when used as an agitator;
- Limits on the capacity of the mixer to no more than 65% of the gross internal volume of the bowl when used as a mixer, and no more than 80% when used as an agitator unless testing in accordance with the Standard permits a higher figure.
- Procedures for determining or confirming the minimum mixing time or number of revolutions at mixing speed for batch mixers.

Continuous mixers are also required by AS 1379, to carry an identification plate, in this case indicating both the name of the manufacturer, and the maximum discharge rate in tonnes per hour.

6.1.6 Production and Delivery

NZS 3104 also sets out a number of requirements governing the production and delivery of concrete from batching plants.

The following are of particular note:

- All materials other than liquids have to be proportioned by mass, i.e. weigh batched. (A limited number of mixes may use volume proportioning – see Chapter 20).
- The quantity of each ingredient in a batch should be measured within the tolerances shown for each ingredient in **Table 6.1**.

Table 6.1 **Accuracy of Measurement (from NZS 3104)**

Material	Volume
Cement	±1.0%
Water (mass or volume)	±2.5%
Aggregates (mass)	±2.0% Any fraction provided that total mass of aggregate is within 1%
Admixture (mass or volume)	±10.0% of amount specified

- Water may be added to a mixed batch of concrete, prior to its complete discharge, only if the following relevant conditions are satisfied:
- The supplier's approval is obtained. (Only the supplier's representative can add water or admixtures to a mixed batch prior to its discharge. This is because the supplier is responsible for the quality of the concrete up to the point of acceptance of delivery. The addition of water and/or admixtures will affect the quality of the concrete and may cause it to fail to meet the specified properties.)
- Immediately after the water is added, the mixing bowl is rotated for 30 revolutions at mixing speed, or for such time as is necessary to re-establish the uniformity of the mix.
- If water is added once discharging has commenced, this fact is noted on the identification certificate for the batch.
- If a maximum water-cement ratio has been specified, the quantity of water added does not cause this ratio to be exceeded.

- Discharge of all concrete from the batch should be completed within 90 minutes of mixing having been commenced (or sooner if proper placement and compaction cannot be achieved). This requirement may be waived, however, if the consistence of the concrete can be maintained for a longer period without the addition of extra water to the mix.

- Unless otherwise specified, concrete at the point of delivery should have a temperature of not less than 5°C nor more than 35°C. (For additional precautions in cold or hot weather see Chapter 12 Hot- and Cold-Weather Concreting.)

6.1.7 Records

An essential feature of a Quality system is the maintenance of records. Ready mixed concrete production entails the following records related to quality:

Material Supply and Plant Certificates

- Plant tests on aggregates and sand which also record testing frequency and evidence that the results are monitored and action taken when necessary.

- Test certificates for weighing and testing equipment, including scale checks by plant personnel as specified.

- Cement certificates from cement manufacturers.

Order Records

- Technical requirements of the purchaser taken with the order including:

  (a) Nominated compressive strength.

  (b) Nominal aggregate maximum size.

  (c) Slump required on delivery.

  (d) Proposed compaction method if other than high frequency vibration.

  (e) Whether the concrete is to be pumped

  (f) Any other requirements.

Delivery Records

- Type of cement and nominal maximum aggregate size.

- Specified strength and delivery slump ordered.

- Date and time of completion of mixing.

- Quantity delivered.

- Any other special requirements as ordered by the customer.

Mixing Records

A record must be kept at the plant which identified for each batch the following:

- Specified strength and size of batch.

- Slump ordered, target slump and the actual slump when measured.

- Mix proportions including admixture content either directly or by code.

- Amount of added water.

- Mixing time.

6.2 SITE MIXED AND PACKAGED CONCRETE

6.2.1 Site Mixing

Whilst it is rare nowadays for mixing to be done on site, except on very large or remote projects where a central batching/truck mixing plant may be installed, here are occasions when site mixing is necessary. For example, small quantities of concrete may be required in which special aggregates are incorporated. Alternatively, small but significant projects may be remote from central sources of supply **Figure 6.2** (page 6.6)

NZS 3104, Section 3, sets out batch quantities for Prescribed mixes which are shown in **Table 6.2** (page 6.6). The accuracy of measurement is shown in **Table 6.3** (page 6.6).

Materials handling and storage on site should be such as to:

- prevent contamination by extraneous materials;

- prevent segregation of the aggregates or intermingling of the different aggregate sizes;

- ensure that the cement is kept dry by either storing it in weathertight silos, or in enclosed weathertight buildings on pallets, i.e. off the ground;

- ensure that materials such as fly ash or ground granulated blastfurnace slag, if used, are clearly identified;

- ensure that admixtures are clearly identified and properly dispensed.

Table 6.2 Prescribed Concrete Mixes (from NZS 3104)

Mix	Proportions (volume) damp[1]		Prescribed mixes – basic information			
			Amount per cubic metre			Yield per cement bag
			SSD[2]	Damp[3]	Wet[4]	
10 MPa dry mix 50 mm slump	Cement Builder's mix Water	1 9.00 0.40	200 kg 2,050 kg 160 litres	200 kg 2,110 kg 100 litres	200 kg 2,160 kg 50 litres	0.200 m^3
15 MPa 130 mm slump	Cement Builder's mix Water	1 6.75 0.80	240 kg 1,875 kg 200 litres	240 kg 1,925 kg 150 litres	240 kg 1,975 kg 100 litres	0.145 m^3
17.5/20 MPa 130 mm slump	Cement Builder's mix Water	1 5.50 0.60	300 kg 1,860 kg 200 litres	300 kg 1,910 kg 150 litres	300 kg 1,960 kg 100 litres	0.135 m^3
25 MPa 130 mm slump	Cement Builder's mix Water	1 4.75 0.55	340 kg 1,835 kg 200 litres	340 kg 1,885 kg 150 litres	340 kg 2,035 kg 100 litres	0.120 m^3

Note:

[1] Materials are batched in bulk volume except as provided for in 3.3.4.

[2] SSD is the mix design based around aggregates which are assumed to be saturated inside buy have a dry surface so that the builder's mix neither absorbs water from the mix nor contributes free water to the mix.

[3] Damp conditions are considered to be 3% free moisture in the builder's mix.

[4] Wet conditions are 5% free moisture.

Where a problem is consistently experienced with water demand, the aggregate grading needs to be checked.

Figure 6.2 **Typical small on-site plant with fan-shaped bins in front of a single hopper. (The large dial above the mixer indicates the weight of materials in the hopper, while the small dial near the operator is a flow meter indicating the amount of water.)**

Table 6.3 Accuracy of Measurement (from NZS 3104)

Material	Volume
Cement	±2.5%
Water	±2.5%
Aggregates	±5.0%

Mixing-on-site for small projects is normally done in either a tilt-drum or horizontal-drum mixer. The former may range in size from as little as 50 litres (0.05 m^3) to as large as 6–10 m^3, the latter being used on large projects such as dams. Horizontal-drum mixers range in size from 100 litres to 5 m^3.

Volume proportioning is permitted with the limited range of mixes shown in **Table 6.2**. Cement contents are set high to offset potential large strength variations due to the inaccuracies associated with volume batching.

The order of loading is not unimportant. Ideally, the coarse aggregate plus a little of the mixing water should be loaded first as this helps clean the mixer drum. This is then followed by the sand, the cement and finally the remaining water. Where a loading skip is employed, a layer of coarse aggregate, followed by a layer of cement, and finally a layer of sand will help prevent the fine cement being blown away.

Efficient mixing will be promoted if the mixer is not overloaded. Loading above the rated capacity will increase mixing time disproportionately or result in incomplete mixing.

Similarly, too short a mixing time will result in patchy, non-uniform and low-strength concrete. On the other hand, excessive mixing times may also be undesirable, by grinding soft aggregates and increasing the water demand of the concrete. A good rule is to allow 1½ minutes for mixing 1 m^3 plus ½ minute for each additional 0.5 m^3.

6.2.2 Packaged Concrete

Where reasonably small quantities of concrete are required for non-structural purposes, bagged concrete can provide an alternative to batching on site. Packaged to provide approximately 0.02 m^3 of plastic concrete, bagged concretes may be expected to achieve strengths in excess of 12 MPa at 7 days provided they are adequately mixed and compacted with slumps in the range 90-110 mm. The quantity of water required to achieve this slump is normally marked on the bag. Some caution should be exercised, however, in relying on packaged concrete to achieve particular strengths. In particular, it cannot be assumed that it will comply with the requirements of either NZS 3104 or NZS 3109 in relation to structural concrete.

Supply of Concrete

Chapter 7

Chapter 7

Supply of Concrete

This chapter deals primarily with the outline specification and supply of concrete to the building or construction site.

INTRODUCTION

There are two New Zealand Standards that are interrelated to the specification and control of production of concrete.

NZS 3109 primarily looks at the overview of supply and testing requirements for the specifier and general contractor in terms of construction activity. NZS 3104 specifies in more detail what actions are expected of a concrete manufacturer, whether offsite as a ready mixed concrete supplier or site mixing. The Standard is divided into four parts with Part 2 having specific requirements for the production of Normal Mix or Special Mix Concrete where weigh batching and a quality assurance testing programme is mandatory.

Part 3 of the Standard deals with the Prescribed Mix concrete. In this case, volume batching and the use of "all in" aggregates i.e. Builders mix is permitted. Higher cement contents are used in these mixes to offset the greater variability of concrete strength.

Part 4 deals with the manufacture of concrete mixers. Most construction projects in New Zealand utilise ready mixed concrete as the most convenient method of manufacturing concrete. This is also associated very largely with the ability of the ready mixed concrete industry to operate independent testing systems that meet the requirements of NZS 3109 and NZS 3104, hence providing a significant service to the specifier.

Relevant New Zealand Standards

NZS 3104 *Specification for concrete production*

NZS 3109 *Concrete construction*

NZS 3112 *Methods of test for concrete*

NZS 3113 *Admixtures* (being withdrawn use AS 1478)

Relevant Australian Standards

AS 1012 *Methods of testing concrete* – parts 1-20

AS 1379 *The specification and manufacture of concrete*

AS 1478 *Chemical admixtures in concrete*

AS 1478.1 *Admixtures for concrete, mortar and grout*

AS 2758 *Aggregates and rock for engineering purposes*

AS 2758.1 *Concrete aggregates*

AS 3582 *Supplementary cementitious materials for use with Portland cement*

AS 3582.1 *Fly ash*

AS 3582.2 *Slag - Ground granulated iron blastfurnace*

AS 3600 *Concrete structures*

AS 3648 *Specification and methods of test for packaged concrete mixes*

AS 3972 *Portland and blended cements*

Note: *The Australian Standard references are provided but not referenced in this text because the approaches to specifying and control are different to the New Zealand methods although the end results are the same.*

7.1 OUTLINE SPECIFICATION AND ASSURANCE CONTROL

7.1.1 Outline Specification

A variety of arrangements are possible for the production and delivery of concrete to construction sites. To help achieve some uniformity and, thus, efficiency and economy in the production and delivery of concrete, NZS 3109 sets out a number of ways in which concrete may be specified and ordered.

(a) Specified as normal (N) or special (S) or prescribed mix (P) in accordance with NZS 3104 together with:

   (i) the specified compressive strength;
   (ii) nominal maximum aggregate size;
   (iii) workability;
   (iv) method of placement; and
   (v) any additional requirements associated with special concrete.

(b) Manufactured in accordance with NZS 3104.

Normal concretes are to be selected a standardised strength list N 17.5, 20, 25, 30, 35, 40, 45 and 50 MPa.

Prescribed concretes are to be selected from a restricted list of P 17.5, 20 and 25 MPa. Special concretes are to be specified to identify the special performance parameters required together with specified testing and compliance tolerances. High strength mixes i.e. over 50 MPa are considered to be Special concretes. These principal descriptions apply whether or not the concrete is produced on site or by ready mixed concrete.

More detail is provided in Chapter 20 *Specifying and Ordering*.

7.1.2 Assurance Control

The quality of concrete supply, for concrete construction to comply with NZS 3109, is specified in NZS 3104 *Concrete Production*.

In addition to the usual internationally recognised requirements for the production of concrete, the Standards include the concept of an audit of the quality control procedures the manufacturer uses. NZS 3104 Part 3 *Prescribed Mix* concrete is restricted to a maximum specified strength of 25 MPa. Cement contents have a prescribed minima and total water content has a prescribed maxima. Plants which are not audited to work to NZS 3104 Part 2 and do not conform to these prescribed limits, operate outside New Zealand Standard requirements. More detail is provided in Chapter 6.

NZS 3104 Part 2 specifies a quality control system which requires that the measuring and monitoring of all inputs and outputs of the concrete making process, including the design of concrete mixes, are the responsibility of a qualified and suitably experienced Chartered Professional Engineer or Registered Engineering Associate. NZS 3104 Part 2 does not prescribe any particular limits on any of the materials in the mixes. The quality control system allows for greater certainty in the prediction of the properties of the concrete which is produced, and this allows for more economical design of concrete mixes.

NZS 3104 Part 2 sets out the basis of quality specification of concrete supply in terms of an initial evaluation of the production facility including the mix designs and plant's past performance shown by test results. Procedures are then detailed for the subsequent continuous monitoring of the process and the test results by the plant engineer.

Monitoring includes the statistical evaluation of test results.

The Plant Audit Scheme of the New Zealand Ready Mixed Concrete Association is also based on an initial evaluation of the plant after which an audit certificate of having a quality control system compliant with NZS 3104 for the plant may be issued for a maximum period of 12 months. A routine review of grading occurs each 12 months and the certificate of grading may be reissued, usually for a further 12 months.

Essentially the Plant Audit Scheme certifies that currently audited plants have the quality systems in place which are required by the New Zealand Standards NZS 3104 and NZS 3109.

The scheme, introduced in 1962, has, over the years, been closely monitored, developed and refined. NZRMCA Plant Audit scheme has an additional advantage for the specifier because the Scheme itself is subjected to an independent annual review for compliance with ISO 9001.

The scheme provides a convenient assurance mechanism for the specifier. Alternative assurance methods can also be used by following the provisions of NZS 3109/NZS 3104.

The production of high quality concrete is a blend of art and science and for their successful blending a significant degree of experience is needed by the concrete producer's staff.

7.2 SUPPLY

7.2.1 General

The procedures which determine concrete supply quality are implemented before the concrete leaves the plant. The tests on hardened concrete samples merely provide confirmation of the effectiveness. NZS 3109/NZS 3104 uses 28 day standard cured compressive strength as the basis for the evaluation on concrete quality. Some overseas Standards use other properties in addition such as water/cement ratio, minimum cement content, and modulus of rupture, to name some others.

Compressive strength is easy to measure and this well suited as a control test of quality. Whilst in few applications, concrete strength is of no interest directly, the required special characteristics can be related to specific compressive strength level, either on the basis of past experience or preconstruction study. Such characteristics may include:

- Durability.
- Resistance to chemical attack.
- Abrasion resistance.
- Permeability to fluids and gases.
- Limitation of temperature rise during hardening.
- Tensile strength and modulus of elasticity.

Such concrete falls in the category of Special concrete where the specifier is required to set testing/compliance parameters for the special properties.

To ensure compliance with the requirements of the specification, concrete should be sampled and tested at regular intervals by the supplier and, if required, by the user. The frequency with which such sampling and testing is carried out is related firstly to the importance of the work, and secondly to the volume of concrete being produced.

NZS 3104 sets out the following parameters for which concrete may be samples and tested on a regular basis:

- Slump.
- Compressive strength.
- Air content.
- Alkali level below 2.5kg/m^3.
- Chlorides.
- Uniformity of mixing.

These are the fundamental characteristics of Normal concrete.

7.2.2 Mix Design

Unless agreed otherwise mix design and properties are the responsibility of the concrete producer. This responsibility covers:

- Proportions and amounts of coarse aggregate and sand.
- Water/cement ratio and cement content to meet the appropriate specified performance requirements.
- Suitability, quantity and performance of any admixture used. In normal practice the use of admixtures is recorded as required in NZS 3104 but with the intention that the plant engineer as defined in NZS 3104 accepts an overview role for the concrete performance with the admixture.
- Concrete workability.
- Batch yield.

The producer's responsibility may be disclaimed if the purchaser covers any of the above by specification or if additional ingredients are added at the construction site without the producer's approval. There are concrete mix design criteria for each concrete strength.

The principal feature of the mix design is that the concrete strength will only have a statistical risk of 5% of tests falling below the specified strength. This means that the producer must design the concrete mixes to a higher strength than the specified strength. This strength is known as the Target Mean Strength. The lower the accuracy of batching and mixing, the higher the target strength must be set Hence there is some encouragement for producers to demonstrate statistically that their production is at the highest standard see **Figure 7.1**.

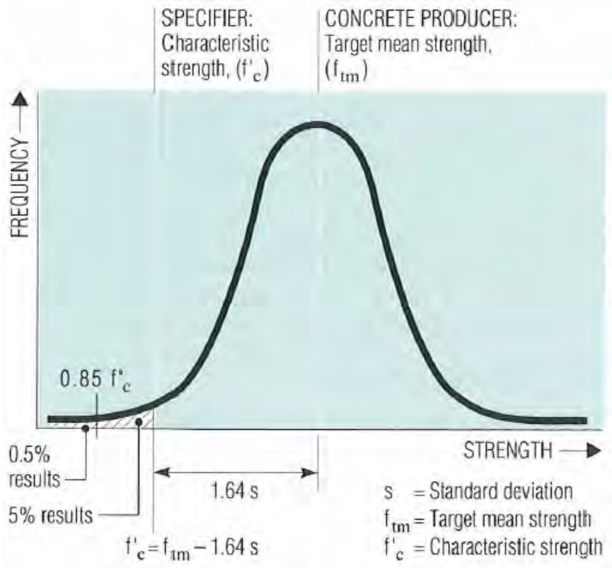


Figure 7.1 **Statistical relationship between mean strength and specified characteristic strength**

Table 7.1 on page 7.5 (Table 2.8 A & B NZS 3104) illustrates the specified strength and the target strengths required. NZS 3109 also sets criteria for rejection of concrete which is expressed as 0.85 f'_c, (specified strength) or f'_c -3.5 MPa whichever is the greater based on a representative sample of concrete being tested.

The two tables A & B illustrate the use of different frequencies of compression testing each month. As the testing is reduced the risk of detecting failure goes up and hence the target strengths are revised. The cautionary limits are used in the monitoring process and the rejection limits set so that the specifier can order the removal of suspect hardened concrete.

7.2.3 Strength

General

When concrete is specified by 28 day specified strength, the supplier is required to sample, test and assess it for strength in accordance with procedures which are described in detail in NZS 3104 and NZS 3112.

Production Assessment

Production assessment is the continuous statistical evaluation of the strength of up to six strength types.

Evidence of Grade of Production

Performance record – Data from a series of not less than 30 consecutive compression test results of a particular mix from a plant which otherwise complies is evaluated as specified.

Table 7.1A Evaluation Criteria for Plants opting for not less than 10 tests per month (from NZS 3104)

Specified Strength f'c MPa								
Grade MPa	17.5	20	25	30	35	40	45	50
Max. C of V%	12.5	11.5	11	10.5	10	9.5	9	8.5
Min. Target Mean Strength Mix MPa	22	24.5	30.5	36	42	47	53	58
Cautionary limit to be equaled or exceeded by the mean of any consecutive group of 6 Results (b)								
MPa	20	22.5	28.5	34.5	39.5	44	50	55
Cautionary limit to be equaled or exceeded by the mean of any consecutive group of 30 Results (c)								
MPa	21.5	24	29.5	35	40.5	46	51.5	56.5
Rejection Limit (a) Individual Result								
Rep. Sample MPa	15	17	21.5	26.5	31.5	36.5	41.5	46.5
Snatch Sample Size	14	16	20.5	25.5	30.5	35.5	40.5	45.5

Table 7.1B Evaluation Criteria for Plants opting for not less than 6 tests per month (from NZS 3104)

Specified Strength f'c MPa								
Grade MPa	17.5	20	25	30	35	40	45	50
Max. C of V%	12	11.5	11	10	9.5	9	8.5	8
Min. Target Mean Strength Mix MPa	24	27	33	38.5	44.5	50	55.5	61
Cautionary limit to be equaled or exceeded by the mean of any consecutive group of 6 Results (b)								
MPa	22	25	31	36	41.5	47	52.5	57.5
Cautionary limit to be equaled or exceeded by the mean of any consecutive group of 30 Results (c)								
MPa	23	26	32	37.5	43	49	54	59.5
Rejection Limit (a) Individual Result								
Rep. Sample MPa	15	17	21.5	26.5	31.5	36.5	41.5	46.5
Snatch Sample Size	14	16	20.5	25.5	30.5	35.5	40.5	45.5

Having established the grade of production, the suitability of the mix design is based on the results of at least 12 tests on the mix or on the basis of a rational mix design from an equivalent series from a mix at a different strength level.

Data is to be held at the plant and available for inspection by the purchaser's engineer supervisor shall show:

- Batch masses.
- Target total water content.
- Target added water.
- Target strength.
- Target slump.

The tables shall make allowance for water in the aggregates on both the added water and the aggregate masses.

7.2.4 Volume of Concrete

The method of determining the volume of concrete supplied is related to the mass of concrete delivered divided by the average mass per cubic metre of the concrete. Testing for volume is not usually carried out unless it is specified. NZS 3104 allows a tolerance of 2% on under supply for the volume delivered. The Standard notes that if the volume of concrete is to be measured at any time then the method of determining the mass of supplied concrete will need to be specified.

Concern is frequently expressed because on site the ordered volume does not fill the forms the volume of which, it is assumed, is known. The reasons why this may occur include: spillage and wastage on site, variation in dimensions of the forms as constructed and deflection of forms, and the compaction of concrete.

7.2.5 Slump

Where a strength grade concrete is specified, NZS 3104 requires that a slump test be carried out on each strength sample. Generally, additional slump tests will need to be performed if water is added to the concrete after discharge from the mixer has commenced. Slump tests will have to be performed if slump is one of the specified parameters.

Where the slump of the sample, as determined in accordance with NZS 3112, is not within the limits shown in **Table 7.2**, a repeat test may be made from the same sample, or from a fresh sample taken and tested immediately.

Table 7.2 **Permissible tolerances on slump (Table 2.6 in NZS 3104)**

Target slump (mm)	**Tolerance**	
	Representative Sample (mm)	**Snatch Sample** (mm)
60 or less	±20	±20
70 - 110	±20	±30
120 and above	±30	±40

7.2.6 Supervision

The mix designs and quality control are supervised by the plant engineer who must be a Chartered Professional Engineer or Registered Engineering Associate experienced in these functions. If not resident at the plant he must visit often enough to fully discharge these responsibilities. In his absence 'the person in continuous control', usually the plant manager or supervisor, has responsibility for quality matters.

NZS 3104 places much emphasis on the monitoring role of the supervision. Routine tests are required to be under the continuous review of the supervisor and evaluated by the engineer. Other control tests are to be reported to the engineer at least monthly, except that non-complying results are to be reported Immediately

7.3 CONTROL AND ASSURANCE TESTS

NZS 3104 sets out or refers to testing methods, testing frequencies and criteria to be achieved in respect of the following:

- Slump test.
- Yield test.
- Air content test.
- Performance test for mixers and truck mixers.
- Strength tests for proof of control.
- Evaluation of strength test results.

The specifier's control of the concrete production varies with the type of concrete specified i.e. Normal or Special.

If Normal concrete is specified the specifier relies on the testing being carried out by the supplier in order to comply with NZS 3104. This is why it is important that the specifier has confidence that the supplier's quality control programme has been independently checked by an organisation like the NZRMCA Plant Audit Scheme.

However with Special concrete, the specifier needs to discuss the testing regime that is needed for the specific project. Usually the specifier will require testing from the specified project under construction. Often these Special concretes will not have sufficient test results for full statistical analysis which is why additional testing is likely to be required. The testing may not always be for compressive strength buy may be for other properties such as abrasion resistance, marine durability, permeability etc.

For extra information see Chapter 20.

7.4 AUDIT CERTIFICATION

NZS 3104 sets out the requirement for an independent audit of the quality control measures being undertaken by the plant.

This can be done by an independent Auditing Engineer or in the case of the majority of members of the New Zealand Ready Mixed Concrete Association (NZRMCA), by an independent committee of professional engineers. This committee includes members representing IPENZ and the New Zealand Concrete Society. The current membership can be checked by reference to *www.cca.org.nz*.

Each year the statistics of plant performance are sent to the Plant Engineer/Plant Supervisor for review. Every second year the plant is physically inspected for compliance.

If the Plant Audit Committee is satisfied that the information demonstrates compliance with NZS 3104, then the Audit Certificate will be issued. The Certificate is valid for 12 months only. An up to date list of Audited Plants is held and can be checked by reference to *www.cca.org.nz*.

The Committee can withhold a certificate, require a special inspection which may or may not be pre-notified and issue an Interim Certificate which is valid for three months only.

During the course of the year, quarterly statistics of testing are required to be submitted which again can result in Plants defaulting on testing frequency to be removed from the list of Audited Plants.

The NZRMCA Audit Scheme is itself independently audited each year by Bureau Veritas Quality International (BVQI) for compliance with ISO 9001.

Figure 7.2 shows the Certificate of Audit displayed by an Audit Certified Plant in the NZRMCA scheme.


THE NEW ZEALAND READY MIXED CONCRETE ASSOCIATION INC.

Certificate of Compliance

Company ____________________

Plant location ____________________

This is to certify that the above ready mixed concrete plant has been audited as having a production quality control system which complies with the quality assurance requirements of NZS 3104:2003

AUDITED PLANT
NEW ZEALAND READY MIXED CONCRETE ASSOCIATION
QUALITY ASSURED NZS 3104

Valid to ____________________

President ____________________

Chairman ____________________
Plant Audit Committee

Plant Audit Scheme ISO 9001 Certified 12165

Figure 7.2 **NZRMCA Plant Audit Scheme Audit Certificate**

Handling and Placing

Chapter 8

Chapter 8

Handling and Placing

The aim in handling and placing concrete will always be to distribute it from the point of delivery on a construction site to its final location as smoothly and efficiently as site conditions will allow, whilst, at the same time, maintaining it in a condition where it is both workable and free from segregation. This chapter describes methods, plant and equipment which may be used to handle and place concrete on a variety of construction sites.

INTRODUCTION

Concrete is delivered to most construction sites in either an agitator truck or transit-mixer. Even on those projects where the concrete is batched and mixed on site in a central plant, e.g. large highway projects, it will often be convenient to move the concrete from the mixing plant to the point of placement in such trucks. They have the advantage that they can transport workable concrete over quite long distances. They also permit some adjustment to be made to the workability of concrete, immediately prior to discharge, by the addition of controlled amounts of water and some remixing of the concrete. NZS 3104 and NZS 3109 sets out the conditions under which this may be done.

The handling of concrete on site may therefore be said to commence when the concrete is discharged from the truck, or from other means used to transport it from the batching or mixing plant. The aim in handling concrete will always be to move it (to the point of final placement) as quickly and as efficiently as the site conditions will allow, whilst, maintaining it in a workable condition free from segregation.

A variety of methods, plant and equipment are available for this purpose. In choosing a distribution method, care should be taken to ensure that it is appropriate to the site. Care should then be taken to plan its use on the site to ensure that, once concreting operations commence, they proceed smoothly and without delay. Special care should always be taken to ensure that the capacity of handling equipment is sufficient to maintain placing operations at their planned rate.

Relevant New Zealand Standards

NZS 3104 *Specification for concrete production*

NZS 3109 *Concrete construction*

Relevant Australian Standards

AS 1379 *The specification and supply of concrete*

AS 3600 *Concrete structures*

8.1 PRELIMINARY CONSIDERATIONS

8.1.1 Workability

The workability required of concrete will normally be determined by the nature of the building element or project in which it is to be placed. For example, concrete to be placed in thin or narrow forms will need to be quite workable if it is to be placed and compacted satisfactorily. On the other hand, concrete to be placed in massive sections may have quite low workability. Obviously, the method chosen to distribute the concrete from the point of delivery to the point of placement must be able to handle concrete of the workability required for the project. Concrete pumps, for example, require plastic and cohesive mixes if they are to operate satisfactorily.

Equally important, the equipment must be able to maintain the concrete in the required condition. High temperatures and high winds especially can cause concrete to lose workability while being transported to and moved around the site; high temperatures by accelerating the rate at which the concrete stiffens, high winds by causing it to lose moisture and dry out. It is essential therefore that methods of handling concrete on sites keep the concrete cool and prevent it from drying out. (For further information on this aspect see Chapter 12 *Hot and Cold Weather Concreting.)*

Corrective measures for losses of workability in excess of those anticipated depend on the reasons for the losses, which are not always clear. If there is only a slight reduction, remixing may be enough to restore workability. If the loss is through evaporation and/or absorption, workability may be restored by adding water and cement in the same ratio as that in the original mix design. In general water alone should never be added to restore workability as this will reduce strength and durability, perhaps to unacceptable levels. If the loss is due to hydration of the cement, which should occur only through an extensive delay, the addition of water and cement will not restore workability. However, NZS 3104 (2.9.3) does specify certain circumstances in which a limited addition of water is allowable.

8.1.2 Segregation

Segregation in concrete is the separation of the coarse aggregate from the mortar. This results in the hardened concrete being non-uniform and with weak/porous or honeycombed patches.

To avoid segregation during transport, the concrete should be cohesive and thoroughly mixed. As far as practicable, jolting and vibration of the concrete while distributing it around the site should be minimised and the concrete discharged vertically into its final position in the forms or into the distributing equipment.

8.2 PLANNING

8.2.1 Site Access

Access to the site by trucks delivering the concrete, either to the distribution equipment or to the point of placement, is an important factor in avoiding delays and interruptions to the work.

In planning access to the site, important considerations are:

- ground conditions, e.g. ability to support loaded trucks;
- headroom and ground clearances;
- availability of turning circles;
- access to discharge chutes by distribution equipment;
- holding area for trucks awaiting discharge.

The dimensions of typical concrete trucks are shown in **Figure 8.1**.

A prime consideration in planning access to the site is to avoid the delays caused by delivery trucks having to manoeuvre whilst on site, particularly when a continuous flow of concrete is required.

8.2.2 Delivery Rate

The delivery rate which can be achieved on a site may be determined by the access to the site, i.e. the rate at which the delivery trucks can move on and off it **Figure 8.2** (page 8.4).

More often, however, it is determined by the rate at which the concrete can be placed. This should always be such as to ensure that the work proceeds smoothly and that the formation of unplanned construction joints (cold joints) does not occur. At the other extreme, it should not be such that the concrete cannot be adequately compacted and finished, e.g. in thin walls and columns.

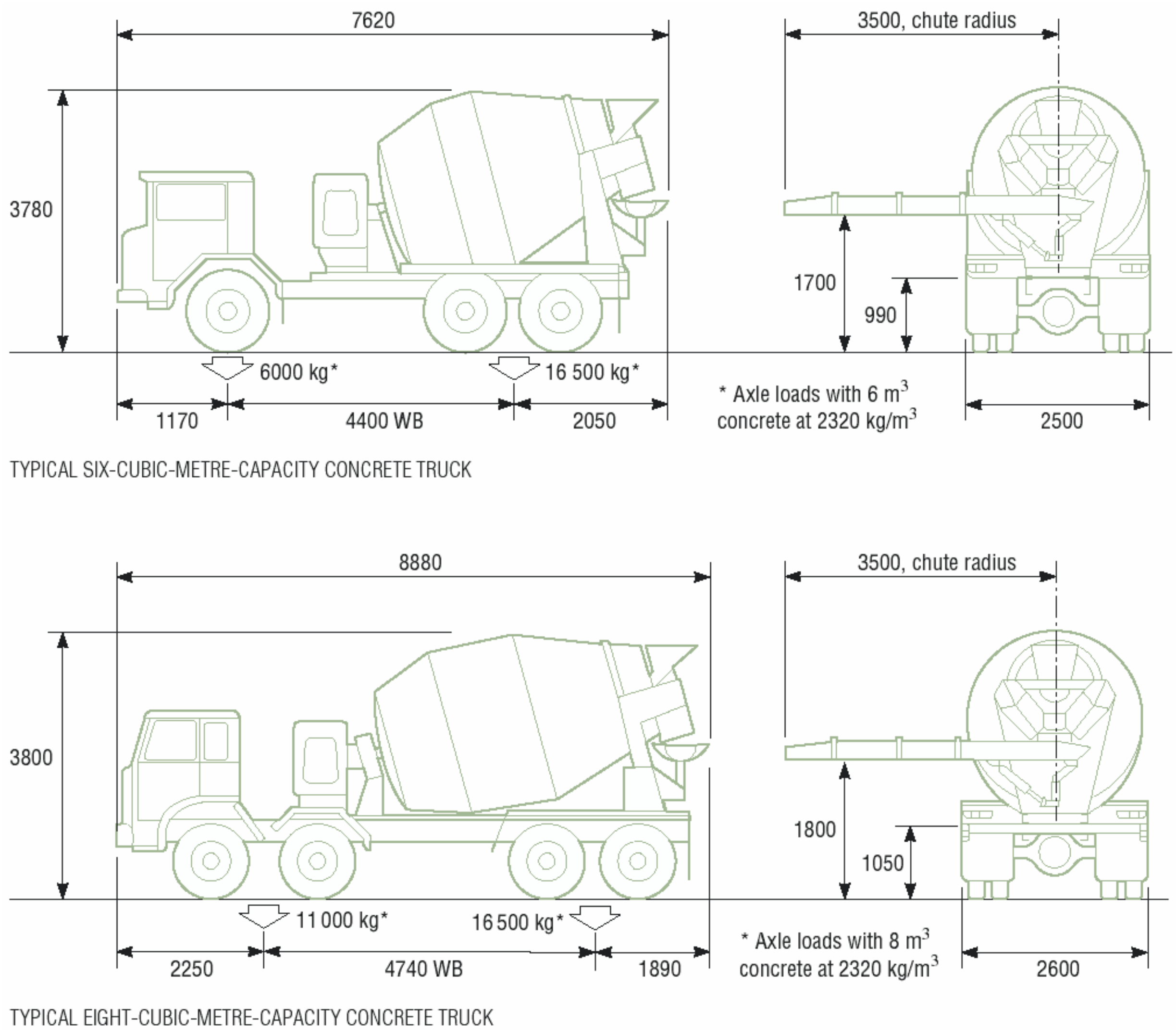


Figure 8.1 **Typical 6- and 8-m^3 transit mixers**

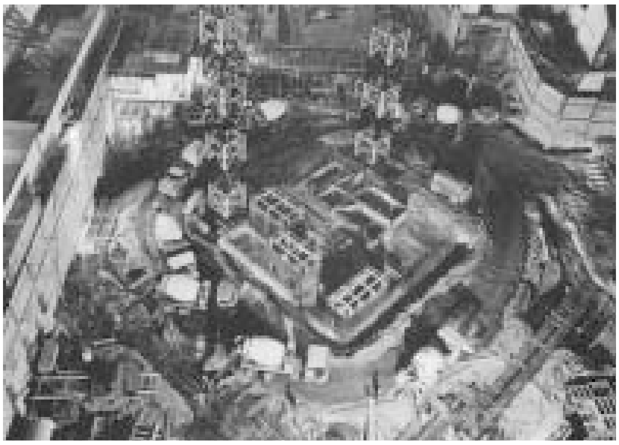


Figure 8.2 **Access to the site (and particularly the ease with which delivery vehicles can move on and off it) has a significant influence on the overall concrete supply rate**

Figure 8.3 **Delivery from a transit-mixer chute is the quickest, most convenient and economical method of distribution**

8.3 DISTRIBUTION METHODS

8.3.1 General

The methods for distributing concrete on site range from simple barrows to sophisticated pumps. Whatever the method chosen, it should be capable of moving the concrete uniformly, without delay, and at a rate appropriate to the method of placing.

8.3.2 Chutes

On most sites, the transit-mixer chute is the initial means of delivering concrete on site, either to another method of distribution or direct into its final position **Figure 8.3**. The latter is ideal for elements such as strip footings, house floor slabs, road pavements and low retaining walls, provided:

- truck access to within chute radius is available;
- the element is below truck tray level;
- free-fall of concrete does not exceed two metres.

Chutes can also be a useful means of distributing concrete from a higher to a lower level. In such applications, care must be taken that the chute has sufficient slope for the concrete to flow freely. A minimum slope between 1:2 and 1:1 is often suggested. On long chutes, those which slope steeply, or where the free-fall of the concrete exceeds two metres, additional controls should be provided **Figure 8.4**.

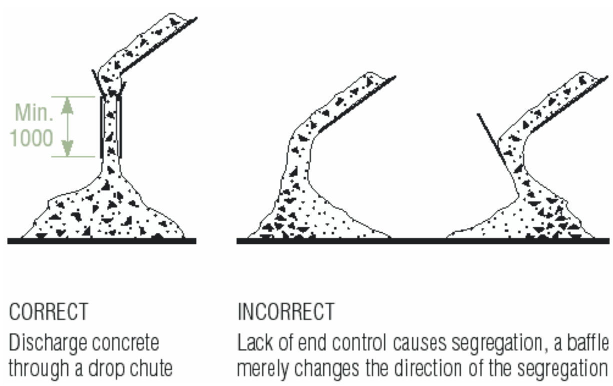


Figure 8.4 **Discharging from long chutes (i.e. longer than standard transit-mixer chutes)**

8.3.3 Barrows

Barrows and small handcarts are an appropriate means of moving concrete on small sites or where only small quantities of concrete have to be placed **Figures 8.5 and 8.6** (page 8.5). They are highly labour intensive, however, and hence have largely been replaced by more-efficient methods. Other limitations are that:

- only a low placing rate of about 1 to 1.5 m^3/h can be achieved;
- the travel distance is limited to about 50 m for continuous work.

When used, care should be taken to provide near-level, smooth runways and access ways to avoid jolting and hence segregation of the concrete.

8.3.4 Crane and Bucket

The use of a crane and bucket or skip is an appropriate means of handling concrete on sites where adequate crane time is available and/or a concrete mix which is difficult to pump is required. Buckets or skips of 1- to 2-cubic-metre capacity are most commonly used. The 'lay-down' variety may be filled readily from a truck-mixer **Figure 8.7** (page 8.5). Normally, they have hand-operated discharge gates which permit adequate control of location and discharge **Figure 8.8** (page 8.5).

Figure 8.5 **Barrows, despite their limitations, are the most suitable distribution means on small projects**

Figure 8.6 **Small handcarts (of about 100-litre capacity) have been largely superseded by more efficient methods**

Figure 8.7 **'Lay-down' crane buckets are easily filled from transit-mixers**

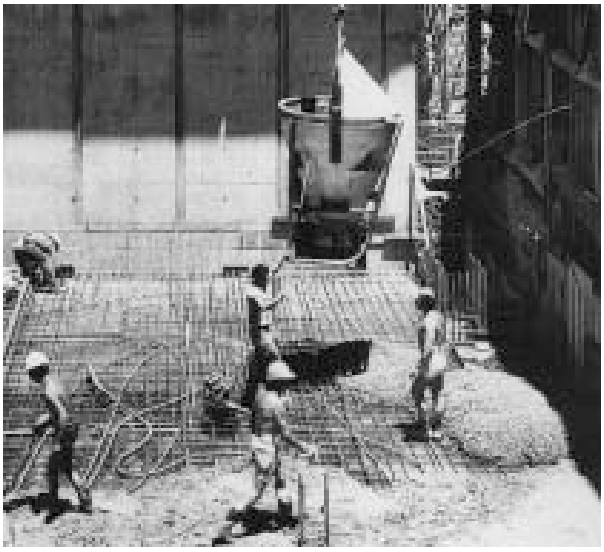


Figure 8.8 **Hand-operated gates on crane buckets give control over concrete discharge**

On large mass concrete projects, buckets of up to 6-cubic-metre capacity may be employed with the discharge gates operated by compressed air. In discharging buckets and skips, care must be taken that formwork and reinforcement are not damaged by the impact of the concrete. This is likely to occur if the concrete is discharged from a height of more than about two metres.

The placing rate is dependent on the bucket capacity and the height and distance from the pick-up point.

For example, about 13 m^3/h could be placed on a tenth-floor level using a 1 m^3 bucket, while about 20 m^3/h could be placed using a 2 m^3 bucket. On a fifth-floor level, the placing rates would be only about 10% higher.

8.3.5 Pumps and Pipelines

General Concrete pumps and pipelines are perhaps the most widely used of all methods of distributing concrete on construction sites **Figure 8.9** (page 8.6) in New Zealand and Australia today. The ready availability of mobile pumps, and their relative reliability, make them an efficient and economical means of transporting concrete, even on quite small sites.

A wide range of pump types are available, generally trailer- or truck-mounted, although fixed installations are not uncommon where the pump has to be in frequent operation **Figure 8.10** (page 8.6).

Usually, however, concrete pumps are mobile and are often fitted with an articulated boom which enables the unit to deliver concrete over a radius of 30 m or more **Figure 8.11** (page 8.6). Such units require virtually no setting up and, hence, are especially versatile in the range of applications they can handle. They may also be coupled to fixed pipelines for delivering concrete over greater distances, say 60 m vertically and 300 m horizontally. For greater distances, more powerful pumps are required.

Figure 8.9 **Concrete distribution by pump (from a discharge point in the street where permitted) is the most common method**

Figure 8.10 **Fixed pumps generally have the highest pumping capacity and are the usual choice for major projects**

In tall city buildings, concrete has been pumped to heights of 200 m or more and on large flat sites, horizontal distances of up to 1000 m. Such installations require quite rigidly fixed pipelines to withstand the considerable pressures involved.

The advantages of the use of pumps include:

- high output;
- versatility and flexibility (they can distribute concrete both vertically and horizontally and require little space);
- continuous distribution;
- short set-up time;
- low labour requirement.

It should, however, be noted that:

- not all concretes can be pumped;
- there is a likelihood of increased concrete shrinkage;
- downhill pumping is difficult or limited.

Figure 8.11 **Mobile concrete pumps are quick to set up and versatile in their range of applications**

Pump Selection

The rate of delivery which can be achieved will depend on the type of pump and its power, the distances to be pumped horizontally and vertically, the number of bends and the type of concrete mix. Smaller pumps may deliver up to 10 m^3/h and high performance units up to 80 m^3. However, this rate is rarely achieved in practice because of the need to move and reposition pipelines.

The selection of a suitable pump will depend on the maximum required output and pumping pressure. The output is a function of the placing rate and the actual time the pump will be operating. Thus, if an overall placing rate of 30 m^3/h is required but the pump will be in use for only 45 minutes in each hour, the required output will be 30 x 60/45 = 40 m^3/h.

The required pumping pressure will depend on the:

- required output as determined above;
- pipeline diameter (often controlled by the maximum aggregate size);
- total equivalent length of the pipeline (actual horizontal length plus an equivalent horizontal length for vertical pipe, bends and any reducer pipe or hydraulic placing boom that may be used);
- plastic properties of the concrete (often expressed as its slump).

From this information the required pumping pressure can be determined from a nomograph such as that shown in **Figure 8.12**.

The pumping power required can be calculated from the equation:

Power (kW) = Output (m^3/h) x Pressure (MPa)/2.5

The design of a successful pumping operation is a matter for an experienced operator. Of paramount importance is preplanning and, in particular, close liaison between the contractor, the pump operator and the concrete supplier.

Pumping Operations

Before pumping commences, the pump and pipelines must be lubricated by coating the internal surfaces with a cement slurry or mortar, pumped through the pipes at the rate of about 2.5 litres of slurry per metre of pipeline. After pumping is completed, the pipelines must be cleaned out as soon as possible as any mortar residue will increase pipe friction and may eventually cause blockages.

Pipelines should be adequately supported and fixed in position since quite substantial forces (thrusts) can be generated as the concrete is forced along the lines. Joints should be watertight as loss of mortar can lead to blockages whilst, obviously, the wall thickness of the pipe should be adequate for the pressure. Pipelines should also be readily accessible for maintenance and cleaning should a blockage occur.

Once commenced, concrete pumping should be continuous to avoid blockages in the pipeline. If concrete is to be discharged directly into the forms or on grade in flatwork, adequate means to compact and finish it must be available. In other words, the rate of pumping must be consistent with the rate of placing and finishing.

Whilst 'pumpable' concrete mixes are now readily available in most New Zealand and Australian cities, it is still necessary that the supplier be notified 'of the intended method of placement' (see

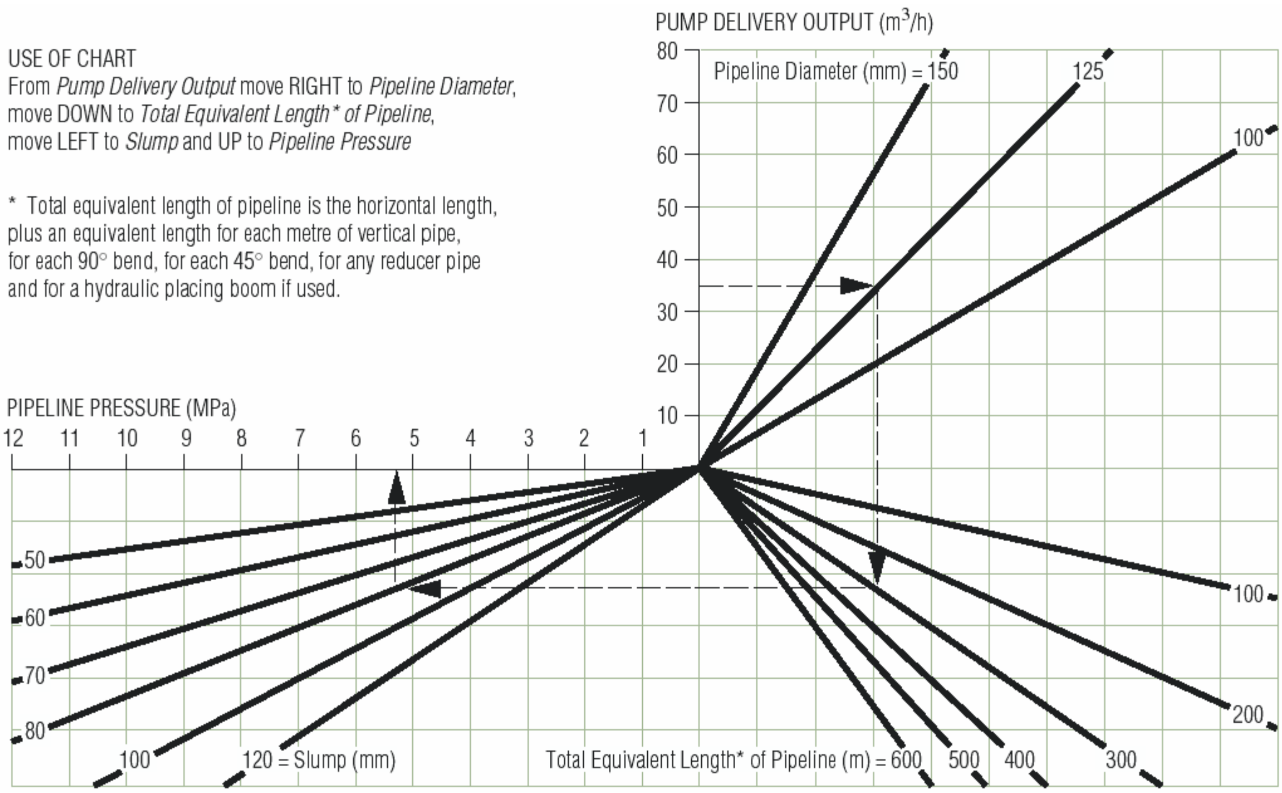


Figure 8.12 **Nomograph for determining the required pumping pressure**

Clause 1.6.3.2(d) of AS 1379 and Clause 6.2 of NZS 3109). Not all concrete mixes can be pumped successfully. For example, mixes required to have very low shrinkage characteristics may be difficult to pump because of the limitation on the fines content. Similarly 'pumpable' mixes may not be the best suited to very high standards of off-form finish. Low slump concretes are generally not pumpable.

8.4 PLACING

8.4.1 General

As with the handling of concrete, certain fundamental considerations govern placing techniques. First and perhaps foremost is the need to avoid segregation of the concrete caused by improper techniques. Second is the need to ensure thorough compaction of the concrete. Whilst compaction itself is discussed in Chapter 9 Compaction, the manner in which concrete is placed can have a significant influence on its ability to compact under vibration.

8.4.2 Avoiding Segregation

The most important rules for avoiding segregation during the placing of concrete, in any element, are:

- Concrete should be placed vertically and as near as possible to its final position.
- It should not be made to flow into position. Where concrete must be moved it should be shoveled into position.

Other techniques for avoiding segregation during placing depend on the type of element being constructed and on the type of distribution equipment being used.

For flatwork and slabs incorporating ribs and beams (i.e. shallow forms) the techniques shown in **Figure 8.13** should be adopted. For walls and columns (i.e. deep, narrow forms), problems occur when the concrete is dropped from too great a height and ricochets off the reinforcement and form-faces, resulting in segregation. The means of avoiding this vary with the type of distribution equipment being used **Figure 8.14** (page 8.9).

8.4.3 Aiding Compaction

To aid subsequent compaction of the concrete, care should be taken to place concrete in layers which are of a suitable depth for the compaction equipment. Layers that are too deep make it virtually impossible to adequately compact the concrete, leaving entrapped air which will create voids and blow holes in the surface of the concrete, and prevent it achieving its potential durability and strength.

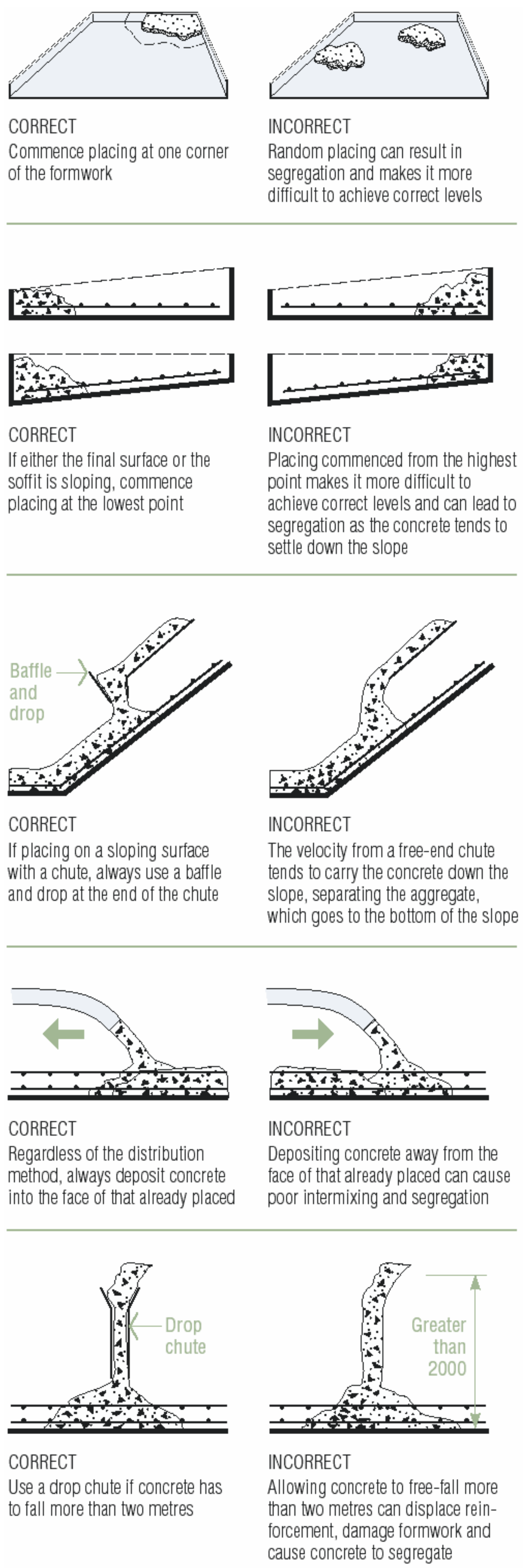


Figure 8.13 **Placing techniques for flatwork**

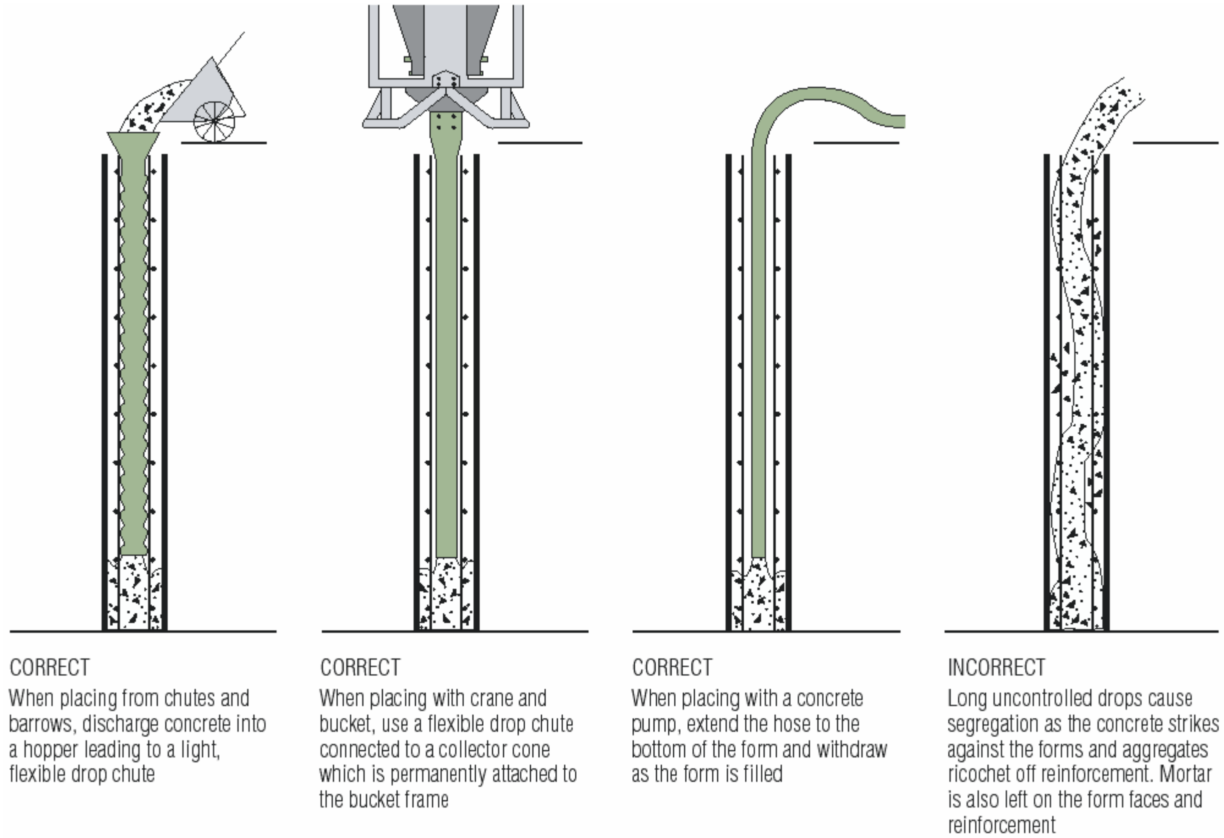


Figure 8.14 **Placing techniques for walls and columns**

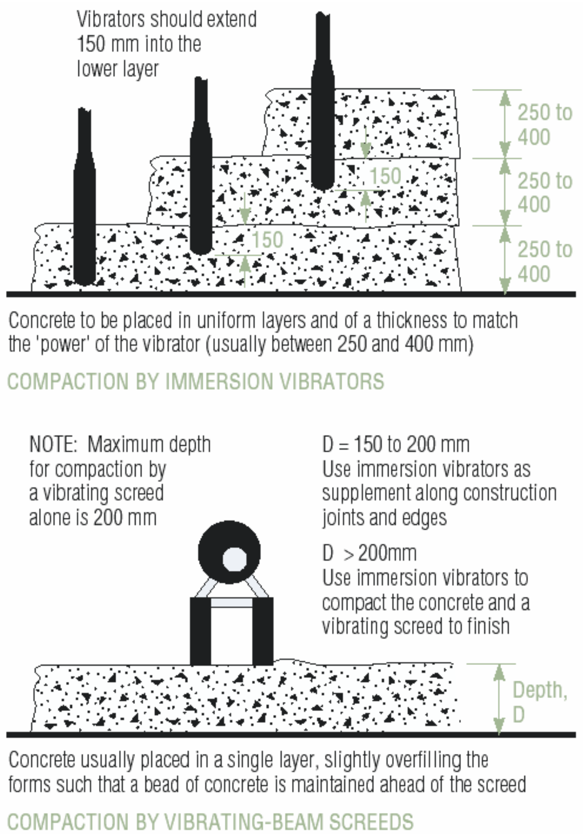


Figure 8.15 **The depth of the layers in which concrete is placed should be appropriate for the compaction method to be used**

The two main types of compaction equipment are immersion (poker) vibrators and vibrating-beam screeds. The effective radius of action of an immersion vibrator depends on its frequency and amplitude.

The common sizes found in normal concrete construction work have a radius of action between 200 and 350 mm. This means, in practice, concrete should be placed in uniform layers ranging from 250 to 400 mm, depending on the vibrator used. To ensure each layer is properly melded together, the vibrator should penetrate about 150 mm into the lower layer **Figure 8.15**.

The effective depth of compaction of vibrating-beam screeds depends on the beam weight, the amplitude, the frequency and the forward speed. For the common available range of surface vibrators, the maximum effective depth is 200 mm. For slabs between 150 and 200 mm thick, immersion vibrators should be used alongside all construction joints and edges to supplement the surface vibrator in these areas.

For slabs greater than 200 mm thick, immersion vibrators should be employed to compact the concrete and the vibrating-beam screed to finish it **Figure 8.15**.

Summary

PLACING METHODS

Method	Application	Comment
Chute	Where work is below level of truck tray. Ideal for strip footings, house floor slabs, road pavements, low retaining walls, etc.	May be direct from transit mixer if work is within radius of its chute. Free fall of concrete should not exceed 2 m without additional end controls.
Barrows and hand carts	Suitable for small projects such as domestic construction.	Labour intensive. Low placing rate (typically 1 to 1.5 m^3/h). Maximum distance about 50 m for continuous work. Requires relatively level, smooth access.
Crane and bucket	Suitable for mass concrete structures and heavyweight concretes. Can be used when concrete is unsuitable for pumping.	Adequate crane time must be available. Limitations dependent on bucket size, crane capacity and reach.
Pumps and pipelines	Versatile and flexible – can distribute concrete both vertically and horizontally.	Require little space. High output. Continuous distribution. Short set-up time. Low labour requirement. Not suitable for all concretes. Likelihood of increased concrete shrinkage. Downhill pumping is difficult.

Compaction

Chapter 9

Chapter 9

Compaction

In this chapter the techniques used to compact or consolidate concrete so as to achieve its optimum density are outlined. Generally, compaction and finishing (see Chapter 10 *Finishing*) are two separate operations. However, on flat horizontal surfaces (flatwork), they are often parts of the same operation and need to be considered together.

INTRODUCTION

Compaction is one of the important site operations that together enable the fresh concrete to reach its potential design strength, density and low permeability. Properly carried out it ensures that concrete fully surrounds and protects the reinforcement, tendons and cast-in inserts. It also has a direct impact on achieving the specified surface finish.

The compacting and finishing of concrete are generally two separate operations but sometimes, particularly with flat horizontal surfaces, they become parts of the one operation. In such circumstances, it should be noted that a smooth surface finish is not necessarily evidence of good compaction underneath it. Care should always be taken to ensure that concrete is adequately compacted.

Those interested in a deeper discussion of the issues than is given here should consult the following:

ACI Committee 309, *Guide for Consolidation of Concrete Report 309R – 96* ACI Manual of Concrete Practice Part 2, Chicago 2000.

ACI Committee 309, *Behaviour of Fresh Concrete During Consolidation Report 309.1R – 99* ACI Manual of Concrete Practice Part 2, Chicago 2000.

ACI Committee 309, *Consolidation-Related Surface Defects Report 309.2R – 98* ACI Manual of Concrete Practice Part 2, Chicago 2000.

ACI Committee 309, *Guide to Consolidation of Concrete in Congested Areas Report 309.3R – 92* ACI Manual of Concrete Practice Part 2, Chicago 2000.

Relevant New Zealand Standards

NZS 3104 *Specification for concrete production*

NZS 3109 *Concrete construction*

Relevant Australian Standards

AS 1379 *The specification and supply of concrete*

AS 3600 *Concrete structures*

9.1 PURPOSE

Compaction is the process that expels entrapped air from freshly placed concrete and packs the aggregate particles together so as to increase the density of the concrete. It significantly increases the ultimate strength of concrete and enhances the bond with reinforcement. It also increases the abrasion resistance and general durability of the concrete, decreases the permeability and helps to minimise its shrinkage and creep characteristics.

Proper compaction also ensures that the reinforcement, tendons, inserts and fixings are completely surrounded by dense concrete, the formwork is completely filled – i.e. there are no pockets of honey-combed material – and that the required surface finish is obtained on vertical surfaces.

NZS 3109 specifies that concrete shall be compacted during placing so that:

- a monolithic mass is created between the ends of the member, planned joints or both;
- the formwork is completely filled to the intended level;
- the entrapped air is expelled;
- all reinforcement, tendons, ducts, anchorages and embedments are completely surrounded;
- the specified finish to the formed surfaces of the member is provided;
- the required properties of the concrete can be achieved.

9.2 THE PROCESS

When first placed in the form, normal concretes (i.e. excluding those with very low or very high workability) will contain between 5% and 20% by volume of entrapped air. The aggregate particles, although coated with mortar, will also tend to arch against one another and are prevented from slumping or consolidating by internal friction.

Compaction of concrete is, therefore, a two-stage process **Figure 9.1** (page 9.3). First, the aggregate particles are set in motion and the concrete consolidated to fill the form and give a level top surface (liquefaction). In the second stage, entrapped air is expelled. This description of the process is true whether compaction is carried out by rodding, tamping and similar manual methods, or when vibration is applied to the concrete. The latter, by temporarily 'liquefying' a much larger volume of the concrete, is generally much more efficient than tamping or rodding by hand, and hence is almost universally used.

It is important to understand that compaction is a two-stage process and to recognise each stage because, with vibration, initial consolidation of the concrete (liquefaction) can often be achieved relatively quickly. The concrete liquefies and the surface levels, giving the impression that the concrete is compacted. Entrapped air takes a little longer to rise to the surface. Compaction should therefore be prolonged until this is accomplished, i.e. until air bubbles no longer appear on the surface.

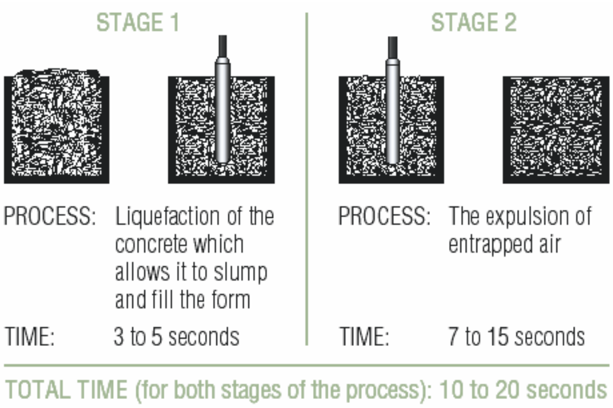


Figure 9.1 The process of compaction

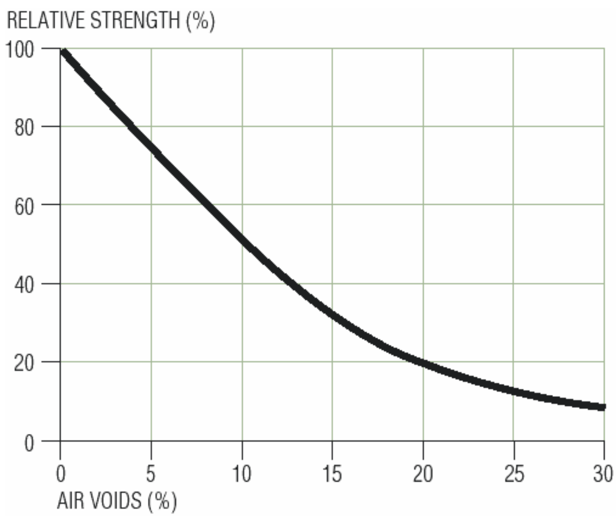


Figure 9.2 Loss of strength through incomplete compaction

9.3 EFFECT ON FRESH CONCRETE

The effect of vibration on the properties of fresh concrete needs to be understood to ensure that the type and amount of vibration applied to the concrete are appropriate. Otherwise, defects such as excessive mortar loss and other forms of segregation can be caused.

The concrete mixture as supplied to the project needs to be properly proportioned. Concretes lacking fines can be difficult to compact and, even when fully compacted, can have a high porosity. On the other hand, those with too high a fines content, particularly if they also have a high slump, may be prone to segregation and excessive bleeding. Nevertheless, it should be noted that properly proportioned concretes are difficult to over-vibrate and cautionary notes in specification regarding over-vibration may result in concrete on the project being under-vibrated with resulting loss of potential strength and durability.

Concretes with lower workability, i.e. stiffer mixes, will require a greater energy input to compact them fully. This may be achieved by using a high-energy vibrator or by vibrating the concrete for a longer time. In the latter case, the vibrator must have at least sufficient capacity to liquefy the concrete. Conversely, more workable mixes will require less energy input.

The size and angularity of the coarse aggregate will also affect the effort required to fully compact concrete. The larger the aggregate, the greater the effort required, while angular aggregates will require greater effort than smooth or rounded aggregates.

9.4 EFFECT ON HARDENED CONCRETE

Since compaction of concrete is designed to expel entrapped air and optimise the density of the concrete, it benefits most of the properties of hardened concrete. As may be seen from **Figure 9.2**, its effect on compressive strength is dramatic. For example, the strength of concrete containing 10% of entrapped air may be as little as 50% that of the concrete when fully compacted.

in addition to expelling entrapped air, promotes a more even distribution of pores within the concrete, causing them to become discontinuous. The durability of the concrete is consequently improved except, perhaps, in freeze-thaw conditions, where excessive vibration can expel amounts of purposely-entrained air which is designed to increase the freeze-thaw resistance of hardened concrete (see Chapter 19 *Properties of Concrete*).

The abrasion resistance of concrete surfaces is normally improved by adequate compaction. However, excessive vibration, or excessive working of the surface, can cause an excessive amount of mortar (and moisture) to collect on the surface, thereby reducing its potential abrasion resistance. In flatwork a careful balance is therefore required to expel entrapped air without bringing excessive amounts of mortar (fines) to the surface of the concrete.

9.5 METHODS AND EQUIPMENT

9.5.1 General

Two types of vibrators are common on building sites (immersion vibrators and surface vibrators. Each has its sphere of application, although on floors and other flatwork it is not uncommon for one to augment the other. A third type, form vibrators, is commonly used in factories for precast work, and sometimes on building sites.

9.5.2 Immersion Vibrators

Frequently referred to as 'poker' or 'spud' vibrators, immersion vibrators consist essentially of a tubular housing which contains a rotating eccentric weight. The out-of-balance rotating weight causes the casing to vibrate and, when immersed in concrete, the concrete itself. Depending on the diameter of the casing, and on the frequency and the amplitude of the vibration, an immersion vibrator may have a radius of action of between 100 and 600 mm **Table 9.1**.

Immersion vibrators may be driven by:

- a flexible shaft connected to a petrol, diesel, or electric motor;
- an electric motor situated within the tubular casing;
- compressed air.

Flexible-shaft vibrators may have either a conical pendulum, which runs around the inside of the casing like an epicyclic gear, or a straight rotating weight. Those with the former have the advantage that they generally have thinner heads (useful in reinforced members). They also have higher amplitudes at the tip than further up the casing. This helps compact the concrete near the top of the pour as the vibrator is withdrawn from the concrete.

Electrically powered vibrators, with the motor in the head driving an eccentric weight, are relatively light in weight and, with a switch located at the vibrator, are easy to handle.

Vibrators powered by compressed air normally have the motor driving an eccentric weight located within the casing. They are most common in the larger diameters used in compacting mass concrete, e.g. in dams.

Table 9.1 Characteristics and applications of internal vibrators

Diameter of head (mm)	**Recommended frequency** (Hz)[1]	**Average amplitude** (mm)[2]	**Radius of action** (mm)[3,5]	**Rate of concrete placement** (m^3/h per vibrator)[4,5]	**Application**
20–40	150–250	0.4–0.8	80–150	0.8–4	High slump concrete in very thin members and confined places. May be used to supplement larger vibrators where reinforcement or ducts cause congestion in forms.
30–60	140–210	0.5–1.0	130–250	2.3–8	Concrete 100–150 mm slump in thin walls, columns, beams, precast piles, thin slabs, and along construction joints. May be used to supplement larger vibrators in confined areas.
50–90	130–200	0.6–1.3	180–360	4.6–15	Concrete (less than 80 mm slump) in normal construction, e.g. walls, floors, beams and columns in residential, commercial and industrial buildings.
80–150	120–180	0.8–1.5	300–500	1–31	Mass and structural concrete of 0 to 50 mm slump deposited in quantities up to 3 m^3 in relatively open forms of heavy construction.

Adapted from Table 5.15 ACI Committee Report: Consolidation of Concrete ACI Manual of Concrete Practice 1993 Part 2.

1 *While vibrator is operating in concrete.*

2 *Computed or measured. This is peak amplitude (half the peak-to-peak value), operating in air. Reduced by 15–20% when operating in concrete.*

3 *Distance over which concrete is fully consolidated.*

4 *Assumes insertion spacing 1½ times the radius of action, and that vibrator operates two-thirds of time concrete is being placed.*

5 *Reflects not only the capability of the vibrator but also differences in workability of the mix, degree of de-aeration desired, and other conditions experienced in construction.*

Figure 9.3 **Use of an immersion vibrator**

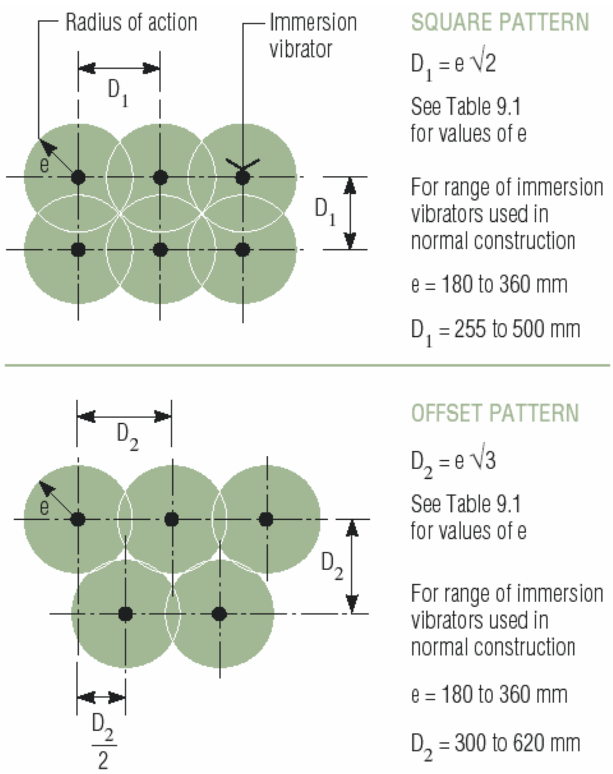


Figure 9.4 **Alternative patterns for use of immersion vibrators**

The effectiveness of an immersion vibrator is dependent on its frequency and amplitude, the latter being dependent on the size of the head, the eccentric moment and the head weight—the larger the head, the larger the amplitude.

Table 9.1 summarises the characteristics and applications of internal vibrators. As a general rule, the radius of action of a given vibrator not only increases with the workability of the concrete, but also with the diameter of the head. A good general rule is to use as large a diameter head as practicable, bearing in mind that vibrators with diameters in excess of 100 mm will probably require two men to handle them. Below this diameter, the appropriate head size will be dependent on the width of the formwork, the spacing of the reinforcement and the cover to it.

The *frequency* of a vibrator is the number of vibrations per second (Hz). In general, high-frequency vibrators are most suited to high-slump concrete and small maximum-sized aggregates, and low frequencies to low slumps and large maximum-sized aggregates. The *amplitude* is the maximum displacement of the head from its point of rest, measured in mm. It will be larger in air than in concrete which has a damping effect. As a general rule, high-amplitude vibrators are most suited to low-slump/large maximum-sized aggregate concrete and low amplitudes to high slumps and small maximum-sized aggregates.

Immersion vibrators should be inserted vertically into concrete, as quickly as possible, and then held stationary until air bubbles cease to rise to the surface, usually in 15–20 seconds **Figure 9.3**. The vibrator should then be slowly withdrawn and reinserted in a fresh position adjacent to the first. These movements should be repeated in a regular pattern until all the concrete has been compacted **Figure 9.4**. Random insertions are likely to leave areas of the concrete uncompacted. The vibrator should not be used to cause concrete to flow horizontally in the forms, as this can lead to segregation.

In deep sections such as walls, foundations and larger columns, the concrete should be placed in layers about 300 mm thick. The vibrator should penetrate about 150 mm into the previous layer of fresh concrete to meld the two layers together and avoid 'cold-pour' lines on the finished surface. In small columns where concreting is continuous, the vibrator may be slowly raised as the concrete is placed. However, care should be taken to ensure that the rate of placement is slow enough to allow the concrete to be fully compacted and the entrapped air able to reach the surface. Care should also be taken to avoid trapping air on the form face and a means of lighting the interior of the form while the concrete is being placed and vibrated should be provided.

The vibrator should not be allowed to touch the forms as this can cause 'burn' marks that will be reflected on the finished surface. Generally, the vibrator should be kept about 50 mm clear of the form face. Similarly, the vibrator should not be held against reinforcement as this may cause its displacement.

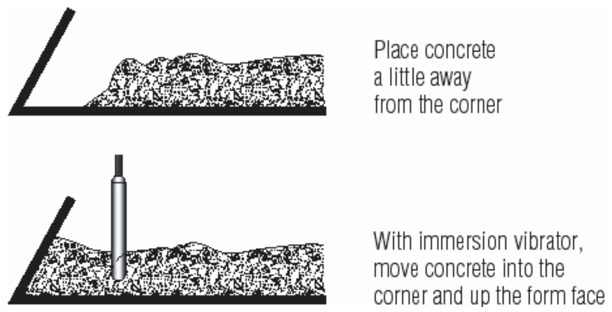


Figure 9.5 **Compaction at stop ends and inclined forms**

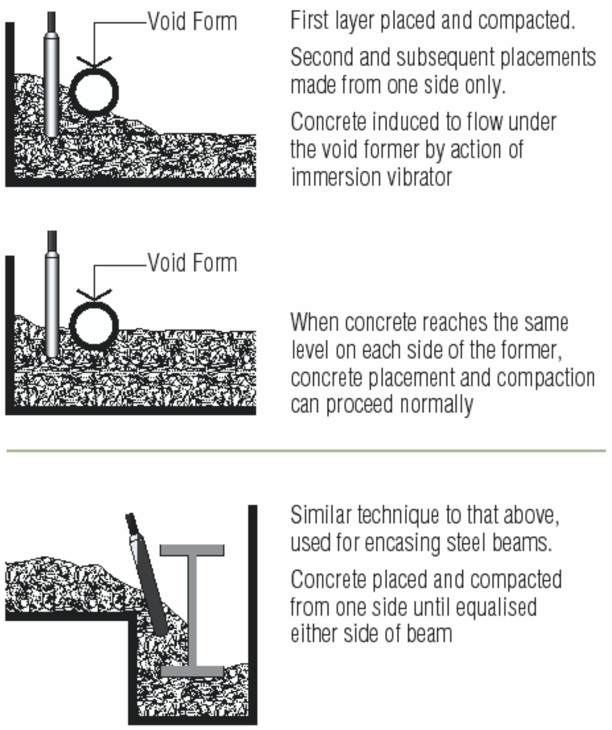


Figure 9.6 **Compacting around void formers and encased beams**

Figure 9.7 **Typical screed vibrator**

Stop-ends, joints and, especially, inclined forms are prone to trapping air. To minimise this tendency, the best technique is to place the concrete close to, but away from, the form and insert the immersion vibrator close to the leading edge of the concrete forcing it to properly fill the corner **Figure 9.5**.

Void-formers are prone to trapping air on their undersides if concrete is placed from both sides and then compacted. Concrete should be placed at one side and, maintaining a head, vibrated until it appears at the other side. (Note that the void-former will need to be fixed so as to resist the pressure of the concrete – sideways and vertical.) When the top of the concrete is fully visible from above, then placing can continue normally **Figure 9.6**. This technique should be used in other similar situations, such as encasing steel beams.

9.5.3 Screed Vibrators

Screed vibrators are applied to the top surface of concrete and act downwards from there. They are very useful for compacting slabs, industrial floors, road pavements, and similar flat surfaces. They also aid in levelling and finishing the surface.

A number of types of screed vibrators are available. Some of these, e.g. vibrating-roller screeds and pan-type vibrators, are used mainly on very specialised equipment such as road paving plant, but the most common type is the single or double vibrating-beam screed.

A vibrating-beam screed consists of either one or two beams, made from aluminium, steel or timber, to which is attached some form of vibrating unit. This may be a single unit, mounted centrally, or may consist of a series of eccentric weights on a shaft supported by a trussed frame and driven from a motor at one end. In general, the centrally mounted units have a maximum span of about 6 m, but the trussed units may span up to 20 m. The small units are normally pulled forward manually, whereas the larger units may be winched, towed or be self-propelled **Figure 9.7**.

The intensity of vibration and, hence, the amount of compaction achieved, decreases with depth because screed vibrators act from the top down. They are most effective, therefore, on slabs less than about 200 mm thick. With slabs greater than 200 mm in thickness, immersion vibrators should be used to supplement the surface vibration. A thick slab compacted by both immersion and screed vibrators will have a denser, more abrasion-resistant surface than one compacted by immersion vibrators alone.

With centrally mounted vibration units, the degree of compaction achieved may vary across the width of the beam. When they rest on edge forms, the latter may tend to damp the vibration at the extremities of the beam **Figure 9.8**. It is generally desirable, therefore, to supplement vibrating-beam compaction by using immersion vibrators alongside edge forms.

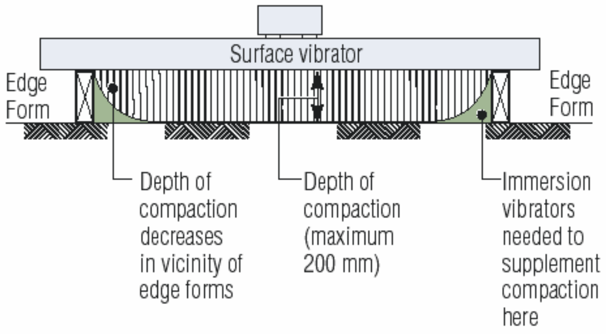


Figure 9.8 **Degree of compaction varies across width when screed vibrators are supported off edge forms**

Figure 9.9 **Use of an immersion vibrator at a slab edge**

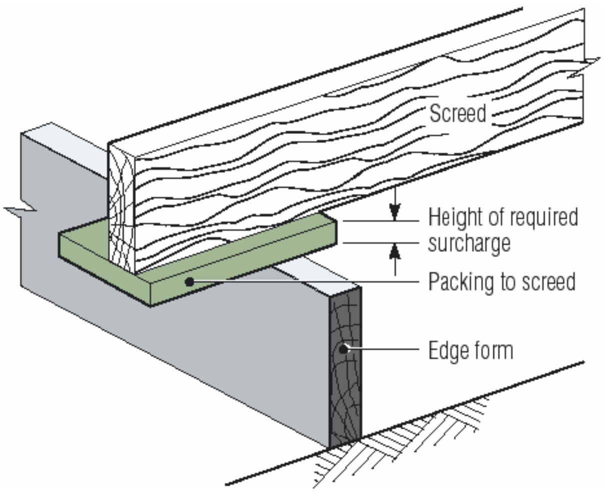


Figure 9.10 **Method of providing an even surcharge to the uncompacted concrete**

The effectiveness of vibration and, hence, degree of compaction increases with an increase in the beam weight, the amplitude and the frequency, and decreases with an increase in forward speed. Forward speed is critical in the correct use of vibrating-beam screeds and should be limited to between 0.5 and 1.0 m/min.

Generally speaking, vibrating-beam screeds are not suitable for concretes with slumps greater than about 75 mm, as an excessive amount of mortar may be brought to the surface. Ideally, they should be used only on concretes with slumps between 25 and 50 mm. For the reasons given above, slabs 200 mm in thickness or over should be compacted initially with immersion vibrators. Slabs of less than 200 mm may also benefit from the use of immersion vibrators along their edges **Figure 9.9**.

In using vibrating-beam screeds to compact concrete, the uncompacted concrete should first be roughly levelled above the required final level, i.e. a surcharge should be provided to compensate for the reduction in slab thickness caused by the compaction of the concrete. The amount of surcharge should be such that, when the beam is moved forward, a consistent 'roll' of concrete is maintained ahead of the beam. An even surcharge may be provided on slabs of up to about 4 m in width by the use of a 'surcharge-beam'. This is simply a straightedge, usually made of timber, with small packing pieces on the ends, which 'ride' on the edge forms **Figure 9.10**.

The surcharge-beam is pulled over the uncompacted concrete without any attempt being made to compact or finish it. The sole purpose is to provide an even surcharge. The correct thickness for the packing pieces (and hence the surcharge) is soon found by observing the 'roll' of concrete. Providing an even surcharge has the advantage that one pass of the vibrating-beam screed is generally sufficient to compact, level and provide the initial finish. This is preferable to multiple passes, as a slower single pass is more effective than two faster passes.

The forward speed is most important and should be between 0.5 and 1.0 m/min. The lower speed should be used for thicker slabs and where reinforcement is close to the top face. A second, faster pass may be made as an aid to finishing.

9.5.4 Form Vibrators

Form vibrators are normally called 'external' vibrators and are useful with complicated members or where the reinforcement is highly congested. They are clamped to the outside of the formwork and vibrate it, thus compacting the concrete contained in the form **Figure 9.11** (page 9.8).

Since form vibrators impose large forces on the formwork, it requires special design and construction. Determining the positioning of the vibration units requires skill and experience. For all these reasons, the use of form vibrators is most common in the manufacture of precast members and products. When consideration is being given to their use, it should be noted that air bubbles tend to migrate towards the source of vibration. Hence, if a high standard of surface finish is important, careful consideration must be given to the location of form vibrators.

For some products, formwork may be clamped to a vibrating table, i.e. a rigid unit isolated from its supports by springs, neoprene pads or similar means, which is set in motion by vibrators attached to it. The whole unit, including the formwork, then vibrates to compact the concrete. These units are most commonly employed in products manufacture, where, with very stiff mixes, pressure may also be applied to the surface of the unit to compact it, e.g. in the manufacture of concrete blocks.

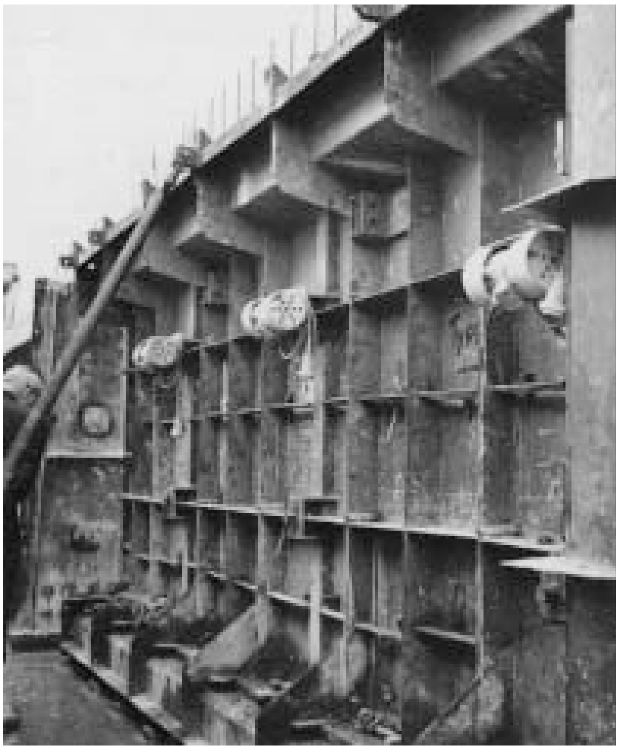


Figure 9.11 **Electric form vibrators attached to the steel formwork of a bridge girder**

9.6 UNDER-VIBRATION AND OVER-VIBRATION

Normal-weight concretes, which are well proportioned, are not readily susceptible to defects caused by over-vibration. These defects result from segregation and are characterised by an excessive thickness of mortar on the surface of the concrete. The surface may also have a frothy appearance.

Over-vibration may cause problems when grossly oversized equipment is operated for an excessive length of time, but is more likely to cause problems with poorly proportioned mixes or those to which excessive amounts of water have been added.

When signs of over-vibration are detected, the initial reaction may be to reduce the amount of vibration. The proper solution is to adjust the mix design.

Under-vibration is far more common than over-vibration and, when it occurs, can cause serious defects. Invariably, the concrete is incompletely compacted which reduces its strength, its durability and possibly adversely affects its surface finish.

Despite this, many specifications contain a caution against over-vibration (and even lay down a length of time for vibration that must not be exceeded) whilst neglecting totally the question of under-vibration.

9.7 REVIBRATION

Revibration of concrete is the intentional systematic vibration of concrete which has been compacted some time earlier. It should not be confused with the double vibration that sometimes occurs with the haphazard use of immersion vibrators or multiple passes of a vibrating-beam screed.

Whilst it is generally agreed that revibration of concrete can be beneficial to its strength, its bond to reinforcement and its surface finish, the practice is not widely used, partly due to the difficulty of knowing just how late it can be applied. A good rule of thumb is that revibration may be used as long as the vibrator is capable of liquefying the concrete and sinking into it under its own weight.

Situations in which revibration may be beneficial include:

- To bond layers of concrete into those preceding them. In elements such as walls, deep beams and columns, which are being filled in successive layers, the vibrator should penetrate the previous layer.
- To close plastic shrinkage and settlement cracks. These form within the first few hours of concrete being placed and can be closed by vibration. However, a reasonable level of energy input is required since mere reworking of the surface may simply close the cracks superficially. They will then reopen as the concrete dries out.
- To improve the surface finish at the tops of columns and walls by expelling the air which tends to congregate there as the concrete settles in the formwork.
- To improve the wear resistance of floors. Revibration, coupled with a trowelling action, helps to create a burnished wear-resistant surface layer.

Summary

CAUSES OF SURFACE DEFECTS RELATING TO CONCRETE, PLACEMENT AND COMPACTION

	Causes		
Defects	**Properties of fresh concrete**	**Placement**	**Compaction**
Honeycomb	Insufficient fines, low workability, early stiffening, excessive mixing, too large an aggregate for placing conditions.	Excessive free fall, too thick a layer (lift) of concrete in forms, drop chute omitted or of insufficient length, too small a tremie, segregation due to horizontal movement.	Vibrator too small, too low a frequency, too small an amplitude, too short immersion time, excessive spacing between immersions, inadequate penetration.
Air surface voids	Lean, sand with a high FM, low workability with low FM sand, excessive cement content, particle degradation, excessive sand, high air content.	Too slow, caused by inadequate pumping rate, undersized bucket.	Too large an amplitude, external vibration inadequate, head of vibrator only partially immersed.
Form streaking	Excess water or high slump.	Improper timing between placing and timing.	Excessive amplitude or frequency for form design.
Aggregate transparency	Low sand content, gap-graded aggregate dry or porous, excessive coarse aggregate, excessive slump with lightweight concrete.		Excessive external vibration, over-vibration of lightweight concrete.
Subsidence cracking	Low sand, high water content, too high slump, poorly proportioned mix.	Too rapid.	Insufficient vibration and lack of revibration.
Colour variation	Non-uniform colour of materials, inconsistent grading, variation in proportions, incomplete mixing. Calcium chloride can cause darker colour. Too high a slump.	Segregation (slump too high).	Vibrator too close to form, vibration next to forms variable, over-working of the concrete.
Sand streaking	Lean over-sanded mixtures and harsh wet mixtures deficient in fines.	Too rapid for type of mix.	Excessive vibration, excessive amplitude, over-working the concrete.
Layer lines	Wet mixture with tendency to bleed.	Slow placement, lack of equipment or manpower.	Lack of vibration, failure to penetrate into previous layer.
Form offsets	Excessive retardation of time of setting of concreter.	Rate too high.	Excessive amplitude, non-uniform spacing of immersion, horizontal movement of concrete.
Cold joints	Too dry, early stiffening, slump loss.	Delayed delivery, layers (lifts) too high.	Failure to vibrate into lower layer(lift), insufficient vibration.

Adapted from ACI Committee 309 Report: Consolidation-Related Surface Defects ACI 309.2R – 98 ACI Manual of Concrete Practice Part 2

Chapter 10

Finishing Concrete Flatwork

Chapter 10

Finishing Concrete Flatwork

This chapter provides information on the finishing of freshly placed concrete. Generally compaction (see Chapter 9 *Compaction*) and finishing are two separate operations, however, on flat horizontal surfaces (flatwork), they are often part of the same operation and need to be considered together. Applied and off-form finishes for vertical and inclined surfaces are discussed in Chapter 15 *Formwork*.

INTRODUCTION

In this Chapter the techniques used to finish flat horizontal surfaces after the concrete has been compacted are described and discussed.

The compacting and finishing of concrete are generally two separate operations but sometimes, particularly with flat horizontal surfaces, they become part of the one operation. In such circumstances, it must always be remembered that a smooth surface finish is not necessarily evidence of good compaction underneath it. Care must always be taken to ensure that concrete is adequately compacted.

Relevant New Zealand Standards

NZS 3101	*Concrete structures*
NZS 3104	*Specification for concrete production*
NZS 3109	*Concrete construction*
NZS 3114	*Concrete surface finishes*
AS/NZS 4586	*Slip resistance classification of new pedestrian surface materials*

Relevant Australian Standards

AS 1379	*The specification and supply of concrete*
AS 3600	*Concrete structures*
AS/NZS 4586	*Slip resistance classification of new pedestrian surface materials*

10.1 GENERAL

'Flatwork' refers to any concrete floor or paving such as industrial floors, floors in other buildings (both on ground and suspended), paths, patios, driveways, roads, etc.

The finishing of flatwork involves a combination of the following processes:

- Levelling.
- Floating.
- Trowelling.
- Other treatments.

These are carried out while the concrete is still plastic. The purpose of finishing is to achieve the desired:

- level or profile;
- flatness;
- surface density and texture.

10.2 LEVELLING (SCREEDING)

10.2.1 General

Levelling or screeding is the initial operation carried out on a concrete slab after the concrete has been placed in the forms and (if necessary) roughly levelled by shovel. Screeding is carried out by working a beam backwards and forwards across the concrete to achieve a level surface or by means of vibrating-beam screeds working off forms or guide rails. It should be done before bleed water rises to the surface.

Usually, the final surface will be level but the same technique can be used on sloping surfaces, e.g. driveways and ramps. In this case, the screeding should be commenced at the lower end and proceed up the slope.

10.2.2 Hand Screeding off Forms or Screed Rails

Screeding off edge forms involves the use of a screed board to strike off the concrete to the height of the forms. Screed rails are temporary guides to support the screed board. They have to be removed after the surface is screeded, and the surface made good whilst the concrete is plastic.

The striking surface of a screed board should always be straight and true. Proprietary screed boards, such as hollow magnesium straightedges, should be used for major commercial work and for house slabs. Lengths of dressed timber are satisfactory in minor work.

To enable it to be worked backwards and forwards without losing its level, the straightedge should be between 300 and 600 mm longer than the greatest distance between the forms.

The surface is struck off by pulling the screed board forward, while moving it back and forth with a saw-like motion across the top of the edge forms. A small roll of concrete should always be kept ahead of the straightedge to fill in low spots and maintain a plane surface. Excessive amounts should be removed and placed ahead of the screed board.

Where a smooth final finish is needed, a bull float (see 10.3.2) is used on the surface immediately screeding is finished and before bleed water rises.

10.2.3 Hand Screeding Off Wet Screeds

'Wet-screeds' consist of pads or narrow strips of concrete (approximately 200 mm wide) placed to the correct level in advance of the main pour. The concrete finisher then uses the pads or strips as the control for levelling the slab.

This method allows large areas to be screeded without intermediate forms or guide rails and without the necessity to accurately level the edge forms. However, more skill is required and surveying equipment to set out the height of the wet screeds has to be available.

Generally, proprietary aluminium or magnesium screed boards with a handle are preferred for this work.

The ability to achieve full concrete compaction through the slab thickness is to a degree compromised.

10.2.4 Screeding Using Vibrating-Beam Screeds

Vibrating-beam screeds provide significant compaction in addition to their screeding capability. Their use and operation are described in Chapter 9 *Compaction*.

The accuracy of the surface level achieved is dependent on the formwork on which the vibrating-beam 'rides'. This formwork must therefore be accurately levelled and firmly fixed so that it will not distort under the weight of the vibrating-beam. Special care should be taken at joints of formwork boards.

The screed itself should not 'sag' or distort under the weight of the vibration unit and, for this reason, a 4 m width is about the limit for twin-beam, centrally-mounted vibration unit screeds. However, trussed vibrating-beam screeds can span 20 m with minimal 'sag' and can be used to provide floors with very tight surface tolerances **Figure 10.1**.

Figure 10.1 **Typical trussed vibrating-beam screed**

10.2.5 Machine Mounted Screeds (Laser Screeds)

The latest development in mechanising the screeding and compacting of concrete floors and pavements is the 'laser screed'. These four-wheel drive machines are positioned and then stabilised on hydraulically extended legs **Figure 10.2**. The telescopic arm with the screed at the end is extended. The concrete is spread by auger and compacted by the screed as the arm is retracted towards the machine. Laser sensors mounted at the ends of the screed monitor the level and adjust the height automatically. The machines are able to produce floors to very stringent requirements in terms of flatness and levelness. Depending on the size of machine, screeds are up to approximately 3.5 m wide and the telescoping arms extend out to approximately 6 m.

Figure 10.2 **Typical machine-mounted beam screed**

10.3 FLOATING

10.3.1 General

The purpose of floating a concrete surface is to impart to it a relatively even but still open texture preparatory to other finishing operations, and thus to:

- embed large aggregate particles beneath the surface;
- remove slight imperfections and produce a surface closer to the true plane;
- compact the concrete and consolidate the mortar at the surface in preparation for other finishing operations;
- close minor surface cracks which might appear as the surface dries.

Floating is carried out by working the surface of the concrete with hand floats, or by rotary finishing machines fitted with appropriate floats or shoes. It should not begin until all bleed water has evaporated from the surface, or has been removed with a Hessian drag, and the concrete begun to harden to the point where it can withstand the finisher walking on it and making only minor indentations in the surface. Such indentations should, in fact, be removed by the floating operation.

10.3.2 Bullfloating

The bullfloat is a large float on a long handle which is worked back and forth on the concrete in a direction parallel to the ridges formed by screeding, i.e. transversely across the slab **Figure 10.3**. The blade is typically aluminium or magnesium but may also be wood. The blade and handle are usually pivoted so that the angle of the blade can be changed depending on whether the stroke is forward or backward.

Bullfloating is particularly useful as an initial floating operation to smooth the concrete surface immediately after screeding and should be completed before bleed water appears on the surface.

To minimise the number of ridge marks left at the edge of the blade, bullfloat passes should not overlap by more than 50 mm.

A second use of the bullfloat may sometimes be required but care should be taken not to overwork the surface.

10.3.3 Floating by Hand

Three types of hand float are in common use – wooden, magnesium and composition.

Wooden floats require skilled operators and timing is important. If used too early, they stick, dig in, and can tear the surface. Used too late, they roll the coarser particles of fine aggregate out of the surface.

Magnesium floats require less effort and will not roll coarse particles of fine aggregate out of the surface. They can be used after wood or power floating to give a more uniform swirl finish, which is not quite so rough in texture as that produced by a wooden float.

Well-worn magnesium floats should be discarded. They develop an edge almost as sharp as that of a steel trowel, and use of them risks closing the surface too soon.

Composition floats have resin-impregnated canvas surfaces. They are smoother than wooden floats but slightly rougher than magnesium floats. They also can be used after wood or power floating.

The hand float is held flat on the surface and moved in a sweeping arc to embed the aggregate, compact the concrete, and remove minor imperfections and cracks. Sometimes, the surface may be floated a second time, after some hardening has taken place, to impart the final desired texture to the concrete **Figure 10.4**.

Figure 10.3 **Bullfloating**

Figure 10.4 **Hand floating**

Figure 10.5 **Power floating in a regular pattern**

Figure 10.6 **Ride on machine trowel**

10.3.4 Floating by Machine

Machines for floating are usually trowelling machines with float shoes or, for use on low-slump concrete or toppings, disc-type machines (Kelly floats).

Float blades are wider than trowel blades and are turned up along the edges to prevent them digging into the surfaces whilst in the flat position. For this reason, floating with a trowelling machine equipped with normal trowel blades should not be attempted.

The power-float should be operated over the concrete in a regular pattern leaving a matt finish **Figure 10.5**.

Concrete close to obstructions, or in slab corners, that cannot be reached with a power-float should be manually floated before power floating is begun.

The use of water sprays or other means of wetting the surface during finishing operations should not be permitted as such practices almost inevitably cause dusting of the slab at a later date.

10.4 TROWELLING

10.4.1 General

Trowelling is carried out some time after floating. The delay is to allow some stiffening to take place so that aggregate particles are not torn out of the surface.

For a first trowelling, the trowel blade should be kept as flat against the surface as possible since tilting or pitching the trowel at too great an angle can create ripples in the concrete.

Additional trowellings may be used to increase the smoothness, density, and wear resistance of the surface. Successive trowellings should be made with smaller trowels pitched progressively more. This increases the pressure at the bottom of the blade and helps compact the top surface.

Blisters forming on the surface during trowelling indicate that the angle of the trowel is too great. As soon as blisters are seen they should be pushed down immediately and rebonded to the base concrete using a magnesium float or a flat trowel, depending on the stiffness of the concrete. The angle of the trowel should then be reduced to prevent more blisters forming at this stage.

A blistered surface will not be durable. Blisters can be broken out by traffic, and will show through any resilient tile placed over them.

10.4.2 Trowelling by Hand

A trowel for hand finishing has a flat, broad steel blade and is used in a sweeping arc motion with each pass overlapping the previous one.

The time for trowelling to be most effective calls for some experience and judgement, but, in general terms, when the trowel is moved across the surface it should give a ringing sound.

10.4.3 Trowelling by Machine

The trowelling machine (power trowel or 'helicopter') is a common tool for all classes of work and consists of several (generally four) steel trowel blades rotated by a motor and guided by a handle. Larger machines are ride-on and are suitable for trowelling large areas such as factory floors. **Figure 10.6**.

Trowelling by machine should be carried out systematically over the concrete in a regular pattern. Corner areas, areas close to obstructions and small irregularities should then be 'touched-up' with a hand trowel.

Successive trowellings, with a break to allow further hardening, will 'densify' the surface, providing increased wear resistance. Successive trowellings should be at right angles to each other for maximum effectiveness.

10.5 EDGING

Edging provides a quarter-round arris along the edges of footpaths, patios, curbs and steps. It is achieved by running an edging trowel along the perimeter of the concrete. Edging trowels are steel and incorporate a quarter-round forming edge. They are available in a variety of widths and with various diameter quadrants.

Edging improves the appearance of many types of paving and makes the edges less vulnerable to chipping. However, edging should not be used at joints in industrial or warehouse floors or in floors which will be tiled or carpeted.

Joints in industrial floors should have a crisp right-angled corner. On formed edges this is achieved principally by the form boards which should have sharp, right-angled edges. Hand trowelling is generally used along such edges to ensure the sharpness of corners.

10.6 SURFACE TREATMENTS

10.6.1 General

Surface treatments should be chosen to suit the anticipated service conditions or to give the concrete a particular appearance.

The choice of finish will be influenced by the following considerations:

- The type of traffic and its frequency.
- Whether the floor is subject to impact-loading.
- Whether chemicals will come into contact with the slab.

Consideration should also be given to the operations to be carried out on the floor, which may determine how smooth it should be, and the necessity for hygiene and dust prevention.

Surface treatments which can be used to provide different appearances include colouring, exposing the aggregate and texturing or imprinting.

10.6.2 'Driers' and 'Dry-Shake Toppings'

One of the most difficult questions related to concrete floor finishing is whether to permit the use of 'dry-shake toppings', and, if so, under what conditions. Clearly their use to mask or patch up an unsatisfactory finish should not be permitted. On the other hand, when used by a skilled finisher, they can impart special finishes to flatwork, e.g. coloured and abrasion-resistant surfaces. In the hands of a skilled finisher, they may also be useful for correcting minor imperfections in a surface.

As a general rule, therefore, it is well to agree, before finishing commences, whether dry-shakes will be permitted and if so, under what circumstances.

When 'driers' (neat cement or mixtures of cement and sand) are used to soak up bleed water, the surface will almost certainly have a variable water-cement ratio resulting in poor wear resistance. The surface is almost certain to craze and in extreme cases may delaminate.

'Dry-shake toppings' may also used to 'mask' concrete which is not of the correct quality and/or which has been poorly placed and compacted. Clearly, such practices are undesirable since (although the surface might appear hard in the first instance) the base concrete is inadequate for the purpose for which it is intended.

10.6.3 Abrasion-Resistant Toppings

The correct wear (abrasion) resistance, impact resistance and chemical resistance is generally achieved by specifying the appropriate strength of concrete and properly compacting, finishing and curing it.

Since the wear resistance of concrete is directly related to its compressive strength, NZS 3101 stipulates minimum requirements for resistance to abrasion as shown in **Table 10.1** (page 10.7).

Where very high levels of wear resistance are required, metallic dry-shakes can be used to good effect. They consist of cement mixed with either specially treated malleable graded iron filings, or a mixture of carborundum (silicon carbide) and emery particles.

The application of metallic dry-shakes and subsequent finishing of the concrete is a skilled operation, usually performed by specialist operators. The metallic dry-shake is distributed over a floated concrete surface. The surface is then floated again and may then be trowelled.

Metallic shakes or metallic aggregates are also used where impact is severe.

The use of surface hardeners, such as products based on sodium silicate or silico-fluoride compounds, may provide some additional wear resistance but should not be used to justify lower grades of concrete than those specified in NZS 3101. Whilst having some effect during the early life of a floor, re-application will be necessary as the floor wears.

10.6.4 Slip and Skid Resistance

Slip and skid-resistant concrete surfaces can be created by texturing the plastic concrete. The term 'slip' relates to pedestrian surfaces while 'skid' is the term used for vehicular pavements. Finishing the concrete with a wooden or sponge float, will give the surface a degree of slip resistance. Such surfaces will be suitable for foot traffic on level or near-level paving.

AS/NZS 4586 sets out required slip resistance for various areas in domestic and pedestrian areas. Bowman[10.1] provides a detailed discussion of the topic of slip resistance and an explanation of how to use the Standard.

A stiff-bristled broom or dampened hessian sheet, drawn across the trowelled surface, can produce a greater degree of skid-resistance, suitable for vehicular traffic.

For greatest skid-resistance, on ramps or high-speed roadways, the freshly-trowelled concrete can be grooved with a steel-tyned comb (see also under Texturing below).

10.6.5 Chemical Resistance

Good quality concrete can withstand attack from many chemicals. Provision of a high grade of concrete properly placed, compacted, finished and cured is generally the best way to provide maximum chemical resistance. In some cases, chemical resistance may be further increased by the use of surface hardeners such as sodium silicate, silico-fluoride compounds or other protective coatings. Where the surface is subjected to attack from very aggressive chemicals the use of a suitable protective coating is required. Such coatings should be applied after the concrete has been properly cured but before it is exposed to the chemical attack. (For further guidance on this topic see Chapter 19 *Properties of Concrete*.)

10.6.6 Coloured Concrete

Concrete can be coloured by incorporating a pigment into the mix. However as pigments are expensive, in New Zealand and Australia it is far more common to apply a dry-shake topping, containing a pigment, onto normal uncoloured concrete.

Table 10.1 Requirements for abrasion resistance for a specified intended life of 50 years from Table 3.8 NZS 3101

Class	Service conditions	Application	Finishing process	Curing	Minimum specified compressive strength f'_c (MPa)
Special	Severe abrasion and impact from steel or hard plastics wheeled traffic or scoring by dragged metal objects.	Very heavy duty engineering workshops and very intensively used ware-houses.	Special flooring techniques may be used. The suitability of concrete flooring for this class should be established with the manufacturer or flooring contractor.		
AR1	Very high abrasion: steel or hard plastics wheeled traffic and impact.	Heavy duty industrial workshops and intensively used warehouses.			
AR2	High abrasion: steel or hard plastics wheeled traffic.	Medium duty industrial and commercial.	Power floating and at least two passes with a power trowel.	7 days water curing using ponding or covering; or the use of a curing membrane that meets NZS 3109.	40 MPa
AR3	Moderate abrasion: Rubber tyred traffic.	Light duty industrial and commercial.			30 MPa
Commercial and industrial floors not subject to vehicular traffic.			As nominated by the designer.	3 days minimum.	25 MPa

The dry-shake consists of a mix of cement, pigment and clean, sharp sand. Typical proportions are 1 part cement: 0.06–0.1 part oxide: 2 parts clean, sharp sand. The exact proportion of oxide depends on the shade required, there being no point in using extra pigment when colour saturation has been reached.

All materials should be thoroughly blended before use. First the pigment and cement are mixed, and then the sand added.

Timing is crucial when coloured dry-shakes are used – all bleeding should have ceased and the water sheen on the concrete should no longer be visible. The dryshake is then broadcast over the surface sufficiently thickly to produce a topping 3–4 mm thick. It is then floated and trowelled onto the concrete without the surface being overworked.

10.6.7 Texturing

Brooms of varying degrees of stiffness, hessian or sponges can produce finishes which are both functional and attractive.

Brooms may be used to provide a variety of textures. The timing of brooming, and the angle at which the broom is held, will affect the appearance. An extension handle is usually fitted so that the broom can be pulled right across the surface in one motion and, after each traverse of the concrete, the broom head should be tapped or cleaned to prevent an accumulation of mortar in the bristles.

Where a broomed texture is used and traffic is heavier than domestic or light commercial traffic, the texture should be deeper. Lightly broomed textures look attractive when first done but wear quickly in industrial situations, whereas a medium or coarse broom texture should provide a good, skid-resistant surface over the design life of the floor or pavement **Figure 10.7**.

Figure 10.7 **Broom finishing to provide skid resistance**

Exposed aggregate finishes are achieved by washing away the top layer of cement mortar from the surface of the concrete once initial setting has taken place. This delay is crucial to achieving a good exposed aggregate finish.

The surface of cement paste is generally removed with a fine water spray, supplemented by light brooming with a soft brush, or alternatively by using a surface retarder.

Concrete mixes may be 'modified' for exposed aggregate finishes, e.g. by increasing the proportion of the size of aggregate which it is desired to feature.

Where a 'special' aggregate is to be exposed, this is spread evenly over the levelled concrete and tamped into the surface which is then floated. After a delay to allow some hardening to take place, the cement paste on the surface is washed away to expose the aggregate. To ensure a durable surface, less than one third of the stones should be exposed.

10.6.8 Imprinting

Imprinting or 'pattern paving' provides a whole range of texturing possibilities including slate and brick look-alikes. The usual technique is for the concrete to be placed, compacted, bullfloated, and a coloured dry-shake topping applied. The surface is then covered with plastic sheeting and the patterning moulds are systematically stamped into the surface. On completion of stamping, the moulds and plastic are removed and the surface is lightly broomed and subsequently cured. It is common practice to apply a 'sealer' which helps provide a uniform colour and often gives a wet or polished look to the surface.

It should be noted, however, that skill and experience are generally necessary to achieve satisfactory results with this form of finish.

10.7 TOLERANCES AND FINISH SPECIFICATIONS

The tolerances specified for the surfaces of slabs or other flatwork should be appropriate to their final use. Achieving tight tolerances increases costs. It may be necessary, for example, to have tight tolerances in warehouses with high-racking bays but it would be unnecessarily expensive to have very tight tolerances for the loading dock areas where the delivery trucks are received.

NZS 3109 specifies floor tolerances to ensure that the structural behaviour is not impaired (it does not specify tolerances for the serviceability or usefulness of the floor.

Floors generally have to meet two independent tolerance criteria. One deals with the desired elevation and the other the 'flatness' of the floor.

The 'elevation tolerance' gives the permitted variation of the slab surface from a fixed external reference point or datum.

NZS 3114 specifies in more details the 'flatness tolerances'. This Standard sets out 11 different types of what it defines as 'unformed' finishes for slabs. These are designated U1 through to U11. The more common finishes used are described:

U1 Screeded

U2 Floated

U3 Trowelled – manual or machine steel trowelling

U4 Machine screeded

U5 Shallow texture – bristle broom

U6 Deep texture – wire broom.

Tolerances are set for the finishes which are considered normally achievable for the type of work. However, it may be necessary to have tighter tolerances in the aisles of premises using high-stacking forklift trucks. It has to be understood, however, that as the floor tolerances are reduced, then so the cost of producing the floor will be increased. An abrupt deviation of 3 mm is acceptable, except where floors are to receive thin sheet tiles such as vinyl or carpet.

The 'flatness tolerance' is most usually expressed in terms of a permitted deviation under a straightedge of specified length, usually 3 m.

The requirement for flatness given in NZS 3114 for most exposed concrete is:

- 5 mm maximum gradual variation under a 3 m straight edge
- 3 mm maximum abrupt variation under a 200 mm straight edge

This means the difference in elevation between the highest and lowest point under a 3 m long straight edge is permitted to be 5 mm, or similarly under a 200 mm long straight edge, the difference in height is permitted to be 3 mm.

A tolerance of 3 mm under a 3 m straightedge should be specified only for very high quality floors where flatness is a major functional requirement, for example in a warehouse where turret-type, high-stacking forklift trucks are used. The exact requirements for the project and the floor areas over which the tolerance applies should be clearly defined.

An American system based on ASTM E1155 to assess the accuracy of the floor profile in terms of an F_r number which is based on a flatness over 600 mm and a levelness over 3 m, it available for use where additional accuracy of floor profiles is necessary. Because of the accuracy of measurement equipment needed and the amount of data required the method should only be considered where extra-ordinary accuracy of flatness is required usually when using a sophisticated automatic storage and retrieval system of high level racking.

For pavements requiring very high tolerances (e.g. warehouses in which loosely stacked items are moved on forklift pallets), reference should be made to the CCANZ's TM 26 and TM 38 *Concrete Ground Floors and Pavements for Industrial and Commercial Use*[10.2], Parts 1 and 2 respectively and C&CAA's Industrial Floors and Paverments[10.3].

REFERENCES

10.1 Bowman, R. *An Introductory Guide to the Slip Resistance of Pedestrian Surface Materials* (HB 197) CSIRO and Standards Australia, 1999.

10.2 *Concrete Ground Floors and Pavements for Industrial and Commercial Use* : *Part 1* (TM26) Cement & Concrete Association of New Zealand, 1999. *Concrete Ground Floors and Pavements for Industrial and Commercial Use*: *Part 2* (TM 38) Cement & Concrete Association of New Zealand, 2001.

10.3 Industrial Floors and Pavements – Guidelines for design construction and specification (T48) Cement and Concrete Association of Australia, 1999.

ACKNOWLEDGEMENT

Figure 10.3, 10.4, 10.5 and 10.6 – Binding Concrete Limited, Hamilton, on behalf of the New Zealand Master Concrete Placers' Association.

Curing

Chapter 11

Chapter 11

Curing

This chapter discusses the curing of concrete, providing: first an outline of the hydration of cement, to highlight the fundamental importance of keeping concrete moist during its early life; then describing the effect of curing, or its lack, on the properties of concrete; and finally the methods which may be used to cure concrete under the wide variety of conditions met on building and construction sites. In this Guide, 'water curing' describes any method of curing designed to keep concrete moist during its early life by preventing the loss of moisture from it.

INTRODUCTION

Curing is the process or operation that controls the loss of moisture from concrete after it has been placed in position, or in the manufacture of concrete products, thereby providing time for the hydration of the cement to occur. Since the hydration of cement does take time (days, and even weeks, rather than hours) curing must be undertaken for some specified period of time if the concrete is to achieve its potential strength and durability. Curing may also encompass the control of temperature since this affects the rate at which cement hydrates.

The curing period will depend on the properties required of the concrete, the purpose for which it is to be used, and the ambient conditions, i.e. the temperature and relative humidity of the surrounding atmosphere.

Since curing is designed primarily to keep the concrete moist by preventing the loss of moisture from the concrete while it is gaining strength, it may be done in two ways:

- by preventing an excessive loss of moisture from the concrete for some period of time, e.g. by leaving formwork in place, covering the concrete with an impermeable membrane after the formwork has been removed, or by a combination of such methods; or
- by continuously wetting the surface thereby preventing the loss of moisture from it. Ponding or spraying the surface with water are methods typically employed to this end.

In the manufacture of concrete products, the temperature of the concrete may be raised to accelerate the rate of strength gain. Very importantly, the concrete must be kept moist during such treatment. Curing the concrete in saturated steam, or curing it with high-pressure steam in a suitable container, i.e. autoclaving it, are used to cure concrete at elevated temperatures. Other methods that are or have been employed include the use of flue or exhaust gases, the use of heated formwork, and electrical curing, but these are beyond the scope of this Guide. Some of these methods are used overseas in colder climates and reference can be made to overseas literature for information on them.

Relevant New Zealand Standards

NZS 3101 *Concrete structures*

NZS 3109 *Concrete construction*

Relevant Australian Standards

AS 3600 *Concrete structures*

AS 3799 *Liquid membrane-forming curing compounds for concrete*

11.1 HYDRATION OF CEMENT

11.1.1 General

When water is mixed with portland or blended cement a series of chemical reactions commence, which proceed rapidly at first, but then more slowly, for just about as long as moisture is present. These reactions result in new chemical compounds being formed which cause the cement paste first to stiffen, then to harden and gain strength.

We need not concern ourselves in this Chapter with the details of these reactions (for further information see Chapter 2 *Hydraulic Cements*), except to note the following:

- The different compounds in the cement react with water at different rates. Those which are responsible for the early stiffening of the paste and its early strength react quite rapidly but then contribute little to subsequent strength gain.
- Those compounds which contribute most to the strength of the paste and, hence, to the strength of the concrete, react more slowly. As a result, they require the paste to be kept moist until the concrete gains its strength.
- Allowing the paste to dry out causes the chemical reactions to cease (for all practical purposes). Whilst rewetting the paste causes the reactions to recommence, their effect on the subsequent strength and other desirable properties of the paste may be permanently impaired or reduced.

Figure 11.1 (page 11.3) provides a schematic representation of the chemical reactions which take place when water is mixed with cement, and the time-dependent nature of these reactions.

11.1.2 Effect of Temperature

The temperature of the cement paste can have a quite marked effect on the rate at which it hydrates. The temperature may also affect the nature of the new compounds formed and, hence, have a permanent effect on the long-term strength and durability of the concrete.

Thus, lower temperatures reduce the rate at which hydration occurs whereas high temperatures increase the rate of hydration, hence rate of strength gain, but reduce the potential strength of the concrete achieved at later ages.

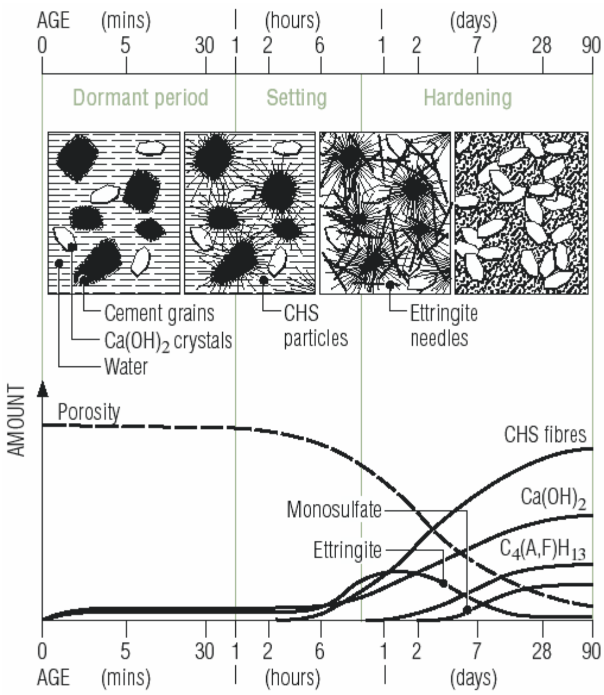


Figure 11.1 Schematic representation of chemical reactions when cement and water are mixed

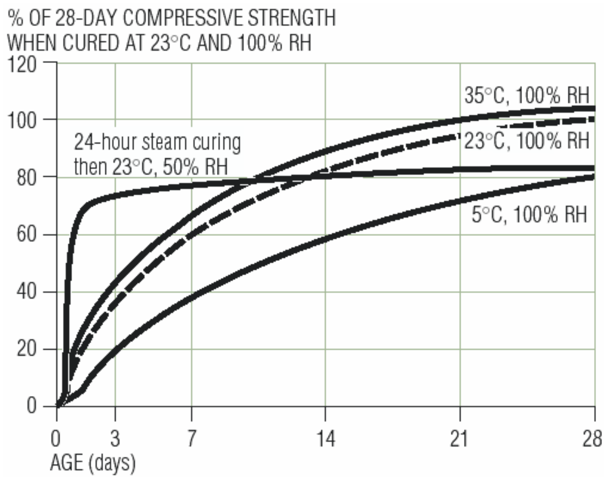


Figure 11.2 Effect of curing temperature on the rate of strength gain of concrete

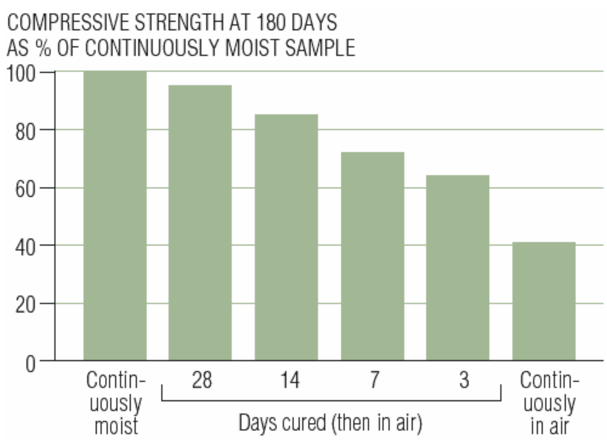


Figure 11.3 Effect of duration of water curing on strength of concrete

Figure 11.2 illustrates the effect of curing temperature on the rate of strength gain of concrete. The figure is illustrative only as the magnitude of temperature effects is very much related to the composition and fineness of the cement.

For practical purposes, however, it may be noted that, provided the temperature of the concrete is maintained within the normal range of ambient temperatures encountered in temperate zones of New Zealand and Australia, no significant harm will result to the strength of the concrete. For concrete operations outside this range, i.e. in very hot or very cold weather, special precautions may be necessary. These are discussed in Chapter 12 *Hot- and Cold-Weather Concreting*.

11.2 EFFECT OF DURATION OF CURING ON PROPERTIES OF CONCRETE

11.2.1 Effect on Strength

As will be discussed in Chapter 19 *Properties of Concrete*, the strength of concrete is affected by a number of factors, one of which is the length of time for which it is kept moist, that is, cured. **Figure 11.3** illustrates this, comparing the strength (at 180 days) of a concrete which has been:

- kept moist for 180 days;
- kept moist for various periods of time and allowed to dry out; and
- allowed to dry out from the time it was first made.

As may be seen in this example, concrete allowed to dry out immediately achieves only 40% of the strength of the same concrete water cured for the full period of 180 days. Even three days water curing increases this figure to 60%, whilst 28 days water curing increases it to some 95%. Keeping concrete moist is, therefore, a most effective way of increasing its ultimate strength.

11.2.2 Effect on Durability

The durability of concrete is affected by a number of factors including its permeability and absorptivity (see Chapter 19 *Properties of Concrete*). Broadly speaking, these are related to the porosity of the concrete and whether the pores and capillaries are discrete or interconnected. Whilst the number and size of the pores and capillaries in cement paste are related directly to its water-cement ratio, they are also related, indirectly, to the extent of water curing. Over time, water curing causes hydration products to fill, either partially or completely, the pores and capillaries present, and, hence, to reduce the porosity of the paste.

Figure 11.4 illustrates the effect of different periods of water curing on the permeability of cement paste. As may be seen, extending the period of curing reduces the permeability.

Whilst it is absolutely essential that concrete be kept moist for as long as practicable if it is to achieve its potential strength and durability, in practice it is often left uncured or, at best, cured for a very short period of time. This is bad practice since, inevitably, it results in the concrete performing less well than it might otherwise have done. Whilst the effects of inadequate curing are often difficult to determine in the short term, defects such as poor abrasion resistance (wear and dusting of floors), unexpected cracking and crazing, and corrosion of reinforcement, are typical of the results of such bad practice.

On the other hand, the cost of delays to the job, or other factors such as the safety of those on site, may dictate that curing regimes be maintained for the minimum period necessary for the concrete to achieve its specified properties. Where these properties cannot be specified precisely, for example concrete durability, some intelligent estimate must be made of a minimum curing period.

To safeguard the general quality of concrete construction, NZS 3101/NZS 3109 sets out the minimum periods for which concrete must be cured. These vary with the strength of the concrete and the conditions to which it will be exposed. These periods range from three days for the lower strength concretes to seven days for the higher strength concretes and more severe exposure conditions **Table 11.1**. The XA exposure series relate specifically to concretes for chemical durability resistance.

Using water sorptivity as a measure of concrete durability, **Figure 11.5** illustrates the effect of the duration of curing for Grade 25 concrete cured in timber formwork. This shows the very significant benefit of curing for up to three days, the lesser benefit of extending the curing for up to seven days, and the minimal benefit of extending it beyond that.

11.3 CURING METHODS

11.3.1 General

Methods of curing concrete fall broadly into three categories:

- Those which minimise moisture loss from the concrete by covering it with a relatively impermeable membrane.
- Those which prevent moisture loss by continuously wetting the surface of the concrete.
- Those which keep the surface moist and, at the same time, raise the temperature of the concrete, thereby increasing the rate of strength gain.

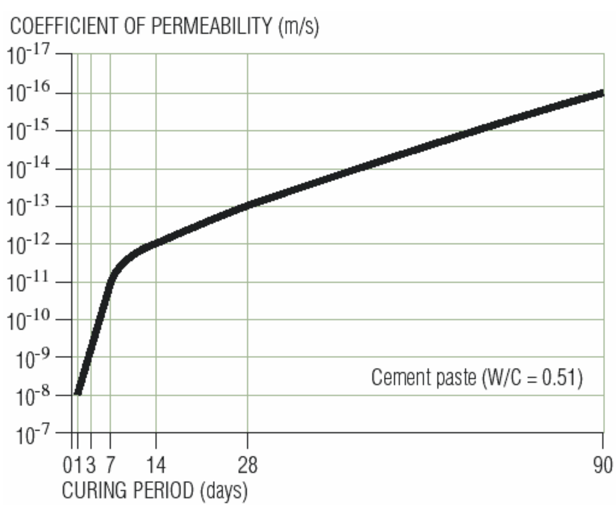


Figure 11.4 **Effect of duration of water curing on the permeability of cement paste**

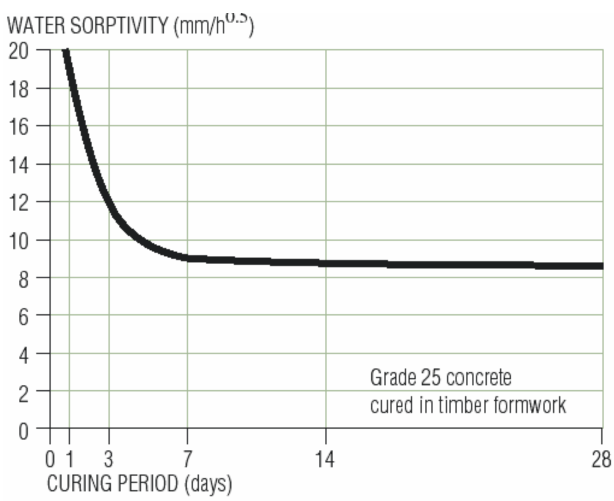


Figure 11.5 **Effect of duration of curing on water sorptivity of concrete**

Table 11.1 **Minimum initial continuous curing periods (based on Clauses NZS 3101 and NZS 3109)**

Exposure classification		Minimum f'$_c$ at 28 days (MPa) of w/c ratio	Minimum period initial continuous curing (days)
Mild	A1/A2/B1	20	3
	B2	30	7
Severe	C	40-45	7*
	XA1	0.50 w/c	3
	XA2	0.45 w/c	7*
	XA3	0.40 w/c	7*

* direct water curing such as ponding, continuous sprinkling or continuous mist spray.

11.3.2 Impermeable-Membrane Curing

Formwork

Leaving formwork in place is often an efficient and cost-effective method of curing concrete, particularly during its early ages. In very hot dry weather, it may be desirable to moisten timber formwork, to prevent it drying out during the curing period, thereby increasing the length of time for which it remains effective.

It is desirable that any exposed surfaces of the concrete (e.g. the tops of beams) be covered with plastic sheeting or kept moist by other means. It should be noted also that, when vertical formwork is eased from a surface (e.g. from a wall surface), its efficacy as a curing membrane is significantly reduced.

Plastic Sheeting

Plastic sheets, or other similar material, form an effective barrier against water loss, provided they are kept securely in place and are protected from damage. Their effectiveness is very much reduced if they are not kept securely in place.

They should be placed over the exposed surfaces of the concrete as soon as it is possible to do so without marring the finish. On flat surfaces, such as pavements, they should extend beyond the edges of the slab for some distance, e.g. for at least twice the thickness of the slab, or be turned down over the edge of the slab and sealed.

For flatwork, sheeting should be placed on the surface of the concrete and, as far as practical, all wrinkles smoothed out to minimise the mottling effects, due to uneven curing, which might otherwise occur. Flooding the surface of the slab under the sheet is a useful way to prevent mottling. Strips of wood, or windrows of sand or earth, should be placed across all edges and joints in the sheeting to prevent wind from lifting it, and also to seal in moisture and minimise drying.

For vertical work, the member should be wrapped with sheeting and taped to limit moisture loss. Where colour of the finished surface is a consideration, the plastic sheeting should be kept clear of the surface to avoid hydration staining. This can be achieved with wooden battens or even scaffolding components, provided that a complete seal can be achieved and maintained.

Care should also be taken to prevent the sheeting being torn or otherwise damaged during use. A minimum thickness is required to ensure adequate strength in the sheet; ASTM C171 Sheet Materials for Curing Concrete specifies 0.10 mm. **Figure 11.6** illustrates the lack of effectiveness of plastic sheeting with holes representing only 1.7% of the sheet's surface area.

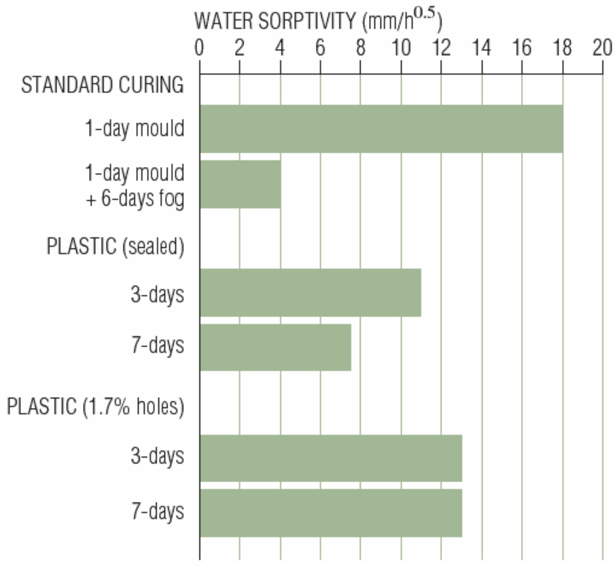


Figure 11.6 **Effectiveness of plastic sheeting**

Plastic sheeting may be clear or coloured. Care must be taken that the colour is appropriate for the ambient conditions. For example, white or lightly coloured sheets reflect the rays of the sun and, hence, help to keep concrete relatively cool during hot weather. Black plastic, on the other hand, absorbs heat to a marked extent and may cause unacceptably high concrete temperatures. Its use should be avoided in hot weather, although in cold weather its use may be beneficial in accelerating the rate at which the concrete gains strength.

Clear plastic sheeting tends to be more neutral in its effect on temperature (except in hot weather, where it fails to shade the surface of the concrete) but tends to be less durable than the coloured sheets, thereby reducing its potential for re-use.

Curing Compounds

Curing compounds are liquids which can be brushed, sprayed, or squeegeed (usually sprayed) directly onto concrete surfaces and which then dry to form a relatively impermeable membrane which retards the loss of moisture from the concrete. Their properties and use are described in AS 3799 and NZS 3109 requires compliance with ASTM C309-95.

They are an efficient and cost-effective means of curing freshly placed concrete or that which has been partially cured by some other means. However, they may affect the bond between concrete and subsequent surface treatments. Special care in the choice of a suitable compound needs to be exercised in such circumstances.

Curing compounds are generally formulated from wax emulsions, chlorinated rubbers, synthetic and natural resins, and from PVA emulsions. Their effectiveness varies quite widely, depending on the material and strength of the emulsion, as is illustrated in **Figure 11.7**.

When used to cure fresh concrete, the timing of their application is critical for maximum effectiveness. They should be applied to the surface of the concrete after it has been finished, as soon as the free water on the surface has evaporated and there is no water sheen visible. Applying too early dilutes the membrane; too late results in it being absorbed into the concrete and not forming a membrane.

They may also be used to reduce moisture loss from concrete after initial moist curing or the removal of formwork. In both cases, the surface of the concrete should be thoroughly moistened before the application of the compound to prevent its absorption into the concrete.

Curing compounds can be applied by hand spray, power spray, brush or roller. The type or grade of curing compound should be matched to the type of equipment available and the manufacturer's directions followed. The rate of application should be uniform with coverage normally in the range 0.20 to 0.25 L/m^2. Where feasible, two applications applied at right angles to each other will help ensure complete coverage.

Pigmented compounds also help ensure complete coverage and are advantageous in helping concrete surfaces reflect rather than absorb heat. **Figure 11.8** shows pressure spraying of a white-pigmented curing compound.

Finally, it should be noted that many curing compounds are solvent-based. Adequate ventilation should always be provided in enclosed spaces and other necessary safety precautions taken. Manufacturer's recommendations should always be followed.

11.3.3 Water Curing

General

Water curing is carried out by supplying water to the surface of concrete in a way which ensures that it is kept continuously moist.

The water used for this purpose should not be more than about 5°C cooler than the concrete surface. Spraying warm concrete with cold water may give rise to 'thermal shock' which may cause or contribute to cracking. Alternate wetting and drying of the concrete must also be avoided as this causes volume changes which may also contribute to surface crazing and cracking.

Ponding

Flat or near-flat surfaces such as floors, pavements, flat roofs and the like may be cured by ponding. A 'dam' or 'dike' is erected around the edge of the slab and water is then added to create a shallow 'pond' **Figure 11.9**.

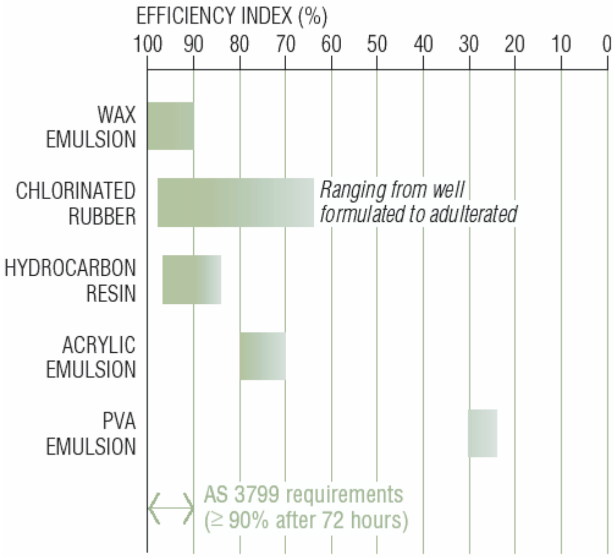


Figure 11.7 **Comparative efficiency of curing compounds**

Figure 11.8 **Spray application of curing compound**

Figure 11.9 **Ponding method of water curing**

Ponding is a quick, inexpensive and effective form of curing when there is a ready supply of good 'dam' material (e.g. clay soil), a supply of water, and the 'pond' does not interfere with subsequent building operations. It has the added advantage of helping to maintain a uniform temperature on the surface of the slab.

Care should be taken that material used for the dam does not stain or discolour the concrete surface.

Sprinkling or Fog Curing

Using a fine spray or fog of water can be an efficient method of supplying additional moisture for curing and, during hot weather, helps to reduce the temperature of the concrete.

As with other methods of moist curing, it is important that the sprinklers keep the concrete permanently wet. However, the sprinklers do not have to be on permanently; they may be controlled by an intermittent timer.

Sprinklers require a major water supply, can be wasteful of water and will probably need a drainage system to handle runoff. This will usually be required to be a 'closed' system where the water is collected and recycled.

Sprinkler systems may be affected by windy conditions and supervision is required to see that all of the concrete is being kept moist and that no part of it is being subjected to alternate wetting and drying. This is not always easy to achieve.

Wet Coverings

Fabrics such as hessian, or materials such as sand, can be used like a 'mulch' to maintain water on the surface of the concrete. The fabric or sand is kept wet with hoses or sprinklers. On flat areas, fabrics may need to be weighed down. Also, it is important to ensure that the whole area is covered.

Wet coverings should be placed as soon as the concrete has hardened sufficiently to prevent surface damage.

Fabrics may be particularly useful on vertical surfaces since they help distribute water evenly over the surface and, even where not in contact with it, will reduce the rate of surface evaporation. Care should be taken, however, that the surface of the concrete is not stained, perhaps by impurities in the water, or by the covering material.

11.3.4 Accelerated Curing

General

Accelerated curing of concrete is designed to increase or accelerate the rate at which the concrete gains strength. Invariably it involves some method of increasing the temperature of the concrete in a controlled way. Control of the rate at which the concrete heats (or cools) is critical to avoid potentially severe losses in ultimate strength and/or cracking of the concrete due to thermal shock.

It is also critical that exposed surfaces of the concrete be kept moist during the curing regime.

Steam Curing

Low pressure steam curing, the application of saturated steam to concrete in suitable
chambers or under removable covers, to heat it and, hence, accelerate the rate of strength gain, is widely used in the precast concrete industry. Its cost is justified by the resulting more rapid turnaround of formwork and, hence, greater productivity. Strict control of the steaming cycle is critical ***Figure 11.10***. A detailed discussion of this is beyond the scope of this Guide and readers are referred to the Concrete Institute of Australia's Recommended Practice[11.1] for more information.

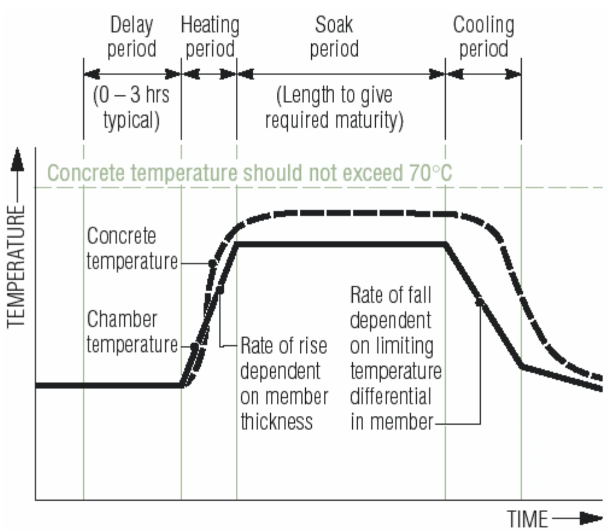


Figure 11.10 **Typical steam-curing cycle**

Autoclaving Curing with high pressure steam, or autoclaving, refers to the curing of certain concrete products in an atmosphere of saturated steam at temperatures in the range 160–190°C and steam pressures in the range 6–20 atmospheres.

It is a specialised process requiring quite expensive equipment. Its use is therefore limited, although it is often employed in the manufacture of lightweight aerated concrete products to improve their strength and dimensional stability. **Figure 11.11** (page 11.8) shows high-pressure steam curing of concrete blocks (which is a typical use for this method).

Autoclaving modifies the normal chemical reactions which occur when cement hydrates. Specifically, it causes the lime generated by hydrating cement to combine with any finely divided silica which may be present. Advantage is generally taken of this reaction by replacing up to 30–40% of the cement with a reactive silica to improve both the strength and durability of the resulting product. More-detailed information on high-pressure steam curing may be obtained from the ACI Publication SP-32[11.2].

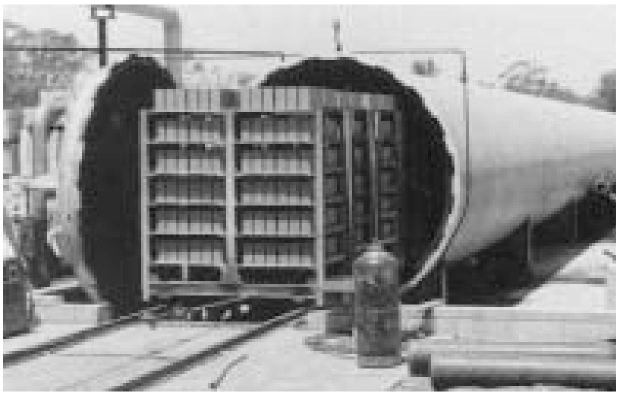


Figure 11.11 Autoclaving concrete blocks

11.4 SELECTING A METHOD OF CURING

Curing is one of the critical procedures which determines whether concrete will reach its potential strength and durability. Whilst site conditions may often indicate that curing will be inconvenient (it is at best a messy procedure), only very rarely will the cost savings resulting from failure to cure outweigh the very real damage which will be done to the long-term strength and durability of the concrete by its neglect. It is always feasible to choose a method of curing which will be both effective and economic. It should be automatic to do so.

The factors which affect the selection of a curing method include:

- the type of member to be cured, e.g. slab, column, wall, etc
- the specified finish for the concrete member, e.g. will the 'bond' of a subsequent layer or finish be affected by the application of a curing compound?
- whether the curing process will influence the appearance of the concrete?
- the construction schedule for the project, e.g. will work need to continue in the area during the curing period?
- the cost and availability of materials, e.g. is water available and how much will it cost?
- safety restrictions, e.g. are there any restrictions which may mean some methods are not appropriate for health or safety reasons, e.g. toxic fumes in an enclosed space, slippery surfaces from plastic sheeting.
- weather conditions, exposure and location.

REFERENCES

11.1 *Recommended Practice: Curing of Concrete* (Z9) 2nd edition, Concrete Institute of Australia, 1999.

11.2 *Menzel Symposium on High Pressure Steam Curing*, American Concrete Institute Publication SP-32, 1972.

Summary

CONSIDERATIONS FOR SELECTING A CURING METHOD

General	Type of member	Is the member vertical or horizontal? Some methods are affected or excluded by orientation, e.g. ponding. Is the member thin or thick? Thick sections such as large columns or mass concrete are mostly 'self-curing' but require temperature gradient at outer layers to be limited. Is the member insitu or precast? Precast members are suited to low-pressure steam curing while precast products may benefit from autoclaving.
	Environment	Does the location affect the availability or cost of some curing materials? e.g. water in an arid region. Is the weather likely to be hot or cold? If the temperature is higher than about 30°C or less than 10°C special precautions need to be taken. Is the site exposed to winds? If so, special precautions may be required to prevent plastic shrinkage cracking; sprinkling methods may be affected; or extra care required when using plastic sheeting.
Impermeable membrane curing	Retention of formwork	What is the effect on site operations and construction cycle schedule? Is there likely to be cold weather? This method allows easy addition of insulation. Is uniform concrete colour specified? If so, a constant stripping time will need to be maintained to avoid hydration colour change.
	Plastic sheeting	What is the effect on access and site operations? Is there a safety consideration? Plastic sheeting may be slippery, and therefore a hazard in horizontal applications. Is there likely to be hot or cold weather? Colour of sheeting should be selected to suit. Is the situation such that the seal can be maintained with minimum risk of holing? Is uniform concrete colour specified? If so, the sheeting must be kept clear of the surface to avoid hydration staining.
	Curing compounds	What are the manufacturer's recommendations? Both the rate of application and the timing are critical for effectiveness. What is the concrete surface texture? Coarse textures require higher application rates. Can a uniform application be achieved in the particular situation? Two applications at right-angles help. Sites exposed to wind create problems. Is there likely to be hot or cold weather? A suitably pigmented compound can help. Are there to be applied finishes (render, tiles, etc)? Compounds can affect the 'bond' of applied finishes. Is there a health consideration? Compounds may be toxic, and their use in enclosed situations therefore hazardous.

Summary *(Considerations for selecting a curing method continued)*

Water curing	Ponding	What is the effect on access and site operations? Is suitable 'dam' material available? A clay soil is the most suitable. Is there likely to be hot weather? Ponding is an efficient means of maintaining a uniform temperature on slabs. Is concrete colour or appearance a consideration? 'Dam' materials, particularly clay, tend to stain.
	Sprinkling	What is the effect on site operations? Is there an adequate water supply? What is effect of run-off? Usually some form of drainage is required. Will required volume/timing be such as not to damage the concrete surface? Can application be maintained continuously? Intermittent wetting and drying can be deleterious. Is site exposed to winds? This makes continuous application very difficult.
	Wet coverings	What is the effect on site operations? Can they effectively cover all surfaces? Is site exposed to wind? Wet coverings are easier to keep in place than plastic sheeting. Is concrete colour or appearance a consideration? If so, sand should have low clay content; fabrics and water should contain no impurities. In the case of sand, is supply or removal a problem? Can coverings be kept continuously moist? Intermittent wetting and drying can be deleterious.
Accelerated curing	Low-pressure steam curing	What is the effect on the production cycle? Will there be a cost benefit through greater productivity? This usually results from quicker turnaround of formwork. Is high early strength required? Steam curing can help in achieving this.
	Autoclaving	Will the process increase productivity? Will the process increase quality? Does the product require the process?

Hot and Cold Weather Concreting

Chapter 12

Chapter 12

Hot and Cold Weather Concreting

This chapter contains information on the precautions which should be taken when concreting operations have to be carried out in either very hot or very cold weather. Whilst what constitutes hot and cold weather is nowhere specifically defined, however, it is usual that concrete temperatures at the point of delivery be within the range 5°C to 35°C. Precautions will always be necessary when air temperatures lie outside this range, but may well be necessary even when they lie within it. Special care may need to be taken when the air temperature is less than 10°C or more than 30°C. A knowledge of the effect of high and low concrete-temperatures on the properties of concrete will enable sensible decisions to be made on when and what precautions are necessary.

INTRODUCTION

It is generally well recognised that when concrete has to be mixed and placed in either very hot or very cold weather, it is necessary to take precautions to ensure that it is not damaged or adversely affected by the ambient weather conditions. At temperatures below freezing, for example, freshly placed concrete may be damaged by the formation of ice within its pore structure. In very hot weather the concrete may stiffen prematurely preventing it from being compacted and finished properly, or the temperature of the concrete may rise to the point where thermal cracking occurs as it cools.

It is perhaps not so well recognised, however, that even at moderate air temperatures, strong dry winds can cause concrete to dry out prematurely and to crack.

There are few fixed rules, therefore, on what constitutes hot or cold weather in respect of concreting operations. NZS 3109 requires that concrete temperatures at the point of delivery be within the range 5°C to 35°C. Precautions will always be necessary when air temperatures lie outside this range.

They may well be necessary, however, at air temperatures within this range, at less than 10°C or more than 30°C, say. At the lower temperatures, the concrete, whilst in no danger of freezing, may take an excessively long time to gain its specified strength. At the higher temperatures, particularly if accompanied by hot dry winds, plastic cracking and premature stiffening of the concrete may take place.

This chapter aims to provide guidance therefore: first on the effects of high and low temperatures on the properties of concrete; then, in the light of these effects, on the precautions which should be taken when air temperatures fall outside the range, say 10°C to 30°C, or when strong dry winds prevail.

Relevant New Zealand Standards

NZS 3109 *Concrete construction*

Relevant Australian Standards

AS 1379 *The specification and supply of concrete*

AS 3600 *Concrete structures*

12.1 CONCRETING IN HOT WEATHER

High air temperatures, particularly when combined with strong dry winds, can affect the quality of both fresh and hardened concrete in a number of ways:

- By heating the constituent materials, notably the aggregates, they can increase the temperature of the freshly mixed concrete to the point where slump loss, increased water demand, and reduced setting times may occur.
- By causing the surface of the concrete to dry prematurely, they can cause cracking, even before the concrete has stiffened and begun to harden – this is known as plastic cracking.
- By accentuating the temperature rise in concrete caused by the hydrating cement, particularly in massive sections, they give rise to thermal shock (cracking) when the concrete subsequently cools.

12.1.1 Effect of High Concrete Temperatures

As the temperature of concrete rises, the setting time is reduced and the time available in which to place, compact and finish it is also reduced. More water is often added to the mix to maintain or restore workability with a consequent loss in both potential strength and durability. Where water is not added, the reduced setting time increases the dangers of incomplete compaction, the formation of cold joints or poor finishes **Figures 12.1 and 12.2** (page 12.3).

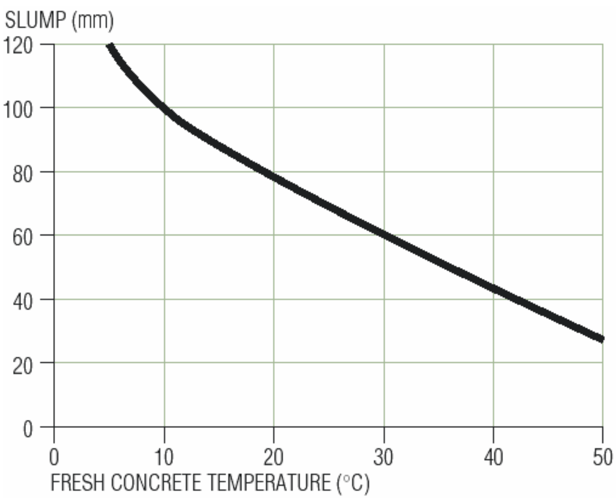


Figure 12.1 **Decrease in workability of fresh concrete (as measured by slump), made with constant water content, as temperature increases**

Even when potential strength and durability are maintained, by the addition of cement to the mix for example, the final strength of the concrete may be reduced by the higher temperatures **Figure 12.3**. It may be noted that, whereas increased concrete temperatures result in an increase in the early rate of strength gain, in the longer term, concretes cured at the lower temperatures achieve higher ultimate strength (see also **Figure 12.7**). Curing concrete at temperatures between 10°C and 25°C tends to achieve optimum results.

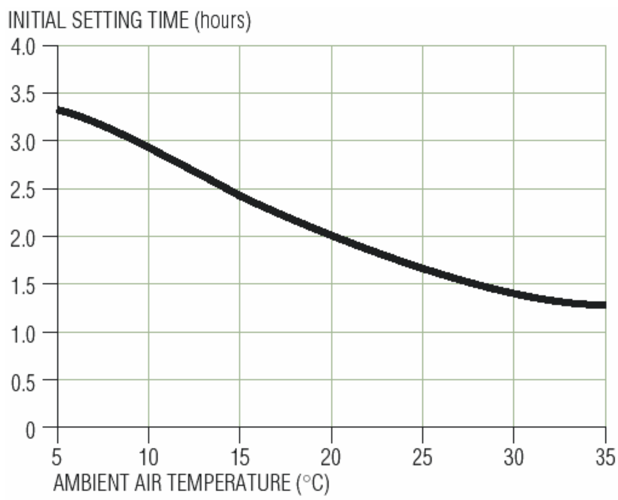


Figure 12.2 Influence of air temperature on setting times of concrete made with Type GP cement

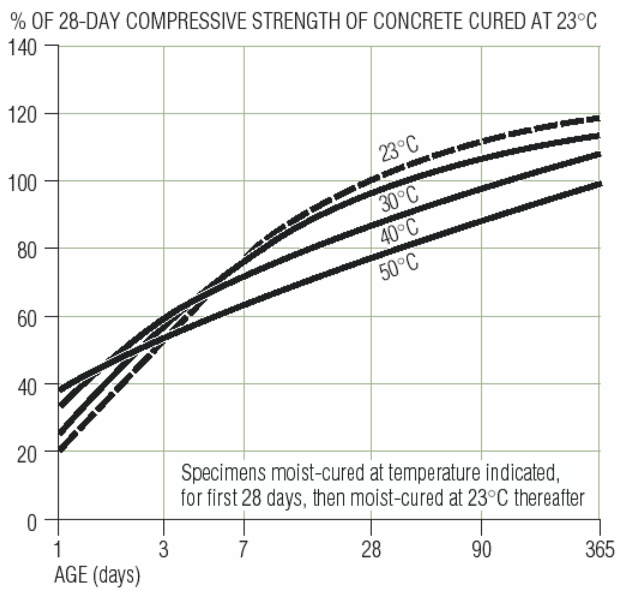


Figure 12.3 Effect of high curing temperatures on concrete compressive strength

12.1.2 Controlling Concrete Temperature

Estimating the Temperature of Fresh Concrete

The temperature of fresh concrete may be estimated from the following equation:

$$T = T_aW_a+T_cW_c+5T_wW_w/W_a+W_c+5W_w$$

where

- T = temperature of the freshly mixed concrete in (°C)
- T_a = temperature of the aggregates in (°C)
- T_c = temperature of the cement in (°C)
- T_w = temperature of the mixing water in (°C)
- W_a = mass of aggregates including free moisture (kg)
- W_c = mass of cement (kg)
- W_w = mass of mixing water (kg)

(*Note:* This equation gives approximate results only but is sufficiently accurate for practical purposes. For more accurate results a knowledge of the specific heats of the constituent materials is necessary.)

By substituting typical mix proportions in the above equation it may be readily seen that the aggregates (and their temperature) have a dominating effect on the temperature of freshly mixed concrete. Next in significance is the temperature of the mixing water, whilst the cement has a minor effect unless, as may infrequently occur, its temperature is much higher than those of the other materials.

If the temperature of the cement and the aggregate are assumed to be the same, a quick approximation of the concrete temperature may be obtained from the chart in **Figure 12.4**.

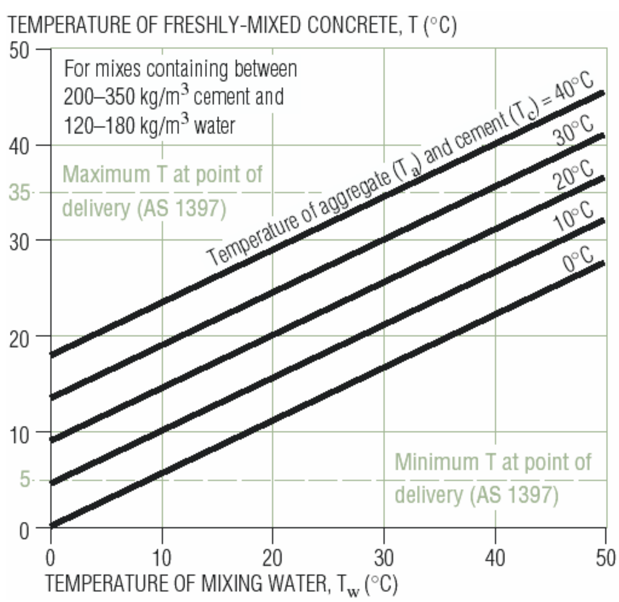


Figure 12.4 Estimation of the temperature of freshly mixed concrete made with Type GP cement

Aggregates

As the temperature of the aggregates is the most significant, measures taken to limit it have the greatest effect in minimising the temperature of freshly mixed concrete. Shading stockpiles from the sun and/or keeping them moist with sprinklers are commonly used means of reducing the temperature of aggregates. Storage in bins (painted white) will also assist.

Water sprays, continuously applied as a fine mist, are particularly effective and serve also to suppress dust in hot, dry and windy conditions. Adequate provision for drainage and/or recycling of the water must be made, however, to prevent the storage site becoming unworkable. A continuous spray is preferable to intermittent spraying in order to maintain a constant moisture content in the aggregates and thus to avoid variations in the water-cement ratio of the concrete.

Water

The temperature of the mixing water may have a significant effect on the temperature of the concrete. For example, if stored on site in tanks unprotected from the sun it may become quite hot. Conversely, if cooled by refrigerating the water supply or by adding crushed ice to it, it will serve to lower the temperature of the concrete and offset higher temperatures in the other materials.

More normally, of course, water will be drawn from town water supplies. In such cases, reticulation lines should be shaded and lagged to protect them against solar radiation. Intermediate surge or storage tanks should be similarly protected.

Cement

The temperature of cement does not usually contribute significantly to the temperature of freshly mixed concrete because of its low specific heat combined with its relatively small mass in the mix. Nevertheless, unnecessary rises in temperatures should be avoided by painting silos white or other reflective colours.

The type of cement will affect the properties of the freshly mixed concrete, however, and advantage of this may be taken in some situations. Blended cements and low heat cements, for example, may provide additional time for placing and finishing, depending on the proportion of fly ash and/or slag used in the mix.

The use of rapid-hardening cement should be avoided except where very rapid strength gain is essential.

Admixtures

Admixtures are very helpful in offsetting the effects of hot weather and high concrete temperatures. They may be used to improve the workability of the concrete without the addition of extra water and to retard setting.

Admixtures do not offset the other ill-effects of high concrete temperatures. They do not replace, therefore, appropriate techniques for cooling constituent materials nor those for transporting, placing and curing the concrete.

Liquid Nitrogen Injection

For large and important pours where temperature control is critical, cooling may be achieved by injecting liquid nitrogen directly into the mixer or agitator truck **Figure 12.5**.

Figure 12.5 **Injection of liquid nitrogen into an agitator truck to lower concrete temperature**

The quantity of nitrogen is adjusted to the temperature of the constituent materials and, in this way, effective control of temperature is maintained. Injection lances, storage tanks, etc are available from the suppliers of industrial gases.

12.1.3 Batching, Mixing and Transporting

To minimise the effect of high ambient temperatures on the concrete during the batching, mixing and transporting operations a number of simple precautions should be taken:

- All handling equipment such as chutes, conveyors and pump lines, should be either enclosed or alternatively shaded and painted white or with a reflective colour.
- Site mixers themselves should be shaded and/or painted white.
- Transport from the mixer to the site, and on the site itself, should be planned carefully to minimise transport time and avoid unnecessary

delays. Transit mixer trucks should be discharged as soon as possible after the water has been added to the mix. Prolonged mixing should be avoided.

Fortunately, these precautions tend to coincide with the need, in urban areas at least, to minimise noise and dust pollution of the environment.

12.1.4 Placing and Compacting

Formwork and Reinforcement

Wherever possible, subgrades, formwork and reinforcement should be shaded to minimise surface temperatures but in any event should be cooled by spraying with water prior to concrete being placed. A fine mist spray is well suited to this purpose but care must be taken that water does not collect on the subgrade or in the forms. Surfaces at the time of concreting should preferably be damp but not wet.

Placement

As far as practical, concrete placement should be carried out in the cooler parts of the day. For most of Australia and New Zealand these are in the early morning. This permits the concrete to be finished in the natural light and for curing to commence immediately.

In very hot areas night-time pours may be advantageous, particularly in mass concrete structures. Because the time during which the concrete remains workable is generally reduced in hot weather, the provision of stand-by equipment and/or additional manpower to eliminate delays due to breakdowns becomes more crucial.

Placing of slabs should be organised so that a 'minimum' front is employed to which fresh batches of concrete are added. Concrete walls and deep beams should similarly be placed in shallow layers to avoid the 'cold joints' which occur when fresh concrete is placed against concrete already stiffened.

12.1.5 Finishing and Curing

Finishing

Two separate, albeit related, problems may be experienced in finishing concrete during hot, dry and windy conditions.

The time available in which to finish the concrete is generally reduced under these conditions. Finishing operations should therefore be carried out promptly once the water sheen has disappeared from the surface and it is strong enough to support the weight of a man. Temporary sunshades and windbreaks will assist to lengthen the time during which finishing can be done.

The second problem which may occur in hot, dry, windy conditions, or, indeed, even at moderate temperatures with strong dry winds, is known as plastic cracking. This can occur when the surface of the freshly placed concrete is allowed to dry out rapidly, generally before the body of the concrete has had time to take its initial set.

Under these conditions, fine cracks may open in the surface of the concrete. Whilst they may be closed over during finishing operations, they constitute a line of weakness in the surface and will very often open up again as the concrete dries out following curing operations. Special care may be necessary to prevent this occurrence. Necessary precautions are further discussed below (see Clause 12.1.6 *Plastic Cracking* below).

Curing

Curing should commence as soon as practical to prevent moisture being lost prematurely from unformed concrete surfaces.

Whilst the concrete is still plastic and unable to be cured by conventional means (see Chapter 11 **Curing*****) loss of moisture due to evaporation can be minimized by spraying the surface of the concrete with an aliphatic alcohol, available from manufacturers of concrete admixtures. It forms a thin film over the surface of the wet concrete which reduces evaporation by up to 80% in windy conditions without interfering with subsequent finishing operations. The technique is particularly useful in the prevention of plastic cracking. As soon as the concrete has hardened sufficiently, normal curing procedures should commence.***

In hot, dry conditions, water curing is the preferred method because it not only ensures that the concrete is kept moist but also assists in cooling the concrete whilst it hardens and gains strength. The use of a wet covering, such as hessian, is particularly useful for this purpose as it also shades the concrete. It should be kept continually wet with a fine mist of water (which minimises water usage) or more simply, perhaps, with soaker-hoses. Care should be taken that the temperature of the water is not higher than that of the concrete, the result, perhaps, of exposed reticulation lines. Where adequate water supplies are available water curing should be maintained for at least seven days.

In situations where water is not readily available, or even when site conditions are not favourable, every effort should be made to water cure for at least 24 hours. It should be followed immediately by some other form of curing, e.g. the application of a suitable curing compound or the use of a membrane such as plastic sheeting.

Where the latter is used in hot, windy weather it is essential that it be well secured and anchored at edges and joints lest much of its effectiveness be lost. There is always the danger also that the sheeting will be torn loose by strong winds.

12.1.6 Plastic Cracking

Plastic cracking, the formation of cracks in the surface of the concrete before it has taken its initial set, may be caused in a number of ways:

- By drying out of the surface of the concrete before the body of the concrete has set.
- By settlement of the concrete around reinforcing bars, aggregate particles or other obstructions.
- By settlement or movement of the formwork.

Cracks caused by settlement of the concrete and/or the formwork are discussed in Chapter 14 *Control of Cracking.*

Plastic Shrinkage Cracking

Plastic shrinkage cracks, i.e. cracks caused by too rapid drying out of the surface, most often occur in hot, dry, windy conditions but are not unknown in even quite moderate temperatures if the wind velocity is high enough and/or the relative humidity is low. The primary cause is always the too rapid loss of moisture from the surface of the concrete.

Figure 12.6 may be used to estimate the likelihood of plastic shrinkage cracking occurring and, hence, the need for suitable precautions to be taken. As may be seen, the factors which affect the rate of evaporation of moisture from the surface include:

- air temperature;
- relative humidity;
- concrete temperature;
- wind velocity.

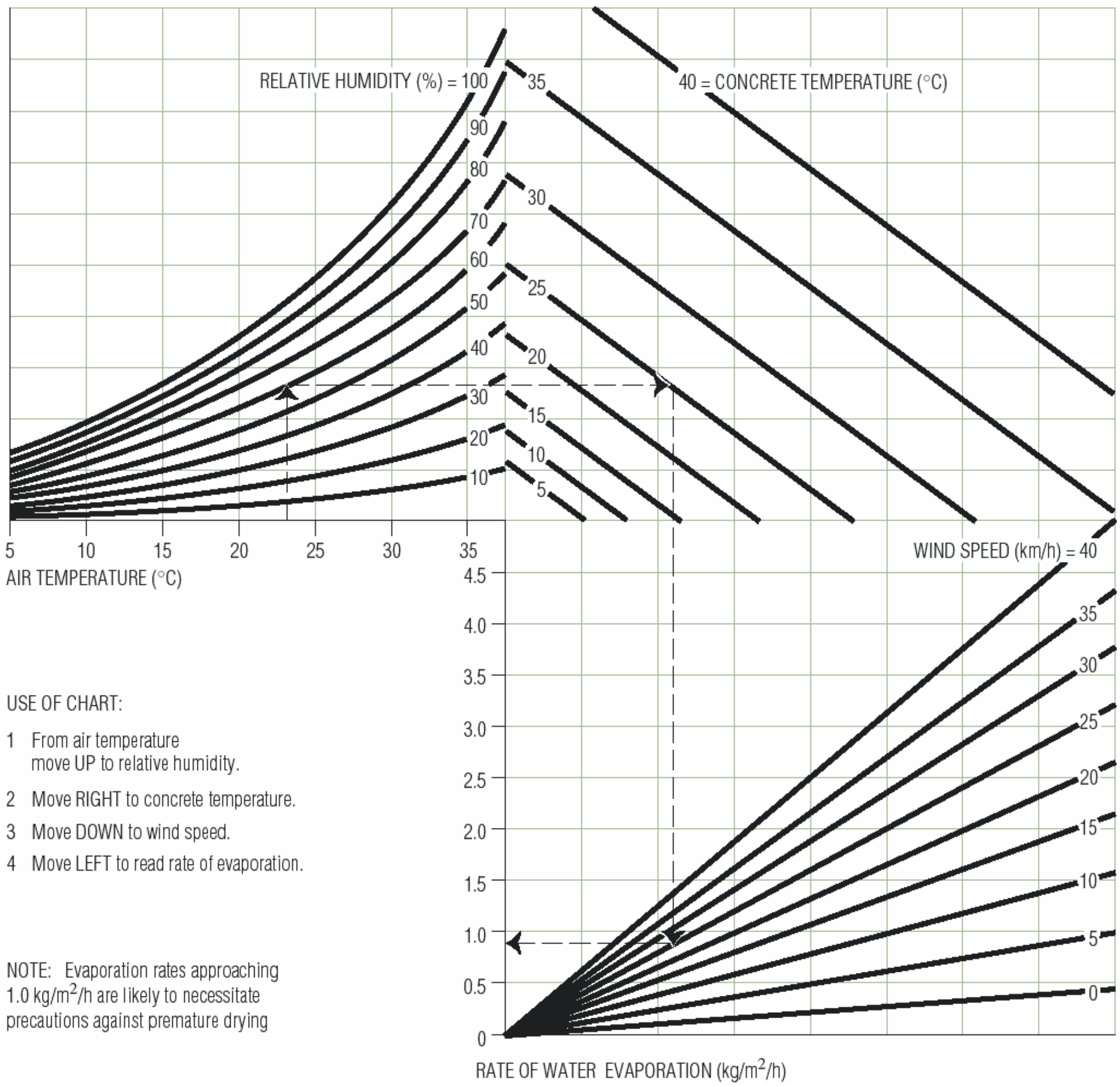


Figure 12.6 **Effect of concrete and air temperatures, relative humidity and wind velocity on the rate of evaporation of surface moisture from concrete (after ACI 305, 1999[12.1])**

Where these factors combine to produce a rate of evaporation greater than 1 $kg/m^2/h$, then plastic shrinkage cracking is likely and precautions should be taken. As may be noted, high air temperatures are not necessary for this to occur; concrete temperature and wind velocity have a greater effect.

An alternative to using the nomograph in **Figure 12.6** is the equation shown below. Both are based on evaporation from a water surface and are not applicable after bleed water, the sheen, disappears from the surface.

Alternative equation to calculate evaporation rate[12.2]

$$E = 5([T_c + 18]^{2.5} - r[T_a + 18]^{2.5})(V + 4) \times 10^{-6}$$

where

E = evaporation rate, $kg/m^2/h$
r = Relative Humidity/100
T_a = air temperature, °C
T_c = concrete (water surface) temperature, °C
V = wind velocity, km/h

Precautions

The most effective way to reduce the risk of plastic shrinkage cracking is to prevent rapid loss of moisture from the surface of the concrete. Practices to achieve this are:

- Dampen subgrade and forms ensuring any excess water is removed prior to placing concrete.
- In hot weather, lower the temperature of the fresh concrete by using cool aggregates and chilled mixing water.
- Add polypropylene fibres to the concrete mix[12.3].
- Erect wind breaks to reduce wind velocity over the concrete surface.
- ***Use aliphatic alcohols sprayed over the surface prior to and after finishing before curing can commence to reduce rate of evaporation from the surface.***
- Commence curing promptly after finishing is complete and ensure the surface is subject to continuous curing.

Revibration

If plastic cracking does become evident before the concrete has taken its initial set, the cracks may be closed by revibration of the concrete over the full depth of the cracks. The feasibility of doing this should be assessed by an experienced operator, but a good rule of thumb is to permit revibration of concrete only if the vibrator will sink into the concrete under its own weight. Surface revibration may be only partially effective as it may not close the cracks to their full depth. They will then almost certainly recur as the concrete dries out.

12.2 CONCRETING IN COLD WEATHER

In New Zealand, freezing conditions are generally restricted to the mountain regions of both islands. The South Island experiences a higher incidence of widespread frosts.

While generally the ambient temperatures in New Zealand remain above freezing, they are still low enough to have potentially adverse effects on the progress of work.

12.2.1 Effects of Low Concrete Temperatures

By reducing the rate at which the cement hydrates, low concrete temperatures have a number of effects on the behaviour of the concrete. Firstly, and most noticeably, the setting time will be increased, delaying concrete finishing operations **Figure 12.2**. At the same time bleedwater will take longer to evaporate.

Under these conditions, there is a temptation, in finishing flatwork, to have recourse to 'driers' (cement or mixtures of cement and sand applied to the surface of the work) to mop up excess water and allow finishing to proceed. This practice leads almost inevitably to poor wear resistance.

Secondly, if the low temperatures are prolonged, the concrete will take longer to harden and gain strength, thereby delaying the removal of formwork **Figure 12.7** (page 12.8). NZS 3109 sets out minimum periods for which formwork and formwork supports must be left in place; periods which vary with the average ambient temperature over the period specified **Table 12.1** (page 12.8).

When freezing conditions are encountered, irremediable damage may be done to the concrete whilst it is still plastic or when it is commencing to harden (see Clause 12.2.5 *Freezing Conditions*).

12.2.2 Admixtures

Perhaps the most commonly used method of offsetting the effects of cold weather is the addition of an accelerating admixture to the concrete. There is a wide variety of these, ranging from water-reducing admixtures which have had accelerators incorporated in them to chemicals whose sole purpose is to reduce the setting time and accelerate

Table 12.1 Stripping/removal times (Table 5.3 from NZS 3109)

Formed Surface	Classification	Hot Conditions >20°C	Average Conditions ≤20°C >12°C	Cold Conditions ≤12°C >5°C
Beam and slab soffits	Forms	4 days	6 days	8 days
	Supporting members (shores or backprops)	12 days	18 days	24 days
Vertical faces	Finishes F6, F5, F4 (see Note 1)	1 day	2 days	3 days
	Finishes F3, F2, F1	9 hours	12 hours	18 hours
	A minimum of 2 days applied to the stripping of vertical faces where frost damage is likely.			

Note:

1. Finish references are from NZS 3114.
2. The stripping times for beam and slab soffits for members cured in conditions less than 5°C shall be increased by half a day for each day on which the daily average temperature was below 2°C.
3. Temperatures shall be taken as the average of the maximum and minimum air temperatures for a day.

the rate of strength gain. Accelerating admixtures, increasing the rate at which the cement hydrates, also result in heat being generated more rapidly within the concrete thereby increasing its temperature.

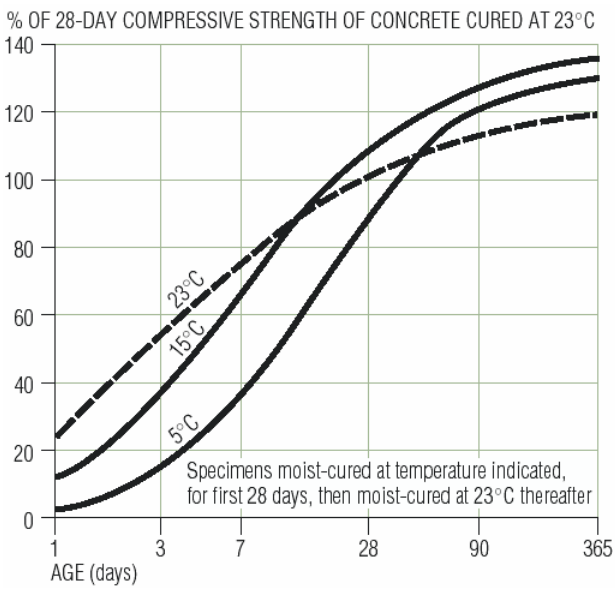


Figure 12.7 Effect of low temperatures on concrete compressive strength

Accelerators may perform, therefore, a very useful purpose but their use should be approached with caution. In general, the use of admixtures containing chlorides should be avoided. If these must be used, the chloride content must be known and a check made to ensure that the limits on the chloride content of concrete, laid down in NZS 3109, are not exceeded.

12.2.3 Hot Water

The use of hot water is another common method of compensating for the effects of cold weather. Its use as mixing water raises the temperature of the concrete which accelerates the rate at which the cement hydrates.

The temperature of mixing water should never exceed 70°C, however, to ensure that 'flash setting' of the cement does not occur.

Care should be taken also to ensure consistency in the temperature of the concrete delivered to the site. Significant variations in the temperature of the concrete can lead to variations in the setting time of adjacent batches of concrete, thereby complicating finishing operations. Sufficient heating capacity should be available, therefore, to ensure an adequate supply of hot water.

12.2.4 Cement Type and Content

The type of cement and the amount used will also have a bearing on the performance of the concrete in cold weather. High-early strength cements (Type HE) will tend to set somewhat more quickly than general purpose portland cements (Type GP) but the differences are not really significant. Hardening or strength gain will proceed more rapidly. Blended cements (Type GB) have a range of characteristics, depending on the blend, but in general will tend to gain strength more slowly than Type GP cements.

Of greater significance is the amount of cement used in the concrete. Whilst this has little or no impact on setting time, except with low cement content mixes, the rate of strength gain can be increased significantly.

12.2.5 Freezing Conditions

Freshly placed concrete is vulnerable to freezing conditions both before and after it has stiffened. If allowed to freeze whilst still plastic, the damage done to the pore structure of the cement paste (water expands as it freezes) is such that the potential strength of the concrete will be drastically reduced. Freezing of concrete which has partially hardened will also damage it, the extent of the damage depending on its age and strength when frozen.

Precautions in Freezing Conditions

It is always desirable to take precautions against freezing when the air temperature drops below 5°C. At the very least, the concrete temperature should be maintained above 5°C to ensure that setting occurs within a reasonable time and that the concrete gains strength. Damage to the concrete by a sudden and unexpected frost will thereby be minimised.

If there is any likelihood that the temperature will drop below zero and freezing conditions ensue, then additional precautions will be required.

Form Insulation

Concrete can be protected and kept from freezing – at least until it has commenced to harden and gain strength – by the use of insulated formwork and protective covers. During the first 24 hours, hydrating cement gives off a significant amount of heat which, if retained within the concrete by insulation, will protect it from freezing.

Timber formwork is a reasonably adequate thermal insulator and will probably suffice for moderately cold conditions. Additional insulation will be required for more severe conditions or for prolonged periods of freezing weather.

Metal formwork offers little or no protection and should be insulated.

Insulating materials should themselves be waterproof or be protected by tarpaulins, plastic sheeting, or other means, to keep them dry. Whilst materials such as straw and some insulating boards are excellent insulators when dry, they are ineffective when wet. Expanded polystyrene sheets are relatively unaffected by moisture.

Heated formwork may also be employed to protect concrete against freezing over longer periods. This tends to be quite sophisticated, however, and is beyond the scope of this Guide.

Heated Enclosures

In some circumstances the use of a heated enclosure to completely encase the concrete may be a satisfactory alternative. This may take the form of light frames covered with tarpaulins or similar material; or, in some cases, larger heavier frames, sheeted in some way, within which work may be carried out during very cold weather. Heating with hot-air blowers ensures an even distribution of heat within the enclosure. However, loss of moisture from the concrete surface needs to be addressed.

Curing

Curing poses particular problems during prolonged periods of freezing weather. Whilst loss of moisture from the concrete due to evaporation will be greatly reduced, very cold air can be quite dry and it may still be necessary to cure concrete to ensure that it achieves maximum potential durability.

Moist or water curing is rarely appropriate for obvious reasons.

Where the concrete has been placed in insulated formwork, covering the top surface of the member (preferably with an insulated covering) will serve to retain moisture within the member. When the formwork is removed, the member should be further cured by covering it with plastic film, or waterproof tarpaulins, properly lapped at joints and secured to ensure windtightness. On no account should concrete released from insulated formwork or heated enclosure, and therefore warm, be saturated with cold water.

Indeed, when protective measures are discontinued, care should be taken not to suddenly expose warm concrete surfaces to freezing conditions. With formwork, insulation and forms may be eased from the surface of the concrete, but allowed to remain in place whilst the temperature of the surface falls slowly. With heated enclosures, the air temperature should be reduced slowly. Failure to take these measures may cause the concrete to crack, a phenomenon known as ‘thermal shock’.

When hot-air blowers are used to heat enclosures, it should be noted that the air will be very dry unless humidified. The use of fine mist sprays within the enclosure, or, at the very least, placing trays of water in the path of the moving air, is advisable to prevent drying out of the concrete.

12.2.6 Stripping Formwork

Concrete that has been kept warm in an enclosure or with insulated formwork will quickly reach a strength (2 MPa) which will resist frost. At this point, vertical formwork may be removed. However, unless the formwork is required elsewhere, it will be advantageous to leave it in position as this will accelerate the hardening process and shorten the time to removal of soffit boards and props. By maintaining a record of the curing temperature of the concrete, an assessment of its strength can be made at any time to assist in determining when it is safe to remove loadbearing formwork.

As was noted above, in stripping forms care should be taken not to expose warm concrete to low temperature conditions too suddenly. Care should be taken also to prevent too great a temperature differential developing between the external surfaces and the interior of a concrete section. This is of particular significance with massive structures which may take some time to cool down. Even after forms have been removed it may therefore be desirable to continue to insulate the concrete.

In the absence of more specific information such as a record of the temperature of the concrete, guidance on permissible stripping times may be obtained from **Table 12.1**.

REFERENCES

12.1 ACI Committee 305, 'Hot Weather Concreting' *ACI Manual of Concrete Practice Part 2: Construction practices and inspection, pavements* American Concrete Institute, Farmington Hills, USA, 1999.

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12.3 Berke, N. S. & Dallaire, M. P. 'The effect of low addition rates of polypropylene fibers on plastic shrinkage cracking and mechanical properties of concrete' *Fiber reinforced concrete: Developments and innovations SP-142* American Concrete Institute, Detroit, USA, 1993 pp 19–42.

Summary

CONTROLLING THE EFFECTS OF HOT AND COLD WEATHER

Aspect	In hot weather	In cold weather
Preplanning	Preplan carefully to avoid delays at all stages. Have standby equipment and manpower for all stages. Pay particular attention to speed of application, effectiveness and duration of curing arrangements. Schedule night-time placement if possible.	Preplan carefully to ensure adequate equipment and manpower available especially if there is a likelihood of temperatures below 0°C.
Concrete	Use water-reducing retarding admixtures in the concrete. Reduce the temperature of the concrete by (in order of effectiveness): ▪ reducing temperature of aggregates ▪ using liquid nitrogen injections in the mixed concrete ▪ reducing temperature of mixing water ▪ using cement with lower heat of hydration ▪ reducing temperature of cement.	Reduce the setting time of the concrete by (in order of effective-ness): ▪ heating mixing water (maximum 70°C) ▪ using (chloride-free) accelerating admixture ▪ using higher cement content ▪ using high-early-strength cement.
Batching, mixing and transporting	Shade batching, storage and handling equipment or at least paint with reflective paint. Discharge transit mixer trucks as soon as possible.	
Placing and compacting	Shade reinforcement, formwork and sub-grades if possible and spray with water. Ensure that slabs have minimum 'fronts' to which concrete is added. Place concrete in walls and deep beams in shallow layers. Use burlap covers if there is any delay between load deliveries.	Thaw frozen subgrades and heat frozen forms (particularly steel) before placing concrete. Warm, insulate or enclose handling and placing equipment. Avoid delays in handling and placing.
Finishing and curing	Use sunshades and windbreaks to lengthen finishing time (or, if hot/dry winds present, to control plastic shrink-age cracking). For flatwork use aliphatic alcohol after initial screeding if hot/dry winds present. Use revibration to correct plastic shrink-age cracking. Use water curing as the preferred method for at least 24 hours.	Maintain concrete temperature until safe strength reached by means of form insulation, insulated covers or heated enclosures. Delay striking of formwork for as long as possible. Avoid thermal shocks and temperature variations within a member. This includes not using cold water for curing, and removing protective measures gradually.

Control of Surface Finishes

Chapter 13

Chapter 13

Control of Surface Finishes

The control of off-form concrete finishes – architectural concrete as it is sometimes known – involves careful planning of all aspects of the work, from the form faces and release agents to be employed, the choice of concrete materials and mix proportions to the techniques used to place, compact and cure the concrete. This chapter aims to highlight the factors which influence off-form finishes and the ways in which these factors can be controlled.

Further information can be found in CCANZ publications TM 01 *Architectural concrete cladding* and IB 33 *Specification and production of concrete surface finishes*.

INTRODUCTION

This chapter deals with the control of surface finishes on off-form or 'architectural' concrete, i.e. concrete which is intended to have a predetermined appearance. Such finishes are produced by combining appropriate formwork with the use of good quality concrete and correct placing, compaction and curing techniques.

Off-form finishes, to be successful, require very high standards of design, specification and construction. Above all, they require good communication between the architect and the contractor and a high degree of knowledge and skill on the part of the workforce. They are not necessarily 'easy' or 'cheap' to produce. This is not to suggest that good quality off-form finishes are beyond the skills of the average contractor but rather to emphasise that such finishes are the result of good planning and execution, i.e. they do not simply happen.

Relevant New Zealand Standards

NZS 3109 *Concrete construction*

NZS 3114 *Concrete surface finishes*

Relevant Australian Standards

AS 1012 *Methods of testing concrete*

AS 1379 *The specification and supply of concrete*

AS 3600 *Concrete structures*

AS 3610 *Formwork for concrete*

Supplement 1 *Blowhole and colour evaluation charts*

Supplement 2 *Commentary*

13.1 FACTORS INFLUENCING THE APPEARANCE OF CONCRETE

13.1.1 General

Factors which influence the colour and texture of off-form finishes include:

- the formwork;
- the use of formliners;
- the release agents;
- the concrete materials and mix design;
- the use of pigments;
- the placing and compaction techniques;
- the curing; and
- the protection given the finished work.

Since many of these factors are both interrelated and inter-reliant, they all have to be considered if visually good quality concrete is to be achieved.

13.1.2 Formwork

General

The quality of the formwork, and particularly the form faces, has a major influence on the appearance of the concrete cast against it. Not only is the off-form finish a direct negative of the form face, it is also affected by the formwork's:

- stiffness;
- absorbency; and
- watertightness.

If the formwork is not stiff, deflection and movement during concrete placing and compaction may contribute to a number of surface defects such as colour variation or a mottled appearance sometimes referred to as aggregate transparency.

Variable absorbency of the form face will also result in colour variation, possibly even dark staining of the surface. This is caused by changes in the water-cement ratio of the concrete at the surface. Whilst this is superficial in one sense, a sufficient depth may be effected that subsequent tooling of the concrete may not remove the staining. The colour variations are usually most noticeable at changes of absorbency from one panel of timber formwork to the next. Note that the absorbency of 'new' timber forms changes after a number of uses.

Also the uniformity of the release agent coating can affect the absorbency of the form face **Figure 13.1**.

Loss of moisture and/or cement grout through lack of watertightness leads to other problems, notably honeycombing. The joints between adjacent planks or formwork sheets should therefore be accurately made and rigidly held together and the joints between elements, e.g. between side wall and soffit formwork for beams, sealed with foamed plastic strips or timber fillets fixed into the joints. Alternatively, a waterproof tape or joint sealant can be applied to the joints. It should be noted that the presence of tapes will be reflected on the finished concrete surface.

Figure 13.1 **Hydration staining resulting from variable absorbency of formwork**

Formwork Design

All formwork should comply with the provisions of NZS 3109. The formwork drawings should show the patterns of the form face, if any, and typical joints between formwork panels. Careful detailing of such joints is critical to the success of off-form finishes **Figure 13.2**. For example, all control and construction joints on vertical surfaces should be indented, or otherwise disguised **Figure 13.3**.

See also CCANZ publications IB 29 *Formwork for concrete* and IB 41 *Formwork detailing*.

Form Face Materials

A number of materials can be used to provide the form face against which concrete is cast. Each will give a characteristic texture/finish to the concrete surface. For a given situation (orientation of form face, exposure and desired appearance) some will be more suitable than others. For example, smooth faced materials such as plastic-coated plywood and fibreglass should not be used on surfaces that will be viewed close-up, i.e. from closer than three metres. This is because it is difficult to ensure that such surfaces are blemish-free and very difficult, if not impossible, to repair. However, they can be used for surfaces visible only from greater distances. Similarly, a board-marked finish will tend to hold dirt on the surface and may harbour fungal growth in tropical climates and thus be unsuitable for external surfaces in some locations.

Figure 13.2 **Example of carefully detailed off-form concrete**

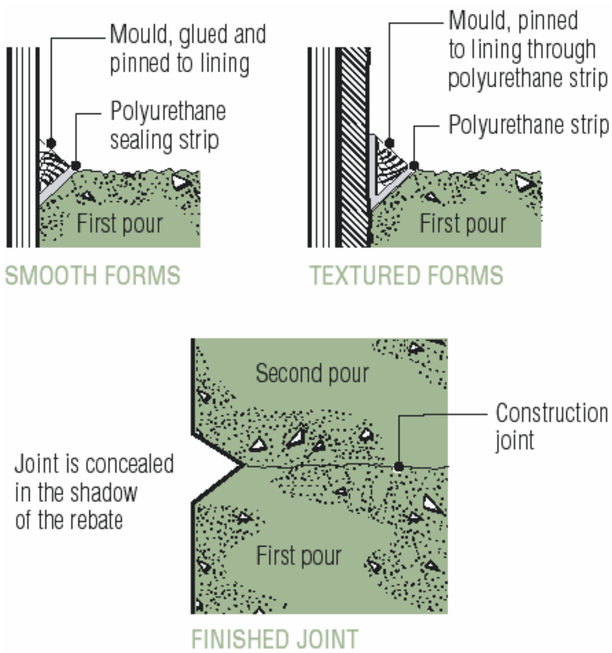

Figure 13.3 **Construction joint on vertical surface**

Traditionally sawn timber has been used extensively as a form face or lining to produce 'board marked finishes'. Oregon boards are to be preferred, rough sawn and even lightly sandblasted to bring out the grain. To avoid variable absorbency, new boards should be sealed with several applications of a form oil and then 'pickled' by the application of a cement grout or slurry to the surface, which is then allowed to dry before the slurry is brushed off. Sawn boards may be used to produce profiled finishes **Figure 13.4**.

Plastic coated plywood produces a smooth finish. However, this formwork type as noted above is not recommended for surfaces that are to be viewed close up. A light sanding of the face with fine sandpaper will help improve colour control as will 'pickling' the formwork surface before use.

As with sawn timber, a suitably detailed joint between panels is essential. It is almost impossible to disguise the joints between adjoining plywood sheets so, aesthetically, it is best to emphasise them. A rebate at the joint will normally be satisfactory, but in any event, sealing the joint between plywood sheets with a preformed foam strip is essential to prevent leakage of moisture and/or cement grout.

Fibreglass forms and form liners are often used for complex shapes and profiles that would be difficult or impossible to achieve by other means. They give a very smooth, mirror finish to the concrete (unless textured) and because of this they should be used for surfaces that can be viewed only from a distance. The joints between adjoining panels or shapes are difficult to disguise and as with other materials, they are best accentuated.

Other materials which have been used to achieve specific effects include rubber and other forms of plastic form liner, hardboard sheets with the textured side exposed, rope lightly secured to the formwork and then subsequently stripped from the concrete surface, as well as a variety of even more exotic processes. Experimentation and the construction of test panels with these materials is essential to confirm the anticipated texture and appearance as well as ensure satisfactory results for the member and surfaces involved.

13.1.3 Release Agents

Both the type of release agent and the method of application can affect the quality and colour of a surface finish. Whilst it is beyond the scope of this Guide to discuss in detail the wide range of release agents available, it can be noted that chemical release agents are most likely to provide satisfactory results. Water-in-oil emulsions or neat oil with surfactants have also proved satisfactory. Test panels built prior to construction provide the best method for assessing the suitability of a release agent for the given application.

No matter what is used, it is essential that it be applied uniformly and evenly over the form surface at the minimum rate consistent with full coverage. Surplus agent should be removed prior to concreting. Also, if colour control is specified, the same release agent should be used throughout the project.

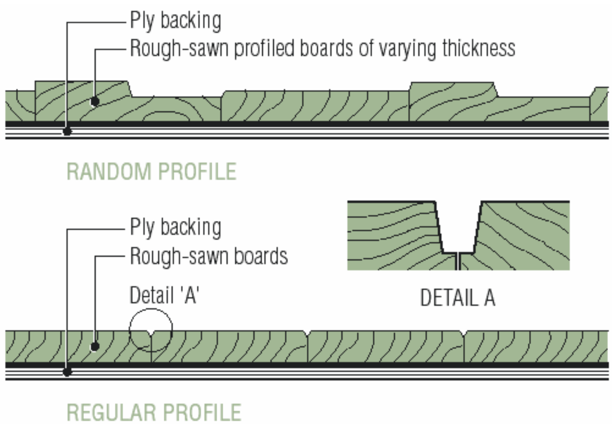

Figure 13.4 Form linings for sawn-timber finishes

13.1.4 Concrete Materials and Mix Design

The requirements for concrete that will give consistent, high quality surface finishes are more demanding than those imposed by the simple strength/durability parameters of structural concrete. These requirements may be expected to cover such matters as:

- the type of cement and supplementary cementitious materials, their source and relative proportions, to minimise colour variations due to cement throughout the work;
- the sand, and its source, again to ensure minimum colour variations;
- the coarse aggregates and especially the amount of flat, flaky or elongated particles to be permitted (a minimum practical limit is advisable because of the adverse effect such particles have on the textural quality of off-form finishes); and
- a minimum cement content. The mix design for concrete for high quality finishes will, typically, have a higher cement content and a lower water-cement ratio than may be necessary for the strength/durability requirements of the work. The concrete is sometimes less workable than plain structural concrete and, hence, may not be suitable for pumping. It may also require more intensive vibration to compact it.

On many jobs, in fact, a suitable mix design will be agreed only after adequate field testing has been carried out, using the method of placement intended, and after test panels have been constructed. These may then serve as reference panels as the work proceeds. Sometimes, however, reference can be made to previous projects which are similar in finish and colour to that proposed, thereby reducing the amount of field testing required.

Once chosen, it is essential that the mix remains constant throughout the project. All materials should come from constant sources and their proportions remain unchanged. The control of the water-cement ratio is particularly crucial. Mixes with a high sand content tend to give better colour control but more blowholes in smooth finishes. Some compromise may therefore be necessary for best overall results. Over-sanded mixes should always be avoided.

Because of these special requirements, concrete for off-form finishes must always be specified as 'Special-class concrete' in terms of NZS 3109.

13.1.5 Placing and Compacting

Whilst good practice in placing and compacting concrete is always desirable, it is especially necessary with high quality off-form finishes. Appropriate techniques are discussed in Chapters 8 and 9 of this Guide but specific attention is drawn to the following:

- The concrete should be placed at a continuous rate and consistently for each section of the work. In walls, the placing rate should be such that the lateral pressure assumed in the formwork design is not exceeded and the settlement in each layer is substantially complete before the next layer is placed (but no cold joints are formed).

- Placement should occur in uniform horizontal layers, care being taken that the concrete is not moved horizontally or made to flow by the use of vibration.

- The concrete should be thoroughly compacted using the techniques described in Chapter 9. Special care should be taken to avoid touching the form face with immersion vibrators to avoid damaging it, and to avoid the formation of sand streaks in the surface of the concrete.

- To minimise the formation of blowholes in the top 0.5 m of walls and columns, the concrete should be rodded and/or revibrated prior to it stiffening.

13.1.6 Curing

Curing of concrete is discussed in detail in Chapter 11. With off-form concrete, however, some special precautions are required to ensure work is not stained or discoloured during the curing process if colour control has been specified.

For example, there are special problems associated with the use of formwork to cure concrete. Generally speaking, to ensure adequate curing by formwork it is best to leave it in close contact with the concrete, thereby preventing air movements which may cause the surface to dry out.

With off-form finishes, however, it is often best to ease the formface from the concrete at an early age to prevent scabbing **Table 13.2** (page 13.10). When this is done, it is essential to ensure that all faces are loosened otherwise uneven curing and colour variations may occur. Other causes of discolouration are more obvious but should always be checked. For example on vertical surfaces:

- Water curing can cause streakiness and non-uniform discolouration whilst run-off onto completed work can cause similar problems. Iron salts or similar impurities in the water may have disastrous effects.

- Curing with hessian can also cause problems. Firstly, the hessian itself must be thoroughly washed before use to ensure it does not stain the surface. Secondly, it is necessary to ensure it is kept uniformly wet to avoid uneven colouration of the cured surfaces.

- Curing with plastic sheets is a satisfactory method, provided the sheets are prevented from making contact with the concrete. Uneven contact can result in dark patches at the point of contact.

Plastic sheeting has the advantage that it helps protect finished work. A good method of preventing contact is the use of a light plastic or wire mesh stapled to a light timber frame secured to the wall through the tie-bolt holes. This may be left in place to protect the finished work as long as is necessary. Note that some colour variation may occur under the timbers so the size should be kept to a minimum.

Curing compounds may also be employed to cure off-form concrete, although, as with other materials, preliminary trials are advisable to ensure there is no permanent staining from them.

13.1.7 Treatment of Tie-Bolt Holes

The treatment of tie-bolt holes is especially important to the overall appearance of off-form concrete **Figure 13.5** (page 13.6).

Holes may be made good or filled with either plastic or concrete plugs fixed in position with epoxy mortar. Alternatively, they may be filled with a dry-packed mortar rammed into position. In either case, the plug or filler should be recessed some 6–10 mm below the surface of the concrete finish.

Where possible, precast concrete plugs should be made with the same concrete as used in the element, to avoid colour contrasts.

If a dry-pack mortar mix is used, this should consist of a 1:3 cement:sand mixture employing the cement and sand used in the original concrete, except that some 30–40% of the cement should be replaced with an off-white cement to lighten the colour of the mortar. This compensates for the generally darker colour of small patches which in this case may be accentuated by the shadow effect of the recessed surface or plug.

To reduce shrinkage, and the possibility of a more fluid material staining the surface of the finished work, the mortar should be an earth-damp mix which is compacted by ramming.

Figure 13.5 **Example of bold treatment of tie-bolt holes (and the use of a ribbed finish which disguises minor defects)**

13.1.8 Protection of Finished Work

Finished work should be protected from both accidental damage and staining.

Accidental damage can be caused in any one of a number of ways but normal care should suffice to minimise the occurrence of such accidents. One not always guarded against, however, is the accidental splashing of finished work with fresh concrete or mortar, or staining by grout lost from subsequent lifts.

Protection of finished work should therefore commence immediately after completion, i.e. as soon as the formwork has been stripped. As has already been noted, one means of doing this is to wrap the element in polythene film, taking care, however, that it does not contact the fresh concrete surfaces. Surfaces which have been cured and allowed to dry out will not be harmed by wrapping them in polythene.

Work should also be protected from rust washed onto it from projecting (and unprotected) reinforcement, from formwork and screens on upper lifts, from props or from other steel products used in subsequent lifts. Reinforcement may be protected by painting it with a cement slurry or wrapping it in plastic (not recommended in areas of high humidity) **Figure 13.6**. Other staining may be prevented by ensuring that materials used in above completed work are clean and free from rust.

Another cause sometimes neglected is the staining of work at ground level by mud or soil 'splashed' onto it during rain or by passing vehicles. Protection of the concrete and good site management are obvious precautions against this.

Figure 13.6 **Completed work and projecting reinforcement protected by wrapping in building paper and plastic sheeting respectively**

13.2 THE SPECIFICATION OF SURFACE FINISHES

13.2.1 General

There are three broad approaches to the specification of surface finishes, viz:

- by performance;
- by method; and

- by a combination of performance and method.

In New Zealand the primary specification requirements for surface finish are set out in NZS 3114. The document includes reference material for the incidence of blow holes and colour variations. It deals with formed finishes (F), unformed e.g. slabs (U) and exposed aggregate (E).

In Australia performance specifications are based on the provisions of AS 3610 and Supplement 1 to that Standard. Section 3 of AS 3610 deals with surface finish and details five classes of finish by their visual characteristics and suitability for use in different situations **Table 13.1** (page 13.9). Supplement 1 provides a series of photographs which may be used to evaluate the occurrence of blow holes in smooth finishes and a series of colour charts which may be used to evaluate colour consistence or control in finished work.

The New Zealand range of finishes, F1 to F6, have been annotated to this Australian-based table. It should be noted that finish quality referencing is reversed, i.e. an Australian Class 1 is similar to a New Zealand F6 finish.

The Standard also provides details of the documentation required for each class of finish, tolerances for both linear and angular dimensions, and guidance on acceptable variations in colour.

A combination of method and performance in the one specification is the least satisfactory although it can be made to work if there is some objective standard, such as a test panel, against which to measure performance.

13.2.2 Test Panels

Test panels comprise, probably, the single most useful tool for determining compliance with a specification as they prove the acceptability of both materials and techniques. Indeed, NZS 3114 requires test panels to be provided for:

- F4, F5 and F6 untreated surfaces;
- colour control of surfaces; and
- surface treatments **Figure 13.7**.

Test panels should be constructed on site using the materials, formwork and formwork details, release agents, etc to be used in the actual work. This implies that they need to be of a size similar to that of the actual construction. Small sample panels, especially in a laboratory, will not reflect the ability of on-site construction techniques to produce the desired finish. Where surface treatments such as bush-hammering are to be applied, a separate panel should be provided which may later be placed alongside the completed work for comparison.

Test panels may also be used to indicate the acceptability of repair techniques should these be required at a later date.

Figure 13.7 **Example of bush-hammered finish which would require a test panel under NZS 3114 and AS 3610**

13.3 DEFECTS IN OFF-FORM CONCRETE

The production of good quality off-form concrete depends, to a large extent, on recognising the factors which cause defects in it and how these effects might be minimised or even eliminated.

Tables 13.2 and 13.3 (pages 13.10 and 13.12) set out some of the more common (and some less common) defects which may be encountered in off-form concrete, and their probable causes. Once the latter have been identified, action can usually be taken to eliminate them.

13.4 REPAIRS AND REMEDIAL WORK

Repairs and remedial work to off-form concrete are undesirable because of the difficulty of achieving visually satisfactory results. When necessary, the following precautions and procedures will assist in securing the best possible results:

- As far as is practicable, repairs should always be carried out by skilled and experienced crews.

- Repair techniques should be established early in the construction programme, preferably using the pre-construction test panels, and an acceptable standard established. Note that repairs are not permitted in the highest class of finish to NZS 3114 – Class F6. Extra care must therefore be taken to ensure the formwork will produce a blemish free surface.

- Repairs should then be undertaken at the earliest possible opportunity, preferably as soon as the form has been stripped, in order to ensure that the repair and the concrete are given the same curing and/or other treatments.

- Surfaces which are to be tooled, and which exhibit significant defects such as blowholing or honeycombing, must be patched prior to tooling. Reliance should not be placed on tooling to mask such defects. Sufficient time should be allowed for the patches to gain strength before tooling is commenced.

- Extreme care should be taken to establish a colour match between the concrete surface and the patch. To achieve this, it will generally be necessary to substitute part of the original cement (perhaps as much as 40%) with off-white cement. Patching with the original mix will almost inevitably result in a darker colour.

The choice of materials to be used and the repair technique will depend on the size and configuration of the defect. Blowholes, for example, may be filled with a colour-controlled patching mortar using a spatula. The surface should be lightly moistened prior to patching and an earth-damp mixture forced into the hole. Care should be taken not to smear the surface of the surrounding concrete with the patching mortar.

Repair techniques for honeycombing vary with the depth and the area involved. In shallow areas, all loose or partly adhering material should be removed and the periphery of the area trimmed to a depth of 4–6 mm. The existing concrete should then be primed with a bonding agent and a suitable mortar packed into the hole and consolidated. The surface should then be finished to match the surrounding concrete, being careful not to overwork it.

Acrylic-modified-portland-cement materials are available for patching work and, in general, appear to provide better performance than unmodified materials.

Where more extensive repairs and patching are required, it may be possible to form up the area and to place concrete behind the forms. Forms used in this situation should have patterns and absorbency characteristics similar to the original formwork.

Bonding agents may be employed in such situations but care should be taken that they are suitable for the application. For example, PVA-based bonding agents should not be used in locations where the concrete may become wet, as they tend to re-emulsify in such conditions.

Defects such as minor grout runs, form scabbing and some hydration staining can be remedied by rubbing the surface with a carborundum stone. Such treatments should, however, be limited to small areas.

Acid etching, bleaching or similar treatments should be considered only as a last resort as the results may well exacerbate the problem instead of curing it. Indeed, very careful consideration should always be given to whether repairs and remedial work will improve or worsen the appearance of the concrete.

Table 13.1 Applicability of surface classes (from Table 3.3.1 in AS 3610 with New Zealand references ex NZS 3114)

	Class 1	Class 2	Class 3	Class 4	Class 5
	New Zealand references ex NZS 3114				
	F6	F5	F4/F3	F2*	F1
Visual characteristics	Visual quality important. Highest quality attainable. Subject to close scrutiny. Best possible uniformity of texture. Excellent quality of edge and joint details.	Visual quality important. Uniform quality and texture over large areas. Built to close tolerances. Consistently good quality of edge and joint details.	Good visual quality when viewed as a whole.	Visual quality not significant. Texture not important. Good general alignment.	Visual quality not significant. Alignment and texture not important.
Suitable uses	Selected small elements. Areas of special importance in limited quantities. Elements contained in a single pour.	General external and internal facades intended to be viewed in detail.	General external and internal facades intended to be viewed as a whole.	Surfaces concealed from general view. Surfaces to have thick applied finishes after preparation.	Totally concealed areas.
Applied finish	Not applicable.	Reference should be made to permitted tolerances prior to selection of applied material.	Reference should be made to permitted tolerances prior to selection of applied material.	Reference should be made to permitted tolerances prior to selection of applied material.	Not suitable.
Situations where not to be used	Trafficable slopes, soffits, formed tops of slopes, liners. Is not applicable where treatment is to 100% of surface.	Formed tops of slopes.	No restriction.	No restriction.	
Colour control	May be specified. Refer to Clause 3.6.3(b) in AS 3610 for the limits of the best colour consistency that can be expected. Clause 105.6.3 NZS 3114.	May be specified. Refer to Clause 3.6.3(b) in AS 3610 for the limits of the best colour consistency that can be expected. Clause 105.5.3 NZS 3114.	May be specified. Refer to Clause 3.6.3(b) in AS 3610 for the limits of the best colour consistency that can be expected. Clause 105.4.3 NZS 3114.	Excluded.	
General	If these classes are required they must be specified in the project documentation.	If these classes are required they must be specified in the project documentation.	If these classes are not specified in the project documentation, selection of appropriate class is by the visual characteristics and suitable uses set out above.	If these classes are not specified in the project documentation, selection of appropriate class is by the visual characteristics and suitable uses set out above.	If these classes are not specified in the project documentation, selection of appropriate class is by the visual characteristics and suitable uses set out above.

** F2 finish is specifically described as suitable for receiving solid plaster coating.*

Table 13.2 Physical defects and their causes

Defect	Description	Most probable causes
Honeycombing	Coarse stony surface with air voids, lacking in fines.	▪ Formwork – leaking joints ▪ Concrete mix – insufficient fines – workability too low ▪ Placing methods – segregation – inadequate compaction ▪ Design – highly congested reinforcement – section too narrow
Blowholes	Individual cavities usually less than 12 mm diameter. Smaller cavities approximately hemispherical; larger cavities often expose coarse aggregate.	▪ Formwork – form face impermeable, with poor wetting characteristics – face inclined, face too flexible ▪ Release agent – neat oil without surfactant ▪ Concrete mix – too lean – too coarse sand – workability too low ▪ Placing methods – inadequate compaction – too slow rate of placing
Mortar loss or grout loss or scouring	Sand textured areas, devoid of cement. Usually associated with dark colour on adjoining surface. Irregular eroded areas and channels having exposed stone particles.	▪ Formwork – leaking at joints, tie holes, and the like ▪ Concrete mix – excessively wet – insufficient fines – too lean ▪ Placing methods – water in forms, excessive vibration of wet mix – low temperature
Misalignment	Step, wave, bulge or other deviation from intended shape.	▪ Formwork – damaged, deformed under load – joints not securely butted ▪ Placing methods – too rapid or careless
Plastic cracking	Short cracks, often varying in width across their length. On vertical faces, cracks are more often horizontal than vertical.	▪ Formwork – poor thermal insulation – form profiles or reinforcement which restrain settlement of the concrete ▪ Concrete mix – high water-cement ratio – low sand content – excessive bleeding of mix ▪ Ambient conditions – conditions leading to high evaporation of moisture from concrete

Table 13.2 continues on next page.

(Physical defects and their causes continued)

Defect	Description	Most probable causes
Scaling, spalling or chipping, and form scabbing	Scaling is the local flaking or peeling away of a thin layer of mortar from the concrete. Spalling or chipping is the local removal of a thicker layer or edge of mortar. Form scabbing is the adhesion of portions of form surface, including sealant or barrier paint, to the concrete.	▪ Formwork – inadequate stripping taper – inadequate stiffness – movement of form lining due to change of hydrostatic pressure of concrete with depth keying of concrete into wood grain, saw kerfing, and interstices in form surfaces – local weakness of form face ▪ Ambient conditions – frost action may cause spalling ▪ Stripping – too early stripping may cause scaling – too late stripping may cause scabbing
Crazing	A random pattern of fine shallow cracks dividing the surface into a network of areas from about 5 to 75 mm across.	▪ Formwork – form face of low absorbency, smooth or polished ▪ Concrete mix – a high water-cement ratio combined with a cement-rich mix can be a contributory cause ▪ Curing – inadequate

Table 13.3 Colour variations and their causes

(NOTE: Some of the undermentioned defects may lessen or disappear with time, especially on surfaces exposed to weathering, but it is not practicable to state exactly what can be expected to happen to any given surface. Some defects may appear sooner than others after stripping the forms).

Defect	Description	Most probable causes
Inherent colour variation	Variation in colour of the surface.	▪ Materials – change of cement brand – change of source of fine and coarse aggregate – variation in admixtures ▪ Concrete mix – variations in mixing procedure
Aggregate transparency	Dark areas of size and shape similar to the coarse aggregate. Mottled appearance.	▪ Formwork – too flexible, causing a 'pumping' action during compaction ▪ Concrete mix – low sand content – gap grading of sand ▪ Placing methods – excessive vibration
Negative aggregate transparency	Light areas of size and shape similar to the coarse aggregate. Mottled appearance.	▪ Materials – aggregate dry or highly porous ▪ Curing – too rapid drying
	Variation in shape of the surface. Hydration staining and discolouration have a tendency to be severe at the top of a lift and at construction joints due to localised variations in water-cement ratio, incomplete compaction, and differential loss of moisture. Indentation of construction joints tends to disguise this discolouration by throwing the affected areas into shadow.	▪ Formwork – variable absorbency – leaking through joints ▪ Release agent – uneven or inadequate application ▪ Curing – uneven
Segregation discolouration, or sand runs (separation of fine particles due to bleeding at the surface of the form)	Variation in colour or shade, giving a flecked appearance.	▪ Formwork – low absorption – water in bottom of forms ▪ Concrete mix – lean, high water-cement ratio – unsuitably graded aggregate ▪ Placing methods – excessive vibration – low temperature

Table 13.3 continues on next page.

(Colour variations and their causes continued)

Defect	Description	Most probable causes
Dye discolouration or contamination	Discolouration foreign to the constituents of the mix.	▪ Formwork – stains, dyes, dirt on form face, timber stains, rust from reinforcement or metal form components ▪ Release agent – impure or improperly applied ▪ Mix materials – dirty – contaminated by pyrites, sulphates, clay, organic matter or other impurities ▪ Curing – impure curing compounds – impure curing water – dirty covers
Oil discolouration	Cream or brown discolouration. Sometimes showing sand or coarse aggregate.	▪ Release agent – excessive amount – low viscosity – impure – applied too late or unevenly
Lime bloom, or efflorescence	White powder or bloom on surface.	▪ Design – permitting uneven washing by rain ▪ Release agent – type ▪ Curing – uneven conditions
Retardation dusting	Matrix lacking in durability. Dusty surface which may weather to expose aggregate and which will erode freely under light abrasion at early ages, particularly in the period immediately following stripping of formwork.	▪ Formwork – retarder in or on form faces – loss of contact between form face and hardening concrete (rapid drying) ▪ Release agent – unsuitable – excessive use of chemical release agent – water soluble emulsion cream* – unstable cream – oil with excessive surfactant ▪ Curing – inadequate (very rapid drying)
Banding	Coarse texture corresponding to the width of the slipform, the bands often being of different colour	▪ Slipforming – stop-start method of slipforming – hardened concrete behind slipform cannot be finished off at the same age as the rest and has different hydration conditions – a more nearly continuous slipform motion causes less prominent banding

** 'Cream' refers to an emulsion of an oily constituent in water.*

Control of Cracking

Chapter 14

Chapter 14

Control of Cracking

Cracks form in concrete construction for a variety of reasons, sometimes before the concrete has hardened, sometimes long after. This Chapter summarises information on the various types of cracking which may be encountered; the principal causes of such cracking; and means which may be taken to minimise or prevent it. Chief amongst these is the adequate provision of appropriate joints in the construction. Information is provided also on repair techniques which may be employed, should cracking occur.

INTRODUCTION

Cracks may occur in concrete construction for a variety of reasons. Indeed, unless appropriate measures are taken to control it, cracking in concrete construction is inevitable because concrete, like most other building materials, moves with changes in its moisture content. Specifically, it shrinks as it loses moisture. Being a brittle material with a low tensile strength, if this shrinkage is restrained the concrete is liable to crack as it shrinks, unless appropriate measures are taken to prevent this, e.g. by the provision of control joints.

Shrinkage cracking, although perhaps the most common form of cracking in concrete construction, is not the only form. Cracks may occur also due to settlement of the concrete, movement of the formwork before the concrete member is able to sustain its own weight, or due to changes in the temperature of the concrete and the resulting thermal movement.

Appropriate measures will at least minimise, if not prevent entirely, these forms of cracking. In all cases, joints at appropriate intervals will control cracking and ensure that it does not occur in a random fashion to the detriment of the appearance and long-term durability of the structure.

Relevant New Zealand Standards

NZS 3101 *Concrete structures*

NZS 3109 *Concrete construction*

Relevant Australian Standards

AS 3600 *Concrete structures*

14.1 PREHARDENING CRACKS

14.1.1 General

Cracks which form before concrete has fully hardened (in less than eight hours, say) are known as prehardening cracks. There are three main types, viz:

- Plastic shrinkage cracks.
- Plastic settlement cracks.
- Cracks caused by formwork movement.

All occur as a result of construction conditions and practices although, obviously, faulty formwork design may lead to its movement and/or failure. Prehardening cracks are usually preventable by the adoption of good construction procedures.

14.1.2 Plastic Shrinkage Cracks

Plastic shrinkage cracks are formed in the surface of the concrete whilst it is still plastic, i.e. before it has set and begun to harden, although they may not become visible until some time later. They are due to the too rapid loss of moisture from the surface of the concrete, e.g. during hot, dry or windy conditions.

Usually, they form without any regular pattern and may range from 25 mm to 2 m in length. They are fairly straight and vary from a hairline to perhaps 3 mm in width. Since they occur most often in hot weather, they are discussed in Chapter 12 *Hot- and Cold-Weather Concreting* to which reference should be made for further information and for guidance on procedures to prevent their occurrence.

14.1.3 Plastic Settlement Cracks

General

Most concrete, after it is placed, bleeds, i.e. water rises to the surface as the solid particles settle. The bleed water evaporates and there is a loss of total volume (i.e. the concrete has 'settled'. If there is no restraint, the net result is simply a very slight lowering of the surface level. However, if there is something near the surface, such as a reinforcing bar, which restrains part of the concrete from settling while the concrete on either side continues to drop, there is potential for a crack to form over the restraining element **Figure 14.1** (page 14.3).

Differential amounts of settlement may also occur where there is a change in the depth of a section, such as at a beam/slab junction **Figure 14.2** (page 14.3).

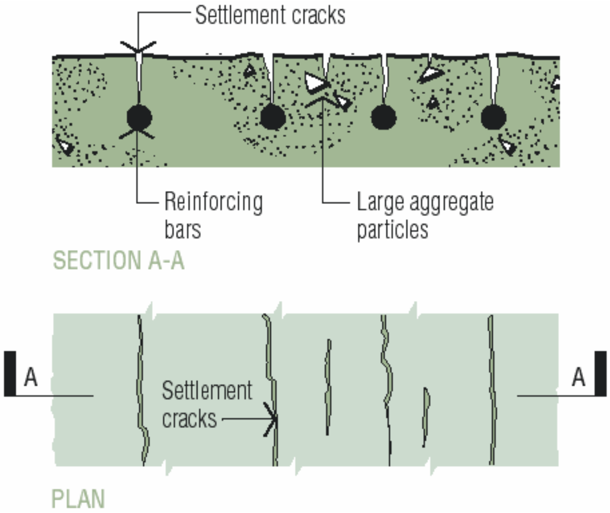

Figure 14.1 Settlement cracking

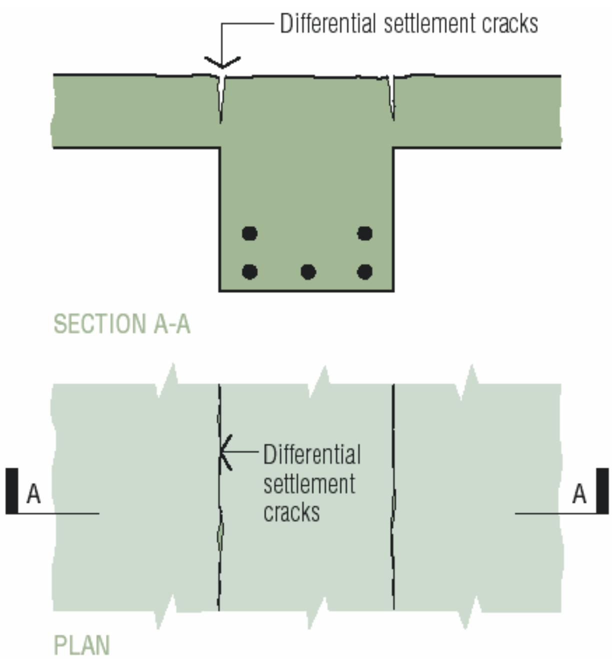

Figure 14.2 Differential settlement cracking

Settlement cracks tend to follow a regular pattern replicating the lines of restraint, usually the reinforcement, or a change in section. Generally, the cracks are not deep but, because they tend to follow and penetrate down to the reinforcement, they may reduce the durability of a structure.

Factors which may contribute to plastic settlement include:

- rate of bleeding;
- the time over which settlement can take place, e.g. time before the concrete begins to set;
- the depth of reinforcement relative to total thickness of the section;
- the depth of reinforcement/size of bar ratio;
- the constituents of the mix; and
- the slump.

Prevention of Plastic Settlement Cracking

Plastic settlement cracks may be prevented, or rather closed, by revibrating the concrete after settlement is virtually complete and it has begun to set, e.g. after half an hour to one hour. Revibration closes the cracks, and enhances the surface finish and other properties of the concrete. Careful timing is essential to ensure that the concrete reliquefies under the action of the vibrator and that the cracks close fully. Applying vibration before the concrete has begun to stiffen may allow the cracks to reopen. Applying it too late, i.e. after the concrete has begun to harden, may damage the bond with reinforcement or reduce its ultimate strength (see Chapters 9 and 10 *Compaction* and *Finishing*).

Other procedures which may help reduce plastic settlement cracking include:

- using lower slump mixes;
- using more cohesive mixes;
- using an air entrainer to improve cohesiveness and reduce bleeding; and
- increasing cover to top bars.

Where there is a significant change in section, the method of placing may be adjusted to compensate for the different amounts of settlement. If the deep section is poured first to the underside of the shallow section, this concrete can be allowed to settle before the rest of the concrete is placed. However, the top layer must be well vibrated into the bottom layer.

Avoiding the use of retarders is sometimes suggested as a way of reducing plastic settlement cracking but, for hot-weather concreting, the advantages of retarders generally outweigh the disadvantages.

14.1.4 Cracks Caused by Formwork Movement

If there is movement of the formwork, whether deliberate or unintentional, after the concrete has started to stiffen but before it has gained enough strength to support its own weight, cracks may form. Such cracks have no set pattern.

To avoid cracking from this cause, formwork must be:

- sufficiently strong and rigid to support the weight of the concrete without excessive deflections; and

- left in place until the concrete has gained sufficient strength to support itself.

Some guides for the stripping time of formwork assume that Type GP cement is being used. Concretes incorporating supplementary cementitious materials, such as fly ash, may take longer to gain strength and allowance should be made for this.

14.2 CRACKS IN HARDENED CONCRETE

14.2.1 General

Cracks occur in hardened concrete for two principal reasons, viz:

- volume changes in the concrete ; and
- chemical reactions within the body of the concrete that cause expansion and subsequent cracking of the concrete.

Volumetric movement in concrete cannot be prevented. It occurs whenever concrete gains or loses moisture (drying shrinkage) or whenever its temperature changes (thermal movement). If such movements are excessive, or if adequate measures have not been taken to control their effects, the concrete will crack.

Chemical reactions within the body of the concrete, which can cause it to expand and crack, include reinforcement corrosion and sulphate attack (see Chapter 19 *Properties of Concrete*), and alkali-aggregate reaction (see Chapter 3 *Aggregates for Concrete*). Provided adequate care is taken in the selection of materials and good quality concrete is properly placed, compacted and cured, these reactions should not occur except in extreme environmental conditions.

14.2.2 Crazing

General

'Crazing' describes the very fine cracks which appear on the surface of concrete after it has been exposed to the atmosphere for some time. It can occur on both trowelled and formed surfaces but is more noticeable on the former, particularly when wet. It occurs as the concrete surface expands and shrinks during alternate cycles of wetting and drying, or as it carbonates and shrinks during long exposure to the air. The use of cement-rich mixes on the surface of the concrete, 'driers', exacerbates the problem, as does overworking (bringing excess mortar to the surface) or trowelling bleed water back into the surface.

On formed surfaces, crazing tends to occur on smooth faces cast against low-permeability form-face materials.

In New Zealand or Australia, crazing does not normally lead to durability or other serious problems.

Prevention of Crazing

To avoid crazing on trowelled surfaces:

- avoid very wet mixes;
- do not use 'driers';
- do not overwork the concrete;
- do not attempt finishing whilst bleed water is present;
- do not steel trowel until the water sheen has gone;
- commence continuous curing promptly; and
- do not subject the surface to wetting and drying cycles.

On formed surfaces, very wet and over-rich mixes should be avoided and curing should be continuous. The concrete should not be subjected to wetting and drying cycles during curing.

14.2.3 Drying Shrinkage Cracks

General

Hardened concrete shrinks, i.e. it reduces in volume as it loses moisture due to:

- the hydration of the cement; and
- evaporation.

The shrinkage caused by moisture loss is not a problem if the concrete is completely free to move. However, if it is restrained in any way, then tensile stress will develop. If that stress exceeds the ability of the concrete to carry it, the concrete will crack. A number of factors influence the shrinkage of concrete, in particular the total water content. Others include:

- the content, size and physical properties of the aggregate;
- admixtures, especially those containing calcium chloride; and
- the relative humidity;
- the curing conditions.

The cement content of concrete influences shrinkage drying almost only to the extent that it influences the amount of water used in a mix.

In order to reduce the total shrinkage of concrete:

- the water content should be minimised (consistent with the requirement for placing and finishing);
- the amount of fine material should be minimised;
- the highest possible aggregate content should be used;
- the largest possible maximum aggregate size should be used;
- good curing practices should be adopted; and
- the use of shrinkage admixtures.

However, simply reducing the shrinkage of a concrete will not necessarily reduce cracking since this is also influenced by the restraint, detailing, geometry, construction practice, etc.

Preventing Cracking due to Drying Shrinkage

The prevention of uncontrolled cracking, due to drying shrinkage, starts with the designer. Appropriate design and detailing is essential.

Specifically, attention should be given to the following:

- The provision and location of adequate reinforcement to distribute the tensile stress caused by drying shrinkage. This is particularly important in floors, slabs-on-ground, and similar applications where reinforcement may not be required for load-carrying or structural reasons.
- The provision, location and detailing of joints to isolate restraints and permit movement between discrete parts of the construction.

Construction practice is also important for it should ensure:

- that the concrete is properly placed, compacted and cured in order to minimise the magnitude of drying shrinkage;
- that the designer's details are correctly put in place before the concrete starts to dry out; and
- the removal of restraint by the formwork.

14.2.4 Thermal Movement Cracks

Thermal movement occurs when the temperature of concrete changes, due either to environmental changes or to the heat generated when the cement first hydrates.

Thermal movements due to changes in the ambient temperature are normally not a problem in concrete structures, provided an adequate number of control or movement joints in long straight walls and in similar members are included; and provided isolation joints are provided at restraints which might prevent the concrete from contracting or expanding.

14.3 JOINTS

14.3.1 General

Joints in concrete construction may serve a number of purposes but are of two basic types, viz:

- those that allow no relative movement of the concrete on either side of the joint; and
- those that allow such movement.

The former, construction joints, aim at bonding the concrete on either side of the joint in such a way that it acts monolithically. The latter aim to allow movement of the concrete in a controlled manner. Thus, they may be contraction joints, which allow for shrinkage movements; expansion joints, which allow movement towards, or away from, the joint but prevent movement in other directions; or isolation joints, which allow two abutting concrete faces to move freely relative to one another.

14.3.2 Construction Joints

General

Construction joints are concrete-to-concrete joints made in such a manner that the two faces are held together to prevent any relative movement across the joint. They are required whenever there is a break in concreting operations which is sufficiently long that the concrete which has been placed begins to harden. Such joints may be planned or unplanned.

Whilst unscheduled interruptions to the placing of concrete are to be avoided, as far as is possible, they do occur. Some interruptions can, however, be foreseen, for example at the end of the day, and should be planned carefully to ensure that the joint is placed in a position where it will have the least effect, either structurally or visually. Ideally, such interruptions should be planned to coincide with an expansion, contraction or isolation joint. This will minimise the number of joints and also the possibility of faulty construction joints.

Faulty construction joints weaken the structure and may allow moisture to penetrate into or through the joint; possibly causing reinforcement to rust, certainly resulting in efflorescence and staining of the concrete surfaces.

NZS 3109 does have three grades of finish for joints:

- A is a clean, lightly textured surface;
- B is a textured surface 5 mm amplitude; and
- C is a stepped or keyed joint.

Location

The designer should nominate/approve the location of construction joints in structural members because they usually result in a plane of weakness. Thus, they are normally located where shear forces in the member are low, e.g. in the middle third of beams and slabs.

Suitable locations for construction joints should be shown on the design drawings, and should not be changed without the approval of the designer. Nor should additional joints be made without the designer's approval.

NZS 3109 and AS 3600 requires that, unless otherwise specified, construction joints must be made at the soffits of slabs or beams and their supporting walls or columns **Figure 14.3.** As a general rule, horizontal joints are never allowed in slabs nor vertical joints in beams or slabs near their supports because shear stresses at these locations may be high.

Vertical Joints

When a construction joint has to be made in a beam or slab, a stop-end or bulkhead should be used to ensure that a vertical joint is properly formed **Figure 14.4**. If the concrete is left free, it will subside at an angle and be impossible to compact. The result will be a weak joint.

To assist the transfer of loads across vertical joints, dowels or keyways are advisable in slabs over 150 mm in depth **Figure 14.5**. Reinforcement should not be cut at construction joints so that, where necessary, stop-ends must be slotted or fitted in sections. They should permit reinforcement to pass through them but should prevent mortar leakage.

The treatment to be given the partially hardened concrete before fresh concrete is placed against it will depend on its age. If it is less than four hours old, it should suffice to brush it with a wire brush to roughen it, and then to remove all loose material. Where the surface is more than four hours old, at the time the fresh concrete is placed, scabbling, water-blasting or other means may have to be used to expose the coarse aggregate. The exposed surface should then be cleaned and dampened before fresh concrete is placed against it. A good mechanical keying of the coarse aggregates is the secret to a good vertical construction joint. See comments on NZS 3109 in *'General Requirements'* section. Reliance on grouts or other 'adhesives' to provide bond is not recommended.

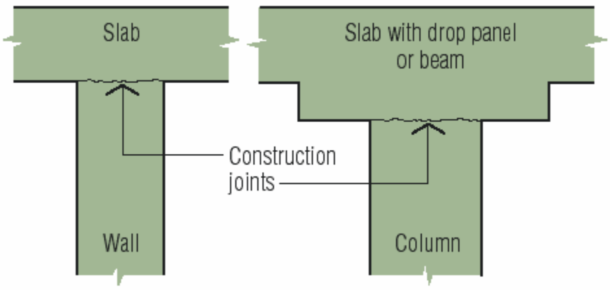

Figure 14.3 **Construction joints between horizontal and vertical elements**

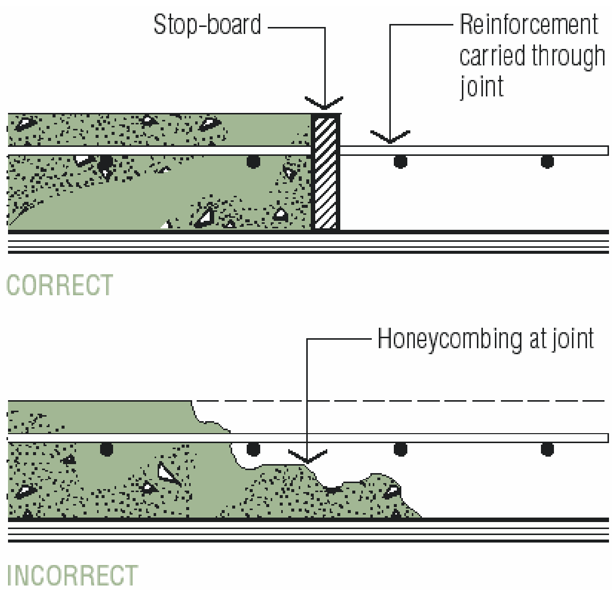

Figure 14.4 **Construction joint in slab**

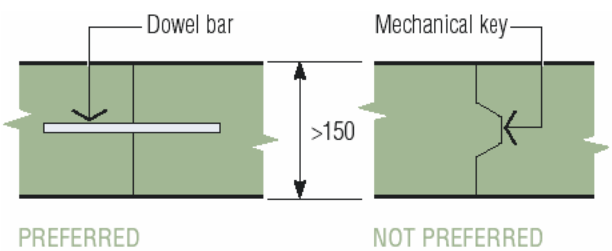

Figure 14.5 **Load transfer across construction joints in slabs over 150 mm thick**

Horizontal Joints

When fresh concrete settles, or is compacted mechanically, a layer of laitance, watery grout, tends to form on the top surface. If this is allowed to harden, it forms a plane of weakness. Whenever possible, therefore, laitance should be removed as early as practicable from the surface of concrete against which a horizontal joint is to be formed. When the joint surface is not more than four hours old, this is relatively easy. Surfaces may be simply wire-brushed to expose sound concrete and all loose material removed. Fresh concrete should then be thoroughly compacted against the old surface.

Where the joint is being made against concrete more than a few hours old, additional treatment may be necessary, depending on the time elapsed. Wire brushing, scabbling, bush-hammering, the use of high-pressure water jets and even sand-blasting are all methods which have been employed to expose sound concrete for the surface of a horizontal construction joint. The exposed surface should then be cleaned of all loose material and *free-standing wate*r; dampened, if necessary, and fresh concrete compacted against it. Lengthy delays between clean-up and concreting may require the surface to be cleaned and dampened again before concreting operations are resumed.

Where a clean neat line is needed (e.g. in an exposed or rendered wall) typical formwork details are shown in **Figure 14.6**.

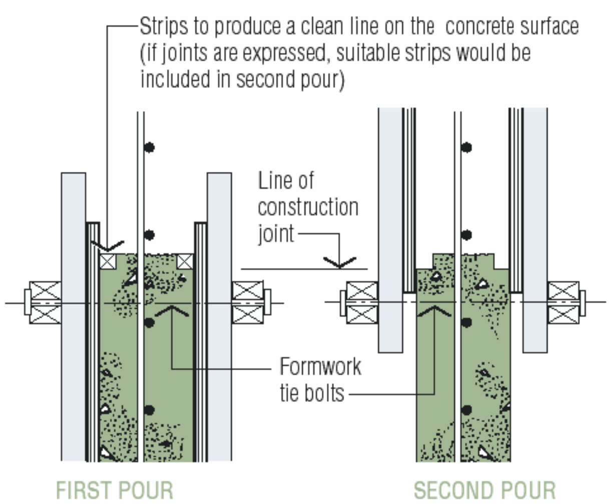

Figure 14.6 **Horizontal construction joint in wall when a clean, neat line is needed**

14.3.3 Contraction Joints

General

A contraction joint is one in which the two concrete surfaces are free to move away from one another as a result of shrinkage or thermal movement. Relative movement in the plane of the joint is prevented.

As concrete hardens and dries out, it shrinks. Unless this shrinkage is unrestrained, it creates tensile stresses in the concrete which may cause it to crack.

Whilst reinforcement will resist these tensile stresses and help prevent the formation of large cracks, it does not completely prevent cracking. It merely ensures that the cracks, as they occur, are more closely spaced and of smaller width. In properly designed reinforced concrete, they will not be obvious or of concern when seen from normal viewing distances.

Unreinforced concrete, on the other hand, will tend to develop somewhat larger cracks at more irregular intervals; wherever the tensile strength of the concrete is exceeded by the shrinkage stresses.

To prevent such cracks, contraction joints must be installed at appropriate intervals. It may also be advisable to install contraction joints in reinforced concrete rather than relying solely on reinforcement to control shrinkage stresses.

Contraction joints may also be required in mass concrete, or very large members, to allow for the shrinkage or reduction in volume which occurs as concrete cools or loses temperature after it has been placed.

Location

The location of contraction joints is a matter for the designer or supervising engineer to decide. For example, their location will often be defined on the drawings for pavements, industrial floors and similar applications, while in other cases they will be in a regular pattern or be an integral part of the architectural features.

Generally they will be situated where the greatest concentration of tensile stresses resulting from shrinkage are to be expected:

- at abrupt changes of cross-section; and
- in long walls, slabs.

Contraction joints are most common in large areas of concrete pavement where they are used to divide the concrete into bays. Ideally, these should be approximately square. They may also be necessary in long walls, particularly where an unplanned crack would be undesirable.

Contraction joints form a convenient point at which to stop concrete work at the end of the day. Construction joints should never be formed in the middle of a bay.

Construction

Contraction joints are formed by creating a vertical plane of weakness in the slab or wall. Movement is allowed at this point to accommodate that due to shrinkage. On the other hand, it is usually necessary to prevent movement in other directions, i.e. in directions parallel to the plane of the joint **Figure 14.7**. These twin requirements have the following consequences:

- The bond between abutting concrete surfaces in the joint must be broken.
- Reinforcement is terminated on both sides of the joint.
- Dowel bars if used must be unnbonded on one side of the joint.

Control Joints

A control joint is a form of contraction joint which is formed by building a plane of weakness into either a vertical or horizontal member. As the concrete shrinks, tensile stress is concentrated on this plane causing the concrete to crack there rather than elsewhere.

Normally, mechanical interlock across the two faces of the joint is expected to prevent other movement in the joint.

Control joints are, therefore, a relatively simple alternative to a fully formed contraction joint. They are placed wherever a formed joint would have been placed and are most widely used in unreinforced floors and pavements. Joint spacing in these applications range from 1 m for thin pedestrian pathways and driveways to, say, 5 m for road pavements.

Control joints can be made at any one of three stages during construction, viz:

- A premoulded strip may be inserted into the concrete, as it is being placed, to create a plane of weakness. Metal strips inserted into terrazzo or preformed plastic strips inserted into concrete pavements to form the centre line of the pavement are examples.
- A joint can be formed in the surface of the concrete with a suitable jointing or grooving tool. Upon hardening, the concrete cracks at this point, creating a joint.
- After the concrete has hardened sufficiently to prevent ravelling of the edges, a sawn joint may be formed. The joint should be made as early as possible and prior to drying shrinkage starting to occur. Delay can result in unplanned cracking of the pavement. The sawn joint is then filled with a joint sealant to prevent dirt and other debris entering it **Figure 14.8** as unsealed joints tend to fill with dirt and become ineffective.

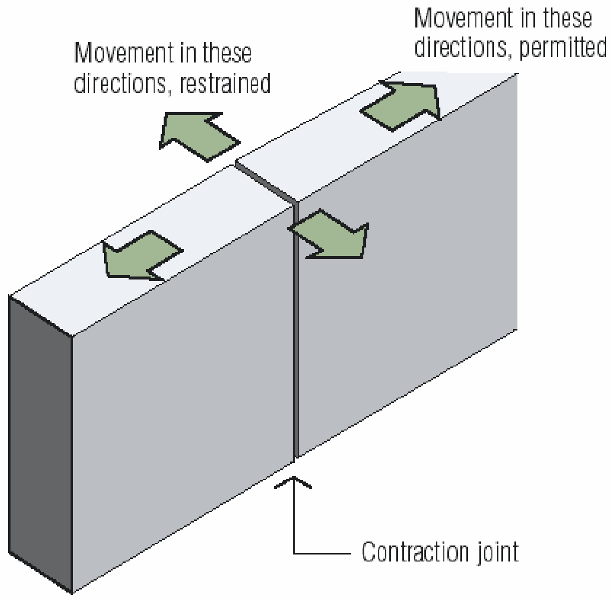

Figure 14.7 **Vertical contraction joint**

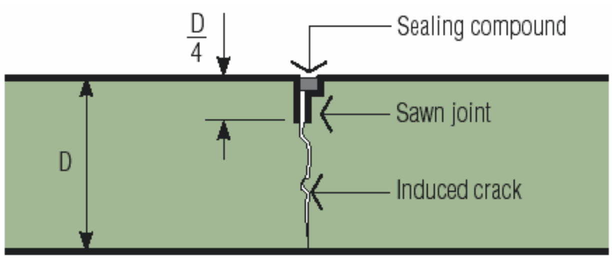

Figure 14.8 **Sawn joint in concrete pavement**

14.3.4 Expansion Joints

General

Expansion joints are formed to permit concrete elements to expand as the temperature of the concrete increases. Although the thermal expansion of concrete is low (approximately 0.01 mm/m/°C), it is sufficient to cause distress under Australian and some New Zealand climatic conditions where the surface temperature of a concrete pavement might increase by as much as 40–50°C during a hot summer's day.

Nonetheless, there is considerable divergence of opinion on the necessity for expansion joints in concrete structures. Most often, such structures have contraction or control joints, which, if properly protected from becoming filled with dirt or other debris, will accommodate the thermal expansion of concrete under most conditions. On the other hand, expansion joints are normally too widely spaced to function as contraction joints.

In the final analysis, it is the designer who must give careful consideration to the need for expansion joints in a particular building or structure. Consider-ations which might influence that decision are:

- Whether the structure contains contraction or control joints. (Some reinforced concrete structures incorporate reinforcement to control shrinkage cracking and omit contraction or control joints.)
- Whether the structure is likely to be subjected to a considerable range of temperature.
- Whether there are fixed restraints which are likely to cause damage (or be damaged) should thermal expansion take place. A pavement abutting a bridge deck is a good example.
- Whether the structure is likely to be subject to a significant temperature rise before it has dried out and drying shrinkage has occurred.

Construction

Since expansion joints are designed to permit movement in only one plane, i.e. at right angles to the plane of the joint, some provision must be made to prevent movement in the plane of the joint. This may take the form of a dowel or dowels **Figure 14.9**. Keyed joints are not usually satisfactory because of the difficulty of sealing and maintaining them. Those which become packed with dirt or other debris cease to function and may result in damage to the building or structure.

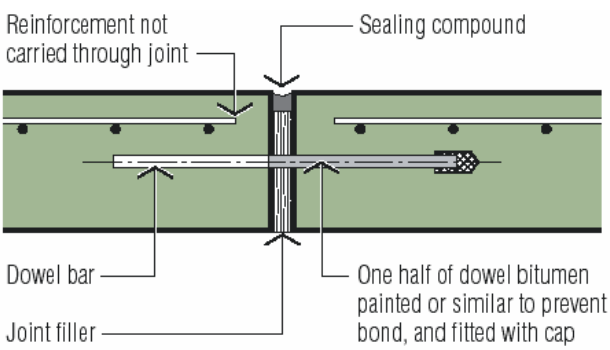

Figure 14.9 **Dowelled expansion joint**

14.3.5 Isolation Joints

An isolation joint is one that allows complete freedom of movement on either side of the joint as they have to accommodate both vertical and horizontal movements.

Location

Isolation joints are located in buildings and other structures at points where differential movement is likely to occur. Where such movements include both vertical and horizontal components, an isolation joint is indicated. They are used, for example to isolate:

- machinery footings from the rest of the building;
- one part of a building from another, basement slabs from columns by boxing out the column support **Figure 14.10**, a floor from a wall **Figure 14.11** (page 14.10); and
- delicate equipment.

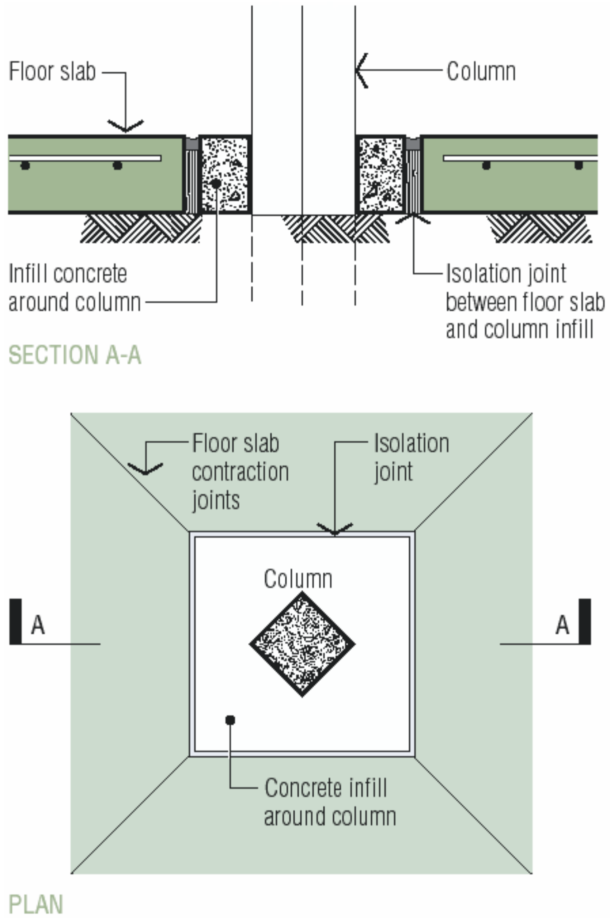

Figure 14.10 **Isolation joints around column**

14.3.6 Watertightness

In such structures as reservoirs, water tanks, sludge tanks and other liquid-retaining structures, watertightness is a very important consideration. In consequence, both vertical joints and horizontal joints require special attention to ensure that they remain watertight in service.

Vertical construction joints require sealing as they tend to open up as the concrete shrinks. Similarly, contraction joints and expansion joints, which are designed to move, require special treatment.

The most common solution in all three cases is the insertion of a waterstop in the joint. This may be one of two types, viz:

- A metal waterstop, normally a strip of copper sheeting placed in the joint so that it extends equal distances on either side.

- A flexible waterstop, normally a rubber or PVC moulded shape. It may have the shape of a dumb-bell or have a central bulb **Figure 14.12**.

Where specific sealing of an expansion joint is required, the waterstop must be capable of movement itself. Copper strips with a central crimp or flexible stops with a central bulb meet this requirement.

Isolation joints may need similar treatment. Horizontal joints, in walls for example, will not normally require a waterstop since, if properly pre-pared, there is less tendency for them to open up.

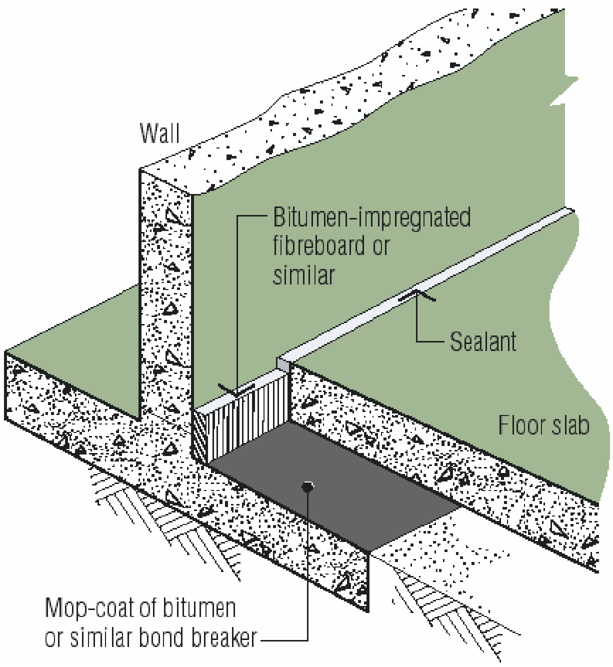

Figure 14.11 **Isolation joint between slab and wall**

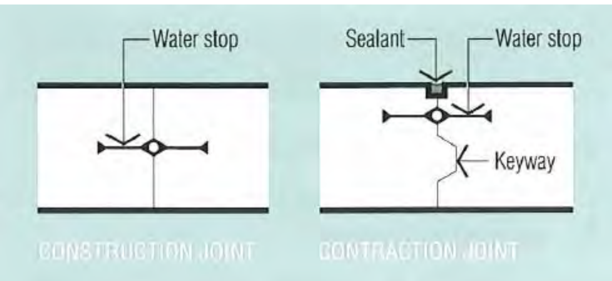

Figure 14.12 **Joints in water-retaining structure**

14.4 CRACK REPAIR

14.4.1 General

When repairs to a crack are being considered, the following factors should be taken into account:

- Whether the crack is dormant, i.e. it is unlikely to extend or open further; or whether it is live, i.e. it is likely to be subject to further movement.
- The width and depth of the crack.
- Whether or not sealing against pressure is required, and, if so, from which side of the crack will the pressure be exerted.
- Whether or not appearance is a factor.

Above all, it is necessary to determine the cause of the cracking. Whilst this may seem obvious, it is not always so. The repair of cracks caused by corroding reinforcement, for example, without remedying the cause of the cracking, will inevitably provide only a short-term solution.

Dormant cracks, i.e. those judged not likely to move further, have traditionally been filled by chasing them out and then sealing them with a cement grout or mortar. Whilst this is still an effective method in many cases, many materials are now available which are more effective, albeit also more expensive. They include epoxy resins, polyester resins and synthetic latex.

Live cracks, i.e. those judged to be still moving, require a sealant to be flexible if it is to be effective, e.g. polyurethane resins, acrylic gels and flexible epoxy resins. Since there is such a wide variety of these materials available, it is not possible to give detailed instructions on their usage. What follows is intended, therefore, to provide general guidance only. More-detailed information should be sought from the manufacturers of particular products.

14.4.2 Dormant Cracks

Dormant cracks may range in width from 0.05 mm or less (crazing) to 5 mm or more. Obviously, the width of the crack will have considerable influence on the materials and methods chosen for its repair.

Very fine cracks, e.g. crazing, are very difficult to repair effectively and in many cases the best option may be to do nothing. Autogenous healing of very fine cracks may occur with time.

If the problem is an aesthetic one, rubbing down the surface with a carborundum stone followed by sealing with a water-repellent material, such as sodium silicate, may provide a solution. Dirt, collecting in very fine cracks, tends to accentuate them.

Fine cracks, those up to about 1 mm in width, may often be sealed against water penetration by simply rubbing in a cement grout or slurry. The grout may be modified with a styrene butadiene or styrene acetylate polymer to increase adhesion.

Fine cracks may also be sealed by injecting them with either a cement grout or an epoxy resin. In recent years, epoxy resins have become the favoured material for this purpose and formulations are reported to be available which will penetrate cracks as fine as 0.1 mm in width, or less.

Epoxy grouts are widely used because:

- they adhere strongly to both fresh and hardened concrete;
- formulations are available which will adhere to most surfaces and harden even under wet conditions;
- they have good mechanical strength and low shrinkage; and
- they are resistant to a wide range of chemicals, including alkalis.

Epoxy grouts are normally injected under pressure. Nipples or injection points are fixed along the line of the crack and the surface is then sealed, on both sides of the cracked element, should this be necessary. The epoxy is then injected under pressure, using specialised equipment. In some instances a vacuum may first be applied to the crack to exhaust the air and assist the inflow of resin when the vacuum is released.

Wider cracks, i.e. those 1 mm or more in width, may also be sealed by injecting epoxy resin, particularly cracks on vertical surfaces. On horizontal surfaces it may be possible to simply pour the grout into the crack. For cracks wider than say 2 mm, a cement grout may be the most satisfactory, and is often preferred because of its total compatibility with the parent material and its ability to maintain an alkaline environment around reinforcement.

Other materials, such as polyester resins and synthetic latexes, have also been used satisfactorily to seal fine cracks. They can have lower viscosities than epoxies and, hence, can penetrate more easily. However, they may not achieve the same bond strengths and may be less reliable in damp or wet conditions. Polyvinyl acetate, for example, is water soluble.

14.4.3 Live Cracks

Live cracks must be sealed with a flexible material which can accommodate the movement in the crack. This is especially so when cyclic movements are anticipated.

Flexible epoxy resins are available which will accommodate a small amount of movement but the more usual procedure is to choose a mastic, thermoplastic or elastomer.

Mastics are generally viscous liquids such as non-drying oils, butyl rubber or low melting asphalts. They are used in conjunction with a groove or chase cut into the surface of the crack which is then filled with the mastic. They are the cheapest of the available sealants but their use is restricted to vertical surfaces or horizontal surfaces which are not trafficked. Movement in the crack, particularly in hot weather, may cause the sealant to extrude.

Thermoplastic materials are those which soften and become liquid or semi-liquid at higher temperatures, normally in excess of 100°C. Although less susceptible to temperature than mastics, they suffer from much the same disadvantages.

Elastomers include a wide range of materials, such as polysulphides, polyurethanes, silicones and various acrylics. Some are one-part, some are two-part materials. They have the advantage that they are less susceptible to temperature in the normal range experienced in buildings and other structures; adhere strongly to concrete; and are able to accommodate quite significant movements without failure. Reference should always be made, however, to the information supplied by the manufacturer to ensure the correct application of particular products to particular situations.

Formwork

Chapter 15

Chapter 15

Formwork

Formwork has a dual function in concrete construction. It supports the plastic concrete until the latter is sufficiently strong to support the actions/loads imposed upon it and it imparts a finish to the concrete surface. This Chapter describes the different types of formwork used in modern concrete construction and outlines the requirements which must be met for formwork to perform satisfactorily. The special requirements associated with the achievement of visually satisfying surface finishes are discussed in Chapter 13 *Control of Surface Finishes*.

Supplementary information on formwork is contained in CCANZ publications IB 29 *Formwork for Concrete* and IB 41 *Formwork Detailing*.

INTRODUCTION

Formwork is the temporary structure which moulds concrete into the desired shape, and holds it in the correct position until it is able to support the loads imposed upon it. It also imparts the required surface finish. Formwork and its supports (falsework) is a structural system and must be designed and built accordingly. The actions (loads) on it may be temporary but they can be extremely large. Frequently they are different in nature to those imposed on the finished concrete structure.

Concrete is an extremely plastic and mouldable material which will accurately reflect the shape, texture and finish of the surface against which it is cast. Any imperfection or inaccuracy in this surface will be indelibly inscribed on the concrete surface. Form-face materials must therefore be chosen both to achieve the required surface finish and, in conjunction with all the supporting elements, to maintain accuracy and stability under all the loads imposed during erection and concreting, and for some days into the life of the concrete structure.

At early ages, the concrete will not be able to support the loads imposed on it. Until it is able to do so, the formwork (and falsework) will therefore continue to be a loadbearing structure. Only when the concrete has achieved sufficient strength can the formwork be removed without any detrimental effect to the concrete structure.

Failure to meet the accuracy, stability and strength requirements will lead to formwork failures in the form of bowing, warping, misalignment, etc. reflected in the final structure. It could even lead to the catastrophic collapse of part or all of the formwork.

New Zealand does not have a specific standard for formwork but has requirements in NZS 3109 and NZS 3114. NZS 3109 also cross-references to the *Formwork for Concrete* AS 3610 document.

The cost of formwork is often a very significant item in the overall cost of a project. The formwork system should be the most economical available but cost should never be permitted to overrule the criteria governing safety, strength and stability. Indeed, the first cost of formwork may be a very poor guide to its suitability for a project. Multiple uses of good quality formwork can result in substantial overall economies. Formwork design and selection of materials should therefore always be approached on the basis of cost per use.

Relevant New Zealand Standards

NZS 3109 *Concrete construction*

NZS 3114 *Concrete surface finishes*

Relevant Australian Standards

AS 3600 *Concrete structures*

AS 3610 *Formwork for concrete*

Supplement 1 *Blowhole and colour evaluation charts*

Supplement 2 *Commentary*

15.1 BASIC COMPONENTS OF FORMWORK

The basic components of formwork for typical concrete elements are shown in **Figures 15.1 to 15.4** (page 15.3). It will be noted that the basic structure of almost all formwork is the same. It comprises:

- formface, e.g. a metal or plywood sheet, sawn timber;
- studs, or joists, lengths of sawn timber or, sometimes, metal sections, which support the formface and prevent it from bulging or bowing in one direction; and
- walers, or bearers, which brace the studs or support the joists, and prevent bulging or bowing in the other direction.

An important facet of formwork design and construction is the choice of spans (or centres) between studs, and then centres between walers or bearers, to prevent bulging and bowing.

15.2 REQUIREMENTS FOR FORM-WORK

15.2.1 General

Although formwork is constructed only to contain and support concrete until the cast structure is strong enough to support the imposed loads, it must provide a safe environment for all those working on or around it.

In addition to being strong enough, it must also be stable against overturning, uplift, and sideways movements. It must also meet all statutory requirements for access ladders, guardrails, working platforms, etc.

The requirements for formwork are summarised in **Table 15.1** (page 15.3). A great deal of further information is contained in AS 3610 and the two Supplements to that Standard. Supplement 2 is particularly useful for assessing the safety of formwork.

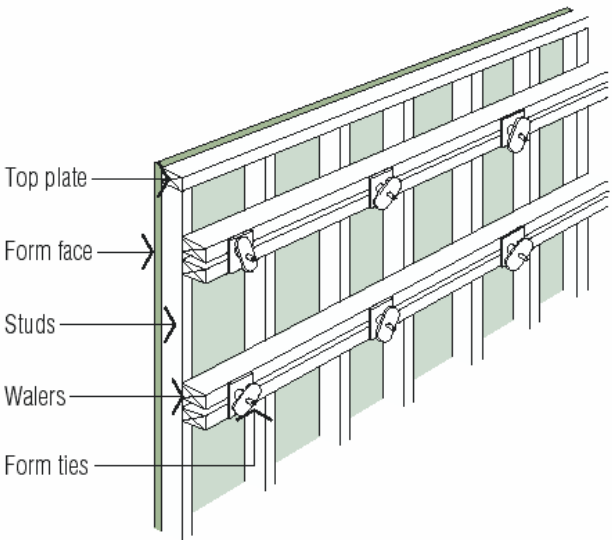

Figure 15.1 Wall forms

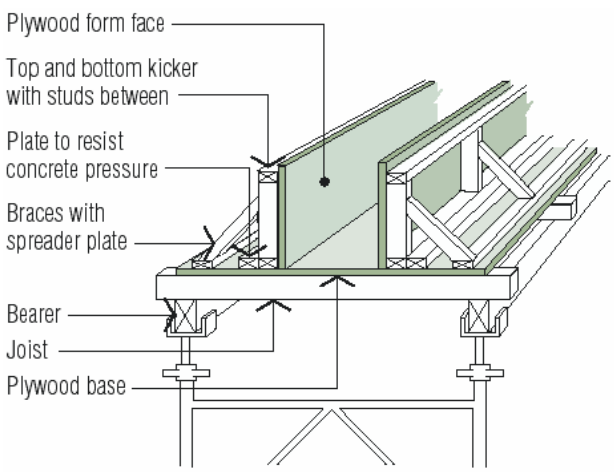

Figure 15.2 Beam form and supports

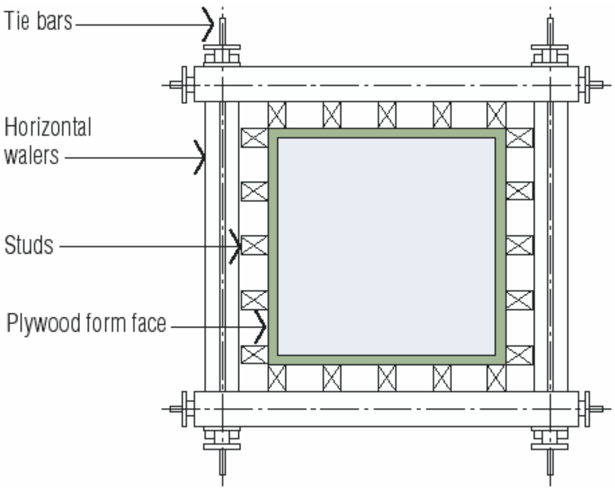

Figure 15.3 Column forms

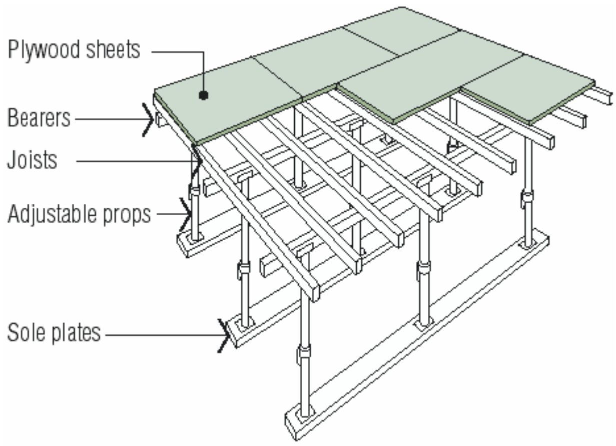

Figure 15.4 Typical soffit forms and falsework (diagrammatic only, bracing not shown)

Table 15.1 Requirements for formwork

Property	Purpose
Strength	Carry imposed loads.
Stiffness	Maintain specified shape and avoid distortion of concrete elements.
Accuracy	Ensure shape and size of concrete elements. Ensure specified cover to reinforcement.
Watertightness	Avoid grout loss and subsequent honeycombing of the concrete.
Robustness	Enable re-use.
Ease of stripping	Avoid damage to concrete surfaces.
Standardisation	Promote economy.
Safety	Ensure a safe working environment.

NZS 3109 and NZS 3114 also contain specific requirements.

With new materials, these requirements may be readily met. With re-use, all materials, except perhaps metal components, may be weakened; and even metal components may become loose fitting, or broken, due to wear. All formwork materials and components should be checked regularly to ensure that they are sound and safe.

15.2.2 Strength

All components should be designed to cater for the most severe loads that are likely to be imposed on the formwork. To achieve this, the design should be carried out by a person experienced and competent in formwork design.

Care should then be taken to ensure that the design details are met and that the construction loads imposed on the formwork are within the limits designated by the designer.

Sound materials should always be used. Re-used material may be satisfactory, but should be checked regularly to ensure it is adequate for the job in hand.

The strength of each item of formwork material contributes to the overall safety of the temporary structure.

15.2.3 Stiffness

Formwork should not bow, bulge, sag or otherwise move in such a way that the completed concrete element is outside the tolerances specified for the work.

The formwork designer should detail the formwork elements to have adequate stiffness, but site personnel are responsible for ensuring that the correct, good-quality materials are used in the proper manner.

For example, plywood sheeting for general formwork use has a greater capacity in one direction than in the other. It should always be used in the correct orientation **Figure 15.5**.

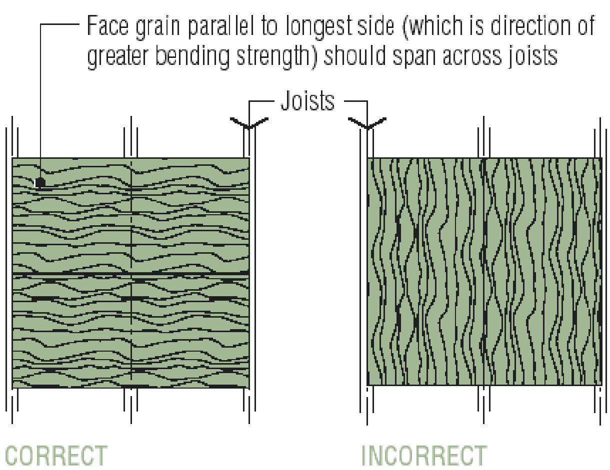

Figure 15.5 **Orientation of plywood**

15.2.4 Accuracy

In general, formwork should always be built to an accuracy greater than that desired in the finished concrete structure or element.

All support structures should ensure that this accuracy is maintained until the concrete has hardened.

The accuracy required may affect the selection of the material from which the formwork is to be built as some materials may be finished to tighter tolerances than others.

15.2.5 Watertightness

All joints should be sealed to stop grout (the cement and water) leaking from the formwork. Grout loss causes ragged edges, hydration staining and honeycombing, which in turn can affect strength, durability and appearance.

15.2.6 Robustness

Formwork should be robust enough to withstand repeated stripping, storing and erection. Re-use of formwork is important to the overall economy of the structure.

15.2.7 Ease of Stripping

Formwork should be easy to remove if damage to the concrete and/or to the form is to be avoided. Consideration should therefore be given to providing adequate draw (taper) on vertical faces and, also, to the movement which must be allowed in supports to facilitate easy removal of horizontal soffit forms and specialist systems such as table forms.

15.2.8 Standardisation

As far as possible, formwork components should be standardised in size to avoid unnecessary cutting. They should be able to be stripped, shifted and re-erected rapidly if speed of construction is to be maintained. This necessitates a system that comes apart easily, has a minimum of elements needing to be replaced (i.e. those damaged during removal) and is easily shifted with the available equipment. On small jobs, this will involve manhandling, but on large jobs the crane capacity may be used to maximum effect. Standardisation for speed of construction frequently requires more-expensive formwork but, once re-use is taken into account, lower overall project costs can result.

15.2.9 Safety

Formwork must provide a safe working environment for all those working on and around it. In addition to being of adequate strength, it must also be stable against overturning, uplift, and sideways or sliding movements. Properly guarded walkways should be provided around all areas of suspended work to provide safe access to them during construction and also a safe means of withdrawal as concreting progresses. Specifically, all statutory requirements must be met.

The tightness of all components must be thoroughly checked.

The stripping procedures specified must not be modified and the limit placed on stacked materials anywhere on the formwork must not be exceeded.

15.3 MATERIALS FOR FORMWORK

15.3.1 General

Formwork can be constructed in a variety of ways and from a number of materials. The size and nature of the project is most likely to determine which materials and which systems are likely to prove both technically sound and economic.

For example, on some projects, particularly small ones, certain formwork elements are likely to be used only a relatively few times. Considerable cutting and fitting may be involved with consequent wastage of materials. The use of lower grade materials may then be justified, provided safety is not jeopardised.

On larger projects, or even between project and project, the use of made-up elements leads to overall economy. Standardisation and interchange-ability then become particularly important.

15.3.2 Choice of Materials

Many materials may be used for formwork. **Table 15.2** provides a brief overview of the characteristics of those in common use.

Before the final selection of the formwork material is made for a particular job, a number of factors should be considered, including:

- the size of the forms;
- the shape of the forms;
- the surface finish required;
- the accuracy required;
- the number of re-uses required;
- the handling methods proposed;
- the methods of compaction proposed;
- the methods of curing proposed; and
- safety.

The weighting given to each factor will vary from project to project. Thus, on small projects, where multiple uses of formwork elements are unlikely and a great deal of cutting and fitting may be required, timber sections may well be indicated. On major projects, where standardised components can be employed, and multiple re-use achieved, heavier steel sections may well be warranted. Modular units may also be viable in such circumstances. In the final analysis, the choice of formwork materials is largely a matter of cost and availability. Most of the commonly accepted materials can be made to work in particular situations. The quality of the finish required and the overall cost of the formwork are likely to be the principal determinants.

Table 15.2 Formwork materials

Material	Uses
Timber	Commonly used for studs, bearers, joists, walers, etc. as it is readily available and easily worked with conventional tools. Has good load-carrying capacity and some suitable species are relatively light in weight, e.g. Oregon. Australian hardwoods tend to be heavier and more susceptible to warping. Some species of pine also tend to splinter, or split, when nailed.
Steel	Steel sections are used in formwork framing, particularly in patented systems. Strong and robust, steel-framed formwork is capable of multiple re-uses but requires a measure of standardization to warrant its additional cost. It is commonly used in precasting yards, particularly for repetitive work.
Coated plywood	Commonly used for soffits or as form liners in beams, columns and similar elements. Readily worked, coated plywood (properly handled) is capable of multiple re-uses.
Cardboard	Has been used in column and waffle forms. Normally suitable for one-off use only.
Glass reinforced cement (GRC) or plastic	Commonly used as permanent formwork, where it provides a decorative finish, or as the moulds for intricate shapes, particularly precast elements. Is relatively durable and capable of multiple re-uses.
Concrete	Precast concrete elements are used as permanent formwork – where the precast element is exposed to view in the completed structure. Also used to provide permanent forms in precast concrete factories where it is very economical for standard elements or components.
Rubber, thermoplastic and polystyrene materials	Used as formliners to provide intricate effects and for decorative finishes. Rubber and thermoplastic sheeting is used for the latter and is capable of multiple uses.

15.4 FORMWORK SYSTEMS

15.4.1 Modular Formwork

A number of systems of modular units are available on a sale or hire basis. The systems generally incorporate modular panels so that they can be re-used on a wide variety of jobs. Panels may use a steel frame with plywood facing which can be replaced when necessary. Generally, such systems incorporate simple but effective means of support and fixing.

15.4.2 Gang Forms

Gang forms are individual components, often modular, made up into large panels that are then tied and braced so that they can be moved as a complete unit.

Adequate cranage is essential for handling gang forms but the cost of the cranage is offset by the increase in speed of construction offered by moving large units of formwork from one location to another.

15.4.3 Table Forms

Table forms are a type of gang form used to form soffits. Large sections of soffit form, complete with propping and bracing elements, are fabricated into a single unit which, after use, can be lowered from the soffit, transported to the edge of the floor, lifted to the next level by the crane and realigned ready for the next concrete placement **Figure 15.6**.

Figure 15.6 **Typical use of table forms**

A 'transporter' is often used to wheel the table forms to the edge of the building, where a special rig enables the crane to handle them efficiently.

Table form systems are of great use in multi-storey building construction where speed is important, adequate cranage is available and first-off cost of formwork is offset by multiple re-uses.

15.4.4 Jump/Climb Forms

Jump or climb forms are gang forms for casting vertical elements such as walls and shafts. They are equipped with simple and rapid mechanical means of handling and require a minimum of labour and no reliance on cranage **Figure 15.7**.

The system strips the form, shifts it to the new position and then re-aligns it using its own inbuilt jacking system. Daily casting cycles are common.

Jump or climb form systems are capable of producing a high quality finish with good colour control.

Figure 15.7 **Typical self-climbing formwork system**

15.4.5 Slipforms

Slipform systems incorporate continuously moving formwork to speed construction and to eliminate the need for large areas of formwork. The concrete being 'extruded' must have adequate stiffness to hold its shape once it is free from the slipform. Slipforming can be undertaken either vertically (e.g. silos, towers and lift shafts) or horizontally (e.g. roads and safety barriers).

On vertical elements, the slipform has shutters on both faces that are lifted vertically, at a predetermined rate by a series of hydraulic jacks **Figure 15.8** (page 15.7). Typical rates of slipforming vary from 300–400 mm per hour. Some projects are slipformed continuously, whilst on others the free-standing height is limited to a few storeys.

Slipforming is not recommended where a high degree of colour control on the finished surface is necessary as colour banding is very difficult to avoid.

On horizontal construction, it can be used in its most simple form to construct kerbs and channels and, in the more sophisticated form, to construct roads or channel linings. Horizontal paving rates of up to 2 km per day have been achieved on large projects but an average rate of 300–500 m per day is more common. No edge forming is used for this work but the concrete must be made to a consistency to avoid slumping once it is free of the machine.

Figure 15.8 **Slipforming a vertical element**

15.4.6 Permanent Formwork

Permanent formwork is a type of formwork which is left in place to become part of the finished structure **Figure 15.9**. It may assist in taking some of the structural load or simply provide a permanent decorative finish.

Precast concrete and glass reinforced cement (GRC) are commonly used for permanent formwork, the former being used where the form takes part of the structural loads, the latter where decorative finishes only are required. The use of permanent forms minimises subsequent finishing operations and, hence, the scaffolding and falsework often required for these operations.

Figure 15.9 **Precast permanent formwork used for an edge-beam of a multi-storey building**

15.5 DESIGN OF FORMWORK

15.5.1 General

The design of formwork, particularly on large projects, calls for a considerable degree of skill and experience. Not only can the loads on it be both large and complex, but stripping procedures, and the manner in which they cause loads to be transferred to the concrete structure, can be of considerable importance.

Whilst the actual design should always be undertaken by a specialist formwork designer, all involved with either the erection or removal of formwork on the construction site should be aware of the factors which affect its performance, and in particular its strength and stability – and hence its safety. AS 3610 sets out requirements for the design and construction of formwork which are aimed at ensuring its safety.

15.5.2 Loads on Formwork

Formwork should be designed to support both the vertical and horizontal loads which are imposed on it whilst it is being erected and whilst it is in position. In supporting these loads, it should not deflect excessively, buckle, bulge or otherwise move out of position.

The most severe loading generally occurs when the concrete is being placed. However, this is not always the case, so that it is common to consider the loads on formwork at three stages of construction:

- ***During Erection***

  Loads on formwork during erection can arise from two principal sources: the weight of material, equipment, etc. which may be stacked on it prior to concreting; and the effects of wind which may exert both vertical and horizontal forces on the formwork and its supports. Care should therefore be taken to avoid excessive load concentrations and to ensure that bracing is installed as early as possible, and certainly before the formwork is used as a working platform **Figure 15.10**.

- ***During Concreting***

  During concreting, the concrete itself imposes a considerable dead weight on the forms. In addition, the weight of men and equipment on the platform should be considered. At this stage, also, lateral stability should be considered. The formwork with its load of plastic concrete is inevitably top-heavy and, hence, particularly susceptible to sideways movement. The possibility of impact arising from faulty handling of a concrete bucket or similar mishap should also be taken into account **Figure 15.11**.

- ***After Concreting***

  On multi-storey projects, it is usual for work to proceed on upper floors whilst the concrete structure below is still gaining strength. Consideration should therefore be given to the additional loads being imposed on the formwork, and particularly on the props supporting lower floors (see Clause 15.7.3).

  Of prime importance, however, is the lateral pressure exerted on side forms during and after concrete compaction. Vibration liquefies the concrete and increases the pressure exerted **Figure 15.12**. Due allowance should be made for this, particularly with deep pours, such as columns.

The lateral pressure exerted by fluid concrete during compaction is by far the most severe loading experienced by vertical forms. Problems such as formliners bulging and deflecting between supports frequently arise because its magnitude is underestimated. This is particularly the case with deep narrow forms, where it is often assumed the loads will be less than in, say, heavy columns. In fact, the width of formwork has little influence on lateral pressure, the principal consideration being the height of the fluid concrete. Factors influencing lateral pressure are set out in **Table 15.3** (page 15.9).

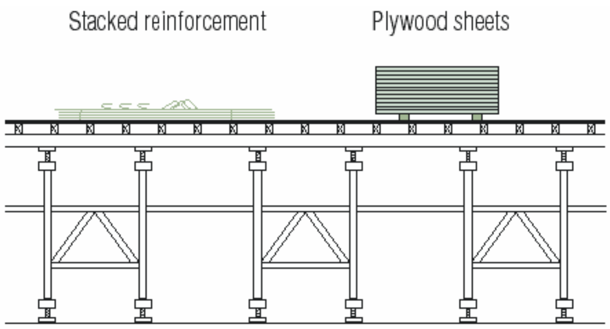

Figure 15.10 **Loads on formwork prior to construction**

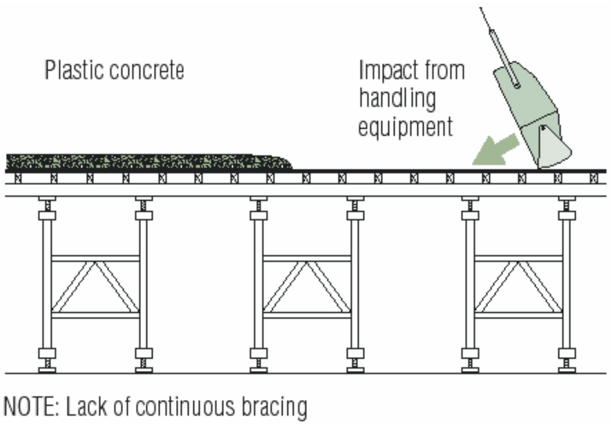

Figure 15.11 **Loads on formwork during concreting**

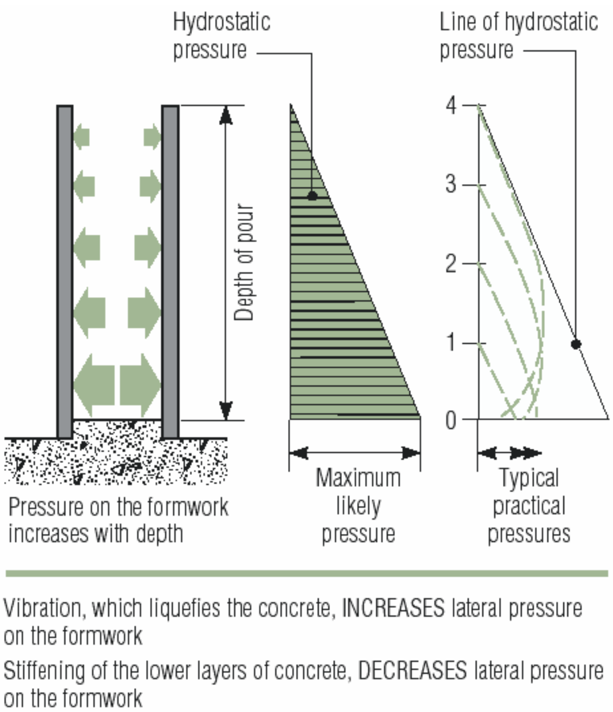

Figure 15.12 **Lateral pressures on formwork during compaction**

Table 15.3 **Factors affecting lateral pressure on formwork**

Factor	Effect on lateral pressure
Increasing concrete density	Increases
Increased rates of placing	Increases
Increased heights of pour	Increases
Internal vibration	Increases
Increased slump	Increases
Increased fluidity, e.g. superplasticity	Increases
Increased concrete temperatures	Decreases
Faster setting cements including accelerators	Decreases

In general terms, any factor which increases the fluidity of the concrete, or the height of fluid concrete, increases the lateral pressure on the formwork. Conversely, any factor which reduces these, reduces lateral pressure **Figure 15.12**.

15.6 FALSEWORK

15.6.1 Design of Support Structures

All propping, bracing and fixing elements should be considered as part of the total formwork system as it is these elements which transfer the loads from the working face to a stable foundation, e.g. the ground.

They must also be able to resist any tendency to overturn, i.e. the formwork as a whole must be stable during erection and concrete placement.

All support systems should be adequately braced to ensure stability and prevent progressive collapse. Bracing should be provided in two directions at right angles to each other and be provided near the edges of the system where concrete placement is likely to commence. All bracing should be between 30° and 60° to the horizontal.

Design of falsework systems should also take into account the final support conditions, e.g. the ground, and detail the size of base plates/spreader beams necessary to take the loads without sustaining excessive deflections.

Where falsework is supporting a structure that is to be post-tensioned, it is important to realise that the loads on the falsework will be significantly changed as the stressing takes place. It is necessary therefore to carefully design the falsework for these additional loads that may result during the stressing operation. The collapse of a partially built motorway ramp in Auckland illustrates the seriousness of problems that may occur.

In multi-storey construction, the propping should extend down a sufficient number of floors to ensure the loads are supported without excessive stress to or deflection of the recently cast structure. This design should take into account the rate of concrete strength gain with age and the effect that environmental conditions may have on it. Concrete gains strength more slowly in cold weather.

The design of support structures should also take into account the method to be used for stripping the formwork. It is normal practice to strip soffit formwork in two stages: first, the sheet/formface elements which are to be re-used quickly; and second, the support structure which is to remain in place until the concrete can carry the loads.

15.6.2 Undisturbed Shores

Proprietary systems are available that enable the support structure to remain in place whilst the formface materials are removed for re-use.

In these systems, the props extend from the base to the soffit of the concrete slab and the deck system is removed around them. This is to be preferred, as the props remain untouched until removal at a later date. Thus, the risk of deflection and stress changes in the concrete slab during reshoring is eliminated. It also ensures that the props for successive storeys remain in vertical alignment and there is no chance of props being overtightened, causing reverse stresses in the concrete slab.

15.6.3 Reshoring Systems

Reshoring systems involve the removal of a section of the formwork and support structure. The support structure is then replaced once the formwork is clear. With proper control and good supervision, these systems can give acceptable results. Props must be replaced in the original pattern and not overtightened to avoid causing undesirable stresses in the concrete.

The three usual methods of reshoring are:

- ***Secondary reshoring*** in which shores are placed before any formwork or props are moved. They are placed under the soffit form as close as possible to the original props. The original props and forms are then removed, taking care to mark the location of the original elements as the final stage is to replace the original props and remove the secondary props.

- ***Partial reshoring*** in which the soffit is stripped, bay by bay, and props are replaced on the correct grid and retightened. Typical bays are 2–3 m in width.

- ***Total reshoring*** which involves complete stripping of the soffit and subsequent replacement of the props. This is the least desirable method as it can impose severe stresses on the relatively immature concrete and give rise to excessive deflections.

15.7 CONSTRUCTION OF FORM-WORK

15.7.1 Erection of Formwork

On many projects the formwork is supplied and erected by a specialist subcontractor. Whilst this has many advantages, it can also cause some problems if there is not good communication between the project designer, the main contractor and the formwork contractor.

Specific matters to which attention should be given include:

- Limitations on the stacking of materials on either partially completed formwork, completed formwork, or on freshly placed concrete. These loads can be substantial and, unless controlled, can lead to overloading of partially completed structures.

- Limitations on the bracing of formwork against concrete elements of the permanent structure. Depending on the age of such elements they may not be able to support such loading without damage.

- Protection of surface finishes on existing work.

- Safety. The maintenance of a safe working environment is the responsibility of all involved with the project. Attention may therefore need to be given to such matters as the provision of: access ladders, guardrails and working platforms; safe-load areas and overhead protection for those working below; suitable lighting and similar facilities.

15.7.2 Preparation for Concreting

Cleanliness

Once the formwork is erected and set in the correct position, all enclosed areas and surfaces should be cleaned of all foreign debris that may affect the finished surface, including timber, reinforcing steel, tie wires, sawdust, sand, mortar, etc. This may necessitate a 'window' at the base of the form through which such material can be removed.

Where formfaces will be inaccessible after erection, e.g. wall forms, release agents should be applied to them before they are erected.

Immediately formwork has been stripped, it should be cleaned without damaging the formface. If necessary, any repairs should then be made to restore the surface. Formwork should be stored to avoid damage and should be stored/stacked to enable easy retrieval.

Release Agents

Most surfaces require the application of a release agent to allow the formwork to part easily from the concrete after it has hardened without damage to either surface. However, there are a few specialist plastic formliners that may not need a release agent.

Release agents permit easy separation of the formwork from the concrete and help to preserve the formwork. In selecting a release agent for a particular project, care should be taken in checking that it will neither:

- cause unacceptable discolouration to the concrete surface; nor

- leave any material on the concrete surface which will prevent bonding of subsequent treatments, e.g. render, paint.

In the case of wall and column forms, release agents should be applied to clean formwork before it is erected; in the case of soffit forms, before the reinforcing steel is placed **Figure 15.13**. The material can be applied by spray, brush, roller, squeegee, etc., depending on its characteristics, but on no account should it be allowed to coat reinforcing steel or any construction joint.

Figure 15.13 **Release agent being applied to soffit form before reinforcement is placed**

Inspection

Formwork must be set accurately in plan and be capable of maintaining the correct line, level, plumb, shape and tolerance during concreting and until the hardened concrete can take the loads.

This requires a detailed inspection procedure to ensure that all elements of the formwork are adequate, clean, in the correct place and wedged/bolted tight.

Before the formwork is assembled check that:

- the forms are clean;
- repairs have been completed;
- the correct release agent has been used and properly applied to vertical forms; and
- joints have been sealed.

Before concreting commences check that:

- the line, level and plumb are correct;
- dimensions are correct;
- all ties are at correct centres and tight;
- props and supports are in the correct locations;
- all bracing systems are in place;
- all wedges are nailed;
- all clamps are tight;
- all bolts, jacks, etc are tight;
- the supports are founded on solid material;
- all foreign material has been removed from forms;
- release agent has been correctly applied to soffits; and
- joints are sealed and cramped/wedged tight.

During concreting check for:

- line, level, and plumb maintenance;
- any settlement;
- any leakage; and
- any loosening of wedges, bolts, nails.

15.7.3 Stripping of Formwork

General

The project designer is normally required to provide a schedule of stripping times for formwork which is in accord with the requirements of NZS 3109. These are minimum stripping times designed to ensure that the structure remains secure from collapse and from damage which might affect its later performance, e.g. cracking or deformation in excess of that anticipated by the designer.

NZS 3109 also provides guidance on stripping times, which refines the requirements to take account of the specified class of surface finish **Table 15.4**.

Table 15.4 Minimum formwork stripping times – insitu concrete (from NZS 3109)

Formed Surface	Classification	Hot Conditions >20°C	Average Conditions ≤20°C >12°C	Cold Conditions ≤12°C >5°C
Beam and slab soffits	Forms	4 days	6 days	8 days
	Supporting members (shores or backprops)	12 days	18 days	24 days
Vertical faces	Finishes F6, F5, F4 (see Note 1)	1 day	2 days	3 days
	Finishes F3, F2, F1	9 hours	12 hours	18 hours
	A minimum of 2 days applied to the stripping of vertical faces where frost damage is likely.			

Note:

1. Finish references are from NZS 3114.
2. The stripping times for beam and slab soffits for members cured in conditions less than 5°C shall be increased by half a day for each day on which the daily average temperature was between 2°C and 5°C, or by a whole day for each day on which the daily average temperature was below 2°C.
3. Temperatures shall be taken as the average of the maximum and minimum air temperatures for a day.

The stripping times given in the Standard are subject to a number of general conditions which:

- limit the ratio of the span between supports to the overall depth of the section to less than 280/√(D +100) where D is the overall depth of the section in millimetres;
- require normal class concrete to have achieved at least 45% at 3 days OR 75% at 7 days of its 28-day characteristic strength; and
- limit superimposed loads on slabs to 2.0 kN/m^2.

Subject to these general provisions, stripping of formwork should be done at the earliest time which is consistent with the strength of the concrete. Where it is desired to leave vertical formwork in place, either to assist in curing the concrete, or because it suits the construction sequence to do so, it is desirable to ease the forms from the concrete surface as soon as possible to minimise colour variations.

Multi-storey Construction

Whilst AS 3610 provides some guidance on the minimum stripping times required for multistorey construction, it also points out that the construction and stripping of formwork systems which involve reshoring should be in accordance with the project and formwork documentation. In other words, it is incumbent on the project designer to provide this information.

Reshoring is a hazardous operation which, unless carried out in a correct and systematic manner, can lead to unacceptable loads being placed on the concrete at an early age.

This is particularly so for prestressed concrete as the stressing operations can cause quite substantial loads to be transferred to the shores, reshores, backprops and other temporary supports.

The advice of the project designer should therefore always be sought for both reinforced and prestressed concrete construction before specified procedures are changed in any way. If such procedures are not provided in the project documentation, they should be sought. In this context, it should be noted that AS 3610 designates the project designer as the person responsible for providing this information – not the formwork designer.

Summary CONSTRUCTION CHECK LIST

- **Loads**

  What are the stacked load limits at all stages?

  Are the stacked materials on spreaders?

  Will the loads be exceeded by any construction procedure?

- **Materials**

  Are the correct form materials being used?

  Is the formface appropriate to the finish required?

- **Position**

  Are the forms in the correct location?

  Are they to dimension and within tolerance?

  Are they accurate to line, level and plumb?

- **Fixing**

  Is the nailing/screwing adequate?

  Are the ties the correct type?

  Are they on the correct grid?

  Are all ties, clamps and bolts tight?

  Are wedges tight and nailed?

- **Bracing/Props**

  Are the props plumb?

  Are all loads centrally placed?

  Are supported elements wedged and nailed?

  Are props straight?

  Are base plates on adequate foundations?

  Is the bracing correct?

  Is the bracing firmly connected?

- **Cleanliness**

  Are the formfaces cleaned?

  Is any damage correctly repaired?

  Is the correct release agent in use?

  Is it being correctly applied?

  Has all debris been removed from within the form?

- **Watertightness**

  Are all joints properly sealed and cramped?

  Are the construction joints sealed?

- **Reinforcing Steel/Inserts**

  Is the reinforcement correct?

  Are all inserts/blockouts in the correct location?

- **Concrete/Concreting**

  Is the mix design in accordance with the specification?

  What is the maximum rate of placement permitted?

  Are the forms maintaining line, level, plumb, shape, etc. during concreting?

- **Stripping**

  What are the minimum stripping times?

  Has the project designer permitted modification of these?

  Do the procedures enable stripping without damage to form or concrete?

  Are the provisions consistent with the re-use times required?

  Has the crane the necessary slings, etc to move the forms quickly?

  What curing methods are to be used once the formwork is removed?

  Is the storage area for the formwork organised?

- **Safety**

  Are there adequate guardrails, handrails, walkways, signs, etc. in position?

- **Inspection**

  Are there enough experienced inspectors on the job to provide the correct supervision?

Reinforcement

16

Chapter 16

Reinforcement

Reinforced concrete is a composite material made up of concrete and some form of reinforcement – most commonly steel rods, bars or wires. This chapter provides basic information on the way in which steel and concrete combine to provide a versatile construction material. It also provides information on the types of reinforcement used in New Zealand and Australia (including types other than steel), and guidance on its handling and fixing.

INTRODUCTION

Reinforced concrete is a material that combines concrete and some form of reinforcement into a composite whole. Whilst steel rods, bars or wires are by far the most widely used forms of reinforcement, other materials are used in special applications, e.g. plastic fibres of various kinds. This chapter deals primarily with concrete reinforced with steel, but other materials are discussed briefly.

The aim of the reinforced concrete designer is to combine the reinforcement with the concrete in such a manner that sufficient of the relatively expensive reinforcement is incorporated to resist tensile and shear forces, whilst utilising the comparatively inexpensive concrete to resist the compressive forces.

To achieve this aim, the designer needs to determine, not only the amount of reinforcement to be used, but how it is to be distributed and where it is to be positioned. As we shall see, these latter decisions are critical to the successful performance of reinforced concrete and it is imperative that, during construction, reinforcement be positioned exactly as specified by the designer.

It is important, therefore, that both those who supervise the fixing of reinforcement on the job-site, and those who fix it, have a basic appreciation of the principles of reinforced concrete as well as the principles and practices of fixing it.

Relevant New Zealand Standards

AS/NZS 4671 *Steel reinforcing materials*

NZS 3101 *Concrete structures*

NZS 3109 *Concrete construction*

Relevant Australian Standards

AS 1310 *Steel wire for tendons in prestressed concrete*

AS 1311 *Steel tendons for prestressed concrete – 7-wire stress-relieved steel strand for tendons in prestressed concrete*

AS 1313 *Steel tendons for prestressed concrete – Cold-worked high-tensile alloy steel bars for prestressed concrete*

AS 1554 *Structural steel welding* (known as the *SAA Structural Steel Welding Code)*

AS 1554.3 *Welding of reinforcing steel*

AS 3600 *Concrete structures*

AS/NZS 4671 *Steel reinforcing materials*

16.1 REINFORCEMENT TYPES

16.1.1 General

In New Zealand and Australia, the reinforcement in reinforced concrete is usually provided by steel bars or by steel wires welded together to form a mesh. Bars are normally associated with beams and columns and mesh with floors and walls. However, mesh may also be used in beams and columns, and bars used in floors.

Concrete may also be reinforced with fibres, the main types being steel and glass. Polypropylene fibres are also available but do not increase the tensile strength of a concrete member in the same way as bars, steel mesh or other fibre types (see Clause 16.1.6).

Reinforcement (reinforcing steel) is defined by NZS 3101 as '*steel bar, wire or mesh but not tendons*'. This definition precludes the use of fibres (steel and other types), non-metallic reinforcement and non-tensioned prestressing strand, bars and wires. It also requires that reinforcement be deformed bars or mesh (welded wire mesh) except that plain bars or wire may be used for fitments. However, steel fibres are covered in Appendix A-C5 of NZS 3101.

NZS 3101 calls up AS/NZS 4671. The following comments in this chapter relate to the requirements for reinforcement set out in AS/NZS 4671.

16.1.2 Standard Bars

Manufacturing Processes

Reinforcing bars ('rebars') are manufactured in New Zealand and Australia to comply with the requirements of AS/NZS 4671. There are a number of processes by which they can be manufactured and these, along with the chemical composition of the steel, can significantly affect the properties of the bar.

'Micro-alloyed' reinforcement is produced by adding small amounts of an alloy, e.g. niobium, vanadium, or vanadium and nitrogen, to the steel during its manufacture. During the hot-rolling process, these precipitate as very fine nitrides, or carbides, which increase the minimum yield strength.

'Quenched and tempered' (QST) reinforcement is produced by the controlled water-quenching of the outer layers of hot-rolled bar, thereby hardening it and increasing the minimum yield strength. At the same time, the process preserves the excellent durability and weldability of the parent material.

Both processes can achieve satisfactory bendability, re-bendability and weldability in high-strength bar. Nevertheless, all reinforcing bars do not behave in the same manner in respect of these properties. Care should therefore always be taken to ensure that 'rebar' complies with the requirements of AS/NZS 4671.

The Australian Certification Authority for Reinforcing Steels (ACRS) is an independent body formed in 2001 to undertake third-party product certification on steel reinforcing bar, wire and prestressing tendons. Modelled on European practice, ACRS certification ensures end-user confidence that supplied reinforcement materials meet the relevant Australian Standards.

Classification and Designation of Reinforcement

In accordance with AS/NZS 4671 reinforcing steel is classified by: shape; strength grade; relative ductility and size.

- ***Shape***

  Reinforcing bars can be either plain, deformed ribbed or deformed indented. The shapes are designated by the letters R (Round), D (Deformed ribbed) and I (deformed Indented) respectively. Generally, only D (deformed ribbed) bars will meet the intention of the requirement in NZS 3101 that reinforcement be deformed. However, AS/NZS 4671 contains provisions outlining a test method to measure the bond performance of indented bars or ribbed bars with ribs not meeting the specification set out in AS/NZS 4671.

- ***Strength grade***

  The tensile strength of reinforcement measures how strong it is when it is pulled or stretched. When steel is stretched and then released, it will return to its original length, provided it is not overloaded, i.e. it will behave elastically. However, as the load increases, there comes a point where it will not recover (the steel is permanently stretched or has yielded). The steel is then classified as having a yield strength of so many MPa, the stress at which it first began to yield.

  Strength grade is designated by the numerical value of the lower characteristic yield stress, 250, 300 and 500 MPa. The 300 strength grade refers to an earthquake grade specifically manufactured for New Zealand conditions. Reinforcing steel with a strength grade above 250 MPa is also required to comply with the specification of an upper characteristic yield stress. (Note: Strength grades under the previous standards were 250 and 400. For comparison, the tensile strength of concrete is typically 2–4 MPa.)

- ***Ductility class***

  There are three classes of ductility designated L, N and E for low, normal and earthquake respectively. E class has been especially formulated for the situation in New Zealand and is not expected to be either manufactured or available in Australia. All steel used in New Zealand is designated Ductility Class E.

- ***Size***

  The size of the reinforcement is designated by the nominal diameter of the bar expressed in millimetres. The common sizes of reinforcing bars available in New Zealand and Australia of the various grades and classes are shown in **Table 16.1**.

Reinforcement is designated by stating the above designators in the order of shape, strength grade, ductility class and size. For example a deformed ribbed bar of grade 500 MPa earthquake ductility steel with a nominal diameter of 16 mm is designated 'D500E16'.

Table 16.1 **Design data for reinforcing bars (after AS/NZS 4671 for New Zealand)**

Nominal diameter (mm)	Cross-sectional area (mm^2)	Mass per metre length (kg)	Product grade and class
12.0	113	0.888	500E
16.0	201	1.58	500E
20.0	314	2.47	500E
24.0	452	3.55	500E
28.0	616	4.83	500E
32.0	804	6.31	500E
36.0	1,020	7.99	500E

Identification of Standard Grades of Reinforcement

The standard grades of reinforcing steels can be identified by either an alphanumeric marking system on the surface of the bar or by a series of surface features on the product at intervals of not more than 1.5 m, see **Figure 16.1** (page 16.4). In addition deformed reinforcement has to carry marks enabling the steel producer to be identified.

Further, AS/NZS 4671 sets out requirements for the labelling of each bundle of reinforcing steel or mesh.

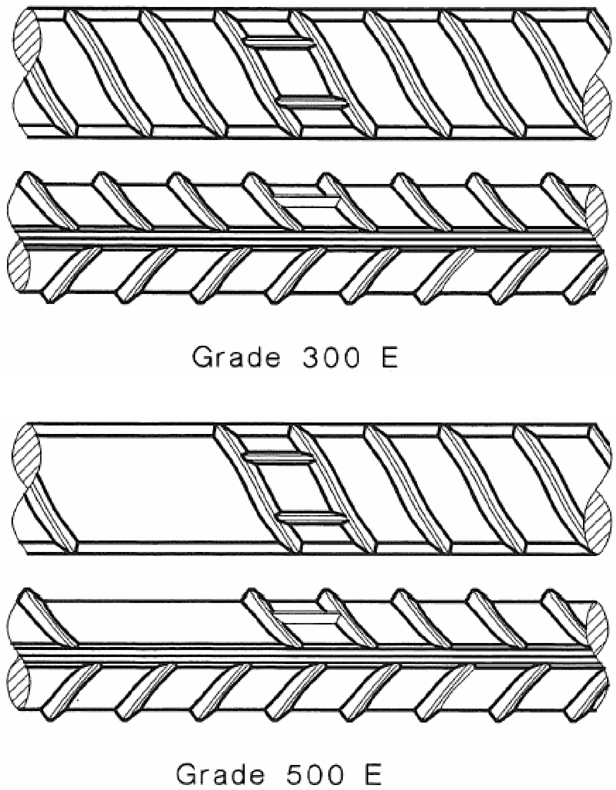

Figure 16.1 **Examples of grade identifiers (after Figure 4 AS/NZS 4671)**

Weldability

Reinforcement conforming to AS/NZS 4671 is weldable. Depending on the manufacturing process used and the chemical composition of the steel, requirements for welding may vary from those required for reinforcement complying with AS/NZS 4671. Designers should consult the manufacturer's literature for specific advice. Welding should be carried out in accordance with AS 1554.3. More-detailed information and guidance can be gained from the Welding Technology Institute of Australia (WTIA) Technical Note TGN-BC-01. Note that 500 MPa reinforcement manufactured overseas may not conform to AS/NZS 4671. It may have a higher carbon equivalent content, making the requirements for welding more stringent.

Generally, reinforcement complying with AS/NZS 4671 will require:

- The use of hydrogen-controlled electrodes.
- The use of special precautions in adverse conditions, e.g. wet weather, temperatures ≤0° C.
- The use of preheating when bars over 25 mm diameter are being welded.

Note the limitation on the location of welds in a bar that has been bent and re-straightened, i.e. it shall not be welded closer than $3d_b$ to the area that has been bent and re-straightened.

Bending and re-bending reinforcement

AS/NZS 4671 specifies for bars of diameter ≤16 mm a 90° bend and re-bend test and for bars ≥20 mm a 180° bend test. It is thought these requirements will ensure that bars likely to be re-straightened in the field, i.e. with d ≤16 mm, can be safely re-bent.

16.1.3 Mesh Reinforcement

Manufacturing Process

Mesh reinforcement consists of a 'mesh', or grid of cold-rolled steel wires welded together in a regular pattern (either square or rectangular. The wires used in the manufacture of mesh may be either plain, deformed or indented, and are required to comply with the requirements of AS/NZS 4671. Deformed wire is the more widely used, but plain or indented wire may be appropriate for certain applications.

Mesh is manufactured on automatic machines that weld 'transverse' bars to the 'longitudinal' bars to produce a mesh that is then cut to standard lengths. The longitudinal bars may vary in diameter between 5 and 11.9 mm. When the mesh pattern is square, the transverse wires are the same diameter as the longitudinal wires. Rectangular mesh has transverse wires of 7.6 mm diameter at 200 mm pitch regardless of the diameter of the longitudinal wires.

Designation of Welded Mesh

Welded mesh is designated in a similar fashion to reinforcing steel. The designation reflects:

- ***Shape*** – the shape of the bars by the letters; R (Round), D (Deformed) or I (Indented),
- ***Strength grade*** – by the numerical value of the lower characteristic yield stress,
- ***Configuration of orthogonal bars*** – by the letters S (Square) or R (Rectangular) configuration,
- ***Ductility class*** – by the letters L (Low), N (Normal) or E (Earthquake),
- ***Size*** – by the numerical value of the nominal diameter expressed in millimetres,
- ***Transverse spacing of the longitudinal steel*** – by the numerical value of the transverse spacing expressed in millimetres divided by 100, and

- ***Transverse reinforcement in rectangular meshes*** – by the numerical value of the nominal diameter expressed in millimetres.

Mesh is designated by listing the above designators in the order of shape, strength, configuration, ductility, size, spacing and secondary reinforcement if applicable. For example, a square mesh consisting of 9 mm diameter deformed ribbed bars at 200 mm centres, of grade 500 MPa low ductility steel is designated 'D500SL92'. If all the welded mesh ordered or required for the project was to be deformed ribbed bars, of the same strength but varied in other respects then the designation for that project could be abbreviated to 'SL92'.

Unfortunately at the time of writing, the New Zealand Mesh Manufacturers have not yet accepted the AS/NZS 4671 convention for describing meshes.

Table 16.2 sets out meshes commonly available in New Zealand with current designations of mesh types. Where meshes have a D designation, i.e. the MDT series, they can be regarded as having ductile E status with all other meshes being ductile L, being manufactured from low-carbon steel which is drawn through a die to produce a high tensile strength. This process is a form of 'cold working' the steel. Typically wires are in the strength range of 575 to 775 MPa. Wires traditionally formed by this process tend to have a low ductility and hence their use in structural applications is limited.

A recent development in New Zealand are meshes where the wires have a more acceptable ductile characteristic which improves performance in earthquake conditions. A limited D range is likely to be available for this special mesh compared to the sizes currently available and should be discussed with the manufacturers.

Mesh is most commonly used in slabs and walls. Rectangular mesh is used in road pavements and slabs that span one way or are rectangular, whereas in slab-on-ground construction square mesh is most popular.

Special meshes include: 'girder wrap' for use in fire protection work; 'trench mesh' for use in footings in domestic and other low-rise structures; and 'ductile mesh' for suspended slabs. Mesh can also be bent to form reinforcing cages or fitments for beams and columns.

Table 16.2 Dimensions of welded square mesh fabric

		Main and Cross Wire		Welded Fabric	
Mesh type	**Nominal pitch** (mm)	**Diameter** (mm)	**Cross-sectional area** (mm^2)	**Cross-sectional area per metre width** (mm^2)	**Mass per square metre** (kg)
333 M	75	6.30	31.17	409	6.426
334 M	75	6.00	28.27	371	5.829
335 M	75	5.30	22.06	290	4.548
338 M	75	4.00	12.57	165	2.590
661/0 M	150	8.00	50.27	330	5.181
661 M	150	7.50	44.18	290	4.554
662 M	150	7.10	39.59	260	4.081
663 M	150	6.30	31.17	205	3.213
664 M	150	6.00	28.27	186	2.914
665 M	150	5.30	22.06	145	2.274
666 M	150	5.00	19.63	129	2.024
668 M	150	4.00	12.57	82	1.295
6610 M	150	3.15	7.79	51	0.803
MDT 500 Series Ductile Meshes					
500-200	250	8	50.27	200	3.157
240	210	8	50.27	240	3.758
300	250	10	78.57	300	4.932
350	225	10	78.57	350	5.480
400	200	10	78.57	400	6.615
450	175	10	78.57	450	7.046

16.1.4 Stainless Steel Bars

Stainless steel reinforcement, is becoming more readily available and is sometimes used in extremely aggressive situations where its higher cost can usually be justified. It is not required to be isolated from normal reinforcement and can be used in locations which are subjected to aggressive exposure while normal reinforcement is used in more protected locations. Stainless steel can be welded using appropriate electrodes and techniques. Care is required when fabricating and bending it to prevent contamination from normal reinforcement.

There can also be a significant loss of bond with plain stainless steel bars but, for deformed bars, the bond strength is similar to that for normal reinforcement.

16.1.5 Surface Coatings

General

Provided the concrete is of an appropriate grade, is properly compacted and cured, and the reinforcement has the proper concrete cover, surface coating of the reinforcement should not be necessary under normal circumstances. However, if additional protection from corrosion is thought necessary, then steel reinforcement may be galvanised or given an epoxy coating by fusion bonding.

It should be noted, however, that neither NZS 3109 or AS 3600 permit any reduction in the requirements governing durability when coated reinforcement is used.

Galvanising Reinforcement is galvanised by first immersing it in acid to clean it, and then dipping it in molten zinc at a temperature of about 450°C. The zinc reacts with the steel and, in a few minutes, forms a coating between 60 and 100 microns thick, which is chemically bonded to the reinforcement.

Care must be taken that this coating is not subsequently damaged. Hence, reinforcement should be cut and bent before being galvanised. Where damage does occur, the area should be repaired with a zinc-rich paint.

Galvanised reinforcement may also react with the alkalis in cement, with the evolution of hydrogen, and cause hydrogen-embrittlement of the steel. It is good practice, therefore, to passivate the bars by the application of a 0.2% sodium dichromate solution.

Care should be taken when handling galvanized reinforcement because contact with chromates may cause dermatitis.

16.1.6 Fibres

Steel Fibres

Steel fibres in a range of shapes and sizes can be used to reinforced concrete. Concrete structures can be designed to incorporate these fibres to replace, or partly replace, conventional reinforcement. NZS3101:2006 documents a test method that may be used to determine the material properties of steel fibre reinforced concrete (SFRC) and provides guidance on the design of SFRC used in structural applications, in the ultimate and serviceability limit state.

Steel fibres are manufactured from a variety of different processes and raw materials. They are available in a range of shapes and sizes, and can be loose or collated (glued together in strips). Typically they are between 20 and 60 mm long and combine a tensile strength of between 800 and 2,500 MPa with a modulus of elasticity of around 210,000 MPa.

Steel fibres can be used as the main and unique reinforcing for industrial floor slabs, shotcrete and prefabricated concrete products. They can also be used for structural purposes in the reinforcement of slabs on piles, the full replacement of the standard reinforcing cage for tunnel segments, cellars, piles, slab foundations, as well as the shear reinforcement in pre-stressed elements.

In well compacted concrete the corrosion of steel fibres is restricted to the surface of the concrete. Staining may be unsightly and should be accounted for in architectural applications and when appearance is important.

Specifications for steel fibres usually require compliance with either EN 14889-1 or ASTM A820.

Glass Fibres

Glass fibres are not normally used to replace conventional steel bar or mesh since they lose strength rapidly at high temperatures. Even at comparatively low temperatures (25°C), some long-term loss in strength must be expected, although, depending on the temperature and humidity conditions, this does tend to stabilise. Glass fibres find their principal application in New Zealand and Australia in the manufacture of glass-reinforced cement (GRC) which, in turn, is used mostly in the production of architectural claddings, permanent formwork, and in the simulation of sandstone and similar building materials.

Synthetic (Polymer) Fibres

In New Zealand and Australia, synthetic fibres are supplied for use in concrete, mortar and grout.

There are two main types of polymer (usually polypropylene) fibres: micro and macro.

Micro-synthetic fibres are further classified as either mono-filamented, which are hot drawn through a circular cross section die; or fibrillated, which are extruded rectangular films that are slit longitudinally and fibrillated to produce a lattice pattern. Micro-synthetic fibres are primarily used to mitigate cracking in fresh concrete, and to increase the impact and abrasion resistance of hardened concrete. They cannot be substituted for conventional steel reinforcement, or for increasing *recognised* control joint guidelines.

Monofilament polypropylene fibres are used to reduce the risk of spalling in concrete under fire conditions. Concrete with low w/c ratio, the capillary pores are discontinuous and steam generated inside the concrete under fire conditions cannot escape. This can cause spalling of the outer layers of concrete. By adding polypropylene fibres to the concrete, pressure is released by melting of the fibres which allows steam to escape, lowering the risk of spalling.

Macro-synthetic fibres have dimensions similar to steel fibres, and can be used to provide concrete with some post-cracking, load-bearing capacity. The long-term performance of these fibres under sustained loading should be considered during the design stage. The fact that these fibres soften when subjected to fire may also be a consideration.

Specifications for synthetic fibres usually require compliance with EN 14889-2, or the acceptance criteria for fibre reinforced concrete prescribed in ASTM C1116,

Other Fibres

Other fibres used in conjunction with cement include cellulose (which has replaced asbestos in sheet products), and carbon fibres. Reference should be made to manufacturers' data or specialist publications for further information on these materials.

For further information on Fibre Reinforced Concrete refer to CCANZ Information Bulletin IB 39.

16.2 FABRICATION

16.2.1 General

The fabrication and fixing of reinforcement, within the tolerances specified for the project, are two of the most important facets of concrete construction. Reinforcement is placed in concrete members to resist the stresses in the member that result from the loads imposed on it. The designer calculates the magnitude of the stresses and then determines both the amount and the position of the reinforcement necessary.

If the structure is to perform as intended then the appropriate shape, strength grade, ductility class and size of reinforcement must be fabricated, fixed and surrounded by concrete as shown in the drawings.

16.2.2 Scheduling

The first step in the fabrication of reinforcement is the preparation of a schedule which lists each individual bar shape or sheet of mesh required for the job. This will show:

- the shape, strength grade, ductility class and size of reinforcement for each item;
- the shape and dimensions of each item;
- the number of identical items;
- identifying numbers or positions; and
- the total mass.

It is prepared by a scheduler from the structural drawings and other instructions. From this schedule, the reinforcement supplier will cut, bend and, where required, fabricate reinforcement for delivery to the site.

16.2.3 Cutting

Straight bars are cut normally by shearing, which may slightly distort the end of the bar. If smooth, square ends are required (e.g. on dowels for use in movement joints), friction cutting or sawing is preferred. Where mesh is to be supplied in sheets less than 6 m long, the reinforcement supplier uses a full width guillotine. On site, the mesh is cut and trimmed with bolt cutters, oxy-acetylene equipment or angle grinders.

16.2.4 Bending

Reinforcement may need to be bent during fabrication to accommodate it within the shape of the concrete member, to provide reinforcement in areas of tension or to provide anchorage. Bending may be carried out whilst the reinforcement is cold, i.e. at normal temperatures, or whilst it is hot, i.e. at temperatures up to 600°C.

When reinforcement is cold-formed, it loses a certain amount of its ductility, i.e. it becomes more brittle. When steel is overstressed during bending operations, or is re-bent, further reducing its ductility, it may become subject to 'brittle failure', i.e. a sudden fracture of the steel under load.

To prevent such brittle failures and to avoid overstressing of the concrete inside the bends, NZS 3109 specifies minimum diameters for bends in bars of different strength grades to be used in different situations. These recommendations are shown in **Table 16.3** (page 16.7) and actually take the form of recommended minimum diameters for the pins around which the steel is wrapped or bent during fabrication and take into account:

- the strength grade of steel;
- the diameter of the bar;
- the purpose of the reinforcement;
- the possibility of re-bending; and
- whether or not the bar is coated.

Typical pin diameters range from three times the diameter of wire to be used in fitments to eight times the diameter of coated bars 20 mm in diameter or greater.

Heating of the cold worked steel is permissible provided the temperature is not allowed to exceed 600°C as an absolute maximum. If the temperature exceeds 450°C, the bars are downgraded, i.e. treated as 250 grade.

Micro alloy steel produced in New Zealand is not so temperature sensitive.

Finally, it should be noted that the recommendations set out in NZS 3109 on the bending of reinforcement are formulated for bars complying with AS/NZS 4671 Ductility E. Steels not complying with these specifications, e.g. some steels manufactured overseas, may be damaged by bending to the diameters recommended. In this context, it should also be noted that bending deformed bars over a too small diameter pin can also damage the bar. The deformations themselves may be crushed, causing minute cracks which act as stress initiators during subsequent bending operations.

16.2.5 Re-bending

Although in principle the re-bending of reinforcement is undesirable because of the reduction in its ductility, occasions do arise on site where some re-bending is unavoidable. In all such cases, the proper equipment should be used. 'Bending' with the aid of a pipe and/or sledge hammer is not acceptable.

If bars are already partially encased in concrete, a bending-tube with a bell-shaped mouth should be used. A uniform force should be applied and hammering of the bar avoided.

For larger diameter bars, heating may be the only solution. In such cases, the temperature of the bar should be checked, with the heat-indicating crayons normally used for welding, to ensure that the maximum permissible temperatures are not exceeded. In such cases, AS 3600 requires the allowable stress in the cold worked steel to be drastically reduced. Heating of reinforcing steel on site should therefore never be undertaken without the approval of the design engineer.

Table 16.3 Minimum radii for bends using micro-alloy steel reinforcement (NZS 3109 Table 3.1)

f_y (MPa)	Bar type	Bar diameter, d_b (mm)	Minimum diameter of bend, d_i (mm): Plain bars	Deformed bars
300 or 500	Stirrups and ties	6-20	$2d_b$	$4d_b$
		24	$3d_b$	$6d_b$
	All other bars	6-20	$5d_b$	$5d_b$
		24-40	$6d_b$	$6d_b$

Table 16.4 Bending Tolerances from Clause 3.9 NZS 3109

Item	Tolerance
Cranks stirrups and ties where:	
member depth is less than 200 mm	+0, –5 mm
member depth is 200 mm or more	+0, –10 mm
Other steel	+0, –15 mm
Length of straight bars	+0, –15 mm
Length of straight bars where length fitment is not critical	+20 mm

16.2.6 Tolerances

Tolerances on the fabrication of reinforcement stipulated in Clause 3.9 of NZS 3109 are shown in **Table 16.4**. Maintenance of these is necessary, firstly to ensure that when fabricated, the reinforcement will fit within the mould or formwork for which it is intended; but secondly, and most importantly, that the concrete cover necessary to protect the reinforcement from the environment is maintained. Thus it will be noted that reinforcement and fitments must not be longer than specified.

16.3 FIXING

16.3.1 General

The position of the reinforcement may well be more important than the amount. For example, reinforcement specified to be placed in the top of a

Table 16.5 Tolerances on position of reinforcement from Clause 3.9 NZS 3109

Item	Tolerance
Tolerances on bar spacing/position	
Spacing of main bars in beams and columns	±10 mm
Distance between layers of main steel except it shall not be less than 25 mm	±5 mm
Distance between bars along the face of walls or slabs	±20 mm
Spacing of stirrups or ties in beams and columns	±20 mm
Longitudinal position of splice	±30 mm
Tolerances on concrete cover relative to the values shown on the drawings and specifications	
In slabs and walls	+10 –0 mm
In beams and columns	+10 –0 mm
At ends of members	+25 –0 mm
Large bars	
For bars of diameter greater than 20 mm, the tolerances in Table 12.5 and above shall be increased by 5 mm except that where the stipulated value is zero there shall be no change.	

multi-span beam or slab, to resist the tension over intermediate supports, will be totally ineffective if placed in the bottom of the beam or slab.

Reinforcement also requires a minimum amount of cover to protect it from the effects of fire and/or from the environment that may cause it to rust and corrode. The tolerances specified for the fixing of reinforcement are designed to ensure that these minimum requirements are met.

16.3.2 Handling

Reinforcement should be checked for loose scale, mud and oil.

Loose scale is normally removed as the bars are handled in the fabricating factory, or during loading and unloading, and it is not usually therefore necessary to carry out any special 'cleaning' procedure to remove it. Mill scale and light rust are generally thought to have little effect on bond. Indeed, moderate rusting is thought to improve bond.

On the other hand, mud and dirt should be washed off before the bars are placed in the forms as they could be detrimental to bond and to the quality of the concrete.

Oil and grease should also be removed (with solvents) and care taken that bars do not become coated with form oil during fixing operations.

16.3.3 Positioning

General

It is essential that reinforcement be fixed in the position specified by the designer in the structural drawings. If it is not, then the structural performance, durability or fire resistance (perhaps all three) could be seriously impaired. Reference should be made to the placement tolerance set out in **Table 16.5**.

A number of methods are used to locate reinforcement correctly.

Chairs

Bar chairs are generally used to support bar or mesh reinforcement above horizontal surfaces. They are available in a variety of shapes and may be made from wire, plastic or concrete.

They are also manufactured in a range of sizes, each of which provides a specific thickness of concrete cover. Indeed, some are manufactured so that different thicknesses of cover may be achieved with a single unit.

Typical are concrete blocks which can be used with different faces uppermost and plastic chairs which can be positioned in a number of different ways. A range of bar chairs is illustrated in **Figure 16.2** (page 16.10).

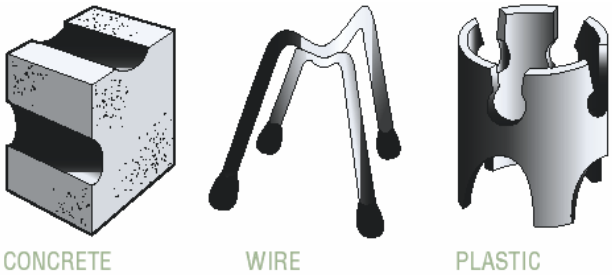

Figure 16.2 Typical bar chairs

Factors which should be considered in the choice of a chair appropriate to the work in hand include:

- ***Cover.*** A bar chair should be selected to provide the correct cover – not one 'close-to' that required. In using a multi-cover chair, care must be taken that it is positioned correctly.

- ***Exposure conditions.*** It is vital that unprotected bar chairs are not used in situations where they can corrode. For example, to use an unprotected steel chair in a slab with an exposed soffit could mean that the chairs corrode, producing staining and spalling even though the reinforcement itself is correctly located.

- ***Appearance***. Where the soffit is exposed, the tips of the bar chairs may be seen. It is necessary, therefore, to consider the appearance of the completed element in choosing a suitable support for reinforcement.

- ***Membrane damage***. Bar chairs which could puncture damp-proof membranes during placing operations should be avoided, or supported on purpose-made 'saucers'.

- ***Stability.*** Some types of bar chairs are easily displaced or knocked over during concrete-placing operations. Selection should ensure that the risk of this is minimised.

- ***Spacing of bar chairs.*** The spacing of chairs must ensure that the reinforcement is in the required position. Spacing will depend upon the placing methods and the grade of reinforcement. Thus the minimum spacing may range from 0.5 to 1 m. For most meshes continuous bar chairs are recommended; alternatively, 16-mm rods may be used between individual chairs in order to prevent sagging.

Spacers

Spacers which snap onto reinforcing bars are available to maintain the required distance from the bar to the face of the concrete. They are generally made of plastic. As for chairs, the selection and positioning of spacers must always be such as to ensure that the reinforcement is correctly positioned and that the surface appearance of the concrete is not marred.

Tying

Reinforcing bars may be tied together, or to stirrups, to form a 'cage' which helps maintain the bars in position during the subsequent concreting operations. Obviously, the cage must be strong enough to achieve this – sufficient ties must be used for this purpose **Figure 16.3**.

The most common tie material is a black annealed wire, 1.6 mm in diameter; although other forms of wire and plastic clips are available.

It is not necessary to tie bars at every intersection as ties add nothing to the ultimate strength of the structure. They serve only to keep the reinforcement in place during concreting. Nevertheless, it is better to err on the side of too many than too few, particularly at the edge of slabs, around openings, at corners, and in similar locations where positioning of the reinforcement is particularly critical.

Figure 16.3 Reinforcement being tied in position

Welding

Reinforcing steel should not be welded except with the approval of the engineer. Such welding must then comply with AS 1554.3.

The locational welding of main bars into the corner of fitments may be approved but other welding should not be carried out within 75 mm of any bend of a radius less than eight times the bar size.

Splicing Reinforcement

Lengths of reinforcing bar or mesh may be joined or 'spliced' together in a variety of ways. The most common method is simply to lap the bars or mesh. The lapped portion of the bars or mesh must always be in contact unless otherwise indicated on the drawings.

When mesh is lapped, the two outermost wires of one sheet must overlap the two outermost wires of the other. Meshes are available with the edge wires spaced closer together, thus reducing the area of the lapped zone and increasing the coverage of the sheet.

A variety of proprietary mechanical splices are also available for joining bars. These have different applications, advantages and disadvantages. It is vital, therefore, that the correct type of splice is used in any given situation and that the manufacturer's instructions on installation are followed.

Tolerances

A tolerance provides an acceptable allowance for small variations to the specified length or position of reinforcement. For reasons that include structural performance, durability and fire resistance, reinforcement must be in the position intended for it within an appropriate tolerance.

Tolerances for the positioning of reinforcement and tendons stipulated in Clause 3.9 of NZS 3109 are shown in **Table 16.5**. A knowledge of these tolerances is essential for all those concerned with the fixing or checking of reinforcing.

Chapter 17

Prestressing

Chapter 17

Prestressing

Prestressed concrete may be defined as reinforced concrete in which the reinforcement, high tensile steel wires or bars, is stretched or tensioned before being bonded with the concrete in some way. he force in the steel is transferred to the concrete, placing it in compression and thereby increasing its ability to withstand tensile forces. The development of prestressed concrete has enabled greater spans and more-slender structures to be achieved.

This chapter outlines the materials and components required for prestressed concrete, the techniques used to tension the reinforcement (or tendons, as they are known) and to bond it to the concrete. Since prestressing operations can be hazardous, very strict safety procedures should be followed when they are being undertaken.

INTRODUCTION

Like reinforced concrete, prestressed concrete is a composite material in which the weakness of concrete in tension is complemented by the tensile strength of steel (in this case, steel wires, strands, and bars.

The compressive strength of the concrete is used to advantage by applying an external compressive force to it that can, depending on the magnitude of the force, keep it permanently in compression even when loads are applied to it during its service life. Tensile stresses can be prevented, thereby, from developing in the concrete.

The pre-compressing or prestressing of concrete can be likened to picking up a row of books by pressing the books together **Figure 17.1**. The greater the number of books (the longer the span) the greater the force that has to be applied at either end of the row to prevent the row (the beam) collapsing under its own weight. A load applied to the top of the books would require an even greater force to be applied to prevent collapse.

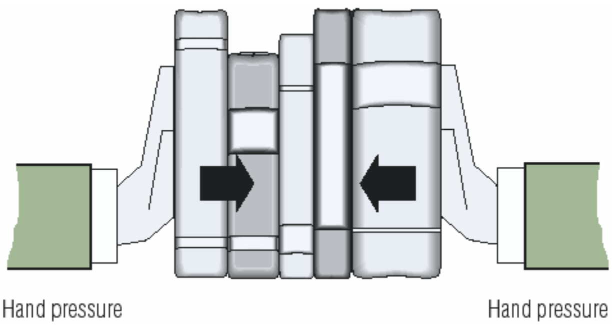

Figure 17.1 **Prestressing can be likened to picking up a row of books**

In reinforced concrete, the steel reinforcement accepts all of the tensile stresses and, in some cases, even some of the compressive stresses. In prestressed concrete, the steel is used primarily to keep the concrete in compression. This is achieved by stretching the steel, (placing it in tension) and then bonding it to the hardened concrete in some way before releasing it. The force in the steel is transferred to the concrete, compressing it.

A fully prestressed concrete member is designed to be permanently under compression, effectively eliminating most cracking. In this case, if the member is slightly overloaded, some tension cracks may form but these should close up and disappear once the overload is removed, provided always that the steel has not been overstrained beyond its elastic limit. In partially prestressed members, some tensile stresses, and therefore some cracking, is accepted at the design ultimate load.

In reinforced concrete, the steel is not designed to operate at a high level of stress, as elongation of the steel will lead to cracking of the concrete. In prestressed concrete, the steel does carry very high levels of tensile stress. Whilst it is well able to do this, there are some penalties attached. Firstly, because of the forces involved, considerable care must be exercised in stretching the tendons and securing them. Stressing operations should always be carried out, and supervised by skilled personnel. Secondly, the structure must be able to compress, otherwise the beneficial prestressing forces cannot act on the concrete. The designer should detail the structure so that the necessary movements can occur.

Relevant New Zealand Standards

AS/NZS 4672 *Steel prestressing materials*

NZS 3101 *Concrete structures*

NZS 3109 *Concrete construction*

Relevant Australian Standards

AS/NZS 4672 *Steel prestressing materials*

17.1 METHODS OF APPLYING PRESTRESS

17.1.1 Pre-tensioning

In a pre-tensioned member, tendons are first carefully positioned within the formwork and the design load or tension applied to them. Then, whilst tensioned, the concrete is cast around them and allowed to harden until it achieves sufficient strength (usually above 30 MPa) to resist the forces to be applied to it. The ends of the steel tendons are then released from their restraints and the stress in them transferred to the concrete by the bond between the two materials.

The tendons used in pretensioning are usually in the form of small-diameter wires or strands (a combination of smaller wires). The diameters of these materials are kept small to increase the surface area available for bonding with the concrete. Crimped or indented wire is also commonly used to further increase bond **Figure 17.2** (page 17.3).

17.1.2 Post-tensioning

When a member is to be post-tensioned, the concrete is first allowed to harden before the steel tendons are stretched or tensioned. They cannot therefore be allowed to bond with the concrete, at least not initially. Usually they are placed in ducts or holes that have been cast in the concrete, although sometimes they are greased and sheathed in plastic to prevent bond. In other cases, the tendons are fixed to the outside faces of the member.

After the concrete has gained sufficient strength, the tendons are tensioned and then fixed or anchored in special fittings cast into the ends of the concrete member.

A wide variety of patented fittings and systems are available for this purpose. Typical slab and beam anchorages are shown in **Figures 17.3 and 17.4** respectively. The ducts are then filled with a cement grout which, when set, bonds the tendons to the concrete.

17.1.3 Applications

Although both pre-tensioning and post-tensioning systems are designed to apply prestress to concrete members, there are some practical differences in their fields of application. Thus, pre-tensioning is normally confined to the factory production of repetitive units where the cost of the relatively large abutments or restraints, against which the prestressing jacks operate, can be justified. Alternatively, very strong and robust formwork may be constructed and wires anchored against its ends.

Post-tensioning is more flexible in its application and may be carried out onsite. It permits the use of curved tendon profiles, and is also suited to a wide variety of construction techniques, such as 'segmental construction' and 'stage stressing'. Since stressing is not carried out until the concrete has hardened, the concrete member itself provides the restraint against which the stressing jack operates **Figure 17.5**.

An example of a prestressed concrete bridge is shown in **Figure 17.6**.

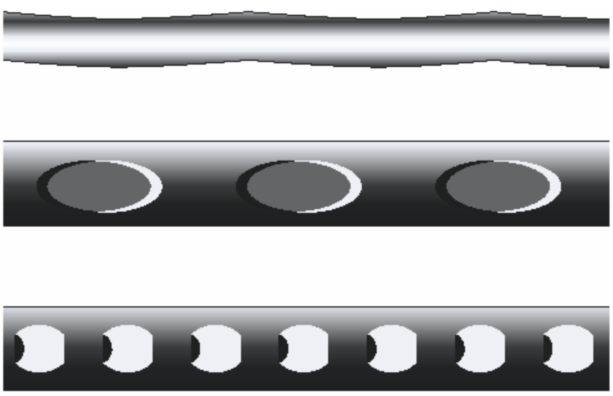

Figure 17.2 **Crimped or indented wire**

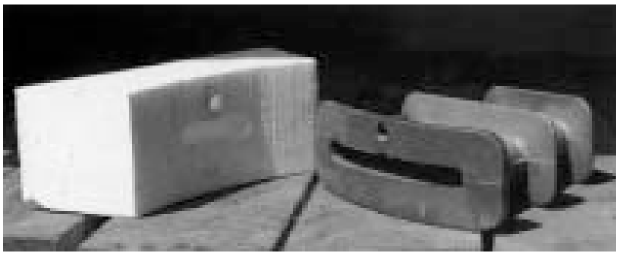

Figure 17.3 **Typical slab anchorage**

Figure 17.4 **Typical beam anchorage**

Figure 17.5 **Post-tensioning jack operating on end of concrete girder**

Figure 17.6 **Multi-strand, post-tensioned bridge, Mooney Mooney, NSW**

17.2 MATERIALS AND COMPONENTS

17.2.1 Concrete

The use of concrete, normally with strengths in excess of 40 MPa at 28 days, enables efficient use to be made of the potential created by high-tensile-strength steel. Close attention must therefore be given to the proportioning, batching, mixing, placing, compacting and curing of the concrete to ensure that it achieves its specified strength. Failure to do so is likely to result in failure of the unit or member being stressed.

Because prestressed members can be considerably smaller in their cross-sections than equivalent conventionally reinforced members, the difficulty of placing and compacting stiff, high-strength mixes may be increased. Indeed, the minimum size of the member may be dictated by the size and spacing of the prestressing ducts and the other reinforcement. On the other hand, the use of high-strength concrete permits the cover to reinforcement to be reduced. The reduced cover means, however, that greater care must be exercised in fabricating and fixing the reinforcement to ensure that the appropriate tolerances are maintained.

17.2.2 Tendons

General

The tendons used in prestressed concrete are generally manufactured from high tensile steel. They may be 'normal stress-relieved' or 'low-relaxation stress-relieved', although the latter is by far the more common.

When steel is tensioned to a high stress, and then held at a constant length under that stress, there will be a loss of stress in the steel as it 'relaxes' under the load. Low-relaxation steel is commonly specified because it can maintain a higher tensile stress over time than normal steel. Normal-relaxation and low-relaxation steel are not therefore directly interchangeable.

All prestressing tendons should carry a mill certificate from the manufacturer, or a nominated testing authority, which clearly identifies them. Particular attention should be paid to the physical and chemical properties of the steel, protective coatings, physical damage, corrosion, and to its handling and storage. Rejected material should be clearly marked and removed from the site.

Prestressing steel is sensitive to rusting, notches, kinks and heat. The steel is protected against rusting in transit to the site and, on site, should be suitably stored under cover in dry surroundings.
Research has shown that a light, hard oxide on the tendons is desirable in pre-tensioned members, since it improves the bond characteristics of the tendons. It should also be desirable in bonded, post-tensioned work. However, prestressing steel is more sensitive to corrosion than ordinary reinforcing steel because the individual prestressing wires or strands are small in diameter in comparison to reinforcing bars. Corrosion and, in particular, pitting reduces the cross-sectional area of the tendon by a relatively large amount. Tendons must therefore be checked for indications of pitting corrosion. When this is found, the tendons should be rejected.

For much the same reason, tendons should be checked for notches or kinks. By providing focal points for stress concentrations, they invite stress-corrosion, or in severe cases, over-stressing.

Tendons are also susceptible to excessive heat which can destroy or alter the high-tensile characteristics of the steel. Welding operations should never be carried out on, or adjacent to, prestressing tendons.

Tendons may consist of individual wires, strands, or of bars as shown in **Table 17.1**.

Table 17.1 Tensile strength of commonly used wire strand and bar

Material type and relevant Standard	Nominal diameter (mm)	Area (mm^2)	Minimum breaking load (kN)	Minimum tensile strength (MPa)
Wire – AS/NZS 4672	5	19.6	30.4	1,550
	5	19.6	33.3	1,700
	7	38.5	65.5	1,700
7-wire super strand – AS/NZS 4672	9.3	54.7	102	1,860
	12.7	100.0	184	1,840
	15.2	143	250	1,750
	15.2 EHT	143	261	1,820
Bars – super grade only – AS/NZS 4672	23	415	450	1,080
	29	660	710	1,080
	32	804	870	1,080
	38	1,140	1,230	1,080

Prestressing Wire

High tensile steel wire, up to 8 mm in diameter, is most commonly used for the tendons in pre-tensioned concrete. It should comply with the requirements of AS/NZS 4672 and may be normal stress-relieved or low-relaxation stress-relieved.

Wire diameters are kept small to increase the surface area available for bond, or bond may be improved by rolling small indentations into the wire or by crimping **Figure 17.2**.

Wire is usually supplied on specially wrapped coils. Before unwrapping, the coils should be placed on a purpose-made spindle that has outside restrainers and a brake to prevent unravelling and crossing of the wire. Care should be exercised when first releasing the wire from the coil as the end can flick out and cause injury.

Prestressing Strand

Strand is composed of a central wire tightly enclosed by other wires laid helically around it.

Strands usually consist of seven wires (7-wire strand) and are normally between 8 and 18 mm in diameter. They should comply with the require-ments of AS/NZS 4672. In Australia and New Zealand, the most common strand is the 12.7 mm diameter 7-wire super-grade stress-relieved low-relaxation strand. Its minimum breaking load is 184 kN at an average steel stress of 1840 MPa.

Strand is supplied on large drums or in large coils with a centre pull to unwind. The same care should be taken when releasing the first section as with wires. The drum should be mounted on a spindle and a reliable brake provided to check the momentum of the drum when rapidly paying out the strand.

Centre pulling of coils is a more convenient method, provided certain precautions are taken. The first precaution is to prevent the coil expanding, collapsing or tangling. The second precaution is to ensure the lay of the strand is tightened as it is pulled off the coil. Strand acquires a twist as each loop is removed, and this twist should be directed in such a way as to tighten the lay. Manufacturers should be consulted for the direction of the lay **Figure 17.7**.

Prestressing Bars

Prestressing bars should comply with AS/NZS 4672. They are used to provide large forces in restricted areas, being relatively easy to handle and simple to couple with threaded connections. Bars are suited to short length stressing or where restressing or coupling is required.

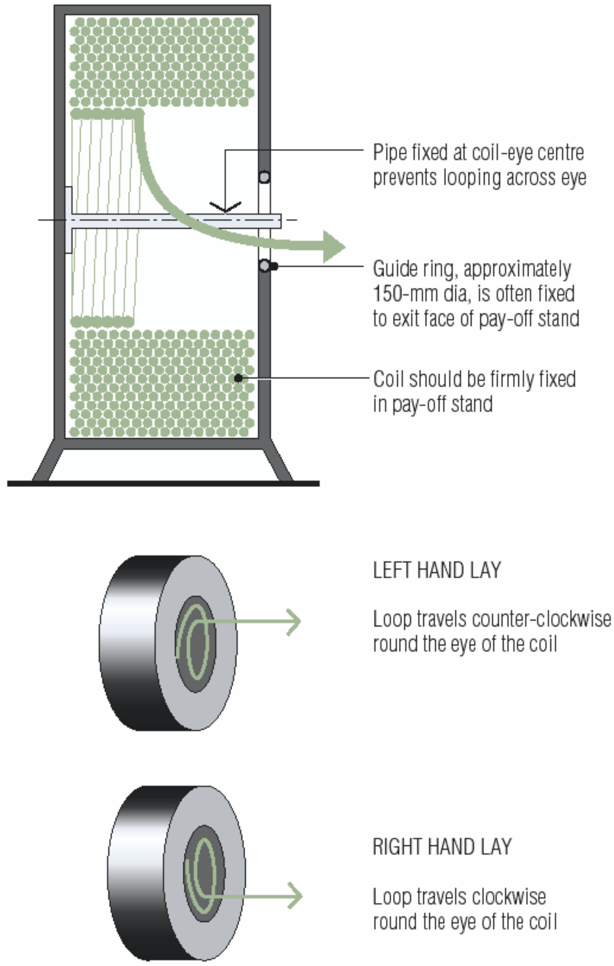

Figure 17.7 Centre pulling of wire and strand

17.2.3 Ducts

Ducts can be formed in concrete by casting in a flexible metal or plastic tube, by using an inflatable rubber tube or by using a removable steel former.

The use of a flexible metal tube is the most common method of forming a duct. The tubes are relatively thin yet can withstand rough handling. Normally, tendons are cut to length and 'pulled through' or 'pushed into' the duct, i.e. positioned within it, prior to concreting. This helps to locate and restrain the duct during concreting and avoids the major problem of trying to thread the tendons through the duct should it be damaged.

Where it is not possible to place the tendon in the duct prior to concreting, the duct may be held in position with a plastic tube, an inflatable rubber duct or a bundle of wires. Straight ducts can also be located with the aid of a slightly undersize steel tube.

Inflatable rubber formers should be supported and inflated to the manufacturer's instructions. They will normally require support at 300 mm centres and be inflated to about 200 kPa. When rubber formers are used in steam-cured concrete, care should be taken that the heat does not increase the pressure in the tube by an unacceptable amount. Rubber formers are usually deflated in steps and withdrawn immediately the concrete has set and begun to harden, e.g. after about four hours.

The use of removable steel formers is a somewhat risky procedure and is therefore normally limited to small lengths. Greasing of the tubes to prevent bonding with the concrete can interfere with subsequent bonding of the grout.

17.2.4 Anchorages

Anchorages comprise units or components which enable the tendon to be stressed, and then transfer the force in the stressed tendon to the concrete member or structure. They also commonly incorporate facilities to enable the ducts to be injected with a cement grout to protect the tendons from corrosion and bond them to the concrete.

17.3 CONSTRUCTION

17.3.1 Prestressing Systems

Prestressing systems may be loosely described as the combination of methods and equipment that are used to tension the tendons and then to fix them so that they transfer their load to the concrete. They therefore include not only the anchorages, and in some cases, the tendons, but also the jacks which are used to stretch the tendons.

It is beyond the scope of this Guide to provide information on the many and varied systems which are used in New Zealand and Australia. Most are patented. Recourse should be had to manufacturers and/or suppliers for details of them.

17.3.2 Fixing Ducts and Anchorages

The correct placement of ducts within the formwork and securing them against movement during concreting are very important steps in prestressed concrete construction. In post-tensioned construction, tendons are very often draped or profiled within the member in order to obtain the maximum benefit from the prestress. This tendon profile, as it is known, is an important feature of prestressed design and any significant deviation from it may cause the member to deflect or behave in a way not anticipated in the design.

The importance of the tendon profile is recognised by NZS 3109 and AS 3600 which requires that the profile be maintained within 5 mm of that specified.

In positioning ducts it is important to remember that the centreline of the duct will not coincide with the centreline of the tendon. With draped cables, the tendons, when tensioned, will bear against the top of the duct in the centre of a span, and with continuous cables, on the bottom of the duct over the supports.

In positioning and securing ducts within the formwork, care must be taken, therefore, that the profile is maintained **Figure 17.8**. This is achieved by tying the duct to the reinforcing steel, chairs, or other supports. The fixings should be sufficiently rigid, and at sufficiently close centres, to prevent displacement of the duct during the concrete operation. Small ducts should be supported at about 1 m centres. Supports for large ducts, which naturally maintain an approximately correct profile due to the stiffness of the duct, should be 3 m or less, depending on the duct stiffness. In addition to displacements likely to be caused by the weight of concrete and the operation of the vibrator, displacement can occur due to flotation of the ducts. Fixing should prevent this from occurring.

Figure 17.8 **Positioning the ducts in the formwork**

Particular care is necessary to ensure that the ducts are correctly located adjacent to the anchorages so that unintentional angular deviations do not occur. Untensioned reinforcement, particularly beam stirrups and end-zone reinforcement, should have been detailed carefully by the designer to ensure the ease, accuracy and quality of duct placement.

Fabrication and placement details for anchorages are normally provided by the supplier and should include such details as anchorage blockout dimensions, bolt hole dimensions, clearance requirements for stressing equipment, etc.

Anchorages must be fixed to prevent movement during concreting. In cases where anchorages are attached to the end formwork, the latter must be sufficiently rigid to withstand the horizontal forces which can be imposed on the anchorages during the concreting operation, and the fixing detail should be such that the ingress of grout at this point is prevented.

Figure 17.9 **Typical hydraulic jack (with hydraulic hoses from compressor unit in foreground)**

17.3.3 Concreting

The concreting programme should be prepared in good time and must be carried out with the greatest possible care since defects in concreting are liable to cause trouble during the stressing operation.

Just prior to concreting, the tendons and anchorages should be inspected carefully to ensure they are securely tied at all locations and that there is no possibility of mortar leaking into the duct or anchorage device during placing and compacting the concrete.

Proper tendon alignment must be maintained ahead of the concrete placement and care taken that ductwork is not damaged. Ducts should not be stepped on nor damaged with vibrators.

If the duct is damaged, repairs should be made to prevent concrete from bonding to the tendons. Small holes can be repaired by using waterproof adhesive tapes; larger holes should be covered by metal strips wrapped around the duct. The overlap should be at least 100 mm and the joints should be sealed by a waterproof adhesive tape.

Particular care should be taken at the end-zone and at grout pipes, air bleeds and reinforcement to ensure uniform compaction and to avoid unnecessary voids.

Immediately after concreting, where possible, cables should be pulled back and forth to ensure that they remain free.

17.3.4 Stressing

The majority of stressing systems use hydraulic jacks to tension the steel tendons which may be tensioned singly or in groups. Jacks capable of exerting forces of up 1,800 t have been developed for stressing operations in large dams and similar applications but on most construction sites jacks of capacities up to 300 t would be employed **Figure 17.9**.

In single-tendon stressing, each tendon is individually stressed. In multiple stressing, all the tendons in the duct are stressed at the same time. The smaller jacks used for single pulling allow easier jack handling but the number of operations is increased. The large jacks used in multiple stressing reduce the number of stressing operations but may require mechanical handling.

The type of jack employed must correspond to the prestressing system used and to the dimensions of the tendons. This must always be checked as must the stroke of the jack to ensure it is appropriate to the job. Stressing operations are carried out by crews specially trained in the use of the particular type of equipment used.

The time and sequence of stressing is determined by the designer, however, to achieve certain objectives, viz:

- Early partial stressing to minimise the development of shrinkage cracks.
- Early partial stressing to balance the self weight of the slab and to enable formwork to be more economically used. (For multi-storey construction, the early capacity to support subsequent floors is a primary consideration.)
- The proper stressing sequence to avoid large differential stresses in adjacent cables or areas.
- In stage prestressing, to balance the loads being applied as the structure progresses.

The measurement of stressing load is usually based on load cells or dynamometers, confirmed by measurement of the elongation in the cable. Readings of extensions should be made with an accuracy of 1 mm. The first increment, which removes slack, will normally be 10–20% of the final jacking force. At this stage, the zero-reading for extensions are usually made.

The theoretical extension takes into account the tendon profile and friction.

After stressing has been completed, the tendons are anchored in accordance with the standard procedure of the prestressing system.

All data observed during the stressing operations should be recorded immediately in the stressing log. As these are the only available evidence of the required prestressing force having been reached, they should be signed by the person responsible for the stressing and kept in a safe place. The figures in the stressing log should take into account adjustments for zero readings and the elongation of tendons beyond the anchorages.

The load/elongation measurements provide vital information on the prestressing force obtained and on possibly significant deviations from the design assumptions. Meticulous stressing records are essential for a complete evaluation of the quality of the work. Before the stressing log is submitted to the designer, the recorded extensions should be checked for any inconsistency. Two ducts with the same number of tendons, same drape and same stressing force should not have extensions varying by more than about 5%. The inconsistencies should be investigated in consultation with the designer.

Tendons should not be cut or grouted and should be kept in such condition that they can be re-stressed until permission for work to proceed has been granted by the designer.

Because the measurements during stressing are influenced by random factors, acceptable limits for the difference between calculated and observed values should be stated by the designer. Where tolerance in extensions has not been specified, a realistic value may be taken as ±5 to 10%.

17.3.5 Grouting

In Australia and New Zealand, post-tensioned tendons are usually grouted in their ducts after the stressing operations for the following reasons:

- A reliable bond between the stressed tendon and the concrete member is established (in addition to the end anchorages).
- Should unforeseen circumstances cause the ultimate strength of a member to be exceeded, a properly designed member with bonded tendons will develop many distributed small cracks and fail in a ductile manner.
- The best protection the tendon can have is to be surrounded by cement-rich grout or concrete that is well compacted and impermeable. Steel cannot corrode in an alkaline environment except when chlorides are present. These are prohibited in prestressed concrete.

Grouting should be carried out as soon as possible after stressing. However, the tendons must not be cut, nor must the duct be grouted until final approval of the stressing has been given. Grouting should generally not be delayed for more than seven days unless special precautions are taken. The period should be shorter in cases with aggressive environments.

Specification of the grouting procedure is essential to successful grouting and should address such items as grout composition and properties, duct soundness (i.e. there should be no obstacles or grout paths between ducts), grouting sequence, grouting pressure and rate, venting, volume checks, regrouting or topping up, communication between operators at duct inlets and outlets, and safety.

Before grouting, the duct may be tested for blockages by means of compressed air (not preferred) or water. Connections for the grout hose to the duct should be free from concrete, dirt, etc. and vents should be inspected to make certain that they can be properly closed.

In cold climates, precautions should be taken to prevent the freezing of water in the ungrouted duct. After a period of frost, care must be taken that the duct and tendon are free from ice.

All grout used for the grouting of prestressing ducts should consist of portland cement and water. Acceptable admixtures may be used if tests have shown that their use improves the properties of the grout, e.g. by increasing the workability, reducing the bleeding, entraining air or expanding the grout. Admixtures should be free from any product liable to damage the steel or the grout itself, such as chlorides, nitrates and sulphides.

Grouting records should be kept for each cable, and should contain itemised information on grout properties, pump pressures, volumes, rate of progress and environmental conditions. The approval of the grouting for cables or groups of cables should be clearly marked by authorised signatures on record sheets.

From time-to-time difficulty may be experienced in grouting, due to such problems as the grout being improperly mixed or proportioned, improper flushing prior to injection, or unintended obstructions in the post-tensioning ducts. The result is that one or more tendons may become partially grouted. In order to salvage members with problems such as these, holes must be drilled into the post-tensioning duct with great care in order to not damage the tendons. The extent of the grouting or the location of possible obstructions can thus be observed.

After this has been done, the ducts should be flushed with lime water and the tendons grouted, using the drilled holes as ports. Alternatively, vacuum-assisted methods can be used. This is a specialised operation, to be undertaken only by skilled crews in conjunction with the designer.

17.3.6 Safety

Prestressing involves the use of very large forces and high pressures in the hydraulic pipelines. Appropriate precautions must be taken to prevent accidents as these can have very serious consequences.

A number of organisations have prepared recommendations on safety precautions during stressing. These include:

- FIP Guide to Good Practice *Prestressed Concrete: Safety Precautions in Post-Tensioning* Thomas Telford, London, 1989.
- *Safety Precautions for Prestressing Operations (Post-Tensioning)* The Concrete Society, London, 1980.
- AS 1481 *Prestressed Concrete Code* (superseded), Standards Australia, 1987.
- Code of Practice, Workcover NSW, 1993.
- *Stress Safe, Stress Smart – Prestressing of Concrete Structures* (video), available from the major post-tensioning companies.

Addendum

Reproduction of Appendix B to the superseded AS 1481 *Prestressed Concrete Code*

SAFETY PRECAUTIONS FOR PRESTRESSING OPERATIONS – Notes for Guidance

B1 INTRODUCTION

The purpose of this Appendix is to state some simple but sensible precautions to ensure that stressing is carried out with the maximum amount of safety. The operations involved in tensioning and de-tensioning prestressing tendons are not dangerous, as long as sufficient care is taken. The main problems are ignorance, lack of thought, and over-familiarity.

These notes have been based on successful experience over many years, and are intended for use by the supervising engineer or supervisor in charge of stressing.

The following assumptions have been made:

(a) Stressing operations will be carried out by experienced personnel under a competent supervisor.

(b) The design and construction of the units concerned is of the required high standard.

(c) All equipment is in full working order and properly maintained.

B2 PRECAUTIONS TO BE TAKEN BEFORE STRESSING

B2.1 General

(a) Ensure that sightseers are kept away from stressing operations.

(b) Erect stout double-faced screens at the back of the jack to form a safety barrier.

(c) Display a large sign, 'ATTENTION – STRESSING IN PROGRESS – KEEP CLEAR', on the outside face of the safety screen to warn workmen and passers-by.

(d) Fence off the area between the safety screens and the unit being stressed, so that no one can pass between them during the stressing operations.

(e) Always refer to the supplier's detailed instructions for the equipment being used, and follow these instructions carefully.

(f) Check all equipment before use and report any signs of wear or defects.

(g) Instruct all operatives and supervisors to wear safety helmets during stressing operations.

(h) Display a notice adjacent to the stressing plant, giving the maximum design load of the bed and the upper limit of the position of the centre of gravity of the stressing wires.

(j) Ensure that adequate precautions have been taken to restrain any possible skewing or lifting of the stressing equipment during stressing or release.

(k) Do not permit any welding near high-tensile prestressing steel.

(l) Do not permit any prestressing steel to be used for earthing electrical equipment of any kind.

(m) Keep all equipment thoroughly clean and in a workmanlike condition (as badly maintained equipment always gives rise to trouble and consequently is dangerous).

B2.2 Handling of Materials and Equipment

(a) Make sure that operatives wear gloves when handling prestressing tendons.

(b) Temporarily suspend any other construction operations which might require a workman to stand directly behind the jack during stressing.

(c) Be careful when handling coils of high-tensile wire or strand as these may whip back with force if not securely bound.

(d) When assembling tendons, check each individual wire or strand for obvious flaws.

(e) Do not allow grips to be exposed to the weather and become rusty.

(f) See that wedges and the inside surfaces of anchorages are clean so that the wedges are free to move inside.

(g) Ensure that the threads of bars, nuts and couplers are cleaned and oiled, and thread-protecting wrappings removed only at the last moment before use. (Threaded bars for pre-formed ducts must have suitable protection to the thread to avoid damage by abrasion.)

(h) Arrange for stressing to take place as soon as possible after the grips have been positioned.

B3 PRECAUTIONS TO BE TAKEN DURING STRESSING

B3.1 Using a Prestressing Jack

(a) NEVER STAND BEHIND A JACK DURING STRESSING OPERATIONS.

(b) Do not allow operatives to become casual because they have stressed hundreds of tendons successfully before. (The forces they are handling are enormous and carelessness may lead to loss of life.)

(c) Regularly examine hydraulic hoses as a matter of necessity, and likewise regularly drain and filter oil in the pump reservoir.

(d) Use only self-sealing couplings for hydraulic pressure pipes, and take particular care that no bending stresses are applied to end connections.

(e) Whenever possible, use only hydraulic equipment supplied with a bypass valve that is pre-set to a maximum safely load before stressing. (The maximum safety load should not be more than 90 percent of the minimum specified ultimate strength of the tendons.)

(f) Check hydraulic pressure pipes for flaws or bubbles after each stressing operation.

(g) Double-check the grips or fixing of tendons to the prestressing jack before stressing.

(h) Keep the wedges clean and free from dirt, remembering that wedge teeth do not last forever.

(j) In systems where more than one wire or strand is gripped at a time around the body of the jack, make sure the wedge pieces are not worn. (A slip of one wire or strand may well cause overloading on the others, which may lead to failure.)

(k) Tension tendons to a low initial stress (say 62 MPa), and then recheck wedges, fixings and position of jack, and set the extension gauge to zero at this stage.

(l) Do not strike the equipment with a hammer to adjust the alignment of the jack when the load is on.

(m) Check the fixings at the non-jacking end.

(n) Ensure that a competent person is always available at the non-jacking end to check on anchorages during stressing.

(o) Double-check tendon fixings before releasing tensions.

B3.2 Pretensioning

(a) NEVER STAND BEHIND A JACK DURING STRESSING OPERATIONS.

(b) Pin-up the top wires or strands before the others, and on completion check that they have been pulled straight and are not tangled or caught up in the forms. (Pinning-up refers to the initial pull in a tendon before marking for measurement of elongation.)

NOTE: A pinning-up force of 2.2 kN is recommended for wire of 5 mm diameter, and a force of 4.4 kN for a strand of 12.5 mm diameter. This should be enough load to free any tangles and clear obstructions.

(c) Before tensioning, ensure that all the wires or strands are secured against the possibility of flying loose, and regard the following as safeguards:

(i) Shutters and end-plates.

(ii) Hoops and stirrups enclosing tendons.

(iii) Heavy timers laid over tendons.

(iv) Rolls of hessian laid across tendons.

(d) Insist that during stressing operations all personnel must stand clear.

(e) Insist that the operator, when stressing strands singly, must not stand directly behind grips that have recently been tensioned.

(f) *Stressing, multi-wire or multi-strand.* When stressing multi-wire or multi-strand, apply a small extension initially and check the line to ensure that there are no loose or caught-up wires or end-plates, and only after this inspection should the full load be applied.

(g) In placing the packers, take care not to score the ram of the jack.

(h) *Stressing, single wires or single strands.* When stressing single wires or single strands, apply the full load and extensions to each of the wires or strands and then lock-off. (The loads and extensions should then be carefully noted by the supervisor.)

(j) Place a protective guard over the grips before starting multi-strand stressing, and immediately after single-strand stressing is completed.

B4 PRECAUTIONS TO BE TAKEN AFTER STRESSING

B4.1 Post-tensioning

(a) After stressing, cut off wires or strands behind the anchorages, preferably with a disc cutting tool, a cropper or a snapping-off tool.

(b) Ensure that a clear eye shield is worn by operatives during grouting operations.

(c) Before grouting, check all ducts to make sure that none are blocked.

(d) If possible, use only threaded connectors between grout nozzles and grouting points. (A sudden spurt of grout under pressure can cause severe injury, especially to the eyes.)

(e) Do not peer into duct bleeders to see if grout is coming through. (Grout may jam temporarily and, as pressure is applied, may spurt suddenly from the bleeders, or the far end of the duct, causing serious injury.)

(f) When grouting over railways or public roads or other public places, take precautions to see that escaping grout does not cause a hazard to traffic below.

B4.2 De-tensioning

(a) Before de-tensioning, remove all obstructions to the free movement of the units.

(b) Allow the crosshead to be jacked back only the small amount that is just sufficient to free the packers.

(c) De-tension slowly and evenly, as any sudden movement may cause damage to the concrete units.

(d) If the tendons are de-tensioned one at a time, do this in the required sequence.

(e) Ensure that the supervisor keeps a record book and records the following information:

(i) Date into service of all new equipment.

(ii) Dates of exchanges of equipment, wedges, barrels, etc.

(iii) Number of uses to date of wedges, barrels, etc.

(iv) Confirmation that the inspection detailed below has been carried out.

(f) (i) Inspect and clean all wedges after each use, and record the fact in the book provided.

(ii) Clean the teeth of the wedges with a wire brush in order to remove any dirt or rust accumulated in the valleys of the teeth.

(iii) Replace worn segments as necessary.

(iv) Coat the backs of the wedges with graphite or wax, according to the grip manufacturer's instructions.

(g) Return all barrels to the stores for cleaning and checking along with the wedges. As a matter of necessity when returning barrels, see that the insides of the barrels are clean and that the wedges are free to move inside the taper.

(h) Inspect weekly for the following:

(i) Distorted anchor-plates.

(ii) Distortion of stressing equipment, crossheads, etc.

(iii) Any cracked welding of the equipment.

Safety

Chapter 18

Chapter 18
Safety

This chapter provides information on the general aspects of safety on building sites. It does not cover off-site processes or specific safety matters relating to particular construction phases, such as prestressing and formwork, which are dealt with in the appropriate chapters.

INTRODUCTION

In building construction work there are some inherent dangers. The very nature of the work means that for a large percentage of the time, the structure is in a partially completed state. Openings to the exterior and interior have to be kept clear of obstructions to permit free passage of material and equipment. Loose materials have to be kept on hand ready for installation and heavy loads have to be hoisted or manoeuvred into place. All manner of cutting and penetrating tools, implements and projections abound, and relatively large quantities of potentially dangerous waste materials are generated. Each of these presents a particular hazard to the safety of construction personnel and, where the construction is close to public access areas, to the general public as well.

The legal responsibilities of the principal and the contractor for the safety of site personnel and the public are set out in the *Health and Safety in Employment Act 1992*, while general guidance on this subject is provided in *Occupational Safety and Health (OSH) Guidelines for the Construction Industry*.

The reader is referred to the appropriate OSH for information on requirements applicable for the individual project. Worksafe New Zealand publish a series of informative booklets giving guidance on particular work processes and hazards. Those involved with safety on construction sites should regularly acquaint themselves with topics covered and the latest information available.

A Risk Assessment should be carried out for each individual site/project identifying the potential hazards that need to be addressed. However, the basis of safe working practices is an attitude to safety by all site personnel. Creating a safe working environment requires that in addition to any formal rules of conduct, all personnel are continually aware of the potential dangers of their surroundings and the particular activities in which they are involved as identified in the Risk Assessment. Safety is not someone else's problem; it is everyone's responsibility.

Relevant New Zealand Standards

Health and Safety in Employment Act 1992

Health and Safety in Employment Regulations

Electricity Act 1992

Electricity Regulations 1993

Relevant Australian Standards

AS 1470 *Health and safety at work – Principles and practices*

AS 3012 *Electrical installations – Construction and demolition sites*

18.1 GENERAL SAFETY

There are perhaps three specific areas where personnel working with concrete need to be aware of specific hazards:

The use of chemicals

When using chemicals such as admixtures the manufacturer's instructions should always be followed and any safety data provided by the manufacturer for the particular product consulted for specific advice.

Handling wet concrete

Concrete is highly alkaline and abrasive contact with fresh concrete can cause irritation to the skin and eyes, e.g. cement burns or dermatitis. Any safety data provided by the concrete supplier should be consulted for specific advice. As set out under *Personal Safety* below, workers should wear appropriate protective clothing, e.g. goggles, complying with the appropriate Australian Standards. Clothes should be worn so as to avoid traps for fresh concrete, e.g. sleeves over gloves, trouser legs over boots.

Cement and concrete dust

Concrete contains crystalline silica and activities such as handling bagged concrete, breaking, cutting and grinding concrete can generate dust containing crystalline silica. It may also be present in fly ash, etc. Any safety data provided by the supplier should be consulted for specific advice. Exposure to dust containing crystalline silica over a long period of time could result in lungs being scarred or silicosis and therefore it should be prevented from entering the lungs. When exposed to dry materials during mixing concrete or dust arising from cutting or grinding hardened concrete, appropriate personal protection equipment should be worn.

Apart from these common hazards the following briefly outlines some of the other potential hazards and/or the practices which should be instituted to provide general safety for those involved directly and indirectly with concrete construction.

Access to forms

Properly guarded walkways should be provided around formed areas of suspended work, so that the various tradespeople will have safe access to them while carrying out their tasks before concreting commences, and a safe means of retreat as concreting progresses. Where ladders are being used, *one person at a time* is the safety rule.

Clear areas

When heavy loads, e.g. formwork components, reinforcement or concrete, are being hoisted by crane, the path over which the load travels should be kept clear of all personnel. Adequate warning should be given to persons working in these areas so that they can get clear before the load is lifted.

Clear areas should also be maintained around the anchorages of prestressing tendons while stressing is in progress, in case failure of an anchorage occurs (see Addendum to Chapter 17 *Prestressing*).

Loose objects

Unfixed materials and hand tools should be kept well away from unguarded edges of suspended formwork or openings through it, or kept entirely within the forms, to prevent them from falling onto people below.

Form cleanliness

Forms should be maintained in a clean condition at all times. This is important not only for safety and good-housekeeping reasons but is also an essential requisite for producing good concrete. Off-cuts of timber, steel, electrical wiring and conduits, plumbing pipes and like debris should be removed at regular intervals (not longer than daily), as they are all potential causes of people tripping, falling or otherwise injuring themselves.

Projecting reinforcement

The cut ends of starter bars or fabric which project from construction joints in columns, walls and slabs can be a source of serious injury to persons falling on or against them. Proprietary plastic caps or other simple forms of protection should be used until the joining or lapping reinforcement is being placed.

Sheet materials Lightweight rigid sheet materials should not be left lying around loose but should be tied or weighted down, particularly overnight. Such material can easily become airborne in the strong wind gusts which are common in many parts of Australia and if left loose, they become lethal missiles.

Electrical wiring

Safe practices for temporary electrical installations, such as supporting power-tool leads clear of working areas, are set out in AS 3012 and should be followed. Adequate safeguards are most important where overhead powerlines cross or are close to the work area, particularly where cranes are being used.

18.2 PERSONAL SAFETY

The major hazards encountered by concrete construction workers as outlined in the introduction to this chapter are: loose materials (for either installation or disposal); heavy loads being hoisted/manoeuvred into place; and the use of cutting/penetrating tools. Most minor injuries to persons working on construction sites can be prevented, or at least minimised, by the wearing of appropriate clothing and personal-protection devices. While this applies to all construction personnel, it applies particularly to those engaged in concrete construction, as the injuries they are designed to protect against are common in the various stages of concrete construction.

Clothing

Overalls or tough trousers and a heavy duty, long-sleeved shirt or jacket, offer reasonable protection from scratches by nails, tie wire, cut timber edges and cut reinforcement ends. They also give protection from harmful ultraviolet radiation from the sun. Shorts and T-shirts provide little or no protection from any of these sources of injury.

Safety helmets

An approved type of 'hard hat' is required by industrial regulations in most States. Common sense should, however, dictate that this is an essential device in areas where there is a constant risk of objects falling from above and where headroom is likely to be restricted by temporary construction, such as formwork and falsework.

Safety boots

Safety boots with heavy-duty soles and protective toecaps minimise the chance of pierced feet from protruding nails, or crushed toes from dropped timber or steel props. Like helmets, these are often required by regulations.

Work gloves

All concrete construction work involves some degree of manual labour. Appropriate work gloves should therefore be used when handling undressed timber, reinforcing bars, cut mesh sheets, or formwork props. They should also be worn for all activities involving the handling of fresh concrete, because it is strongly alkaline and can cause corrosive burns on bare skin, or strong allergic reaction in some instances.

The 'slurry' of cement, water and sand, in which the coarse aggregate is suspended, is also very abrasive and will rapidly damage the outer layers of skin when rubbed against it.

Safety goggles

Safety goggles should always be used when cutting or grinding with power tools. They should also be worn whenever there is a chance of eye damage from airborne grit, cement dust, or splashed concrete slurry.

Masks and face respirators

Concrete contains crystalline silica and processes such as breaking, cutting and grinding concrete can generate dust containing it. This dust is especially harmful and it should be prevented from entering the lungs.

The use of personal protective equipment such as disposable face masks and face respirators is required depending on the level of dust being encountered.

While practices such as good ventilation, the use of extraction systems, spraying with water and keeping the work area clean will all help in reducing the hazard.

Sunglasses and sunscreens

Glare from sheet metal formwork and smooth, light-coloured concrete can be hazardous in the short term (by obscuring a potentially dangerous situation) and in the long term by causing permanent damage to the eyes. Sunglasses are therefore recommended in these situations. Adequate publicity in recent times of the dangers associated with long-term exposure to the harsh Australian sunlight should provide sufficient reasons for using sunscreens on those parts of the body which cannot be otherwise protected.

Ear muffs

Exposure to high noise levels can result in irreparable damage to hearing. For this reason, ear muffs or plugs should be used by those exposed to high noise levels.

Manual handling

All tasks should be carried out using the correct equipment. All personnel should be aware that their back is the most likely part of the body to be injured as a result of poor lifting techniques or attempting to lift too heavy a load.

Properties of Concrete

Chapter 19

Chapter 19

Properties of Concrete

This chapter describes how the various properties of concrete - in both the plastic (wet) and hardened (dry) states - are influenced by the materials from which it is made. Mention is also made of how the hardened state properties are influenced by the concrete's treatment while it is plastic and while it is hardening, i.e. by its handling (on-site movement), placing, compacting, finishing and curing. More detailed information on these influences is provided in the chapters devoted to those particular topics.

INTRODUCTION

As outlined in the introductory text on page 1 *'Introduction'* of this Guide, concrete is required to have certain properties at two distinct stages, viz when it is still plastic and when it has hardened. The plastic-state properties determine the ease with which it can be placed and finished, the hardened-state properties, how well it will perform in the completed structure.

This chapter provides discussion on all these properties, stressing the inter-relationship between many of them.

Relevant New Zealand Standards

NZS 3104	*Specification for concrete production*
NZS 3109	*Concrete construction*
NZS 3112.1	*Methods of test for concrete - Tests relating to fresh concrete*
NZS 3112.2	*Methods of test for concrete - Tests relating to the determination of strength of concrete*
NZS 3112.3	*Methods of test for concrete - Tests on hardened concrete other than for strength*
NZS 3112.4	*Methods of test for concrete - Tests relating to grout*

Relevant Australian Standards

AS 1012	*Methods of testing concrete*
AS 1012.1	*Sampling of fresh concrete*
AS 1012.2	*Method for the preparation of concrete mixes in the laboratory*
AS 1012.3	*Methods for the determination of properties related to the consistence of concrete*
AS 1012.8	*Method for making and curing concrete compression, indirect tensile and flexure test specimens, in the laboratory or in the field*
AS 1012.10	*Method for the determination of indirect tensile strength of concrete cylinders (Brazil or splitting test)*
AS 1012.11	*Method for the determination of the flexural strength of concrete specimens*
AS 1379	*The specification and manufacture of concrete*
AS 3600	*Concrete structures*

19.1 PLASTIC-STATE PROPERTIES

19.1.1 General

When first mixed, concrete is normally plastic and workable, i.e. able to be placed in formwork and compacted with relative ease. However, some concretes are harsh when first made and, although capable of compaction by pressure or prolonged vibration, would not be described as workable. Other concretes are almost fluid, i.e. they flow so readily that little compactive effort is required.

Between these two extremes lies the bulk of concrete delivered to construction sites, material which is workable and cohesive without being fluid or over-wet. Both workability and cohesiveness are important characteristics of concrete in its plastic state. Workability, because it determines the ease with which the concrete can be placed and compacted; cohesiveness, because it determines the tendency of the components in the concrete to segregate one from the other during handling and placing.

Thus a concrete may be workable but lack cohesion resulting in segregation, honeycombing and similar defects.

The workability and cohesiveness of fresh concrete must be such, therefore, as to suit the particular placing conditions and the compaction equipment available. Concrete with 'low' workability will normally require a large compactive effort to achieve maximum density, whilst 'high' workability concrete will be relatively easy to compact.

19.1.2 Workability

Influence of Water Content

For given proportions of cement and aggregates in a concrete mix, the higher the water content, the more workable the concrete will be. However, increased water content will increase the water-cement ratio and thereby reduce strength and durability. It will also increase the potential for cracking caused by drying shrinkage **Figure 19.1** (page 19.3). Normally, therefore, only very minor adjustments to workability should be made by the addition of water alone.

Influence of Cement Content

Because the cement paste acts as a lubricant to the aggregate particles whilst concrete is in the plastic state, the higher the cement content at a fixed water-cement ratio, the more workable the concrete will be. Therefore, adjustments to workability made by the addition of water should always be accompanied by an addition of cement to maintain the water-cement ratio **Figure 19.2** (page 19.3).

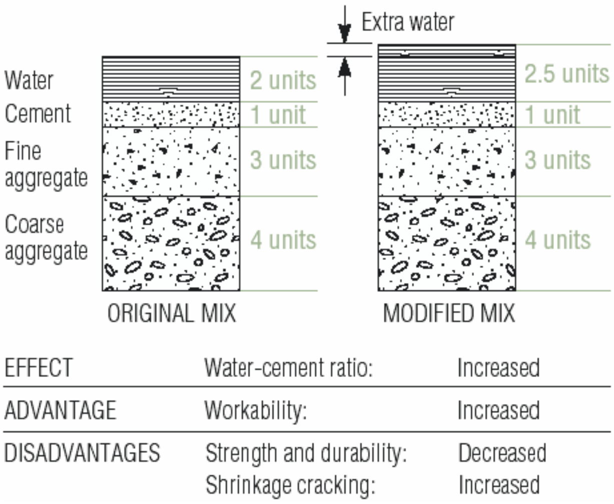

Figure 19.1 **The effects of increased water content**

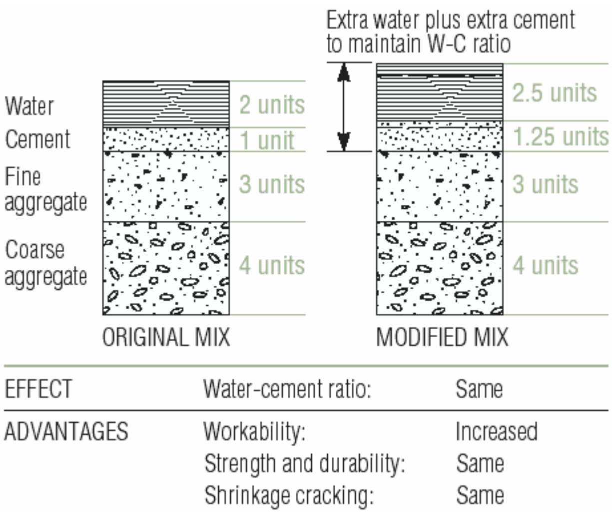

Figure 19.2 **The effects of increased water and cement contents**

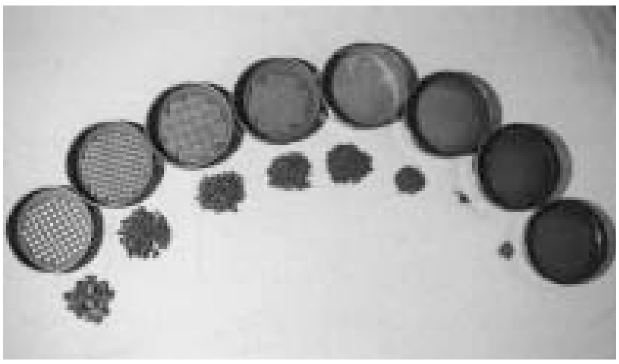

Figure 19.3 **Typical range of aggregate**

Influence of Aggregate Particle Size Distribution (Grading)

The combination of fine and coarse aggregates in the concrete mix provides a grading of particles from large to small **Figure 19.3**. The grading will affect workability, because the amount of water necessary to wet all the solids in the mix will depend on the surface area of the aggregates. This is determined by the particle size grading.

It is usual to aim for a smoothly graded aggregate to achieve optimum workability. Nevertheless, within quite wide limits, a variety of aggregate gradings may be used satisfactorily. Hence, a compromise reflecting the availability of materials and their relative costs is quite normal.

Influence of Aggregate Particle Shape and Size

The shape of the aggregate can have an effect on workability. For similar mix proportions, rounded or roughly cubically shaped aggregates will produce more workable concrete than that produced using flaky or elongated particles. A proportion of flaky or elongated particles is permissible but will increase the amount of cement paste required to achieve the necessary workability. The maximum size of particles has an effect also; the larger the particle size, the greater the workability for a given cement content and water-cement ratio.

19.1.3 Consistence

Consistence is a term used to describe the ease with which concrete will flow or the degree of wetness of the concrete. Although it is a different characteristic from workability, in practice the two terms are often confused and merged into one – the 'slump' of concrete.

This latter term is derived from the standard test procedure for determining the consistence of concrete, known familiarly as the 'slump test', which is described in Clause 19.1.4.

In general, 'high' slump concretes are wetter than 'low' slump concretes, and are more workable. However, concretes of the same slump can have varying degrees of workability.

Table 19.1 provides an indication of the appropriate slump for various elements of construction.

Table 19.1 **Typical ranges of slump for various elements (not applicable to superplasticised concrete)**

Element	Typical range of slump (mm)
Mass concrete	30–80
Plain footings, caissons and substructure walls	50–80
Pavements and slabs	50–80
Beams	50–100
Reinforced footings	50–100
Columns	50–100
Reinforced walls	80–120

19.1.4 Cohesiveness

General

The cohesiveness of concrete is a measure of its ability to resist the segregation of its different components during handling, placing and compacting. Segregation can occur as the separation of coarse aggregates from the cement paste, or as 'bleeding' the migration of water to the surface during handling and placing, and also after compaction.

Discussion on various factors affecting the cohesiveness of concrete follows:

Influence of Specific Gravities of the Constituents

The typical specific gravities of materials in a normal-weight concrete mix are shown in **Table 19.2**.

Jolting of the mix, or sudden changes of velocity and direction of the concrete during the placing operation, can cause particles of different specific gravities to dislodge from the plastic mass. This is commonly referred to as 'segregation' and can result in honeycombed or 'boney' patches in compacted concrete.

Table 19.2 **Typical specific gravities**

Material	Specific gravity
Water	1.00
Fine aggregate	2.50–2.70
Coarse aggregate	2.50–3.00
Cement	3.14

Influence of Consistence

The higher the water content in the mix (which usually means higher slump), the greater is the risk of segregation and bleeding occurring.

Firstly, the thinning out of the cement paste reduces its capacity to hold aggregate particles together during the handling and placing phase. Secondly, high water content retards the stiffening of concrete during its very early life, allowing sedimentation of heavier particles in the mix to continue for a longer period, thus promoting bleeding. Cold weather can also retard setting and promote bleeding.

Dry mixes, on the other hand, can be friable and also prone to segregation.

A very useful indication of the cohesive qualities of concrete can be gained by lightly tapping the side of the slump-test specimen with the tamping rod after the slump measurement has been made (see Clausel.19.1.4). If the cone breaks up, the mix will be prone to segregation.

Influence of Aggregate Grading

Mixes that are deficient in very fine aggregate tend to segregate more readily during handling. Bleeding can also be promoted due to the lack of fines. On the other hand, excessive fines make the concrete 'sticky' and, although very cohesive, it will be difficult to move, place and compact.

In mixes where there is a deficiency in very fine particles, problems with bleeding may be reduced by the use of air-entraining agents. The microscopic air bubbles act as an artificial fine aggregate which restricts the movement of water to the surface. (See Chapter 5 *Admixtures*.)

19.1.5 Test Methods

General

Procedures used for the testing of plastic concrete have been standardised by Standards Australia and Standards New Zealand and are set out in AS 1012 or NZS 3112 Part 1. They range from procedures for sampling the fresh concrete to those for determining its consistence, setting rate and other plastic properties.

The use of standard procedures for testing concrete, not only in the laboratory but in the field, is of the utmost importance. Such procedures are designed to eliminate, as far as possible, the random variations which may otherwise occur in test results. On construction sites, these variations can render normal quality control procedures more difficult and lead to unnecessary disputes on the quality of concrete.

The Slump Test

The slump test is fully described in NZS 3112 Part 1 Section 5. The equipment required to conduct the test is relatively simple. It comprises a mould (the hollow frustum of a cone 200 mm in diameter at the bottom, 100 at the top, and 300 mm high) made of galvanised sheet metal and fitted with handles and foot-pieces; a steel tamping rod; a rule; and auxiliary equipment such as a scoop, a steel tray and a container in which to collect the sample to be tested.

The test is conducted by first obtaining a representative sample of the concrete to be tested. This should be done in accordance with NZS 3112 Part 1 Section 5.

The mould, or slump cone, is filled with the concrete to be tested in three approximately equal volumes, each layer being rodded 25 times to compact it before the next layer is added. Surplus concrete is struck off the top of the cone which is then removed from the concrete by lifting it slowly and the concrete allowed to subside. The amount by which it subsides is then measured and is known as the slump **Figure 19.4**.

If, in subsiding, the concrete cone shears or collapses, the test should be repeated using a fresh portion of the sample **Figure 19.5**. If the concrete again shears or collapses, this fact should be recorded as it indicates a lack of cohesiveness in the mixture.

Figure 19.4 **The slump test**

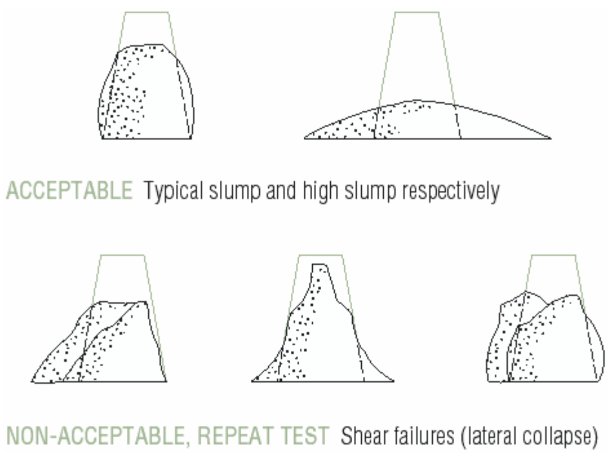

Figure 19.5 **Examples of slump**

Variations in slump indicate that some changes have occurred in either the batching or mixing system. While changes in water content are an obvious cause, other factors which affect workability (such as cement content, aggregate grading and particle shape) could also be varying.

Some variation between successive measurements is to be expected. **Table 19.3**, taken from NZS 3109, provides guidance on acceptable variations.

Gross batching errors will usually result in dramatic changes to the slump and will be readily apparent.

Table 19.3 **Permissible tolerances on slump**

Nominated slump (mm)	**Tolerance** (mm) Representative Sample	**Snatch sample**
≤60	±20	±20
70–110	±20	±30
≥120	±30	±40

Compacting Factor Test

Another test procedure described in AS 1012.3.2 is the Compacting Factor Test. Although not widely used in Australasia, it provides a better measure of the workability of concrete than the slump test (which really measures consistence) and is better suited to controlling the production of low-slump concrete mixes. The test measures the compaction achieved in a sample of concrete by performing a standard amount of work on it. The latter is achieved by allowing an amount of concrete to fall through two cone-shaped hoppers into a cylindrical container **Figure 19.6** (page 19.6). The amount of concrete is such that the cylindrical container will be overfilled. After the excess concrete has been struck off, the mass of concrete in the cylinder is determined by weighing, and then discarded.

A fresh portion of the test sample is then used to refill the cylinder, with the concrete on this occasion being fully compacted by rodding or by vibration. The mass of concrete in the cylinder is again determined by weighing.

The ratio of the mass of concrete contained in the cylinder, partially compacted by the fall through the two cones, to the mass contained in the cylinder, when fully compacted, is the compacting factor. The higher the ratio, the more workable is the concrete.

The Vebe Test

The Vebe Test, also described in AS 1012.3.3 and NZS 3112 Part 1 Section 7, determines the consistence of concrete by measuring the time taken for a cone of concrete (moulded with a standard slump cone) to completely subside in a cylindrical mould under the action of vibration **Figure 19.7** (page 19.6).

The test is most useful in laboratory investigations as it is more sensitive to changes in material properties than the slump test. Indeed, it can be sensitive to changes in the early hydration rate of cements and is therefore not particularly suitable for controlling consistence in the field.

Figure 19.6 **The Compacting Factor Test**

Figure 19.7 **The Vebe Test**

Figure 19.8 **Compression testing**

19.2 HARDENED-STATE PROPERTIES

19.2.1 Strength

General

Concrete is a naturally strong material in compression, i.e. it can resist quite high crushing loads. On the other hand, it is relatively weak in tension, i.e. it cracks fairly readily if stretched or bent. It is therefore normally reinforced with steel when it is to be subjected to tension or bending.

Concrete has some tensile strength, however, and this is an important property of the material when it is used in pavements, floor slabs on the ground and in similar applications. In such cases, the tensile strength must be sufficient to resist any bending loads which are applied to the concrete member.

Because its compressive strength is readily determined, and because most of the desirable hardened-state properties of concrete improve with its compressive strength, this parameter is commonly used as a measure of the quality of the material.

Types and Test Methods

- ***Compressive Strength***

  The compressive strength of concrete is a measure of its ability to resist loads which tend to crush it. It is assessed by measuring the maximum resistance to crushing offered by a standard test specimen **Figure 19.8**.

  In New Zealand, compression test specimens are usually 100-mm-diameter x 200-mm-high cylinders. Occasionally 150-mm-diameter x 300-mm-high cylinders may be used for larger aggregate concrete, e.g. 38 mm.

  Concrete may also be tested in a cube specimen with 150-mm sides, this being common practice in some other countries, e.g. the UK.

  It should be noted that different sized and shaped test specimens will give different results with a given concrete.

  The 150-mm cube gives a higher reading than the cylinder specimens, however, and appropriate conversion factors must always be applied to compare results. Also, in evaluating compressive-test results reported from other countries, care should be taken to ensure that the size of the test specimen is known, or at least recognised as a factor in such evaluations.

  When test specimens are fabricated, cured and crushed in accordance with NZS 3112 Part 2, any variation in their compressive strengths should reflect, almost entirely, variations in the properties of the concretes, rather than the specimens or the test procedures. If the procedures laid down in the Standard are not followed precisely, random variations may be introduced into the results.

- ***Characteristic Strength***

By carrying out a statistical analysis of the 28-day test results obtained from a given mix, the level of strength above which 95% of the concrete is expected to have its strength can be calculated **Figure 19.9**.

This level is known as the 'characteristic strength'. It is used in the design of structures, in the ordering of concrete and in its acceptance on delivery to the construction site. It is the characteristic strength of concrete which must be specified for projects covered by NZS 3109.

The 28-day characteristic compressive strengths of the normal strength grades specified in NZS 3109 are N17.5, 20, 25, 30, 35, 40, 45, and 50 MPa.

It should be noted that the characteristic strength gives a 'potential' strength of the concrete. It is not necessarily the strength which is actually achieved in the structure, this being dependent, amongst other factors, on the compaction achieved and the curing given the concrete once it has been placed in position.

- ***Tensile Strength***

The tensile strength of concrete is a measure of its ability to resist forces which stretch or bend it. As has been noted previously, concrete is relatively weak in tension. Nevertheless, it is an important property in many applications.

There are three methods of assessing the tensile strength of concrete. These involve the application of either direct, or indirect, tensile forces to a test specimen.

The testing of specimens in pure tension is very difficult and it is usual nowadays to determine the tensile strength of concrete by indirect means, either by 'splitting' a cylindrical specimen along an axis, or by testing a rectangular beam specimen in flexure.

- ***Indirect Tensile Strength***

The determination of the indirect tensile strength of concrete, sometimes known as the Brazil or splitting test, is described in NZS 3112 Part 2 Section 8.

It involves the making of a test cylinder, which is then placed, with its axis horizontal, between the platens of a compression testing machine. Load is then applied until the specimen splits down its vertical diameter **Figure 19.10**.

The indirect tensile strength of the specimen may then be calculated using the equation provided in NZS 3112 Part 2 Section 8, viz:

$$T = 2P/\pi dl$$

where

T = indirect tensile strength (MPa)
P = maximum applied force indicated by the testing machine (N)
l = cylinder length (mm)
d = cylinder diameter (mm).

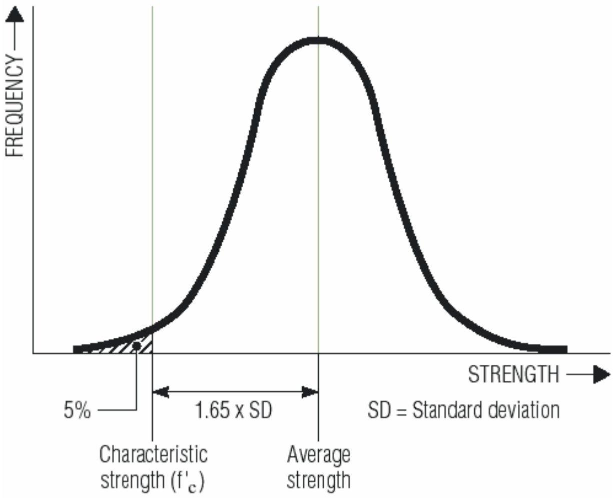

Figure 19.9 **Graphical representation of characteristic strength**

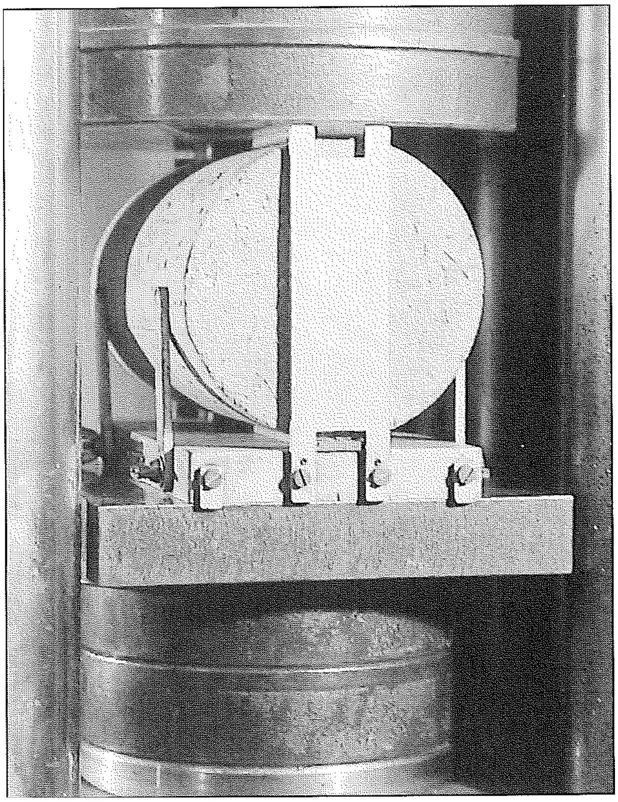

Figure 19.10 **The Brazil or splitting test**

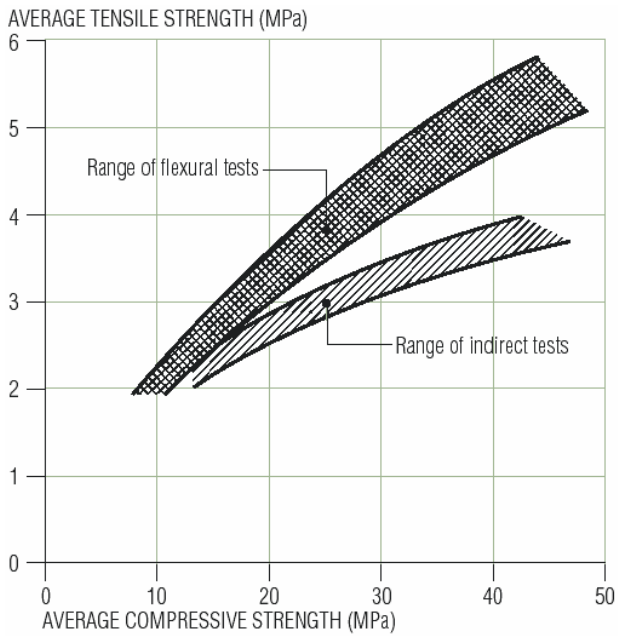

Figure 19.11 The relationship between compressive and tensile strengths

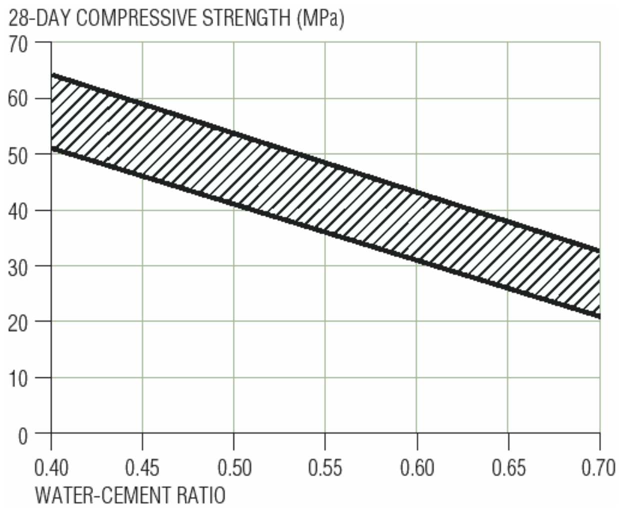

Figure 19.12 The influence of water-cement ratio on 28-day compressive strength (type GP Cement)

- ***Flexural Strength***

The flexural strength of concrete, a measure of its ability to resist bending, may be determined by the method described in NZS 3112 Part 2. A plain beam of concrete is prepared using the methods described in NZS 3112 Part 2 Section 9. The size of specimen is determined by maximum aggregate size but beams are usually 100 x 100 mm by 400 mm long. After appropriate curing and, if necessary, conditioning to ensure that its surfaces are saturated, the specimen is subjected to bending, using third-point loading until it fails.

The flexural strength of the specimen, or more properly, its modulus of rupture, is then calculated using the equation given in NZS 3112 Part 2 Section 9, viz:

T_f = PL/bd^2 where

T_f = modulus of rupture (MPa)

P = maximum applied force indicated by the testing machine (kN)

L = span length (mm)

b = average width of the specimen at the section of failure (mm)

d = average depth of specimen at the section of failure (mm).

For a given concrete, the flexure test gives a considerably higher value of tensile strength than the splitting test, and there is not a direct relationship between them.

Neither is there a fixed relationship between compressive and tensile strength. This has been widely investigated, however, and a number of authorities have proposed bands within which such a relationship might be expected to fall. One such band is illustrated in **Figure 19.11**.

The design of concrete pavements is based on the flexural strength of concrete. However, it is usual practice to determine the relationship between the flexural strength and compressive strength for the given concrete and to control the quality of the concrete on the project in terms of compressive strength.

Factors Influencing Strength

- ***Water-Cement Ratio***

The water-cement ratio of a concrete mix is one of the most important influences on concrete strength since it is one of the factors which governs the porosity of the cement paste and, hence, its strength. It is calculated by dividing the mass of 'free' water in the concrete by the mass of cement. Thus:

water-cement ratio = mass of free water/mass of cement.

Free water is that which is available to combine chemically with the cement and excludes that which is absorbed into the aggregates.

The influence of the water-cement ratio on the strength of concrete is illustrated in **Figure 19.12**. As may be seen, the strength is increased as the ratio is reduced.

In calculating and in controlling this ratio, it is important to take account of the free water which is normally present in the aggregates, particularly the sand. This can be a very significant amount. Conversely, it is important to realise that dry aggregates can absorb water. In either case, appropriate adjustments should be made to the amount of water included in the mix.

Standard compaction and standard (i.e. extended moist) curing are essential for the relationship to hold true. Normally, water-cement ratio curves are produced for concretes that have been cured for 28 days.

Similar curves can be produced for different types of cement and aggregates, for different curing regimes and at different ages. They are extremely useful in predicting the potential strength of a concrete (once the water and cement content of the mix has been 40 - established) and are essential for any mix-design process.

- ***Extent of Voids***

The use of excessive amounts of water results in voids and capillaries as it bleeds to the surface and evaporates from the paste. Control of the water added to the concrete is doubly important for this reason.

For a given concrete mix, the maximum potential strength will be achieved only with full compaction, i.e. if all voids or spaces between the particles of aggregate are filled with cement paste and all air is expelled from the system. The influence of voids on the potential strength of concrete can be seen from **Figure 19.13**.

- ***Degree of Hydration***

Because the reaction between cement and water is time-dependent, it is essential that moisture is present for a sufficient time to allow the reaction to proceed and full strength to develop. The effect of three different curing regimes can be seen from **Figure 19.14**. The substantial reduction in potential strength which results from inadequate curing should be noted.

The hydration reaction, and therefore strength development, will continue for long periods of time. The reaction is most vigorous in the first week, but then slows progressively to an almost imperceptible rate which may continue for many years if water is present.

- ***Type of Cement and Concrete***

The rate of strength development will depend also on the type of cement. **Figure 19.15** illustrates the effects of cement type, and age, on the strength of concrete. It will be noted that, in general, Type GB cements produce concretes that gain strength more slowly during the first few days than do Type GP cements, but that at 28 days and later may achieve higher strengths.

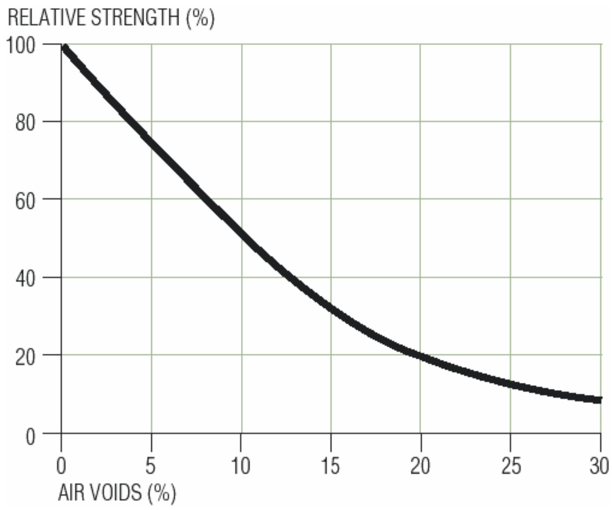

Figure 19.13 **The effect of air voids on potential concrete strength**

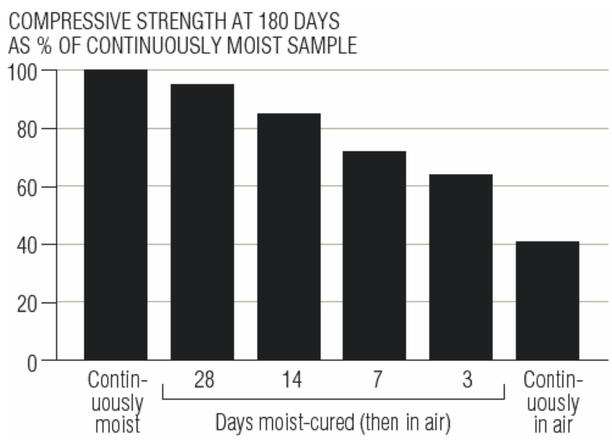

Figure 19.14 **The influence of moist curing on the strength of concrete (w/c = 0.5)**

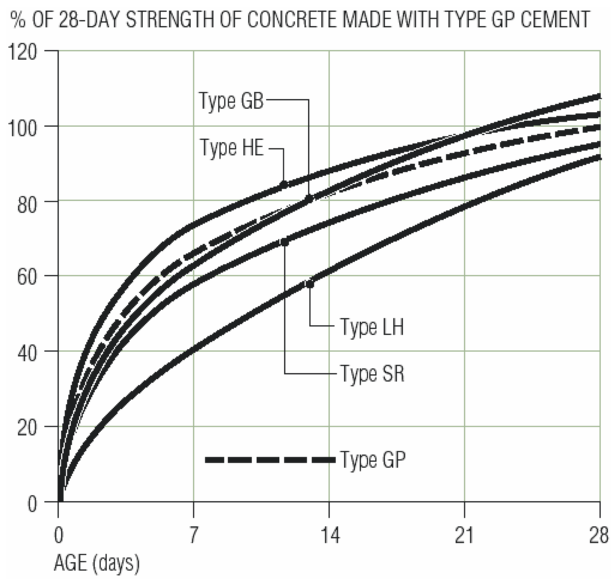

Figure 19.15 **Concrete strength development with age**

- ***Other***

  Other factors which may affect the strength of concrete, either directly or indirectly, include the quality of the aggregates, the quality of the mixing water, and the type of admixture used (if any). These factors are discussed more fully in other chapters but their effects may be summarised as follows:

  - ***Aggregate Quality***

    Almost any rock or stone which is sound and durable can be used to make good concrete. However, those which are weak and friable (e.g. sandstones), or those which expand and contract when wetted and dried (e.g. those containing clays and clay minerals) should be avoided.

    Particle shape and surface texture are also important, particularly where a high tensile strength is being sought. Thus, roughly cubical aggregate particles are to be preferred to flat 'slivery' particles; and a slightly rough texture, which binds well with the cement paste, is to be preferred (in general) to smooth, glassy surfaces. However, it cannot be too strongly emphasised that good concrete can be made from a wide range of rocks and stones. Whilst it is appropriate to exercise care in the selection of aggregates, specification and use of only the 'best' materials leads to uneconomical use of what is sometimes a limited resource.

  - ***Water Quality***

    In general terms, any water which is suitable for drinking, and which has no marked taste or odour, is suitable for use in concrete. Water which is contaminated with organic matter, or which contains dissolved salts, may be unsuitable because the contaminating matter may affect the strength of the concrete or embedded reinforcement. On the other hand, certain alkaline waters may not greatly affect strength. Where any doubt exists, testing of the water by the production of test specimens, and their comparison with similar specimens made with 'pure' water, is desirable.

  - ***Admixtures and Additives***

    Admixtures used in concrete range from air-entraining agents, used to enhance the resistance of concrete to alternate cycles of freezing and thawing, to high-range water-reducers used to make concrete flow almost like water. Additives include simple pigments and pozzolanic materials, such as fly ash, where not part of the cement. Almost all are likely to have some effect on concrete strength, either to reduce it or to increase it, although some admixtures are carefully formulated to have no effect. In all cases, however, the effect of an admixture should be investigated before it is used.

19.2.2 Durability

General

The permeability and absorptivity of concrete are important durability properties; firstly, because they affect directly its watertightness; secondly, because they affect indirectly its ability to protect steel reinforcement from corrosion, and its resistance to chemical attack and other deteriorating influences. Volume change can also be an important property.

These two general properties (permeability and absorptivity being regarded as one) and the material attributes affecting them are dealt with below. The importance of these general properties is, however, their influence on concrete's resistance to various in-service conditions which is also covered later.

Permeability and Absorptivity

Broadly speaking, the absorptivity of concrete is a measure of the amount of water (or other liquid) which the concrete will 'soak up' when immersed in it. The permeability of concrete, on the other hand, is a measure of its resistance to the passage of gases or liquids through it (including through the cement paste). Both properties are affected by much the same factors, notably the porosity of the concrete and whether the pores and voids are separated – discrete – or interconnected. Thus, it is possible to have concrete which has a high absorptivity, but a relatively low permeability – if the pores and voids in it are relatively large but disconnected, e.g. a piece of foamed lightweight concrete. Normally, however, high absorptivity and high permeability tend to go together.

The main material attributes affecting permeability and absorptivity are:

- ***Water-Cement Ratio***

  The permeability of cement paste is directly related to its water-cement ratio since water not taken up in the hydration of the cement either bleeds to the surface, creating passages or capillaries within the paste, or – with time – dries out, leaving voids or pores. As may be seen from **Figure 19.16** (page 19.11), the permeability of the paste increases rapidly with the water-cement ratio.

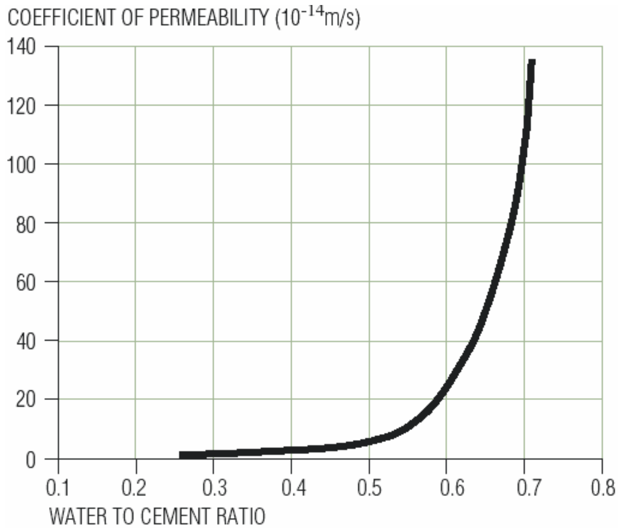

Figure 19.16 The effect of water-cement ratio on the permeability of concrete paste

Table 19.4 Curing time required for capillary discontinuity of cement paste

Water-cement ratio by weight	Curing time required for capillary discontinuity
0.40	3 days
0.45	7 days
0.50	14 days
0.60	6 months
0.70	1 year
over 0.70	Impossible

- ***Extent of Voids and Capillaries***

Incomplete compaction of concrete results in comparatively large air voids being present after it has hardened. In most cases, incomplete compaction will also result in water being trapped under aggregate particles, leaving further voids as it dries out. Incomplete compaction results, therefore, not only in lower concrete strengths but also in higher permeabilities.

Although low water-cement ratios are necessary for the production of low-permeability concrete, their reduction below that necessary for good workability (and therefore ease of compaction) can have contrary effects. Micro voids, resulting from higher-slump mixes, are probably preferable to the macro voids caused by incomplete compaction.

The hydration of cement produces products that not only bind the aggregate particles together but also reduce the size of voids and capillaries within the paste, thereby reducing its permeability. Curing the paste for a sufficient period of time is important, therefore, in the production of low-permeability concrete.

As may be seen from **Table 19.4**, this time is a function of the water-cement ratio of the paste, which helps to explain why limiting the water-cement ratio to a figure below 0.5 is so often recommended for the achievement of low-permeability concrete. Rarely is it possible to cure concrete for a sufficient length of time to achieve capillary discontinuity at water-cement ratios above this figure.

- ***Type of Cement***

Pozzolanic materials incorporated in concrete tend to reduce its permeability by reacting with hydration products to form new insoluble materials which are deposited in the pores and capillaries, reducing their size and volume.

Blended cements, i.e. mixtures of portland cement, fly ash and/or ground granulated blastfurnace slag, are often used, therefore, to help produce low-permeability concrete. Curing is especially important with blended cements, as the pozzolanic reaction takes time to occur.

- ***Admixtures and Additives***

Chemical admixtures may also help reduce the permeability of concrete. Water-reducing agents, for example, by permitting a reduction in the water-cement ratio of the paste for a given workability, help reduce the permeability of the paste.

Volume Change

During its life cycle, concrete may undergo many changes to its initial volume. Firstly, there is the initial reduction in volume, or contraction, as the concrete is compacted and air and moisture are expelled from it. Secondly, there is the slight expansion which takes place as the cement hydrates. Then there is the contraction, or shrinkage, which occurs as the concrete dries out.

Subsequent cycles of wetting and drying will cause it to expand and contract as it gains and loses moisture. Indeed, these cycles continue throughout the life of the concrete as it gains and loses moisture with changes in the relative humidity of the atmosphere **Figure 19.17** (page 19.12).

Finally, there is the movement which occurs when concrete is heated and cooled, i.e. thermal expansion and contraction.

If concrete was free to move without restraint, these changes would be of little moment. However, this is rarely the case as it is normally restrained in one way or another, for example, by the ground or by adjoining members.

Volume changes under these conditions can cause significant stresses, particularly tensile stresses. It is important, therefore, to minimise them to prevent undue cracking. In some cases, it may also be important to reinforce the concrete to resist these stresses.

For convenience, it is normal to measure movements in concrete as a change in length per unit length, rather than as a change in volume. Movements may be expressed as a coefficient in parts per million, as a percentage change in length, as a movement in millimetres per metre, or as a strain in microstrain. Thus, a movement of 600 parts per million is equivalent to a change in length of 0.06%, 0.6 mm/m, or 600 microstrain.

- ***Drying Shrinkage***

Volume change due to drying shrinkage is an important property where excessive cracking is detrimental to either durability or appearance. For example, in pavements, cracking must be strictly controlled to ensure the integrity of the pavement.

Figure 19.18 illustrates the drying shrinkage which occurs as the material is dried out over a period of three months, but, depending on the mix and its components, normal drying shrinkages may range from 200 to 1200 microstrain.

Research has shown that the major factor influencing the drying shrinkage is the total amount of water in the concrete. This should be kept to the minimum amount necessary to achieve adequate workability. Other factors which can affect drying shrinkage include:

- ***Nature of Aggregates***

Aggregates which themselves exhibit significant moisture movement characteristics are particularly detrimental.

- ***Contamination of Aggregates***

Aggregates contaminated with clay or very fine material increase the water demand of the concrete.

- ***Maximum Aggregate Size***

Larger-sized aggregates tend to reduce drying shrinkage.

- ***Cement Content***

High cement contents tend to increase drying shrinkage.

- ***Thermal Movement***

Concrete moves with changes in temperature, expanding when heated, contracting when cooled. While the amount of movement is not great (ranging from 5 to 12 microstrain per °C) stresses induced by thermal expansion can be significant. Hence, it is normal practice to introduce expansion control joints into concrete structures at appropriate intervals.

The type of aggregate used in the concrete is the major factor influencing thermal expansion **Table 19.5**.

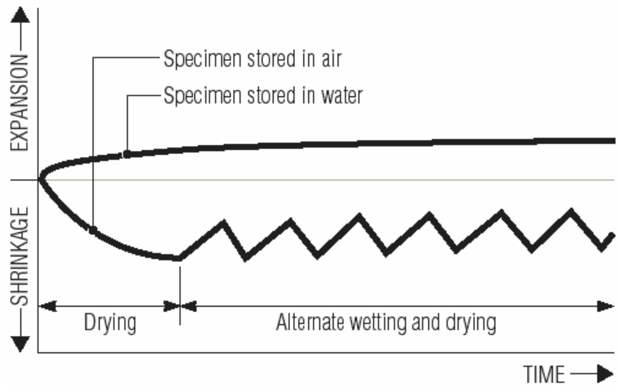

Figure 19.17 Diagrammatic illustration of moisture movement in concrete

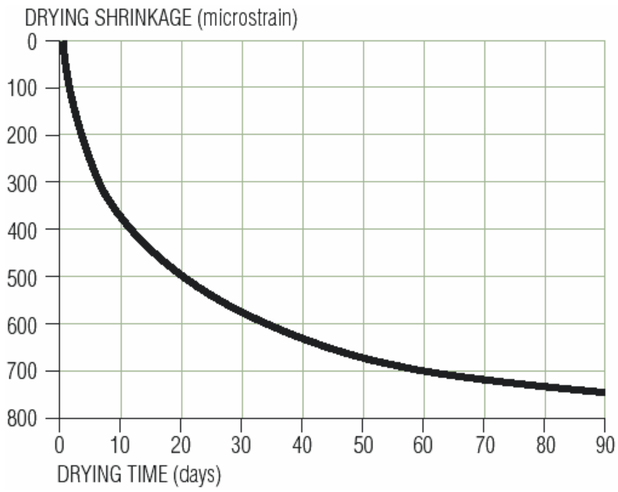

Figure 19.18 Drying shrinkage vs time curve for a typical concrete specimen

Figure 19.5 Coefficients of expansion

Aggregate type	Coefficient of expansion of resulting concrete (microstrain/°C)
Quartz	11.9
Sandstone	11.7
Gravel	10.8
Granite	9.5
Basalt	8.6
Limestone	6.8

In-Service Durability Properties

- ***Resistance to Corrosion of Reinforcement***

  Perhaps the most common form of deterioration in concrete is that caused by the corrosion of reinforcement. This is normally accompanied by cracking and, ultimately, disintegration of the member. Under normal circumstances, concrete protects steel embedded in it in two ways. Firstly, it encloses it in an alkaline environment (in excess of pH 12), that effectively 'passivates' the steel and prevents it from corroding or rusting. Secondly, it minimises the access of moisture and oxygen to the steel, both of which are necessary for the corrosion reactions to occur.

  This protection can be breached in two ways, viz:

  - ***Carbonation***

    Carbon dioxide from the atmosphere reacts with the hydration product, reducing the alkalinity and thus in time the steel is 'depassivated' and able to corrode.

  - ***Chlorides Permeating the Concrete***

    Chloride salts 'depassivate' the reinforcement even though the alkalinity may not be reduced. Further, the presence of chloride salt will tend to accelerate the corrosion process. It is now widely recognised that the presence of chlorides in reinforced concrete, above quite low levels, can be so deleterious to its long-term performance that limits are placed on the chloride content of both the concrete and its constituent materials.

    Both processes are inhibited by the use of low-permeability concrete, i.e. concrete with a low water-cement ratio. In addition, concrete with low volume-change characteristics (and therefore less susceptible to cracking) will be beneficial. These measures must also be accompanied by the use of adequate cover to the reinforcing steel.

- ***Resistance to Chemical Attack***

  Concrete, or, more specifically, the cement paste in concrete, is susceptible to attack by a number of different types of chemical.

  In most circumstances, the chemical converts the constituents of the cement paste into a soluble salt, which is then dissolved out by water.

The intensity of the attack will depend on:

- the nature of the chemical and its concentration in solution;
- ambient conditions; and
- type of exposure, i.e. intermittent or continuous.

Notwithstanding these factors, the rate of attack by any particular chemical is determined, primarily, by the permeability of the cement paste. Without exception, low-water-cement-ratio pastes with corresponding low permeabilities will perform better than those with high permeabilities because the attack tends to be confined, initially at least, to the surface.

Other measures for limiting volume change will also be beneficial.

- ***Acids***

  Most commonly-available acids attack the cement paste by converting the chemical constituents in cement into readily soluble salts. Hydrochloric acid, for example, which is commonly used to etch or to clean cement-based products, forms chlorides which are readily soluble in water. Similar effects occur with most strong acids, such as sulphuric and nitric acids. Oxalic, tartaric, and hydrofluoric acids are unusual in that the products of their reactions with cement are almost insoluble. They are sometimes used, therefore, to provide a measure of chemical resistance or 'hardening' to concrete surfaces. Their application produces a layer of reacted material which protects from further attack. Naturally-occurring water is sometimes acidic due to dissolved carbon dioxide, but attack in such cases is usually slight – except with running water when significant deterioration can occur in time.

- ***Soft Waters***

  Very pure, or soft, water can attack concrete by leaching out calcium-bearing compounds from the cement paste, particularly calcium hydroxide, leaving behind material of little strength. This is not a common occurrence because most waters contain sufficient dissolved carbon dioxide to reduce significantly the solubility of calcium salts in them. Attack can occur, however, in areas of high rainfall or with melting snow. Again, a dense low-permeability concrete will help resist this form of attack. The use of pozzolanic materials, to reduce the free calcium hydroxide in the hydrated paste, is also of value.

- ***Sulphates***

Solutions of soluble sulphates can attack concrete quite strongly. The reactions are accompanied by an increase in the volume of the reaction products which causes an expansion of the paste and, ultimately, disintegration of the concrete. The most common form of sulphate attack arises primarily from sulphur components in the geothermal areas in New Zealand as well as in special situations such as pipes.

The resistance of concrete to sulphates can be improved, first and foremost, by the production of dense and low-permeability concrete which restricts ingress of the sulphate solutions to the interior of the mass. It may then be further improved by the use of sulphate-resisting cements.

- ***Seawater***

Seawater is a solution, primarily of dissolved chlorides, eg sodium and magnesium chlorides (88-90%), and dissolved sulphates, e.g. magnesium, calcium and potassium sulphates (10-11%).

For all practical purposes, the chlorides in seawater do not attack concrete (although they may cause corrosion of any reinforcing steel embedded in the concrete), and, despite the high sulphate content of seawater, its effect on concrete products fully immersed in it is far less than might be expected. The presence of chlorides in solution suppresses the rate of attack which becomes very slow in low-permeability concrete, irrespective of the type of cement. Nevertheless, the use of high-slag-content blended or sulphate-resisting cement is recommended because of the added protection which these provide.

Cement fly-ash blends have also been shown to have good performance in seawater conditions.

On the other hand, concrete partially immersed in seawater can be damaged by the crystallisation of salts inside the mass in zones subject to wetting and drying, i.e. tidal areas. The permeability of the concrete is a critical factor if damage is to be avoided in these situations. The more permeable the concrete, the more rapid will be the deterioration.

- ***Abrasion Resistance***

In many applications, such as industrial floors, concrete surfaces are subjected to wear, or some form of attrition from things such as vehicular traffic, sliding/scraping objects or repeated blows.

In hydraulic structures wear can also be caused by the action of abrasive material in water or by cavitation. Foot traffic can be one of the most damaging sources of abrasion, and areas where a concentration of pedestrians occur, eg shopping malls, are subject to very high levels of wear.

Because the actual abrasion which occurs in a given situation depends so much on the exact cause, it is impossible to be precise regarding the characteristics required of concrete to resist wear. However, tests have shown that, in general, the higher its compressive strength, the better its wear resistance. The lower the compressive strength, the more important will be the wear-resistant properties of the aggregates since these will soon be called upon to provide the wearing surface.

Guidance regarding the required grade of concrete for various wear situations is given in **Table 19.6** (page 19.15). Proprietary topping and shake mixtures are commonly added to the surface of floors to increase wear resistance. In effect, these materials provide a thin, high-strength layer (case hardening) which may also incorporate very-hard-wearing aggregates.

- ***Freeze-Thaw Resistance***

As the temperature of saturated concrete is lowered below freezing point, the water held in the capillary pores freezes and expands. The force which the expanding ice exerts may then exceed the tensile strength of the concrete and cause the surface layer to scale or flake off. Repeated cycles of freezing and thawing cause successive cycles of scaling and, ultimately, complete disintegration of the concrete.

To improve the freeze-thaw resistance of concrete, it is normal practice to incorporate entrained air in the mix, i.e. discrete microscopic air bubbles in the cement paste. These small voids relieve the hydraulic pressure which is built up during the freezing process and help prevent the surface-scaling which would otherwise occur.

It is also normal practice to reduce the water-cement ratio and to extend curing times, thereby reducing the number and volume of capillaries and pores in which water may be retained. Reduced water-cement ratios also increase the tensile strength of the concrete.

Table 19.6 **Recommended concrete strengths and cement contents for abrasion resistance**

Duty	Typical application	Characteristic compressive strength (MPa)
Exposed pavements and floors protected by coverings subject to light toot and/or trolley traffic	Offices, administration blocks	25
Floors and pavements subject to light traffic	Light industrial and commercial premises	30
Floors and pavements subject to medium or heavy traffic	Medium industrial and light engineering works, stores, warehouses, bus depots, garages	30-40
Floors and pavements subject to heavy industrial traffic including vehicles with solid tyres	Heavy engineering works, repair workshops, stores, warehouses	≥40

ACKNOWLEDGEMENTS

Permission to reproduce/adapt material from other publications is acknowledged as follows:

- ***American Concrete Institute***

  Figure 19.16. Based on Figure 6 in Journal ACI 51, November 1954.

- ***Australian Standards***

  The use of material from Australian Standards as indicated is also acknowledged:

  - Figure 19.5 Based on Figure 1.2 in AS 1012.3 *Methods of Testing Concrete Part 3 - Methods for Determination of Properties Related to the Consistence of Concrete*.
  - Figure 19.11 Based on Figure C6.1.1 in AS 3600 Supplement 1 *Concrete Structures – Commentary.*
  - Figure 19.12 W/c curve supplied by Building Research Association NZ.
  - Table 19.3 Based on Table 9.1 in NZS 3109 *Concrete Construction*.

Specifying and Ordering

20

Chapter 20

Specifying and Ordering

This chapter deals with the issues that need to be addressed when specifying concrete for a project and when ordering concrete for supply to the construction site.

INTRODUCTION

NZS 3104 *Specification for concrete production* covers site-mixed, factory-mixed, and truck-mixed concrete. In addition to specifying requirements for concrete materials, plant and equipment, the Standard sets out procedures for the specification and ordering of concrete, its production and delivery, and it's sampling and testing for compliance with the requirements of the specification. This chapter comments on general matters regarding specifications and the procedures for specifying concrete in the Standard. The principles governing specification aim to ensure the supply of a material that meets, consistently and uniformly, the parameters for the concrete assumed in the design in terms of strength, serviceability and durability required by NZS 3109 and NZS 3101.

Relevant New Zealand Standards

NZS 3101 *Concrete structures*

NZS 3104 *Specification for concrete production*

NZS 3109 *Concrete construction*

NZS 3112.1 *Methods of test for concrete - Tests relating to fresh concrete*

NZS 3112.2 *Methods of test for concrete - Tests relating to the determination of strength of concrete*

NZS 3112.3 *Methods of test for concrete - Tests on hardened concrete other than for strength*

NZS 3112.4 *Methods of test for concrete - Tests relating to grout*

Relevant Australian Standards

AS 1012 *Methods of testing concrete*

AS 1379 *The specification and supply of concrete*

AS 3600 *Concrete structures*

20.1 SPECIFICATIONS

20.1.1 General

The general principles for specifying concrete are the same as those for any other material. The specification along with the plans are the mediums by which the designer's intentions for the project are communicated to the contractor. While they also function as legal documents setting out the requirements to be fulfilled by the parties to the contract, this should not override or obscure the primary function of communication.

The requirements in both documents should be consistent, clear and unambiguous. Above all they should be consistent, e.g. use the one terminology for the same parameter every time it is used.

A variety of arrangements is possible for the production and delivery of concrete to construction sites. To help achieve some uniformity and, thus, efficiency and economy in the production and delivery of concrete, NZS 3104 sets out a number of standard ways in which concrete may be specified and ordered in accordance with NZS 3109.

The Standards documents, NZS 3104 and NZS 3109, nominate three types of specification methods for concrete mixes:

- Prescribed Concrete.
- Normal Concrete.
- Special Concrete.

The choice of concrete specification is the prerogative of the design consultant. The detailed production requirements of the three concretes is contained in NZS 3104.

The terms used previously like ordinary, high and special grades have all been dispensed with. These terms broadly related to the accuracy to which concrete could be produced.

The term 'grade' has been reused to mean strength of the material in the same way that the term was used for reinforcing steel, e.g. Grade 300.

20.1.2 Prescribed Concrete

The prescribed concrete permitted by NZS 3109 and NZS 3104 ranges from 17.5 MPa to 25 MPa. As such, the concrete application fits with concrete used in NZS 3604 and NZS 4229. The mix quantities are fully listed in Part 3 of NZS 3104 and this part sets out the production requirements for the concrete. (Miscellaneous details are in Chapter 7.)

This concrete is not tested for strength but by checking that the materials used are batched correctly.

Because of the limited checking requirements, the cement contents of the mixes are significantly higher than those where testing for strength is a routine requirement, e.g. normal and special concretes.

The specifiers final control over these mixes is by way of checking cement contents. It is difficult to carry out this test at the fresh concrete stage and it is more usual to test hardened concrete for cement content by chemical analysis. (BS 1881-124: *Testing concrete. Methods for analysis of hardened concrete*). Some allowance for the test accuracy has to be allowed and hence Clause 3.2.3.1 of Part 3 states that the concrete shall be liable for rejection where the average cement content from two samples is more than 25 kg below the prescribed limits detailed in Table 10. (See Chapter 7.)

Typical use of prescribed concrete would be on small remote projects outside the operating areas for ready mixed concrete plants, and where concrete strength is not required over 25 MPa.

20.1.3 Normal Concrete

Specifications calling for the use of normal concrete 17.5 to 50 MPa in accordance with NZS 3109 and NZS 3104 should be used where the structural designer's primary concern is the compressive strength of the concrete.

The normal concrete permitted by NZS 3109 and NZS 3104 ranges from 17.5 to 50 MPa (N 17.5, 20, 25, 30, 35, 40, 45, 50). This is the predominant range of strengths used for most structural projects, and as such it probably represents 80% of all production. It is also the range of concretes that has been subject to a statistical quality assurance programme in New Zealand for 35 years.

Originally under NZS 3109, the structural designer was required to approve concrete mix designs put forward by the contractor or concrete producer. This stemmed from the days of project site mixing where each project might have a series of special concretes and where there was often a resident engineer or clerk of works. It was quite normal at that time for checking to be undertaken.

With the current predominance of ready mixed concrete supply, it has been considered necessary to change the approach altogether, making the concrete producer fully responsible for the concrete mix and production to meet the structural designer/contractor requirements for 28 day strength and workability at time of delivery.

The structural designer now has the following to specify:

(a) Concrete strength at 28 days.

(b) Workability (slump).

(c) Maximum nominal aggregate size. The detailing of reinforcement may lead to close spacing of steel which may require a maximum aggregate size of other than 19 mm to be specified.

(d) Intended method of placement (i.e. pumped or not).

Based on this information the concrete producer will design and produce the concrete. The quality assurance that concrete will be produced in accordance with NZS 3104 lies in requirements in NZS 3104 that obliges the concrete producer to have an independent audit of the plant's production capability and viability of production on a statistical basis. Essentially, the concrete producer must carry out routine equipment checks e.g. cement scales are checked monthly and regularly test the concrete for strength, slump, air content and yield. The testing statistics are submitted quarterly to the auditing engineer and a full analysis of 12 month results each year.

You cannot specify w/c ratio for Normal concrete only strength and workability. If for some reason you wish to consider w/c ratio then the concrete must be designated 'Special'.

There is also a requirement that each ready mixed concrete plant must have an assigned plant engineer who is either a chartered engineer or registered engineering associate. This technical person is not necessarily based at the plant but must visit and be in regular communication with the plant manager.

The auditing engineer(s) who carry out an audit under NZS 3104 must not be employees of the concrete producer under audit.

The NZRMCA has set up for its members an auditing team of assessors, previously known as the 'Classification Committee', which meet these criteria. The engineering group consists of five independent professional engineer assessors and two industry assessors. These are direct appointments from the Institution of Professional Engineers and from the Concrete Society.

As part of this assessment scheme, plants have in addition to the quarterly and annual paper assessment, one plant inspection every two years.

The audit status on any NZRMCA plant can be immediately checked by visiting the Cement &

Concrete Association of New Zealand website www.cca.org.nz. The Audit Certificate is only issued for 12 months.

20.1.4 Special Concrete

As the name implies this concrete will have performance requirements that may be outside the strength range 17.5–50 MPa or have special features not necessarily measured by strength such as shrinkage, exterior durability, etc.

60, 70, 80, 90 > 100 MPa concretes are all deemed to be ‘Special’.

Clearly a special concrete is still most likely to be a designed concrete requiring specialist skills of the concrete producer. The structural designer must now specify the special features required, together with a test method or other means that the concrete supplier can demonstrate specification compliance.

To understand the requirements for this, the statistical evaluations of normal concrete need to be underlined. The development of statistics from the plants total production is generated in a random way across the range of normal concretes, i.e. not all projects supplied with concrete will necessarily have had concrete on that project tested. The concrete can be related on a statistical basis to other concretes produced.

This will not be the case for special concretes that are project based. For this reason, a testing specification has to be developed for the project. This has to be done at the time of tender because testing costs can become an important factor. For example, the structural designer may require a test frequency which sees every truck tested, i.e. one test in 5 m^3. However any regime can be specified, e.g. one test for every 30, 40, 50 m^3 etc. However, there clearly is an increase in concrete cost to cover the increased frequency of testing.

The statistical testing routine in normal concrete is primarily one in 75 m^3, with plants on large daily volumes able to increase the frequency to one in 250 m^3.

The specifier also needs to get some prior assurance that these special mixes will perform at the time of the project. NZS 3109 requires the specifier to enter into dialogue with the concrete producer. Clearly if the concrete producer is able to produce records from a different project that may satisfy the specifier, then assurance may be satisfied.

If, however, pre-trials are going to be required, then time and resources will need to be planned for and financed.

The use of proprietary products in special concretes is also a case where the specifier may decide to include a dosage of proprietary materials based on the supplier’s information, i.e. there is no definite check required on the performance enhancement. However, the specifier may require that the concrete producer also provides dosage records of the products in the concrete.

The important issue for the specifier to realise is that for special concretes, not only must the ‘special’ requirements of the concrete be specified, but the method of demonstrating pre/post project start compliance needs to be defined, i.e. a project related test programme may be needed.

The starting point for special concrete is to have a concrete plant that is audited to produce normal concrete. The additional project related testing requirements are then grafted onto the standard testing procedures.

Further guidance on specification for special concretes reference should be made to *Specifying concrete for performance* at www.cca.org.nz.

20.2 ORDERING

It is most important when concrete is being ordered from an external supplier that the supplier is made fully aware of all the requirements specified for the concrete in the project specification.

It is first necessary to advise the supplier if the concrete is either 'normal-class' or 'special-class'. This should be stated in the contract documents, e.g. plans and specification, and depends on whether the specification for the concrete contains requirements other than those permitted by NZS 3104, NZS 3101 and NZS 3109 for normal class concrete.

If the concrete is normal-class, then NZS 3104 sets out a series of parameters that have to be specified by the customer, viz:

- a standard strength grade;
- the slump at the point of acceptance;
- the maximum nominal size of aggregate;
- the intended method of placement;
- whether or not project assessment is required to be carried out by the supplier; and
- if required, a level of air entrainment.

Values for each of these parameters will be set out in the project specification. If in doubt about any of them, the specifying authority should be consulted.

It is important that the quality of the concrete matches that assumed in the design otherwise it may be deficient in strength or durability.

In this context, it should be noted that a supplier is required, by NZS 3104, to warrant the performance of normal-class concrete in terms of the parameters specified in the purchase order and those set out in the Standard. Note also that unless specified it will be assumed that project assessment is not required, i.e. not 'special'.

When special-class performance concrete is specified, the order should include all the requirements set out in the project specification for the concrete. In accepting the order, the supplier guarantees the concrete in terms of the physical parameters which have been specified, and, if appropriate, the criteria for compliance. It is particularly important that there be no misunderstanding at this point.

The order should also include the following information:

- The name of the project.
- The address and details of the delivery location, including any restrictions that may apply, e.g. traffic and time of working.
- The volume of the order.
- The time for the delivery of the first batch and the rate of delivery.
- The name and contact details of the person responsible for the concrete at the site and who should be advised of any problems with the delivery.

Similarly, it should be clearly understood that, under NZS 3104 provisions, a supplier is freed of the obligation to guarantee the physical properties of the concrete if it is specified by proportions. In this instance, i.e. special-class prescription concrete, the supplier is required to guarantee only that the specified prescription has been met.

It is important, therefore, when preliminary enquiries are being made with a supplier, to indicate whether normal or special-class concrete will be required. The latter is almost invariably more expensive than the former, for equivalent strength grades, because of the additional requirements imposed on the manufacturer. These days, ordering procedures are very much standardised. However, it is still possible for mistakes to be made if the clear difference between normal and special-class concrete is not recognised.

Chapter 21

Testing

Chapter 21

Testing

Tests are carried out on concrete, either in the laboratory or in the field, to determine its properties. Unless these tests are conducted by standardized procedures, the results will be of little value because they will not be comparable with the results of other similar tests.

This chapter describes the common methods used to sample and test concrete, highlighting the principal precautions which should be taken to ensure comparable, i.e. repeatable, results.

INTRODUCTION

Tests are carried out on concrete, either in the laboratory or in the field, to determine its properties. This information may then be used in a number of ways: to determine whether the concrete complies with the requirements of a specification; to forecast how it will perform in service; to determine the effect of different materials; or simply to determine whether some change is necessary in the mix proportions, e.g. the water content.

Whatever the purpose of the testing, it is imperative that it be conducted in accordance with standard or otherwise agreed procedures so that there can be confidence that the material meets the specified requirements and that the results are not affected by chance or random factors which would make them meaningless.

This chapter describes the more common tests used to determine the properties of concrete and highlights the more important precautions which need to be taken in carrying them out. Full details of the various test methods are to be found in the relevant New Zealand and Australian Standards.

Relevant New Zealand Standards

NZS 3101 *Concrete structures*

NZS 3104 *Specification for concrete production*

NZS 3109 *Concrete construction*

NZS 3112.1 *Methods of test for concrete - Tests relating to fresh concrete*

NZS 3112.2 *Methods of test for concrete - Tests relating to the determination of strength of concrete*

NZS 3112.3 *Methods of test for concrete - Tests on hardened concrete other than for strength*

NZS 3112.4 *Methods of test for concrete - Tests relating to grout*

Relevant Australian Standards

AS 1012 *Methods of testing concrete*

AS 1012.1 *Sampling of fresh concrete*

AS 1012.2 *Preparation of concrete mixes in the laboratory*

AS 1012.3.1 *Determination of properties related to the consistency of concrete – Slump test*

AS 1012.3.2 *Determination of properties related to the consistency of concrete – Compacting factor test*

AS 1012.3.3 *Determination of properties related to the consistency of concrete – Vebe test*

AS 1012.3.4 *Determination of properties related to the consistency of concrete – Compactibility index*

AS 1012.4.1 *Determination of air content of freshly mixed concrete – Measuring reduction in concrete volume with increased air pressure*

AS 1012.4.2 *Determination of air content of freshly mixed concrete – Measuring reduction in air pressure in chamber above concrete*

AS 1012.4.3 *Determination of air content of freshly mixed concrete – Measuring air volume when concrete dispersed in water*

AS 1012.5 *Determination of mass per unit volume of freshly mixed concrete*

AS 1012.6 *Method for the determination of bleeding of concrete*

AS 1012.8.1 *Method of making and curing concrete – Compression and indirect tensile test specimens*

AS 1012.8.2 *Method of making and curing concrete – Flexure test specimens*

AS 1012.9 *Determination of the compressive strength of concrete specimens*

AS 1012.10 *Determination of indirect tensile strength of concrete cylinders (Brazil or splitting test)*

AS 1012.11 *Determination of the modulus of rupture*

AS 1012.12.1 *Determination of mass per unit volume of hardened concrete – Rapid measuring method*

AS 1012.12.2 *Determination of mass per unit volume of hardened concrete – Water displacement method*

AS 1012.13 *Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory*

AS 1012.14 *Method for securing and testing cores from hardened concrete for compressive strength*

AS 1012.16 *Determination of creep of concrete cylinders in compression*

AS 1012.17 *Determination of the static chord modulus of elasticity and Poisson's ratio of concrete specimens*

AS 1012.18 *Determination of setting time of fresh concrete, mortar and grout by penetration resistance*

AS 1012.19.1 *Accelerated curing of concrete compression test specimens – Hot water method*

AS 1012.19.2 *Accelerated curing of concrete compression test specimens – Warm water method*

AS 1012.20 *Determination of chloride and sulfate in hardened concrete and concrete aggregates*

AS 1012.21 *Determination of water absorption and the apparent volume of permeable voids in hardened concrete*

AS 1141 *Methods for sampling and testing aggregates*

AS 1379 *The specification and supply of concrete*

AS 1478 *Chemical admixtures for concrete, mortar and grout*

AS 1478.1 *Admixtures for concrete*

AS 2350 *Methods of testing portland and blended cements*

AS 3600 *Concrete structures*

21.1 SAMPLING

It is essential that the test results (whatever use is to be made of them) are representative of the concrete being tested. Hence, it is essential that the test sample be representative of the concrete from which it is taken. NZS 3112 sets out procedures for obtaining representative samples from freshly mixed concrete for either consistence (slump) tests or the moulding of specimens for other tests.

NZS 3104 also imposes a number of requirements on the sampling of concrete. Where the sample is being taken to check the quality of the concrete being supplied to a project, it requires that samples be taken after completion of mixing but prior to site handling. Generally, this means that the concrete is sampled at the job site from the delivery truck, although sampling at the concrete plant after mixing is permitted.

Sampling at the point of placement in the forms may also be specified on occasions, generally to check on-site delivery methods, e.g. where concrete is being pumped long distances. Whilst sampling at this point is perfectly proper, the information obtained from such samples cannot be used to determine the quality of the concrete delivered to the site. The point at which concrete is sampled is an important factor in determining the use to which test information may be put.

There are two types of 'sampling' methods:

1. **Snatch sample**. In this case a single sample is taken from one position in the concrete.

2. **Representative sample**. In this case three or more samples are taken from different positions in the concrete and are then mixed together to form the single sample.

To ensure that samples are representative of the concrete being delivered to the site, it is first necessary to ensure that they are collected in a random manner, i.e. the batches of concrete or delivery units from which the individual samples are taken must be selected randomly, e.g. by using a list of random numbers to select batches. Selection should never be made on what the concrete looks like as it is being discharged. Secondly, the actual sampling must be done in the prescribed manner.

When a consistence or slump test only is to be performed, the test sample will normally be taken from the delivery or mixer truck immediately after the first 0.1 m^3 of concrete has been discharged.

For other tests, including consistence tests on concrete sampled from non-agitator delivery units or from other locations on the site, composite samples are used. These are samples obtained by taking three or more approximately equal increments during the whole of the discharge. (Increments are not taken during the first nor the last 0.2 m^3 of the batch.) The increments are then mixed together to form a composite whole from which the test specimens are moulded.

NZS 3112 should be consulted for details of a number of other specific precautions which must be taken to ensure that composite samples are representative of the batch.

21.2 TESTS ON FRESH CONCRETE

21.2.1 General

A number of tests are carried out, more or less routinely, on fresh concrete. These are tests for its consistence, its air content, its mass per unit volume and, perhaps less routinely, its bleeding characteristics. Consistence does not refer, as might be supposed, to the uniformity of concrete, but rather to the ability of the concrete to hold its shape when unsupported and to do so without segregating or falling apart. The most commonly used test for this is the slump test.

The consistence of concrete is closely related to its workability, i.e. the ease with which it can be moulded and compacted. Since it is really the workability in which we are interested tests have been devised to measure this property but they are more difficult to carry out than the slump test. The latter has therefore retained its popularity although it measures only indirectly the workability of concrete.

21.2.2 The Slump Test

The slump test is described in Chapter 19 *Properties of Concrete* and, in detail, in NZS 3112 Part 1. The test is carried out by filling a mould, in the shape of a truncated cone, with concrete and then withdrawing the mould. The amount by which the concrete subsides or 'slumps' is then measured **Figures 21.1 and 21.2**.

After the slump has been measured, the concrete is tapped gently on the side to obtain an indication of the cohesion of the mix. Mixes which are well proportioned and cohesive tend to subside a little further. Poorly proportioned, harsh mixes tend to fall apart.

The test does not work well for concretes with either very high or very low workabilities. Very workable concretes may simply lose their shape completely by subsiding and flowing; concretes of very low workability may not subside at all.

Some mixes may lack sufficient cohesion for the test to be carried out properly. The cone of concrete may shear or otherwise collapse as the mould is withdrawn. If this occurs, the test must be repeated with another part of the sample. If the concrete again shears or collapses, the slump is not measured but a shear or lateral collapse is recorded **Figure 21.3**.

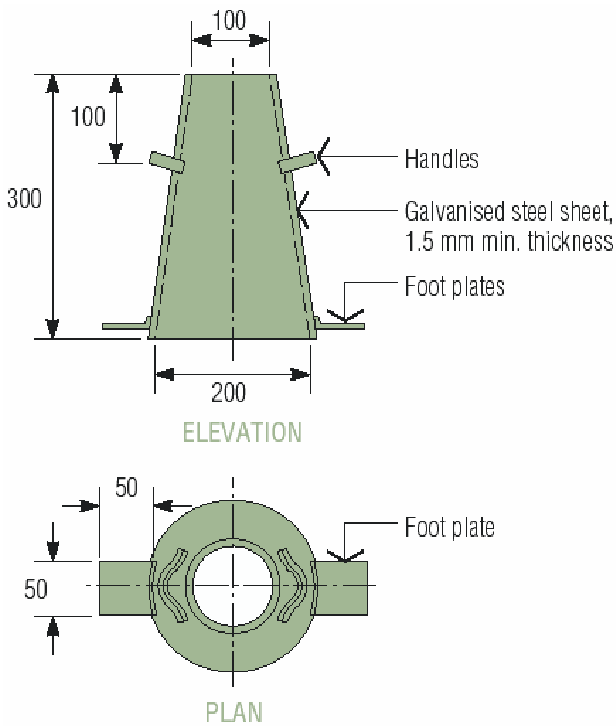

Figure 21.1 **Typical mould for slump test**

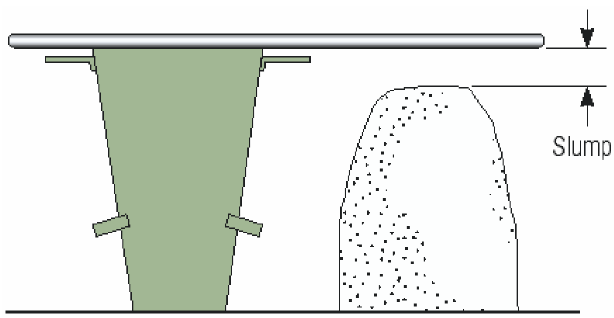

Figure 21.2 **Measuring the slump**

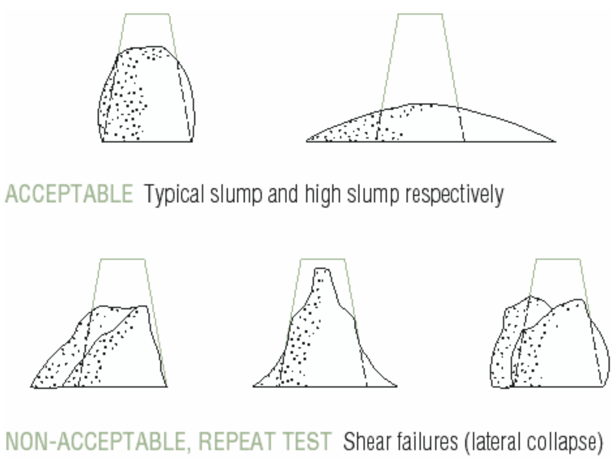

Figure 21.3 **Examples of slump**

21.2.3 The Compacting Factor Test

The compacting-factor test is generally regarded as a more direct indicator of the workability of concrete than the slump test. Moreover, it can be used on concretes for which the slump test is not suitable, e.g. concretes with very little or no slump.

It is, however, quite sensitive to the early stiffening of concrete as hydration of the cement commences. In the laboratory it is normally carried out within four minutes of water being added to the mix. Obviously this is not practical on site, but the sensitivity of the test to this factor should be recognised in interpreting the results.

The test is described in AS 1012.3.3 and is carried out by measuring the compaction achieved in a sample of concrete by performing a fixed amount of work on it. There is no equivalent New Zealand Standard test procedure for this test.

The apparatus is illustrated in **Figure 21.4**. The upper hopper is filled with concrete and then the trapdoor in the hopper opened, allowing the concrete to fall freely into the second or lower hopper. The trapdoor in this hopper is then opened, allowing the concrete to fall into the cylinder. Excess concrete is struck off and the mass of concrete in the cylinder is determined.

The cylinder is then emptied and refilled with a fresh portion of the sample under test, rodding or vibrating each layer of the concrete as it is placed in the cylinder to ensure that it is fully compacted. The mass of fully compacted concrete in the cylinder is then determined and the compacting factor calculated as the mass of concrete in the cylinder (when filled by falling from the hopper above) divided by the mass of concrete in the cylinder (when fully compacted). The higher the ratio, the more workable the concrete.

As was noted above, the test is quite sensitive, not only to early stiffening of the concrete but to the method of compaction used to fill the cylinder. This should be borne in mind when comparing results.

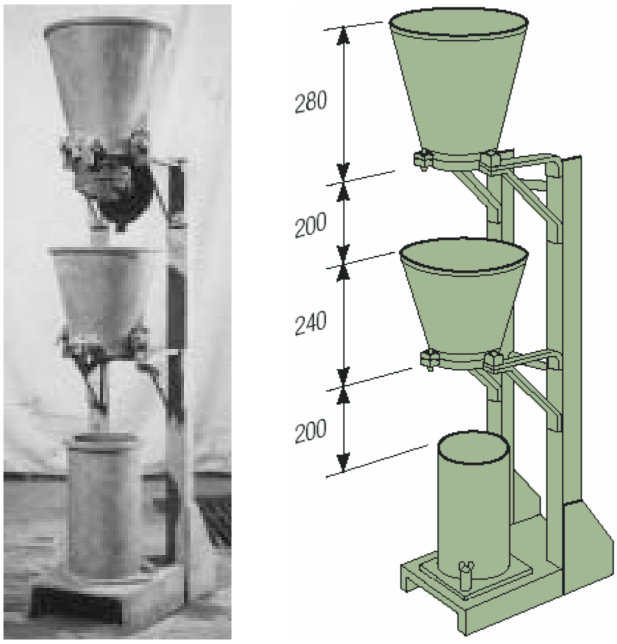

Figure 21.4 **Compacting factor apparatus**

Figure 21.5 **Vebe consistometer**

21.2.4 The Vebe Consistometer Test

The Vebe test is described in NZS 3112 Part 1. The equipment consists of a vibrating plate or table on which is mounted a metal cylinder inside which a conical mould or slump cone is placed **Figure 21.5**.

The test is carried out by determining the time taken for a cone of concrete (moulded with the slump cone) to subside completely inside the cylindrical mould when subjected to vibration. Whilst the test is sensitive to changes in materials, early stiffening of concrete and other factors which affect its workability, it is not easy to carry out with consistent results. Its application in the field is therefore limited but it has been used quite widely in the laboratory to investigate materials and their impact on workability. It works well for concrete having either very high or very low workability.

21.2.5 Comparison of Consistence Tests

Because the various test procedures used to determine the consistence and/or workability of concrete actually measure different parameters, it is

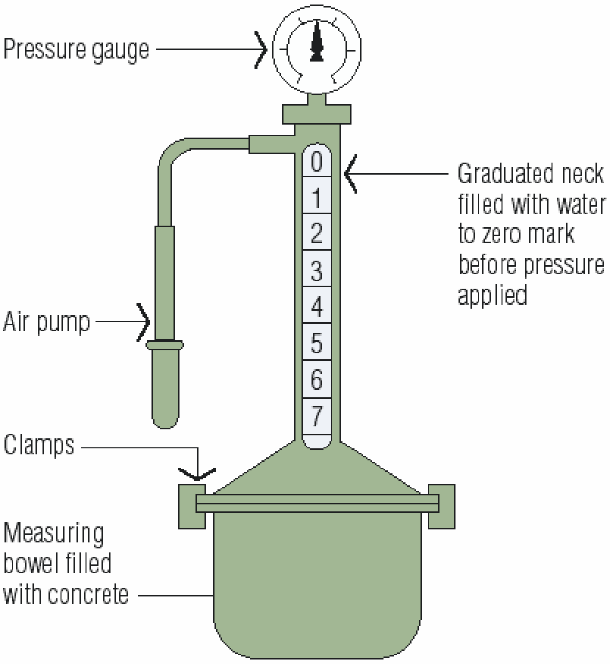

Figure 21.6 **Typical arrangement of apparatus for determining air content of concrete by applied air pressure**

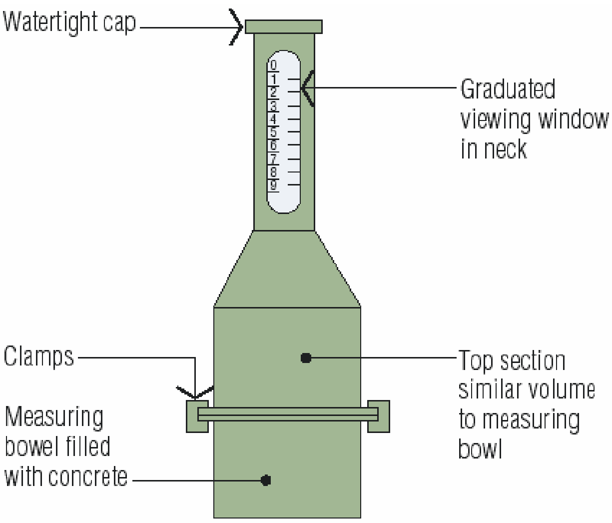

Figure 21.7 **Apparatus for measuring air content of fresh concrete by volumetric method**

not advisable to compare directly the results of one procedure with another. Certainly the results obtained by one test procedure cannot be used to determine compliance with the specification based on another test procedure.

21.2.6 Air Content of Plastic Concrete

Determination of the air content of plastic concrete may be necessary when the purposeful entrainment of air has been specified to enhance the durability of concrete or when it is desired to check the amount of air being entrained by admixtures used for other reasons, e.g. to improve workability.

Three methods of determining the air content of plastic concrete are described in AS 1012.4.1, AS 1012.4.2 and AS 1012.4.3. Two of these, based on determining the change in volume of a given quantity of concrete when subjected to an increase in air pressure, are suitable for normal-weight, relatively dense aggregates. The third method, based on displacing the entrained air with water, is suitable for lightweight and porous aggregates.

In New Zealand the measurement of air content follows NZS 3112 Part 1, Section 9, which relates to the pressure methods.

The two methods that apply pressure to the concrete, measure the reduction in the volume of air entrained within the concrete. From this figure and the pressure applied, the actual air content can be calculated. However, the equipment must be calibrated for the height above sea level at which it is being used and a correction may have to be applied for air contained within the aggregates. For this reason, it is not suitable for porous aggregates **Figure 21.6**.

The volumetric method entails the displacement of the entrained air with water. It is not necessary therefore to calibrate the equipment for height above sea level nor to correct for the air content of the aggregate. The test does, however, take longer to perform than the pressure methods **Figure 21.7**.

21.2.7 Mass Per Unit Volume

The mass per unit volume, i.e. density, of freshly mixed concrete is determined by a simple test in which the mass of concrete in a container of known volume is measured. The standard procedure for conducting this test is described in NZS 3112 Part 1, Section 4. Its principal application is the determination of the volume of concrete produced from a given mass of materials. Thus, it can be used to determine the volume of concrete delivered to major sites by weighing delivery

21.2.8 Bleeding of Concrete

Tests for the bleeding characteristics of concrete are normally carried out in the laboratory to evaluate trial mixes or to evaluate the influence of different materials, e.g. for the evaluation of admixtures under AS 1478. The actual procedure is described in NZS 3112 Part 1, Section 8. A sample of the concrete to be tested is placed in a cylindrical container and compacted, either by rodding it or by vibration. The container is then covered and placed on a level surface. Bleed water is drawn off with a pipette at regular intervals until the amount collected during a 30-minute period is less than 5 mL. The results may be expressed either as the volume of bleed water collected in a given time per unit surface area of the cylinder, or as a ratio of bleed water to total mixing water if the latter is known.

21.3 TESTS ON HARDENED CONCRETE

21.3.1 General

A variety of tests may be carried out on hardened concrete to determine its properties or to measure its performance under different service conditions. They range from relatively simple tests to determine, say, the strength of the concrete to more-sophisticated and more-expensive tests to determine, say, its fire resistance; and from tests which can be carried out quickly and without damage to the concrete, e.g. the Schmidt Rebound Hammer test, to those which may take months or even years to complete, e.g. long-term creep tests.

Viewed in another way, tests on hardened concrete fall into four groups, viz:

- Tests on specimens moulded for the purpose
- Tests on cores taken from hardened concrete
- Tests on concrete in situ
- Tests on concrete elements.

Only tests in the first two categories are considered in any detail in this Guide. Tests in the other two categories usually require special equipment and special skills not normally found on a construction site.

Three forms of concrete strength tests are described in NZS 3112 Part 2 (the compressive strength test, the indirect tensile strength test, and the flexural strength test. The first two are carried out on concrete cylinders and the last on a concrete beam. The Standard also deals with methods of taking cores from hardened concrete for compressive strength tests and indirect tensile strength tests.

Also included are methods for determining the drying shrinkage and creep of concrete as well as a number of other properties which, whilst important, are less relevant to everyday concrete construction.

21.3.2 Test Specimens

The need to standardise procedures for testing hardened concrete is every bit as important as that for testing plastic concrete. Thus, in addition to the care which must be taken in sampling concrete, care must also be taken in the preparation of test specimens. NZS 3112 Part 2, Sections 3, 4 and 5, describe the necessary procedures for moulding and curing compression, indirect tensile and flexural test specimens made from plastic concrete respectively. NZS 3112 Part 2, Section 9, describes the procedures for obtaining cores from hardened concrete.

There is a belief in some quarters that the making of test specimens is a simple procedure which can be entrusted to any site personnel. This is not so. Proper preparation requires proper training. It is therefore not unusual to find in concrete specifications a requirement that all site testing be carried out by a laboratory registered for the purpose by the International Accreditation New Zealand (IANZ). Whilst it is not a mandatory requirement of the Standard, it helps to ensure that personnel making test specimens are trained for the task. CCANZ has a training programme for technician training covering correct sampling and testing.

21.3.3 Compressive Strength Tests

The determination of the compressive strength of concrete is described in NZS 3112 Part 2, Sections 4 and 6, for two sizes of concrete cylinder to be used, either 150-mm-diameter x 300-mm-high, or 100-mmdiameter x 200-mm-high **Figure 21.8**. The smaller cylinder may be used provided the maximum aggregate size does not exceed 20 mm and the designer's permission is obtained. Whilst the two cylinder sizes tend to give the same average compressive strength, and hence may be used to determine compliance with the concrete specification, the coefficient of variation of the individual results may be different. Hence, results from the two specimen sizes cannot be combined in determining the average.

Figure 21.8 **Moulds for the two sizes of concrete test cylinders**

Cylinder tests are quite sensitive to the planeness of the ends and to the capping material used to ensure plane surfaces **Figure 21.9** (page 21.9). NZS 3112 Part 2, Section 4, devotes considerable attention to this, setting quite stringent limits on the condition of the cylinder ends before capping and then on the materials and methods which may be used to cap cylinders. Reference should be made to the Standard for full details.

An alternative to capping procedures is to use neoprene cap as explained in NZS 3112 Part 2, Section 8.

Figure 21.9 **Capped concrete test cylinders in each of the two sizes**

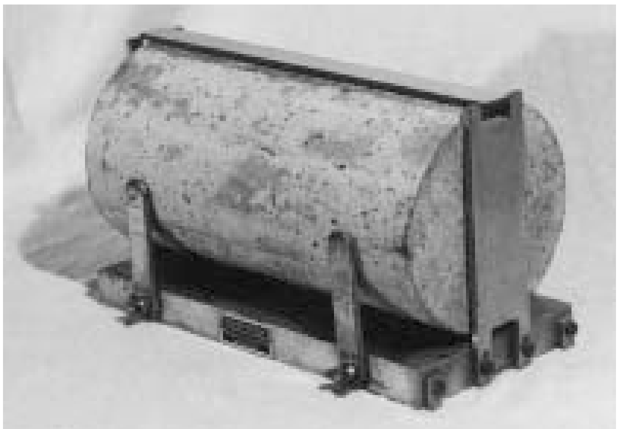

Figure 21.10 **Concrete cylinder in jig ready for indirect tensile strength testing**

The Standard also sets down requirements for testing machines and testing procedures to ensure that test results from a single batch of concrete are as uniform as possible.

21.3.4 Indirect Tensile Strength Test

The indirect tensile strength, the Brazil or splitting test, is conducted on a standard 150- x 300-mm concrete cylinder (held in a jig **Figure 21.10**) by placing it horizontally in a testing machine and applying a compressive force to it. When tested in this way, the cylinder splits, enabling the tensile strength of the concrete to be determined. NZS 3112 part 2, Section 8, describes the procedure.

21.3.5 Flexural Strength Test

Tests to determine the tensile strength of concrete in flexure have been largely superseded by the indirect tensile strength test (see Clause 21.3.4), although it is still specified occasionally on pavement and other similar projects where the strength of concrete in flexure, or bending, is of prime importance. The test method is described in NZS 3112 Part 2, Section 7.

For a given concrete, the flexure test gives a higher value for the tensile strength than the indirect or splitting test and there is not a direct relationship between the two values. In citing tensile strengths of concrete, care should therefore always be taken to nominate the method by which the value has been obtained. Further information on the tensile strength of concrete is provided in Chapter 19 *Properties of Concrete*.

21.3.6 Shrinkage and Creep Tests

Limits on the shrinkage and creep of concrete are specified by designers in an attempt to limit both short- and long-term movements in buildings and other structures and, thereby, the undesirable effects of such movements. For example, drying shrinkage can lead to unsightly cracking and, in extreme cases, loss of structural integrity. Similarly, creep can lead to long-term differential shortening of columns and walls in tall buildings which can damage other elements of the building not designed for such movements.

Whilst most drying-shrinkage specimens and creep specimens are prepared in the laboratory, they may have to be prepared in the field to check the characteristics of concrete being delivered to the site. Methods for the preparation and testing of drying-shrinkage specimens are set out in AS 1012.13.

This test is being used in preference to NZS 3112 Part 2, Section 3. This New Zealand Standard also includes thermal expansion and hardened density of concrete.

The specimens required for the determination of drying shrinkage are prisms 75 x 75 x 285 mm with gauge studs set in either end. The drying shrinkage of the specimen over time is determined by measuring the change in distance between the gauge studs. Since drying shrinkage is susceptible to the initial curing of the specimens, particularly once they have been demoulded, it is essential that their treatment be strictly in accordance with the Standard.

Methods for the determination of concrete creep are set out in NZS 3112 Part 2. The test is conducted on standard cylinders prepared in accordance with NZS 3112 Part 2. A constant load is applied to the cylinders, which are stored in a controlled environment, and the change in their length with time is compared with that of companion cylinders which are unloaded. Both sets of specimens shrink. Hence, the difference between the two movements gives the true creep of the loaded specimens **Figure 21.11**.

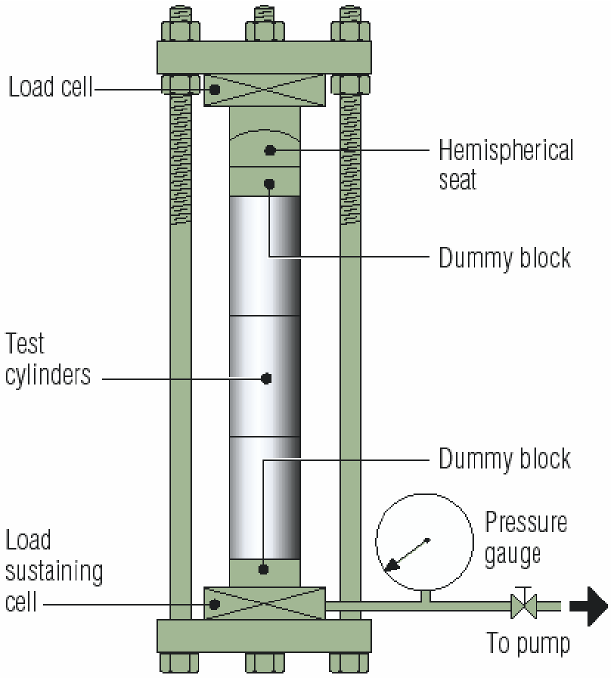

Figure 21.11 **A typical arrangement for testing the creep of concrete specimens**

21.3.7 Other Tests

A number of other tests may be carried out on hardened concrete. These include the determination of its density, see NZS 3112 Part 2, Section 5, (mass per unit volume) as a measure of its compaction, and the static-chord modulus of elasticity and Poisson's ratio. All these tests are based on the use of standard 150 x 300 mm cylinders, although the Standard does provide a method for determining the density of irregularly shaped specimens.

Durability and chemical tests may also be carried out on hardened concrete to establish the concrete's resistance to sulphate attack and to the penetration of chlorides which are now concerns of NZS 3101 and NZS 3109. NZS 3101 part 2 lists a number of tests that can be used to assess reinforced concrete durability which are essentially tests to measure the permeability of the concrete either near the surface of the concrete or within the thickness of the concrete.

The tests are:

- ***Surface tests***
  - Absorption to AS 1012.21.
  - Sorptivity by Hall.
- ***Thickness tests***
  - ASTM 1202 *Rapid Chloride Test.*
  - NT BUILD 443 *Chloride Diffusion Test*.
  - NT BUILD 492 *Rapid Migration Test.*

An in-depth analysis of durability tests applicable to marine concrete is given in BRANZ Study Report 145 *'Durability of Reinforced Concrete Structures under Marine Exposure in New Zealand'.*

As was mentioned earlier in this chapter, concrete may also be tested in situ by means of a number of non-destructive tests. These range from the Schmidt rebound hammer, a device which measures the surface hardness of concrete and thereby provides an estimate of its strength, to ultrasonic pulse velocity tests which measure the time taken for an ultrasonic pulse to travel a measured distance through the concrete. An estimate of the strength of the concrete can be obtained given some knowledge of its constituent materials, their proportions and the moisture content of the concrete at the time of test.

Other tests are available to estimate the position of reinforcement in concrete and its potential to corrode.

In general, non-destructive tests are seldom used to ensure compliance with a specification. Nevertheless, they can be useful on occasions to provide information on the behaviour of the member and/or its condition. Further information can be obtained from various sources.

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