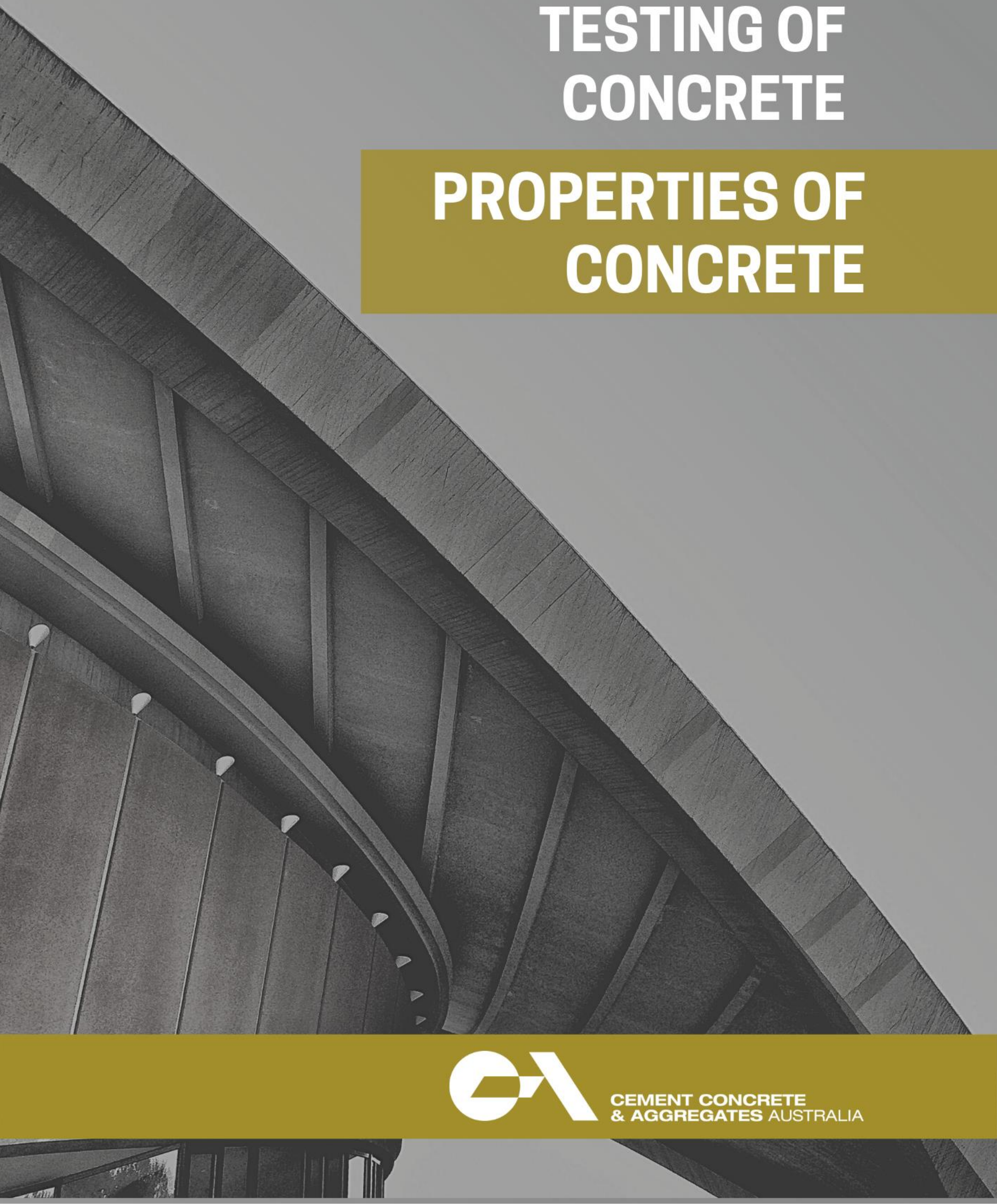
PART VIII.
PROPERTIES & TESTING OF CONCRETE

PROPERTIES OF CONCRETE



CEMENT CONCRETE
& AGGREGATES AUSTRALIA

This Section describes how the various properties of concrete – in both the plastic (wet) and hardened (dry) states – are influenced by the materials from which concrete 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 Sections devoted to those particular topics (in Part V of this Guide).

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1. INTRODUCTION

As outlined in the Introduction in this Guide, concrete is required to have certain, defined properties at two distinct stages, i.e. when it is in the initial plastic state and after it has hardened. The plastic-state properties determine the ease with which it can be placed and finished, and the hardened-state properties determine how well it will perform in the completed structure, and for how long. As might be expected, different plastic and hardened state properties may be required for different projects depending on (a) the concrete specification and the site conditions, and (b) the serviceability requirements of the project, respectively.

This Section provides discussion about the most important properties and the inter-relationship between many of them.

2. PLASTIC STATE PROPERTIES

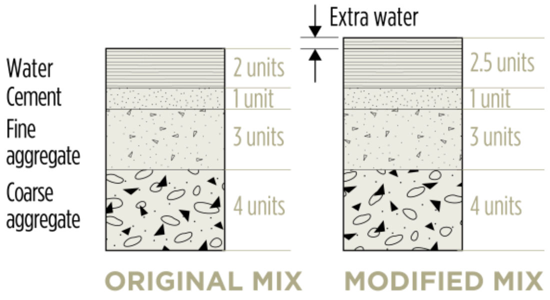
2.1 WORKABILITY

General – There is no singular way of describing concrete workability. Arguably it refers to the ease with which a concrete mix can be compacted without the risk of segregation. However, the desired workability of a concrete mix will depend in part on what means of compaction are available as well as the type of concrete element being placed (e.g. the workability requirements for slip-form paving versus a high-strength column with congested reinforcement are vastly different).

When concrete is being compacted, work is applied to the mix to eliminate any entrapped air – until it is fully consolidated. This work needs to overcome the friction between particles as well as the friction between the mix and any adjacent surfaces (e.g. reinforcing, formwork) – called internal friction and surface friction respectively. It is only the ‘internal friction’ that is a function of the mix itself. Some work will also be wasted trying to consolidate already consolidated concrete – meaning that only ‘useful’ work (i.e. work actually involved in compaction) should be considered when assessing workability, which can be defined as ‘the amount of useful internal work necessary to produce full compaction’ [1]. The American Concrete Institute (ACI 116R-00) defines workability as ‘that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated and finished to a homogenous condition’.

A number of mix components affect the degree of ‘internal friction’, as described below.

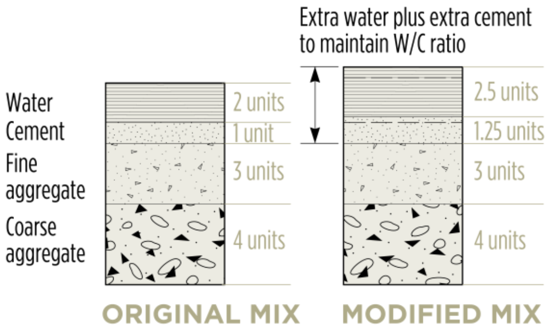
Influence of Water Content – For given proportions of cement and aggregates in a concrete mix, the higher the water content, the more workable the concrete will be. However, increased water content will increase the water/cement ratio and thereby reduce strength and durability. It will also increase the risk of cracking caused by drying shrinkage (**Figure 25.1**). Normally, therefore, only very minor adjustments to workability should be made by the addition of water alone.



EFFECT	Water/cement ratio:	Increased
ADVANTAGE	Workability:	Increased
DISADVANTAGES	Strength and durability: Shrinkage cracking:	Decreased Increased

Figure 25.1 – The Effects of Increased Water Content

Influence of Cement Content – Because the cement paste lubricates the aggregate particles when 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 25.2**).



EFFECT	Water/cement ratio:	Same
ADVANTAGES	Workability: Strength and durability: Shrinkage cracking:	Increased Same Same

Figure 25.2 – The Effects of Increased Water and Cement Contents

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, and a combined grading curve describes the proportion of aggregate of each particle size in a mix (see Part II, Section 3 of this Guide). The overall grading will affect workability because the amount of water (or paste) necessary to wet all the solids in the mix will depend on the surface area of the aggregates. Sieving (**Figure 25.3**) is used to determine the combined grading curve.

Figure 25.3 – Aggregate Combined Grading determined by Sieving

It is usual to aim for a smooth combined grading curve to achieve optimum workability. Nevertheless, within quite wide limits, a variety of aggregate gradings may be used satisfactorily.

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 from flaky or elongated aggregate particles. A proportion of flaky or elongated particles is permissible but they will increase the amount of cement paste required to achieve the required workability. The maximum size of particles also has an effect – the larger the particle size, the greater the workability for a given cement content and water/cement ratio.

2.2 CONSISTENCY

'Consistency' is a term used to describe the ease with which concrete will flow and is often used to reflect 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 descriptor – the 'slump' of concrete.

This ‘slump’ term is derived from the standard test procedure for determining the consistency of concrete, known familiarly as the 'Slump Test', which is described generally in 2.4 and in more detail in Section 26*.*

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 25.1 provides an indication of the appropriate slump for various construction elements.

Table 25.1 – Typical Ranges of Slump for Various Elements (except super-plasticised 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

2.3 COHESIVENESS

General – The cohesiveness of concrete is a measure of its ability to resist segregation into its separate components during handling, placing and compacting.

Segregation can occur as the separation of coarse aggregates from the cement mortar, or as 'bleeding' –the displacement of water to the surface of the concrete as the heavy materials settle towards the bottom of the element. Bleeding generally occurs after compaction and bull floating and continues until the mix stiffens sufficiently to prevent further settling.

There are several factors that can affect the cohesiveness of concrete, as follows:

Influence of Specific Gravities of the Constituents – The typical specific gravities of materials in a normal- weight concrete mix are shown in **Table 25.2**.

Table 25.2 – Typical Material Specific Gravity Values

Material	Specific Gravity
Water	1.00
Fine aggregate	2.5-2.7
Coarse aggregate	2.5-3.0
Cement	3.15
Fly Ash	2.1-2.5
GGBFS	2.9

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 honey-combed or 'boney' areas in compacted concrete. In flowing concretes, it can mean the separation of the mortar and aggregate components as the concrete flows within the forms (or in the Slump Flow Test as described in 2.4).

Influence of Consistency – The higher the water content in the mix (which usually means higher slump) the greater is the risk of segregation and bleeding occurring.

Adding water leads to thinning-out of the cement paste which reduces its capacity to hold aggregate particles apart during the handling and placing processes. In addition, a higher water content delays the stiffening of concrete during its very early life, allowing sedimentation of heavier particles in the mix to continue for a longer period resulting in more bleeding. Cold weather also retards stiffening/setting and allows bleeding to continue for a longer time.

Dry mixes, which can be friable, are also prone to segregation.

A very useful indication of the cohesiveness 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 2.4). If the cone breaks up, the mix may 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 increased due to a lack of fines. On the other hand, excessive fines (e.g. High-Volume Fly Ash Concrete, concrete containing silica fume) 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, issues with excessive bleeding may be reduced by the use of air-entraining agents. The microscopic air bubbles act like a fine aggregate by increasing surface area which limits the movement of water to the surface (See Part II, Section 5 *'Admixtures'*).

2.4 TEST METHODS

General – Procedures used for the testing of plastic concrete have been published by Standards Australia within the AS 1012 set of Standards. They range from procedures for sampling the fresh concrete to those for determining its consistency, setting times and other plastic properties. They are described in more detail in Section 26 of this Guide.

The strict application of standard procedures for testing concrete – both in the laboratory and the field – is of great importance. Such procedures are designed to eliminate, as far as possible, the operator-induced variability that may otherwise occur with test results. On construction sites, testing variability can result in a lower standard of quality control test results which may lead to unnecessary disputes about the quality of concrete and increased costs to all parties.

The Slump Test – The slump test is fully described in AS 1012.3.1. The equipment required to conduct the test is relatively simple. It comprises a Slump Cone – a mould (the hollow frustrum of a cone 200 mm in diameter at the bottom, 100 mm diameter at the top, and 300 mm high) made of galvanised sheet metal and fitted with handles and foot-pieces; a steel tamping rod; a ruler; and auxiliary equipment such as a scoop, a steel tray and a container in which to collect the sample(s) 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 AS 1012.1 if the concrete is to be sampled in the field; or AS 1012.2 if the test is to be done in a laboratory.

The slump cone is filled with the concrete to be tested in three approximately equal layers – each layer being rodded to compact it before the next layer is added. Surplus concrete is struck off the top of the mould before removing the mould from the concrete by lifting it slowly (in 3-4 seconds) and allowing the concrete to subside. The distance by which it subsides is then measured, with the result (expressed in mm) being reported as the slump value (**Figure 25.4**).

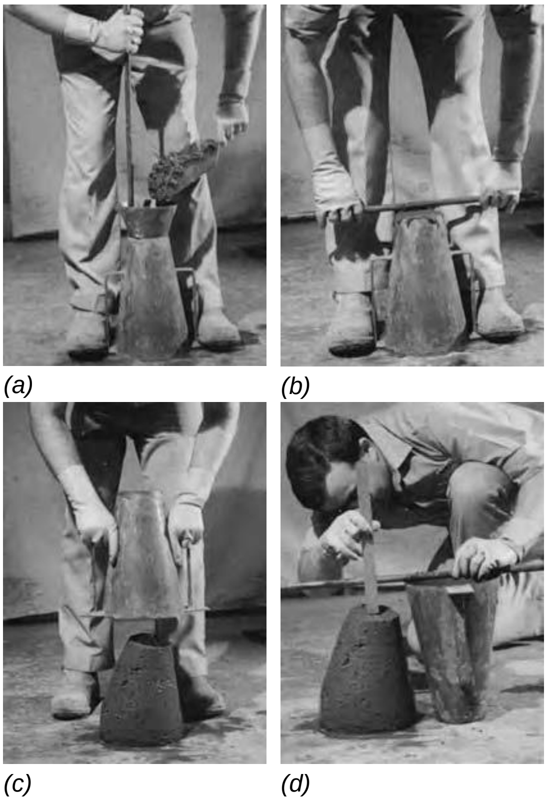
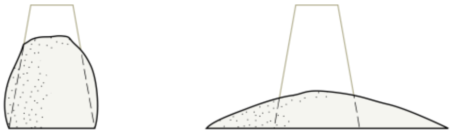
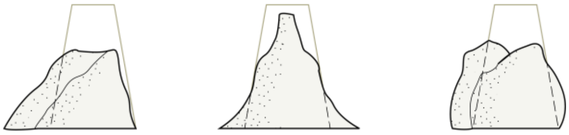


Figure 25.4 – The Slump Test (mould filling; surface struck-off; mould lifted; measure slump)

If, in subsiding, the concrete cone shears or collapses, the test should be repeated using a fresh portion of the sample (**Figure 25.5**). If on retest the concrete again shears or collapses, this fact should be recorded as it indicates a lack of cohesiveness in the mix.



ACCEPTABLE Typical slump and high slump respectively



NON-ACCEPTABLE, REPEAT TEST Shear failures (lateral collapse)

Figure 25.5 – Examples of 'Slumped Concrete' after Testing

The slump test has another important role to play in the control of concrete quality. Slump measurements taken from successive batches of the same concrete mix indicate whether a consistent product is being produced and provide an assessment of the degree of control being achieved during manufacture at the concrete plant.

Variations in slump for a given mix indicate that some changes have occurred in either the batching or mixing processes. While changes in water content (e.g. due to changes in aggregate moisture contents) are an obvious possible cause, other factors which affect workability (e.g. cement content, aggregate grading and particle shape) may also require investigation.

As slump testing is not very precise, AS 1379 allows some variation between measured slump and specified slump when testing slump at site. If measured slump varies by more than the allowed tolerance from the specified slump, that may be cause for rejection of the load from site. Note that the allowable variability increases as the slump value increases. In part this is due to the higher sensitivity of slump to water addition at the higher slump levels (**Table 25.3**).

Table 25.3 – Permissible Tolerances on Slump (AS 1379)[25.1]

Specified Slump (mm)	Tolerance (mm)
< 60	±10
≥60 ≤80	±15
>80 ≤110	±20
>110 ≤150	±30
>150	±40

Gross batching errors will usually result in dramatic changes to the slump and should be readily apparent.

Compacting Factor Test – A test procedure described in AS 1012.3.2 is the Compacting Factor Test. Although not widely used in Australia, it provides a better measure of the workability of concrete than the slump test (which really measures consistency) 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 'standardised work' component is achieved by allowing an 'amount' of concrete to fall (defined distances) from an upper sample hopper into a lower hopper and then into a cylindrical container (**Figure 25.6**). 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 this portion of the sample is then discarded.

Figure 25.6 – The Compacting Factor Test Apparatus

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 compacted concrete in the cylinder is 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 Compacting Factor ratio, the more workable is the concrete.

The Vebe Test – The Vebe Test, also described in AS 1012.3.3, determines the consistency 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 25.7**). The conditions of test are not unlike those experienced in the actual placement of concrete.

Figure 25.7 – The Vebe Test

The test is most useful in laboratory investigations, and particularly for very dry mixes. 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 consistency in the field.

Workability Tests for Flowing Concrete – The (now) common use of flowing concrete mixes has led to the development of a number of 'workability' tests that are useful for the assessment of flowing or Self Compacting (SCC) or Super Workable Concretes (SWC). Some of the tests that are in common use are:

- Slump Flow test;
- T-500 test;
- Visual Stability Index;
- L-Box; U-Box and J-Ring;
- Orimet Test Method.

While workability tests for flowing concrete are described more fully in Part VI, Section 22 and Part VIII, Section 26 of this Guide, a brief description of several is given below.

Slump Flow Test – The Slump Flow Test, also described in AS 1012.3.5, uses a standard slump cone. The slump cone is filled with the flowing concrete mix (no compaction step is necessary) and then lifted as is done in a normal slump test. Two measures of the flow characteristics of the concrete can be obtained from this test, namely (1) the final diameter of the concrete after flowing can be measured and the resultant 'spread' expressed in mm; and (2) using a marked ring at 500 mm diameter, the time taken from when the slump cone is lifted until the flowing concrete reaches the 500 mm line gives a value known as the T-500 value. For SCC or SWC, a typical 'spread' might be 600 mm; while a T-500 value of 2-10 seconds is typical (**Figure 25.8**).

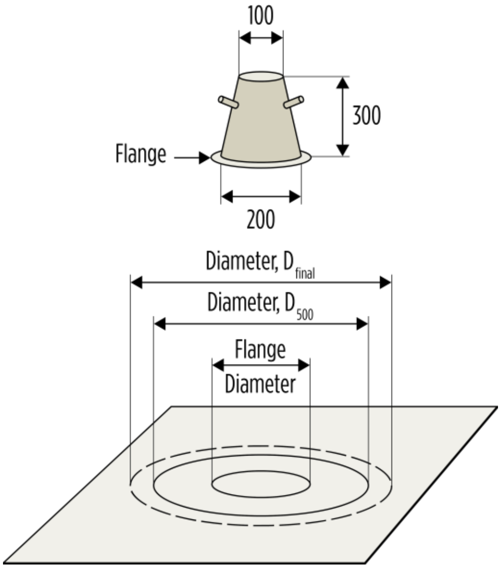


Figure 25.8 – Slump Flow Test (all dimensions are in millimetres)

Visual Stability Index (VSI) – The VSI, also described in ASTM C1611, is established by observing the presence or otherwise of bleed water at the leading edge of the concrete or if aggregate remains in the middle of the concrete sample after the Slump Flow Test. VSI values range for ‘0’ for highly stable to ‘3’ denoting unacceptable stability.

L-Box; U-Box and J-Ring Tests – These tests are used to measure the flow of a fluid concrete, under its own mass, through various types of impediments typical of what might be encountered as flowing concrete moves through congested reinforcement or around other components in a structure (**Figures 25.9** and **25.10**).

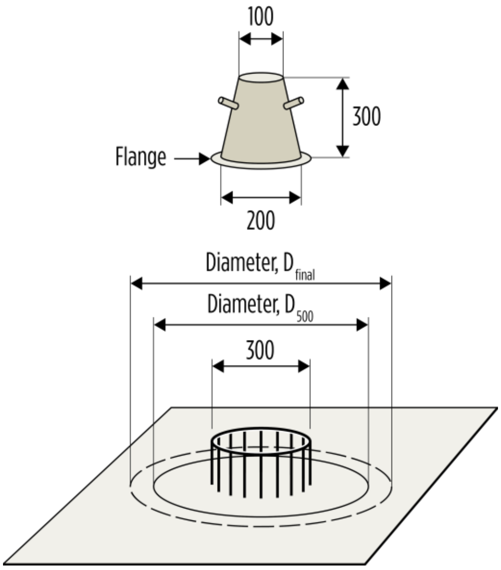


Figure 25.9 – Slump Flow and J-Ring Method (all dimensions are in millimetres)

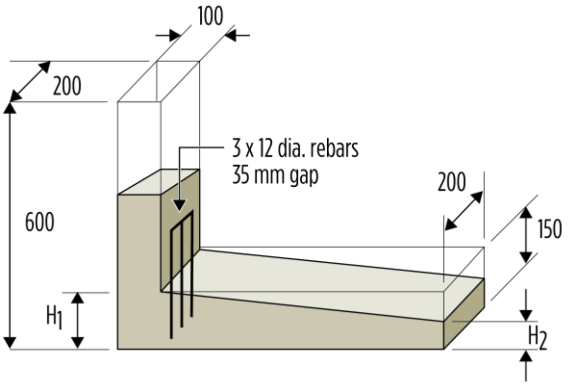


Figure 25.10 – L-Box Method (all dimensions are in millimetres)

Orimet Test Method – The Orimet test Method provides an indirect measure of the ability of a concrete to flow into a confined space under its own mass. The funnel is filled with concrete, and after the trapdoor is released, the time taken for the concrete to flow fully out of the funnel is determined and used as a measure of fluidity (**Figure 25.11**).

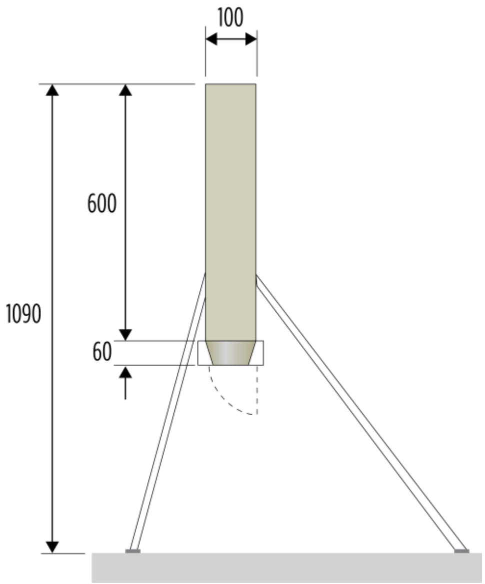


Figure 25.11 – Orimet Test Method (all dimensions are in millimetres)

3. HARDENED STATE PROPERTIES

3.1 STRENGTH

General – Concrete is a strong material in compression (i.e. it can resist quite high crushing loads) but it is relatively weak in tension (i.e. it cracks readily if stretched or bent). To improve its resistance to tensile (and shear) stresses concrete is normally reinforced with steel – as was discussed in Part I of this Guide.

Concrete has tensile strength at a level of about one-tenth of its compressive strength. Its tensile and flexural strengths are important properties of the material when it is used in pavements, slabs on the ground and similar applications. In such cases, the tensile strength of the concrete must be sufficient to resist any bending actions that are applied when the concrete member is loaded.

Because compressive strength is readily determined, and because most of the desirable hardened-state properties of concrete improve as compressive strength increases, compressive strength is the parameter commonly used as a measure of the overall quality of concrete. In AS 1379, the grade of concrete is a primary descriptor – with characteristic strengths of the various grades ranging from 20-100 MPa.

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 standardised test specimen (**Figure 25.12**).

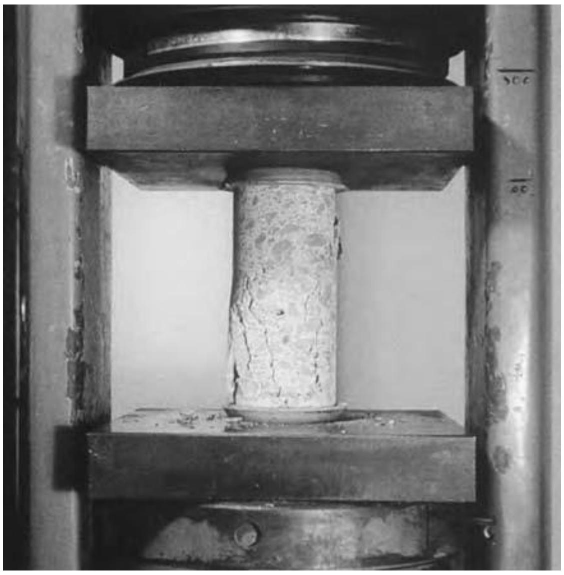


Figure 25.12 – Testing a Cylinder for Compressive Strength

In Australia, specimens used for compressive strength testing may be either 150 mm diameter × 300 mm high cylinders; or 100 mm diameter × 200 mm high cylinders – with the latter size being most commonly used. Note that the length : diameter ratio is 2 : 1.

Concrete may also be tested using a cube specimen with 150 mm sides – this being common practice in many other countries (e.g. the UK and USA).

It should be noted that different sized and shaped test specimens will give different results for a given concrete and that strength comparisons are only valid if test specimens of the same shape and dimension are used.

The compressive strength difference when using the two cylinders size options is slight and AS 1012.8.1 allows either to be used for determining compressive strength – but data from the two groups may not be combined. The 150 mm cube specimens give higher values than those obtained from cylinder specimens, and appropriate conversion factors must always be applied to allow results to be compared.

*(**NOTE**: When evaluating compressive strength data reported from other countries, care should be taken to ensure that the size and dimensions of the test specimen are known, and suitable conversions made if required.)*

When test specimens are prepared and cured in accordance with AS 1012.8.1 and crushed in accordance with AS 1012.9 it is expected that any variation in compressive strength results should reflect (almost entirely) variations in the properties of the concrete, rather than variability due to the specimen shape and size or the test procedures used. It is important to ensure that the procedures described in the Standards are followed exactly so that unwanted variations do not affect the results obtained.

Characteristic Strength: The characteristic strength for a concrete mix is the strength level above which 95% of the 28-day compressive strength results lie. The characteristic strength is determined by carrying out a statistical analysis of the 28-day test results obtained for a given mix (**Figure 25.13**).

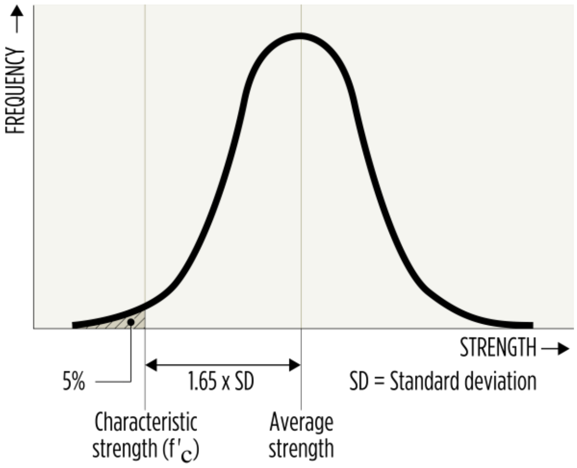


Figure 25.13 – Graphical Representation of Characteristic Strength

The ‘characteristic strength’ 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 undertaken to meet the requirements of AS 3600 and is the strength on which AS 3600 bases many of its design calculations.

The 28-day characteristic compressive strengths of the standard strength grades specified in AS 1379 are 20, 25, 32, 40, 50, 65, 80 and 100 MPa.

It should be noted that the characteristic strength is determined from samples which have undergone laboratory curing and testing and effectively gives a 'potential' strength of the concrete. It does not imply that this is the strength which is actually achieved in the structure. The strength achieved in a structure is dependent, amongst other things, on the level of compaction achieved and the curing given to the concrete after 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 on 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 its 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 AS 1012.10. It involves (a) making a 150 mm × 300 mm test cylinder, and (b) after curing, placing the cylinder in a rig between the platens of a compression testing machine. Load is then applied across a diameter through two bearing strips until the specimen splits down its length (**Figure 25.14**).

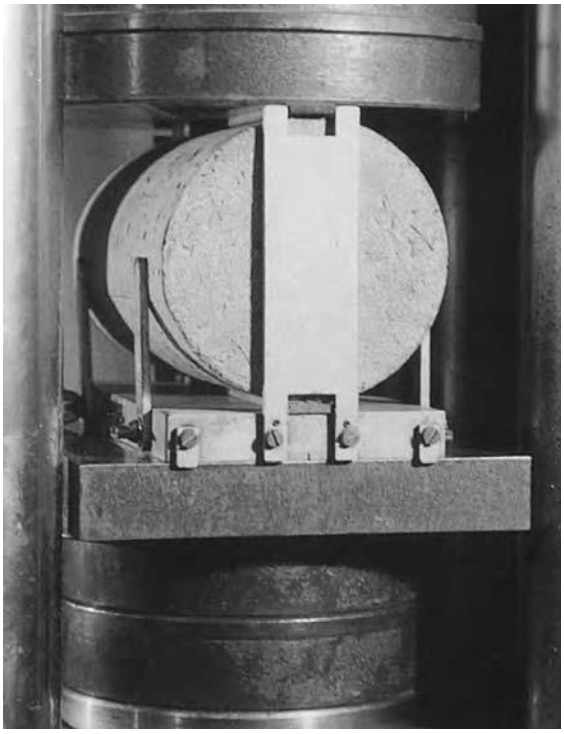


Figure 25.14 – The Indirect Tensile / Brazil / Splitting Test

The indirect tensile strength of the specimen may then be calculated using the equation provided in AS 1012.10, viz:

$f_{ct} = 2000P/\pi LD$ …..**Eq.25.1**

where:

f_{ct} = indirect tensile strength (MPa);
P = maximum applied force indicated by the testing machine (kN);
L = cylinder length (mm);
D = cylinder diameter (mm).

Flexural Strength: The flexural strength of concrete, a measure of its ability to resist bending, may be determined by the method described in AS 1012.11. A plain beam of concrete is prepared using the methods described in AS 1012.8. It may be either 150 mm × 150 mm in cross-section by 500 mm in length; or 100 mm × 100 mm by 350 mm in length. After appropriate curing and (if necessary) conditioning to ensure that its surfaces are saturated, the specimen is subjected to bending, using loading at the one-third points on the top of the beam until it fails (**Figure 25.15**).

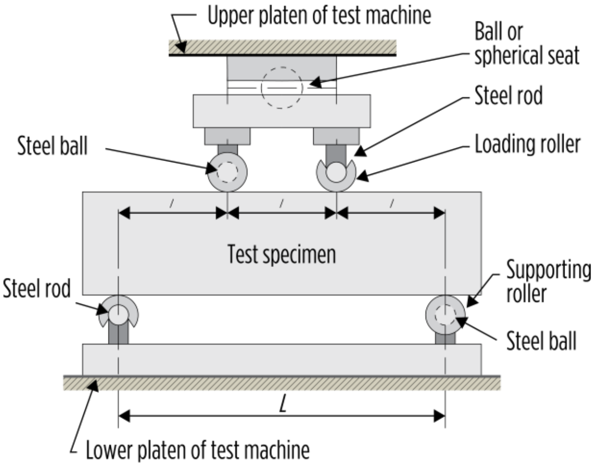


Figure 25.15 – Flexural Strength Test

The flexural strength of the specimen, or more properly, its modulus of rupture, is then calculated using the equation given in AS 1012.11, viz:

$f_{cf} = PL(1000)/BD^2$ …..**Eq.25.2**

where:

f_{cf} = 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 flexural strength test gives a considerably higher value of tensile strength than the splitting test, and there is not a direct relationship between them. In AS 3600, the characteristic flexural strength can be calculated as $0.6\sqrt{f'_c}$ and this value is used for design purposes.

*(**NOTE**: f'_c is the characteristic compressive strength.)*

There is also no fixed relationship between average compressive and average tensile strength. This relationship has been widely investigated and a number of authorities have proposed bands within which such a relationship might be expected to fall. One example of the relationship is illustrated in **Figure 25.16**. It can be seen that there is a different relationship for compressive strength versus either flexural strength or indirect tensile strength. All strength properties are affected by the water/cement ratio of the mix and by the level of compaction and nature of curing. It has also been found that (a) the tensile strength of concrete increases more slowly than its compressive strength, (b) air content has a greater effect on compressive strength, (c) the size, shape and surface texture of coarse aggregates has a greater effect on tensile strength, and (d) the variability (Standard Deviation) of tensile strength testing is about twice that of compressive strength testing.

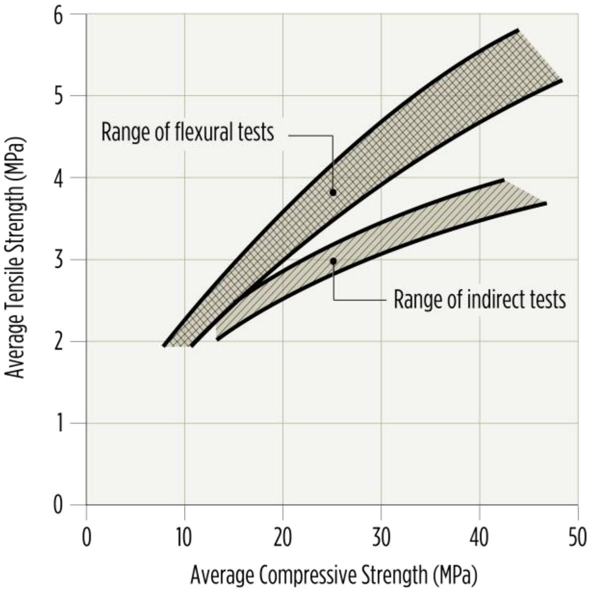


Figure 25.16 – Relationships between Compressive and Tensile Strength[25.2]

The design of concrete pavements is typically based on the flexural strength of concrete. From a practical perspective, given the relative simplicity of compressive strength testing, it is usual practice to determine the relationship between the flexural strength and compressive strength for the particular concrete mix being used and to control the quality of the concrete produced for the project by controlling its compressive strength. The higher precision of compressive strength testing is also of assistance in these situations.

***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, consequently, its strength. W/C ratio is calculated by dividing the mass of 'free' water in the concrete mix by the mass of cementitious material. Thus:

Water/cement ratio (W/C) = mass of free water/mass of cementitious material

*[**NOTES**: (1) Where cement only is used, the W/C ratio calculation uses only the mass of cement. Where SCM's are also used, the W/C ratio calculation uses the sum of the masses of cement + SCM(s). (2) 'Free water' is water which is available to combine chemically with the cement and to increase workability and excludes the water which is absorbed into the aggregates.]*

The influence of the water/cement ratio on the strength of concrete is illustrated in **Figure 25.17**. As can be seen, compressive strength increases as the W/C ratio decreases.

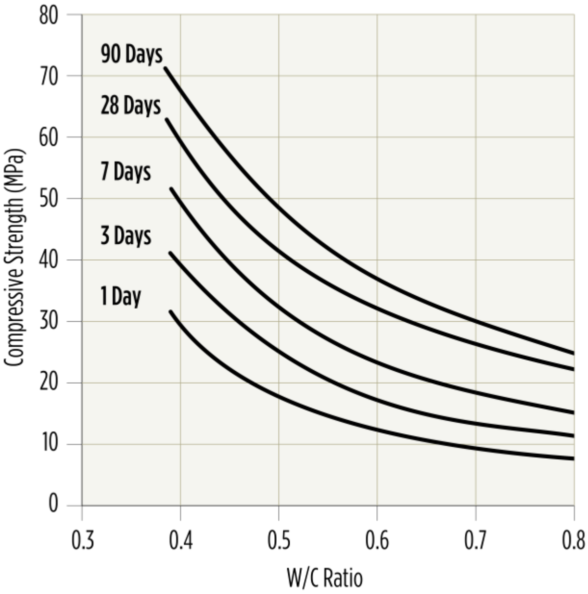


Figure 25.17 – The Influence of W/C on Compressive Strength at Various Ages

In calculating and in controlling this ratio, it is important to be aware of the 'free water' which is normally present in the aggregates, particularly in the sands. This can be a very significant amount in the context of the whole mix. Conversely, it is important to realise that dry aggregates can absorb water. In both cases, appropriate adjustments should be made to the calculation of the amount of 'free water' available in the mix.

Standard compaction and standard (i.e. extended moist) curing are essential for the relationship to be definitive. Normally, water/cement ratio curves are produced for concretes that have been cured for 28 days but can be produced at all ages.

Similar curves can be produced for different types of cement and aggregates, for different curing regimes and for different ages. They are extremely useful in predicting the potential strength of a concrete (when the free water and cement content of the mix are known) and are essential in any mix-design process.

Extent of Voids: The presence of voids in concrete can occur in several ways. Poorly compacted concrete has void spaces due to the presence of entrapped air (air not removed during compaction), and voids are also present due to intentionally entrained air when AEA's are used in the concrete mix. At the micro-scale, high levels of capillary porosity are present in mixes with high W/C ratios.

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 entrapped air is expelled from the concrete during placing. The influence of voids on the compressive strength of concrete can be seen in **Figure 25.18**.

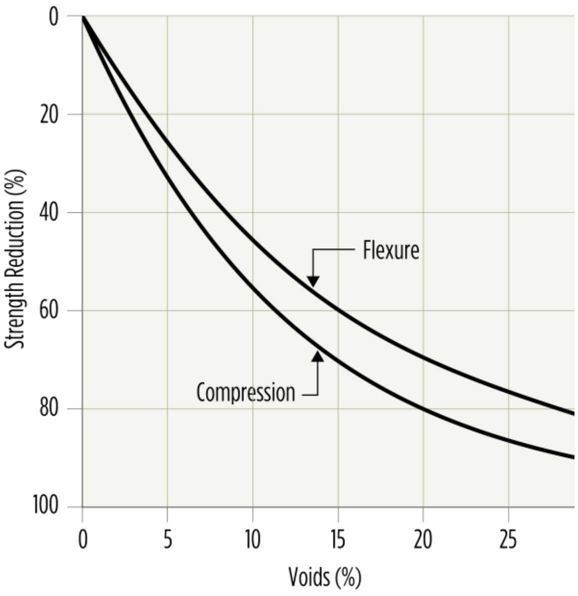


Figure 25.18 – The Effect of Air Voids on Compressive and Flexural Strengths of Concrete

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 for full strength to develop. The effect on compressive strength when different curing regimes are used can be seen in **Figure 25.19**. The substantial reduction in potential strength which results from inadequate curing is obvious. In the case of 'air curing', there is total reliance on the water included initially in the mix and which has not been evaporated from the surface of the concrete, for ongoing hydration and strength development.

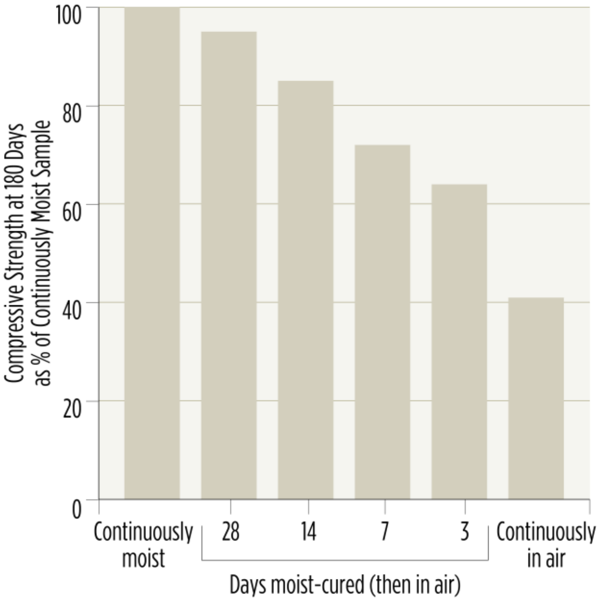


Figure 25.19 – The Influence of Moist Curing on the Strength of Concrete

The hydration reaction and consequent strength development can continue for significant periods of time. The reaction is most vigorous in the first week, but then slows progressively. Hydration and strength development may continue for long periods when water is present – particularly if SCM's are included in the mix.

Type of Cement: The rate of strength development will depend on the type of cement used.

Figure 25.20 illustrates the effects of cement type and age on the strength of concrete. It can be seen that, in general, Type GB cements produce concretes that gain strength more slowly during the first few days relative to Type GP cements. After 28 days the strength of mixes containing Type GB cements generally increases more substantially.

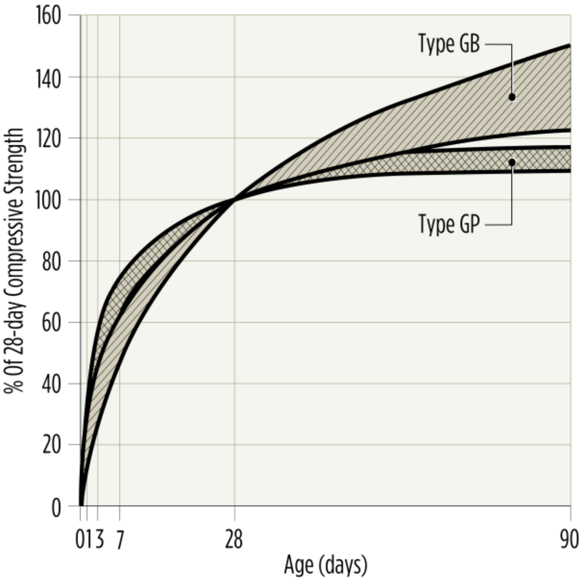


Figure 25.20 – Concrete Strength Development – Type GP and Type GB Cements

Curing Temperature: The cement hydration reaction is a chemical reaction, and like any chemical reaction the rate of reaction is influenced by temperature. Higher temperatures (either ambient temperatures or steam curing) accelerate the rate of strength gain and initial compressive strengths are higher than would otherwise be expected. It is also noted that 28-day strengths with high temperature curing are lower than when the same mix is cured at (say) 23°C. Low temperature environments lower the rate of strength gain and can be problematic when trying to place concrete in cold environments (see Part V, Section 18 of this Guide *'Hot- and Cold-Weather Concreting'*).

Other Factors: 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, the type of admixture used (if any) and density. These factors are discussed more fully in other Sections of this Guide, but their effects can 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 high tensile strength is being sought. Approximately 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 needs to be emphasised that good concrete can be made from a wide range of rocks/stones. Whilst it is appropriate to exercise care in the selection of aggregates, specification and use of only the 'best' materials can lead to uneconomical use of what is becoming 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 making concrete. Water which is contaminated with organic matter, or which contains dissolved salts, may be unsuitable because the contaminant may affect the strength of the concrete or lead to corrosion of embedded reinforcement. Where any doubt exists, testing of the water in concrete should be carried out. Testing of samples from a concrete mix made with the unknown water and comparison with samples from concrete of known performance should be undertaken and any effect on compressive strength and setting time noted. AS 1379 sets limits for the allowable effects on these properties.

Admixtures and Additives: A wide range of admixtures may be used in concrete – ranging from air-entraining agents used to enhance the resistance of concrete to alternating cycles of freezing and thawing to high-range water-reducers (superplasticisers) used to make flowing concrete. Additives may include simple oxide colourants through to highly reactive pozzolanic materials like silica fume that vastly improve strength and durability performance. 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 minimal effect. In all cases, the effect of an admixture or additive should be investigated by trial mixes before being used.

Density: The Standards AS 1379 and AS 3600 generally relate to ‘normal weight’ concrete mixes, although AS 3600 does include reference to ‘lightweight’ concretes with a density range of 1,800-2,100 kg.m^{-3}. If concrete density is reduced by using any of a variety of means – e.g. foaming, using light-weight aggregates or using polystyrene beads as a partial aggregate replacement – then lower compressive strengths will be achieved.

3.2 DURABILITY

General – The permeability and absorptivity of concrete are important properties that impact the durability performance of concrete. These properties of concrete directly impact watertightness and directly and indirectly they affect (a) the ability to protect steel reinforcement from corrosion, (b) the resistance to chemical attack and (c) resistance to other deteriorating influences. In addition, any internal or external agent that can result in a concrete volume change can have a significant impact on concrete durability.

These properties and the material attributes affecting them are discussed below. These properties contribute to the ability of concrete to resist various in-service conditions which are also discussed.

Permeability and Absorptivity/Sorptivity – Broadly speaking, the sorptivity of concrete is a measure of the amount of water (or other liquid) which the concrete will absorb when immersed in it – in circumstances where no head of water (or other liquid) exists. This absorption, due to capillary suction, occurs through the surface of the unsaturated concrete element. The permeability of concrete is a measure of its resistance to the passage of fluids (gases or liquids) through it under pressure. Both properties are affected by similar factors, namely (a) the porosity of the concrete (i.e. the volume of voids or pores in the concrete) and (b) whether these voids or pores are separated (discrete) or interconnected. There is no direct relationship between porosity and permeability – it is possible to have concrete which has a high porosity, but a relatively low permeability (if the pores and voids in it are relatively large but disconnected). Similarly, it is possible to have concrete with a high absorptivity but low permeability. However, in practice, concrete with a high absorptivity will generally have high permeability.

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. High W/C ratio mixes have high levels of capillary porosity and, while up to a point this porosity can be filled by ongoing hydration reaction product, long periods of water curing are required for this to occur. To achieve reasonably low levels of permeability, the W/C ratio of a mix should be less than 0.5 (**Figure 25.21**).

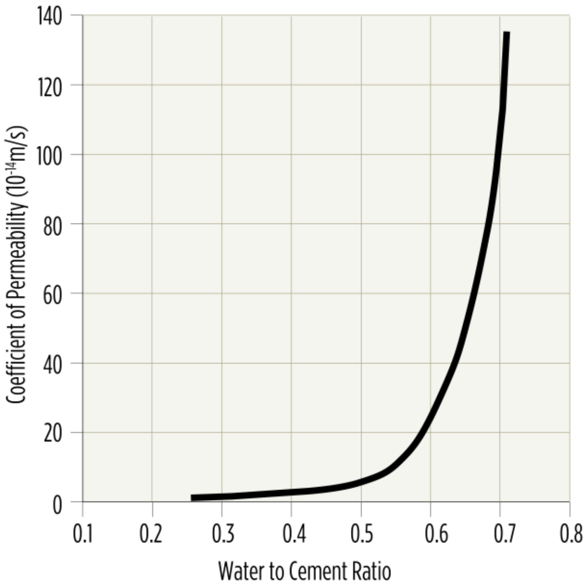


Figure 25.21 – The Effect of Water/Cement Ratio on the Permeability of Concrete[25.3]

Extent of Voids and Capillaries: Incomplete compaction of concrete results in comparatively large (entrapped) 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 permeability.

Although low water/cement ratios are necessary to achieve low-permeability concrete, any reduction below that needed for good workability (and therefore ease of compaction) can have contrary effects. In modern concrete technology, the use of admixtures (and particularly HRWR) has allowed low W/C ratio mixes with good workability to be produced.

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 in the production of low-permeability concrete. As can be seen in **Table 25.4**, 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. It is difficult to practically cure concrete for a sufficient length of time to achieve capillary discontinuity at water/cement ratios greater than 0.5.

Table 25.4 – Curing Time required for Capillary Discontinuity of Cement Paste

Water/cement ratio (by mass)	**Curing time required for capillary discontinuity**
0.40	3 days
0.45	7 days
0.50	14 days
0.60	6 months
0.7	1 year
over 0.7	Impossible

The effectiveness of curing in practice is shown in **Figure 25.22** which illustrates how a significant reduction in water sorptivity of a nominal 25 MPa concrete is achieved in over as little as three days when cured in timber formwork.

Type of Cement: Pozzolanic materials incorporated in concrete tend to reduce its permeability by reacting with cement hydration products to form additional cementitious products which are then deposited in the pores and capillaries, reducing their size, volume and continuity.

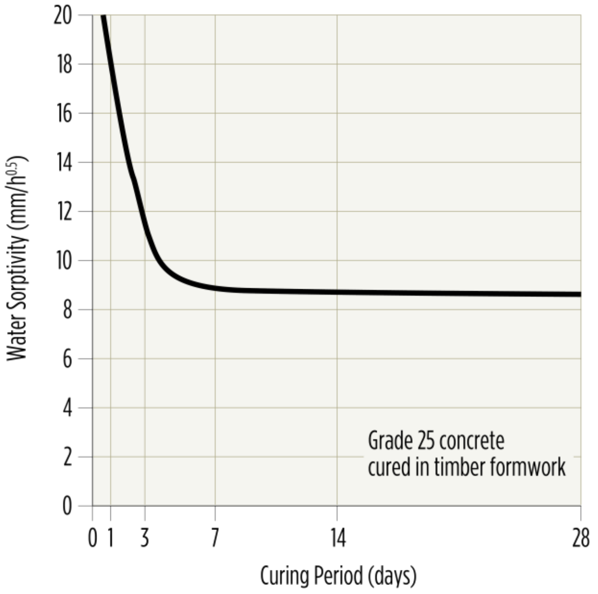


Figure 25.22 – The Effect of Curing Time on Water Sorptivity

Blended cements (e.g. Type GB cements or Type GP cement + SCM's) are often used in the production of concrete with low permeability. Curing is especially important with blended cements, as the pozzolanic reaction occurs over a much longer time period.

Admixtures and Additives: Chemical admixtures may help reduce the permeability of concrete. Water-reducing agents – 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. Initially, there is a reduction in volume (or contraction) as the concrete is compacted and air and moisture are expelled from it. Later, there is the slight expansion which takes place as the cement hydrates. Eventually there is further contraction (or shrinkage) which occurs when the hardened concrete dries out through evaporation of moisture from its surface.

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 25.23**).

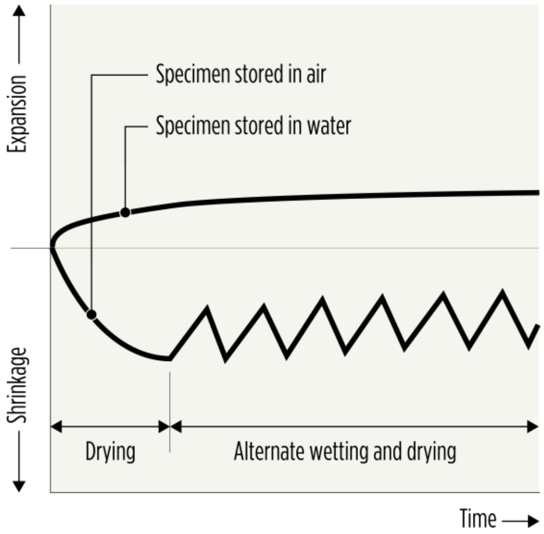


Figure 25.23 – Diagrammatic Illustration of Moisture Movement in Concrete

In addition, there is 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 concern. However, this is rarely the case as most concrete elements are normally restrained in one way or another (e.g. by friction between a slab and the ground or by adjoining/attached elements).

Volume changes under restraint conditions can create significant stresses – particularly tensile stresses. It is important, therefore, to minimise these changes to prevent cracking. In some cases, it may also be important to reinforce the concrete to help 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 (a) parts per million, (b) as a percentage change in length or (c) as a movement in millimetres per metre. In concrete technology, movement is typically reported using the term *microstrain* which is *parts per million* (e.g. a change in length described as being 850 microstrain is 850 parts per million, which is equivalent to a change in length of 0.085% or 0.85 mm/m).

Drying Shrinkage: Volume change due to drying shrinkage is an important property as excessive drying shrinkage can lead to cracking that is detrimental to performance, durability and/or appearance (e.g. in pavements, cracking must be strictly controlled to ensure the integrity of the pavement as well as limit ingress of materials that might cause corrosion of reinforcement).

Figure 25.24 illustrates the drying shrinkage that occurs when concrete dries out over a period of three months. Concrete drying shrinkage is measured on beams in a laboratory test environment and results are reported after 56-day drying at a temperature of 23°C and at 50% RH. Specifications are generally written on the basis of drying shrinkage values determined using this test, however the laboratory results are generally much higher than those found in concrete exposed in the field. Drying shrinkage will continue for years, but when considered after 20 years, it is found that about 65% of the total (20-year) drying shrinkage occurs in about 3 months and 75% in the first year.

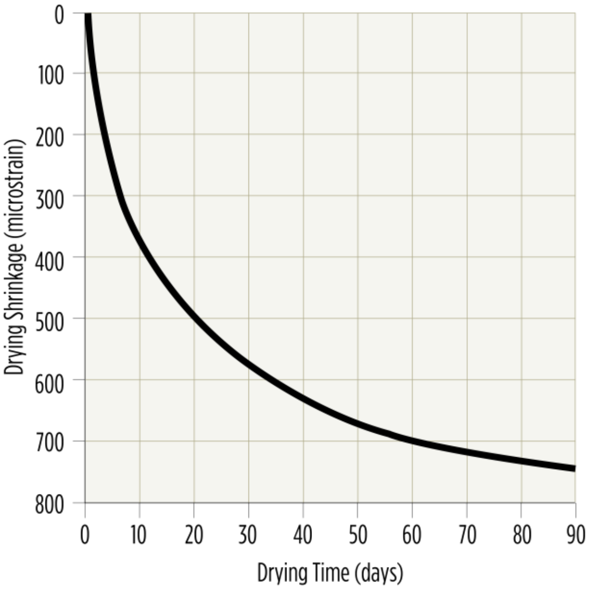


Figure 25.24 – Drying Shrinkage vs. Time Curve for a Typical Concrete Specimen

Research has shown that the major factor influencing levels of 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:

Proportion and Nature of Aggregates: The higher the volume proportion of aggregates in a mix, the lower will be the drying shrinkage because (1) the aggregates tend to restrain drying shrinkage, and (2) more aggregates means less cement paste – and it is the paste that shrinks. Aggregates which themselves exhibit significant moisture movement characteristics will adversely affect drying shrinkage performance.

Contamination of Aggregates: Aggregates contaminated with clay or very fine material increase the water demand of the concrete which may lead to increased drying shrinkage.

Maximum Aggregate Size: Larger-sized aggregates tend to reduce drying shrinkage through being more effective in restraining shrinkage.

Cement Content: High cement contents mean higher paste contents which leads to higher levels of drying shrinkage. Almost invariably, water loss contributing to drying shrinkage comes from the paste and not from the aggregates.

Creep – Creep is a form of concrete deformation that occurs over long periods of time – namely years. Examples of the effects of concrete creep include the shortening of building columns, deflection of floors or beams and loss of strength in prestressed concrete. While it can be detrimental, concrete may be too brittle if there was no creep. Some creep is desirable.

Figure 25.25 shows how creep increases slowly after load is applied to a concrete element, and then decreases to an extent when the load is removed. However, the element does not recover to its initial state as a proportion of the creep is 'residual'. Creep can be related to the stiffness and permeability of concrete, and consequently the factors that affect these properties also affect creep. The concrete strength and modulus of elasticity at the time of loading also affect the amount of creep deformation as do the applied load and conditions such as moisture content and RH.

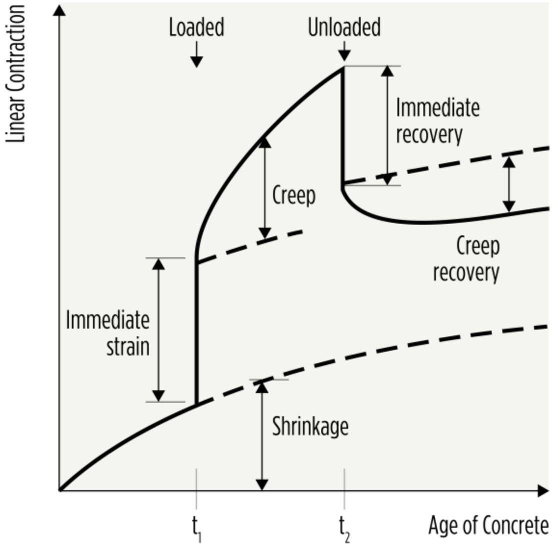


Figure 25.25 – Creep Deformation of Concrete

Thermal Movement – Concrete moves with changes in temperature – expanding when heated and contracting when cooled. While the amount of movement is not great (ranging from 5-12 microstrain per °C) stresses induced by thermal expansion can be significant. As a result, it is normal practice to introduce control joints into concrete structures at appropriate intervals.

The type of aggregate used in the concrete is the major factor influencing thermal expansion (**Table 25.5**).

Table 25.5 – Coefficients of Expansion resulting from Use of Different Aggregate Types

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 of Reinforcement to Corrosion:* Perhaps the most common (and obvious) form of deterioration in concrete is that caused by the corrosion of reinforcement. This is normally accompanied by cracking and spalling and ultimately, by disintegration of the member. Under normal circumstances concrete protects steel embedded in it in two ways. It encloses the steel in an alkaline environment (with a pH >12) that 'passivates' the steel (by allowing the formation of a thin, resistant iron oxide film on the surface of the steel) and prevents it from corroding. It also minimises the movement of moisture and oxygen through the concrete – both of which are necessary for corrosion to occur.

This passivation protection can be breached in two ways, viz:

Carbonation: Carbon dioxide from the atmosphere reacts with the lime that creates the high concrete paste pH. The result is that concrete pH is reduced, with the consequence being that the steel can be 'depassivated' and corrosion initiated.

Chloride Ion Penetration into the Concrete: Chloride ions can destabilise the passivating oxide layer on the reinforcement even though the alkalinity may not have been reduced. Chloride ions may be present in the concrete materials and slowly act on the steel. Chloride ions may also be introduced to the concrete by exposure to sea water or from other salt-containing environments and these chloride ions can then slowly diffuse through the concrete until they reach the steel. To minimise the likelihood of chloride containing materials being incorporated in concrete, Standards (for cement, SCM's and admixtures) now contain strict chloride limits.

The effects of both carbonation and chloride ion diffusion can be managed by the use of low-permeability concrete [i.e. concrete with a low water/cement ratio and generally containing SCM(s)]. The benefits of using SCM's are shown in **Figure 25.26** and **Figure 25.27**. In addition, concrete with low volume-change characteristics (i.e. concrete that is less susceptible to cracking) is also beneficial. As well as using high quality concrete, adequate concrete cover is necessary to protect the reinforcing steel, with guidance in relation to cover depths being provided in AS 3600 in the form of a table that defines the minimum requirements for cover depth which are dependent on the local exposure classification (see **Figure 25.32**) and the grade of concrete being used (**Table 25.6**).

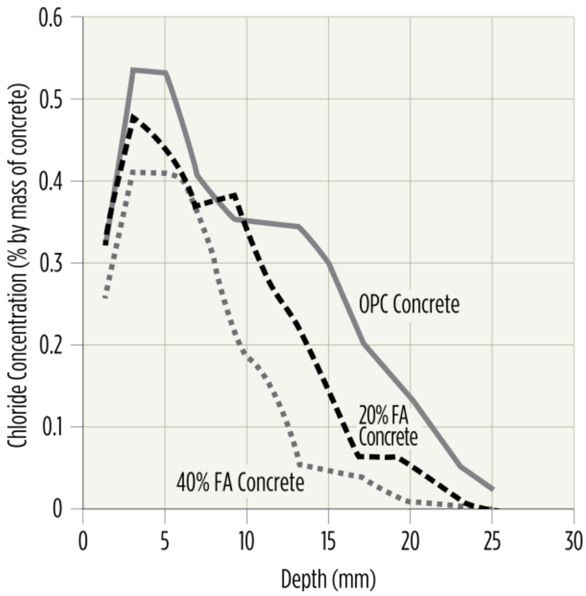


Figure 25.26 – Chloride Ingress reduced by Fly Ash

Resistance to Chemical Attack – Concrete, or, more specifically, the cement paste in concrete, is susceptible to attack by a variety of common chemical species.

In some circumstances, the chemical agent converts the constituents of the cement paste into a soluble salt, which can then be dissolved and removed by water.

The intensity of the attack will depend on:

- The nature of the chemical and its concentration;
- Ambient conditions; and
- The type of exposure (e.g. Intermittent or continuous; in a static or flowing environment).

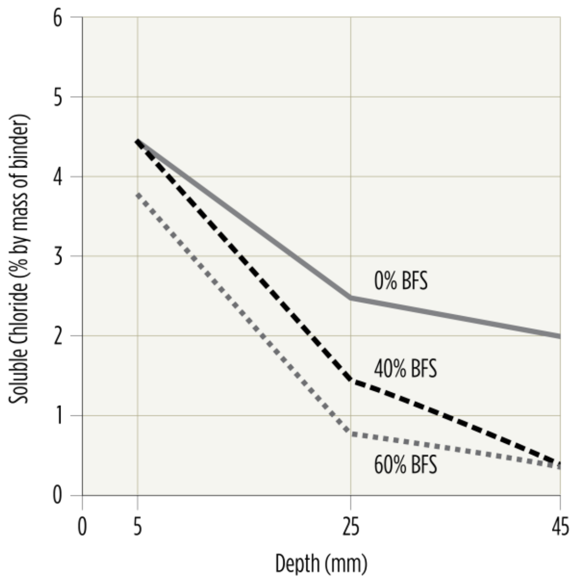


Figure 25.27 – Chloride Ingress reduced by GGBFS

Table 25.6 – Concrete Cover Requirements – AS 3600[25.4]

Exposure classification	**Required cover (mm)**				
	Characteristic strength f'_c (MPa)				
	20 MPa	**25 MPa**	**32 MPa**	**40 MPa**	**≥50 MPa**
A1	20	20	20	20	20
A2	(50)	30	25	20	20
B1		(60)	40	30	25
B2			(65)	45	35
C1				(70)	50
C2					65

Notwithstanding these factors, the rate of attack by any particular chemical agent is determined significantly by the permeability of the cement paste. Without exception, low water/cement ratio pastes with corresponding low permeabilities will perform better than those with higher permeabilities as reactions may be able to be confined to the surface of the concrete.

The effects from a number of common materials are discussed below.

Acids: Most acidic (low pH) materials will attack the (high pH) cement paste by converting the lime and CSH into readily soluble salts. (e.g. hydrochloric acid, which is commonly used to etch or to clean cement-based product surfaces, forms chloride salts which are readily soluble in water.)

Similar effects occur with other strong acids including sulfuric 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 insoluble reaction product which helps to protect the surface from further attack.

Naturally occurring waters (e.g. ice melt) are sometimes acidic due to dissolved carbon dioxide, but attack in such cases is usually slight. Where such water is flowing at high velocity there can be significant deterioration of the concrete over time.

Soft Waters: Very pure (or soft) water can attack concrete by leaching out calcium-bearing compounds from the cement paste (e.g. calcium hydroxide) leaving behind material with reduced strength. Such attack can occur 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 help reduce permeability and to reduce the free calcium hydroxide in the hydrated paste, is also of value.

Sulfates: Solutions containing soluble sulfates can attack concrete vigorously. In some cases, the reactions result in the formation of reaction products with higher volumes than the original material which causes an expansion of the paste and cracking and (potentially) disintegration of the concrete.

Sulfates are found in industrial effluents, in sewerage and in some soils and groundwaters. Sodium sulfate reacts with lime to form expansive calcium sulfate, resulting in concrete cracking.

The resistance of concrete to sulfate attack can be improved by the use of dense, low-permeability concrete (**Figure 25.28** and **Figure 25.29**) which restricts ingress of the sulfate solutions to the interior of the element. It may also be improved by the use of sulfate-resisting (Type SR) cements and SCM's in the concrete mix (**Figure 25.30** and **Figure 25.31**).

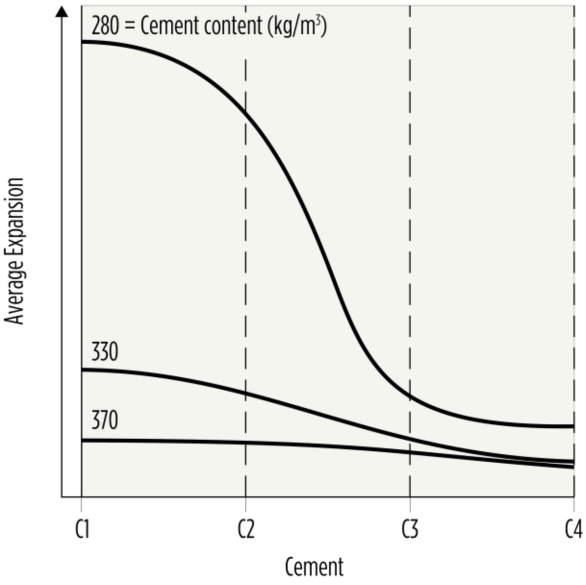


Figure 25.28 – Cement Content and Sulfate Attack

Seawater: Seawater contains about 3.5% of dissolved salts, primarily sodium and magnesium chloride, as well as dissolved sulfates (e.g. magnesium, calcium and potassium sulfates).

The chlorides in seawater do not attack concrete directly but exposure can lead to corrosion of any reinforcing steel embedded in the concrete. The sulfates in sea water, and particularly magnesium sulfate, will cause damage to immersed concrete elements, and more-so if the water flows at a reasonable velocity. Magnesium sulfate will actually attack the CSH and cause the body of the concrete to disintegrate. In general, as well as using concrete with low permeability, 'Marine Cement' (typically a cement containing Type GP + 65% GGBFS) is used for concrete intended for this type of environment.

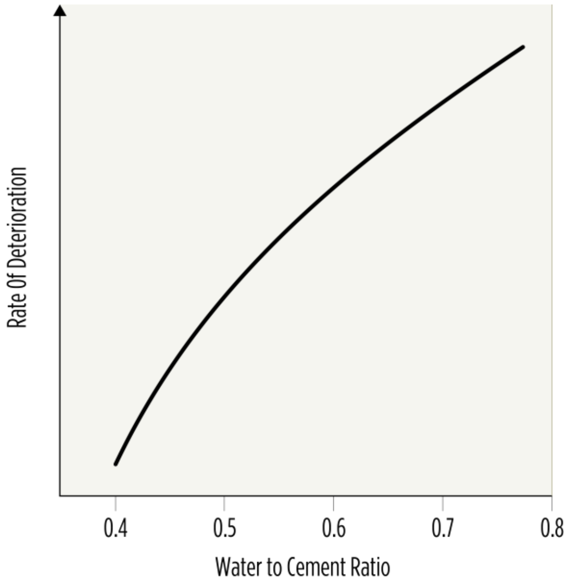


Figure 25.29 – W/C Ratio and Sulfate Attack

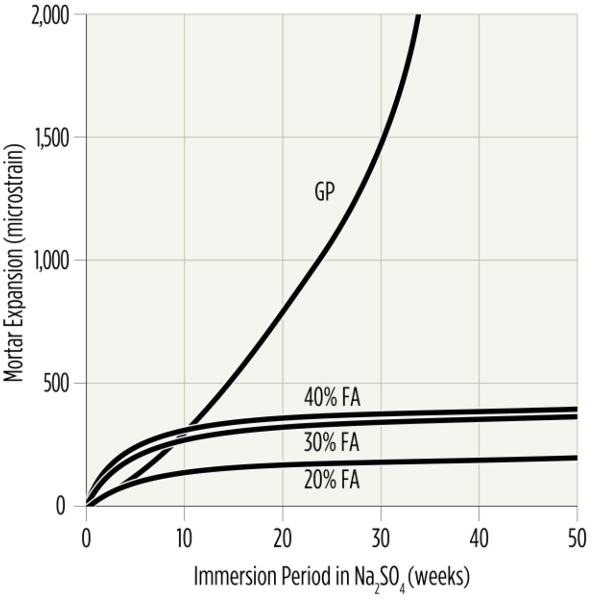


Figure 25.30 – Fly Ash Use and Sulfate Attack

Concrete partially immersed in seawater which undergoes wetting and drying cycles (e.g. in the inter-tidal zone) can be damaged by the crystallisation of salts inside the concrete surface in zones subject to the continual wetting and drying. 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.

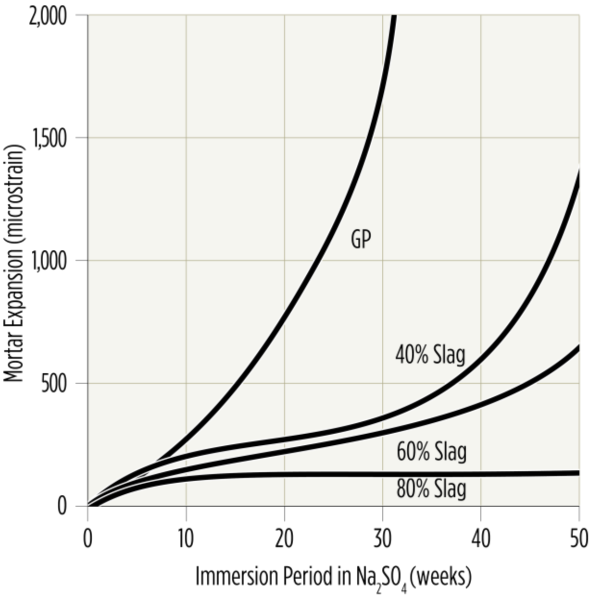


Figure 25.31 – GGBFS Use and Sulfate Attack

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 (e.g. 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 the compressive strength, the better is the wear resistance of concrete. With lower concrete compressive strength, the wear-resistance properties of the aggregates become important as they will eventually need to provide the wearing surface.

Guidance regarding the required grade of concrete for various wear situations is provided in AS 3600 and shown in **Table 25.7**.

Proprietary topping and shake mixtures are commonly added to the surface of floors to increase improved wear resistance. In effect, these materials provide a thin, high-strength layer which may also incorporate very hard-wearing aggregates. Steel fibres are also sometimes added to increase resistance to abrasion in industrial situations.

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 surface of the concrete.

To increase the freeze-thaw resistance of concrete it is normal practice to incorporate entrained air in the mix (i.e. create discrete, evenly distributed microscopic air bubbles in the cement paste). These small voids relieve the hydraulic pressure which is built up during the freezing process by providing space into which the frozen water can expand to help prevent the surface-scaling which would otherwise occur. AS 3600 provides guidance as to the levels of air entrainment required (**Table 25.8**).

Table 25.7 – AS 3600 Recommended Concrete Strengths for Abrasion Resistance[25.5]

Member and type of traffic	**Characteristic compressive strength (MPa)**
Footpaths and residential driveways	20
Commercial and industrial floors not subject to vehicular traffic	25
Pavements or floors subject to:	
• Pneumatic tyred traffic	32
• Non-pneumatic-tyred traffic	40
• Steel-wheeled traffic	To be assessed – not <40

Table 25.8 – AS 3600 Requirements for Freeze-thaw Resistance

Exposure condition	**Min f’$_c$ (MPa)**	**Entrained air for nominal aggregate size**	
		10-20 mm	**40 mm**
<25 cycles per annum	32	8%-4%	6%-3%
>25 cycles per annum	40	8%-4%	6%-3%

Table 25.9 – AS 3600 Strength and Curing Requirements for Durability[25.6]

Exposure classification	**Minimum f’$_c$ (MPa)**	**Minimum initial curing**	**Minimum average compressive strength at stripping (MPa)**
A1	20	3 days continuous	15
A2	25		
B1	32	7 days continuous	20
B2	40		25
C1	50		32
C2	50		

It is also normal practice to reduce the W/C ratio and to extend curing times, thereby reducing the number and volume of capillaries and pores in which water may be retained. Reducing the water/cement ratio also increases the tensile strength of the concrete, allowing it to better resist scaling and surface disintegration.

AS 3600 Durability Provisions – AS 3600 provides its durability provisions in Section 4 of the Standard. These procedures require that (1) the exposure classification be determined, (2) the minimum concrete quality required to meet that exposure classification be determined, and (3) the minimum concrete cover to the reinforcement be chosen from tables for the exposure condition, the concrete location, the level of compaction and the concrete strength.

Guidance is provided on climatic zones as they affect durability exposure conditions – as shown in the zones A1 (Arid) – B2 (Coastal) on the map of Australia (**Figure 25.32**) [2].

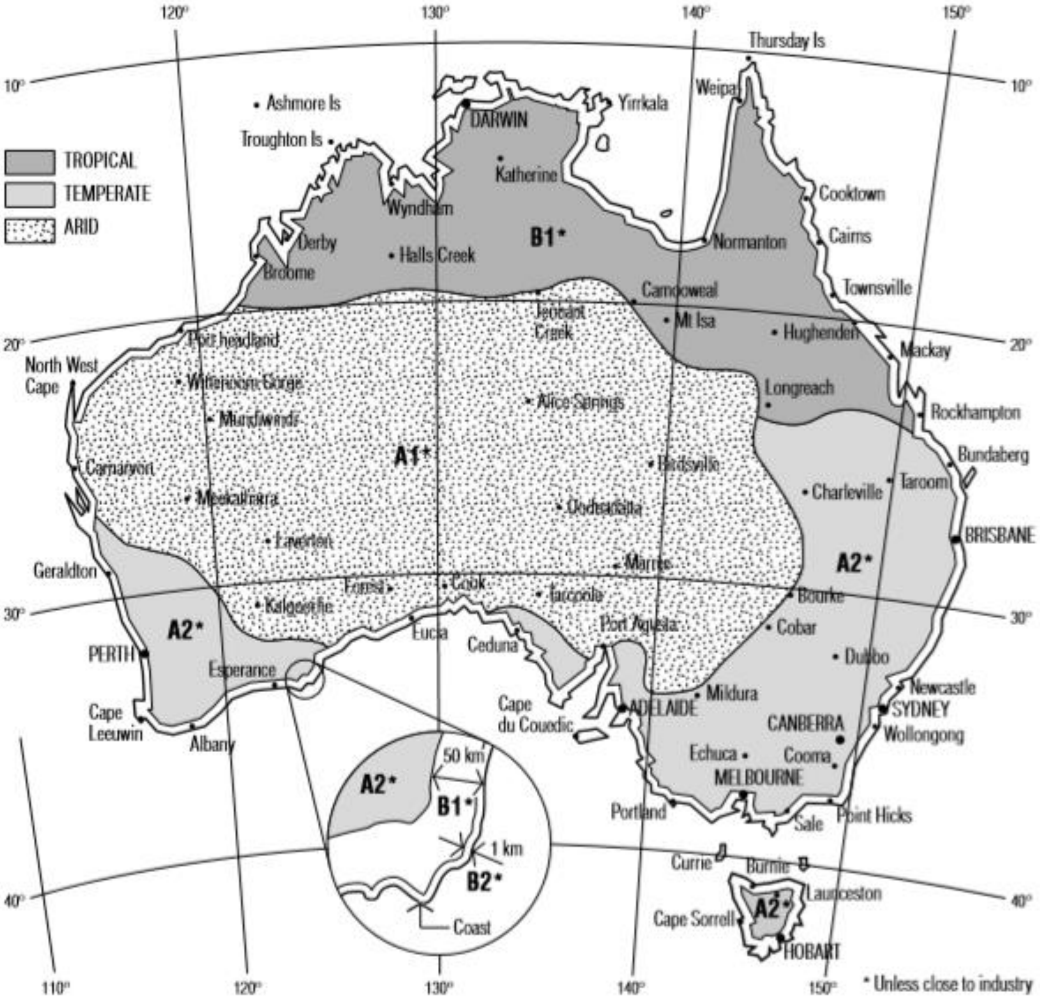


Figure 25.32 – Australian Climatic Zones$^{25.7}$*[2]*

In a marine environment (Zones C1 and C2 – Sea Water exposure), the worst conditions for the corrosion of steel are those in the tidal zone or atmospheric zone as shown in **Figure 25.33**.

In the submerged zone in **Figure 25.33**, there are unlikely to be serious corrosion conditions, but the concrete could still be subject to attack from sulfates in the seawater. In the tidal zone there are a number of factors likely to create issues including attack from sulfates, chloride ion ingress and physical abrasion from the movement of water and suspended materials. The atmospheric zone also has some potentially serious issues including ongoing wetting and drying cycles with sea water containing soluble salts.

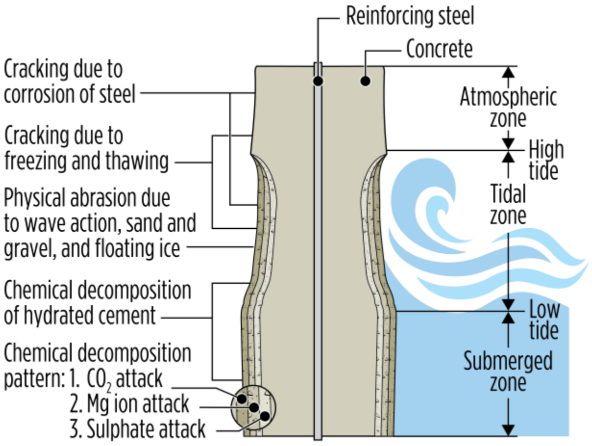


Figure 25.33 – Marine Exposure Conditions

Local environmental factors need to be taken into account when determining the minimum characteristic strength to be used and the curing time required to accommodate the relevant environmental issues. These are shown in **Table 25.9** (from AS 3600).

A series of documents on concrete durability has been prepared by the Concrete Institute of Australia [2-5]. These documents cover a wide range of important aspects related to the understanding of concrete durability, designing durable structures and carrying out durability-related testing of concrete and concrete structures.

4. RELEVANT AUSTRALIAN STANDARDS

1) AS 1012 – *Methods of testing concrete*
2) AS 1012.1 – *Sampling of fresh concrete*
3) AS 1012.2 – *Method for the preparation of concrete mixes in the laboratory*
4) AS 1012.3 (Parts 1-5) – *Methods for the determination of properties related to the consistence of concrete*
5) AS 1012.8 (Parts 1&2) – *Method for making and curing concrete compression, indirect tensile and flexure test specimens, in the laboratory or in the field*
6) AS 1012.9 – *Methods of testing concrete Compressive strength tests – Concrete, mortar and grout specimens*
7) AS 1012.10 – *Method for the determination of indirect tensile strength of concrete cylinders (Brazil or splitting test)*
8) AS 1012.11 – *Method for the determination of the flexural strength of concrete specimens*
9) AS 1379 – *Specification and supply of concrete*
10) AS 3600 – *Concrete structures*

5. OTHER REFERENCES

1) Neville, A.M. *'Properties of Concrete'* (4th Edition), Longman Group Limited, ISBN 0-582-23070-5 (1995), p. 185
2) Concrete Institute of Australia, *'Durable Concrete Structures'*, Recommended Practice Z-07, ISBN 0 909375 55 0 (February 2001)
3) Concrete Institute of Australia, *'Durability Planning'*, Recommended Practice Z-07-01, ISBN 978 0 9941738 0 5 (2014)
4) Concrete Institute of Australia, *'Durable Exposure Classifications'*, Recommended Practice Z-07-02, ISBN 978 0 909375 01 0, (September 2018)
5) Concrete Institute of Australia, *'Performance Tests to Assess Concrete Durability'*, Recommended Practice Z-07-07, ISBN 978 0 9941738 2 9 (2015)
6) ASTM C1611/1611M-18 – *Standard Test Method for Slump Flow of Self Consolidating Concrete,* ASTM International, West Conshohocken, PA (2018), www.astm.org

End Notes:

[25.1] Based on Table 5.1 in AS 1379 *'Specification and Supply of Concrete'*

[25.2] Based on Figure C6.1. in AS 3600 *'Concrete Structures',* Supplement 1 – Commentary (2009)

[25.3] Based on Figure 6 in Journal ACI 51 (November 1954)

[25.4] Based on Table 4. 10.3.2 in AS 3600 *'Concrete Structures'* (2018)

[25.5] Based on Table 4.6 in AS 3600 *'Concrete Structures'* (2018)

[25.6] Based on Table 4.4 in AS 3600 *'Concrete Structures'* (2018)

[25.7] After Figure A.1 (page 45) of *'Durable Concrete Structures'*, reference [2], used with permission of the Concrete Institute of Australia

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