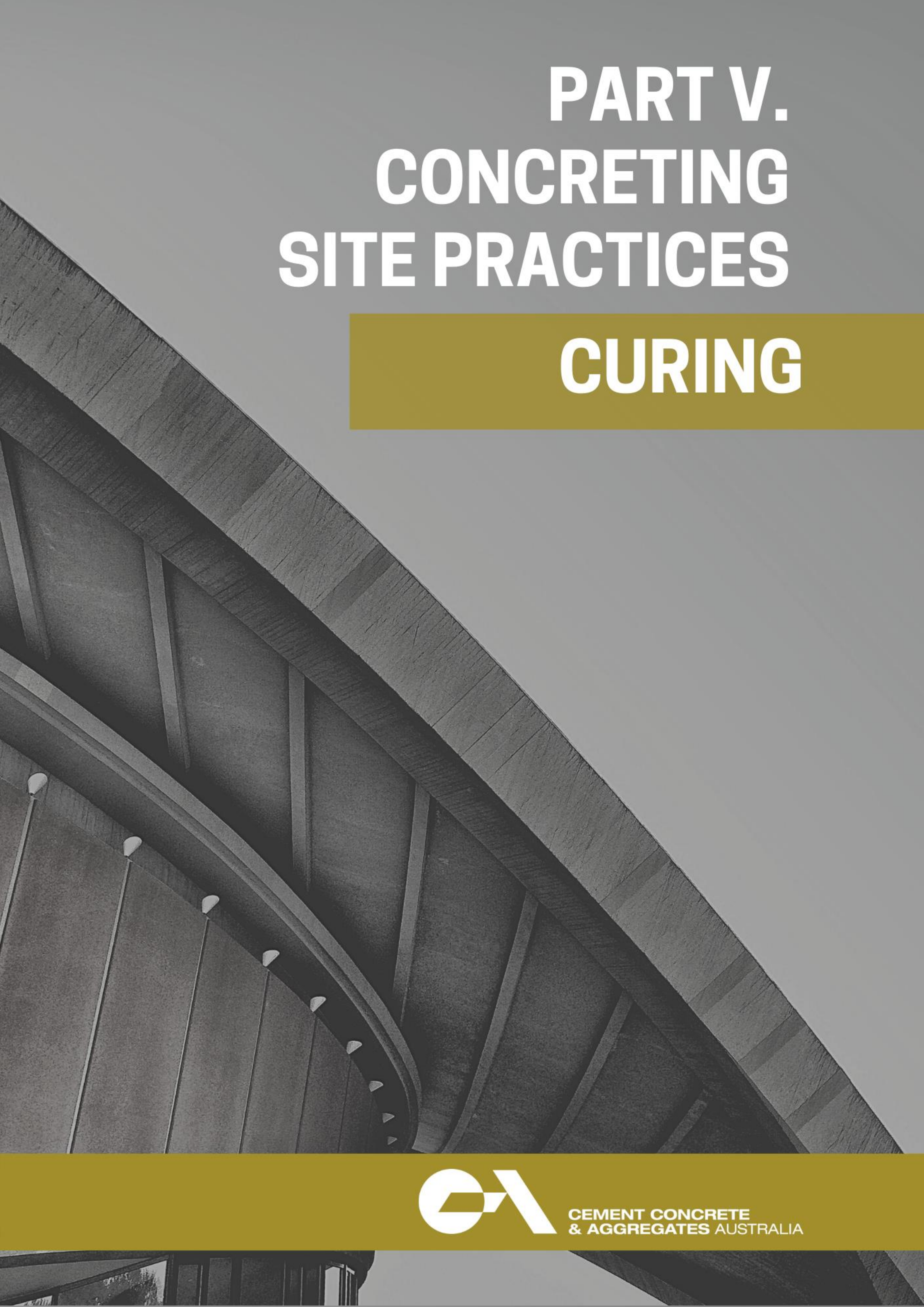

PART V. CONCRETING SITE PRACTICES

CURING

CEMENT CONCRETE & AGGREGATES AUSTRALIA

This section describes aspects of the curing of concrete, providing (a) a review of the cement hydration reaction to highlight the fundamental importance of keeping concrete moist during its early life; (b) a discussion describing the effect of curing (and its absence) on the properties of concrete; and (c) a description of the methods which can be used to cure concrete under the wide variety of conditions found on building and construction sites.

CONTENTS

1. INTRODUCTION

Curing is the process or activity that is used to control the loss of moisture from concrete after it has been finished (or in the case of concrete products, after manufacture), thereby providing time for the ongoing hydration of the cement to occur. Since the hydration of cement takes time (days and weeks – not just hours) curing must be undertaken for a moderate period of time if the concrete is to achieve its full potential strength and durability performance. The curing process may also encompass the control of temperature since it also affects the rate at which cement hydrates.

The curing period will depend on (a) the properties required of the concrete, (b) the purpose for which it is to be used, and (c) 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 water from surface of 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 a certain 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 maintaining a continuously wet surface thereby preventing the loss of moisture from it – where ponding or spraying the surface with water are methods typically employed.

In the manufacture of concrete products, the temperature of the concrete is usually 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 (e.g. an autoclave) are methods used to cure concrete at elevated temperatures. Other methods that can be used include (a) the use of hot flue or exhaust gases, (b) the use of heated formwork, and (c) electrical curing. These methods are only rarely used and will not be elaborated upon in this Guide. Some of the heating methods are commonly used in countries with colder climates, and although their use is widespread in these countries they are not generally applied in Australia.

2. HYDRATION OF CEMENT

2.1 GENERAL

When water is mixed with general purpose or blended cement a series of chemical reactions commence, which proceed rapidly at first, but then more slowly, and can continue for weeks and months – provided sufficient water is present. These hydration reactions result in new minerals being formed and, as the reaction progresses, the cement paste at first stiffens and then hardens and gains strength.

The details of these reactions will not be fully described in this Section (for further information, see Section 1 *'Cements'*), except to note the following:

- The different minerals 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 minerals 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 while the concrete gains strength;
- Allowing the paste to dry out causes the hydration reactions to cease (for all practical purposes). While rewetting the paste causes the reactions to recommence, the effect on the subsequent strength and other desirable properties of the paste may be permanently impaired or reduced.

Figure 15.1 provides a schematic representation of the chemical reactions which take place when water is mixed with cement, showing (a) the time-dependent nature of these reactions, (b) the increasing amounts of reaction products over time, and (c) the decrease in paste porosity over time.

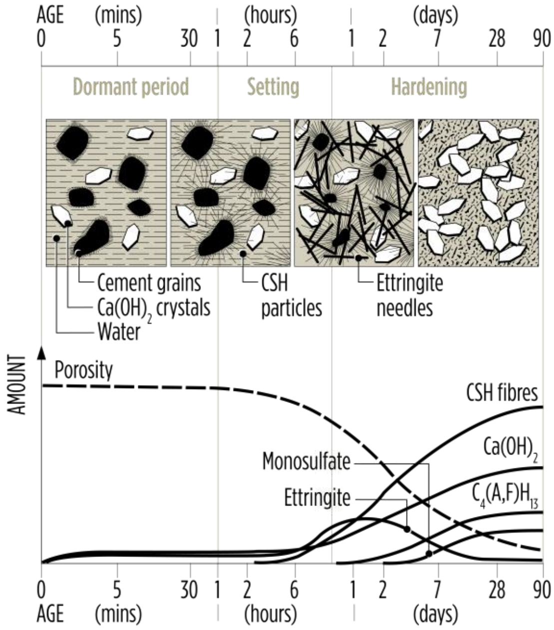

Figure 15.1 – Schematic Representation of Hydration Reactions of Cement and Water

2.2 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.

Lower temperatures reduce the rate at which the hydration reactions occur, while high temperatures increase the rate of the hydration reactions. While higher temperatures increase the rate of strength gain, they also reduce the strength of the concrete at later ages.

Figure 15.2 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 depends on several factors, not the least of which are the composition and fineness of the cement.

For practical purposes, it should be noted that, provided the temperature of the concrete is maintained within the normal range of ambient temperatures encountered in temperate Australia (about 15-30°C), no significant detriment will occur in relation to the strength performance of the concrete. For concrete operations outside this temperature range, i.e. in very hot or very cold weather, special precautions may be necessary. These are discussed in Section 18 *'Hot- and Cold-Weather Concreting'*.

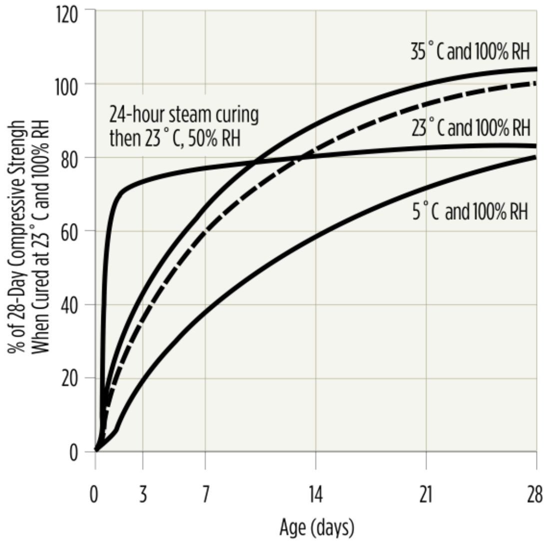

Figure 15.2 – Effect of Curing Temperature on the Rate of Strength Gain of Concrete

3 EFFECT OF DURATION OF CURING ON PROPERTIES OF CONCRETE

3.1 EFFECT ON STRENGTH

As will be discussed in Section 25 *'Properties of Concrete'*, the strength of concrete is affected by a number of important factors, one of which is the length of time for which it is kept moist (i.e. cured) after hardening. **Figure 15.3** illustrates the impact of curing on compressive strength by comparing the compressive strength (at 180 days) of concretes which have been:

- Kept moist for 180 days;
- Kept moist for various periods of time and allowed to dry out; and
- Allowed to dry out (i.e. 'air cured') from the time it was first made.

As can be seen in this example, concrete allowed to dry out immediately achieves only about 40% of the strength of the same concrete water cured for the full period of 180 days. Even three days water curing increases the strength to >60% of the 180-day strength, while 28-day water curing increases it to about 95% of the 180-day strength. A period of moist curing is clearly an effective way of increasing the ultimate strength of concrete.

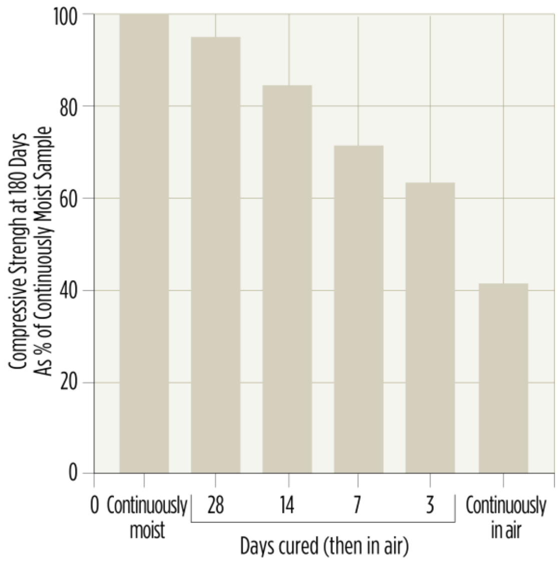

Figure 15.3 – Effect of Duration of Water Curing on Strength of Concrete

3.2 EFFECT ON DURABILITY

The durability of concrete is affected by a number of factors including its permeability and absorptivity (see Section 25 *'Properties of Concrete'*). Broadly speaking, these are related to the porosity of the concrete and, more particularly, to 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 (either partially or completely) fill the pores and capillaries present, and, hence, to reduce the permeability of the paste.

(***NOTE****: Permeability is a measure of the ability of fluids (i.e. liquids or gases) to flow through a medium. A low permeability coefficient means that fluids have difficulty in passing through the medium.)*

Figure 15.4 illustrates the effect of different periods of water curing on the permeability of a cement paste with a W/C ratio of 0.51. As can be seen, extending the period of curing reduces the permeability.

(***NOTE****: The initial (i.e. time = 0 day) permeability coefficient of concrete with a low W/C ratio (e.g. 0.35) will be much lower than that shown in* ***Figure 15.4****; while for a higher W/C ratio (e.g. 0.7)* *the initial permeability coefficient will be much higher.)*

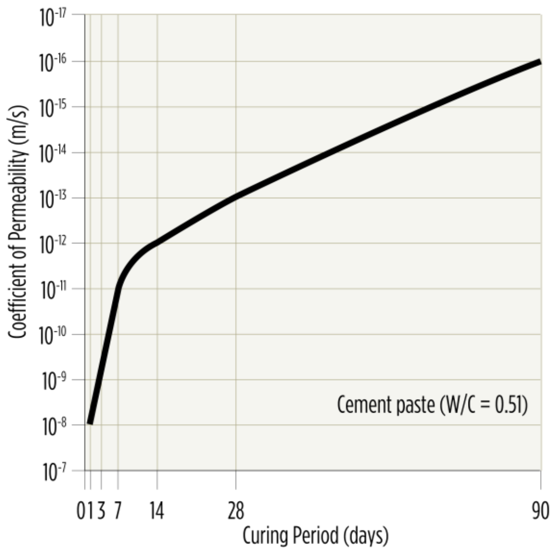

Figure 15.4 – Effect of Duration of Water Curing on the Permeability of Cement Paste

While it is essential that concrete be kept moist for as long as practicable if it is to achieve its potential strength and durability performance, in practice concrete is often not purposefully cured or, at best, is cured for only a very short period of time. This is poor practice as it results in the concrete not achieving its full strength and durability performance. Whilst the effects of inadequate curing are often difficult to determine in the short term, defects such as poor abrasion resistance (i.e. excessive wearing and dusting of floors), unexpected cracking and crazing, and corrosion of reinforcement, are typical outcomes from insufficient curing.

The reality is that 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 the effect on required properties cannot be determined precisely (e.g. the effect on concrete durability), an informed estimate should be made to set a minimum curing period.

To safeguard the general quality of concrete construction, AS 3600 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 exposure conditions (with lower concrete strengths) to seven days for the more severe exposure conditions (with higher concrete strengths) (**Table15.1**).

Table 15.1 – Minimum Initial Continuous Curing Periods (from Table 4.4 in AS 3600)

Exposure Classification	Minimum f'_c (MPa, at 28 days)	Minimum Initial Curing Requirement
A1	20	Cure continuously for at least 3 days
A2	25	
B1	32	Cure continuously for at least 7 days
B2	40	
C1	50	
C2	50	

Using water sorptivity as a measure of concrete durability, **Figure 15.5** 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 three days; the proportionately lesser benefit from extending the curing to seven days; and the minimal additional benefit from extending it beyond seven days.

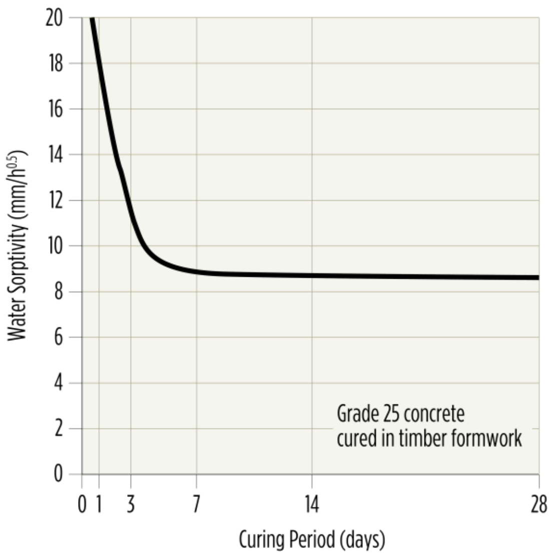

Figure 15.5 – Effect of Duration of Curing on Water Sorptivity of Concrete

4 CURING METHODS

4.1 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.

4.2 IMPERMEABLE-MEMBRANE CURING

Formwork – Leaving formwork in place is often an efficient and cost-effective method of curing concrete, particularly at 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 an effective means of providing curing.

It is important 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 affecting the finish quality. On flat surfaces (such as pavements) the sheets 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 any mottling effects (due to uneven curing) which might otherwise occur. Flooding the surface of the slab under the sheet is a useful way to limit or prevent mottling. Strips of wood (or similar) should be placed across all edges and over joints in the sheeting to (a) prevent wind from lifting it, and (b) to seal in moisture and minimise drying.

For vertical elements, 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/mottling. 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 or by site activities. A minimum thickness is required to ensure adequate strength in the sheet with ASTM C171 *'Sheet Materials for Curing Concrete'* specifying 0.10 mm minimum thickness. **Figure 15.6** illustrates the reduced effectiveness of plastic sheeting with holes (and shows that even as little as 1.7% of the sheet's surface area containing 'holes' affects curing effectiveness).

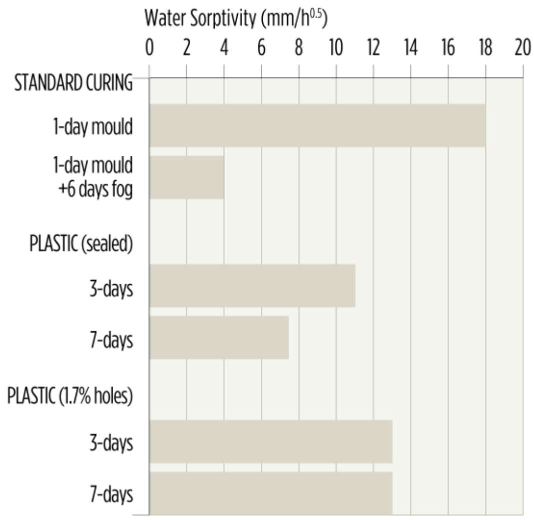

Figure 15.6 – Effectiveness of Plastic Sheet for Curing – Measured by Effect on Water Sorptivity

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 will help to keep concrete relatively cool during hot weather. Black plastic absorbs heat to a marked extent and may cause unacceptably high concrete surface 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 can fail 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.

They are an efficient and cost-effective means of curing freshly placed concrete or concrete that has been partially cured by some other means. However, they may affect the bond between the concrete and subsequent surface treatments (e.g. paint or renders). Special care in the choice of a suitable compound needs to be exercised in such circumstances, or the surface needs to be cleaned before any surface coatings are applied.

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 15.7**.

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; applying it too late results in it being absorbed into the concrete surface and not forming a continuous membrane.

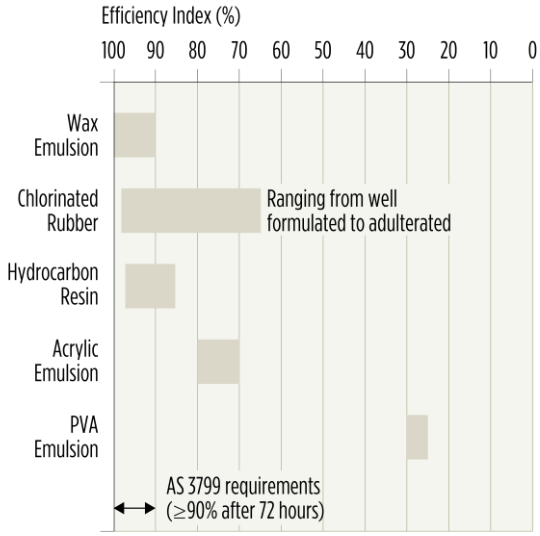

Figure 15.7 – Comparative Efficiency of Curing Compounds

These compounds 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 closely. The rate of application should be uniform with coverage normally in the range of 0.20-0.25 L/m^2. Where feasible, two applications applied at right angles to each other will help ensure complete coverage and effective protection.

Pigmented compounds also help to ensure complete coverage has occurred and are advantageous in helping concrete surfaces reflect rather than absorb heat. **Figure 15.8** shows pressure spraying of a white-pigmented curing compound.

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 when using these materials.

Manufacturer's recommendations should always be understood and followed.

Figure 15.8 – Spray Application of Curing Compound

4.3 WATER CURING

General – Water curing is carried out by placing water on the surface of concrete in a manner which ensures that the concrete 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' is erected around the edge of the slab and water is then added to create a shallow 'pond' (**Figure 15.9**).

Ponding is a quick, inexpensive and effective form of curing when there is (a) a ready supply of good 'dam' material (e.g. clay soil), (b) a supply of water, and (c) the 'pond' does not interfere with subsequent construction 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, it helps to reduce the temperature of the concrete.

Figure 15.9 – Ponding Method of Water Curing

As with other methods of moist curing, it is important that the sprinklers used keep the concrete permanently wet. However, the sprinklers do not have to be on permanently – they may be controlled by a timer system.

Sprinklers require a major water supply, can be wasteful of water and will probably need a drainage system to handle runoff. This water management system 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 ensure that the whole concrete surface 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 – Wetted fabrics such as hessian or materials such as sand can be used 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 to ensure that the surface of the concrete is not stained by either (a) impurities in the water or (b) by the covering material.

4.4 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 (and 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 involves the application of saturated steam to concrete in suitable chambers or under removable covers. It is used to heat the concrete and to accelerate the rate of strength gain and is widely used in the precast concrete industry. Its cost is justified by the more-rapid turnaround of formwork and the resulting greater productivity. Strict control of the steaming cycle is critical (**Figure 15.10**). A detailed discussion of the steam-curing process can be obtained from suitable references, e.g. the Concrete Institute of Australia's Recommended Practice [1].

It should be noted that the maximum steam curing temperature allowed (see **Figure 15.10**) will vary with mix cement type. The maximum temperature of 70ºC may apply to concrete with a binder containing type GP or HE cement but may be increased where some blended cements are used. The reason for this limit is to reduce the risk of 'Delayed Ettringite Formation' in the concrete.

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.

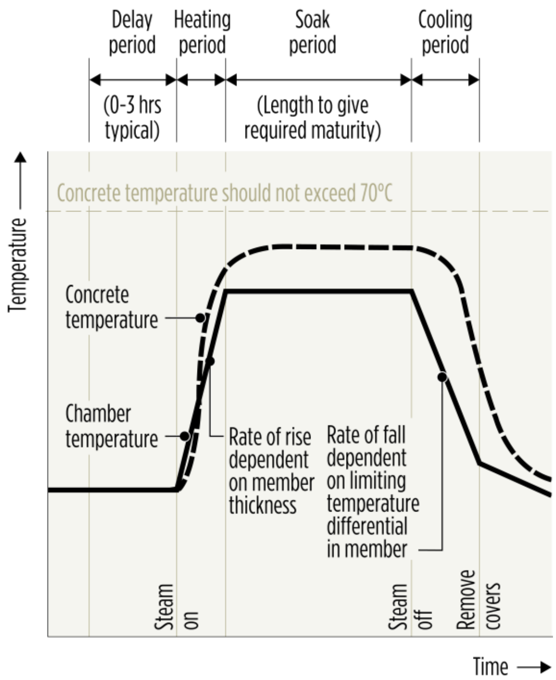

Figure 15.10 – Temperature/time Profile for a Typical Steam-curing Cycle and Concrete using GP or HE Cement

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 15.11** shows an autoclave for high-pressure steam curing of concrete blocks.

Figure 15.11 – Autoclave Equipment used to Harden and Cure Concrete Blocks

Autoclaving modifies the normal chemical reactions which occur when cement hydrates. Specifically, it causes the lime generated by hydrating cement to rapidly 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 reactive silica material 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 [2].

5 SELECTING A METHOD OF CURING

Curing is one of the critical procedures which determines whether concrete will reach its potential strength and durability performance. While site conditions may often indicate that curing will be inconvenient (it is at best a messy procedure), consideration needs to be given to whether the cost savings resulting from failure to cure outweigh the real damage that may be done to the long-term strength and durability performance of the concrete by not curing properly. It is always feasible to choose a method of curing which will be both effective and economic and doing so should be a standard part of concrete placing practice.

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 coating 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 its sprays and supervision cost;
- Safety restrictions – e.g. Are there limitations which may mean some methods are not appropriate for health or safety reasons, e.g. Toxic fumes being generated in an enclosed space or slippery surfaces from plastic sheeting etc.;
- Weather conditions, exposure and location.

6 SUMMARY – CONSIDERATIONS WHEN 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 element in-situ or precast? (Precast members are suited to low-pressure steam curing while some other 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 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-related colour changes.)
	Plastic sheeting	• What is the effect on access and site operations? • Is there any related 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 (paint, render, tiles etc.)? (Compounds can affect the 'bond' of applied finishes.) • Is there a health consideration? (Solvents may be toxic, and their use in enclosed situations may be hazardous.)

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 clays, 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 create any damage to 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 use of this process?

7 REFERENCES

1) *'Recommended Practice: Curing of Concrete (Z9)'*, 2nd edition, Concrete Institute of Australia (1999)
2) *'Menzel Symposium on High Pressure Steam Curing'* American Concrete Institute Publication SP-32 (1972)

8 RELEVANT AUSTRALIAN STANDARDS

1) AS 3600 – *Concrete structures*
2) AS 3799 – *Liquid membrane-forming curing compounds for concrete*

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