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Curing of Concrete

Technical Bulletin No **42**





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Cover Photograph: Curing of Super "T" Beams showing an appropriate combination of curing techniques including water spray, wet hessian and plastic sheeting. But note only partial curing occurs at the beam ends.

Preamble

PREAMBLE ... the outer layer of poorly cured concrete is of low quality...

As an overview of the overall thrust of the objectives of this document, and in order to put things into perspective with regard to the importance of curing in influencing the durability of concrete structures, the following paraphrased extract referenced in a paper written by international concrete expert author Adam M. Neville, is offered for serious consideration by designers, specifiers, suppliers, contractors, contract supervisors etc.

"...We know that the outer layer of poorly cured concrete is of low quality, and therefore even more penetrable than the inner core, and it is this layer that is first exposed to the action of carbon dioxide or to attack by chloride-bearing water. It is in this way that cement characteristics and actual curing are interwind.

It follows that adequate and continuous curing from the moment when the concrete is finished or the formwork is removed is of importance but, like batching and mixing, curing requires close supervision

Curing can make all the difference between having good concrete at the end of the placing operation which becomes good concrete in the structure in service on the one hand and, on the other, having good concrete at the end of the placing operation ruined by the lack of a small effort; It is worth repeating that the benefits of curing apply mainly to the exposed outer layer of concrete and it is this that offers protection to the reinforcement".

Adam M.Neville, "Why Usual Specifications Do Not Produce Durable Concrete"(Ref 1), Bahrain Society of Engineers, 3rd International Conference, Deterioration and Repair of Reinforced Concrete in the Arabian Gulf, 21 - 24 October 1989.

Foreword

The purpose of this bulletin is to provide up to date information for the guidance of personnel involved with the curing of concrete. The bulletin endeavours to increase the awareness in regard to the various methods of curing of concrete and its importance in achieving desired properties such as low penetrability (low volume of permeable voids (VPV)), design strength, stripping times, serviceability and, very importantly, durability.

The document defines curing, describes methods of curing and their effectiveness and discusses the required length of curing, hot and cold weather curing, interrupted or delayed curing, curing for special applications and relative curing costs. The bulletin also presents relevant theoretical aspects, desirable conditions and last but not least the reasons for the curing of concrete.

The overriding message of this bulletin is that effective curing of concrete should start immediately after finishing or removal of formwork and maintained for the required period of time in order to restrict the rate of water loss by evaporation from the surface and therefore prevent any adverse effects.

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About VicRoads

VicRoads is the Victorian State Road Authority responsible for the management of the road network, which includes planning, designing, constructing and maintaining roads, managing road use through registering of vehicles, licensing drivers and traffic management, and providing information and road user services.

GeoPave is an off-budget business unit within VicRoads responsible for developing technical expertise and training in road making materials, geotechnical work and pavement technology. In addition, GeoPave provides an investigation, testing, design and consulting service in these areas of expertise.

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Valuable comments have been contributed by Dom Meadley and Charlie Broadhurst from GeoPave, and staff from the Western Ring Road Project of VicRoads.

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Introduction

Despite ongoing efforts in recent years to raise the awareness of its importance, and despite the comprehensive curing clauses incorporated in specifications, curing of concrete is still seen by many as a meaningless task in the construction/production cycle, and therefore an unnecessary impediment to further progress and the desire to move as soon as possible to the next stage of the work. Even where some effort is made to satisfy specification requirements, this is sometimes done in a half-hearted way and often associated with poor practice.

Curing of concrete is an essential factor during its early stages of life so that desired properties such as low penetrability (permeability/volume of permeable voids (VPV)), design strength, stripping times, serviceability and durability are achieved. Curing requires the application of water or accelerated means (i.e. steam etc), or retention of water in the concrete by other means such as retaining formwork in place, polyethylene sheeting or curing compounds. Curing of the concrete should start immediately after finishing or removal of formwork to restrict the rate of water loss by evaporation from the surface of the concrete and therefore prevent any adverse effects. In particular, specification requirements relating to hot, cold or wet weather concreting must be adhered to.

Although the importance of thorough curing is well recognised in terms of achieving the potential strength of concrete, its even greater importance to the promotion of concrete durability and long term performance is still less widely recognised or appreciated.

It should be emphasised however, that achieving early strength requirements alone, is not an excuse for discontinuing curing of concrete at an early or premature age. In order to develop the full potential of concrete, the curing should not only be adequately and genuinely controlled by Contractors as required by specifications, but also adequately supervised by the Superintendent's Representative. Curing should be taken seriously by specifiers, contractors and contract administrators alike.

Finally, curing is identified as one of only four technical/operational parameters (the 4Cs) which are widely recognised to significantly influence the long term performance of hardened concrete (the other being concrete mix constituents, compaction and cover). This consideration alone, should be a sufficient enough incentive for all levels of the concrete industry (ie designers, specifiers, suppliers, contractors, contract supervisors etc) to strive towards achieving a dense and impermeable concrete in the cover zone to satisfy specific conditions of exposure.

What is curing

Curing is the process by which freshly placed or relatively new concrete is maintained at favourable moisture and temperature conditions which enable the hydration of cementitious materials (ie chemical reaction) to proceed at a satisfactory rate. Under such conditions young concrete is protected from early excessive evaporative moisture losses and temperature extremes which can adversely affect its strength and durability. The harmful effects of such major influencing factors as high wind speeds, air temperature, relative humidity, and variable concrete temperatures (particularly within large cross sections), can be brought under control when a suitable environment is created through good curing practices.

Lack of proper curing essentially results in a more open, more porous and much weaker concrete microstructure which would allow easier and quicker access of aggressive agents (i.e. chlorides, carbon dioxide, moisture, oxygen etc) into the concrete.

Although in the majority of cases lack of proper curing practice does not result in immediate failure or deterioration of structures, many structures have been found to have suffered from premature deterioration and loss of durability as a result of lack of attention to the 4Cs of durability, namely, the constituents of the concrete mix, cover, compaction and proper curing practices and of course the major interaction between these four parameters.

Methods of curing and their effectiveness

Curing methods may be divided into three basic groups. The first group involves the water adding techniques (water curing methods) which counteract evaporation, such as ponding, spraying or sprinkling, wet hessian and damp sand. The second group involves water retaining techniques which minimise loss of water through evaporation, such as covering with polyethylene plastic, spraying-on a curing compound or leaving the formwork in place. The third category involves accelerated curing methods (i.e. at elevated temperatures) such as low pressure steam curing, radiant heat, electrical curing, curing by infra-red radiation, deliberate carbonation and high pressure steam curing or autoclave. Where appropriate a combination of these methods can also be implemented.

In effect the first two groups (i.e. water adding and water retaining methods) fall into the passive category, in that they basically control the heat generated within the concrete itself, whereas accelerated curing methods can be classified as active, as the concrete temperature and curing environment are controlled through the addition of external heat (Ref 2, 3, 4, 5, 6, 7, 8, 9, 10, 11).

3.1 Water Adding Techniques

3.1.1 Ponding

Ponding is considered to be a very effective way of curing concrete, particularly for horizontal concrete surfaces such as slabs, pavements, culvert bases etc. At least 20 mm depth of water should be retained within a dam or dike of earth (i.e. clay or other material) built around the perimeter of the slab. The water should not be more than 5°C to 10°C cooler than the concrete surface to prevent any thermal shock and subsequent cracking. The water would also maintain the concrete at a lower temperature during hot weather. There are some practical disadvantages associated with this method however, and as such it is not used on a frequent basis. These include slabs on a sloping surface, accidental disruption of the earth dam allowing water to escape, staining of the concrete surface by the dam material, creating wet conditions around the construction site and potential interference with general construction operations and traffic.

3.1.2 Spraying or Sprinkling of Water

Spraying (fog spray) or sprinkling of water with spray nozzles or soaker hoses is another efficient way of providing moist conditions on exposed concrete surfaces (Ref Fig. 3.1). However, an effort has to be made to ensure that the whole of the concrete surface is kept wet at all times during the curing period, and any wetting/drying conditions be avoided. This is particularly important in windy conditions. Manually controlled intermittent sprinkling or spraying can be unreliable if not properly supervised, although the use of an intermittent timer system is a very reliable option.

Care should be taken to provide adequate drainage to avoid a muddy/wet surrounding working environment, or alternatively institute a recycling system which could also reduce the cost of water usage. The use of soaker hoses is also a very useful technique, particularly in combination with a hessian for both vertical and horizontal surfaces. Spraying (fogging) is particularly useful as it can commence immediately following screeding thus minimising evaporative moisture losses. All of these techniques can form effective combinations with other techniques.



Fig. 3.1 Moist Curing of In-Situ Concrete via Sprinkling of Water

3.1.3 Wet Hessian

Wet hessian or other absorptive fabric material can be used as a very effective curing method for both flat and vertical surfaces (Ref Fig. 3.2). Water is provided via sprinklers or soaker hoses and these materials can provide a well distributed curing atmosphere to the whole concrete surface. They must be kept saturated on a continuous basis and should not be allowed to dry out particularly in hot weather. Intermittent drying out of the hessian may result in absorption of moisture from the concrete itself which is obviously undesirable. Wetting and drying periods should be avoided as concrete cracking can occur. The hessian is placed on the concrete surface immediately after finishing and once the water sheen has left the surface (i.e. as soon as the surface is set) to prevent surface damage. Hessian strips or other absorbent fabric should be overlapped and held appropriately (weighted down on horizontal surfaces). Wet hessian is a very practical approach compared to ponding and as such its use is strongly encouraged. It can also be used in combination with polyethylene plastic to provide a very effective curing regime.

3.1.4 Wet Sand

Wet sand is an effective moist curing method, but due to its high cost it is not used extensively. Approximately a 50 mm thick layer of clean wet sand is uniformly distributed over the horizontal surface and kept continuously moist. Failure to keep the sand moist will result in moisture leaving the concrete which is of course undesirable. Alternate drying out and wetting of the cover may cause cracking.

3.2 Water Retaining Techniques

3.2.1 Retaining Formwork In-Place

Retention of formwork in position is considered an acceptable way of protecting concrete against the loss of moisture and thus enable the concrete to cure in a satisfactory moisture condition. However, exposed top surfaces need to be cured effectively using one of the other curing techniques, with wet hessian and/or polyethylene plastic being the most widely used options (Ref Fig. 3.3).



Fig. 3.2 Moist Curing with Wet Hessian

Once the formwork has been struck or removed prior to the completion of the required curing period, curing should continue with one of the other acceptable curing methods (i.e. wet hessian/polyethylene etc) for the duration of the curing period. It should be noted that once the formwork is struck, curing by the formwork is considered ineffective. In addition, it is also advisable that in hot weather formwork is kept damp to further enhance the overall curing environment. The curing of surfaces should commence within half an hour of the removal or striking of the formwork from the section (Ref Fig. 3.4).



Fig. 3.3 Curing Blanket utilising Wet Hessian and Polyethylene Plastic over the top



Fig. 3.4 Application of water spraying upon removal of formwork while awaiting the application of other curing

3.2.2 Polyethylene Sheeting (Plastic)

Polyethylene sheeting (plastic) or other impermeable coverings such as waterproof curing paper are another effective method of retaining moisture within the concrete. Although it may be less effective than water curing methods, this curing technique is used with greater frequency compared to other methods because it can be carried out more easily and it provides less impediments to construction progress. Polyethylene sheeting with a minimum thickness of 0.1 mm can be used on both vertical and horizontal surfaces. Overlapping by at least 300 mm is necessary to minimise moisture drying and joints should be sealed effectively with adhesive tape.

On flat surfaces polyethylene sheeting should be secured appropriately using pieces of timber or other objects to prevent wind from lifting the plastic (blowing/flapping about) and also prevent draughts underneath the plastic which can create a wind-tunnel effect and dry out the concrete surface (Ref Figs. 3.5 and 3.6). Care should also be taken to avoid damage by construction traffic.



Fig. 3.5 Curing with Polyethylene Sheetting



Fig. 3.6 Polyethylene Sheetting secured appropriately

Polyethylene sheeting should be placed on flat surfaces immediately after finishing (i.e. essentially within half an hour of finishing and as the water sheen has evaporated). An effort should be made to keep the plastic smooth and flat on the surface in order to minimise uneven curing which may cause discolouration of the hardening concrete. Where possible a frame can be placed over the concrete to prevent any such problems (Ref Fig. 3.7). This can certainly assist where special finishing (i.e. texture finish etc) is required.

In the case of vertical surfaces (i.e. components such as columns and beams) polyethylene sheeting should be effectively wrapped around the component and taped to limit the moisture losses (Ref Fig. 3.8). Overlapping is important here as well. Once again where discolouration may be a problem the plastic should be kept clear of the surface by using timber or other suitable frames. This should certainly be the case where coloured concrete is being cured.

Polyethylene sheeting is available in various colours. Although black plastic is the predominant colour used, lightly coloured sheets may be more preferable during hot weather as they tend to reflect the sun rays and help to keep the concrete surface cool. Black plastic tends to absorb heat to a greater extent and may be inappropriate in hot weather, although in cold weather it may provide a beneficial curing environment.

As mentioned previously the combination of wet hessian and polyethylene sheeting is a very useful and practical combination (Ref Fig. 3.3), although even without hessian, the concrete surface should be moistened with a fine spray of water prior to the placement of the plastic alone, as a matter of good practice.



Fig. 3.7 Placement/Finishing of concrete with polyethylene plastic fixed on frame awaiting placement



Fig. 3.8 Polyethylene sheeting effectively wrapped around component in marine environment

3.2.3 Curing Compounds

Curing compounds are less effective than polyethylene plastic and even less effective than water adding curing techniques (Ref Figs. C2 and C3 and Sections C1 and C2 in Appendix C). Their function is to restrict the loss of water during the early hardening and maturing period by sealing the concrete surface. However, due to their ease of application, their lower relative cost and lack of ongoing maintenance requirements they are still very practicable and an attractive proposition, and as such they are widely used. Nevertheless, to be effective and acceptable they must satisfy the requirements of Australian Standard AS 3799, and in particular they must have an efficiency index of at least 90% after 72 hours. AS 3799 covers a number of classes of curing compounds, including wax-based, hydrocarbon resin based, water based emulsions, synthetic resin based (i.e chlorinated rubber, vinyl and acrylic copolymers) and polyvinyl acetate (PVA based). Both PVA emulsions and sodium silicate solutions should not be used on structural concrete work due to their failure to satisfy the requirements.

Curing compounds can be roller, brush or spray applied on the concrete surface (Ref Fig. 3.9). Hand or power sprayers can usually operate at low pressures of between 0.5 and 0.70 MPa. Curing compounds should be applied immediately after finishing, once the water sheen has evaporated, but while the concrete surface is still damp. A compound should not be applied on dry concrete as it will be absorbed unnecessarily and fail to form a continuous film. In addition, curing compounds should not be applied while the concrete is still bleeding, as this will cause dilution of the compound and be rendered ineffective.

Where a curing compound is to be applied on a concrete surface following the removal of formwork, it must be done immediately. If the concrete is allowed to dry out, it must be wetted down, then the curing compound applied while the concrete is still damp. Curing compounds used on rough or textured surfaces may be less effective due to non-uniform application and as such a higher rate should be applied. Effectiveness in such cases may still be reduced.



Fig. 3.9 Curing Compound Spray applied on finished concrete surface

Construction traffic should not be allowed on applied surfaces for some 12 hours after application or as required by the manufacturer's recommendations. Care should be taken not to damage the membrane and any damage should be made good as soon as possible. Curing compounds should be applied in accordance with manufacturer's recommendations and data sheets and attention given to a number of requirements including the rate of coverage and number of applications, and whether applications should be at right angles to achieve more effective coverage.

Curing compounds are supplied in different colours including clear. Lighter colours should be preferred as they minimise heat absorption (reflect sun rays) compared to darker curing compounds. Although pigmented compounds allow monitoring of application, clear compounds may need the inclusion of a fugitive dye to allow monitoring of application.

Depending on the type of curing compound, it may take between 4 and 12 weeks for these membranes to breakdown naturally and peel off the concrete surface. In some cases, natural breakdown may not be possible and therefore contractors should be prepared to remove these using high pressure hot water wash or by other mechanical means, in order to satisfy construction schedules. Although there are some curing compounds which can be compatible with subsequent application of coatings, bituminous seals or other toppings without requiring removal, many may have to be removed in order to facilitate such operations. The overall effectiveness of curing compounds both between themselves and compared to other methods is discussed further in Sections C1, C2 in Appendix C and Section 3.4.

3.2.4 Self Curing (Internal Curing) of Concrete

This type of curing involves the addition of proprietary liquid admixtures (in a similar manner to normal admixtures) during the manufacture of concrete at the batching plant. When added at the correct dosage levels, these admixtures basically work by promoting a more uniform cement hydration within the whole concrete component which results in further microstructure modification, and by developing an internal membrane which prevents water to evaporate from the freshly placed concrete. According to current literature and some manufacturers' test data, internally cured concrete can perform as good as, if not better than, spray on curing compounds in terms of strength development, watertightness, reduced shrinkage and cracking. In addition it is claimed that these admixtures improve workability and pumpability which can also assist in the overall concrete performance.

This method of curing may be suitable in confined or difficult construction areas where external curing may prove to be impracticable, particularly for wet-mix sprayed concrete applications. It

is recommended however, that due to limited experience with this type of curing within VicRoads, additional laboratory testing and/or field trials should be undertaken prior to allowing use of this method on particular projects. This should also be supplemented with a documented history of the previous performance of the particular product.

3.3 Accelerated Curing Techniques

3.3.1 Low Pressure Steam Curing

The objective of low pressure steam curing (i.e. pressure of around 70 to 100 kPa, which is near atmospheric pressure) is to achieve a higher early strength which would satisfy requirements for early lifting or the transfer of prestressing force requirements, by accelerating the hydration reaction of the freshly placed concrete (Ref 4, 12). This enables the production of precast and/or prestressed concrete products on a daily basis and thus the cost efficient utilisation of casting beds, moulds etc, on a daily cycle basis. Steam curing generally maintains the environment within the curing chamber at both high temperature (i.e. generally 40°C to 75°C) and high humidity (i.e. near saturation with regards to moisture) under carefully controlled conditions.

The steam curing process essentially involves the creation of a steam chamber or protective enclosure by using covers (i.e. tarpaulins etc), which allows free circulation of steam around the concrete product (Ref Fig. 3.10). A temperature recorder(s) is placed at strategic locations within this chamber (as per specification) to ensure the uniformity of temperature of the curing environment. The temperature is recorded on a thermograph as indicated in Fig. 3.11.

The duration of a good curing cycle may range between 12 and 23 hours. This covers four distinct periods all of which can influence the quality and long term performance of the final product. These are the presteam delay period (i.e. initial maturity) of 2 to 5 hours, temperature increase (rise) period of about 2 to 3 hours, maximum temperature or soaking period of about 6 to 12 hours and a cooling period (temperature decrease period) of about 2 to 3 hours.

As discussed in Appendix C the presteam delay period (i.e. delay in the commencement of heating) and the rate of temperature rise must be controlled effectively in order to minimise any adverse effects on strength and penetrability (VPV). The rate of temperature rise should be limited to 24°C/hour and the initial maturity to a minimum 40°Chrs (i.e. 40°Chrs divided by the concrete temperature) but not less than 2 hours after batching of concrete. In this context the maximum temperature of curing should not exceed 75°C and very importantly the cooling period should be controlled adequately, to ensure that the rate of temperature decrease is regulated such that the thermal stresses on precast units are avoided.



Fig. 3.10 Precast Factory with Tarpaulin Curing Chamber in the foreground

The optimum curing process can be affected by a number of factors which are basically interrelated. These include the size of the concrete unit (faster heating of smaller units compared to larger, for example box culverts versus beams etc), the W/C ratio, the cementitious material type and content (i.e. use of Supplementary Cementitious Materials (SCMs) i.e. slag, fly ash and silica fume etc), curing temperature, preheating of concrete aggregates, lifting strength and transfer of prestress requirements and effectiveness of the curing chamber.

A large proportion of the precast concrete industry utilises steam curing for the rapid production of precast concrete components such as prestressed concrete beams, crown units, parapet units, box culverts, pipes, floor slabs, noise barriers etc. Partial steam curing is also employed, although to a lesser extent, particularly for smaller units. This basically utilises a far shorter steaming cycle with the maximum temperature and temperature period significantly reduced (i.e. may be 1 to 3 hours). This phase of the curing cycle has to be continued by one or a combination of other acceptable curing methods such as moist curing, wet hessian, polyethylene sheeting etc (Ref Fig. 3.12). This should not be however, a preferred curing combination as it is time consuming and not as cost effective as it may first appear to be.

The use of steam curing and indeed other accelerated curing methods (Refer Section C1, Appendix C) can result in possible reductions in ultimate strength and corresponding increases in penetrability (VPV), when considering optimal performance, compared to moist curing. As such, an allowance should be made when designing the concrete mix. Such precautions should also be allowed for partial steam curing cycles.

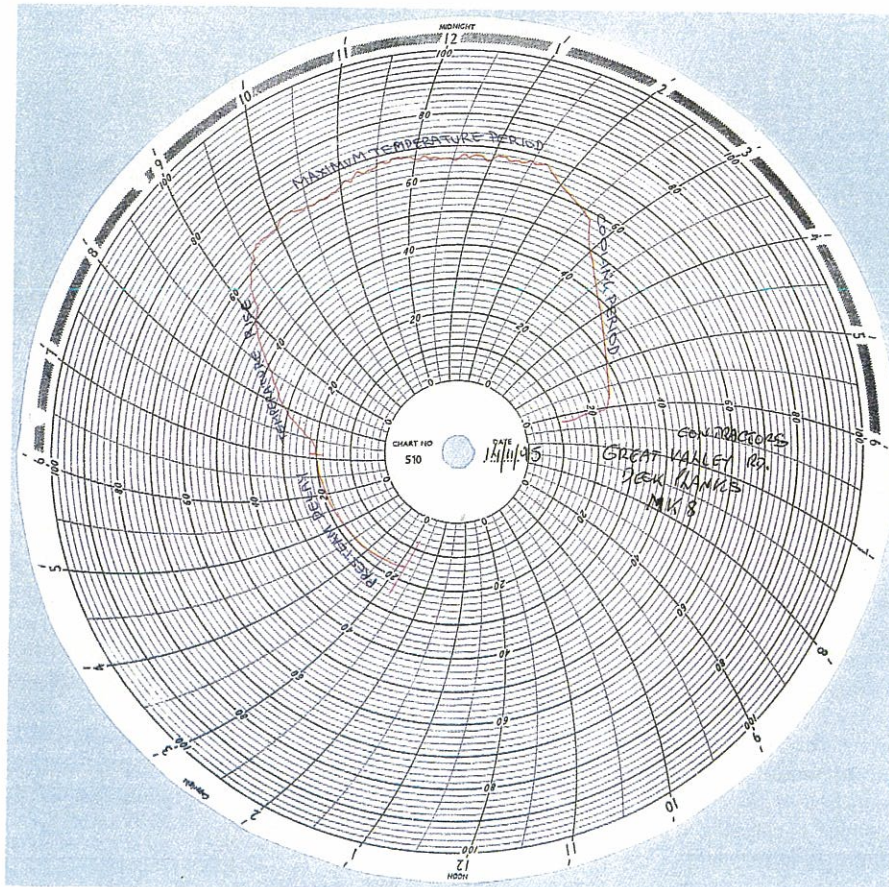


Fig. 3.11 Typical Steam Curing Thermograph

3.3.2 Radiant Heat (Heated Moulds) Curing

Radiant heat curing involves the circulation of hot water through steel jackets/rectangular hollow sections attached to the sides and/or underside of steel moulds to apply heat to the product. This is another convenient way of accelerating the hydration reaction and thus obtain a high early strength for precast concrete products.

All requirements relating to steam curing, in terms of presteam delay, rate of temperature rise, maximum temperature period, temperature controls and monitoring etc are also required to be satisfied by this curing method. The water temperature is controlled by a thermostat which is generally set at 75°C. The temperature difference between ingoing and outgoing water is maintained at less than 10°C, which is in line with temperature variations allowed for in the steam curing process. The top surface of the concrete product is kept moist throughout the curing cycle by a combination of hessian and water mist (or soaker hose). The whole product is subsequently covered with a tarpaulin or similar material to create a suitable curing environment.

The concrete test cylinders are cured in a box which forms part of the overall hot water circulation. However, it is important that the temperature in this box is also monitored throughout the curing period to ensure that cylinders are not treated any more favourably than the concrete product itself. It should be noted that over the last few years this method of curing has been used satisfactorily by some precasting yards to produce precast concrete products for VicRoads works. However, it is still essential that the performance of this curing method should be closely monitored to ensure that specification requirements are being met.



Fig. 3.12 Precast Component Effectively Sealed subsequent to Partial Steam Curing

3.3.3 High Pressure Steam Curing (Autoclaving)

High pressure steam curing, also known as autoclaving, is a special process primarily used in the concrete masonry industry for the manufacture of smaller precast products such as concrete masonry blocks (i.e. hollow cored blocks etc) and small slabs and beams. The thickness of such products generally varies between 100 and 300 mm. This method would be both impractical and cost prohibitive in the manufacture of large, heavy road infrastructure concrete components, mainly due to the nature of the special process, the curing chamber used (i.e. cylindrical steel autoclaves), and the need to transport/place units in the autoclaves. Other technical disadvantages include the reduction in bond strength between steel reinforcement and concrete of up to 50%, an increase in brittleness, reduction in impact strength, etc. High pressure steam curing involves curing with steam at temperatures ranging from 150°C to 180°C and pressures in the order of 500 kPa to 1000 kPa. Because of these higher pressures, compared to pressure of around 70 to 100 kPa for low pressure steam curing, the curing chamber is normally in the form of a pressure vessel (such as cylindrical steel chamber) also known as an autoclave.

At these high temperatures an additional chemical reaction takes place which supplements the primary reactions involved in the normal hydration process. Calcium hydroxide which is liberated as part of the cement hydration process, reacts with finely divided silica which may be present in the aggregate to form an insoluble dicalcium silicate hydrate. This is in contrast to free Ca(OH)_2 on its own which can be leached out of the concrete. As such, leaching and efflorescence is prevented. In addition, a larger proportion of dicalcium silicate (C_2S) hydrates are formed and these react with aluminates to form very stable compounds (i.e. hydro garnets) which are also very resistant to sulphates, and sulphate attack on the concrete.

Normally the concrete mixes used in autoclaving contain between 30% to 40 % of powdered silica (by weight) as a replacement of cement in the mix, depending on the type of aggregate used, to further enhance strength development and other qualities required from autoclaved products (i.e. reduced shrinkage and cracking, high early strength, sulphate resistance, reduced efflorescence, lighter (whitish) colour, lower moisture content etc).

High pressure steam curing cycles are generally in the order of 12 hours, thus allowing two complete curing operations in 24 hours for each autoclave, with concrete products being able to be used virtually 24 hours after casting.

3.3.4 Other Accelerated Curing Methods

There are a number of other curing methods which can be used to accelerate the strength development of concrete products. However, these are very specialised and are essentially beyond the scope of this document. Nevertheless, these have mainly been used as part of experimental works or some full scale projects in the United States, Sweden and Russia. The methods include electric and infra-red curing.

The electric curing method involves the passage of AC current into the concrete through a number of means such as external electrodes, through the reinforcement or by the use of electric blankets aiming to increase the early strength of concrete. The infra-red curing process involves the heating of concrete using thermal radiation in the form of infra-red rays. Once stripping strength is achieved moist curing is applied. The radiation from infra-red heaters is directed at the forms and not the concrete itself.

3.4 Effectiveness of Curing Methods

The effectiveness of the various passive curing methods has been discussed in Sections 3.1 and 3.2 in relation to their effect on such concrete properties as strength development and penetrability (VPV). These comparisons are made based on work undertaken by VicRoads. However, these conclusions are strongly supported by numerous other studies reported in the literature and carried out over the years.

As indicated in Fig. C2, Appendix C, continuous moist curing, if carried out diligently, produces concrete having both superior strength and penetrability (VPV). This is followed very closely by wetting and drying, which resembles intermittent timer controlled water spraying on site. Although polyethylene sheeting is not as effective as the wet curing methods, it is nevertheless considered a very satisfactory curing method particularly when used in combination with a wet hessian and then sealed effectively to minimise as much as possible any moisture losses. When comparing optimum performance, curing compounds were found to be the worst performers with a decrease in strength of 22% (cf air curing with reduction of 43%) and an increase in penetrability (VPV) of 37% (Ref 2, 5).

The superior performance of water adding techniques is clearly demonstrated by the fact that evaporation takes place from the water supplied onto the concrete surface itself, and as such the whole of the concrete section is kept fully saturated, thus providing ideal conditions for the hydration process. On the other hand, in the case of concrete cured by the water retaining techniques, evaporation takes place from within the surface layer (i.e from the first 30 to 100 mm of thickness), thus resulting in a partially saturated surface layer which can adversely affect the much needed refinement of the pore structure and therefore all related concrete properties.

The performance of the various generic types of curing compounds (Ref 8, 9, 10) as compared with the minimum efficiency index of 90% as required by the standard AS 3799 can be summarised as follows.

Wax based-	Efficiency of 91 - 93%
Hydrocarbon-	Efficiency of 94 - 95%
Water based emulsions-	Efficiency of 91 - 93%
Chlorinated Rubber-	Efficiency of 90%
Acrylics-	Efficiency of 70 - 80%

PVA based curing compounds have an efficiency index in the range of 10 - 60%. As such both PVA and Acrylic based resins are not recommended for use on structural work.

3.5 VicRoads Curing Requirements (Section 610)

Curing for VicRoads works is covered by Section 610 "Structural Concrete" of the standard specification (Ref 13). Temperature and evaporation limits as well as concreting operations relating to hot and cold weather concreting are also addressed in Section 610.

The specification allows the use of one or a combination of a number of curing methods. Curing methods covered include water curing, curing by maintaining the formwork in place, polyethylene sheeting, curing compounds, steam curing, partial steam curing (in combination with other methods) and radiant heat (heated moulds) curing.

The contractor is required to submit full details of his proposed methods, as part of his concrete mix design submission, not less than 14 days prior to placement of concrete. It is also required that curing of exposed surfaces should commence immediately after finishing operations are progressively completed and should continue uninterrupted for the specified periods of curing. For practical purposes curing of formed surfaces should recommence within half an hour of stripping of formwork.

The specification allows the use of curing compounds on concrete decks or slabs only if aliphatic-alcohol based evaporative retarding compound is also applied prior to the application of the curing compound, during the finishing operations. This is to further minimise evaporative moisture losses. This is an additional requirement over and above, considering the fact that the performance of curing compounds can not be the same as water curing. The use of PVA based curing compounds is not allowed due to their inefficiency.

Length of curing period

The duration for curing of concrete depends on a number of factors including, climatic conditions, the concrete mix design used, the future exposure conditions, the type of cement used (i.e. whether GP cement or supplementary cementitious materials at various replacements), the required strength and penetrability (VPV), the average curing temperature and moisture conditions, the size of the concrete component etc. Although all properties of concrete are enhanced by a prolonged period of curing, practical considerations have largely dictated the length of curing over the years. As such, curing periods ranging from 3 to 21 days have been specified in various standards and specifications, with 7 days being the most widely used for curing temperatures above a certain limiting value.

In recognition that traditional curing durations were developed empirically, a literature review was conducted by VicRoads (Ref 14) to identify some scientific or technical basis for the adoption of curing periods. The review included a study of maturity requirements to achieve capillary discontinuity as influenced by the gel/space ratio, the W/C ratio and the required degree of hydration.

The current curing periods adopted in Section 610 of the VicRoads Specification as a result of the above review and analysis are presented in Table 4.1. These are related to the concrete grade, exposure classification, type of cement and average air temperature. As a result of the lower W/C ratios, curing periods for higher grade (richer) concrete are slightly reduced. This is because cement particles are in closer contact, therefore resulting in increased rate of hydration and a quicker capillary discontinuity and denser concrete. Due to their higher surface area to volume ratio concrete decks and slabs require two additional days for curing. In recognition of the possible slower strength development in Supplementary Cementitious Materials (SCMs, i.e. slag, fly ash and silica fume) concrete, slightly higher curing periods have been adopted for moderate replacement levels of cement (i.e. up to 40% slag, 25 % fly ash and 10% silica fume).

As SCMs may hydrate more slowly than Portland cement, SCM concretes, particularly at higher replacement levels (i.e. greater than 40% slag, 25% fly ash and 10% silica fume), are potentially more susceptible to poor curing and therefore to adverse effects such as loss of strength and reduction in overall quality and performance. This is mainly due to a concern that increased loss of moisture would greatly affect the already lower rates of hydration reactions and subsequent hydrates formation, and therefore decrease the strength gain and durability. This highlights the importance of curing SCMs concretes adequately and with great care. Furthermore, as SCMs may be more susceptible to plastic shrinkage cracking (particularly silica fume and fly ash) it is even more essential that curing of SCM concretes begin immediately after placing/finishing. For higher replacement levels of SCMs longer periods of curing than those presented in the table should be adopted.

For special applications such as construction in a marine environment the period of moist curing adopted by VicRoads for all cast-in-place concrete has been a minimum of 14 days, and further extended by the number of days the average air temperature falls below 10°C. In such environments it is also required to protect (isolate) all exposed concrete surfaces against the ingress of chlorides for the length of the curing period (Ref Fig. 3.8). No curing compounds are allowed to be used in such an environment. More extended curing periods are also desirable for concrete structures exposed to other aggressive conditions such as chemical and sulphate attack.

In relation to low pressure steam curing moderate replacement levels of SCMs (i.e. up to 40% slag, 25% fly ash and 10% silica fume) can be used successfully in the manufacture of precast concrete units without major effects on the curing cycle. However, higher replacement levels can adversely affect the steam curing period. Precast products utilising up to 10% silica fume are now produced regularly and more recently 20% fly ash and moderate replacement triple blend combinations (i.e. up to 35% slag/fly ash) have been used without any effects on the steam curing cycle. As in the case of passively cured concrete, SCMs have the advantage of refining the pore structure and pore size distribution, which can more than compensate for the adverse effects of a coarser pore structure due to the elevated temperatures. Chloride diffusion and rapid chloride permeability tests undertaken by Detwiler et al (Ref 15) on specimens cured at 23°C, 50°C, 70°C and containing Portland cement only or moderate replacements of 5% silica fume and 30% slag, demonstrated chloride ingress is increased with increases in temperature. However, the results also indicate that SCMs concrete significantly outperforms conventional concrete at all temperatures (i.e. by at least a factor of 3 to 1), thus demonstrating the effectiveness of SCMs when used at elevated temperatures and at moderate replacement levels.

Table 4.1. Specified Periods of Curing in Section 610 of VicRoads Specification

Periods of curing (excluding steam curing)				
Concrete Grade ¹	Exposure Classification	Type of Cement ²	Periods of curing (days)	
			Average Air Temperature During Curing ^{3*}	
			10°C to 17°C	Above 17°C
VR330/32	A,B1	GP	7	6
		GB	9	8
VR400/40	B2	GP	6	5
		GB	8	7
VR450/50	C	GP	5	5
VR470/55		GB	7	7
For concrete decks and slabs, the periods of curing shall be extended by 2 days.				

Notes:

- Where a higher concrete grade is adopted than that shown in the table for a particular exposure classification, the periods of curing for the higher concrete grade may be adopted.
- Type of cement:
GP – General purpose portland cement.
GB – General purpose blended cement.
- When the average air temperature during the specified periods of curing falls below 10°C, the periods of curing specified above shall be extended by 2 days.

* Average air temperature has been adopted in place of concrete surface temperature for practical reasons.

Curing in hot weather conditions

Hot weather conditions can have significant adverse effects on both the quality of freshly mixed concrete and the subsequent properties and long term performance of hardened concrete. This is basically associated with the increased rate of cement hydration at the higher temperatures and the undesirable drying out of surfaces due to the increased evaporative moisture losses from the freshly mixed and placed concrete.

Hot weather concreting is affected by the adverse effects of high temperatures, solar radiation, low relative humidity, high wind velocities and high concrete temperatures. The combined effect of these factors can further exacerbate the problem. Problems associated with hot weather concreting include increased water demand and loss of slump/workability, accelerated setting and therefore difficulty in compacting and finishing, plastic, drying and thermal shrinkage cracking, less uniform surface appearance, lower strengths and increased penetrability (VPV) and essentially lower long term durability. In addition to other measures the VicRoads specification does not allow the placement of concrete when the air temperature exceeds 35°C and requires that the concrete temperature itself should not exceed 32°C. Although care and good practices should be adopted at all times when concreting, it is always advisable that when air temperatures are approaching 25°C - 30°C on the day of concreting, the contractor should be looking to have appropriate procedures in place which can be implemented to protect the proper curing of the concrete.

Various precautionary measures can be undertaken to minimise the adverse effects of hot weather concreting. These include chilled mixing water or crushed ice in the concrete mix, use of SCMs to generate lower heat of hydration and slower strength gain, water-reducing and set-retarding admixtures, shielding of exposed surfaces with wind breaks and sun screens, spraying the reinforcement with water to keep cool, sprinkling and shading the aggregate prior to mixing and placing concrete earlier or later in the day when the climatic conditions are more favourable.

Under these conditions the use of aliphatic alcohol (liquid which produces a continuous film to retard evaporation during finishing operations) or controlled fog spray immediately after initial screeding should be seriously considered in order to minimise evaporative moisture losses (Ref Fig. 5.1). This should be maintained until the concrete has hardened sufficiently and the curing method is ready to be implemented.

The passive curing methods described in Sections 3.1 and 3.2 of this document are still acceptable means of providing effective curing conditions for concrete in hot weather. However, it is more preferable to utilise moist curing in the form of ponding, layer of wet sand or wet hessian which is kept continuously wet with soaker hoses, fine mist or continuous sprinkling. This would also assist in shading the concrete and keeping it cool. Water temperature should be similar to the concrete in place in order to avoid thermal shock and unnecessary cracking. Uncontrolled intermittent wetting may result in wetting and drying effects and subsequent cracking which is undesirable.

Where the use of curing compounds, plastic sheeting or wet hessian covered by plastic sheeting is unavoidable, a greater care must be taken to ensure their effectiveness. Polyethylene sheeting should be well secured and anchored at the edges and joints and a lighter colour (not black) be utilised to minimise the absorption of heat which may be detrimental. White-pigmented curing compounds are more appropriate and should be applied in the correct manner and at the recommended coverage rates.

During hot weather formwork should be kept cool by running water over them. When formwork is removed curing of formed surfaces should recommence within half an hour as described above.



Fig. 5.1 Application of aliphatic alcohol (evaporative retarder) immediately after initial screeding

Curing in cold weather conditions

Cold weather concreting is clearly associated with very low temperatures which slow down the rate of the cement hydration reaction and of course the rate of strength development. Generally temperatures lower than 5°C fall into this category and if left unprotected, concrete can be damaged by freezing and frost action thus resulting in a damaged concrete surface, lower strength, increased penetrability (VPV) and lower resistance to environmental effects. The VicRoads specification (Ref 2) states that the air temperature at the point of placement should not be lower than 5°C when concrete is placed, and that precautionary measures should be adopted to maintain the temperature of the concrete surface above 5°C .

Measures which can be implemented to minimise the adverse effects of cold weather include the heating of concrete ingredients, particularly water and aggregates, using set accelerators to reduce delays in the finishing operations etc. In terms of curing and protection of concrete, consideration should be given to the use of thermal blankets and heated enclosures in order to conserve the heat of hydration and enable the concrete to achieve sufficient early strength. Drying out of the concrete should be avoided particularly when using heated enclosures. In such cases fresh air intake should be provided to reduce the carbon dioxide and carbon monoxide generated. In addition, heat should not be pointed directly onto concrete. Water curing should not be used due to the likelihood of freezing and therefore loss of protection. Large exposed flat surfaces such as bridge decks should be protected with thermal blankets. These should be placed immediately after the concrete has set to avoid surface damage.

In the case of formed concrete components, formwork removal should be delayed for as long as possible to assist in the curing, prevent drying and reduce any unnecessary damage. Depending on the prevailing temperatures, consideration may be given to placing thermal blankets or other coverings over the formwork. When forms are removed curing should recommence if necessary with thermal blankets or other coverings such as polyethylene plastic, weatherproof tarpaulins or a combination of these depending on the prevailing temperatures. To improve its effectiveness such insulation should be kept in close contact with concrete or formed surfaces. Moist curing should not be used upon the formed surfaces due to the potential for thermal shock and unnecessary cracking.

Insulation or other form of protection (i.e. heaters etc) should be removed gradually so that the concrete surface temperature decreases gradually during the subsequent 24 hour period to reduce the likelihood of thermal shock. On this basis formwork should be eased off from the surface and left in place to allow gradual fall of temperature to acceptable limits before forms are fully removed.

Curing to control temperature differentials

It is generally accepted that cracking will occur when the temperature difference across any concrete element (i.e. between the surface and interior of the concrete element) exceeds 20°C . This limitation is also specified in the VicRoads concrete specification Section 610. This is to minimise the build up of excessive thermal stresses leading to early - age thermal cracking of the hardened concrete due to either internal or external restraints (i.e. steel reinforcement, earlier hardening of internal portions of a concrete section compared to surface layers due to non-uniform temperature rise, previously constructed foundations etc). In general, early - age thermal cracking occurs within 1 to 7 days of casting concrete. For massive sections, such cracking can take several weeks to develop.

A number of measures can be undertaken to minimise the temperature difference or gradient. These include the use of cool mix ingredients, special chemical admixtures, blended cements, and thermal insulation blankets.

Thermal insulation can minimise temperature gradients within the concrete mass and ensure that temperature rise occurs more uniformly throughout the concrete element. Thermal insulation blankets generally form part of the overall curing medium. Examples of thermal insulation blankets include the combination of two alternate layers of wet hessian and 50 - 100 mm thick polystyrene blocks covered with polyethylene plastic/tarpaulins, or prefabricated curing blanket of synthetic insulation backing with plastic or similar covering. Subsequent removal of formwork or thermal insulation should be done in a gradual and controlled manner in order to prevent rapid cooling of the concrete surface which can result in thermal shock and induce differential stresses.

If there are any concerns about temperature difference or gradients in large concrete sections, thermocouples should be installed at various locations within the concrete section (including the core, near surface and on the surface) to ensure that the specified temperature differential limit of 20°C is not exceeded, and more importantly to allow for adjustments of the thermal insulation blankets where required.

Interrupted or delayed curing

Re-curing of concrete (using water curing) which has been allowed to dry can still achieve satisfactory bulk properties of the concrete as a whole, due to the further hydration of unhydrated cement in the presence of moisture (Ref 16). These observations however, are only based on investigations utilising small concrete cylinder specimens and test conditions which may not be truly reflecting prevailing climatic conditions or the behaviour of in-situ concrete.

In practical terms bridge decks and other components such as retaining walls, large columns and box girder web walls which are characterised by a large cured surface area to volume ratio would suffer large moisture losses from the exposed surface area, if either effective curing is interrupted or delayed. As such, the drying period before curing or during interruptions would result in a relatively weak and porous (open pore microstructure between partially hydrated cement particles) surface layer of concrete which can be as deep as 30 - 100 mm, depending on the concrete grade. It is the quality of this surface layer that determines the durability of concrete against corrosion of the steel reinforcement and/or spalling and disintegration of the cover concrete matrix.

Although recommencement of curing may be able to regain some of the required properties of concrete as a whole (as reflected by the small specimens) under laboratory controlled conditions, it should not be assumed that it can recover the required durability of the in-situ surface layers of concrete which can be subject to quite variable and adverse conditions.

For practical purposes, the importance of timely, continuous and uninterrupted curing can not be overemphasised, if the quality and long term performance of concrete and in particular the all important 30 - 100 mm surface layer is to be assured. Re-curing of concrete on-site will not fully recover either strength or impermeability and more significantly it will not be able to reverse any plastic, drying or thermal shrinkage cracking that may occur.

Investigation work undertaken by VicRoads (Ref 2) has shown that curing compounds and the use of polyethylene plastic alone are not suitable where cement is replaced by high amounts of SCMs (i.e. greater than 25% fly ash and 50% slag). This work also showed that the use of these high SCM mixes and the subsequent slower reactivity, the mix design water is badly needed to maintain the ongoing hydration process. The loss of mix design water, particularly when using curing compounds and to a lesser extent polyethylene plastic, has a profound adverse effect on the strength development and penetrability (VPV) of this type of concrete. It should be noted however, that all strength requirements, as stated in the VicRoads concrete specification, were met approximately 1 to 10 days later.

As a result of the above discussion it was concluded that the use of curing compounds or polyethylene plastic should not be allowed for curing concrete with high replacement levels of SCMs, particularly in aggressive environments (ie. marine etc.). Continued moist curing should be the only acceptable curing regime. Polyethylene plastic should only be allowed for use in marine and other aggressive environments, particularly substructure components, in conjunction with a wet hessian and subsequent continuous water curing. Such an arrangement would also protect the surfaces of concrete being cured (ie isolate) against the ingress of chlorides from salt water or sea spray (Ref Fig. 3.8) . Curing compounds should not be allowed for use on concrete surfaces located in marine or other aggressive environments.

Curing for special applications

Curing costs

The cost of the various curing methods is greatly affected by the size and location of the job to be cured, the surface to volume ratio, the position of the particular concrete surface within the overall structure, accessibility conditions and whether curing is applied on vertical or horizontal surfaces. Typical costs are presented in Table 10.1.

Table 10.1. Typical Curing Costs

Curing Method	Indicative Costs \$/m ² (1999)
Formwork In-Place	0
Curing Compounds	2 - 5
Polyethylene Sheeting (Plastic)	7
Wet Hessian covered with Plastic	10
Wet Hessian kept wet	15 - 20
Sprinkling water	10 - 20

It should be noted however, that these costs are indicative only and they are aimed at providing some relative measure of the cost of curing (Ref 6, 8).

Curing compounds may be widely used because they are economical, easy to apply, and are maintenance free (if they are applied correctly and not damaged by construction traffic) and other methods are perceived to be associated with practical difficulties. However, it must be emphasised that no curing compounds are as effective in promoting strength development, reduced penetrability (VPV) and readily satisfy specification requirements as the other more superior methods.

Curing is a fundamental parameter in the overall construction process and although it is the last and simplest step in the chain of activities, it should not be regarded as an inconvenience or a hurdle in finishing the work or moving onto the next project. On the contrary, it should be considered an essential requirement if the concrete is to achieve its full potential and be strong and durable. As such, operational personnel should always ensure that such a fundamental specification requirement is always satisfied.

Together with the constituent materials of the concrete mix, compaction and concrete cover (i.e. the 4 Cs of concrete), curing is recognised as a major technical/operational parameter which can significantly influence the long term performance of hardened concrete.

Inadequate curing can result in lower strengths, increased VPV (i.e. increased permeability), excessive cracking and other undesirable effects which will inevitably affect the longevity and serviceability of concrete structures.

Summary

Theoretical considerations of curing

A1 Chemical and Physical Structure of Cement Paste

The main factor controlling concrete penetrability by aggressive agents is the pore structure of the concrete, and in particular the interconnected capillary pores and other void systems within the hardened cement paste matrix.

Portland cements consist principally of four main compounds namely, tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetra calcium aluminoferrite (C_4AF). The compound composition of a cement and the manner in which each of its phases reacts with water (hydration) control both its physical and chemical properties. Essentially each compound hydrates at different rates and generates different amounts of heat.

The overall hydration reaction of the two silicates (ie. C_2S and the faster reacting C_3S) produces after one day a gel of calcium silicate hydrates (CSH), which contributes most of the binding power and strength in the cement paste matrix. It also produces crystalline calcium hydroxide ($Ca(OH)_2$) and a small amount of alkalis (sodium and potassium hydroxide), which are present in the pore liquid of the cement paste. After about 28 days, the hydrates form an extremely dense structure of calcium silicate hydrates. Calcium hydroxide is the compound most readily leached from Portland cement concrete when subjected to the effects of water. In simple terms the hardened cement paste matrix consists of a continuous gel of CSH which also contains crystals of $Ca(OH)_2$, other minor components and unhydrated remnants of cement particles which were originally too large to hydrate completely. The matrix also consists of a system of capillary pores commuting to the surface of the concrete, which represent the volume formerly occupied in the fresh paste by water-filled spaces which have not been filled by the products of hydration.

The volume of capillary pores depends on the water/cementitious material (W/C) ratio and the degree of hydration, and therefore the higher the W/C ratio the greater is the capillary porosity. The degree of hydration of the cementitious materials, and therefore the ability to produce capillary discontinuity for a particular, W/C ratio, depends greatly on the effectiveness and length of curing. Incomplete hydration, usually caused by lack of curing, further increases the volume of capillary pores. The capillary porosity in the paste is the reason why concrete is permeable to both liquids and gases.

Within the structure of the hydrated gel itself there are interconnected interstitial voids known as gel pores, which are considerably smaller than the capillary pores. These may also provide a route by which gases and liquids can permeate through concrete. However, because they are so small their contribution to total penetrability of cement paste is very low.

The penetrability of concrete is generally several times greater than that of cement paste owing to a third pore system which is provided by air voids and micro cracks, some of which are due to bleeding, humidity and temperature changes and inadequate compaction and curing. Cracks may also form at the paste-aggregate interface due to the restraining effect of the aggregate on cement paste shrinkage. Although some of the air voids may be distinct cavities isolated from one another, many others may be connected to one another by the gel pore system. Certain other voids, particularly cracks may be orientated so as to provide a continuous network through the concrete, whereby significantly increasing penetrability. The various pore systems present in concrete (ie, capillary pores, gel pores, air voids and micro cracks) if interconnected, represent the VPV or volume of permeable voids of concrete (Ref 2).

A2 Capillary Discontinuity

Powers et al (Ref 17) established that as curing progresses, capillary pores which are initially continuous begin to fill with the products of hydration and therefore become segmented (discontinuous), thus decreasing the penetrability (permeability) of concrete. They basically found that the greater the volume of capillary pores due to the higher W/C ratios (ie. 0.4 to 0.7) the longer hydration (and curing) was necessary to produce capillary discontinuity.

Essentially they estimated that for W/C ratios of 0.5, more than 14 days of continuous moist curing was required to achieve capillary discontinuity, whereas for W/C greater than 0.70 it was impossible to ever discontinue capillary pores, due to the large distances (gap) between hydrating cement particles.

Table A1 provides the estimated times required to produce sufficient hydration products which would discontinue capillary pores. It is quite obvious from this table that anything other than continuous moist curing would be less than ideal curing, particularly for W/C ratios of less than or equal to 0.50 which are associated with VicRoads structural concrete, let alone neglecting or abusing the provision of adequate curing as prescribed in specifications.

Table A1. Approximate time of continuous moist curing required to produce maturity of concrete at which capillary pores become discontinuous (Ref 17)

Water/Cement (W/C) Ratio	Time of continuous moist curing required
0.40	3 days
0.45	7 days
0.50	14 days
0.60	6 months
0.70	1 year
>0.70	Impossible

Desirable conditions of curing

B1 Moisture Conditions/Humidity

As indicated previously the availability of moist conditions is of paramount importance in producing concrete of low porosity, and therefore loss of water can have an adverse effect on the progress of the hydration reaction. A minimum of 80% RH (relative humidity) is required in the general environment outside the concrete (Ref 3) for the hydration reaction to be maintained. In addition, the rate of hydration decreases substantially as the RH within the concrete pores (ie. internal RH) drops below 95% and no further reduction in porosity is achieved once the relative humidity in the capillary pores falls below 80% (Ref 4). Under such conditions the cover zone will be the most affected, thus resulting in well documented deficiencies such as low strength, reduced durability, and excessive cracking etc.

Although theoretically the amount of mixing water is more than enough to accommodate the hydration process, excessive evaporative moisture losses, due to lack of adequate protection of the fresh concrete immediately after the screeding and finishing operations, can reduce the moisture levels within the concrete below the critical RH mentioned above. To this end the combined effects of wind velocity, relative humidity, air and concrete temperatures should be adequately controlled in accordance with specified requirements. As actual concrete structures may be exposed to temperature extremes (generally 0°C to 40°C), relative humidities of less than 80% and variable weather conditions (Ref 3), attention must be given to counter act these extreme conditions through controlled curing by all parties.

B2 Temperature

The concrete temperature controls the rate at which the hydration takes place (like any other chemical reaction) and therefore satisfactory temperature levels must be maintained for a sufficient period of time, together with favourable moisture conditions, in order to facilitate the strength development and the continuous generation of pore filling hydration products. As such the curing measures adopted must also take into account the prevailing conditions including air temperature, which can greatly affect the concrete temperature, particularly at the cover zone and therefore suitable precautions should be incorporated.

Curing temperatures in ambient conditions can generally range between 5°C and 40°C depending on the prevailing temperature conditions with an ideal curing temperature considered to be around 23°C, at which the overall positive aspects of concrete properties can be optimised. Of course in the case of accelerated steam curing conditions, temperatures can be as high as 75°C, with a more rapid hydration reaction taking place (Ref 2).

It should be noted that the rate of cement hydration is greatly retarded when the concrete temperature is below 10°C and virtually grinds to a halt when the concrete temperature drops below 5°C. As such, it is generally accepted that the minimum curing temperature should be 10°C. In recognition of this, VicRoads specifications prohibit the placement of concrete when the temperature of the fresh concrete as delivered to the site is less than 10°C or greater than 32°C, or when the corresponding air temperature is lower than 5°C or greater than 35°C (Ref 13).

B3 Time

The control of time allowed for curing of concrete is a fundamental parameter which links together both the moisture and temperature conditions of concrete. Generally all properties of concrete improve with time and therefore a number of time dependent relationships are developed when assessing the performance of concrete. Duration of curing is discussed further in Section 4.

C1 Strength Development

As indicated previously curing has a profound effect on the strength development of concrete. Essentially as the chemical reaction of the hydration process continues in the presence of adequate moisture and favourable temperature conditions, strength will continue to increase, albeit at a diminishing rate. This is clearly demonstrated by Fig. C1 which presents the effect of moist curing over time compared to modified moist curing regimes including the effects of continuously air cured samples. Air cured samples exhibit a dramatic 43% decrease in strength compared to continuously moist cured samples at 28 days (Ref 5).

The beneficial effect of thorough curing in the promotion of strength development of concrete is further demonstrated in Fig. C2 which is based on work undertaken by VicRoads (Ref 2). The results also confirm the general trends observed in previous research projects and as recorded in the literature, namely, that continued and uninterrupted moist curing is the most effective curing technique, in achieving the required concrete properties including the ultimate strength development and durability. However, such ideal curing conditions which provide for controlled conditions of temperature and relative humidity are difficult to achieve at the construction site.

In general terms concrete cylinder samples subjected to wetting and drying (i.e. resembling on site moist curing) suffered a reduction in strength development of between 6% and 10%, polyethylene plastic sheeting about 15%, with curing compound running a poor last with at least 22% reduction in strength development compared to fully moist cured concrete. These results compare to a 43% reduction for air cured samples as indicated in Fig. C1 (Ref 5). The general moisture loss from the cured samples is also indicative of the performance of the various curing methods (Refer Fig. C3). As expected the lowest loss of moisture occurred with the higher concrete grade (strength), as there is less water to be lost. However, as every bit of water is required to maintain the hydration reaction for a larger period, such loss of water has a more profound effect on strength development in the case of higher strength concrete.

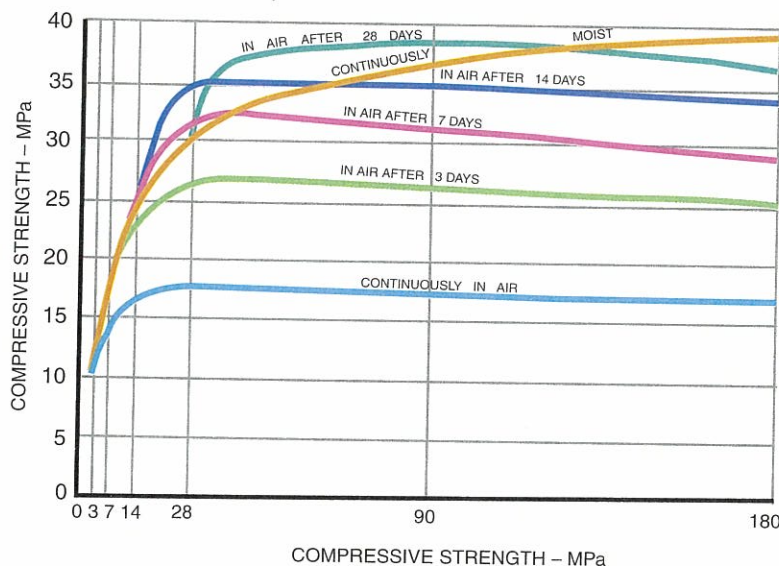


Fig. C1 Influence of Moist Curing (Ref 5)

Reasons for curing – effect on concrete properties

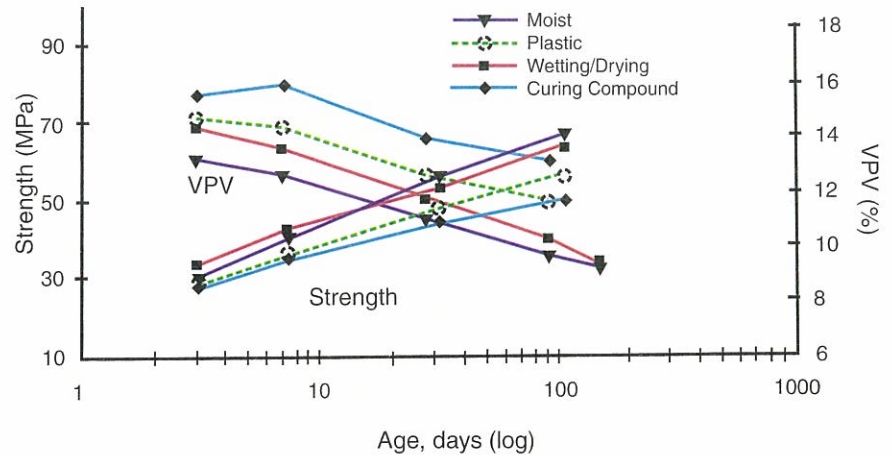


Fig. C2 VPV and Strength vs Curing Method (Ref 2)

Although concrete mixes with high water contents (i.e. high W/C ratio and lower strengths) exhibit substantial amounts of moisture losses (25 to 30%) the difference between the strength development of the various curing methods is not significant, as there is still sufficient moisture in the concrete to help continue the hydration process.

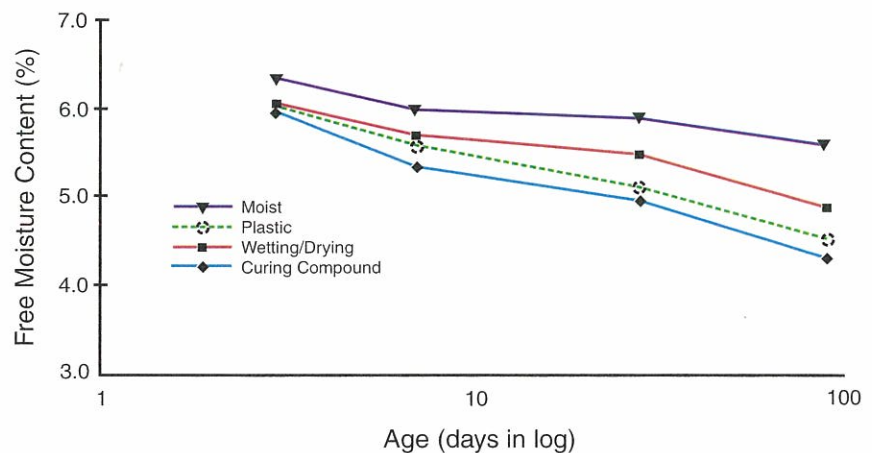


Fig. C3 Free Moisture Content vs Curing Method (Ref 2)

High early ambient or curing temperature can have very adverse effects on various properties of concrete, and in particular the ultimate strength development and penetrability of concrete. Although high early temperature can result in a higher rate of early strength development which can greatly assist in precasting operations, the long term strength of concrete is always lower compared to the ultimate strength of moist cured concrete at normal temperatures (Refer Fig. C4). This is due to the rapid initial hydration process which can result in less uniformly distributed cementitious products and therefore, a more coarser and more porous microstructure. As the hydration products precipitate at a faster rate there is less time for their uniform dispersement away from cement particles and into the interstitial space, resulting in agglomerations of unhydrated cement particles. This shielding effect prevents these cement particles from participating in subsequent hydration reactions which could further refine the pore microstructure. The effects of high early temperature application are demonstrated in Fig. C4 which compares steam curing with moist curing of concrete. As such possible reductions in the 28 strength should be allowed for when designing the concrete mix. Hot weather effects are discussed in Section 5.

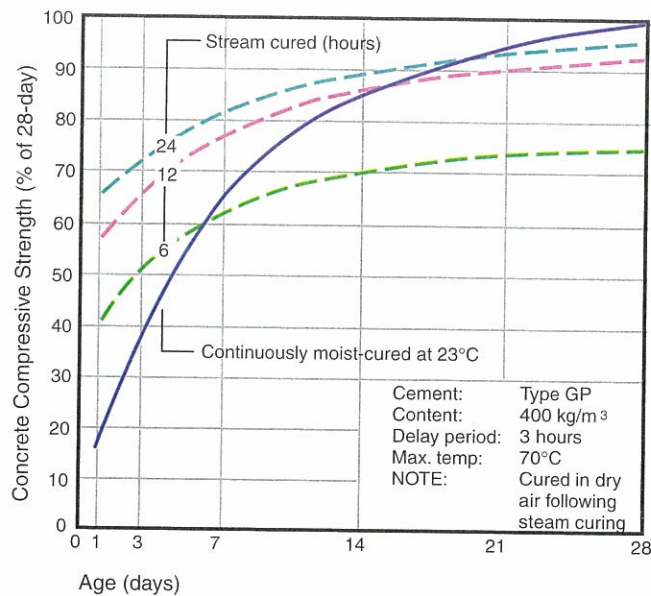


Fig. C4 Strength comparisons for Steam Cured and Moist Cured Concrete (Ref 3)

VicRoads research work (Ref 2) confirmed previous research which shows that the W/C Ratio has a very significant effect on the strength development of all types of concrete. A lowering of the W/C ratio results in sharp increases in compressive strength.

C2 Penetrability (Permeability/VPV) of Concrete

Deterioration types which adversely affect the long term durability of reinforced and prestressed concrete bridges and other structures is generally associated with the ingress of various liquid or gaseous aggressive agents. However, it is widely accepted that all deterioration mechanisms affecting concrete are either influenced or promoted by the availability and transport of water through the permeable voids (interconnected voids) of the pore structure of concrete. Water provides the medium by which many aggressive agents (i.e. chlorides, sulphates etc.) are transported into concrete. It also affects the initiation and rate of some deterioration processes such as carbonation. Deterioration processes such as corrosion of the steel reinforcement, chloride ingress, alkali/aggregate reactions, sulphate and chemical attack can be controlled by restricting the movement of moisture in the concrete, i.e. by controlling penetrability (permeability/VPV).

Current objectives are to achieve low penetrability by modifying/refining the pore structure of the concrete and therefore minimise the VPV. This is generally achieved by the use of good quality materials in proper proportions (i.e. SCMs, low W/C ratio), effective mixing, compaction and last but not least adequate curing. Continuous curing (preferably moist curing) can maximise the hydration process and therefore assist in the effective blocking of continuous capillaries, which significantly reduces the passage of moisture and other aggressive agents.

Research work undertaken by VicRoads (Ref 2) indicates that the type and length of curing have a much greater effect on VPV (i.e. penetrability) compared to the effects on strength development. As expected fully moist cured specimens exhibit the lowest % of VPV (i.e. lowest penetrability). On the other hand concrete cylinder samples subjected to wetting and drying (resembling on-site moist curing) suffered an increase in VPV of about 2 to 6%, polyethylene plastic sheeting about 21% (cf 15% reduction in strength development) and curing compound suffered an increase of the order of 37% (cf 22% reduction in strength development). Clearly curing compounds and to a lesser extent polyethylene plastic can have an adverse effect on VPV and therefore the penetrability capabilities of the concrete (Ref Figs. C2 and C5). The equivalent on site moist curing indicates similar negative effects for both VPV and strength development.

It should be emphasised that although proper curing is vital in achieving impermeability of concrete, good curing can not transform a low quality concrete into a good quality concrete. This is of course clearly demonstrated by Table A1 which indicates that for W/C ratios greater than 0.50, very unrealistic periods of continuous moist curing are required to achieve discontinuity of capillary pores. In fact for really poor concrete with W/C ratios greater than 0.70 watertightness will never be achieved no matter how long the curing period is.

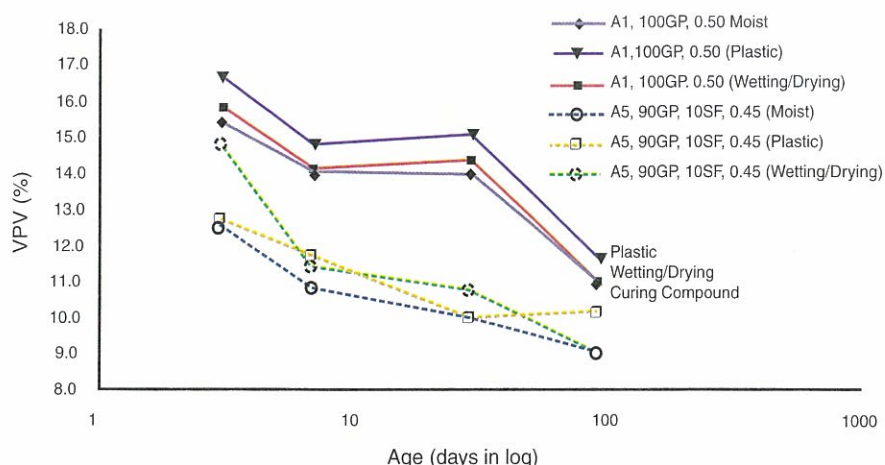


Fig. C5 VPV vs Age (Concrete Grade VR400/40, Silica Fume, Various Curing) (Ref 2)

C3 Shrinkage

All concrete is susceptible to varying degrees of shrinkage when exposed to the atmosphere. A number of measures however, can be undertaken to minimise the amount of both plastic and drying shrinkage of concrete.

In the first instance a well designed concrete mix is a prerequisite to minimising drying shrinkage. Factors which influence the amount of shrinkage include the quantity of water, the size, type and amount of both fine and coarse aggregate, chemical admixtures and so on.

Other factors of course include the provision of control joints and temperature reinforcement, and very importantly, timely and effective curing.

Plastic shrinkage is caused by the rapid evaporation of moisture from the concrete surface during placement and finishing, due to one or a combination of low humidity, high winds and hot weather. The amount of shrinkage which occurs during the drying of hardened concrete (i.e. drying shrinkage) is also related to the amount of water lost from the concrete in drying. The visible effects of shrinkage is the formation of cracks which occur due to the inducement of tensile stresses when the concrete tries to shrink but is restrained.

The amount of shrinkage can therefore be greatly affected by the drying environment surrounding the concrete. As such concrete immersed for the whole of its life in water does not shrink, whereas concrete exposed to a low humidity atmosphere suffers considerable amount of shrinkage.

It is quite clear therefore that both shrinkage and associated cracking can be reduced significantly by minimising the evaporative moisture losses from the freshly placed unprotected concrete (i.e. use of aliphatic alcohol, controlled fog spray etc), and by implementing effective curing immediately after finishing and for an appropriate period of time.

The longer the concrete is delayed from drying out, the less likely it is for shrinkage cracking to take place.

C4 Abrasion Resistance

It is well accepted that the compressive strength of concrete (which is influenced by curing) can provide a good measure of abrasion resistance, in addition to mix composition, aggregate size, type and hardness. Both adequate surface finish (i.e. steel trowel, power floating etc) and efficient curing significantly increase the hardness and long term durability of the outer skin of concrete and improves abrasion resistance.

C5 Creep

Many of the factors influencing drying shrinkage have a similar if not greater effect on creep. These factors include the curing history of the concrete, the moisture and temperature exposure conditions, aggregate properties and the magnitude, time and loading period of the applied stresses. The curing can have a direct effect on characteristics such as porosity, micro cracking and strength all of which can significantly influence creep, and therefore inappropriate or variable curing and humidity conditions can result in an increase in creep of concrete. Components which can be adversely affected by increases in creep include prestress concrete beams, where even a slight shortening of the concrete beam could result in loss of tension in the prestressing tendons. On the other hand concretes cured at elevated temperatures, develop higher early strengths and lower creep, although this is associated with much higher risk of cracking and has to be managed appropriately, particularly in design.

Longer periods of effective curing (such as moist curing) can further reduce creep of concrete. It should be noted however, that in many situations a higher creep is beneficial because it reduces tensile stress induced by restrained drying shrinkage and thermal effects and therefore helps to reduce cracking. As such designers need to take a balanced approach depending on the concrete components under consideration (i.e. concrete decks, prestressed concrete beams etc).

C6 Efflorescence

Efflorescence usually occurs on concrete surfaces subjected to wetting and drying conditions or to permeation of water through permeable or cracked concrete. This is basically the result of the leaching of the calcium hydroxide (Ca(OH)_2) which carbonates on the surface. Although this is mainly an aesthetic problem, extensive leaching would result in an increase in porosity and consequent reduction in strength and durability. The application of adequate and timely curing would enhance the hydration process and therefore reduce efflorescence due to the greater reduction in permeability (VPV) and conversion of a greater proportion of Ca(OH)_2 into cementitious products. Minimisation of evaporative moisture losses from freshly screeded and unprotected concrete surfaces can also help to suppress possible efflorescence by preventing adverse effects due to inadequate provision of early protective and curing measures and other concreting operations.

C7 Other Effects

A number of undesirable problems can occur in hardened concrete. These of course can be the result of a number of inadequate on-site construction practices, one of which is associated with rapid drying of the concrete surface due to lack of prevention of early moisture losses and lack of timely and effective curing. Such problems include blistering, crazing, curling and uneven colour of the concrete.

C8 Durability

Durability of concrete is very much dependent on its properties, some of which have already been discussed in this section and in particular on a dense and impermeable (low VPV) concrete. In particular penetrability (permeability) is considered to exercise the greatest single influence on the long term performance of concrete. To this end it is essential to have an effective control of the vital interaction between the various technical requirements and the practical/on-site processes which have the potential to compromise the overall intent of a durability strategy.

Deterioration types such as corrosion of the steel reinforcement, chloride ingress, carbonation, alkali/aggregate reactions, sulphate and chemical attack, freeze-thaw, abrasion and so on, which adversely affect concrete durability, can all be controlled by effectively controlling the penetrability of concrete. That is, by producing a very dense and well refined concrete microstructure capable of resisting the movement of moisture in the concrete. To this end, it is vital to provide proper attention to the 4 C's of durability, namely, Constituents and proportions of the concrete mix, Cover, Compaction and effective Curing with due allowance made for service conditions.

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