Selection of good quality materials and correct mix design, combined with adequate mixing and placing technique, ensures concrete that is of potentially high quality. The strength and other properties of hardened concrete are realised as a result of water combining with the cement (hydration), and “curing” is the name given to treatments adopted for this purpose.

In plastic concrete, space between the fine aggregate particles is filled with a dispersion of cement particles in water. Some of the cement dissolves, and subsequently elongated crystals of hydrated cement form out of the solution, linking the cement grains to each other and to the aggregate as illustrated in Figure 1.

![Figure 1. Structure of hardened concrete](image)

The amount of water in concrete at the time of mixing is sufficient to complete the chemical reaction of hydration, but excess is required in order to keep the process active. While enough moisture is present, hydration continues at a diminishing rate as an increasing proportion of the cement is hydrated. Even with a continuous supply of moisture, hydration remains incomplete through the typical service life of a concrete product.

Hydration progresses more rapidly at elevated temperature, and techniques which raise the temperature for this purpose may be referred to as “thermal curing”. Hydration generates heat and a stage is reached in the thermal curing cycle when the temperature in the concrete exceeds that at the surface. In thin-walled products heat is lost readily from exposed surfaces or through the mould, but with bulky items such as bridge beams heat of hydration may raise the temperature well above that of the surroundings. Too large an internal rise in temperature can result in cracking, or an altered chemical state of the hydrated cement paste which allows deterioration in the long term.

Curing of products (as opposed to samples made just for testing) may be envisaged as a series of steps which result in the concrete having the required properties at each stage:

1. Where initial curing takes place in the mould, the initial treatment must provide enough strength to enable the product to be removed from the mould and transferred to yard
storage. Drycast products must also be strong enough for transport and storage on the factory site.

2. The next stage is a period at the factory site in which the product achieves threshold levels of any properties required prior to despatch. Typically, curing techniques applied in the factory do not provide any extra water and by and large enough strength has to be achieved for in-service loading with no more than the amount initially present.

3. Virtually all outdoor or underground environments provide enough moisture for curing to continue, with the result that strength and other properties such as durability and dimensional stability (resistance to creep and shrinkage) will continue to improve throughout the service life.

Concrete test cylinders are given curing treatments which are different to those applied to products. AS 1012.8.1 defines a standard curing regime, in which the cylinders are held in a moist environment at 23°C or 27°C depending on the climatic zone. Cylinders given a period at elevated temperature to simulate thermal curing of the product, then immersed in water at the temperature specified for standard curing will have lower strength at 28 days than concrete which has been standard cured for the same period of time, as illustrated in Figure 2.

![Figure 2. Typical effect of curing temperature](image)

**METHODS OF THERMAL CURING**

The most common method adopted by Humes involves injecting steam into an enclosure containing the product, which immediately condenses to a mist and at the same time raises the temperature inside the enclosure. The mist atmosphere helps to maintain a uniform temperature throughout the enclosed space, and is very efficient in transferring heat into the concrete. The method is known as low-pressure steam curing. With an alternative method, sometimes applicable to large products, hot water is channelled through ducts in the mould. This method is very fuel-efficient but presents greater difficulty than steam curing in controlling the temperature of the concrete. A further alternative is flue gas curing, also more fuel-efficient than steam curing, which uses the products of combustion from oil or gas.
directly and is supplemented by spraying water into the flue gas to saturate the atmosphere with moisture.

**THERMAL CURING CYCLES**

Figure 3 shows the stages of a thermal curing cycle. There is initially a period during which no heat is applied, and following this the temperature is increased until the required maximum has been reached. After the maximum has been held for the required period of time, the temperature is allowed to fall until it is low enough for the mould to be stripped from the product without damage to the concrete.

Curing is taking place throughout the entire period shown.

![Diagram of thermal curing cycle](image)

*Figure 3. Elements of a typical thermal curing cycle*

**EFFECTS OF TIME INTERVALS AND TEMPERATURES**

**Delay Period**

Given a fixed overall duration for the curing cycle, the length of the delay period influences the strength at the end of this time and it is a matter of experience that if the delay is too short, lower strength will be obtained. By way of explanation it can be understood if hydration is too rapid at an early stage, hydrated cement deposited around the unhydrated cement particles slows access of water to them and so inhibits the hydration process. On the other hand if the delay is too long, strength will be offset by a shorter time at elevated temperature. The optimum pre-steaming delay depends on the mix temperature and the time available overall for the curing cycle, ranging from four hours or more for concrete at 10°C and overnight curing, to less than an hour for concrete at 30°C and a requirement for re-use of the mould within a few hours.
In our factories, the overall length of the thermal curing cycle ranges between 2 hours (small products) and about 15 hours (prestressed concrete bridge beams, sleepers, piles etc). The shorter cycles enable reuse of moulds 2 or 3 times per day whilst the longer cycles are necessary to achieve release strength, typically giving somewhat more than half of the strength obtained from 28 days of standard curing.

The effect of an inappropriate delay period is lower strength than would otherwise be achieved in the time available between casting & stripping or (for prestress), release. There is no evidence that a shorter or longer delay period influences the durability of the concrete; an investigation carried out to address this issue found no effect.

**Rate of Temperature Rise**

Rapid rises in temperature soon after manufacture can cause some damage, since the fresh concrete has little strength to resist stresses due to temperature gradients in the concrete, or restraint stresses which can occur because of the different expansion rates of the steel mould and concrete.

A comprehensive investigation carried out by CSIRO to determine optimum curing cycles allowing precast products to be manufactured at the rate of one cast per day per mould found that, following the delay period, the greatest strength was obtained for a rate of temperature rise of 24°C per hour. Only uniform rates of rise were investigated and there is therefore no indication from the results that an irregular rate of rise, but still averaging a value close to the optimum, would result in significantly lower strength.

The rate of temperature rise giving the best strength in the time available for the overall curing cycle depends on this time, being greater for shorter than for longer curing cycles. Raising the temperature in steps even as great as 20°C can be just as effective as a constant rate of temperature rise, provided the average is appropriate for the overall cycle duration.

The CSIRO investigation considered effects on strength only, and not separately on durability. There is no evidence that greater or lesser rates of temperature rise affect the durability of the concrete.

Small deviations from a prescribed rate of temperature rise can easily lead to a dispute over compliance. To keep the issue in perspective and assist in having such instances classified as minor, relevant documented information is summarised in Appendix 1.

**Maximum Temperature**

Following the delay period and temperature rise, strength increases most rapidly at the highest temperature which will not damage the concrete. The steam temperature must be high enough to give the required strength in the available time, throughout the product. Heat of hydration of the cement will at some stage cause the temperature of the concrete to exceed that of the steam atmosphere, and so the steam atmosphere must also be limited to a level which will not result in internal temperatures damaging to the concrete. For ordinary thin-walled products requiring only stripping strength at the end of the steam cycle, the interval between these two requirements is quite large, allowing maximum steam temperatures to be adopted anywhere in the range of 50°C to 80°C. However in prestressed items such as bridge beams, having widely varying cross-sections in the same item and high release strength the interval is narrow. While there is ample evidence that such products can be manufactured at
the rate of one mould use per day, conditions may be imposed which unintentionally make this impossible. More detail of the conflicting requirements is set out in Appendix 2.

For large structural items the temperature in the steam enclosure should be limited to 70°C nominal, with tolerance +5°C.

Cool-down

If the concrete surface is exposed to the surroundings while the temperature remains close to the maximum, there will be rapid drying, which will inhibit subsequent strength gain before the product is delivered, and also a thermal shock to the concrete which by itself or in combination with the drying may cause the concrete to crack. The concrete must be allowed to cool in the mould or steam enclosure for long enough to avoid visible damage when covers are removed or the product is stripped.

Optimum Curing Cycles

From the 1970s, thermal curing cycles for prestressed concrete components were controlled by the provisions of Appendix A of AS 1481. "SAA Prestressed Concrete Code". This Australian Standard was superseded in 1988 by AS 3600 "Concrete Structures", which does not specify any curing cycle and requires only that the treatment achieves a level of strength set according to the specified strength grade and the exposure class. Many specifiers regard the AS 3600 provisions as inadequate and the omission has in practice led to prescriptions for particular types of product. AS 1481, Appendix A, remains nevertheless the best guide for achieving the highest strength at the end of a curing cycle, for products cast at the rate of one mould use per day. These are illustrated in Figure 4 and the most significant elements are:

(a) Concrete shall have an initial maturity, defined as the product of concrete temperature (when placed) and time from completion of mixing, of not less than 40°C.h before commencement of thermal curing. The table shows how delay time increases for lower concrete temperatures; see also Figure 4.

<table>
<thead>
<tr>
<th>Concrete temperature when placed, °C (see note)</th>
<th>Time from completion of mixing, hours</th>
<th>Initial maturity, °C.h</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1 1/3</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>40</td>
</tr>
</tbody>
</table>

Note: Some factories in cool climates have used heated aggregates or water to raise the concrete temperature to approximately 30°C during placement, thereby achieving maturity of 40°C.h in 1 1/3 hours. AS 1481 also permitted a trickle of steam to be applied during the delay period in order to maintain concrete at the temperature at which it was placed.

(b) Rate of temperature rise is not to exceed 24°C per hour up to initial maturity of 70°C.h. Higher rates up to 32°C per hour may be considered for greater initial maturities.
(c) Maximum temperature in the enclosure is not to exceed 80°C for normal weight concrete or 75°C for lightweight concrete.

![Figure 4. AS 1481 Thermal Curing Cycle](image)

(d) Steam covers are not removed until the temperature at the surface of the concrete mass has fallen to within 40°C of the ambient temperature.

The period of time at maximum temperature will depend on the required release strength and 28 day characteristic compressive strength. A typical overnight cycle, where ambient temperature is 20°C, to meet requirements of 35 MPa release strength and f'c of 50 MPa would be as follows:

- **Delay period**: 2 hours (to give maturity 40°C.h)
- **Temperature rise**: 3 hours (to say 70°C)
- **Time at top temperature**: 9 - 10 hours
- **Cooldown**: 1 hour
- **Total**: 15 - 16 hours

Reinforced concrete pipes and precast components need to reach a compressive strength of 15 to 20 MPa (depending on size and shape of the pipe or component) before the mould is stripped from the product. If the mould is to be used only once per day, the pipe or component can be given a curing cycle involving a relatively low maximum temperature, and
including a period where it cools slowly in the enclosure. Where circumstances dictate use of moulds more than once during a particular shift, shorter thermal curing cycles are required. Figure 5 illustrates a shortened cycle for precast, suitable for two casts per day from each mould.

Figure 5. Thermal cycles for one or two casts per day

*Tolerance on a Specified Temperature Profile*

Where a maximum temperature is specified either for the enclosure or for a location in the concrete, heating by steam or other means must be controlled so that this temperature is not exceeded during the nominated period of thermal curing. Apart from this, the effect of variations within the normal scope of controls used is simply that less strength is achieved at the end of the cycle.

These tolerances will result in negligible variations in strength at the end of a thermal curing cycle:

- **Initial maturity:** Negative tolerance of 10°C.h.
- **Rate of temperature rise:** \(\pm 10^\circ C\) variation from the nominal value at any time, provided the temperature is within 5°C of the nominal value at the end of the specified period.

*Compliance with Specifications*

While the information set out in preceding paragraphs enables us to design curing treatments which will result in products having strength and durability appropriate for their conditions of service, additional or alternative requirements may be set out in the relevant Australian Standard for the product, or customer specifications. The impact of such requirements on production must be understood at the time of tendering as they can have a significant effect on the rate of production and the equipment required, in particular the number of moulds, and consequently on the cost of manufacturing the product.
POST-THERMAL CURING

Investigations carried out by CSIRO \(^4\) have shown that the best quality achievable by a thermal curing cycle is equivalent to about three days of standard curing. There was no measurable improvement in durability from subsequent application of moisture to the surface, for up to 27 days.

However over longer periods of time in normal atmospheric conditions the surface quality of concrete continues to improve, especially for high strength grades. An investigation found better surface quality after a year of outdoor exposure than from seven days of standard curing \(^5\), even if the initial curing was minimal.

It may be necessary nonetheless to protect pipes or products in the yard from severe drying conditions (eg hot, dry winds), so that enough strength has been reached before the item is despatched. Where products have been given a steam cycle sufficient only to achieve stripping strength, and the client requires that curing must continue for a further period by ensuring that moisture is retained in the concrete, it is most common to coat the product with one of a type of paint-like materials known as curing compounds.

Special requirements apply to pipes subject to hydrotest (which include pressure and sewer pipes) as these must have sufficient strength and impermeability to pass the test before despatch. Such pipes may be water cured out of doors using garden-type sprinklers, but these must be carefully placed so as to provide uniform coverage and protection from the drying effects of wind and sun. Alternatively the pipes may be cured in an enclosed chamber using either water sprays or fog. Water should be recirculated and adequate drainage provided.
APPENDIX 1
Rate of Heating

Investigation of steam curing to supplement knowledge in the public domain has formed a major part of Humes R&D effort from the late 1950s. The research has centred on concrete of low water/cement ratio, typically below 0.4, and it is not implied that the results are applicable to strength grades below 50 MPa.

From the earliest of these investigations (1960) through 1967, delay time and maximum temperature were recorded, but not rate of temperature rise, evidently because up to that time this was not recognised as a measure of any importance. Rate of temperature rise was introduced as one of the variables in an investigation of pipe curing in 1969, which led to recommendations for temperature increase in the range 30°C/h to 60°C/h. It is a matter of public record that the pipe industry has used rates of this order for decades.

A more recent investigation set out to find which constituents of a mix would give the best rate of gain of early strength. For each mix tested, after a brief stand-down the temperature was raised to 75°C at the rate of 45°C/h. Following completion of the steam cycle the samples were given standard curing and the strength measured after 28 days. In parallel tests only standard curing was applied. Ratios of strengths obtained from the two treatments are set out in the table:

<table>
<thead>
<tr>
<th>Cement type</th>
<th>Strength ratio at 28 days steamed v. unsteamed</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP</td>
<td>0.96</td>
</tr>
<tr>
<td>Blended</td>
<td></td>
</tr>
<tr>
<td>Fly ash 20%</td>
<td>0.87</td>
</tr>
<tr>
<td>Slag 20%</td>
<td>0.78</td>
</tr>
<tr>
<td>Silica fume 7%</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Except for the slag blend, these ratios are within the range expected and typically allowed for with any controlled steam curing treatment, including much lower rates of temperature rise. Increasing the temperature at the rate of 45°C/h has not caused any damage to the concrete.

Within the range of mix variables available for commercially-produced steam-cured concrete, the greatest influence on early strength was just the water/cement ratio. A similar effect for concrete which is not steam cured is shown in Figure 2 above. The textbook data from which the two curves for standard curing shown in Figure 2 are derived shows an accelerated rate of relative strength gain for w/c 0.4 v. 0.6 (corresponding approximately to mean strengths of 60 MPa & 40 MPa), but little change for w/c above 0.6. This is a further illustration, in addition to the self-curing effect described on p 8, of a difference in kind between high and low strength grades of concrete.
Even in thin-walled products the internal temperature in the concrete can be as much as 10°C higher than the surrounding steam atmosphere. Given a condition of no heat loss, the heat of hydration of the cement is able to raise the temperature in concrete by as much as 50°C, and so limiting the internal temperature to an acceptable level involves managing heat transfer from as well as into the product. At the same time, for prestress in particular, it is critical that all parts of the product reach a high enough temperature to give release strength in the available time, which will typically require an average of about 70°C throughout the soak period.

Thermal curing results in a somewhat different structure of the cured concrete from that obtained by curing at ambient temperatures, but investigations have shown that, within usual limits of temperatures applied to the surface (c. 80°C), this has negligible effect on the ability of the concrete to protect reinforcement. Higher temperatures may result in a larger effect, but in the context of the temperature rise due to heat of hydration this is not relevant as the layer of concrete which protects the reinforcement extends to only a small depth from the surface. Given a thermal curing cycle which gives the required strength, and does not result in visible disruption, there may be a remaining issue of concern known as “delayed ettringite formation” (DEF), an expansive effect in the cement which if severe will damage the concrete in the long term.

There are three necessary conditions for DEF⁸:
- Late release of sulfate from the cement. This is exacerbated by a high curing temperature but harmful effects, if any, also depend on the chemistry of the cement.
- Pre-existing microcracks.
- Exposure to water as liquid; ie not just permeating moisture.

Pre-existing microcracks imply that materials used or the curing cycle are inappropriate for the manufacture of prestressed concrete products, independently of any concern about DEF. In particular, cracking due to alkali silica reaction is eliminated by the use of non-reactive aggregate or blended cement. When installed, prestressed bridge beams are positioned under carriageways, screening them from rainwater. The concrete is to all intents and purposes impermeable, and even if there is some exposure to water at the surface it will not penetrate to depths from which the heat of hydration has been least able to escape.

Criteria for low pressure steam curing documented in 1971² and adopted as standard practice via AS 1481 allowed a maximum steam temperature of 80°C and no further control on the temperature of the concrete. There’s no doubt that similar parameters would have applied for a considerable period even before this, most likely from the 1950s; there is nonetheless no recorded instance of DEF in concrete bridge structures in Australia.

DEF is not observed in bridge girders because specifications for the concrete, normal criteria for thermal curing and the service environment do not fulfil the conditions for this to occur. Any limitation on maximum temperature which prevents production at the rate of one mould use per day substantially increases the cost of the product with no benefit to the asset owner or users of the structure.
REFERENCES


4/9/14