# Optimum Curing Cycles for Precast Concrete

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## ABSTRACT

With many types of precast concrete, the product is heated to accelerate the strength gain of the concrete, enabling one or more daily uses of the mould. This early curing treatment also serves as a first stage in achieving the strength and durability required for the product in service.
A comprehensive investigation completed by CSIRO in 1971 determined values for maturity before heating and subsequent rate of temperature rise to give the highest strength achievable in a time which would allow one use of the mould per day. Neither multiple daily mould use nor durability were considered in the investigation, but for one cast per day the recommended values for maturity and rate of temperature rise continue to be applied.
With concrete pipe manufacture in particular, moulds will typically be used two or more times through a daily cycle, and strength gained after relatively brief thermal cycles is critical to efficient production. Thermal curing cycles giving optimum strength gain for multiple mould use require briefer delay times and greater rates of temperature rise, but do not prevent the product from subsequently achieving the strength and durability required for its service life.

## INTRODUCTION

When addressing an "optimum" curing cycle we refer to that cycle which affords the lowest total cost of manufacture for a product that performs in accordance with its intended use. For precast concrete, whether pipes or other types of product, the cost of moulds, curing chambers or other types of enclosure, means for generating heat and transferring it into the product, handling equipment and other infrastructure all contribute to the overall cost. As a general rule contributions from these sources, per product made, are reduced if the product can be taken from the mould in a shorter rather than longer period of time.

With some types of product it is possible to remove the mould as soon as the concrete has been compacted, but more commonly it must first reach a minimum "stripping" strength. Economical mould usage is achieved by application of a thermal cycle consisting of four stages:

1. A delay period during which the concrete temperature remains constant or increases only slightly.
2. A period of temperature rise, accelerating the rate of hydration.
3. A stage at constant, elevated temperature, when most of the required strength gain is achieved.
4. Cool-down, to protect the product from thermal shock (where relevant) after stripping.

The requirement for rapid mould turn-around will in many situations result in the use of a concrete mix which is considerably more expensive than the lowest performing mix to comply with a specified strength grade. As an illustration – concrete in prestressed girders may have a specified strength grade of 50 MPa, but must also reach 40 MPa before release of the prestressing tendons. The most economical 50 MPa mix would perhaps reach 40 MPa at 7 days, and while the resulting product would meet specification production on this basis would be hopelessly uneconomic. In fact mixes are designed so that release strength is reached the following day, even though this results in a significant increase in mix cost and 28 day strength typically reaching 80 MPa.

Because of the critical need for concrete in prestressed products to reach "release" strength in time for daily mould use, CSIRO in association with the (then) Australian Prestressed Concrete Group carried out a wideranging investigation 1, concluded in 1971, of effects of different parameters defining the curing cycle on strength achieved in time for the daily production cycle. This investigation found that the highest strength would be achieved with a delay period to give maturity, pragmatically defined as temperature × time from mixing, between 40°C.h and 120°C.h, followed by temperature rise at the rate of 24°C/h. For normal-weight concrete the maximum temperature was limited to 80°C and, if there was visible evidence that the product would be damaged by thermal shock, it was to be protected until the surface temperature of the concrete had fallen to within 40°C of the ambient temperature.

This specification was developed for the prestressing industry to achieve the highest strength consistent with once daily use of the mould. Neither multiple mould utilisation nor durability were considered in the investigation 3.

With regard to the delay period there is a common misconception that this coincides with the time taken for the concrete to reach initial set, on the basis that after initial set the concrete will be better able to resist disruptive forces due to changing and uneven temperatures. One can question immediately whether it is plausible that hardened concrete having tensile strength of some small fraction of a megapascal would be better able to resist thermal stress than in the pre-set condition where it can flow rather that fracture. As explained in the report on the CSIRO work 1, the curing cycle incorporates the measurement of initial delay before steaming in terms of maturity of the concrete because "this seemed to be a better basis than a limitation on the delay time in hours (which neglects temperature effects) or a limitation in terms of the early stiffening of the concrete (which is difficult to assess accurately), or the initial setting time (which may be even less meaningful)." 1 The report does not attempt to explain why the delay results in greater strength after an overall elapsed period of time. However as pointed out by Neville 2, this phase enables the early products of hydration to diffuse away from the associated cement particles. If the initial rate of hydration is too rapid, the hydrated crystals cluster round the unhydrated cement and offset to some extent the accelerating strength gain when the temperature is subsequently increased.

For concrete pipe manufacture in particular, moulds will typically be used two or more times through a daily cycle, and strength gained after relatively brief thermal cycles is critical to efficient production. It is not surprising therefore those manufacturers have embarked on systematic investigations similar to that undertaken by CSIRO in relation to prestressing, to find both optimum thermal cycles, and composition of the concrete mix, to achieve stripping strength in the shortest period of time. One such investigation is reported here.

## SCOPE OF WORK

The investigation used concrete cylinders made with concrete to represent that used in pipe manufacture. In each case the cycle consisted of a delay period followed by a period of rising temperature, during which cylinders were removed at half hourly intervals and tested for compressive strength. The remaining cylinders were subsequently immersed in water at 23°C, and tested for compressive strength at 7 days and 28 days. Other samples from each mix were standard cured (no steam), and also tested at 7 and 28 days.

## CONCRETE MIXES

The mixes included Type GP and Type HE cements, blended cements consisting of Type GP portland cement with fly ash, slag, silica fume or high alumina cement, high range water reducing admixtures and set-accelerating admixtures. With one exception the nominal cement content was 350 kg/m3. For blended cement with fly ash or slag the SCM component was 20% and for silica fume (SF) or high alumina cement 7%. Admixtures were used at typical dose rates for the type of product.

Water content in the mixes was set to correspond to that in concrete pipe at the end of the moulding cycle, controlled via workability of the trial mixes. For this purpose a measure of workability was adopted in which a sample of concrete having known compacted volume is contained in a steel cylinder, partly compacted using a drop table, and a measure obtained of the remaining void space in the sample 4. This test has been found to be highly sensitive to the free water content of mixes of this extremely dry consistency. Water/cement ratios for the various mixes at the constant level of workability were in the range 0.32 to 0.37.

Mixes were batched temperatures between 14 and 21°C.

## CURING

For steam-cured samples the delay from mixing to application of steam was 0.5 to 1.25 hours, followed by temperature rise at the rate of 45°C/h to a maximum of 75°C. Samples for testing at 7 days and 28 days were removed when the strength had reached 20 MPa, transferred to an air box at 23°C until 22 hours had elapsed from the time of mixing, then immersed in water at 23°C. This treatment is denoted by the abbreviation “s”. Standard curing (no steam) is denoted by the abbreviation “w”.

## RESULTS

Details are shown in Table 1. No treatment other than calcium chloride gave stripping strength in a time shorter than the least value obtained just with high range water reducer. Allowing for the inevitable scatter of results, the reduction in cycle time obtained by lowering the water/cement ratio, whether from admixture or extra cement, is about half an hour – too small to have much effect on the cost of production.

*TABLE 1. MIX CHARACTERISTICS AND PERFORMANCE*

| Description [1] | Delay [2] h | Length of Cycle [3] h | Temp.at Mixing °C | Initial Maturity [4] °C.h | Water/ Cement ratio | Later Age Strength MPa | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 7s [5] | 7w [5] | 28s | 28w |
| Type GP cement, no admixture or SCM | 1.00 | 4.00 | 15 | 15.0 | 0.37 | - | 56.8 | 63.0 | 67.0 |
| Increased cement content [6] | 0.75 | 3.45 | 16 | 12.0 | 0.32 | - | 60.0 | 65.7 | 69.8 |
| High range water reducer (a) [7] | 0.75 | 3.65 | 14 | 10.5 | 0.32 | 58.5 | 60.7 | 66.5 | 65.3 |
| High range water reducer (b) | 0.50 | 3.20 | 17 | 8.5 | 0.32 | 53.0 | 55.7 | 62.0 | 65.3 |
| Type HE cement | 0.92 | 3.72 | 16 | 14.7 | 0.37 | - | 59.5 | 66.0 | 65.8 |
| HE + high range water reducer | 0.83 | 3.23 | 21 | 17.4 | 0.34 | 52.8 | 57.3 | 64.5 | 66.3 |
| Blended - fly ash | 0.58 | 3.88 | - | - | 0.36 | - | 53.0 | 60.3 | 69.7 |
| Blended - slag | 1.00 | 4.15 | 15 | 15.0 | 0.36 | 41.5 | 49.5 | 51.0 | 65.7 |
| Blended – SF + high range water reducer | 0.75 | 3.25 | 21 | 15.8 | 0.35 | 54.0 | 57.8 | 65.0 | 72.0 |
| Blended – high alumina cement | 0.50 | 3.65 | 16 | 8.0 | 0.36 | 54.0 | 55.3 | 61.5 | 57.0 |
| Non-chloride accelerator | 0.75 | 3.60 | 17 | 12.8 | 0.37 | 50.8 | 53.0 | 60.3 | 61.5 |
| Calcium chloride [8] | 0.67 | 3.17 | 16 | 10.7 | 0.34 | 55.8 | 53.7 | 64.2 | 63.8 |

**Notes:**

1. Portland cement component is Type GP except for the two mixes designated Type HE.
2. Time in hours from mixing to application of steam.
3. Time in hours from mixing until cylinder strength reaches 15 MPa, taken to be the strength required for stripping the mould from the pipe.
4. Product of delay in hours and concrete temperature in °C.
5. s = steam followed by water curing, w = water curing only, as defined in the text.
6. Type GP at 400 kg/m$^3$
7. (a) and (b) designate alternative types of high range water reducing admixtures.
8. Result for comparison only. AS/NZS 4058:2007 “Precast concrete pipes (pressure and non-pressure)” does not allow chloride at the level in concrete which would result from use of calcium chloride as an accelerator.


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*TABLE 2. STRENGTH RATIOS*

| Description | | 28s/28w | 7w/28w | 7s/28s |
|---|---|---|---|---|
| Type GP cement, no admixture or SCM | | 0.94 | 0.85 | - |
| Increased cement content | | 0.94 | 0.86 | - |
| High range water reducer (a) | | 1.02 | 0.93 | 0.88 |
| High range water reducer (b) | | 0.95 | 0.85 | 0.85 |
| Type HE cement | | 1.00 | 0.90 | |
| HE + high range water reducer | | 0.97 | 0.86 | 0.82 |
| Blended - fly ash | | 0.87 | 0.76 | - |
| Blended - slag | | 0.78 | 0.75 | 0.81 |
| Blended – SF + high range water reducer | | 0.90 | 0.80 | 0.83 |
| Blended – high alumina cement | | 1.08 | 0.97 | 0.88 |
| Non-chloride accelerator | | 0.98 | 0.86 | 0.84 |
| Calcium chloride | | 1.01 | 0.84 | 0.87 |
| **Averages** | Type GP cement, no SCM | 0.96 | 0.87 | 0.87 |
| | Type HE cement | 0.99 | 0.88 | 0.82 |
| | Accelerator | 1.00 | 0.85 | 0.86 |

From Table 2, the four comparable mixes made with GP cement achieved strengths at 28 days, following steam curing, ranging from 0.95 to 1.02% (average 0.96%) of the standard cured strength at 28 days, reflecting the accepted generality that steam curing results in a small reduction in strength in the long term. The very short delay and rapid rate of temperature rise compared with the optimum cycle for one mould use per day has had no effect on the strength achieved at 28 days. Of the two mixes for which results are available, the average ratios of 7 to 28 day strengths are the same for the steam cured samples as for those given only standard curing; i.e. the strength gain profile beyond 7 days is unaltered by the steam curing.

The strength ratios at 28 days for steam v. standard curing for mixes containing SCM are:

- Fly ash 20% - steam cured 87% of standard cured
- Slag 20% - steam cured 78% of standard cured
- Silica fume 7% - steam cured 90% of standard cured

With standard curing, 7% silica fume achieved a stronger result than Type GP at the same overall cement content, in line with expectations, but this was largely offset by the 10% reduction due to steam curing. The 20% slag mix experienced a 22% reduction in steam cured strength compared to standard cured. This does not preclude slag as a supplementary cementitious material for steam cured concrete – only that such mixes have to be designed with this reduction factor in mind.

## DURABILITY

Investigations of steam curing cycles for pipes, giving rates of strength gain similar to that obtained with Type GP cement in the above series, date back more than 50 years, and thermal cycles having corresponding delay periods and rates of temperature rise have been in use for pipe manufacture for at least this (and most likely a much longer) period of time. Clearly this has not interfered with the durability of the product. It may be of interest nonetheless to show results of tests carried out on spun pipe made in this way, aimed specifically at determining the resistance to potentially aggressive conditions in the underground environment.

Non-reinforced spun pipes were manufactured with mixes having Type GP cement at 400 $kg/m^3$ or blended cement with 20% fly ash and total cement content 330 $kg/m^3$ . The curing treatment consisted of a short steam cycle (3 hours total) followed by "air curing" for 3-8 weeks. Test beams of dimensions 50×50×300 mm were then cut from the pipes in the axial direction, and a selection of these tested in flexure for initial strength. The remaining samples were immersed in water and test solutions aggressive to concrete, the latter being corrected periodically to maintain the concentration of the aggressive component for each solution. These were progressively withdrawn and broken in flexure. Results are expressed as flexural strength, derived from fracture loads and the original cross section dimensions of the beams.

Most of the testing was carried out within four years of immersing the samples but some remained in the solutions for 24 years.

Results for samples immersed in water are shown in Fig. 1. Following the steam and air curing treatment, water immersion resulted in a steady increase in strength, most of the strength gain occurring in the first year but with a further small increase over the remaining period. In pH 5 the effect of the acid started to override the effect of continued curing at about one year age. Relative strengths in the acid v. water at 24 years correspond to a depth of attack in the acid of 6 mm, which at the diminishing rate applicable in this situation would increase only to 10 mm at 100 years.

With the Type GP cement used for these tests the level of tricalcium aluminate was only 6%, which is a necessary factor in the high level of sulfate resistance shown in Fig. 3. At 24 years the strength of the fly ash blend is no less than at 4 years.

These tests show very high levels of resistance to acid and sulfate, consistent with the limits in Appendix E of AS/NZS 4058 for 100 year service life.

## CONCLUSION

Thermal curing cycles as developed for the production of prestressed elements are not appropriate where economics favour two or more daily casts. For these situations the optimum delay before heating is less and the optimum rate of temperature rise greater than for single mould use. While brief curing cycles enabling more than one daily use of the mould will not achieve the same level of quality *at the end of the thermal cycle* compared with a longer single casting cycle, the product is able nonetheless to achieve the required strength and durability by subsequent curing, whether this occurs before despatch or in the working environment.


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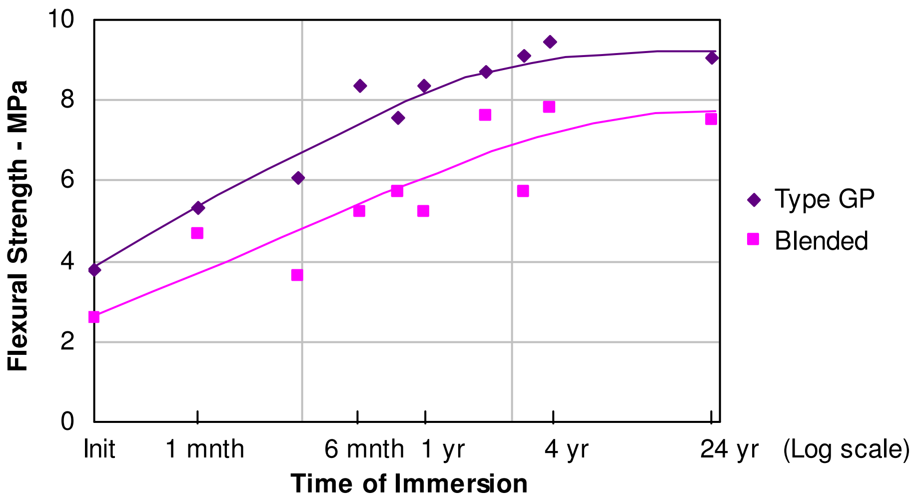


*Figure 1. Strength of Concrete Beams Immersed in Water*

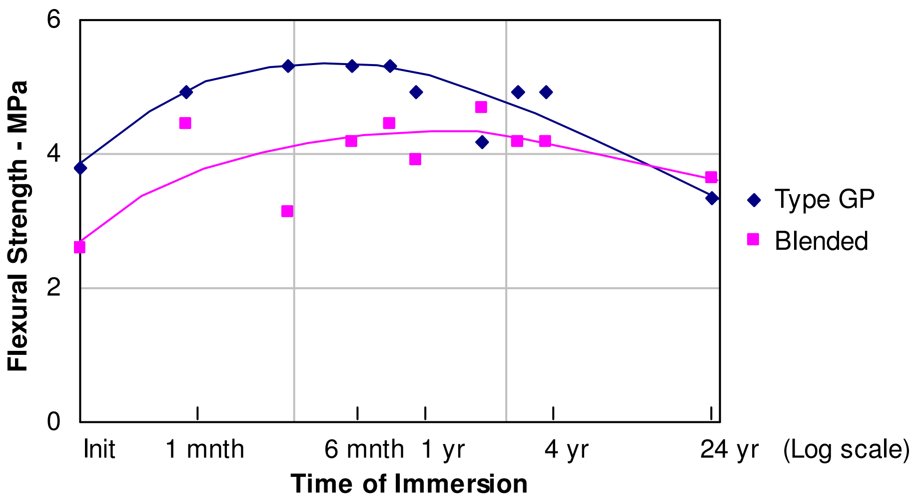


*Figure 2. Strength of Beams in pH 5*

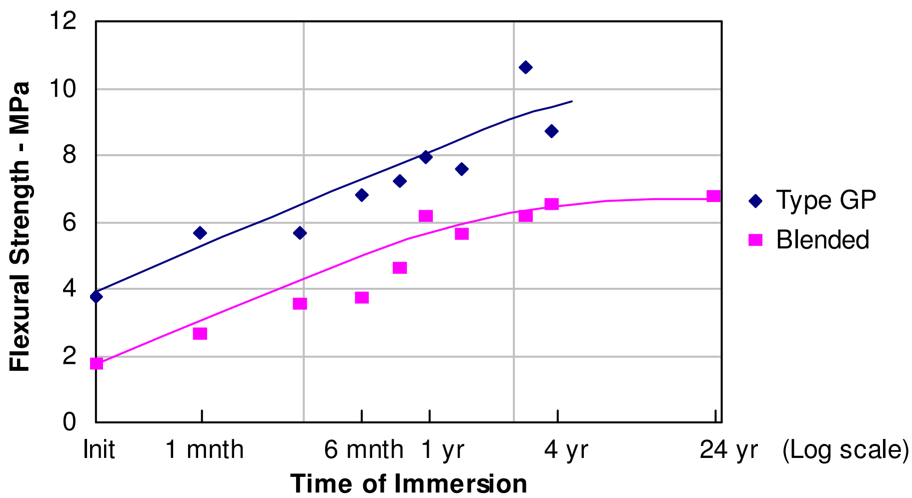


*Figure 3. Strength of Beams in 10,000 ppm Sulfate*

## ACKNOWLEDGMENT

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## REFERENCES

1. "Third Progress Report of the Low Pressure Steam Curing Committee", Concrete Institute of Australia, May 1971.
2. A. M. Neville, "Properties of Concrete", 4th ed., 1995, p 360.
3. D. W. S. Ho & H. T. Cao, "Water Sorptivity of Steam Cured Concrete", CIA Seminar (NSW) on the Structural Use of Precast Concrete, 7 March 1994.
4. Guo Chengju, "Measuring Consistency of Freshly Mixed Concrete", Concrete International, August 1987, pp 62-67.



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