PRELIMINARY ASSESSMENT OF THE INFLUENCE OF ACCELERATED CURING ON CONCRETE QUALITY

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SUMMARY

Curing of concrete is an important topic that is specified in concrete standards such as NZS 3101:2006 and NZS 3109:1997 which provide excellent guidance on what is required. There are still questions especially when considering alternative curing methods such as accelerated curing. Heating of concrete enhances the early-age strength of concrete but reduces long-term strength and durability. The overall effect is complicated since precast concrete manufacturers often use concrete of higher grade than specified to ensure good overnight strengths. Ultimately what needs to be assessed is whether the durability potential of the accelerated cured concrete is at least equivalent to the expected durability of the specified concrete after normal curing has been undertaken.

This paper will summarise curing as outlined in NZS 3101:2006 and NZS 3109:1997. It will explain curing and why it is important not just to ensure strength but also for durability. Commentary will be made on the various types of curing and limitations that various methods may have as well as a discussion over accelerated curing. The results from a preliminary investigation on curing show that both the strength and permeability of heat treated specimens can be restored to the standard moist curing equivalent if subsequent curing is provided after accelerate heat treatment.

INTRODUCTION

Curing of concrete involves maintaining a suitable environment around concrete after casting to ensure cement is able to fully hydrate and form dense and durable hardened cement paste. Curing of concrete involves controlling both moisture and temperature to ensure cement reactions are able to occur under optimum conditions and continue without interruption. Concrete should not be exposed to significant drying before curing starts as calcium hydroxide is deposited in the entrances of capillaries by evaporating pore water, which can block further ingress of water during curing. This is also why periodic wetting may provide less benefit that intended if significant drying occurs between each wetting cycle.

Lack of curing has been shown to reduce the quality of concrete, particularly in the curing affected zone that generally consists of outer 30-40mm cover concrete used to protect reinforcement from corrosion. Maintaining a moist environment at the concrete surface has been shown to lower permeability of concrete and improve properties such as abrasion, carbonation and chloride resistance. The level of curing required is dependent on the exposure conditions and type of concrete being considered with NZS 3101 curing requirements shown in Table 1.
Table 1: Curing guidelines from NZS 3101:2006

<table>
<thead>
<tr>
<th>Exposure classification</th>
<th>Typical Concrete</th>
<th>Cementitious Material</th>
<th>Minimum Curing Period Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1, A2 &amp; B1</td>
<td>20 – 40 MPa</td>
<td>Portland Cement</td>
<td>3 days</td>
</tr>
<tr>
<td>B2</td>
<td>25 – 45 MPa</td>
<td>PC with SCM optional</td>
<td>7 days</td>
</tr>
<tr>
<td>C, XA2, XA3</td>
<td>40 – 50 MPa</td>
<td>PC &amp; SCM’s</td>
<td>7 days wet</td>
</tr>
</tbody>
</table>

The rationale for increasing the level of curing with the severity of exposure is as follows:
- Increasing severity of exposure increases the risk of deterioration of the concrete and therefore requires more effective curing to ensure durability performance.
- Supplementary cementitious materials (SCM’s) are often slower reacting than Portland cement and require longer curing to provide the full durability benefit of these materials.
- Higher strength concrete with water/binder ratios below 0.45 may be vulnerable to self-dessication as all mix water is required for cementing reactions and external wet curing is therefore required.

**CURING EFFICIENCY**

Evaluation of curing efficiency has traditionally been based on strength development given that this is a specified property of structural concrete. Strength is however a bulk property that is less influenced by curing than near-surface changes in microstructure, which affect durability performance. Measuring changes in properties such as permeability or diffusion has been shown to be much more effective method of assessing curing efficiency. The effectiveness of different curing systems could be more objectively compared if related to some estimate of carbonation or chloride resistance of the concrete.

Concrete exposed to mild or moderate environments such as A2 or B1 has relatively low cover depth requirements of typically 30 mm since carbonation-induced corrosion is the most likely serious form of deterioration and this occurs relatively slowly. Carbonation is both diffusion and reaction controlled in concrete; relatively dry conditions are required for diffusion of carbon dioxide while higher moisture contents are needed for the carbonation reaction itself. Oxygen permeability has been used to predict carbonation resistance since it measures the pore network through which gaseous diffusion occurs in concrete. Permeability testing is generally done on the outer 30 mm layer of concrete most affected by curing has been shown to be sensitive to differing levels of moist curing with measured coefficients changing by an order of magnitude depending on the effectiveness of curing as shown in Figure 1 (Alexander et al 1999a).
Similarly curing efficiency can be assessed for concrete being used in more aggressive environments such as C-zone when concrete is directly exposed to sea water. Properties such as chloride resistance and resistivity would be the most appropriate to measure when assessing the influence of curing. This can be seen in Figure 2 where different types of 40 MPa concrete were exposed to marine conditions and shows that concrete without any moist curing will be more vulnerable damage from chloride-induced corrosion (Mackechnie, 1996).

**Figure 1**: Indicative ranges of coefficient of oxygen permeability for GP structural concretes

**Figure 2**: Surface resistivity of concrete exposed to marine tidal exposure for two years

**EQUIVALENT CURING**

Precast concrete manufacturers use accelerated curing to provide rapid gains in early strength to allow quicker demoulding times. Increased temperature causes faster hydration of cement with the formation of denser calcium silicate hydrate shells around cement grains
and less homogeneous distribution of hydration phases and coarser porosity. At lower temperatures the cement hydration is sufficiently slow to allow dissolved ions more time to diffuse before precipitation. This produces a denser cement paste with more even distribution of hydration phases that lowers the coarse porosity that affects both strength and durability.

Precast concrete generally only receives initial curing before stripping during which the material is often cured at elevated temperatures and covered to prevent moisture and heat loss. Most precast elements are not actively cured after stripping except where this is explicitly requested in the specification. One of the primary reasons that concrete only receives overnight curing is that the material is significantly more mature than 18 hours when stripped and lifted. This is illustrated in trials conducted by Mackechnie (2009) and shown in Figure 3 below where NCA refers to non-chloride set accelerator while SPA refers to superplasticiser with strength enhancing properties.

Figure 3: Overnight strength for standard and accelerated concrete mixes in Christchurch

The advanced maturity of precast concrete at the time of demoulding reduces the effect of subsequent drying compared with concrete cured at ambient conditions that has lower strength and microstructural development. The Australian standard AS 3600:2009 uses this approach in recommended that equivalent curing using accelerated means is deemed to be achieved when concrete reaches a compressive strength of 32 MPa.

Casting and initial curing of concrete in a precast environment has the advantage that environmental conditions are controlled without excessive drying and using optimum compaction. Early-age damage of concrete exposed to severe drying can result in plastic shrinkage or thermal cracking that will compromise the durability even if further curing was applied to the structure. These forms of early-age damage are far more prevalent in concrete cast in situ than in precast concrete.
RESEARCH MOTIVATION

Guidance on heating of precast concrete is mainly focused on achieving the desired maturity based on strength and preventing thermal shock by controlling the initial heating rate and cooling. Most industry guidelines do not consider additional water curing to be necessary and what little research is available on the benefits of additional curing is not in agreement. Lee for instance conducted a laboratory investigation following the upper limits recommended by Concrete Institute of Australia where the core temperature reached a peak of 80 °C. This research found little benefit in additional curing except for concrete containing microsilica, which showed almost 40% reduction in chloride resistance. Soroka et al. (1978) using GP cement and shorter elevated curing temperature durations found that the additional wet curing was able to restore the concrete to the equivalent 28 day strength achieved under standard curing conditions. No specific durability tests however were performed. Ronne (2000) found that additional wet curing after steam curing was not able to reduce permeability or porosity significantly.

Table 2 shows some indicative properties of concrete exposed to accelerated curing based on the referenced laboratory findings and other field data (Ronne and Mackechnie 2002).

<table>
<thead>
<tr>
<th>Property</th>
<th>Covers or light heating</th>
<th>Moderate Heating (gas or hot water)</th>
<th>High Heating (hot water or steam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak temperature</td>
<td>35</td>
<td>50</td>
<td>65</td>
</tr>
<tr>
<td>Maturity (K.hr)</td>
<td>575</td>
<td>750</td>
<td>850</td>
</tr>
<tr>
<td>1day/28 day f_c</td>
<td>0.50</td>
<td>0.65</td>
<td>0.75</td>
</tr>
<tr>
<td>Microstructure changes</td>
<td>Negligible change in microstructure compared to normal</td>
<td>Denser hydration with slightly higher porosity levels</td>
<td>Dense hydration shells, higher porosity</td>
</tr>
</tbody>
</table>

Research on the effects of heat curing of concrete containing SCM has some common findings with respect to properties affecting durability. Gesoglu (2010) found concrete containing silica fume or metakaolin was less negatively affected by accelerated curing than GP concrete and sorptivity, resistivity and chloride resistance were better after curing at 70 °C overnight than GP concrete cured in water at 20 °C. Similarly, in a study by Ho et al. (1997) a grade 50 concrete with GP cement and another with 65% slag were subject to either a 24 hour accelerated curing cycle at 65°C followed by air drying until 28 days or a standard casting at 23°C followed by an additional 6 days of moist curing prior to drying. The results from water sorptivity testing indicate the GP heat cured samples had a 28 day permeability value approximately double that of the standard curing samples while the 65% slag heat cured samples had permeability values approximately half the GP standard curing control. It is also interesting to note that the 65% slag standard curing samples had somewhat higher 28 day permeability values that the GP standard curing samples and approximately three times that of the heat cured slag samples. Heat curing of slag concrete seems to provide greater durability protection at 28 days than standard moist curing methods.

There are two separate but related issues related to accelerated heat curing of concrete. The first being what impact does accelerated heat curing have on the long term durability of concrete. In order to answer this question from a precast concrete perspective it is necessary to develop appropriate mixes which are representative of those commonly used in industry and compare them to a cast insitu mix which would be used for the same application. Simply comparing a low w/c ratio precast mix against itself under standard curing conditions is not a fair or appropriate comparison.
The second question relates to the benefits of additional curing following heat treatment. Given the uncertainty in the available literature it is reasonable to question the benefit of applying additional water curing. As with any attempt to answer the first question, it is important to compare equivalent fit for purpose mixes and not identical mix designs. The results present in this paper are part of a larger ongoing investigation and the presented GP mix design is not representative of that which would commonly be used in the precast industry. The results are simply presented to provide additional information on the possible benefits of subsequent curing given the seemingly contradictory information currently available.

EXPERIMENTAL INVESTIGATION

The effects of curing on the properties of a GP cement were examined after accelerated heat treatment for approximately 18 hours. A 50 MPa self-compacting concrete (SCC) mix was developed with a w/c ratio of 0.4, which had a spread of 680mm and a T500 time of 3.5 sec.

SCC was produced in the laboratory using a 250L drum mixer and 44 cylinders of 100 mm diameter by 200 mm were produced. The covered cylinders were placed in an oven and the temperature was increased to 50°C for approximately 18 hours. The specimens were allowed to cool for another 4 hours prior to de-moulding. Once the specimens were removed from the moulds half the specimens were placed in a curing tank at approximately 20°C and the other half were placed under ambient laboratory conditions with no further curing until testing. An additional set of control specimens was also cast which were not subject to accelerated heat treatment but were left under ambient laboratory conditions after casting for 24 hours. After de-moulding the specimens were placed directly into a curing tank. Thermocouples were used to measure the internal temperature for the elevated temperature samples the results of which are provided in Figure 4.

![Figure 4: Internal temperature of GP concrete sample subject to curing at 50°C.](image)

Three cylinders were used for each curing condition to determine the compressive strength at 3, 7 and 28 days. Durability performance was estimated through the determining the coefficient of oxygen permeability, percentage of voids and measuring the AC resistivity of the concrete. The concrete cylinders were cut to produce three 25 mm concrete disks. The
disks were dried at 50°C in an oven until there was no change in mass. The oxygen permeability coefficient was determined using an apparatus and method described by Alexander et al. (1999a, b). Once the oxygen permeability coefficient was obtained the specimens were vacuum saturated in tap water to determine the percentage of permeable voids. AC resistivity testing was finally conducted whereby the disks were placed between two parallel stainless steel plates. Sponges saturated with 5M NaCl were used to make electrical contact between the concrete disks and the steel plates.

RESULTS and DISCUSSION

The results from the compressive strength testing showed virtually identical values for all the mixes 3 days after casting as shown in Figure 5. The compressive strength for the standard curing mix (GP) after one day was approximately 18 MPa compared to 42 MPa for the elevated temperature cured specimens. The decrease in measured strength of the elevated temperature followed by dry curing (GPE – dry) mix at 7 days is likely a function of variability between individual cylinders. There appears to be relatively little change in strength for the GPE – dry specimens between 1 and 90 days after casting. Once the initial strength is reached there appears to be little additional strength development. The measured strength of the elevated temperature follow by wet curing (GPE – wet) showed an increase of approximately 24 MPa between 3 and 90 days which is similar to the increase found in the GP standard curing control mix. At 28 days however the strengths of both the elevated curing specimens was below that of the standard curing control mix.

![Figure 5: Compressive strength development](image)

Water curing subsequent to initial elevated temperature curing resulted in a 90 day strength similar to that of the standard curing control mix despite have a short term 7 and 28 day strength well below that of the control. The effects of additional wet curing on strength development are evident with the GPE-dry specimens having a 90 day strength approximately 15 MPa lower than either the standard cured samples or the elevated cured samples with additional wet curing.
The results from oxygen permeability testing, provided in Figure 6, show a similar trend to those of the compressive strength with the three day oxygen permeability coefficients (K) being similar for all the curing regimes. At seven days those cured under standard conditions had the lowest K followed by the GPE-wet and finally GPE-dry. The K decreased over time for all the specimens subject to wet curing indicating further hydration and refinement of the pore structure. The K of GPE-dry also decreased slightly from 3 to 28 days but not to the same extent as GPE-wet or those subject to standard curing.

Regardless of the curing process the K indicates a concrete with a fairly dense microstructure and low permeability. According to Alexander et al. (1999a) this concrete would be considered to provide excellent durability protection. The accelerated thermal curing without subsequent water curing did not appear to compromise the resistance of the concrete to permeation of gasses, though additional water curing was shown to provide benefit for improving the concrete’s microstructure.

It is apparent from the results provided in Table 3 that there is very little difference in the measured AC resistivity between the different curing conditions. The standard curing mix has shown a slight increase in resistivity between 3 and 28 days while the GPE-wet samples displayed the same relative decrease. The difference of approximately 1 kOhm.cm is fairly minor and within the uncertainty of the test.

<table>
<thead>
<tr>
<th>Mix</th>
<th>3 days</th>
<th>7 days</th>
<th>28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP - control</td>
<td>8.9</td>
<td>8.6</td>
<td>9.8</td>
</tr>
<tr>
<td>GPE - wet</td>
<td>9.5</td>
<td>8.9</td>
<td>8.3</td>
</tr>
<tr>
<td>GPE - dry</td>
<td>8.8</td>
<td>8.7</td>
<td>9.1</td>
</tr>
</tbody>
</table>

A resistivity value less than 9.5 kOhm.cm corresponds with a rapid chloride permeability test (ASTM C1202) charge passed of greater than 4000 coulombs which is considered to have a high penetrability to chloride ions. Even the standard curing control mix, which was fully water cured for 28 days, had a resistivity value which would indicated poor resistance to
chloride ions. The effect of no subsequent curing after the initial elevated thermal curing therefore did not significantly impair the chloride resistance of the concrete which was poor anyway. In situations where exposure to chloride ions is expected a low w/c, in this case 0.4, with ideal curing conditions is still not sufficient and an SCM is needed as recognized in the NZS 3101 code.

The results presented provide a preliminary indication of the likely performance of a limited number of possible curing conditions. The standard curing conditions represents the ideal but unrealistic case of what can be achieved with laboratory concrete. The GPE wet case illustrates the potential for concrete which is given initial accelerated thermal curing and subsequent continuous water curing which is also not realistic option but does provide for a comparison with GPE dry case which is more representative of what might be done in practice. The GPE-dry had the lowest long term strength compared to the other curing conditions but still greater than 50 MPa. The resistivity values for the different curing conditions all showed poor chloride resistance and in this case the GPE-wet had the lowest measured value. While the chloride resistance of the concrete was fairly poor the coefficient of oxygen permeability for all the specimens indicated good performance suggesting a low rate of carbonation.

There are a number of limitations in this investigation including the use of SCC which is not commonly used in precast concrete. Additionally, the effects of curing on the performance of concrete produced with various SCM was not investigated. In a marine application where durability is particularly important an understanding of the effects and limitations of various curing conditions on SCM performance is critical.

CONCLUSION

The long term durability of reinforced concrete structures is dependent upon a number of factors including the selection of appropriate curing methods. When evaluating the final quality of concrete it is useful to compare the measured values from tests, such as gas permeability or resistivity, which have some correlation with real world deterioration mechanisms. The effectiveness of various curing methods therefore should ultimately be evaluated on their measured in-situ performance.

While there remains some debate on the effectiveness of additional wet curing of heat treated concrete, preliminary results from this investigation suggest that wet curing following accelerated heat treatment of GP cement can reduce the permeability characteristics of concrete compared to heat treatment alone. Further detailed investigation using more representative mix designs and heating conditions is necessary however before any conclusions related to the effects of curing on precast concrete can be determined.

REFERENCES


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