Strength development of concrete containing coal fly ash under different curing temperature conditions

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Abstract

Concrete containing fly ash (FA) has been investigated in order to determine the effect of temperature curing conditions on the early age strength. Trial concrete using Portland cement only and concrete containing FA with cement replacement levels of 15%, 30% and 45% and varying water/binder ratios have been investigated under standard 20 °C curing. For a given water/binder ratio, the 3, 7 and 28 day strength was observed to be lower when using fly ash to replace cement. A concrete with target mean strength of 70 N/mm² was then designed using Portland cement and FA concrete, with different water/binder ratios required to achieve 28day target mean strength of 70 N/mm². The strength development of Portland cement and FA concrete with the target mean strength of 70 N/mm² at 28 days has been investigated under isothermal (10 °C, 30 °C, 40 °C, 50 °C) curing regimes and compared to the strength development using standard curing conditions. At 10 °C and 20 °C, the strength development of FA concrete with target 28-day strength of 70 N/mm² was found to be equivalent to that of Portland cement concrete. At an elevated curing temperature all concrete samples were observed to gain strength more rapidly than at 20 °C and had higher 32-day strength with increasing levels of FA. However, the longer term strength is detrimentally affected by the higher curing temperatures, with Portland cement concrete being more detrimentally affected than FA concrete.
Introduction

The use of fly ash (FA) as a cement replacement in concrete results in significant enhancement of the basic characteristics of concrete, both in its fresh and hardened states\(^1\). The advantages of FA in concrete are:

- improved long term strength performance and durability,
- reduced heat of hydration,
- reduced water required for equal workability,
- minimised risk of alkali silica reaction.

In addition FA provides both environmental and economic benefits\(^2\).

At early ages (Figure 1) and with isothermal curing at 20 °C, the strength of a normal grade concrete containing FA has been previously reported as being lower than an equivalent grade Portland concrete\(^3,4\). However at an elevated curing temperature the early age strength of concrete containing FA has been observed to be significantly improved. It has also been observed that the use of FA will have less detrimental effect to the later age strength compared to equivalent Portland cement concrete\(^5\). The rate of the reaction of FA concrete has been seen to be increased by an elevated ambient temperature and also by the elevated temperatures occurring inside structural elements at early ages, which appear to provide the activation energy for the reaction of the fly ash to kick-in earlier\(^6\).

This paper is part of a wider study on the effect of temperatures on the strength development of FA concretes under different curing regimes in order to quantify the strength that may be expected in structural elements and to provide the basis for the development of models to predict in-situ temperature and strength development.

![Life Cycle of Concrete](image)

**Figure 1. Life cycle of concrete**\(^7\)

Research significance

If it can be demonstrated that the use of concrete containing FA under an elevated temperature curing regime has no detrimental effect on the early age strength, this would allow the early removal of forms or the application of post-tensioning and help to reduce the overall cost of concrete structural elements.
Materials

Throughout this study, single batches of Portland cement (PC) and fly ash were used. PC was provided by Castle Cement Ltd and FA was provided by Hargreaves Coal Combustion Products Ltd. Chemical analyses of these materials are given in Table 1. The fly ash used was low-calcium fly ash. The coarse aggregate was crushed granite graded 20-5 mm. The fine aggregate used was 0-4 mm irregular to round sand, which had 66% passing through a 600 µm sieve. All aggregates were oven dried before use and allowance was made for water absorption when calculating batch weights for mixing. The superplasticiser used was polycarboxylate polymer (Fosroc Structuro 11180).

Table 1
Chemical analyses of materials

<table>
<thead>
<tr>
<th>Component</th>
<th>Portland cement % (by mass)</th>
<th>Fly ash % (by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>63.4</td>
<td>1 - 5</td>
</tr>
<tr>
<td>SiO₂</td>
<td>20.6</td>
<td>45 - 51</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5.5</td>
<td>27 - 32</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.5</td>
<td>7 - 11</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.8</td>
<td>0.3 - 1.3</td>
</tr>
<tr>
<td>MgO</td>
<td>2.6</td>
<td>1 - 4</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.7</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.2</td>
<td>0.8 - 1.7</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

Mix design methods

The normal BRE method⁸ was used to design concrete with w/b ratio of 0.4 and above to obtain normal strength concrete. The ratio free water/ (cement+k*fly ash) as defined by the method was used to design FA concrete. The cementing efficiency factor, k was proposed by Smith⁹ to give the same strength as PC concrete of similar workability (the workability required was 60-180 mm). In this study, k was taken as 0.3.

For w/b ratio of 0.4 and below, where the BRE method produced concrete mix proportions with very high cement content, the modified maximum density theory method (MMDT)¹⁰ was used. The fine:coarse aggregate ratio giving minimum void volume was determined in the same manner as used in the usual maximum density method. In the modified method, the fine:coarse aggregate ratio was set slightly lower than that required to give the minimum void content and enough binder and water was added to fill the void volume and give a slight excess of binder and water (defined as a percentage overfill). A polycarboxylate polymer based high range water reducing admixture (Fosroc Structuro 11180) was used to maintain workability in these mixtures.

A total of 51 trial concrete mixes were produced to determine the strength development under standard curing conditions of concrete with PC and also with different levels of 15%, 30% and 45% FA (as a percentage of the total binder content).
A mix volume of 0.012 m³ was prepared for each concrete according to BS1881-125:1986. After the concrete was mixed, the concrete was cast into steel 100 mm cube moulds and then compacted on a vibrating table. The specimens were covered with damp hessian and plastic sheeting. After 24 hours, the specimens were demoulded and cured under water at 20 °C. The compressive strength of three replicate specimens was tested at ages of 3, 7 and 28 days.

To investigate the strength development of concrete cured under 10 °C, 30 °C, 40 °C, 50 °C and standard (20 °C) isothermal curing conditions, mix proportions for concrete with a target mean strength of 70 N/mm² at 28 days were obtained from the results from the above work. The mix proportions for PC concrete and concrete with 15%, 30% and 45% cement replaced by FA are shown in Table 2. These mix proportions were obtained using the Modified Maximum Density Method. The mixing was done according to BS1881-125:1986 in a 0.1 m³ capacity pan mixer.

Table 2
Mixture proportions for grade 70 concretes

<table>
<thead>
<tr>
<th>% Fly ash</th>
<th>Cement (kg/m³)</th>
<th>Fly ash (kg/m³)</th>
<th>Granite (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Free water (kg/m³)</th>
<th>SPA (%)</th>
<th>Free W/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>316</td>
<td>0</td>
<td>1426</td>
<td>612</td>
<td>145</td>
<td>0.20</td>
<td>0.46</td>
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<tr>
<td>15</td>
<td>284</td>
<td>50</td>
<td>1426</td>
<td>612</td>
<td>136</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td>30</td>
<td>243</td>
<td>104</td>
<td>1426</td>
<td>612</td>
<td>123</td>
<td>0.31</td>
<td>0.36</td>
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<tr>
<td>45</td>
<td>202</td>
<td>165</td>
<td>1426</td>
<td>612</td>
<td>110</td>
<td>0.37</td>
<td>0.30</td>
</tr>
</tbody>
</table>

The concrete was cast into 100 mm cubes for compressive strength testing. These cubes were cured under 10 °C, 30 °C, 40 °C, 50 °C and standard curing conditions and were tested at ages of 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, 128 and 256 days.

Strength development of the trial concrete mixes under standard (20 °C) curing conditions

The strength development under standard curing conditions of the trial mixes is shown in Figure 2; the 3 and 28 day strengths are shown as function of water/binder ratio. In all mixes, the strength development depends on the water / binder ratio. The 3 and 28 days strength were highly dependent on the level of FA in the mix. The strength using the same water/binder ratio was lower for the concretes containing higher levels of FA.
Strength development under standard (20 °C), 10 °C, 30 °C, 40 °C and 50 °C curing conditions

The strength development under standard (20 °C) curing condition for PC and FA concrete is shown in Figure 3. At the standard 20 °C curing temperature, the early strength of this particular FA concrete was not significantly affected by the standard curing condition as indicated by earlier studies 3, 4, which reported a lower strength gain of FA concrete at early ages. From an age of 32 days, the strength of FA concretes continued to develop and was higher as the level of FA increased. This finding is consistent with that of the earlier studies 3, 4.

The strength development of PC and FA concrete at 10 °C, 30 °C, 40 °C and 50 °C isothermal curing temperatures is shown in Figure 4. At an early age, the strength development of PC and FA concretes at higher curing temperatures is greater than at lower curing temperatures. This is attributed to an increase in the hydration reaction rate. However at a later age, the strength achieved at higher curing temperatures was reduced. The later age strength of Portland cement concrete was much more detrimentally affected by higher curing temperatures than that of fly ash.
concrete. This is the so-called "crossover effect", where concrete cured at higher temperatures initially has higher strength but later has lower strength than concrete cured at lower temperatures. It is believed to be due to the reaction products not having time to become uniformly distributed within the pores of the hardening paste. In addition, shells made up of low permeability hydration products build up around the cement grains. The non-uniform distribution of hydration products leads to larger pores that reduce strength. As shown in Figure 5, at curing temperatures of 10 °C and 30 °C, the strength development of FA concretes is more or less equivalent to that of PC concrete up to the age of 32 days. From this age onwards the strength of the FA concretes continues to develop due to the pozzolanic reaction. The FA reacts slowly with the lime produced by reaction of the cement to produce cementitious hydrates, providing additional strength gain for up to three to ten years. At curing temperatures of 40 °C and 50 °C, the FA concretes have strength equivalent to PC concrete at early ages. After 4 days at 50 °C, the 30% FA and 45% FA concretes achieved 86% and 97% respectively of their 32-day strength at 20 °C, whereas the equivalent figure for PC concrete was 73%. At later ages, the strength is greater as the level of FA increases, since the Portland cement concrete is more detrimentally affected by the high curing temperatures.

Figure 3. Strength development of PC and FA concrete, under standard (20 °C) curing condition
Figure 4. Strength development of PC and FA concrete, under 10°C, 20°C, 30°C, 40°C and 50°C curing conditions.
Figure 5. Strength development of PC and FA concrete, under 10°C, 20°C, 30°C, 40°C and 50°C curing condition relative to achieved standard 32 day strength.
Conclusions

- The strength development of this particular FA concrete was observed to be similar to that of an equivalent Portland cement concrete at standard curing temperature (20 °C) up to 32 days. From this age onwards the strength continues to develop and is higher as the level of FA increases.

- At 40 °C and 50 °C, the strength development of FA concretes is similar to that of an equivalent Portland cement concrete at early ages. At later ages the strength development is dependent on the level of FA and is higher as the level of FA increases.

- At 10 °C, FA and Portland cement concretes gain strength more slowly than at 20 °C and the strength of FA concrete is approximately equivalent to that of Portland cement concrete.

- The crossover effect is observed earlier as the level of FA decreases and the curing temperature increases.

- This work indicates that FA concrete could be used in projects when early age strength is required without having a detrimental effect on the early or later age strength development. Its early age strength was found to be equivalent to that of Portland cement concrete. The later age strength in a structural element, where temperatures are likely to exceed standard 20 °C curing temperatures, may be significantly higher than the target mean strength of the concrete when FA is used. In contrast to slag cement\(^{15}\), which is detrimentally affected by cold temperatures, FA concrete showed the same strength development at 10 °C as Portland cement concrete and could potentially be used at significant levels even in colder conditions without causing delays to construction schedules. This applies for this particular FA and that it may be different for FA from another source. The effect of temperature on this particular FA seems to be the same as that for PC at early ages– irrespective of whether the temperature is higher than or lower than normal curing temperature.

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References


[7] Centre for advanced cement based materials www.acbm.northwestern.edu


