EFFECT OF ELEVATED TEMPERATURE ON MECHANICAL PROPERTIES OF HIGH STRENGTH CONCRETE

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ABSTRACT
High strength concrete (HSC) is a material often used in the construction of high rise buildings. In case of unexpected fire, building elements such as columns, slabs and walls will be subjected to extreme temperatures. In order to assess the performance of high-rise concrete members to such exposure, it is important to understand the changes in the concrete properties due to extreme temperature. This paper presents an experimental study undertaken to quantify the effect of elevated temperatures of 60, 75, 100, 200, 400 and 600°C with various exposure durations of 4, 8, 12, 72 hours and one month on HSC cylinders. HSC cylinders made of two strengths, namely 80 and 100 MPa are used. For comparing their performance with normal strength concrete, cylinders made with 40 MPa concrete are also investigated. Residual tensile and compressive strengths of concrete as well as weight loss values after high temperature exposures were determined. The detrimental effects of using silica fume for higher strength concrete mixtures are exhibited by the test results.

KEYWORDS
HSC, compressive strength, tensile strength, weight losses, elevated temperatures, exposure duration.

INTRODUCTION
With the many benefits of high strength concrete (HSC) its use in the construction of high rise buildings and bridges with large spans has increased in recent years. The effects of high temperature on the mechanical properties of concrete have been investigated since as early as the 1950s (Malhotra 1956; Schneider 1988; Xiao and Konig 2004; Husem 2006). Also, since the 1950s HSC is widely produced as an appropriate substitute for normal strength concrete (NSC) (ACI Committee 363 1993; Behnood and Ziari 2008). HSC is made using a reduced water/cement ratio. Commonly silica fume is also added to the mix to further increase the strength.

During exposure to high temperatures such as during fire event, the mechanical properties of concrete (strength, elastic modulus and volumetric stability) are significantly reduced. When a concrete structure is subjected to extreme temperatures, it may fail in many of different ways (Cioni et al. 2001). In addition, elevated temperature will reduce the strength in both HSC and NSC. The degree of strength-loss is dependent on the temperature reached and the exposure duration (Castillo and Durrani 1990; Cho-Liang et al. 2005). Other factors which influence the strength loss are the aggregate type and the strength of the concrete at room temperature (Knaak et al. 2010). Further, when exposed to high temperatures, the physical structure and chemical composition of concrete change (Arioz 2007).

HSC is much more likely than NSC to fail through spalling at very high temperatures (Bastami et al. 2011). The likelihood of concrete spalling has been seen to increase with concrete that has a lower water to cement ratio and a lower permeability. It was also found that concrete containing higher volumes of silica fume is likely to fail in violent explosions (Khoury and Anderberg 2000). It should
also be noted that the likelihood of spalling is dependent on the rate at which the temperature is applied. A rapid temperature rise, such as in the case of a fire, is much more likely to cause spalling or explosive spalling in concrete rather than a gradual increase in temperature. The likelihood of spalling also depends on many other factors such as the mineral constituents of aggregates, thermal stresses, the density of the concrete and the moisture content (Chan et al. 2000).

Despite a lot of research conducted in this area, it can be seen that there are inconsistencies between similar studies. Differences in mix proportions and environmental conditions of the concrete lead to differences in results. At 150°C, the residual strength can range from as low as 30% to as high as 120% of the original strength (Khoury 1992). There are many different environmental factors that lead to these discrepancies. Differences in the heating and cooling rate can cause variations. Rapid rates of heating and cooling can also cause thermal stresses. The relative humidity of the environment has also been attributed to these variations in results, as it is believed that after cooling the cement gel will absorb moisture from the surrounding medium (Khoury 1992).

In view of the above, an experimental study was undertaken to quantify the effect of elevated temperatures of 60, 75, 100, 200, 400 and 600°C with various exposure durations of 4, 8, 12, 72 hours and one month on HSC 100 × 200 mm test cylinders. HSC cylinders made of two strengths, namely 80 and 100 MPa are used. For comparing their performance with NSC, cylinders made using 40 MPa concrete are also investigated. Residual tensile and compressive strengths of concrete as well as weight loss values after high temperature exposures were determined. A total of 114 cylinders were tested.

EXPERIMENTAL INVESTIGATIONS

Concrete Mix Design

Concretes of two high strengths namely 80 MPa and 100 MPa and a normal strength of 40 MPa were used for the preparation of standard 100 mm diameter and 200 mm high test cylinders. The mix designs used for achieving the three strengths of concrete are presented in Table 1.

The materials used were normal Type-A General Purpose Portland cement, 10 mm nominal diameter coarse aggregate, washed river sand for fine aggregate, standard silica fume and Sikament 500 high-range water reducer as the superplasticiser.

<table>
<thead>
<tr>
<th>Table 1. Concrete mix proportions</th>
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<tr>
<td>Materials used</td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Cement</td>
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<tr>
<td>Silica fume</td>
</tr>
<tr>
<td>10 mm aggregate</td>
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<tr>
<td>Fine aggregate (sand)</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Superplasticiser</td>
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<td>Total weight</td>
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<td>W/C ratio</td>
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Heating Equipment

A ventilated oven was used to heat the concrete cylinders to a temperature up to 200°C. This oven was also used for preheating the cylinders that were exposed to higher temperatures. For the temperature of more than 200°C, an electrically heated furnace designed for a maximum temperature of 1300°C was used. The furnace was heated by means of exposed heating elements laid on the refractory walls of the inside chamber, which was approximately 460 × 460 × 480 mm in dimension. The test cylinders were stacked with sufficient space between two adjacent cylinders to obtain a uniform heating in each cylinder. Since the chamber had a limited volume the concrete cylinders were heated in batches.
Laboratory Testing

At the age of 28 days, the concrete cylinders were removed from water and dried in air for 24hrs at the laboratory conditions with a mean relative humidity and temperature of 65% and 22°C, respectively. The cylinders were then placed in a ventilated oven at 60°C for 72 hrs before subjecting them to high temperatures in the electric furnace. This step was found to be necessary to avoid the explosion of the concrete cylinders in the furnace due to the formation of steam. The rate of heating was maintained at 200°C/hr. Once the required maximum furnace temperature was reached, the temperature was maintained until the cylinders were removed. For the concrete cylinders subjected to maximum furnace temperatures of 200, 400 and 600°C, the total durations in the furnace were 4, 8 and 12 hrs for each temperature. This was undertaken for concrete cylinders of each of the three strengths. For those exposed to temperatures below 200°C, the maximum oven temperatures were 60, 75 and 100°C, the total exposure durations being 72 hrs, 30 days and 12 hrs, respectively. Once again, test cylinders of each of the three strengths were subjected to these temperature-duration regimes.

At the end of the sustained periods and at the corresponding maximum temperatures, the concrete cylinders were left in the furnace for 24hrs with its power off to cool down inside the furnace to the ambient temperature. The cylinders were then removed from the furnace and cooled in air at the laboratory conditions for further 4 to 6 hrs, prior to strength testing. All cooled concrete cylinders were tested in either compression or in indirect tension. The weights of the cylinders were taken at different stages of heating and cooling.

RESULTS AND DISCUSSIONS

Concrete Strengths

The compressive and tensile strengths measured for the three concrete mixes i.e. 40 MPa, 80 MPa and 100 MPa concrete at 7 and 28 days are presented in Table 2. For each concrete mix, two cylinders were tested for strength determination at each day of testing. The 28-day concrete compressive strengths averaged 42.2 MPa for the target strength of 40 MPa, 74.8 MPa for target strength of 80 MPa and 94.2 MPa for target strength of 100 MPa. The obtained 28-day strength results are very close to the target strengths proving the accuracy of the mix design. The measured slump for the 40 MPa mix was 75 mm, while 80 MPa and 100 MPa mixes were zero slump concrete.

Results of Exposures to Elevated Temperatures

Weight loss after heating

The weight loss from all three concrete mixes increased with the increase in the maximum exposed temperatures and the increase in durations of exposures due to accelerated drying. The average weight losses at different exposure temperatures and durations for the 40, 80 and 100 MPa concrete cylinders are plotted in Figure 1. Note that the average initial weights for 40, 80 and 100 MPa concrete cylinders were 3708, 3805 and 3895 grams, respectively.

Up to the temperature of 100°C, concrete cylinders lost between 1.8 and 2.8% of their initial weights for 40 MPa concrete, between 1.9 and 2.6% for 80 MPa concrete and, between 0.9 and 1.4% for 100 MPa concrete. This was mainly due to the evaporation of free water. In order to verify this fact, two cylinders each of each concrete mix were exposed to a temperature of 75°C for a prolonged period
of more than 30 days. Weights were taken at regular intervals throughout this period and these are presented in Figure 2. It can be seen from Figure 2 that once the free water was evaporated completely, weights became constant after a certain period of time.

![Figure 1](image1.png)

**Figure 1.** Weight losses at different exposure temperatures and durations for the concrete mixes

![Figure 2](image2.png)

**Figure 2.** Changes in weights of cylinders when exposed to a constant temperature of 75°C

![Figure 3](image3.png)

(a) (b)

**Figure 3.** Explosion of concrete cylinders: (a) explosive spalling occurred when temperature reached between 550 and 600°C (b) explosion occurred after exposure to 600°C for 8 hrs and cooling was in progress

When the temperature was increased to 200°C, the maximum losses occurred for the exposure duration of 12 hrs, and the weight losses were 6.8%, 6.2% and 5% respectively for 40, 80 and 100 MPa mixes. When the temperature was increased to 400°C, the maximum losses occurred for the exposure duration of 8 hrs, and the corresponding weight losses were 7.6%, 7.4% and 5.7% respectively for 40, 80 and 100 MPa mixes. The increased weight losses are probably due to the dehydration of the hydration products and the loss of water from the fine pores in the cement paste and aggregate particles. As silica fume was used for 100 MPa mix, the hydration products were more...
stable and there were less water compared to the other mixes for which 100 MPa mix had the minimum weight loss at all temperatures and exposure durations. At 600°C, for all exposure durations, the cylinders exploded completely (see Figure 3).

**Residual compressive and tensile strengths after heating**

In general, the residual compressive strengths for all three mixes decreased with the increase in the maximum temperature and the durations of exposure. The ratios of compressive strengths at different exposure temperatures and durations to their initial 28-day strengths for the 40, 80 and 100 MPa concrete mixes are presented in Figure 4. Note that the maximum reduction in compressive strength took place for 80 MPa mix when exposed to 400°C for different durations.

![Figure 4. Ratios of compressive strengths of concrete mixes exposed to different temperatures and durations to their initial 28-day strengths](image)

Similar results were obtained for tensile strengths of the mixes after exposure to different temperatures and for different durations. However, due to lack of enough cylinders, tensile strengths were not determined for all temperature exposures. The ratios of tensile strengths at different exposure temperatures and durations to their initial 28-day strengths for the 40, 80 and 100 MPa concrete mixes are presented in Figure 5.

![Figure 5. Ratios of tensile strengths of concrete mixes exposed to different temperatures and durations to their initial 28-day strengths](image)
CONCLUSIONS

The main aim of this experimental study was to investigate the effect of elevated temperatures of 60, 75, 100, 200, 400 and 600°C with various exposure durations of 4, 8, 12, 72 hours and one month on HSC cylinders. Two HSC mixes – one with silica fume (100 MPa) and one without (80 MPa), and a NSC mix (40 MPa) were investigated. A total of 114 cylinders were tested. The relationship between the weight loss and maximum temperature is nonlinear but the loss was the least for the highest strength mix for every temperature and exposure duration.

All three concrete mixes showed reduction in strengths in compression and tension when exposed to high temperatures. The maximum reduction was about 44% in compressive strength for 80 MPa mix exposed to 400°C for 12 hrs. Tensile strengths were not measured for higher temperature exposures for lack of enough cylinders. However, there was a reduction of about 18% in tensile strength for 80 MPa mix exposed to 60°C for 72hrs.

All cylinders exposed to the temperature of 600°C exploded either before reaching the required temperature or after the exposure duration during cooling (see Figure 3). This happened more pronouncedly for mix containing silica fume thereby exhibiting the detrimental effect of using silica fume.

REFERENCES

ACI committee 363. (1993) State-of-the-Art Report on High-Strength Concrete, American Concrete Institute, Detroit, USA.