Behavior of Reinforced High-Strength Concrete Short Columns Subjected to High Temperature

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1. Abstract:

The increasing use of high-strength concrete (HSC) for structures has been widely noticed in recent years. The risk of exposing these HSC structures to high-temperatures during a fire has increased significantly in Egypt. Consequently, the safety of such structures during and after a fire is important which depends on the mechanical properties of HSC structure elements subjected to high-temperature. The main objective of this study is to investigate the residual mechanical properties of high-strength concrete short columns with regard to high-temperature effects. This study presents the results of twenty-nine high-strength short columns 100×100×400 mm exposed to high-temperature cycle and tested under static loading up to failure. Different parameters were considered during this study such as percentage of longitudinal reinforcement, thickness of concrete cover, and temperature degree level. Experimental results showed that the compressive strength of high strength concrete has a little change until 400°C; however, beyond this degree of temperature a 55% reduction in the compressive strength was noticed compared with specimens at room temperature. Also, cooling of heated samples in water decreased the residual strength by 36% compared with their counterparts cooling in air.

Keywords: High-strength concrete, High temperature, Residual strength, Reinforced concrete columns.

2. Introduction:

HSC exhibits superior performance in many aspects such as possesses high strength, durability, and workability. As the use of HSC becomes commonplace in buildings, the risk of exposing it to high temperatures also increases. To be able to predict the response of HSC structures when exposed to a high temperature, it is essential that the residual mechanical properties of HSC clearly understood. Recently, experimental and
theoretical studies have been performed in order to investigate the behavior of HSC at elevated temperatures. Hachemi and Ounis, [1], evaluated residual mechanical and physical properties of NSC, HSC and HPC concrete at elevated temperatures. Their study concerned concrete compressive and flexural strength. They noticed that the compressive strength decrease gradually when increasing temperature from 400 to 900 °C. The temperature degree less than 400 °C had a little effect on the compressive strength of concrete. On the other side, the flexural strength of concrete decreased continuously with increasing temperature from 150°C up to 900°C. Bikhiet et al, [2], investigated experimentally and theoretically behavior of normal reinforced concrete short columns exposed to fire. They noticed that the failure load of columns subjected to fire is less than those tested under normal condition by 20-40%. Moreover, the modules of elasticity of concrete reduced by 50-70% after fire. Also, steel parameters and cooling system play an important role on the residual strength of short columns. Robert and Samson, [3], investigated theoretically constitutive model for HSC at elevated temperatures. Their study concerned on compressive strength, tensile strength, elastic modulus, peak strain and stress-strain relationships. They conclude that at 800°C the concrete losses about 90% of its stiffness and strength so it is assumed that above this temperature the concrete has failed and there is less variation in the peak strain. Raut and Kodur, [4], evaluated theoretically response of RC columns under fire-induced biaxial bending. Their study concerned on fire resistance of RC column, exposure conditions, loading and spalling. They noticed that the fire resistance reduces by 20% for every 25 mm increase in load eccentricity due to uniaxial bending and by 30% due to biaxial bending. Also, increase of load eccentricity make decreased of fire resistance due to spalling. Increase of column size make increased of fire resistance 40% for every 100 mm. The fire resistance drops by approximately 50% for the HSC columns due to the reduction of area contributing to flexural rigidity. Park et al, [5], evaluated experimentally factors influencing on thermal behaviors of HSC columns under fire. Their study concerned on the effect of cross sectional areas, cover thicknesses, and arrangements of reinforced bars on temperature distributions. They noticed that the higher temperature distribution is increased as the cross sectional area increases then spalling increased, this may be because the temperature distribution is related to the area of surfaces subjected to temperature. Also, the column with 60mm of cover thickness shows about 20-30% lower temperature distributions compared with 40mm of cover thickness. The column with 60mm of cover thickness shows about 74% area loss compared with 40mm of cover thickness. Khaled, [15], investigated experimentally the effect of cover thickness and polypropylene (PP), on improving of residual compressive strength of RC columns. The analysis showed that, the best amount of PP to be used is 0.75 kg/m³, where the residual compressive strength is 20 % higher than no PP fibers are used at 400 C for 6 hours. Kodur et al, [10], studied effect of temperature on thermal properties of high-strength concrete HSC, self-consolidating concrete (SCC), and fly ash concrete (FAC). They noticed that the thermal conductivity generally decreases with temperature, while the thermal expansion increases with temperature up to 800°C. Also, they noticed that SCC possesses higher thermal conductivity and thermal expansion than both HSC and FAC in the temperature range of 20–800°C. The addition of steel, polypropylene, and hybrid fibers to SCC or HSC does not significantly alter the thermal conductivity. Raut et al, [11], studied experimentally and theoretically response of HSC columns under design fire exposure. They found that there is good agreement between the measured and the predicted rebar temperatures throughout the fire exposure time for the columns. They noticed that the fire resistance of HSC columns can decrease by as much as 65% of the fire resistance of NSC
columns under some scenarios. Also, HSC is more prone to spalling around 40% in 33 min than NSC, due to low permeability. Liu et al., [13], Also investigation experimentally and theoretically size effect on fire resistance of reinforced concrete columns. They noticed that fire resistance increases with an increase of cross-section size and concrete cover thickness. Also, increase of cross-section size causes the increase of load capacity of the columns. Faris and Choi, [14], studied also, experimentally and theoretically the behavior of high strength concrete columns in fire. Their study concerned on loading levels 0.2, to 0.6 of the BS8110 ultimate design load. They noticed that increasing of the loading level from 0.2 to 0.6 has reduced the fire resistance of the columns by an average of 65%. Also, increasing the loading level has increased the probability of concrete spalling particularly under low heating. Low heating rates minimized the risk of explosive spalling, but increased the axial displacements due to thermal creep.

Concrete columns have an important function in the structural concept of many structures, therefore this study aimed to evaluate the residual strength of high strength concrete short columns exposed to one cycle high temperature considering the effect of ratio of longitudinal reinforcement, thickness of cover, time duration and temperature degree.

3. Experimental Work:

The experimental program consisted of twenty-nine reinforced concrete short columns with dimension 100x100x400mm. Details of the studied parameters and the test results are shown in Table (1). Figure (1) and Photo (1) show also the details of the tested specimens. The main parameters considered were the percentage of longitudinal reinforcement, thickness of concrete cover, and cooling system. Five specimens are tested at room temperature, while the others are subjected to one cycle of temperature at degree of 400, 600, 700 and 800°C. The tested specimens are divided into four groups, group A consists of five specimens A1 to A5 tested at room temperature as a control specimens, group B consists of eight specimens B1 to B8 tested after cooling them in water, group includes eight specimens C1 to C8 directly tested after one cycle of heating, and Group D contains eight specimens D1 to D8 tested after cooling the min air.

The considered variables in this study are as follows:
1- Ratio of longitudinal reinforcement 1.5%, 3.0% and 6.0%.
2- Concrete cover thickness 1.5cm, 2.0 cm and 2.5 cm.
3- Degree of temperature 400, 600, 700 and 800 °C

Figure 1: Dimension and reinforcement details of samples
Photo 1: Shape of samples
### 3.1 Preparation of test specimens

All specimens were fabricated to have the same compressive strength 70 MPa. Compressive strength of cubes were determined using cubes 150x150x150mm tested after 28-day. The amount of constituting materials of the mix used are presented in Table (2).

#### Table 1: Details of the tested columns and test results.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Column. No.</th>
<th>% of steel</th>
<th>Temperature degree, °C</th>
<th>Cover, cm</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A1</td>
<td>1.5</td>
<td>0</td>
<td>1.5</td>
<td>41.57</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>3</td>
<td>0</td>
<td>1.5</td>
<td>49.84</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>6</td>
<td>0</td>
<td>1.5</td>
<td>57.01</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>52.43</td>
</tr>
<tr>
<td></td>
<td>A5</td>
<td>3</td>
<td>0</td>
<td>2.5</td>
<td>55.74</td>
</tr>
<tr>
<td>B</td>
<td>B1</td>
<td>1.5</td>
<td>800</td>
<td>1.5</td>
<td>13.35</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>3</td>
<td>800</td>
<td>1.5</td>
<td>19.62</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>6</td>
<td>800</td>
<td>1.5</td>
<td>27.93</td>
</tr>
<tr>
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<td>B4</td>
<td>3</td>
<td>800</td>
<td>2</td>
<td>21.543</td>
</tr>
<tr>
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<td>B5</td>
<td>3</td>
<td>800</td>
<td>2.5</td>
<td>24.43</td>
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<td>3</td>
<td>400</td>
<td>1.5</td>
<td>34.65</td>
</tr>
<tr>
<td></td>
<td>B7</td>
<td>3</td>
<td>600</td>
<td>1.5</td>
<td>30.8</td>
</tr>
<tr>
<td></td>
<td>B8</td>
<td>3</td>
<td>700</td>
<td>1.5</td>
<td>27.12</td>
</tr>
<tr>
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<td>1.5</td>
<td>800</td>
<td>1.5</td>
<td>16.73</td>
</tr>
<tr>
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<td>C2</td>
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<td>800</td>
<td>1.5</td>
<td>22.9</td>
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<td>1.5</td>
<td>30.41</td>
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<td>800</td>
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<td>44.621</td>
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<td>400</td>
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<td>46.45</td>
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<tr>
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<td>D7</td>
<td>3</td>
<td>600</td>
<td>1.5</td>
<td>43.27</td>
</tr>
<tr>
<td></td>
<td>D8</td>
<td>3</td>
<td>700</td>
<td>1.5</td>
<td>41.64</td>
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</tbody>
</table>
Table 2: Concrete mix design for 1 m³ concrete.

<table>
<thead>
<tr>
<th>Concrete Strength</th>
<th>Cement</th>
<th>Fine Aggregate</th>
<th>Coarse Aggregate</th>
<th>Silica Fume</th>
<th>Super-Plasticizer</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>Kg/m³</td>
<td>Kg/m³</td>
<td>Kg/m³</td>
<td>Kg/m³</td>
<td>Liter/m³</td>
<td>Liter/m³</td>
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<tr>
<td>70</td>
<td>500</td>
<td>525</td>
<td>1200</td>
<td>60</td>
<td>14</td>
<td>135</td>
</tr>
</tbody>
</table>

3.2 Experimental procedures

The specimens were subjected to one cycle of elevated temperature at degree of 400 °C, 600 °C, 700 °C and 800 °C in a furnace. Figure (2) shows time-temperature curve for the furnace and for ASTM E119. The group "A" was subjected to axial load at room temperature while the group "B" was exposed to high temperature at degree of 400, 600, 700 and 800 °C, then the specimens was cooled in water before subjected to axial load test. The specimens were tested directly after cooling i.e. tested in wet condition. Group "C" was exposed to a temperature similar to group B, but the specimens immediately subjected to axial load test without cooling. Finally, Group "D" was exposed to high temperature at degree of 400, 600, 700 and 800 °C, and then the specimens are cooled at air before subjected to axial load test. Photo (2) shows the specimens inside the furnace.

![Figure 2](image-url)  
Figure 2: time-temperature curve for the furnace

4 Discussion of Results:

4.1 Color of specimens

Surface Color of concrete during the heating process had no change until 400 °C; however the increase in temperature resulted in changing the surface color of specimens. Surface color of concrete slightly changed to brown color when temperature was increased up to 600 °C. Beyond 600 °C, observed concrete color was yellow to red color as shown in photo (3).
4.2 Failure modes

The columns are tested under axial load by using digital machine with a loading capacity of 150 tons. Increasing the axial load, leads to “crackle sound with longitudinal cracks appeared in the surface of all tested specimens. Then buckling of longitudinal reinforcement appeared as shown in photos 4 and then typical compression failure of the tested specimens is noticed. Three modes of failure were noticed for the tested specimens. The first mode showed small longitudinal cracks appeared on the surface of the specimens that have small steel ratio. While, the second mode was wide longitudinal cracks appeared on the surface of specimens that have small cover. The third mode was appearing in specimens C4 and D2; it was characterized by longitudinal cracks on the surface of the specimens followed by buckling of longitudinal reinforcement.

![Group (A)](image1)
![Group (B)](image2)
![Group (C)](image3)
![Group (D)](image4)

Photo 4: Failure mode of the tested specimens

4.3 Effect of temperature degree

Based on the experimental results of series “A” and “C”, it is noticeable that the increase in temperature degree results in decrease in the residual compressive strength by 15%, 21%, 31% and 55% for temperature degrees of 400°C, 600°C, 700°C and 800°C, respectively compared with their reference samples at room temperature, see figure(3). These results are in general agreement with Raut et al, [11]. One can notice that the degree of reduction in the compressive strength is insignificant till temperature degree of 400°C, while beyond this temperature degree the rate of reduction increases dramatically.

4.4 Effect of cooling system

The experimental results of group “B” and “D” are devoted to investigate the effect of cooling system on residual strength ratio. At 800°C, it is observable that cooling of tested columns in water decreases their residual strength ratio by 36% than cooling system at air. Also, cooling the specimens in water reduced the residual strength by 61% compared with specimens tested at room temperature. On the other hand, cooling the specimens at air reduced the residual strength
by 39% compared to specimens tested at room temperature. These results are in agreement with Bikhi et M. Mohamed et al., [2]. Therefore, it is recommended to avoid cooling the structural elements subjected to high temperature levels using water as a cooling system. Moreover the effect of cooling system depends on the temperature degree as shown in Figure (4).

4.5 Effect of concrete cover thickness

Investigation of results in Table 1 shows that the increase in concrete cover thickness leads to an increase in the residual strength of the columns at the room temperature. Figures (5 and 6) show the effect of concrete cover thickness on the residual compressive strength ratio after heating and after applying the adopted cooling systems. At room temperature, the compressive strength increased by 10% when the concrete cover thickness changed from 15-mm to 25-mm due to decrease in the buckling of the longitudinal bars. On the other hand, increasing the concrete cover thickness of specimens subjected to one cycle of heating from 15-mm to 25-mm caused an increase in the compressive strength by 17%. This is because the increase in concrete cover thickness resulted in a decrease in the effect of high temperature on steel bars as it is far from the surface. Also, at cooling in water, there was an increase in the compressive strength by 20% when the concrete cover thickness increased from 15-mm to 25-mm. While cooling the specimens at air increased the compressive strength by 15%. These results are in general agreement with Mohammed, [15]. Therefore, it is recommended to use concrete cover thickness not less than 25mm and this result agree with the recommended values by the available design code provisions.

4.6 Effect of percentage of longitudinal steel

Figures (7 and 8) show the effect of steel ratio on ratio of residual compressive strength considering the effect of cooling system. At room temperature, the compressive strength increased by 27% when the steel ratio changed from 1.5% to 6.0%. Furthermore, the
compressive strength increased by 47% when steel ratio increased to 6.0% when specimens tested without cooling. Also, cooling the specimens in water increased the compressive strength by 53% when the steel ratio changed from 1.5% to 6.0%. While cooling the specimens at air increased the compressive strength by 50% when the steel ratio changed from 1.5% to 6.0%. These results are agreed with the results of Liu Lixian et-al, [13]. Therefore, it can be concluded that the residual compressive strength is very sensitive to the percentage of steel ratio.

Figure 7: Effect of steel ratio on residual strength ratio.

Figure: Effect of steel ratio on residual strength ratio.

5 Conclusions:

Based on the experimental work carried out on HSC columns in this study, the following conclusions may be drawn out:

- After heating the specimens, the reduction in the compressive strength was insignificant until 400°C, while beyond this temperature degree the rate of reduction increased dramatically.
- At 800°C, the residual compressive strength decreased by 55% compared with specimens tested at room temperature.
- Cooling the tested specimen at air reduced the residual compressive strength of HSC columns by 39% compared with specimens tested at room temperature.
- Cooling the tested specimen in water reduced the residual compressive strength of the columns by 61% compared with cooling the specimens at room temperature.
- Cooling by water in comparison with cooling at air had a substantial effect on the value of the residual compressive strength, where additional decrease by 36% in the residual compressive strength was noticed.
- The residual compressive strength is very sensitive to percentage of steel ratio. The samples attained higher residual loads with the increase in steel ratio.
- The increase in concrete cover thickness could not consider ably affect the residual compressive strength.

6 References


