Influence of Elevated Temperatures on the Behavior of Economical Reactive Powder Concrete

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Abstract In this investigation, the effects of elevated temperatures of 200, 300, 500°C for 2 and 4 hours on the main mechanical properties of economical type of reactive powder concrete (RPC) are studied. The main variables in this study are cement content and steel fibers content in reactive powder concrete samples as well as elevated temperature and heating time. Compressive strength and tensile strength of RPC are obtained after exposure to elevated temperatures. It is found that, RPC can be use at elevated temperature up to 300°C for heating times up to 4 hours taking into consideration the loss of strength. Also, using steel fibers enhance the residual strength of high cement content RPC samples.

Keywords Reactive Powder Concrete, Elevated, Temperature, Strength

1. Introduction

Elevated temperature conditions may affect concrete structures such as concrete foundations for launching rockets carrying spaceships, concrete structures in nuclear power stations and those accidentally exposed to fire, as the case of many tunnels registered in many countries[1]. The fire effect may be defined in terms of elevated temperatures that considers as indirect fire effect.

When normal strength concrete (NSC) and high strength concrete (HSC) are subjected to high temperatures, as in fire, their properties may deteriorate. The main effects of fire may be considered as loss in compressive strength, cracking and spalling of concrete, destruction of the bond between the cement paste and the aggregates as well as the gradual deterioration of the hardened concrete[1].

Elevating the temperature results in decreasing the strength of concrete is decreased up to failure depending on the temperature and exposure time. The first effects of a slow temperature rise in concrete will occur between 100 and 200°C when the free moisture, contained in the concrete mass, evaporates. Direct exposure can result in spalling through generation of high internal steam pressures. As the temperature approaches 250 °C, dehydration or loss of the non-evaporable water begins to take place. Sizable degradation in compressive strength is usually experienced between 200 and 250 °C [2, 3]. At 300 °C the strength reduction is in the range of 15-40%. At 550°C the reduction in compressive strength would typically range from 55-70% of its original value[2, 3]. The range between 400°C and 800°C is critical to the strength loss of NSC[4]. At a temperature over 600°C, all tested concretes suffer deterioration and only a small value of the initial strength is left[2, 5].

The results of recent studies shown that, high-strength concrete HSC behavior at elevated temperature may be significantly different from that of NSC[6-10]. The behavioral differences between HSC and NSC are found in two main areas. The first is the relative strength loss in the intermediate temperature range (100 °C to 400 °C). The second is the occurrence of explosive spalling in HSC specimens at similar intermediate temperatures. In terms of strength loss, studies have shown that, for intermediate temperatures between 100 °C and 400°C, the compressive strength of HSC may be reduced by close to 40 % of the room-temperature strength with a reduction of approximately 20-30 % more than in NSC exposed to the same temperatures[6-9].

Two main types of spalling occur during fire namely explosive spalling and sloughing off of concrete affecting on surface layers. Explosive spalling looks like a series of pop outs and usually occurs within the first 30 min of fire-exposure. Sloughing off is a gradual non-violent separation of the concrete that occurs primarily at the edges of columns and beams[11]. Laboratory tests showed that HSC has a significantly higher potential for explosive spalling than NSC, even at heating rates less than 5°C/min which are lower than that would occur during real fires[7, 8, 12-15]. That may refer to the inability of HSC, due its low permeability and due to mitigate the build up of internal pressure as free water and chemically-combined water are vaporized with increasing concrete temperature. The tendency for explosive spalling of HSC means that HSC
structural elements may be more susceptible than NSC in losing the concrete cover that provides thermal protection for the steel reinforcement. Adding polypropylene fibers PP to concrete mix is much more effective in minimizing spalling in HSC under fire exposure and enhances fire endurance [16-18]. None of the current codes addresses the tendency for explosive spalling of HSC.

The effects of high temperatures are generally visible in the form of surface cracking[2, 11]. The surface cracks became visible when the temperature reached 600°C[19]. The results of compressive test show that the concrete's fire residual compressive strengths are very low. The reduction has reached 70% when heating temperature exceeds 700°C. The cracks become very pronounced at 800°C and increase extremely when the temperature increased to 1000°C[20].

One of the recently used concretes is high strength concrete (HSC) and high-Performance Concrete (HPC). These are considered to be the strongest and stiffest cement based material with a compression strength of approximately 60 MPa, a flexural strength of about 10 MPa, and a Young's modulus of 14 to 42 GPa. Now, given the improvements on a microscopic scale, Ultra-High Performance Concrete (UHPC) can attain compression strengths higher than 120 MPa, flexural strengths of about 30 to 50 MPa and Young's modulus of 50 to 60 GPa[21].

Reactive Powder Concrete (RPC), which is UHPC, lies at the front in terms of innovation, aesthetics and structural efficiency[22]. The technology of the RPC is considered as on type of UHPCs. This new concrete type has compressive strengths of 150-230 MPa and flexural strengths of 30-50 MPa, depending on the type and amount of fibers used[21, 23]. Additionally, the material has a tensile strength in the range between 6-13 MPa that is maintained after first cracking (tensile strengths of traditional concrete ranges from 0.2-4 MPa)[24].

At the very beginning, the easiest way to reach high compressive strength is to reduce the water–cement ratio. Therefore, in HSC, the fifth ingredient, a water reducing agent or super plasticizer, is indispensable[25]. RPC is composed of cement and very fine powders such as crushed quartz and silica fume. RPC also has an ultra-dense microstructure as ultra high strength concrete. RPC based on the densest packing theory with heat curing is investigated and it is observed that it exhibits compressive strength of more than 200 MPa with great ductility[26].

Reactive Powder Concretes are characterized by a high silica fume content and very low water to cement ratio. Very fine granulometry sand and heat treatment are optimized to obtain excellent mechanical and durability properties. Their composition is ordinary Portland cement OPC, silica fume, aggregates as very fine sand with average grain diameter of 250μm, crushed quartz (average grain diameter of 10μm). In order to increase concrete ductility and flexural strength, metallic fibers can be added[27, 28].

The fire performance of RPC is of importance and necessary to be investigated prior to the application to building construction. Liu and Huang.[29] are conducted a series of fire resistance tests. It is found that the residual compressive strength of RPC decreases with increasing fire duration.

Given the many benefits of UHSC and RPC and their increased use in structural applications, it is essential that the fundamental behavior of them at elevated temperatures be understood to ensure that structural fire design involving RPC will be safe. This paper presents available test data on effects of elevated temperature on RPC, including compressive and tensile strength.

2. Research Significance

The main aim of this research is to investigate the performance of an economical type of reactive powder concrete RPC under the effect of elevated temperature. The economy is performed by using valid sand from North Sinai and cheap type of steel fibers as discussed in the given section. The main variables in this investigation are: cement content, steel fiber content, heating temperature and heating time.

The significance of this research is based on current research needs to addressing the behavior of RPC generally and this type especially under the effect of elevated temperature in order to use RPC as pre-cast concrete elements. This research provides data for the researchers concerning the influence of elevated temperature as well as heating time on the main properties of RPC with and without a cheap valid type of steel fibers.

3. Experimental Program

All tests in this research were carried out in the Construction Materials Laboratory in Civil Engineering Department, Faculty of Engineering Science, Sinai University.

The materials used and how to preparing, casting, curing of testing specimens and testing procedures were discussed in this section.

3.1. Materials

The cement used is the ordinary Portland cement CEM I 52.5 N, from the Sinai cement factory and satisfy the Egyptian Standard Specification (E.S.S. 4756-1/2009). The fine aggregate used is the natural siliceous sand that satisfies the Egyptian Specification (E.S.S. 1109/2008). It is clean and nearly free from impurities with a specific gravity of 2.64 t/m³. It is obtained from El-Arish City in North Sinai, Egypt. Its small maximum nominal size (0.6 mm) is suitable to be used in casting RPC. Its mechanical properties are shown in Table (1) and its grading is shown in Table (2) and Figure (1). All the sand used is sieved over sieve of size 0.6mm to discard any possible impurities.
Drinkable clean water, fresh and free from impurities is used for mixing and curing the tested samples according to the Egyptian code of practice.

Silica fume used is a waste by-product of silicon and silicon alloys industry. It consists mainly of non-combustible amorphous silica (SiO₂) particles. It is produced by Egyptian Ferro Alloys Corporation (EFACO). The chemical components analyses are given in Table (3) and the main properties are shown in Table (4). The silica fume used is met the main requirements of ASTM C 1240.

A high-range water-reducing (HRWR) admixtures, super-plasticizer (S.P.), is used to help in increasing the workability of concrete without additional amount of water. A naphthalene sulphonate group based super-plasticizer, supplied by Chemicals for Modern Buildings (CMB) Company, and under the brand name of Addicrete BVF is chosen to be used in this study. Its main properties are shown in Table (5). The used super-plasticizer complies with ASTM C494-Type F and E.S.S. 1899-1.

### Table 1. Physical properties of the sand used

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific weight (t/m³)</td>
<td>2.64</td>
</tr>
<tr>
<td>Volumetric weight (t/m³)</td>
<td>1.62</td>
</tr>
<tr>
<td>Voids ratio (%)</td>
<td>39.8%</td>
</tr>
<tr>
<td>Percent of clay, silt and dust (by weight)</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

### Table 2. Grading of the sand used

<table>
<thead>
<tr>
<th>Sieve size(mm)</th>
<th>0.6 mm</th>
<th>0.3 mm</th>
<th>0.15 mm</th>
<th>0.074 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve No.</td>
<td>No. 30</td>
<td>No. 52</td>
<td>No. 100</td>
<td>No. 200</td>
</tr>
<tr>
<td>% Passing</td>
<td>100</td>
<td>82</td>
<td>49</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The steel fibers used in this investigation are clean of rust of straight steel wire fibers. A high tensile type with ultimate tensile strength up to 1200 MPa that are normally used for UHSC but in this research a mild steel fibers is used as shown in Table (6). The steel wires are cut into 13 mm length fibers from steel wires, locally used in Egypt to tie steel rebars to stirrups as a cheap type. The fibers used are of 0.8 ±0.02 mm in diameter despite of the diameter that usually used in nearly all the researches in producing the reactive powder concrete RPC which is 0.2 mm. The aspect ratio of the steel fiber used is 16.25. This type of fiber is cheap compared to the other types of steel fibers. It used based on the studies of Arab, 2012[33]. The properties of the steel fibers used are shown in Table (6).

### Table 5. Technical information of Addicrete BVF (As Provided by Manufacturer)

<table>
<thead>
<tr>
<th>Base</th>
<th>Appearance</th>
<th>Density</th>
<th>Chloride content</th>
<th>Air entrainment</th>
<th>Compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphthalene sulphonate</td>
<td>Brown liquid</td>
<td>1.18±0.01 kg/litre</td>
<td>Nil</td>
<td>Nil</td>
<td>All types of Portland cement</td>
</tr>
</tbody>
</table>

### Table 6. Mechanical properties of the steel fibers used. (According to tests)

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>Yield Stress (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Modulus of Elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Fibers</td>
<td>289</td>
<td>389</td>
<td>21.6</td>
<td>201</td>
</tr>
</tbody>
</table>
3.2. RPC Manufacturing

The mixture ratios are based on guidelines given in several researches as presented in section 1. Mixture proportions used in this test program are summarized in Table (6). The first mix, coded by (M), is cast without steel fiber content while the second group, coded by (F), is cast using steel fibers content of 40kg/m³ which is chosen in accordance to the researches of (Reeves, 2004; Arab, 2012)[32, 33]. For each group (M and F) three cement contents are used as shown in Table (7). The mechanical properties of RPC mixtures used are shown in Table (8).

The process of concrete mixing is performed using a ring concrete mixer of 7 liters capacity. It includes the following steps; weighting the mixture components carefully then, mixing sand and cement to obtain homogenous mix (about 1 minute) followed by adding silica fume to the mix. For mixes containing steel fibers, these are added to the dry mix. After that, mixing the water and the super-plasticizer then, adding to the dry contents in the drum and then mixing.

The compaction process is performed by means of a concrete vibrator board. Needle vibrator strokes are distributed uniformly over each concrete layer in the mould then the standard rod is used to ensure the best compaction especially for the final layer. After the compaction process, the excess concrete are removed and the surface is finished.

The specimens are de-molded on the next day after casting after 24 hours of in-mould curing. Specimens are cured at water of a temperature of about 75°C for 3 days then, in 25°C for another 3 days. After that, those specimens are removed from the water to a dry place till the testing ages. For maintaining uniform curing all the specimens are cured in the same curing conditions.

3.3. Elevated Temperature and Testing Methodology

Three specimens representing same constituent are used for each test throughout this study and the average values are reported.

At 28 days, a control set of unheated samples is tested for compressive and splitting tensile strength as shown in Figure (2). Other specimens are heated in an electric furnace of 1200°C capacity as shown in Figure (3) at a heating rate of 10°C/min to target temperature. Three target temperatures; namely, 200, 300, 500°C are used. At each target temperature, the specimens are maintained for two durations of 2 and 4 hours.

After exposure to the specified temperature, the specimens are allowed to cool at laboratory room temperature for 24 hours then they are tested to assess the residual strength after 1 day. The specimens are tested under dry surface condition. For each data point of the test, three identical specimens are used to guarantee repeatability in all tests.

**Compression Test:** Cube specimens of dimensions 100x100x100 mm, are prepared for evaluating the compressive strength. A 2000 KN capacity compression testing machine is used.

**Tension Test:** Cylindrical concrete specimens, 100 mm in diameter and 200 mm in high, are prepared to evaluate the tensile strength. Indirect tension test (splitting method) is performed to determine the tensile strength of concrete mixes. A 2000 KN capacity compression testing machine is used.

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### Table 7. Proportions of different mixtures of RPC used

<table>
<thead>
<tr>
<th>Mix Code</th>
<th>Cement (kg/m³)</th>
<th>W/C 18% (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>S.P. 10% C (kg/m³)</th>
<th>Silica fume 30% C (kg/m³)</th>
<th>Steel Fiber Content (kg/m³)</th>
<th>Curing process</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>700</td>
<td>126</td>
<td>1250</td>
<td>70</td>
<td>210</td>
<td>--</td>
<td>at 75°C for 3 days then, at 25°C for other 3 days</td>
</tr>
<tr>
<td>M2</td>
<td>750</td>
<td>135</td>
<td>1250</td>
<td>75</td>
<td>225</td>
<td>--</td>
<td>at 25°C for other 3 days</td>
</tr>
<tr>
<td>M3</td>
<td>800</td>
<td>144</td>
<td>1250</td>
<td>80</td>
<td>240</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>700</td>
<td>126</td>
<td>1250</td>
<td>70</td>
<td>210</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>750</td>
<td>135</td>
<td>1250</td>
<td>75</td>
<td>225</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td>800</td>
<td>144</td>
<td>1250</td>
<td>80</td>
<td>240</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

### Table 8. The mechanical properties of RPC mixtures used

<table>
<thead>
<tr>
<th>Mix</th>
<th>Compressive Strength (MPa) 7 days</th>
<th>Compressive Strength (MPa) 28 days</th>
<th>Modulus of Elasticity (GPa) 7 days</th>
<th>Modulus of Elasticity (GPa) 28 days</th>
<th>Tensile Strength (MPa) 7 days</th>
<th>Tensile Strength (MPa) 28 days</th>
<th>Flexural Strength (MPa) 7 days</th>
<th>Flexural Strength (MPa) 28 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>80</td>
<td>86.8</td>
<td>30.81</td>
<td>31.58</td>
<td>6.94</td>
<td>7.1</td>
<td>7.9</td>
<td>8.2</td>
</tr>
<tr>
<td>M2</td>
<td>101.5</td>
<td>107.5</td>
<td>34.52</td>
<td>35.44</td>
<td>8.55</td>
<td>8.74</td>
<td>10.6</td>
<td>11.3</td>
</tr>
<tr>
<td>M3</td>
<td>134.5</td>
<td>139.15</td>
<td>40.13</td>
<td>40.99</td>
<td>10.02</td>
<td>10.11</td>
<td>12.1</td>
<td>12.5</td>
</tr>
<tr>
<td>F1</td>
<td>93</td>
<td>101.7</td>
<td>34.36</td>
<td>35.45</td>
<td>9.02</td>
<td>9.16</td>
<td>19.67</td>
<td>21.51</td>
</tr>
<tr>
<td>F2</td>
<td>120.5</td>
<td>126.5</td>
<td>39.88</td>
<td>40.95</td>
<td>9.92</td>
<td>10.1</td>
<td>20.16</td>
<td>23.9</td>
</tr>
<tr>
<td>F3</td>
<td>146.3</td>
<td>149.5</td>
<td>44.38</td>
<td>45.10</td>
<td>10.8</td>
<td>11</td>
<td>22.46</td>
<td>26.4</td>
</tr>
</tbody>
</table>
4. Test Results and Discussions

Test results are provided in terms of compressive strength and indirect tensile strength. Based on the data given in Table (8), the using of steel fibers enhances the strength of RPC especially tensile strength at room temperature. The values of compressive, tensile and flexural strengths at 28 days tests enhanced by about 4-10% compared to 7 days test results. It means that, the one can consider the results of 7 days test results despite of using 28 days test results. Percentages of loss in compressive strength values for RPC are given Table (9) while percentages of loss in tensile strength values are shown in Table (10).

4.1. Influence of Temperature and Heating Time

Figures (4) to (5) illustrate that the compressive strength values of samples M1 and M2 increases up to 200°C then drops as temperature and heating time increases starting from 200°C in this research, in agreement with (Toumi et al, 2009)[34] and (Long et al, 2000)[35], while strength values of other samples drop with target temperature and heating time. According to these results, as the temperature is increased up to 200°C for 2 hours heating time, there is a little increase of compressive strength of 6.9% and 1.6% for M1 and M2 also, splitting tensile strength increased at 200°C for M1 and M2 by about 2.8% and 0.7% respectively. Previous studies indicate the increase in normal and medium strength concrete at the range of 200°C, this is caused by the promoted hydration of binder and evaporation of free water and removal of water of crystallization from the cement paste (but it may create micro-cracks in the paste)[36] which may applied for samples M1 and M2. Other samples of this RPC behave nearly the same as high strength concretes HSC, but with greater loss in strength values as compared to HSC.

Test results indicate also that, when the temperature increases up to 300°C for 2 hours heating time, there is a remarkable decrease of compressive strength. For this heating time and for the temperatures of 500°C, samples are exploded.
As shown in Table (9), for a heating time of 2 and 4 hours at 300°C, all tested concretes have revealed a compressive strength loss. The largest value of compressive strength loss is 55.4% for M3 (4 hours) and 53% for F3 (4 hours) when cooling in room temperature. For a heating time of 2 and 4 hours at 500°C, all samples are exploded.

According to (Phan et al., 2001; Ali, 2002)[4, 37], explosive spalling of HSC occurs in the temperature range between 300 and 650°C (about 470°C in this research). Many factors are identified as affecting explosive spalling. These factors include age, moisture content, type of gravel and sand used, curing method and rate of heating.

From Table (9) and Figures (6) and (7), it can be seen that a like the compressive strength, the tensile strength is reduced after elevating the temperature. The smaller values are recorded for M1, M2 and M3. The largest values of decreasing in tensile strength are obtained for M3 as 50.5% (at 4 hours) and for F3 as 55% (at 4 hours).

Increasing the heating time from 2 hours to 4 hours decreases the compressive strength values (Table (9) and Figures (8-10) and (14-15)) and splitting tensile strength values (Table (10) and Figures (11-13) and (16-17)) which agrees with previous researches[19, 29, 34, and 35].

![Figure 6](image6.png)  
**Figure 6.** Effect of elevated temperature for 2 hours of heating time on tensile strength of RPC samples

![Figure 7](image7.png)  
**Figure 7.** Effect of elevated temperature for 4 hours of heating time on tensile strength of RPC samples

![Figure 8](image8.png)  
**Figure 8.** Effect of heating time at 200°C on compressive strength of RPC samples

![Figure 9](image9.png)  
**Figure 9.** Effect of heating time at 300°C on compressive strength of RPC samples

![Figure 10](image10.png)  
**Figure 10.** Effect of heating time at 500°C on compressive strength of RPC samples

![Figure 11](image11.png)  
**Figure 11.** Effect of heating time at 200°C on tensile strength of RPC samples
4.2. Effect of Cement Content

One hundred millimetre cubes are heated according to the conditions in section 4.3 at 200°C, 300°C and 500°C, after which they are stored in air for 1 day. Table (9) and (10) and Figures (4) to (7) illustrate that, the strength increases by increasing cement content for the type of concrete samples with and without fibers up to 750Kg/m³. When the cement content becomes 800Kg/m³, the loss in strength increased as the temperature increased. The increasing of strength decreased the residual strength of RPC due to elevated temperature. Explosive spalling of RPC occurs in a temperature of about 470°C in this research. Increase the cement content decreasing the spalling temperature due to the increasing of the concrete strength as mentioned previously in review.

4.3. Effect of Fiber Content

As can be seen from Tables (9) and (10) and Figures (4) to (7), in general the using of this specific steel fiber enhances the initial values of compressive and tensile strength of RPC. As the temperature is elevated, the compressive and tensile strength values of samples containing steel fibers decreases compared to those without fibers for cement content up to 750Kg/m³. Steel fibers enhance the behavior when the strength is increased due to increasing of cement content to 800Kg/m³ due to the increase of stresses which it may help to carry it. These results may comparable with those when using polypropylene fibers as a solution for spalling.
resistance despite of fiber behavior in high temperature (steel fiber enhance tensile properties, while PP melt and create channels through which the water vapor pressure built-up within HPC as temperature rises is released, which significantly reduces the spalling tendency of HPC under fire conditions)[16-18].

5. Conclusions

In this research, a series of experiments have been performed to investigate the residual strength of RPC subjected to elevated temperatures ranging from 200 to 500°C for two heating durations, 2 and 4 hours. Based on the experimental results presented in this research, the following conclusions may be obtained from this study:

1. The residual strength of RPC decreases as the exposure temperature increases.
2. Increasing heating time decreases the residual concrete strength.
3. Increasing the cement content increases the initial strength of RPC but decreases the residual strength values after heating as the temperature and heating times increased.
4. The steel fibers enhance the mechanical properties of RPC at room temperature up to 150°C. Increasing the temperature decrease the residual strength.
5. Using steel fibers enhance the residual strength of RPC samples of high cement content of 800kg/m³.
6. RPC samples with cement content up to 750Kg/m³ behave nearly the same as normal strength concrete (residual strength increased up to 200°C then drops up to target temperature). Increasing cement content up to 800kg/m³ decreases the residual strength after exposure to elevated temperature.

Finally, one can use RPC as pre-cast concrete elements in elevated temperatures up to 300°C taking into consideration the loss of strength by values up to about 55%. Over that degree, RPC is not recommended to use.

REFERENCES

[9] L.T. Phan, J.R. Lawson, F.R. Davis, Effects of Elevated...


