HYBRID POLYPROPYLENE-STEEL FIBER REINFORCED CONCRETE AT HIGH TEMPERATURES

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Abstract

Extreme environmental conditions, such as exposure to high temperatures, are serious potential risks for buildings and structures. The behavior of concrete, after exposure to a high temperature, depends upon the specific concrete mix proportions, the constituents used and the physicochemical transformations that the heating generates. Within this context, the damage, after thermal treatments, in cement-based matrices was studied using compression and three-point bending tests. Four types of cement based composites were constructed using fiber combinations of polypropylene and steel fibers. The maximum temperature reached using an electric furnace was 750°C. Intermediate temperatures were set at 250 and 500 °C. Compressive and bending strengths, were determined and fracture behavior was studied using interferometric measurements. For the considered combinations, it was demonstrated that a hybrid combination of steel and polypropylene fibers appears to be not particularly effective in enhancing the performance of concrete at high temperatures. Explosive spalling was not observed in concrete specimens during the thermal treatment.

1. Introduction

High strength concrete is a material with enhanced properties that offers significant advantages over ordinary concrete and can fit several requirements for structural applications. However, well known are the low tensile strength and deficient fracture toughness that can be corrected with randomly distributed short fibers [1]. The addition of steel micro-fibers usually improve these essential features. Polypropylene fibers are extensively used when a crack prevention of concrete is required, but they result useless for the reinforcement of cement based materials due to their unsatisfactory properties. However, polypropylene, a relatively inexpensive polymer, remains an attractive raw material that can be used combining high modulus steel fibers with low modulus polypropylene fibers, that develop a full reinforcement capability only at large crack openings [1-2].

One of the major problems for buildings and structures is the exposure to high temperatures. Concrete, the most widely used construction material, is sensitive to thermal effects [3-7]. For example, under high temperature conditions, it is well established that the behavior of concrete is affected by factors such as heating rate, peak temperature and constituent materials [3-10]. Therefore, to assess the structural safety after a fire, it is essential that the residual mechanical
properties of concrete after cycles at a high temperatures be well known. Within this context, the purpose of this paper is to evaluate the benefits of a fiber hybridization \[11-14\], that is the influence of polypropylene fibers may cause to a steel fiber reinforced concrete after exposure to a single cycle at high temperatures (T= 20, 250, 500 and 750 °C). The overall behavior in uniaxial compression and bending is considered. The properties are evaluated with unstressed residual-strength tests characterized by an heating, without pre-load, up to the prescribed temperature. After the cooling, the load is applied at room temperature until the specimen failure. Particular attention will be posed on the evolution of cracking with the load increasing. Therefore, the tests will be monitored with interferometric laser measurements (ESPI). The development of the damage zone in terms of shape and size was established with this sensitive nondestructive testing technique. Fiber hybridization with polypropylene fibers appears to be not particularly effective in enhancing the efficiency of a steel reinforcement. A weakening effect was the results of adding polypropylene fibers to concrete due to the introduction of fibers of poor mechanical properties and additional defects during the processing.

2. Experimental Techniques

2.1. Mix Designs and Test Specimens
Mix-components of the cement-based materials used for this investigation can be summarized as follows: a Portland cement CEM I 52.5 R, according ENV 197/1 European Standard; an uncompacted grey microsilica; an acrylic copolymer superplasticizer, 30% solid content; a natural crystalline quartz of high purity (99% SiO\(_2\)), maximum aggregate size of 3 mm; carbon steel microfibers, diameter 0.15 mm, length 13 mm; monofilament type of polypropylene fibers, diameter 0.18 μm, length 12 mm. The concrete had an aggregate/binder ratio of 2 and a water/binder ratio of 0.22. The superplasticizer dosage, that is the ratio between the dry mass of superplasticizer solids and the mass of cement, was 0.02. The microsilica/binder ratio was 0.1; the steel fiber (SF) contents were 0 and 2 % by volume; the polypropylene (PF) fiber contents were 0 and 0.2 % by volume. The fiber contents by volume of concrete for each batch of specimens are listed in Table 1.

All specimens were prepared using steel molds and consolidated with a high frequency vibrating table, demolded after 24 h, and cured in water at a temperature of 20°C for one week and in air (20°C and 90% R.H.) for three weeks.

Table 1: Fiber contents for each batch of specimens.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Polypropylene Fibers (%)</th>
<th>Steel Fibers (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PF</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>SF</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>SFPF</td>
<td>0.2</td>
<td>2</td>
</tr>
</tbody>
</table>

An electric furnace was used for the thermal treatment: the maximum temperature reached was 750°C. Intermediate temperatures were set at 250 and 500°C. The ramps (Fig. 1) were chosen in order to avoid high gradients: in this way, the specimens were warmed up to the fixed temperature at a speed of 1°C/min, and, after two hours at the peak temperature, they were cooled at a speed of about 0.5°C/min. The considered thermal treatment is coherent with standard proposed methods of assessment of fire resistance [15].

Closed-loop, uniaxial compression and bending tests, at least three specimens for each
geometry and thermal treatment, were performed. The compression tests were controlled with the hoop displacement whereas the bending tests were controlled, using a clip gage, with the crack opening displacement (COD). Figs 1a and 1b show the test setup and the instrumentation used for the compression tests and tensile tests, respectively.

The specimen sizes for the compression tests were prism 50 x 50 x 100 mm, whereas the specimen dimensions for the beam tests were 30 x 100 x 500 mm. All peak stresses were calculated considering the effective working section.

2.2. Testing Apparatus
The testing system consisted of a closed-loop electromechanical testing machine with a maximum capacity of 100 kN. The main characteristics are
a. electromechanical controls with a minimum speed of 2 μm/hour;
b. three control channels, one of which can be external (giving the possibility to choose the feedback signal that allows a stable test control);
c. closed-loop control with integral and derivative gain (in order to remove the effect of the finite stiffness of the machine).

2.3. Strain Measurement
A full field strain measurement technique is required to observe localization. For this reason, the Electronic Speckle Pattern Interferometry (ESPI) technique was used in these tests with the following components: a Melles-Griot He-Ne laser (wavelength λ = 632 nm, P = 30 mW), a Panasonic WV BP310/G CCD camera, and a DT-2861 frame grabber.
ESPI is an interferometric method used to measure a deformation field of diffusely scattering objects. When an optically rough surface is illuminated by a laser beam, a random pattern of irregular or regular dots is observed. This phenomenon is called a laser speckle pattern. On the scale of the wavelength of the illuminating light, almost all materials have a rough surface. In this technique, two laser beams are used to illuminate the object, so that, by combining the object speckle and the reference beam, it is possible to obtain a brightness of the image speckle very sensitive to specimen movement. The ESPI technique consists of electronic image detection and computer fringe analysis. Real-time correlation fringes can be observed directly on a monitor, as the speckle patterns are electronically stored. Furthermore, continuous data-acquisition allows a comparison of any two loading stages by a numerical treatment of the
digitized data (at the two stages). A unique feature of ESPI is the possibility to obtain correlation fringes that can be displayed on a monitor for real-time observation.

In an ESPI test, by superimposing a reflected light to a reference beam, an interference phenomenon is produced. The resulting interference fringes provide the measure of the light path difference between the two beams as multiples of the wavelength, \( \lambda \). In this way, by comparing two recorded interference patterns before and after an object displacement, the deformation can be evaluated. The displacement vector field is evaluated by illuminating the specimen from different points of view. The image of the object is acquired by a camera and transmitted to a monitor through a frame grabber image processing board controlled by a personal computer.

3. Experimental Results

3.1. Compression Tests

The experimental results are summarized in Table 2, while their graphical representation is exhibited in Fig. 2.

Table 2: Compressive strength

<table>
<thead>
<tr>
<th>Temperature</th>
<th>NF (MPa)</th>
<th>PF (MPa)</th>
<th>SF (MPa)</th>
<th>SFPF (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 °C</td>
<td>95.89</td>
<td>69.00</td>
<td>116.14</td>
<td>84.33</td>
</tr>
<tr>
<td>250 °C</td>
<td>107.58</td>
<td>74.83</td>
<td>128.66</td>
<td>67.34</td>
</tr>
<tr>
<td>500 °C</td>
<td>47.48</td>
<td>34.70</td>
<td>63.49</td>
<td>46.37</td>
</tr>
<tr>
<td>750 °C</td>
<td>20.56</td>
<td>20.23</td>
<td>25.24</td>
<td>21.16</td>
</tr>
</tbody>
</table>

Polypropylene fibers, characterized by a low modulus, had little influence in a strong system composed of a high performance matrix with or without steel microfibers. The detrimental influence on the compressive strength, perhaps caused also by introduction of additional defects during the processing stage, after all thermal treatments is visible in Fig. 2: the addition of polypropylene fibers yielded the lowest strength.

![Figure 2: Compressive strength as a function of temperature.](image-url)
In any case, till 250 °C, all the materials maintained their original compressive strength. Apart from strength, an advantage of the hybrid system could be lower decay, and with the increase in thermal treatment, a reduced brittleness in the post-peak regime. After the cycle at 750 °C the different specimens gave the same residual strengths. The steel microfibers did not affect the strength and post-peak response due to a change in poor behavior in term of strength and ductility.

3.2. Bending Tests

Typical load-displacement curves for specimen made of different mixtures and for a given thermal cycle are shown in Fig. 3 together with crack pattern observed at the peak load on the surface of the specimens.

![Figure 3: Load-displacement curves and ESPI images at the peak loads](image-url)

Figure 3: Load-displacement curves and ESPI images at the peak loads (a) undamaged materials (b) 250°C (c) 500°C (d) 750.
For the beams made of plain concrete without any exposure to high temperatures, the behavior is quite brittle and the post-peak response tends to be nonrecoverable due to the pronounced brittleness. After a thermal treatment to high temperatures, both strength and brittleness decreased. Significant improvement in the mechanical behavior can be achieved when fiber reinforcement is added in the concrete composition. An enhancement in strength and strain capacity characterized the fiber-reinforced specimens (generally much more stable responses were obtained). The evolution in strength and brittleness were similar for all the specimens. Fig. 4 shows, as a function of maximum temperature of thermal treatment, the variation of average bending strength of tested specimens. Similar to compressive strengths, after the cycle at 750 °C, the different specimens gave the same residual bending strengths. In particular, the steel microfibers became weak and brittle and the specimens showed a response not influenced by fibers. This is shown in Fig. 5 where pictures of tested specimens, submitted to different thermal treatment, are compared. No fiber pullout was visible in the specimen treated at the highest temperature and the samples of steel fiber reinforced concrete consisted of two independent parts.

![Figure 4: Bending strength as a function of temperature.](image1)

![Figure 5: Pictures of tested specimens.](image2)
4. Discussion

A severe deterioration was observed after an exposure at 750°C, with a visible network of fine surface cracks. No explosive spalling was detected in the concrete, during the thermal treatments and only a visible change in colour (Fig. 6) was observed. Therefore, the significant increase in volume associated with the phase transition from \( \alpha \) to \( \beta \) quartz at 573 °C did not cause disruptive effects on specimens even if made of unreinforced material.

![Figure 6: Change in color due to thermal treatment.](image)

To discuss the residual nominal tensile strength, it is necessary to characterize the evolution of damage at the peak load as a function of temperature. For the unreinforced material, ESPI measurements showed that, at the peak load, the specimens exhibited small cracks. Steel reinforcement improved fracture energy and tensile strength (Fig.7).

![Figure 7: Crack penetration at the peak load at different temperature – no fibers (upper) – steel fibers (bottom).](image)
Conversely, polypropylene fibers caused a clear reduction in strength, as shown in Fig. 2. Therefore strengthening and weakening effects can be the opposite effects of adding fibers to concrete. Usually, strengthen the matrices because their crack-bridging capability but an excess of fibers may be equivalent to an introduction of additional defects. Hence, if an optimum mixing and packing of particles and fibers is not achieved, fibers of not enhanced properties can produce concrete of reduced mechanical properties.

For the bending tests, it is interesting to evaluate the length of the fringe discontinuity and the development of the damage zone in terms of shape and size at the peak load; the observed values of crack penetration were quite different for the specimens with or without fiber reinforcement (Fig. 8).

![Figure 8: Crack penetration as a function of maximum temperature.](image)

For the beams made of the plain material and polypropylene fibers reinforced materials, the length was almost constant, that is, independent of the severity of thermal treatment. In the steel fiber-reinforced beams (with or without polypropylene fibers) damage evolution is already significant in the pre-peak range and, at the peak load, the length of the fringe discontinuity was related to maximum temperature reached (Fig. 8). A decreasing length with the severity of thermal treatment was detected. In addition, the experimental evidence showed that, at the peak load, the localized region increased with the maximum temperature reached.

From a mechanical point of view, this behavior justifies a reduced notch effect in the critical cross-section of the beam, which means a lower stress gradient in the undamaged volume.

At the complete load relaxation in bending tests, all samples of steel fiber reinforced concrete consisted of two parts still connected by fibers bridging the major crack. The crack bridging is operative from the pre-peak range to complete load relaxation. Conversely, the specimens made of plain material and polypropylene fibers reinforced materials were completely separated at ultimate loading.

5. Conclusions

Prismatic specimens of plain and fiber reinforced concrete were subjected to elevated temperatures up to 750°C. The following summarize the experimental observations from
uniaxial compressive and bending tests.

1. In compression, elevated temperatures up to 250°C did not produce a reduction in strength. After 250°C, the concrete lost strength rapidly.
2. In bending, only for steel fiber and hybrid fibers concrete a significant reduction in strength was detected already at 250°C.
3. A severe deterioration was observed after an exposure at 750°C, with a visible network of fine surface cracks. Noticeable an evident damage of steel reinforcement, too weak and brittle for a significant strengthening effect of the concrete matrix.
4. Fiber hybridization, that is combining fibers of similar sizes but different moduli, such as high modulus steel fibers with low modulus polypropylene fibers at the considered dosage rates appears to be not particularly effective in enhancing the efficiency of the steel reinforcement. Only a more progressive reduction of mechanical properties due to the progressive alteration of the internal structure of the concrete was observed after the thermal treatment at high temperatures.
5. No explosive spalling was observed in the concrete, during the treatment.

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References


