Mechanical Characteristics of High Performance Fibre Reinforced Concretes at Elevated Temperatures

By K. K. Sideris, P. Manita, A. Papageorgiou and E. Chaniotakis

Synopsis: Mechanical characteristics of High Performance Fibre Reinforced Concrete subjected to elevated temperatures up to 700 °C were experimentally investigated in this paper. Three different concretes were prepared: a normal strength concrete (NSC with nominal 28 days strength of 40 MPa) and two High Performance Concretes (HPC1 with 28 days strength of 82 MPa and HPC2 with 28 days strength of 94 MPa). Fibre reinforced concretes were produced by addition of steel or polypropylene fibres in the above mixtures at dosages of 40 Kg/m³ and 10 Kg/m³ respectively. A total of 9 concrete mixtures were produced and fibres were added in six of them. At the age of 4 months specimens were heated to maximum temperatures of 100, 300, 500 and 700 °C. Specimens were then allowed to cool in the furnace and tested for compressive strength, splitting tensile strength, modulus of elasticity and ultrasonic pulse velocity. Reference tests were also performed at air temperature (20 °C). Residual strength of NSC and HPC1 was reduced almost linearly up to 700°C and 500 °C respectively but the latter had an explosive spalling at 700 °C. Residual strength of HPC2 was sharply reduced up to 300 °C and explosive spalling occurred at higher temperatures. Addition of steel fibres increased the percentage of residual strength up to 300 °C but spalling still occurred in HPC1 and HPC2 at 700 °C and 500 °C respectively. Such an explosive behavior was not observed when polypropylene fibres were added in the mixtures.

Keywords: Concrete, high performance concrete, silica fume, fire resistance, spalling, steel fibres, polypropylene fibres.
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INTRODUCTION

Reinforced concrete is the most commonly used construction material worldwide. The need for high compressive strength concrete and increased service life of reinforced concrete structures led to the development of high performance concrete (HPC) through the last decades. High performance concrete is a typically concrete prepared with pozzolanic admixtures, such as silica fume, fly ash, slag, etc and low water to binder ratio. Nowadays, it is widely used throughout the world because of its superior strength and durability characteristics as compared to normal concrete. Although changes in the composition of HPC yield in most cases to a better durability performance, it may also lead to a material with brittle behavior under extraordinary exposure conditions such as in the case of fire (1-5). Recent fire, like under the Channel tunnel or more recently like the fires in tunnels in Central Europe showed that damage of HPC may be very serious. This is because HPC has the tendency to spall under certain thermal and mechanical stresses. Small spalls fall from the surface of the concrete as the temperature raises and a sudden failure of the concrete element could occur, accompanied by a large release of energy (explosive spalling). In both cases the load-bearing capacity of the structure is reduced, steel-reinforcement is exposed to fire and complete failure may ultimately occur. The significantly high potential of HPC to spall is observed by many researchers in laboratory tests (5-7) and is mainly attributed to the internal pore pressure buildup due to the vaporization of the free and chemically bound water (5). Since HPC has significantly finer pore structure compared to NSC this internal pressure is not released.
The addition of steel fibres is a common practice used to improve concrete performance. High performance steel fibre reinforced concrete (HPSFRC) is widely used in bridges and tunneling because of its superior performance in terms of ductility, energy absorption and delay of cracking initiation time. Despite its better overall performance, HPSFRC still has the tendency to spall, since addition of steel fibres does not improve the ability of the material to release the vaporized water.

This spalling tendency of HPC under fire conditions is a reason for inhibiting their use in buildings, bridges and tunneling and several safety considerations are raised. A lot of research has been carried out in order to model the spalling tendency of HPC and to propose some alternative solutions such as different mixture proportions or use of materials who provide a passive or active protection against spalling. Among the solutions proposed, the addition of polypropylene fibres seems to be an effective one (8-13). It was reported (14) that polypropylene melts at 160-168°C whereas HPC spalls between 190-250°C (5). Melting of polypropylene fibres creates therefore an additional pathway for drainage of internal vapor stresses at higher temperatures. It was reported (12) that a polypropylene fibre volumetric content of 0.2% significantly reduced spalling of HPCs.

In this paper the effect of high temperature on the mechanical characteristics and spalling tendency of different grades of concretes reinforced with 0.5% per volume of steel or polypropylene fibres is investigated.

**EXPERIMENTAL DETAILS**

Three different concrete grades named NSC, HPC1 and HPC2 were prepared using two classes of Ordinary Portland Cement (I 42.5N and I 52.5N according to European standard EN 197-1). Silica fume and lignite fly ash was also used for the preparation of the HPC2 mixture. The aggregates consisted of crushed granite with maximum size of 32 mm (NSC) and 8mm (HPC1 and HPC2). Steel fibres with hooked edges of dimensions 30/.60 mm and polypropylene filament fibres with a length of 30 mm were added both at a content of 0.5% per volume in all grade concretes. A high range water reducing carboxylic ether polymer admixture was added at different dosages in order to achieve a slump of 150-180 mm. The proportions of all mixtures are presented in Table 1.

The specimens prepared were 100mm cubes and 150x300 mm cylinders. All specimens were initially cured for the first 14 days in saturated lime water at 20±2 °C. For the next 14 days specimens were cured under wet burlaps at the same temperature. From this age onwards they were placed in the laboratory air environment (R.H. = 50-65% and T=20±2 °C). At the age of 4 months specimens were placed in an electrical furnace with heat applied at a rate of 5
°C/min until the desired temperature was reached. A maximum temperature of 100, 300, 500 and 700 °C was maintained for 1 hour. Specimens were then allowed to cool in the furnace and tested for compressive strength (cube specimens), splitting tensile strength, static modulus of elasticity (cylindrical specimens) and ultrasonic pulse velocity. The procedures followed were those described in ASTM standards C39, C496, C469 and C597 for compressive strength, splitting tensile strength, static modulus of elasticity and pulse velocity measurements respectively. Control tests were performed at air temperature (20 °C). Residual compressive strength was determined as the mean value of three cubes tested per temperature, whereas static modulus of elasticity and splitting tensile strength were determined as the mean value of two tested cylinders. Pulse velocity measurements were determined as the mean value of six measurements (two opposite sides of the cubes used for compressive strength measurements) at any temperature.

RESULTS AND DISCUSSION

Residual compressive strength is presented for all mixtures in Fig.1. Compressive strength of NSC is linearly reduced until 700 °C and no spalling occurred at any temperature. Compressive strength of HPC1 was also linearly reduced and it can be said that strength reduction was parallel to NSC (Fig.1). However, explosive spalling occurred above 500 °C and destroyed most of HPC1’s specimens (Fig.2). HPC2 mixture behaved differently against elevated temperatures. Its residual strength decreased sharply and it is noticeable that it was less than the corresponding strength of HPC1 at temperatures above 100 °C (Fig.1). Explosive spalling also occurred but this happened at lower temperatures (380 °C).

Kalifa et al (5) attributed the spalling behavior of HPCs at the increased vapor stresses developed in the interior of the specimens during heating. The researchers investigated the pore pressure development of different grade concrete (M30 and M100 with compressive strengths of 34.9±0.3 and 91.8±0.8 MPa respectively) subjected to temperatures up to 800 °C. They reported much higher pore pressures in M100 concrete at temperatures of 450, 600 and 800 °C attributed to lower permeability properties of HPC.

The concrete mixtures investigated in this study were of different permeability categories. NSC produced with the highest w/c ratio, had the greater permeability and for this reason was not characterized by a spalling behavior. On the contrary, explosive spalling occurred for both HPCs due to their low permeability. HPC1 had high cement content and low w/c ratio and explosive spalling occurred between 470 and 580°C. HPC2 was produced with the addition of silica fume and fly ash, both resulting to the formation of a denser microstructure with even lower permeability. This resulted to explosive spalling
behavior at lower temperatures (360 to 477°C). It is noticeable that no spalling occurred at temperatures higher than 580°C at any HPC mixture.

According to Y.N. Chan et al (7), there are three temperature ranges from the viewpoint of compressive strength loss: 20 to 400°C, 400 to 800°C and 800 to 1200°C. Chan et al investigated the behavior of three grade of concretes prepared with ordinary portland cement. They concluded that for all types of concretes, only a small part or the original strength was lost up to 400°C. This is valid for the portland cement mixtures (NSC and HPC1) tested in this research but not for the HPC2 mixture. The denser cement paste formed due to the addition of pozzolanic materials was more susceptible to the increase of internal pore pressure even from 100°C and changed the behavior of this mixture at a lower temperature range.

The addition of steel fibres does not significantly influence the behavior of residual strength in steel fibre reinforced normal strength concrete (SFRNSC) (Fig.1b). Residual compressive strength was linearly reduced up to 700°C. Spalling was also not observed in this mixture at any temperature.

Performance of SFRHPC1 was similar to that of HPC1 for temperatures less than 300°C. From this point onward, residual strength reduced sharply but spalling was only observed in two specimens at 560°C. Reduction in the residual strength of SFRHPC2 was also smaller for temperatures under 300°C. It could be claimed that for this temperature region the strength loss was negligible. Subsequently, the reduction of residual strength was very and explosive spalling occurred between 456 and 580°C.

The addition of steel fibres improved the behavior of SFRHPC2 at the low temperature range and reduced the spalling tendency of SFRHPC1 at the higher one. According to the authors’ opinion, steel fibres influence the mixture’s behavior under elevated temperature by two ways: steel fibre concretes are less workable and need more compaction; there is therefore additional porosity formed due to incomplete compaction and the threshold temperature for spalling was shifted to higher levels. On the other hand, steel fibres bridge the opposite faces of cracks initiated due to increased vapor pressure and project a more gradual degradation. Further investigation is now in progress in order to fully understand the way that steel fibres influence the spalling behavior of high performance mixtures.

The influence of polypropylene fibres on residual compressive strength of concretes is plotted on Fig.1c. As it was mentioned above, polypropylene fibres melt at 160-168°C, and in this manner an additional pathway is created for the internal vapor pressure to expand. This was crucial for PFRHPCs but not for
PFRNSC. PFRNSC lost its strength at a way similar to NSC and SFRNSC. It seems therefore that addition of polypropylene fibres did not influence the residual strength of PFRNSC at higher temperatures. The permeability of those mixtures was high enough to permit the drainage of vapor stresses and the additional pores that were created after polypropylene fibres melt, were not required to protect this quality of concrete. On the other hand addition of polypropylene fibres was crucial for both HPC mixtures. Their residual strength was sharply reduced at a similar way above 100 °C and no spalling took place until a temperature of 700 °C was achieved (Fig.3). Formation of additional pores led to rapid reduction of residual strength at the temperature range of 100 – 300 °C for both PFRHPC1 and PFRHPC2 mixtures. This is the temperature range in which fibres melt. Residual strength is further reduced in higher temperatures and this was observed more intensely for PFRHPC2.

Residual pulse velocity of three grades of concretes after different peak temperatures compared to the pulse velocity at air temperature (20 °C) is plotted at Fig. 4. A decrease in velocity indicates formation of additional pores due to initiation of cracks in concrete specimens. Factors that cause this type of failure (15) are a) the thermal stresses induced by thermal gradients b) the decomposition of calcium hydroxide (CH) in the cement paste c) the calcination of limestone aggregates or (as in this research) the phase transformation of quartz aggregates at elevated temperature.

Residual pulse velocity is reduced linearly from 20 °C to 700 °C in NSC (Fig. 4a). This was also observed in HPC1 and HPC2 mixtures but only for temperatures until 500 and 300 °C respectively. Explosive spalling occurred above those temperatures and there was only one cube left from each mixture at 700 °C. It is essential to note that residual pulse velocity remains higher in both HPC mixtures at any temperature achieved.

The addition of steel fibres led to a slight increase of pulse velocity at 100 °C in all mixtures (Fig. 4b). It is known that concrete loses its adsorbed water in the range of 60-85 °C and its interior water in the range of 80-100 °C (16). Pulse velocity should therefore decrease in this temperature range. A possible explanation for the observed increase could be the expansion of the steel fibres added in the mixtures. Velocity starts to decrease at higher temperatures for all mixtures but all steel fibre reinforced mixtures retained higher percentage of their initial pulse velocity at any temperature, even in 700 °C.

Pulse velocity of all polypropylene fibre reinforced mixtures decreased gradually from 20 to 700 °C. Polypropylene fibres melt in the range of 160-168 °C creating this way additional pores who are responsible for the higher loss observed in all mixtures. Residual velocity at any peak temperature was the same for all mixtures.
The percentage of residual static modulus of elasticity of all mixtures after subjected to different peak temperatures to the static modulus of elasticity at air temperature (20 °C) is plotted in Figs. 5a to 5c. Modulus of elasticity decreased normally up to 300 °C and at the same rate for all mixtures without fibres (Fig. 5a). Linear decrease continued after that point for HPC1 mixture but not for NSC; modulus of elasticity was sharply decreased in the range of 300 – 500°C in the latter and this mixture retained only 17% of its initial value at 700 °C.

Residual modulus of elasticity decreased linearly up to 700 °C in the case of SFRNSC but the percentage loss in the temperature range of 100-300 °C is higher than NSC. Both SFRHPC mixtures behaved in the low temperature range (20-300 °C) similarly to the HPC1 and HPC2. Residual modulus of elasticity of SFRHPC1 was further reduced in the temperature range of 300 – 500 °C.

The addition of polypropylene fibres did not influence the decreasing rate of residual modulus of elasticity of PFRNSC and PFRHPC1 (Fig. 5c). The behavior of PFRHPC2, compared to SFR mixtures was improved at all temperatures. This mixture retained higher modulus of elasticity values at any peak temperature. It is worth mentioning that the percentage of residual modulus of elasticity at the temperature of 700 °C was the same for all mixtures tested irrespective of the addition of fibres or the grade of concrete.

Residual splitting tensile strength was reduced up to 300 °C for all mixtures produced without fibres. Strength of NSC and HPC1 further reduced their strength and at the temperature of 500 °C both mixtures retained 78% of their initial strength. At the high temperature range, HPC1 mixture was destroyed and NSC lost an additional 40% of its initial strength (Fig. 1a).

The addition of steel fibres did not make any difference in the way NSC and HPC2 reduced their initial splitting strength, but it significantly improved the behavior of HPC1 mixture at the low (20 – 300°C) temperature range (Fig. 1b). SFRNSC was still characterized by a sharp reduction of its residual strength at the high temperature range.

PFRNSC mixture performed worse than NSC and SFRNSC at temperatures up to 500 °C. This mixture lost 25% of its initial strength at 100 °C, had a slight decreasing rate up to 500 °C and performed an additional steep loss up to 700 °C (Fig. 1c). PFRHPC2 and PFRHPC1 mixtures reduced their residual splitting strength linearly up to 300 °C and 500 °C respectively. Both mixtures suffered considerable additional lost up to 700 °C. At this temperature all polypropylene fibre reinforced mixtures retained the same percentage of their initial splitting strength.
CONCLUSIONS

High performance concrete mixtures tested in this study, had an explosive spalling tendency at different temperatures, ranging from 380 to 580 °C. The threshold temperature was reduced by the addition of silica fume and fly ash.

Addition of steel fibres did not eliminate the spalling tendency of HPC mixtures but it shifted threshold temperatures to higher levels. Steel fibre reinforced HPC mixture with silica fume plus fly ash decreased loss of compressive strength, splitting tensile strength and modulus of elasticity at low temperatures. Such an improvement was also observed in HPC mixture without silica fume and fly ash but it was less significant and it mainly took the form of reducing spalling at temperatures above 500°C. Differences observed in the behavior of SFRNSC as compared to that of NSC were almost negligible.

Polypropylene fibre reinforced mixtures were not destroyed at any temperature achieved in this research. Additions of this type of fibres improved the behavior of HPC mixtures, especially that containing silica fume plus fly ash.

REFERENCES

7. Chan Y. N., Peng G. F. and Anson M.: “Residual Strength and Pore Structure of High Strength Concrete and Normal Strength Concrete after


Table 1: Mix proportions and compressive strength of different concretes prepared.

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<tr>
<th>No</th>
<th>Type</th>
<th>Added water</th>
<th>Cement (type)</th>
<th>Silica fume</th>
<th>Fly ash</th>
<th>Aggregates</th>
<th>Sand</th>
<th>Steel fibres</th>
<th>Polyp. fibres</th>
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<td>1017</td>
<td>940</td>
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<td>--</td>
<td>--</td>
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<td>1004</td>
<td>754</td>
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Figure 1: Residual compressive strength of a) no fibre concretes, b) steel fibre reinforced concretes and c) polypropylene fibre concretes
Figure 2: Explosive spalling of HPC1 and HPC2 after heating at 700 °C.
Figure 3: Polypropylene fibre reinforced mixtures after heating at 700 °C. General view of the specimens (a) and slice of PFRHPC2 after splitting test (b)
Figure 4: Percentage of residual pulse velocity of three grades of concretes after subjected to different peak temperatures to the pulse velocity at air temperature (20 °C).
Figure 5: Percentage of residual static modulus of elasticity of three grades of concretes after subjected to different peak temperatures to the static modulus of elasticity at air temperature (20 °C).
Figure 6: Percentage of residual splitting tensile strength of three grades of concretes after subjected to different peak temperatures to the splitting tensile strength at air temperature (20 °C).