Post-fire Behavior of Ordinary Concrete Reinforced with Short Steel Fibers

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Abstract: Concrete is a widely used material in civil construction and may be submitted to high working temperatures under various circumstances. Many factors influence the behavior of this material at high temperatures, which usually leads to the evaporation of the hydrated cement. The dehydrated cement undergoes a contraction, simultaneously with the thermal expansion of the inert fraction of the material. As a consequence of these conflicting expansions and contractions, the material cracks and its strength and modulus of elasticity decrease significantly. On the other hand, the addition of short metallic fibers to the material increases its toughness, probably due to its action on the cracking behavior of the composite. It is thus expected that a concrete containing metallic fibers should maintain its original properties even after exposure to elevated temperatures. This paper presents an evaluation of the influence of steel fibers on the microstructure and toughness of concretes submitted to high temperatures. The bending behavior, under strain rate control, of concretes with a strength of 30 MPa and containing short steel fibers, submitted to a previous treatment at 500 °C, was analyzed. It was observed that, after both heat treatments, the addition of metallic fibers to concrete was able to maintain the pseudo-ductility and load-carrying capacity of this composite material.

Key words: Steel fibers, microstructure, concrete, temperature.

1. Introduction

Concrete may be subjected to high temperatures during its lifetime, especially due to fires: it does not burn or emit toxic gases under heating and usually maintains its strength for relatively long periods of time, thus retarding structural collapse and human casualties [1]. On the other hand, it is important to evaluate the consequences of the heating on its post-fire properties, especially with regard to its load carrying capacity. Concrete cracks due to high temperature exposure, as a consequence of the thermal stresses developed by temperature gradients [2]. In

addition, one should consider the stresses originating from physico-chemical phenomena in the material associated with heating. A saturated cement paste contains hydrated calcium silicate, calcium hydroxide, hydrated calcium sulfo-aluminate, non hydrated clinker grains, and a large quantity of free, capillary and adsorbed water [1]. The free and the capillary water evaporate as concrete approaches a temperature of 100 °C [3] since a considerable amount of vaporization heat is necessary to convert all the available water into vapor, the temperature of concrete does not increase up to the completion of this evaporation step. On the other hand, the vapor evolution causes internal stresses whose magnitude depends on the concrete porosity and humidity: this is especially important in the superficial layers of the

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material, which may crack and fall off, exposing the internal steel rebars of the material. The strength of cement undergoes a further decrease at 300 °C, due to the loss of the combined water in the hydrated silicates. The decrease is accelerated up to 500/600 °C due to the dehydration of the calcium hydroxide, and then by the total decomposition of hydrated silicates around 900 °C [4-6]. The evaporation of the water in the cement paste increases its retraction, simultaneously with a thermal expansion of the inert material. The porosity of the concrete aggregate and the nature of the mineralogical phases have an important influence on the performance of this material under exposure to high temperatures [7-8]. These factors control the internal stresses developed in the material, caused on one side by the intensity of vapor trapping in the closed porosity in the material, and on the other side by the retraction/expansion behavior of the existing phases. As a consequence, the material cracks and becomes weaker. Other studies [9] showed that the elasticity module falls significantly as temperature is raised. This could be attributed to the microcracking in the gravel/cement paste transition zone, which is associated with higher effects on the bending behavior and on the elasticity modulus than in the compression strength. Concretes displaying higher porosity and more combined water than free water display a better behavior at high temperatures.

A growing number of studies are being completed with the aim of improving the performance of concrete in relation to its bending and toughness [10-13]. One of the current tendencies in this direction is the use of cementitious materials reinforced with short steel fibers, which are introduced in the material in order to increase its capacity to withstand high deformations, i.e., in order to make the concrete pseudo-plastic. Cracks occur in the material matrix once its deformation capacity is exceeded, and lead to the brittle fracture of the aggregate in the absence of the metallic fibers. The incorporation of the fibers to concrete inhibits the propagation of the matrix cracks.

In addition, the modulus of elasticity of the fibers is higher than that of the concrete, allowing the transfer of the applied stresses from the matrix to the fiber. The material thus keeps some of its load carrying capacity even after the cracking of the concrete. The final failure of the concrete-fiber composite occurs either when the yield strength of the fibers is reached or when the fiber/matrix adhesion is lost. The decreased crack propagation associated with the presence of the metallic fibers enhances the toughness, the fatigue and the impact strength of the aggregate. On the other hand, the addition of metallic fibers to concrete has a negligible effect on its compression strength. Concretes containing metallic fibers usually display a superior behavior concerning its deterioration, since the decreased crack opening restricts the penetration of aggressive substances. A special attention should be paid to the sensitivity of the metallic fibers to these aggressive agents, especially close to the surfaces, where the protection given by the concrete matrix to the metallic fibers is limited.

It is thus expected that concretes reinforced with metallic fibers should exhibit a better behavior than unreinforced concretes, after their exposure to high temperatures of fires. The present paper evaluates the influence of metallic fibers on the toughness of a metallic fiber reinforced ordinary concrete after it was submitted to high temperatures. No such results seem to have been presented in the literature for this type of concrete. To investigate the influence of the addition of steel fibers on the mechanical behavior of concrete at high temperatures, experiments were conducted to evaluate the concrete before and after exposure to high temperatures. The results for concrete with addition of steel fibers after exposure to elevated temperature were very satisfactory compared to concrete without the addition of steel fibers.

2. Method

The concrete matrix employed a water/cement ratio

of 0.55 and aimed at a compression strength of 30 MPa after 28 days. The components of this matrix were a CP V-ARI cement, silicious medium fine sand and limestone coarse gravel with a maximum characteristic dimension of 25 mm. The composites contained 80 kg/m³ of Wirand[®] FF4 steel fibers with aspect ratio of 80. Cylindrical (10 × 20 cm) and prismatic samples (15 × 15 × 50 cm) were then cast and kept under a saturated atmosphere at 25 °C up to their thermal cycling and bending tests, which occurred 28 days after the fabrication of the specimens.

The exposure of the concrete to elevated temperatures involved the heating of the unloaded and naturally dried samples to a heating rate of about 2 °C/min, up to temperatures of 500 °C. The samples were maintained at this temperature for 3 h and then slowly cooled inside the furnace. These heat treatments were performed in a muffle type furnace under temperature control through a thermocouple close to the samples.

To determine compression strength, five cylindrical specimens that had not been heated (25 °C) and five that had been exposed to a high temperature (500 °C) were tested for each concrete, that is, 10 for concrete without fibers specimens plus 10 for concrete with fibers specimens, for a total of 20 specimens for simple compression tests. The mechanical tests were carried out in EMIC DL30000N twin-screw microprocessed electromechanical universal test machine with two parallel cylindrical guide columns with a load application speed of 0.5 MPa/s. The bases of the specimens were regularized with a neoprene capper with a metallic base. Three unheated cylindrical specimens (25 °C) and three specimens that had been exposed to a high temperature (500 °C) were tested to determine the diametrical compression strength (Brazilian test). The same compression strength testing equipment was used with a load application speed of 0.2 MPa/s. To determine flexural traction strength, two unheated prismatic specimens

(25 °C) and two specimens that had been exposed to a high temperature (500 °C) were tested for each concrete. The prismatic samples underwent four-point bending between supports distant 450 mm from each other, under a bending rate of 0.1 MPa/s. The bending tests were performed at room temperature in a 100 KN EMIC testing machine model DL30000. The specimen displacement at the point of load application was monitored through an independent LVDT (linear variable differential transformer) sensor. Two samples were tested for each situation up to the specimen failure or up to a total displacement of 4.0 mm.

To determine static and dynamic elasticity modulus, two unheated cylindrical specimens (25 °C) and two specimens that had been exposed to a high temperature (500 °C) were tested for each concrete.

3. Results and Discussion

Fig. 1 shows compression strength tests for a concrete without and with the addition of steel fibres, respectively. Results of compression strength of the concrete fibers were inferior. This is due to the difficulty of densification. As the result of slump test was 12.5 cm for concrete without fibers and 4.8 cm for the concrete with fibers with the same relation to water-cement, it can be realized that the loss of compression strength of concrete with fibers was lower after heating at 500 °C.

Fig. 2 shows diametrical compression strength tests for a concrete without and with the addition of steel fibres, respectively. The diametral compression strength

Fig. 1 Compression strength.

Fig. 2 Diametrical compression strength.

was significantly improved by the addition of fibers.

Fig. 3 shows static and dynamic elasticity modulus tests for a concrete without and with the addition of steel fibres, respectively. The modulus of elasticity was negatively affected by the addition of fibers. It is for the same reason of the compression strength.

Figs. 4 and 5 show the load-displacement curves obtained in the bending tests for a concrete without and with the addition of steel fibres, respectively. Concrete without fibers (Fig. 1) is essentially brittle and the exposure of this material to elevated temperature causes it presenting lower load capacity. Heating samples to 500 °C during 3 h lead to collapse loads under bending which are 55%~65% lower than for the unexposed concrete.

Figs. 4 and 5 show that, from the point of view of load carrying capacity, concrete without fibers is much more sensitive to fire exposure than the concrete with fibers. The latter was actually relatively insensitive to its previous heating. Considering the area under the load-displacement curve as an indication of the energy absorbed by the material up to its fracture (the material toughness), one can also conclude from Figs. 4 and 5 that the addition of fibers to the concrete leads to a substantial increase in its toughness. The fibers impart a more “ductile” behavior to the material, increasing about 600%~800% in the material toughness in relation to the material without fibers. The heating of the concrete with fibers up to 500 °C has a small influence on the material toughness, guaranteeing the

Fig. 3 Static and dynamic elasticity modulus.

Fig. 4 Load-displacement curves for concrete samples without the addition of fibers, before and after exposure to 500 °C (tests at 25 °C).

Fig. 5 Load-displacement curves for concrete samples with the addition of fibers, before and after exposure to 500 °C (tests at 25 °C).

pseudo-plasticity of this composite after its exposure to elevated temperatures.

Observing Fig. 4, it can be seen that the initial slope

of the load-deformation of samples that have undergone heating from 500 °C is lower. This would indicate a lower modulus of elasticity of the composite. The lowest tensile strength of the heated samples is given by the deterioration caused by high temperature.

Observing Fig. 5, it is realized that the carrying capacity of concrete with fibers is superior to concrete without fibers, since the concrete reinforced with fibers present after heating capacity next to the concrete without fibers before heating load.

4. Conclusions

The addition of short steel fibers does not contribute to the increase in the compression strength and modulus of elasticity. But at high temperatures, the addition of fibers contributes to the compression strength. The addition of fibers contributes to the increase of diametrical compression strength.

Adding short steel fibers increases flexural tensile strength of the composite and guarantees less loss of mechanical properties than non-reinforced concrete when exposed to high temperatures. Fiber reinforced concrete has flexural traction strength after being exposed to high temperatures at the same values as control concrete before being exposed to high temperatures. Concrete containing short steel fibers displays a considerably better load carrying capacity after fire exposure, in relation to the same material without fibers. Heating cycles of the fiber containing concrete, up to 500 °C, cause no loss of toughness of this material in bending tests: this is not the case for concretes without steel fibers. The addition of steel fibers to concrete guarantees its pseudo-plasticity even when the material is utilized after exposure to high temperatures. This indicates that the addition of such fibers to concrete may be necessary whenever there is a risk of fire or of high working temperatures.

In the existing literatures, there are several studies related to addition of short steel fibers in concrete, but no studies of short-fiber reinforced steel in concrete

situations of fires are found. This work contributes to the scientific development of concrete on the aspect of durability technology requirements after submission to elevated temperatures.

This paper suggests how to research the following topics in the future: (1) evaluation of the inhibition of spalling of concrete in fire situation by addition of short steel fibers; (2) evaluation of mechanical properties of concrete reinforced with short steel fibers during the simulation of fires; (3) finite element simulation of the mechanical behavior of short steel fibers added to concrete.

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