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Fire performance of recycled rubber-filled high-strength concrete

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Abstract

The paper presents the behavior of a high-strength concrete (HSC) with silica fume (SF) modified with different amounts of solid particles recycled from crumbed used truck tires. The aims of including elastomeric materials in a cementitious matrix are reducing the stiffness of HSC in order to make it compatible with other materials and elements of the building, unexpected displacement of foundations and shrinkage, recycling of solid wastes and improving fire performance.

The inclusion of low volumetric fractions of rubber reduces the risk of explosive spalling of HSC at high temperatures because water vapor can exit through the channels left as the polymeric particles get burnt. The temperature reached at a fixed depth of the fire-tested specimens is reduced as the percentage of rubber increase.

A set of mechanical, destructive and nondestructive tests were accomplished in order to obtain optimum quantities of crumbed used tires rubber in the composition, taking into account workability, stiffness and, obviously, strength. The results obtained show that a relatively high-volume fraction of rubber (3%) does not reduce significantly the strength, although it reduces the stiffness. Higher values of rubber produce a progressive reduction of strength and stiffness but might improve the dynamic behavior.

Keywords: Mechanical properties; Waste management; Fire performance; Rubber-filled high-strength concrete

1. Introduction

High-strength concrete (HSC) is a new material that can now be manufactured by most concrete plants. The availability of a variety of additives such as silica fume (SF) and water-reducing admixtures (WRA) allows its widespread use. In terms of architectural advantage, HSC allows smaller size columns to be used in high-rise buildings, which results in more usable space in the lower floors.

Further than strength, HSC has significant differences with regard to normal strength concrete (NSC). Higher stiffness, lower permeability and larger durability are some of these differences. For this reason, some structural codes do not cover the use of this material or present special recommendations for its use as structural material [1].

HSC presents another important difference with regard to NSC. Recent HSC fire tests results have shown that there are well-defined differences between HSC and NSC properties at high temperatures [2]. HSC shows a higher tendency of explosive spalling when subjected to rapid heating, as in the case of fire [2–4]. This behavior is mainly due to the lower permeability that results in a build-up of pore pressure within the cement paste [5]. Some solutions, as the inclusion of polypropylene fibers to allow the water vapor escape from the concrete matrix, have been proposed to reduce the risk of spalling [6,7].

This paper presents some results of an experimental program on HSC filled with solid fiber-shaped particles of recycled tire rubber performed at the Materials Laboratory of the School of Architecture of Madrid. The objectives of this study are as follows:

- Reduce the risk of HSC explosive spalling when fire occurs.
- Management of solid wastes from used truck tires, reducing environmental impact.

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Table 1
Nominal properties of truck tire rubber

Young modulus	
@ 100%	1.97 MPa
@ 300%	10 MPa
@ 500%	22.36 MPa
Tension strength	28.1 MPa
Break point strain	590%
Resilience	
@ 23 °C	44%
@ 75 °C	55%

- Reduce the HSC stiffness without a high loss of strength, enlarging the compatibility of deformation with other building elements.

Some research has been done concerning with rubber-filled NSC (also called rubberized concrete) [8–14], although rubber-filled HSC has not been previously described.

2. Experimental program

A base HSC composition with SF and without fiber was determined. Then three different rubber fiber volumetric fractions (3%, 5% and 8%, respectively) were included to the base composition.

The rheological behavior of the material in fresh state was measured using the slump and the Ve-Be consistometer tests.

In the hardened state, porosity and density were measured. Sets of six cubic specimens (10 cm) of each composition were manufactured. Ultrasonic pulse nondestructive tests were performed at several ages in order to measure the evolution of the hardening process. Compression tests were also made at different ages to measure the increase of strength along time.

Prismatic nonstandard specimens (20 × 30 × 5 cm) of all compositions were manufactured for fire performance tests. The equipment used for performing the fire tests was composed by the following:

- Furnace CHESA, technical data:
  - Six gradual electric resistance
  - Maximum temperature of 1300 °C.
  - Dimensions of fire hole of 15 × 30 cm.
  - Register of furnace temperature with a type S thermocouple.
  - Furnace controller CHESA, with 6 different temperature programs.
- Two type K thermocouple in contact with both internal and external faces, respectively.
- Temperature transducers Testo 925 for type K thermocouples.

Thermogravimetric tests were carried out with pattern samples and samples extracted from several depths of the fire-tested specimens in order to obtain damage spectrums of the rubber-filled HSC compositions under study. With this test, the temperature reached at each distance can be found out, comparing the weight loss of the sample when heated at a certain temperature with a pattern sample.

3. Materials

Four compositions of HSC filled with different small volumetric fractions of solid fiber-shaped particles of recycled tire rubber (0%, 3%, 5% and 8%) were used.

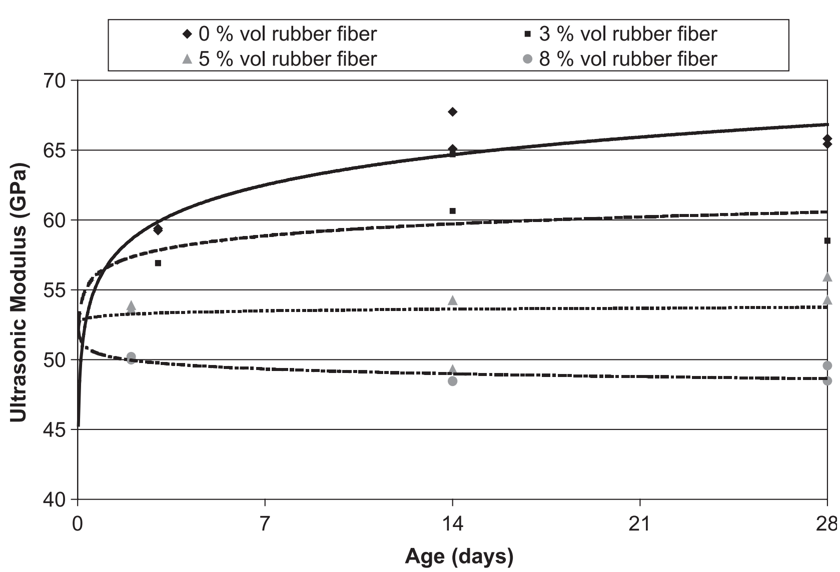

Fig. 1. Ultrasonic modulus of several compositions at different ages of rubber-filled HSC.

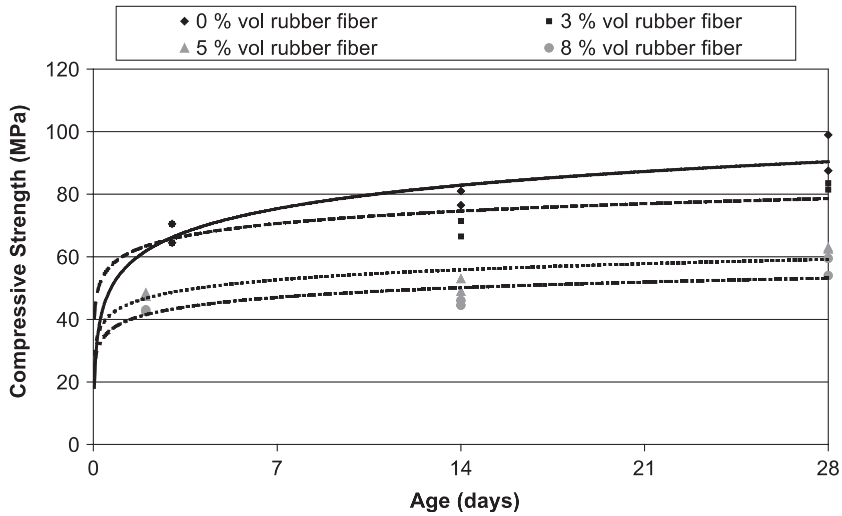

Fig. 2. Compressive strength of different compositions at different ages of rubber-filled HSC.

The base HSC composition is described next (dosage for 1 m^3) [15]:

- Cement type CEM I—52.5 R (Asland)—513 kg
- Rolling siliceous coarse aggregate (maximum size of 16 mm)—1080 kg
- Siliceous fine aggregate (maximum size of 4 mm)—685 kg
- SF (5% of weight with respect to cement)—25.65 kg
- Superplasticizer Glenium C-355 (Bettor-MBT) (3% of weight with respect to cement)—15.7 kg
- Water—128.25 l
- Relation water to cement (w/c) = 0.25
- Relation coarse aggregate/cement = 2.1/1
- Relation fine aggregate/cement = 1.33/1

The rubber fiber is included to this composition in 3%, 5% and 8% volumetric fractions (25.2, 42 and 67.2 kg/m^3, respectively).

The solid fiber-shaped particles of recycled tire rubber come from truck tires wasted away after a second recapping. The length of the fibers is between 0.85 and 2.15 cm, with an average value of 1.25 cm. Its surface is rough and quite damaged due to the cut process. It contains 4% of dust particles that act as air entraining admixture. Its density is 0.84 g/cm^3 and a water absorption rate of 25% has been

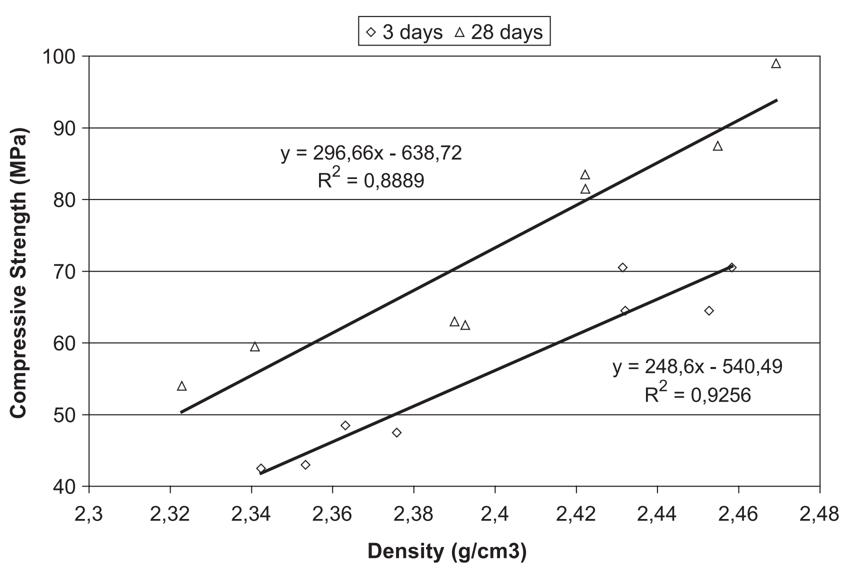

Fig. 3. Relation between compressive strength and density at different ages of rubber-filled HSC.

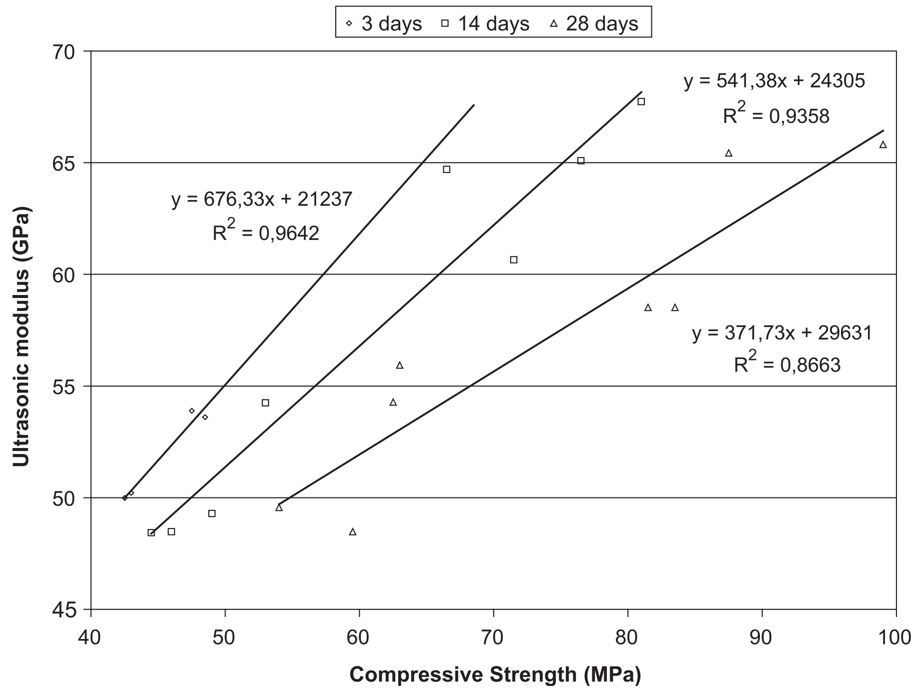

Fig. 4. Relation between ultrasonic modulus and compressive strength at different ages of rubber-filled HSC.

measured. A softening temperature of 175 °C and a combustion temperature of 200 °C have been determined.

Table 1 presents other nominal properties of tire rubber [16].

4. Mixing procedure and rheological behavior

The HSC compositions were mixed using a 50-l horizontal axis mixer. The low w/c ratio used (0.25) and the inclusion of SF forced to change the mixing process with regard to NSC. The coarse aggregate, the cement, the rubber fibers and the SF were mixed first for 2 min. Then the fine aggregate was included, continuing the mixing process for 1 min. At last, water and superplasticizer were added and the process continued for 15 min.

All the slump tests results were larger than 10 cm and the values of time obtained with the Ve-Be tests shorter than 15 s. The Ve-Be time increased as the percentage of rubber increase, although all the compositions had a usable workability.

5. Physical and mechanical characterization results

One set of six cubic specimens (10 cm) and two cylindrical specimens ($\varnothing 15 \times 30$ cm) per composition under study (0, 3, 5 and 8 vol.% rubber fiber-filled HSC)

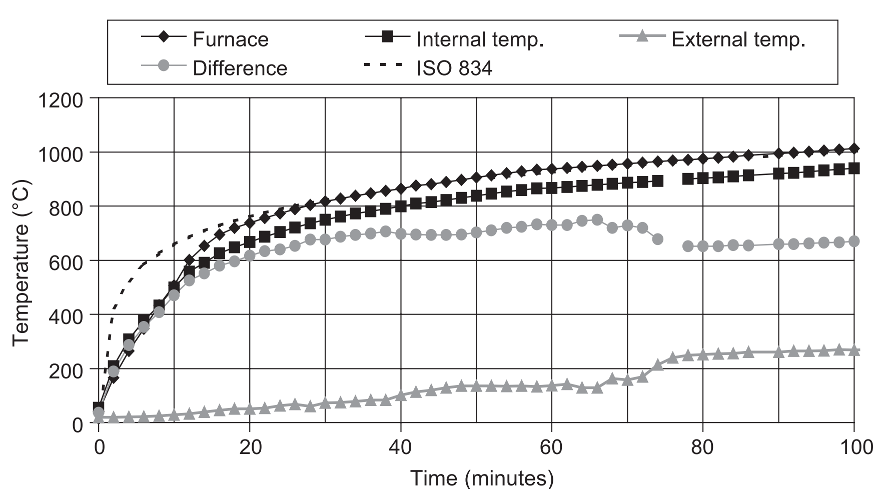

Fig. 5. Fire tests results of rubber-filled HSC specimens without rubber.

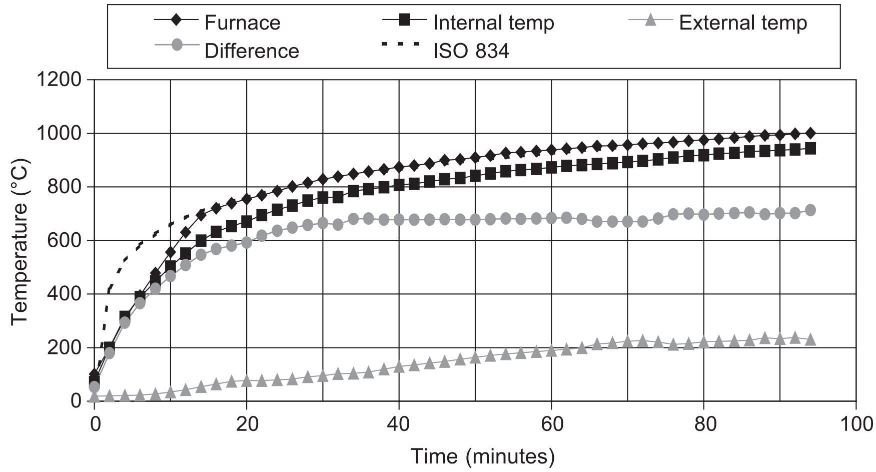

Fig. 6. Fire test results of rubber-filled HSC specimens with 3% volumetric fraction of rubber.

were manufactured. The specimens were produced with steel molds, vibrated the time obtained in the Ve-Be tests, in order to avoid segregation of the mixture. The external face of the specimens was watered in order to avoid superficial drying up. The specimens were demolded 24 h after filled and they were water cured. The specimens were taken out of the water several hours before tested to allow drying. Ultrasonic pulse tests were performed on all the specimens before testing. The results of ultrasonic modulus were obtained with the equation (Eq. 1),

$$E_s = \rho v^2 / 1000 \tag{1}$$

where E_s is the ultrasonic modulus (MPa), ρ is the density (g/cm^3) and v is the velocity of ultrasonic pulse propagation (m/s). Results are summarized in Fig. 1.

The ultrasonic modulus is a good index of the stiffness of the material and is useful as a comparison value [17]. It can be observed that the higher the amount of rubber, the lower the ultrasonic modulus and therefore the stiffness.

Cubic specimens were used for compression tests. In order to avoid stress concentrations on the contact sides of the specimens, which can produce the failure of the specimen at lower strength than normal, 1-cm thick distribution steel plates were used.

Compression test results are summarized in Fig. 2. It can be remarked that the compressive strength decreases with the increase of the amount of rubber fiber. Although for small volumetric fractions of rubber, the decrease is quite reduced. The failure of HSC specimens without rubber occurred in an explosive manner. The specimens with rubber did not show explosive failure.

It can be observed that the shape of the curve that represent the evolution of the strength with age changes when rubber fiber is included.

Fig. 3 relates the compressive strength and the density measured at different ages. Fig. 4 relates ultrasonic modulus

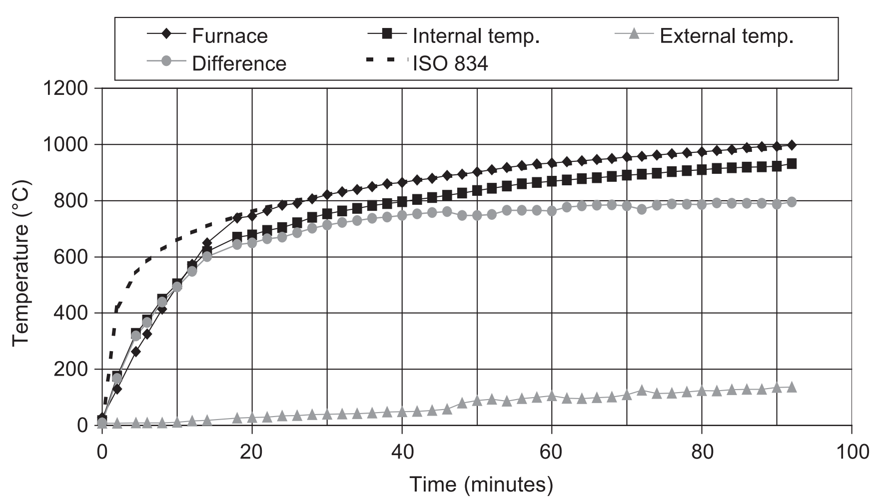

Fig. 7. Fire test results of rubber-filled HSC specimens with 5% volumetric fraction of rubber.

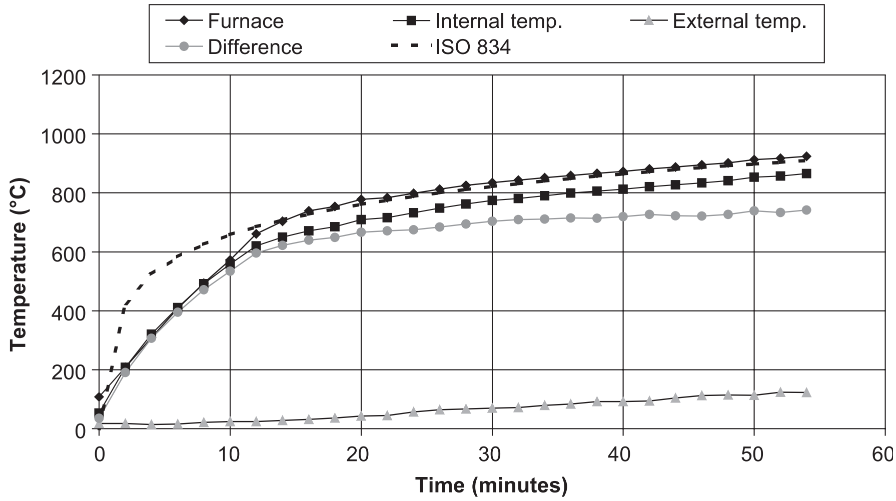

Fig. 8. Fire test results of rubber-filled HSC specimens with 8% volumetric fraction of rubber.

with compressive strength at different ages. Both relations fit with a linear approximation.

6. Fire performance of HSC filled with recycled tire rubber

The study of the behavior of HSC filled with solid fiber-shaped particles of recycled tire rubber under fire included a fire test following EN-UNE 1363-1 (equivalent to ISO 834) [18]. The equation used for the fire curve was (Eq. 2),

$$T - T_0 = 345 \log_{10}(8t + 1) \qquad (2)$$

where T is the temperature at the time t and T_0 is the temperature at the beginning of the test.

Prismatic specimens ($20 \times 30 \times 5$ cm) of all compositions under study (0%, 3%, 5% and 8% rubber fiber volumetric fraction content) were tested. The tests were performed until the exposed side of the specimens reached 1000 °C. The experimental results of the fire tests are summarized in Figs. 5–8.

The specimens tested shown a very different behavior. The specimen of HSC without rubber fiber presented spalling on the exposed side and a very remarkable curvature. Fig. 9 shows the surface exposed to fire of the specimen with 0% of rubber fiber after the fire test. The specimens with rubber fiber did not show spalling and the curvature of the plate was lower as the volumetric fraction of rubber increased. Fig. 10 shows the exposed surface of the specimen with 3% of rubber, and Fig. 11 presents a comparison of the curvatures occurred to the specimens due to fire effect. The curvature measured after fire tests on the tested specimens is represented in Fig. 12. A linear relation between percentage of rubber and radius of curvature has been observed.

Thermogravimetric tests were performed on samples extracted from the fire-tested specimens at different distances from the exposed surface. Samples extracted from the

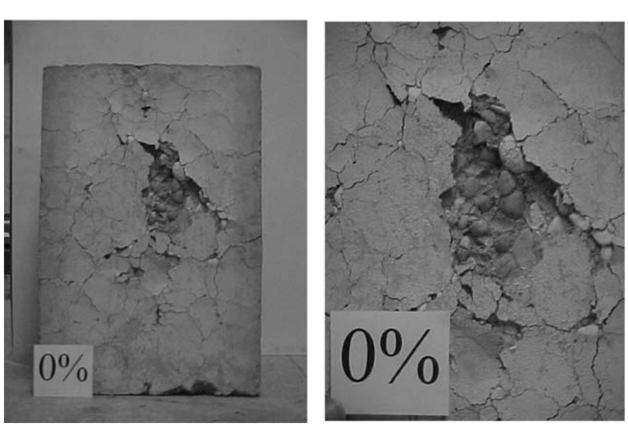

Fig. 9. Exposed surface of rubber-filled HSC specimen with 0% of rubber after fire test. General view and detail.

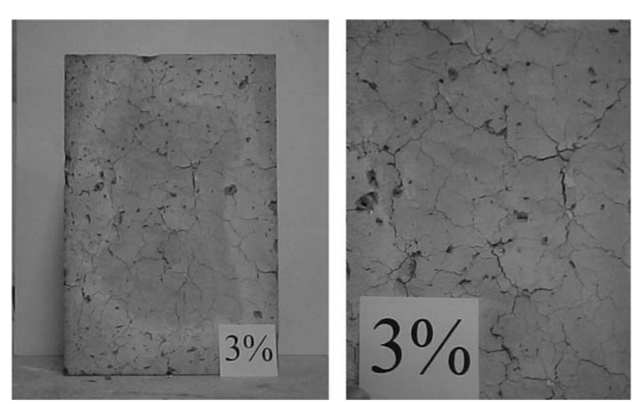

Fig. 10. Exposed surface of rubber-filled HSC specimen with 3% of rubber after fire test. General view and detail.

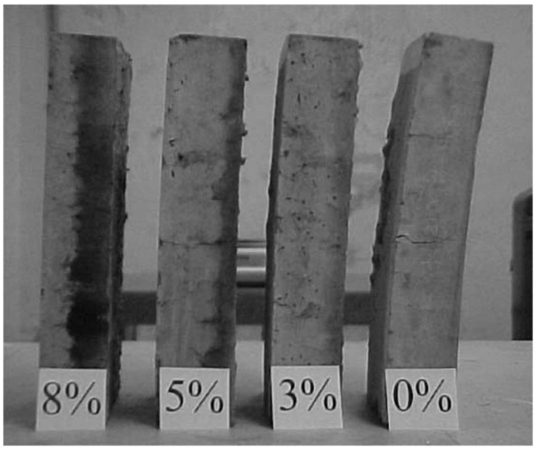

Fig. 11. Lateral view of the fire-tested rubber-filled HSC specimens with different percentages of rubber.

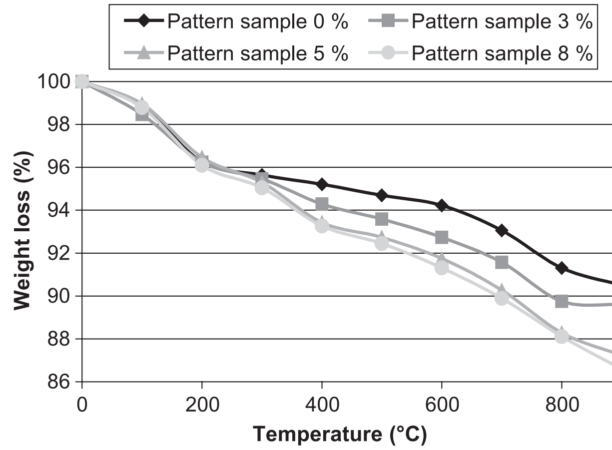

Fig. 13. Thermogravimetric test results of pattern samples extracted from untested rubber-filled HSC specimens with different percentages of rubber.

specimens subjected to compression tests were also tested in order to obtain a pattern to compare with. Fig. 13 summarizes the results obtained from thermogravimetric tests of the pattern samples.

The samples extracted from the plates that were subjected to fire tests were obtained from 1, 2, 3 and 4 cm depth. The samples were heated at temperatures from 0 to 900 °C, on intervals of 100 °C, and weighted after each stage. The results of weight loss were compared with the pattern samples to determine the temperature reached at each depth in the fire test. Fig. 14 summarizes the results obtained from the thermogravimetric tests. It can be observed that the higher the rubber fiber content, the lower the temperature reached at the same depth.

7. Discussion of results

The workability of the rubber-filled HSC decreased with the increase of rubber fiber, though it remained good workability. The combination of static (slump test) and dynamic (Ve-Be test) workability tests gave a knowledge of the rheological behavior of the rubber-filled HSC. The inclusion of SF and rubber in the composition can maintain a good slump, but the Ve-Be times varied. The Ve-Be test gave information about the vibration time necessary to compact the material without segregation.

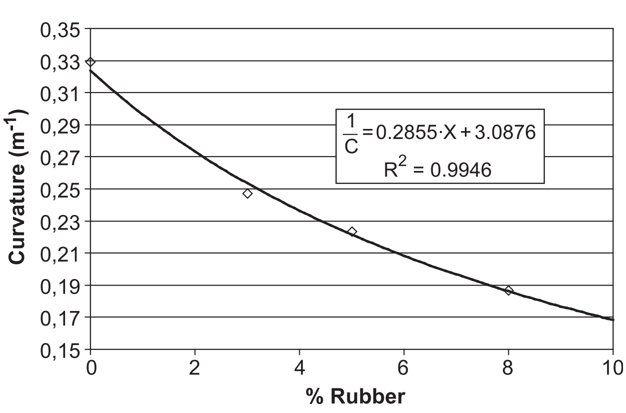

Fig. 12. Curvature of the fire-tested rubber-filled HSC specimens with different percentages of rubber.

In the hardened state, a significant relation among density, ultrasonic modulus and compression strength has been observed, as shown in Figs. 3 and 4. As rubber density, compressive strength and stiffness are lower than HSC properties, the more rubber has the composition, the lower is the density, the compressive strength and the stiffness of the rubber-filled HSC.

For low volumetric fractions of rubber fiber (3%), the reduction of strength is around 10%.

The inclusion of rubber fiber eliminates explosive failure of HSC under compression. Rubber fibers maintained the sides of the cracks together and the failure was progressive.

Fire performance of HSC changes when rubber is included in the composition. Explosive spalling occurred in HSC without rubber, as shown in Fig. 9. The curve of external surface temperature (unexposed to fire) presented a step when spalling happened (Fig. 5).

The open channels left when rubber particles get burnt allows the water vapor escape from the sample, reducing stress due to vapor pressure. Small holes can be observed in the fire-exposed surface of the specimens with rubber fiber (Fig. 10). No holes are present on the specimen without rubber (Fig. 9).

There is a linear relation between percentage of rubber and the radius of curvature measured on the fire-tested specimens. The curvature observed on the fire-tested specimens is produced by thermal gradient and vapor pressure. The more rubber in de composition of HSC, the larger the curvature, as can be observed in Fig. 11.

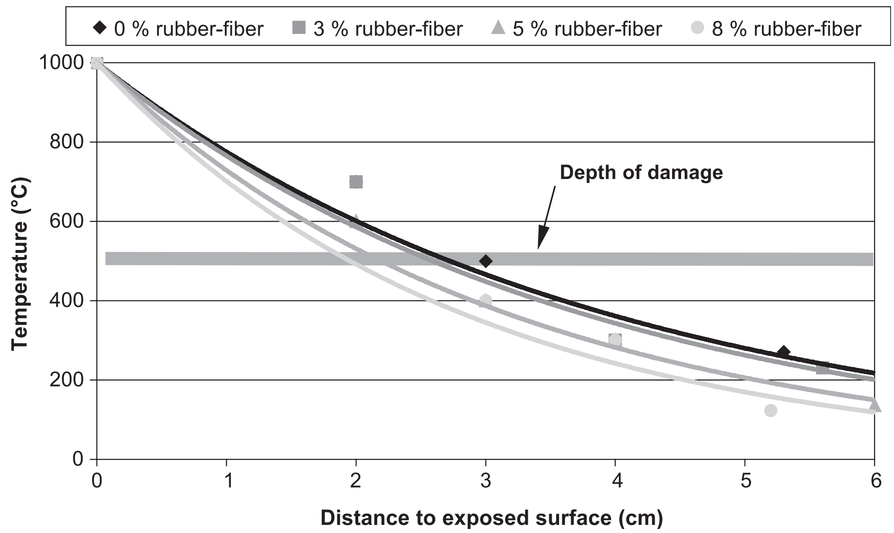

Fig. 14. Temperature reached at different distances from the exposed surface of the fire-tested rubber-filled HSC specimens with different percentages of rubber.

Thermogravimetric test results point out a decrease of the temperature reached at a certain distance from the exposed surface when the amount of rubber increases. Considering 500 °C as the temperature when steel reinforcement loses its mechanical capacity, a depth of damage can be defined on rubber-filled HSC. At larger distances from the exposed surface, the structural integrity can be expected.

Fig. 14 shows that a column of HSC without rubber would need a larger reinforcement covering than other made of rubber-filled HSC in order to guarantee structural integrity. Explosive spalling of HSC has to be taken into account too, as previously mentioned.

8. Conclusions

Rubber-filled HSC shows a decrease of compressive strength and stiffness, with regard to HSC, when the percentage of rubber in its composition increases. This behavior can be profitable when some ductility of the material is required, maintaining high strength. HSC filled with 3% volumetric fraction of rubber present a reduction of mechanical characteristics of only 10%.

The fire tests have shown a reduction of curvature and risk of explosive spalling when HSC is filled with rubber. The depth of damage (temperature over 500 °C for reinforced concrete structures) is also reduced. This could mean a reduction of the reinforcement covering in structural elements or an increase of safety in HSC structural elements against fire.

More research is needed to develop this material though the results obtained show a good behavior in general terms. The management of solid waste is also a goal of this material.

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