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Properties of fibre mortars after exposure to high temperatures

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Professional paper

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Properties of fibre mortars after exposure to high temperatures

Results obtained by testing mechanical behaviour and microstructure of fibre mortars and standard mortars after exposure to high temperatures are presented in the paper. A flame test using propane gas was developed to enable the best possible simulation of fire conditions. The testing was conducted on three different mortars: standard mortar, steel fibre mortar, and hybrid mortar (with equal proportion of steel fibres and polypropylene fibres). The addition of fibres ensured greater ductility of mortar at temperatures from 400 to 700°C. These observations served as a basis for explaining the loss of strength.

Key words:
steel fibres, polypropylene fibres, mortar, high temperature, flame test, flexural strength

Stručni rad

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Svojstva vlaknima ojačanih mortova nakon izlaganja visokim temperaturama

U radu su prikazani rezultati mehaničkog ponašanja i mikrostrukture vlaknastih i standardnih mortova nakon izlaganja visokim temperaturama. Da bi se što vjernije simulirali uvjeti požara, razvijeno je ispitivanje plamenom primjenom plina propana. Ispitivanje je provedeno na tri različita morta: na standardnom mortu, na mortu s čeličnim vlaknima te na hibridnom mortu (s jednakim omjerom čeličnih vlakana i polipropilenskih vlakana). Pri temperaturama od 400 do 700°C dodavanjem vlakana postignuta je veća duktilnost morta. Navedena opažanja poslužila su kao podloga za objašnjavanje gubitka čvrstoće.

Ključne riječi:
čelična vlakna, polipropilenska vlakna, mort, visoka temperatura, ispitivanje plamenom, savojna čvrstoća

Fachbericht

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Eigenschaften faserverstärkter Mörtel nach der Einwirkung hoher Temperaturen

In dieser Arbeit sind das mechanische Verhalten und die Mikrostruktur von Faser- und Standardmörteln nach der Einwirkung hoher Temperaturen dargestellt. Um mögliche Feuereinwirkungen so angemessen wie möglich zu simulieren, sind Versuche mit Propangasflammen entwickelt worden. Drei verschiedene Mörtel sind untersucht worden: Standardmörtel, Mörtel mit Stahlfasern und Hybridmörtel (mit gleichen Anteilen von Stahl- und Polypropylenfasern). Bei Temperaturen zwischen 400 und 700°C ist durch die Zugabe der Fasern eine erhöhte Duktilität erzielt worden. Aufgrund dieser Beobachtungen ist die verminderte Festigkeit erläutert worden.

Schlüsselwörter:
Stahlfasern, Polypropylenfasern, Mörtel, hohe Temperatur, Versuche zur Flammeneinwirkung, Biegefestigkeit

1. Introduction

In building sciences, the innovation partly involves development of new materials and proper use of their properties. The concrete reinforced with fibres is one of these materials. The fibres increase mechanical strength of concrete, reduce its plastic shrinkage, and increase its resistance to impact at room temperature. With this material, engineers are able to develop new structures, original by their design and ability to resist various external solicitations [1, 2].

The characteristics of such materials rely on the presence of fibres which can be of various types: metallic, synthetic, natural, glass, or carbon. Steel fibres and polypropylene fibres are considered in this study.

According to the authors, fibres are characterized: by their ability to control cracking, by their capacity as energy absorbers, by their ability to transfer the load, and by their tensile strength. Nevertheless, the fire behaviour of concrete reinforced with fibres presents a major concern for researchers.

When exposed to elevated temperatures, a cementitious material reinforced with steel fibres may be subjected to a high or low level of damage. Heating causes different changes of its properties and, in particular, changes in microstructure accompanied by the loss of mechanical strength [3, 4].

Polypropylene fibres can benefit concrete by preventing explosive spalling, due to the fact that melting occurs at about 170°C and hence moisture contained in concrete can escape from concrete through inter-connected pores [3-5].

The aim of this study is to test contribution of steel fibres and polypropylene fibres to the risk of mechanical and thermal instability of concrete when exposed to fire.

2. Experimental part

2.1. Specimen preparation

Three types of mortar were prepared: a standard mortar (MN), a mortar with steel fibres (MNA) and a mortar with hybrid steel - polypropylene fibres (MNAP). The total dosage in fibres is 0.58 % by volume, i.e. 45 kg/m^3 of steel fibres or 5 kg/m^3 of polypropylene fibres. This frequently used proportion enables good workability [6-8]. Mechanical properties of fibres and mortar composition are presented in Tables 1 and 2.

Specimens are kept in a humid room (20°C, 95 % RH) for 24 h and then stored in a dry room (20°C, 50 % RH) for 28 days. Under such conditions, a major part of the free water evaporates from the cement matrix [9]. Test specimens are instrumented with thermocouples positioned at different depths (1 cm, 1.5 cm, 2 cm, 2.5 cm, and 3 cm) before being submitted to the propane flame (Figure 1).

2.2. Flame test

Mechanical characteristics are influenced by sample size and by the rate of temperature increase. The temperature gradient inside the samples can cause micro cracks, due to thermal expansion. Moreover, the temperatures attained, and the duration of exposure, lead to chemical and mineralogical transformations [9-13].

The 16×16×4 cm plates made of standard mortar and fibre-reinforced mortar are placed in an apparatus to carry out flame tests (Figure 2).

The high temperature at the face exposed to the flame was set at 1000°C and maintained for one hour. At the end of the test, the plates were naturally cooled at ambient air. After this heating (Figure 3), test specimens were subjected to comparative punching shear tests.

Table 1. Mechanical properties of fibres

Characteristics of fibres	Diameter [μm]	Length [mm]	Density [kg/m^3]	Modulus of elasticity [GPa]	Melting point [°C]	Tensile strength [GPa]
Steel	250	25	7850	200	1400	1,3
Polypropylene	18	12	910	6	170	0,55

Table 2. Mortar composition

Components	Mortar without fibres (MN)	Mortar with steel fibres (MNA)	Mortar with mixed fibres (MNAP)
Cement CEM I 52.5 N, [kg/m^3]	504	504	504
Sand [kg/m^3]	1513	1513	1513
Water [kg/m^3]	252	252	252
Steel fibres [kg/m^3]	0	45	22,5
Polypropylene fibres [kg/m^3]	0	0	2,5
Water/Cement	0,5	0,5	0,5

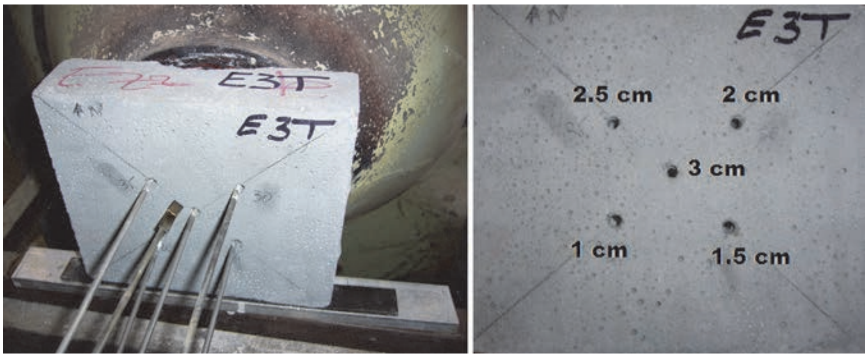


Figure 1. Test specimens with thermocouples a) External face; b) Position of thermocouples

Figure 3. Test specimen face after one-hour exposure to propane flame

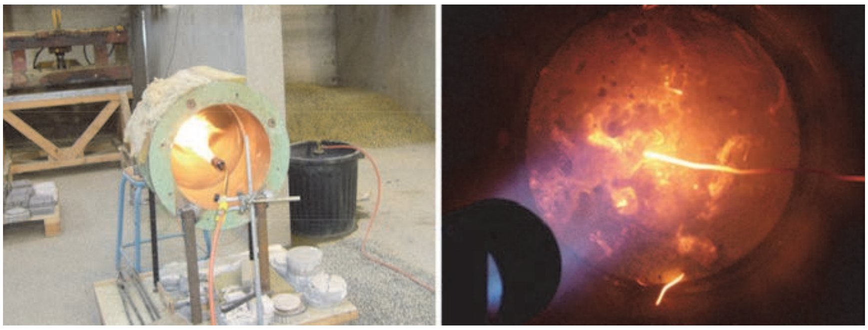


Figure 2. Propane flame heating equipment

2.3 Punching shear tests

The punching shear strength test was performed to enable comparison between the residual mechanical strength values of samples (air-cooled prior to testing) [14]. The equipment used for punching shear tests is shown in Figure 4.

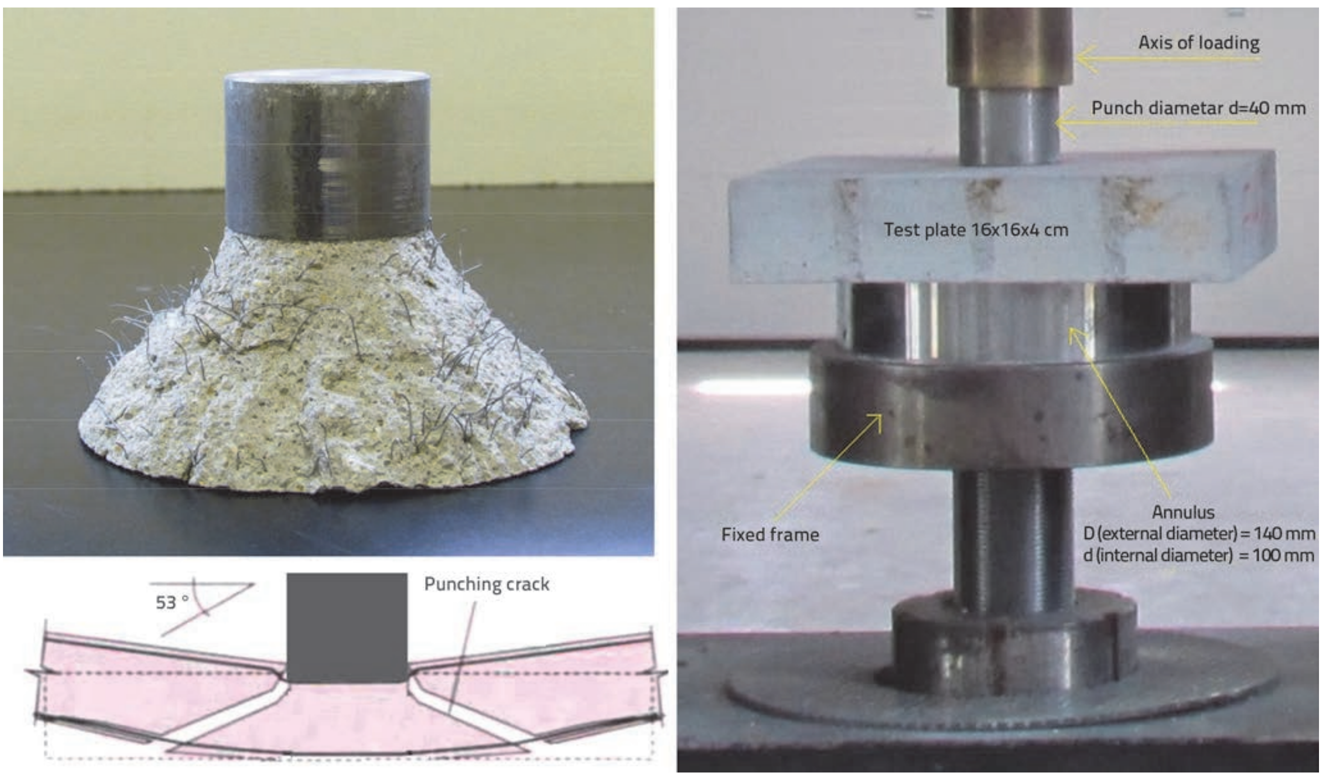


Figure 4. a) Equipment b) Punching shear failure

2.4. Exposure to high temperatures in furnace

Samples measuring 4x4x16 cm^3 ,taken from the same three mortars, were cast and kept as previously indicated. The samples were subjected to an elevated temperature in a muffle furnace. The exposure temperatures were set at 20°C, 400°C, 800°C and 1000°C. The exposure time, at constant temperature, amounted to one hour. This period of exposure was sufficient to obtain a relatively steady temperature state in specimens at all temperatures [15, 16]. The rate of temperature increase was set at 5°C/min (Figure 5).

t °C/min	T_{max} [°C]		
5	400	800	1000

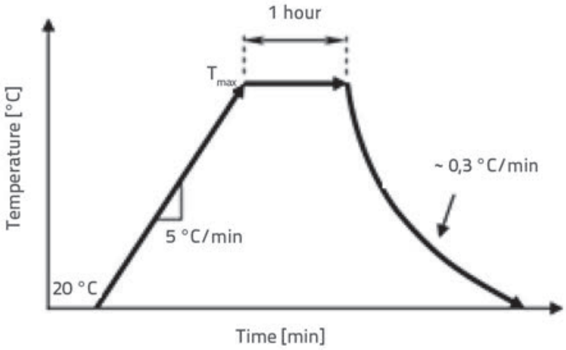
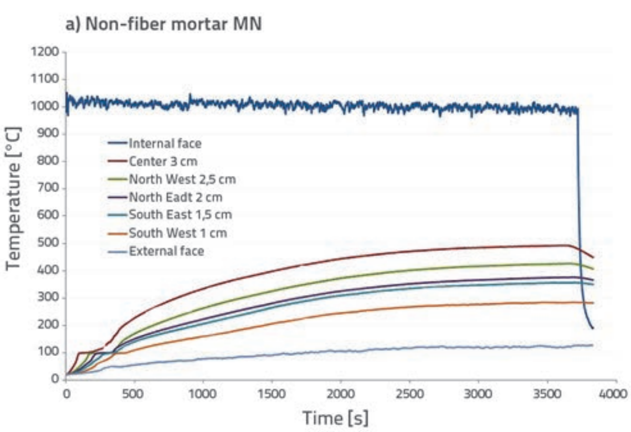


Figure 5. Heating process

2.5. Results

2.5.1. Change of temperature gradient during flame tests

The temperatures change at each measuring point (thermocouple), as related to time, is shown in Figure 6.
It can clearly be seen that the heat transfer in the cementitious mortar is slow. After one hour of heating at 1000°C, the temperature at the unexposed face amounted to 140°C while it was only 380°C at 2 cm in depth. The presence of steel fibres did not alter thermal conductivity of the material.



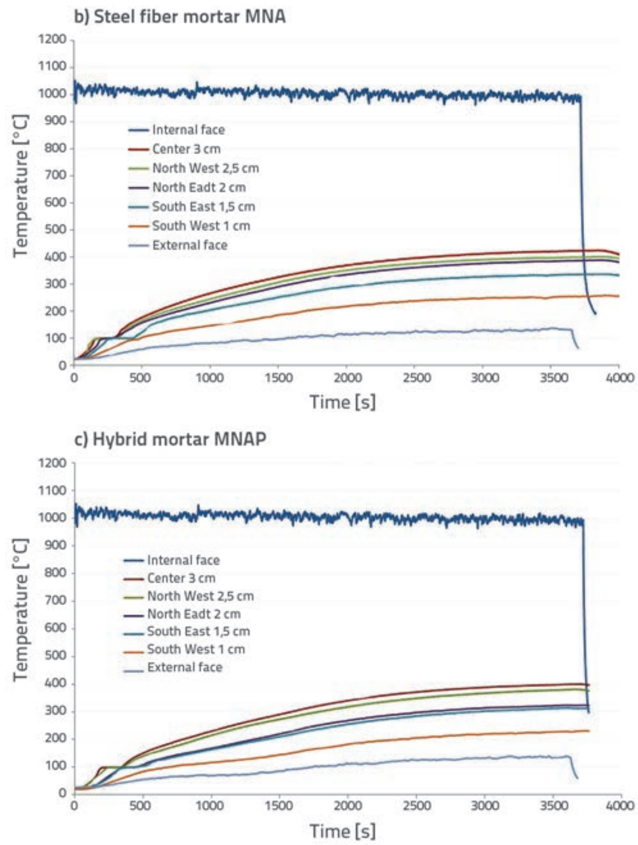


Figure 6. Temperature gradient during flame tests

2.5.2. Shear strength

The specimen is submitted to an axial load. The slab is simply supported by a circular ring. The results (load-deflection) registered for unheated samples and for samples heated to 1000°C are shown in Figures 7 and 8.

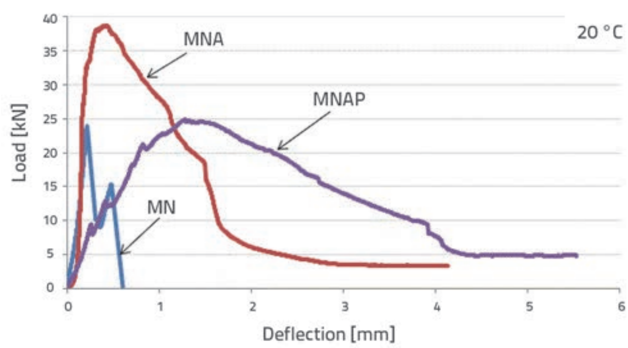


Figure 7. Load-deflection diagram for punching shear (unheated sample)

The shear strength of unreinforced and unheated mortar is 24 kN, but it drops to 5 kN after heating (80 % loss). The shear strength of steel fibre mortar decreases from 38 to 30 kN (21 % loss). With mixed steel-polypropylene fibres, the force decreases from 25 to 15 kN (40 % loss) during the heating process. The effect of steel fibres is very important at room temperature but also on heated elements. The mixed steel/polypropylene fibre reinforced mortars exhibit an intermediate behaviour.

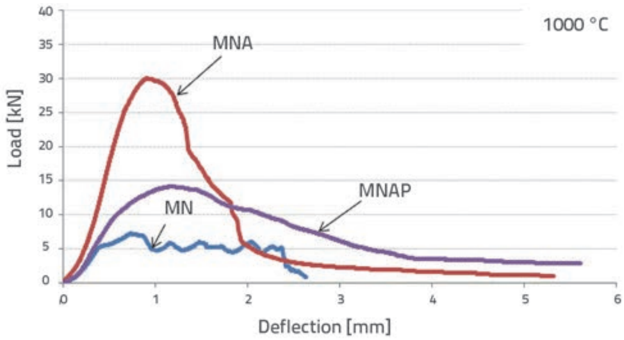


Figure 8. Load-deflection diagram for punching shear (heated sample)

2.5.3. Flexural strength

The flexural strength of these samples, measuring 4x4x16 cm^3, is shown in Figure 9. Results of monotonous flexural tests carried out on the unreinforced mortar (MN), and on mortars reinforced with steel fibres (MNA) and mixed steel/polypropylene fibres (MNAP), are presented in Figure 9.

Curves presented in Figure 9 constitute selection of curves obtained for each sample and each test condition.

At room temperature, the linear elastic behaviour is similar for both types of fibres, i.e. for the same linear slope. Before appearance of macro cracks, fibres do not contribute to the behaviour of the composite, which is mainly governed by properties of the cementitious matrix. The effect of fibres, and the difference in performance according to their nature, is greatly emphasized in the post-peak behaviour. The incorporation of fibres resulted in an improved post-peak behaviour of the composite, and in an increased ductility compared to the brittle behaviour of the matrix alone.

Nonlinear behaviour has been observed with respect to heating temperatures, and the mechanical behaviour of the material evolves with temperature. Exposed to high temperatures, the mortar is subjected to cracking, which is accompanied by important physicochemical changes that affect its bending behaviour.

The results of all these curves, after heating, also show the role of fibres in the ductile behaviour of the composite, although significant differences exist between the fibred materials. Indeed, the mortar reinforced with steel fibres (MNA) has a much superior behaviour (higher max load and higher post-peak load) when compared to the reference mortar (MN) or hybrid mortar (MNAP) at the temperature of 800°C. The behaviour of the mixed mortar MNAP is somewhere in between the mortar reinforced with steel fibres and the unreinforced mortar.

The influence of fibres is clear regardless of the temperature, at least up to 800°C. It diminishes as the temperature of plateau increases.

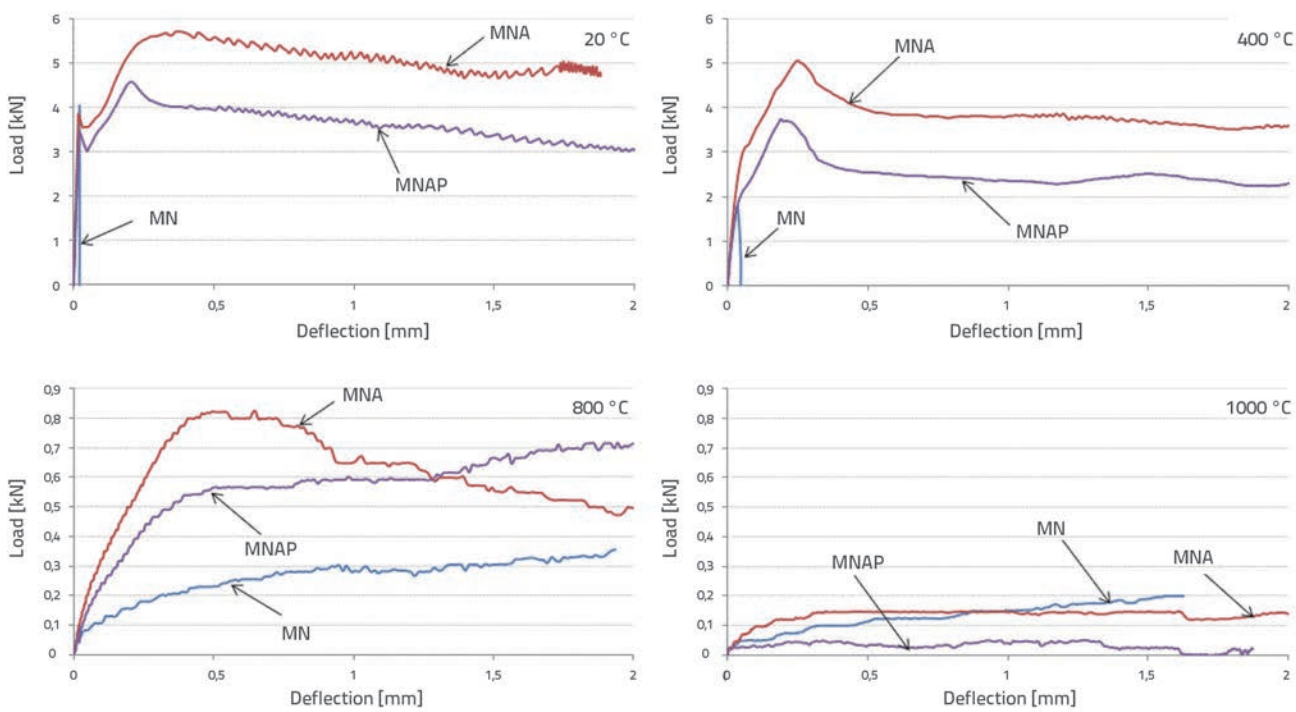


Figure 9. Load- deflection diagrams for 4-point flexural testing of furnace-heated samples

3. SEM observations

SEM observations are shown in Figure 10.a_1 and 10.a_2 for 400°C, 10.b_1 and 10.b_2 for 500°C, and 10.c_1 and 10.c_2 for 800°C.

At 400°C, the original appearance of the fibres is preserved. The deposit on the fibres, consisting of Ca, O, Si and Al from cement hydrates, reveals that the matrix adhesion is still quite good.

At 500°C, the surface of the fibre is modified; it begins to alter, i.e. to oxidize. The microprobe analysis of the fibre surface points to the presence of ferrous oxide (FeO), which only forms at high temperatures (Figure 11). Vourlias and al. [13] have observed similar phenomena on steel heated to 950°C for 15 h.

From 800°C, the section of the fibre decreases and transverse cracks appear (Figure 10.c_2). These cracks and this section reduction are explained by the drop in tensile resistance of the specimens. The bridging effect of the fibres is very small.

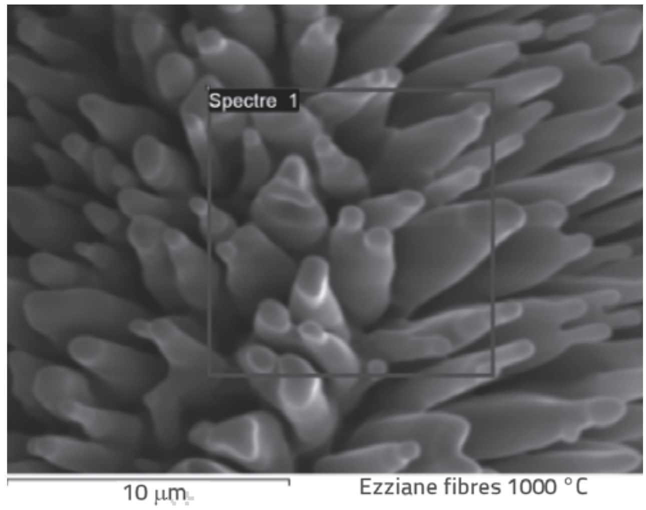
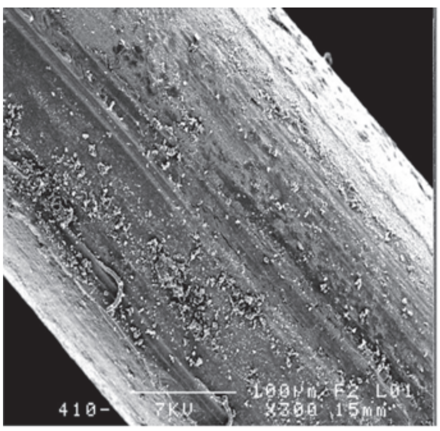
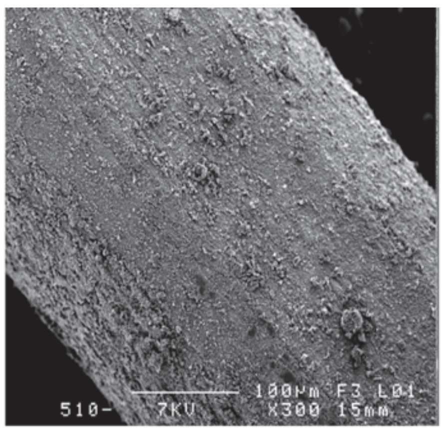


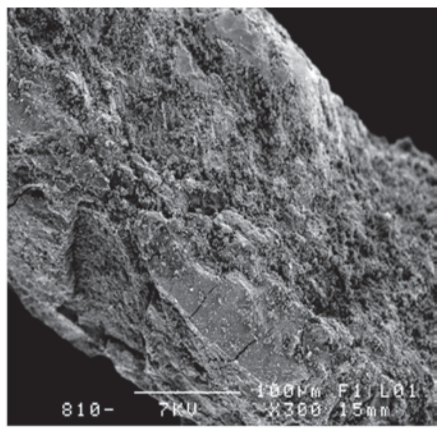
Figure 11. Appearance of oxides formed on the surface of a steel fibre in a specimen heated to 1000°C



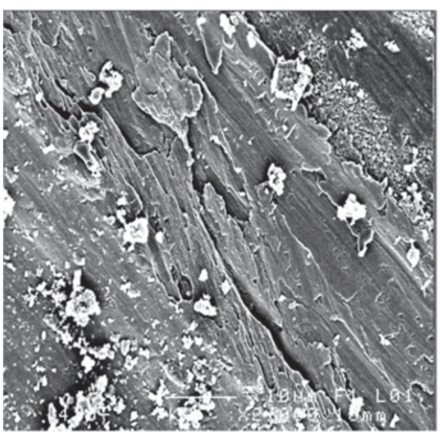
a_1) 400 °C (x300)



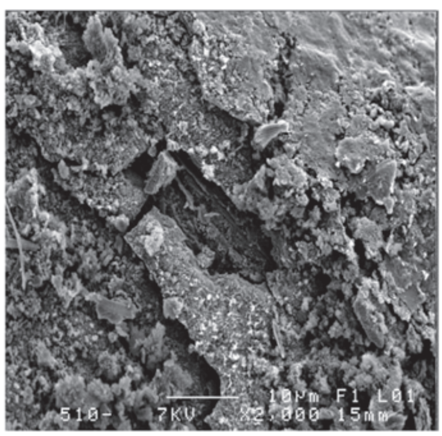
b_1) 500 °C (x300)



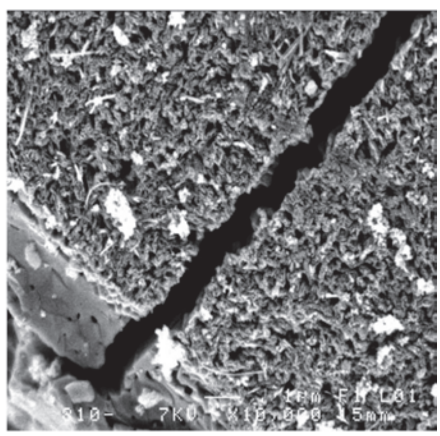
c_1) 800 °C (x300)



a_2) 400 °C (x2000)



b_2) 500 °C (x2000)



c_2) 800 °C (x2000)

Figure 10. Appearance of steel fibres extracted from mortar specimens

4. Conclusions

Traditional mortars exhibit a relatively protective behaviour in fire conditions. But they quickly lose all flexural strength. To improve the latter, it was envisaged to reinforce mortar with fibres. Mechanical behaviour of ordinary mortars is compared with that of mortar reinforced with steel fibres and polypropylene fibres. Those mortars are thermally treated at 400°C, 500°C, 800°C and 1000°C.
The results show that steel fibres contribute to the improvement of tensile strength at high temperatures and limit damage to mortars during thermal treatment. Steel fibres do not alter the physical and chemical degradation, but limit cracking during thermal treatment, and control the spread of these cracks during mechanical loading.
Polypropylene fibres melt at 170°C thus creating a porosity which limits pore pressure due to evaporation of pore water that occurs during heat exposure. Consequently, the cracking is reduced during exposure to heat.
The change of temperature in the material is measured at different points, when heated to 1000°C using propane flame. The fibres do not alter propagation of heat.
After one hour of heating samples are tested to determine their resistance to punching shear. This testing reveals that steel fibres perfectly play their role of improving the resistance to deformation (best ductility), which results in gradual rupture, rather than in sudden failure: the bridging efforts are transmitted by fibres to fracture surfaces. The energy dissipated before sample destruction increases considerably (area under the load-deflection curves). SEM observations and the microprobe analysis show oxidation of steel fibres at high temperatures. This oxidation provokes a loss of strength and an important ductility beyond 800°C, which may limit the interest of adding steel fibres against fire risk. But this temperature is limited to the distance of several millimetres from the flame: at 1 cm away from the flame the temperature does not exceed 500°C after one hour of heating.
Finally, the criterion of strength loss reduces with the introduction of steel fibres (0.58 % in volume). It is very effective with regard to mechanical behaviour when the high temperature does not exceed the plateau of 500°C, at 1 cm away from the flame after one hour of heating. Hybrid mortars appear to offer a good compromise: polypropylene fibres reduce internal pressure that causes cracking during heat exposure, and steel fibres limit cracking during heat exposure and subsequent mechanical loading.

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