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2 **High temperature behaviour of polypropylene fibres reinforced mortars**

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4

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11

12 **Abstract**

13 The aim of this paper is primarily experimental and is intended to analyse the behaviour of two
14 cementitious materials, before and after heat treatment: one unreinforced (i.e. without fibres) and the
15 other reinforced (with polypropylene fibres).

16 At room temperature and after heating up to 500°C, the bending strength is improved by the presences of
17 fibres. The residual young modulus is slightly higher for the fibres reinforced samples.

18 As the temperature increases, the strength gain due to fibres inclusion is reduced. Beyond 500°C, the
19 bending strength is lower for the fibre reinforced cementitious material compared to those without fibres.

20 Fracture energy is also improved for the fibre mortars at room temperature. At 400°C this improvement
21 decreases gradually with the introduction of polypropylene fibres. Beyond this temperature and due to the
22 introduction of polypropylene fibres, the fracture energy is reduced.

23 Another test is developed: rapid heating due to exposure to a flame. The temperature in the front side
24 reaches in few seconds 1000°C. At this temperature and after one hour of exposure, the opposite side

25 reached 140°C. After cooling, the punching shear strength of the fibre mortar is definitely weaker than of
26 the mortar without fibre.

27

28 KEYWORDS

29 Polypropylene fibre mortar, Mechanical behaviour, Fracture energy, Fire test, Spalling, Punching shear
30 test

31

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1. INTRODUCTION

40 The polypropylene fibres are used in the mortars and concrete to decrease the plastic shrinkage, cracking
41 and micro-cracking of surface [1]. They increase cohesion and reduce slump [2]. While inclusion of metal
42 fibres improves the fire resistance [3], the presence of polypropylene fibres in the material does not [4].
43 Only the effect limiting spalling at high temperatures is about to be unanimously recognized. This action
44 is primarily studied in high performance concrete i.e. with low water/cement ratio [4-6].

45 However, during a fire, very strong thermal gradients take place in first centimetres of concrete and the
46 thermal damage rapidly decreases from a maximum to nil [7, 8]. So, in these first centimetres, where
47 temperatures are less than a critical temperature, polypropylene fibres should still have an effect on
48 mechanical behaviour. The objective of this work is then to examine the effect of the temperature on the
49 residual behaviour of the polypropylene fibre mortars. In addition to the classical flexural strength, we
50 focus to the cracking behaviour and more particularly to the fracture energy and to the stress intensity
51 factor. These characteristics are important in connection with the crack resistance and in particular with
52 the resistance to spalling.

53 In this paper two type of heating were studied: low rate heating (2°C/min) and high rate heating (rate
54 similar to ISO 834 standard fire). These two studies allow to separate physicochemical effects and
55 temperature gradient effect.

56

57

2. MATERIALS

58 To ensure an effective bridging of the cracks (to limit the crack opening), the dimension of the selected
59 fibres must be greater than those of the aggregates [4]. At room temperature, the aim of the polypropylene
60 fibres in the composite matrix is to ensure a macro cracking bridging and to maintain high post peak
61 strength at a very large crack [9]. In this study cementitious mortars were studied, and then, 12 mm

62 monofilament polypropylene fibres were chosen. Characteristics of the fibres (given supplier: SIKA) are
63 detailed in table 1.

64

65 **Table 1:** Characteristics of test fibres (given SIKA)

Fibre	Length L (mm)	Diameter \varnothing (μm)	Ratio L/ \varnothing	Density ρ (kg/m^3)	Young Modulus E (GPa)	Melting point ($^{\circ}\text{C}$)	Tensile strength σ (GPa)
Polypropylene	12	18	667	910	6	170	0,55

66

67 A Portland cement is used: CEM1 52,5 N CE CP2 NF. This cement is made up mainly of clinker 95%,
68 whose details of the chemical and mineralogical compositions are reported in table 2.

69 The mortars are made with standardized sand according to CEN 196-1 standard with the ISO 679. The
70 mass proportions of cement, sand and water are 1:3:0.5. The volume proportion of added fibres in the
71 fibre mortars is 0.58% (i.e. $5.2 \text{ kg}/\text{m}^3$). Water was added to cement and mixed to obtain a homogeneous
72 paste; sand then gradually added to the paste and mixed until homogeneous. Fibres were added at the
73 final stage and dispersed manually. The constituents were mixed for two minutes after the introduction of
74 the fibres.

75 The specimens were then stored in a wet room (20°C , 95% RH) for 7 days and then stored in dry room
76 (20°C , 50% RH) up to an age of 28 days. Under these conditions, a significant portion of free water in the
77 cement matrix had evaporated [10].

78

79

80

Table 2: Chemical and mineralogical composition of cement CEM I 52,5.

Elements	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	NaO ₂	SO ₃	IR	LOI	Free CaO
%	22.40	2.96	2.33	66.60	0.95	0.15	0.10	2.13	0.20	1.59	0.50
		C ₃ S = 65.3		C ₂ S = 18.6		C ₃ A = 4.35		C ₄ AF = 7.14			

81

IR : insoluble residue; LOI : loss on ignition.

82

83

3. SLOW HEATING

84 3.1. Heat exposure in an oven

85 Samples, 4x4x16 cm³, were heated in an electric furnace to the desired temperature at a rate of 2°C/min.

86 The exposure temperature was maintained during one hour (1h) and cooling to room temperature was

87 carried out in the closed and disconnected furnace (approximately -0.3°C/min). The controlled

88 temperature is measured in oven chamber (i.e. not in samples). This process conducts to low thermal

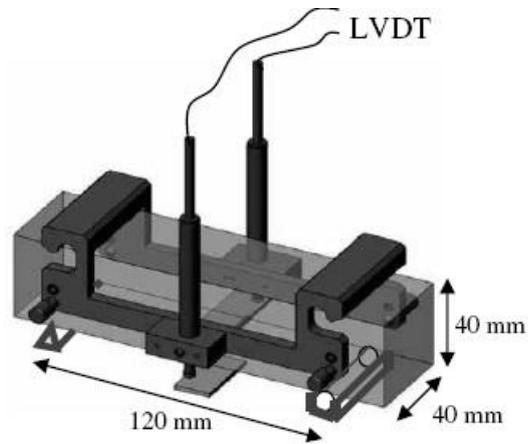
89 gradients. The damages in mortar are mainly of physicochemical origin [11].

90 3.2. Flexural strength

91 After cooling, samples were then tested in a four-point bending configuration. Six specimens were tested

92 for each condition (mortar type and heating temperature). The load is measure with a 50 kN load cell. A

93 template is attached to the specimen to measure deflection using two LVDTs (+/- 1mm) (figure 1).



94

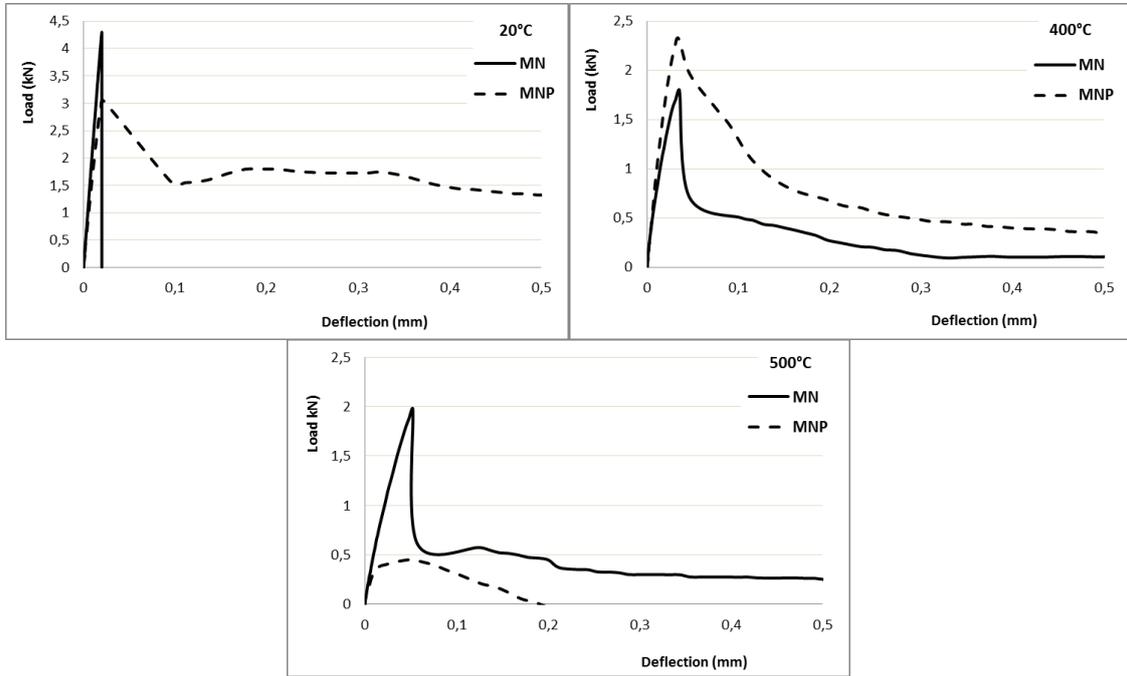
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Figure 1: Four-point sample with measuring t.

96

97 The bending test results carried out on unreinforced mortar (MN) and fibre reinforced mortar (MNP) are
98 presented in figure 2. The post peak residual load clearly highlights the role of fibres when samples are
99 not heated. The stress transfer between the faces of the cracks is significant and result is an increased
100 ductility. As already observed by other authors [12-14], this phenomenon attenuates very quickly between
101 400 and 500°C and disappear beyond 500°C. Figure 3 represents the evolution of the bending strength
102 with respect to the exposure temperature. The polypropylene fibres have a positive role until 400°C as it
103 was stated previously. The experimental values are reported in table 3.

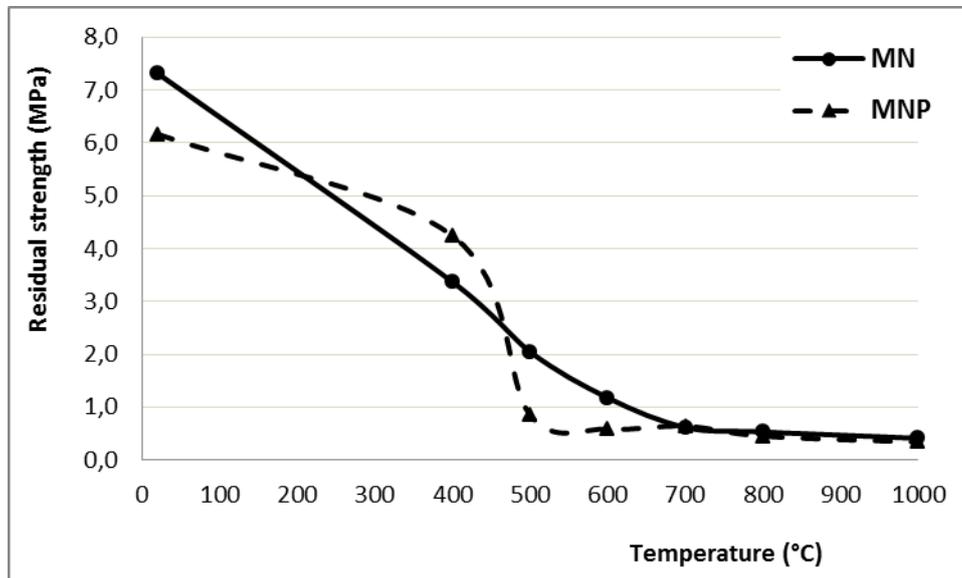
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105

106 **Figure 2:** Representative curves of behaviour of the unreinforced mortar not (MN) and reinforced the
107 0.58% volume one of polypropylene fibres (MNP) in four-point bending test.

108



109

110

Figure 3: Evolution of the four-point bending tensile strengths of the mortars with respect to the exposure temperature (rate: 2°C/min).

111

112

113

Table 3: Evolution of the bending tensile stress (MPa) with temperature.

Mortar	T°C	20°C	400°C	500°C
MN		7.3	3.4	2.0
MNP		6.2	4.2	0.8

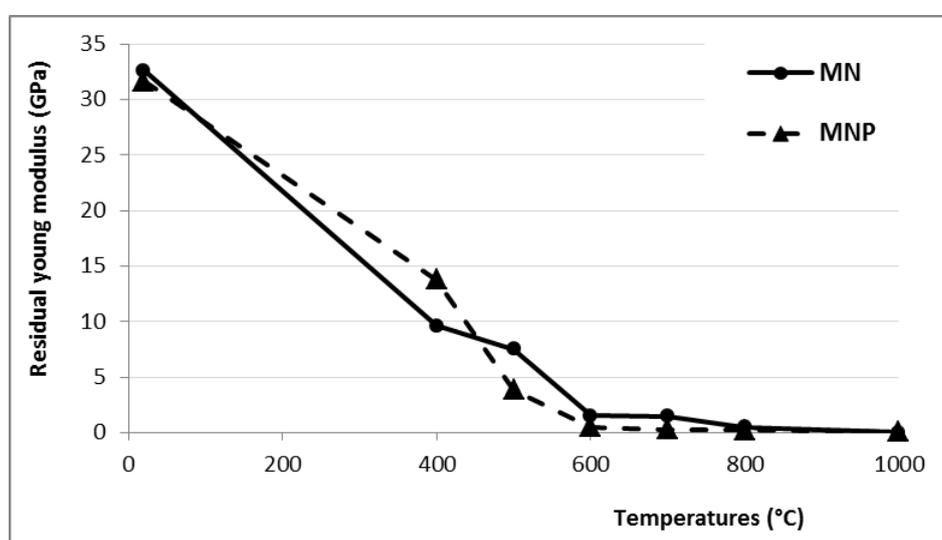
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115

116 3.3. Young modulus

117 Young modulus is defined as the elastic (and linear) stage of the load-deflection curve. The evolution of
 118 the residual Young modulus with respect to the exposure temperature is shown in figure 4 and table 4.

119 According to the test results, we notice that the modulus of the sample with fibre is greater than that of the
 120 non-fibre samples. The variation is accentuated until 400°C. At 500°C; they are identical and beyond this
 121 temperature; the young modulus of the fibred samples becomes almost zero.



122

123 **Figure 4:** Residual Young modulus (four-point bending test) vs. temperature of the heat treatment

124

125

Table 4: Young modulus (GPa) vs. temperature.

Mortar	T°C	20°C	400°C	500°C
MN		32.6	9.6	7.5
MNP		31.6	13.8	3.8

126

127

128 3.4. Fracture energy

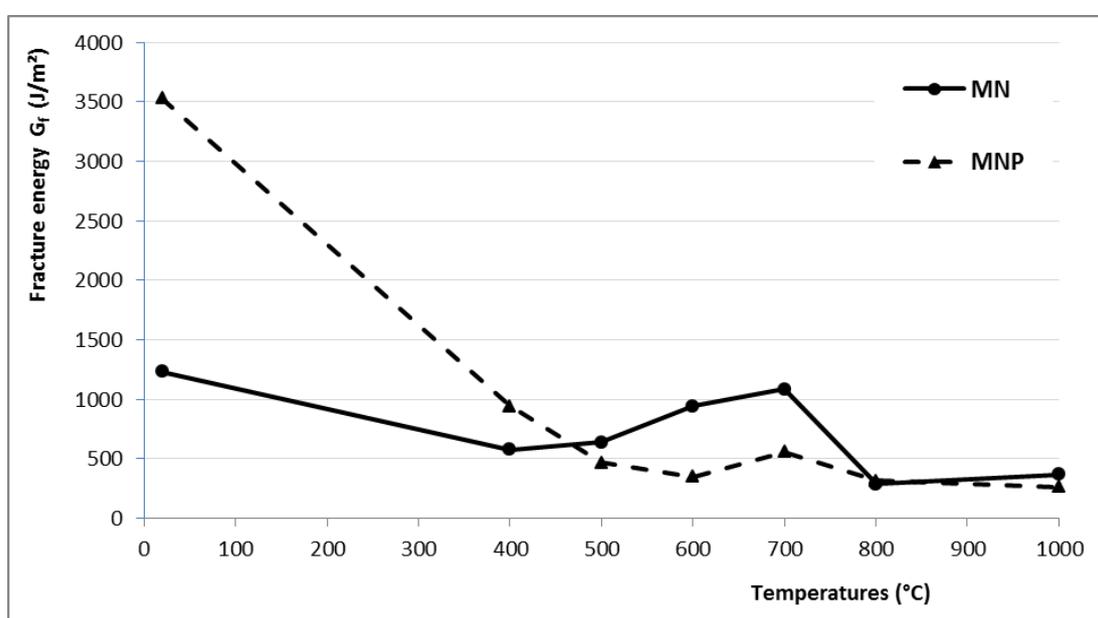
129 The fracture energy is defined as the area under the stress-strain curve of the four-point bending test [15].

130 Figure 5 and table 5 show the test results of the fracture energy with respect to the exposure temperature.

131 When the samples are not heated, the fracture energy of the fibre specimen is about three times the energy

132 of the non-fibre sample. This difference in fracture energy tends to converge and nullify at about 500°C.

133 Above 500°C, gain increase in fracture energy decreases for samples with fibres.



134

135 **Figure 5:** Evolution of the fracture energy with respect to the exposure temperature.

136

137 **Table 5:** Evolution of the fracture energy G_f (J/m²) with respect to the exposure temperature.

Mortar	T°C	20°C	400°C	500°C
MN		1234	577	639
MNP		3531	943	468

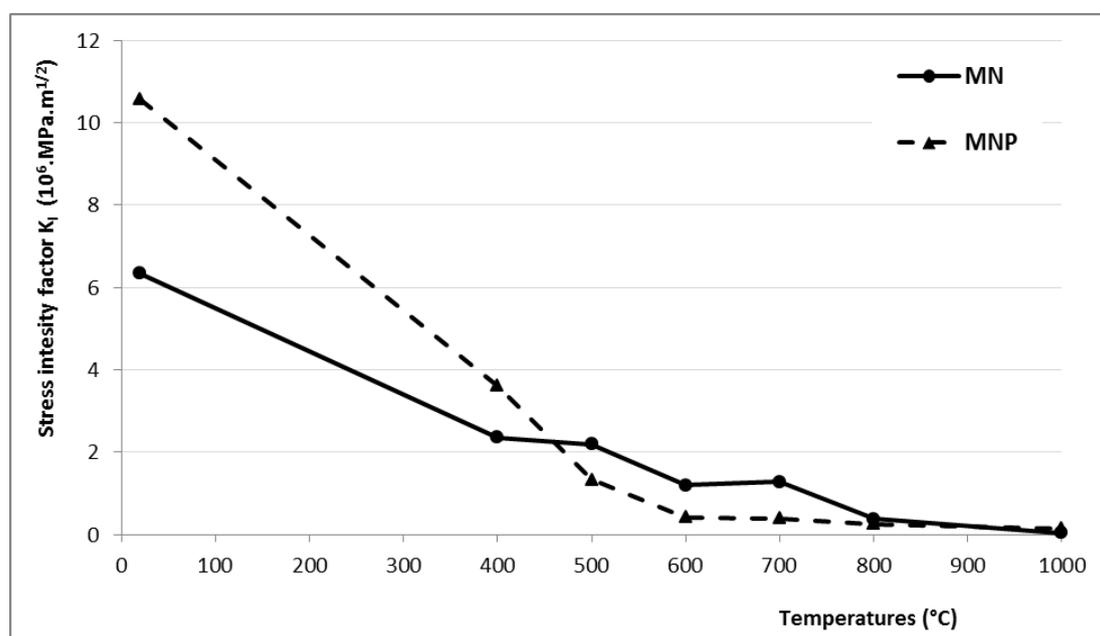
138 3.5. Stress intensity factor

139 The stress intensity factor K_I characterizes the resistance of material to the propagation of the crack and to
140 the damage [16-18]. This parameter can be deduced from the calculation of the fracture energy G_f and of
141 the Young modulus E . It is defined by the following relation:

142
$$K_I = (G_f \cdot E)^{0.5} \tag{eq. 1}$$

143 This parameter takes into account the degradation of the cement matrix; rather quantifiable by the young
144 modulus and the fibre degradation (modification of the characteristics of fibres, loss of cohesion), rather
145 quantifiable by the fracture energy. This is thus a representative parameter of the overall damage of the
146 fibrous material.

147 The evolutions of the stress intensity factor of the mortars with respect to the exposure temperature are
148 illustrated in figure 6 and table 6.



149

150 **Figure 6:** Evolution of the stress intensity factor K_I with respect to the exposure temperature.

151 **Table 6:** Evolution of the intensity factor K_I ($10^6 \text{ MPa.m}^{1/2}$) with respect to the exposure temperature.

Mortar	T°C	20°C	400°C	500°C
MN		6,3	2,4	2,2
MNP		10,6	3,6	1,3

152

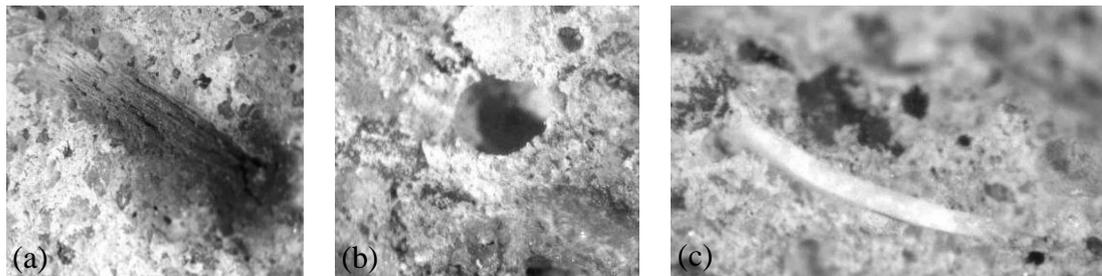
153 According to the test results (figure 5 and figure 6), we notice that the fracture energy and the stress
154 intensity factor have similar behaviour when exposed to equivalent temperatures.

155 The stress intensity factor for the fibre mortar K_I has a great value at 20°C and 400°C. Beyond this limit,
156 we observe a very pronounced decreasing of the stress intensity factor. This decrease is mainly due to the
157 fact that the polypropylene fibres have certainly totally melted and calcined. The fibres that stop crack
158 propagation are no longer present.

159 At the high temperatures, two types of damage appear: (1) the physicochemical modifications and (2)
160 cracking of the cementing matrix [11, 19, 20]. Results from a previous study showed that the
161 polypropylene fibres had more effect on the reduction of cracking than on the reduction of the
162 physicochemical modifications [21]. From 170°C, the polypropylene fibres melt and create a connected
163 porosity [22]. This porosity allows evacuating vapour over-pressures and thus reducing cracking [23].
164 This weaker cracking explains the best results in term of resistance, ductility and fracture energy or stress
165 intensity factor.

166 Moreover, when the temperature of the furnace is 400°C, the temperature inside the specimen is lower
167 and can be not sufficient to destroy all fibres. The propagation of heat is slowed down in the dehydrated
168 cementing matrix [11-17]. The fibres disappear gradually from the periphery of the sample towards the
169 centre: the kinetics of propagation of heat is slowed down by the more or less insulating dehydrated
170 cementing matrix [8]. Fibres remain in the heart of the sample and contribute to the ductility of material.
171 Beyond 500°C, the fibres completely disappeared to create an additional porosity [22-26]. This porosity

172 leads thus to a lower energy than that of the not fibred samples. This process has been observed by optical
173 microscopy (figure 7). Small slice extracted from different depth of a sample exhibits completely calcined
174 polypropylene fibres in the first millimetres. Deeper slice contains yet partially melted fibre.



175
176 **Figure 7 :** Optical microscopy observations. (a) Calcined fibre. (b) Melted Fibre. (c) Partially melted
177 fibre.

178

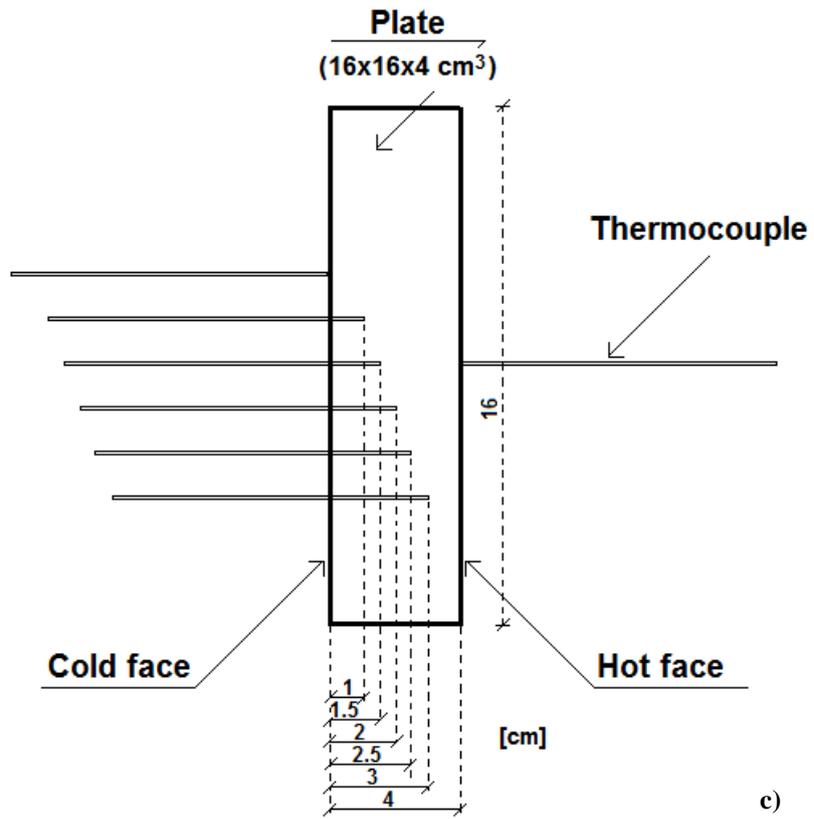
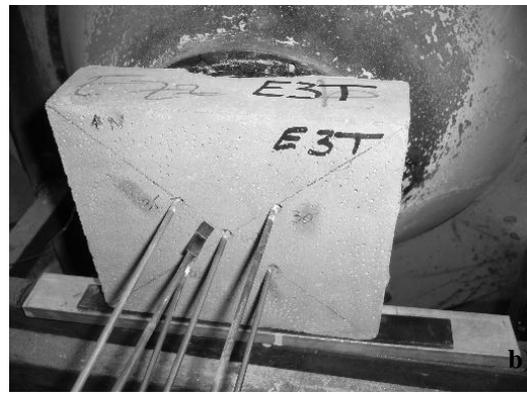
179 4. FLAME TEST

180 4.1. Exposure to fire

181 The second heat treatment consists of placing plates of dimensions $16 \times 16 \times 4 \text{ cm}^3$ made of unreinforced
182 mortar and polypropylene fibre reinforced mortar in a flame test apparatus (figure 8a). Five
183 thermocouples were inserted in the plate (figure 8b) at different depth and two other thermocouples were
184 positioned in contact with the internal face (hot face) and external face (cold face) (figure 8c). The
185 temperature of the exposed face (dimensions $16 \times 16 \text{ cm}^2$) is forced to 1000°C and was maintained for one
186 hour. Figure 9 compares the rate of temperature between the experimental curve and the ISO 834 standard
187 fire. The experimental rate of temperature is similar to that of ISO 834 up to 1000°C . This rate leads to a
188 strong temperature gradient in the sample. The sample dimensions are assumed to be enough to observe
189 spalling.

190 The heat flux is assumed to be unidirectional. The flame position allows setting in a precise manner the
191 temperature of the surface.

192



193

194

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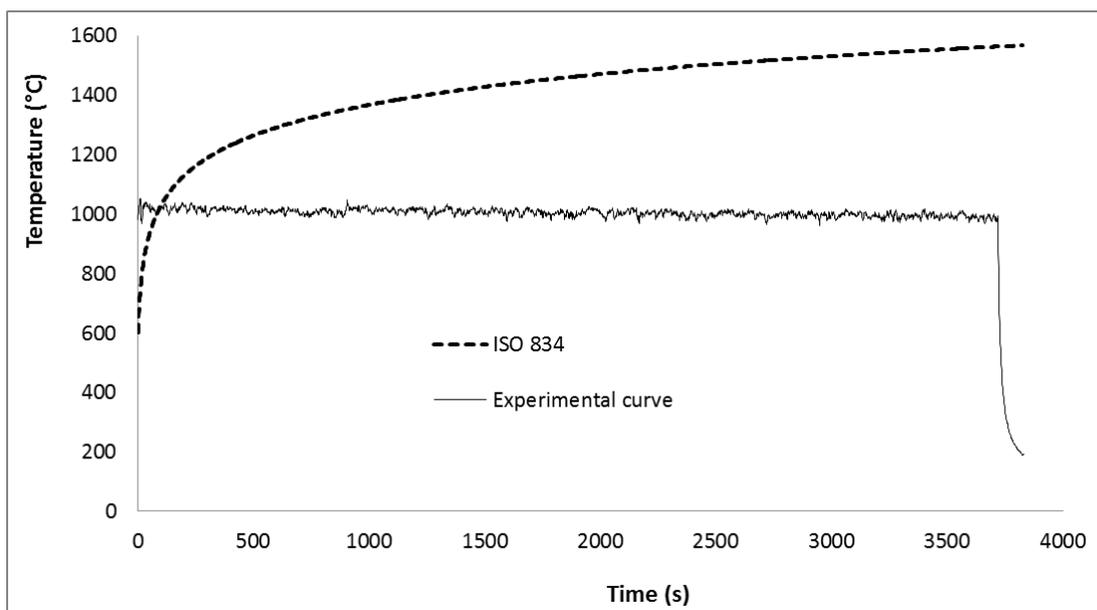
Figure 8: a) mounting flame test, b) drilled external face, c) thermocouples position.

196 Two series of test were performed:

197 - First series (equipped with 7 thermocouples (type K)): the evolution of the temperature of this series is
198 obtained by placing thermocouples (drilled after casting) at different depths of the sample (external face –
199 1 cm – 1.5 cm – 2 cm – 2.5 cm – 3 cm, and the internal side) as illustrated in figure 8c.

200 - Second series (equipped with 2 thermocouples): thermocouples were positioned in contact with the
201 external (cold face) side and at the internal (hot face) side. It has to be noted that this thermocouple
202 measures radiation and convection from the flame, rather than surface temperature at the exposed face.
203 However it was very difficult to achieve the measuring of the surface real temperature.

204 At the end of the test, cooling was performed naturally at room temperature. Punching shear tests were,
205 then carried out for a comparison.



206

207

Figure 9: Comparison between ISO 834 fire and the experimental curve.

208

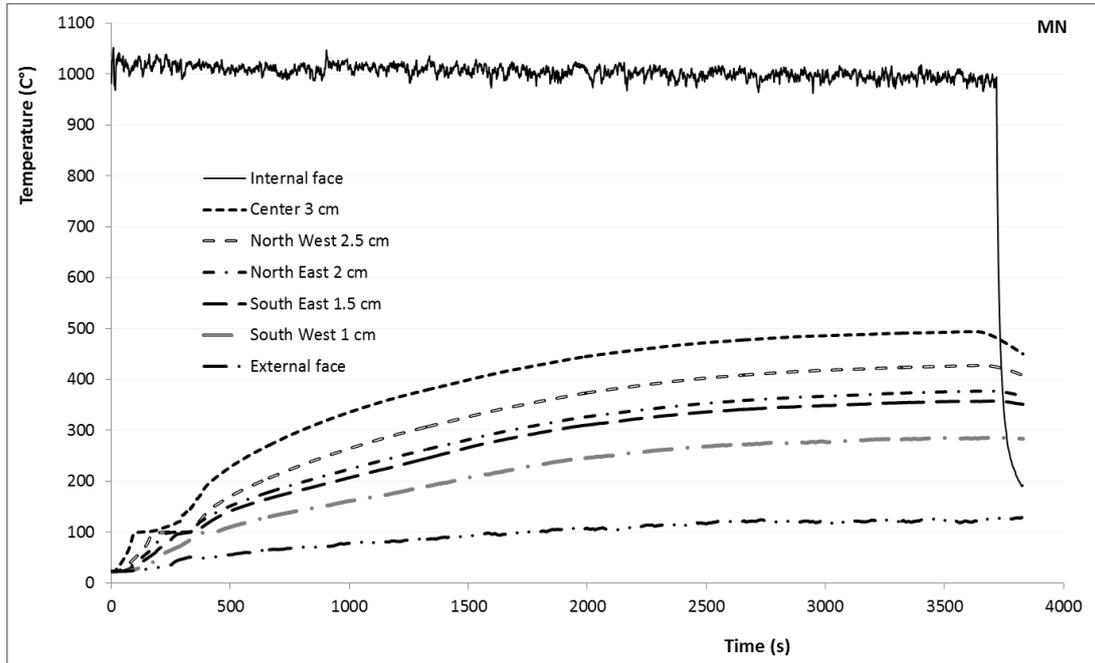
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210 4.2. Heat transfer

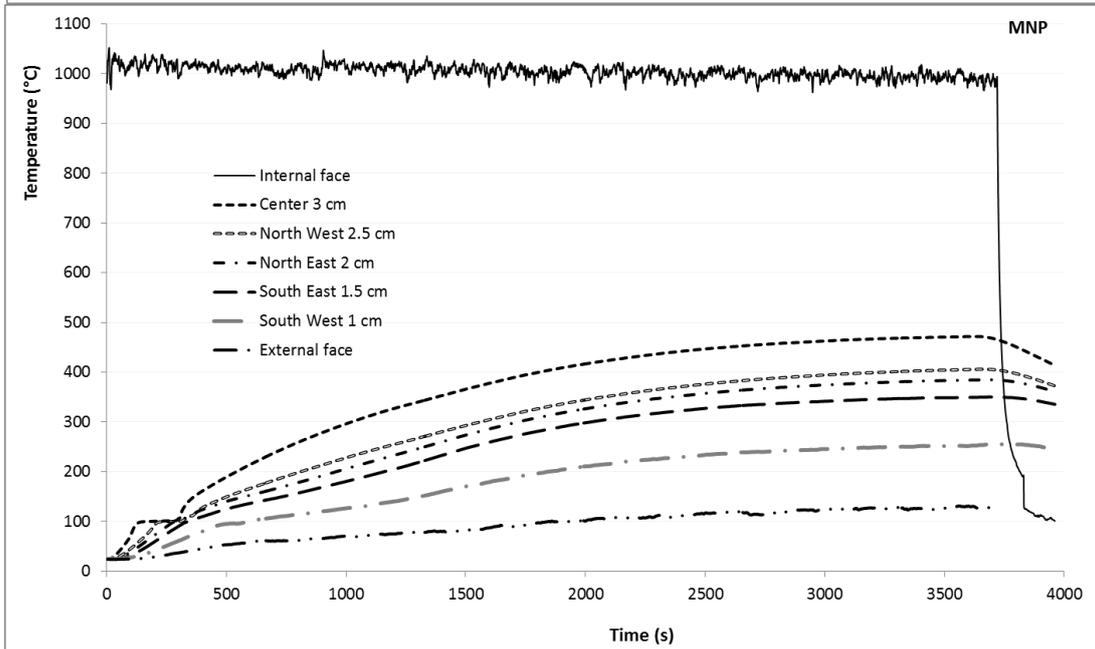
211 During these tests, and after 5 minutes of treatment, we observed, drops of water and water vapour
212 escaping from the drilling of thermocouples of the unexposed surface of the test sample for the 2 types of
213 mortars. Nine minutes after treatment, we observed the apparition of a fist crack in the standard mortar.
214 This crack has developed from lateral side to the centre. However, this phenomenon did not appear for
215 fibre reinforced mortar.

216 Figure 10 shows the evolution of the temperature of both mortars with respect of time and depth. The
217 temperature evolution consists of three stages: a rapid increase of the temperature until 100°C, an
218 isothermal stage around 100°C and an increase of the temperature. The isothermal stage around 100°C
219 corresponds to the evaporation of free water at different depths. Mindeguia et al., [8] observed this
220 plateau at 100°C for low compactness concrete.

221



222

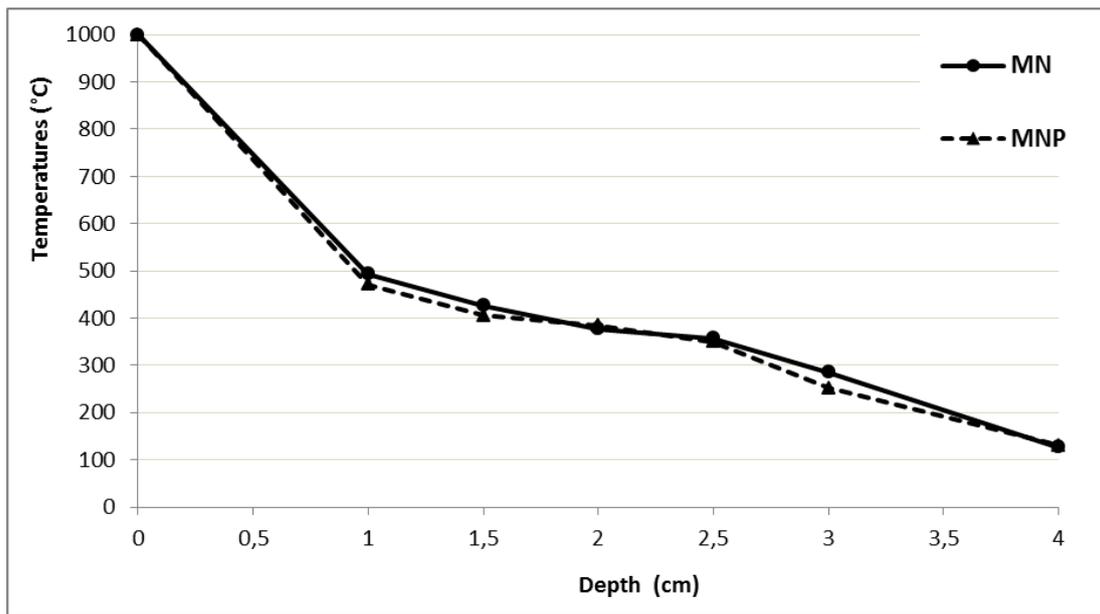


223

Figure 10: Evolution of the temperature at different depths of the non-fibre mortar and fibre mortar.

224

225 It is this possible to quantify the heat propagation in the two mortars using the temperature measured by
226 thermocouples. To check the effect of drilling on this transfer, plates were tested without drillings
227 (without thermocouple), and only hot face temperature and cold side temperature were measured. It was
228 seen that the temperature at the external face is similar for plates with and without drilling. Temperature
229 gradients in plates made of standard mortar and fibre reinforced mortar are shown in figure 11. The
230 presence of polypropylene fibres does not lead to significant changes in the phenomenon of heat
231 propagation. The temperature at 3 cm depth (i.e at 1 cm of the hot face) does not exceed 500°C. In the
232 outer face (i.e. at 4 cm from the hot face), the temperature reaches approximately 140°C after one hour of
233 exposure.



234
235 **Figure 11:** Thermal gradient within test specimens after one hour of thermal exposure during flame
236 tests.

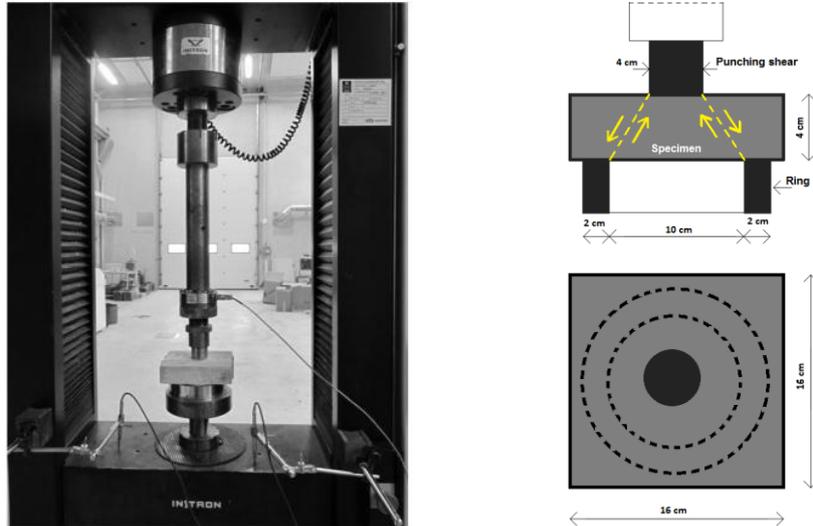
237
238
239

240 4.3. Mass loss after tests

241 The mass loss at the end of the test is almost identical for the two mortars. The mass loss of the standard
242 mortar (MN) and fibre mortar (MNP) is 6.4% and 6.5% respectively. We can say that the fibres
243 embedded in the mortar have virtually no influence on the evaporation of water from mortar and
244 hydroxides OH after this heating. Similar observations were reported by [27].

245 4.4. Residual strength

246 Subsequently, to enable a comparison between the residual mechanical strength of samples a punching
247 shear strength [28] test was performed on non-drilled samples as presented in figure 12. Results are
248 reported on table 7. Each value is the mean between ten samples; the difference between these ten values
249 is maximum 3%. Before flame exposure, punching shear strengths are quite similar for the two mortars.
250 After flame exposure, all mortars show a loss of punching shear strength. Fibre mortars have a lower
251 residual strength compared to those without fibres: strength reduction is 64.5% for mortar without fibre
252 and 73.7% for mortar with polypropylene fibres. A temperature of 1000°C at the hot face for 1 hour
253 conducts to temperature greater than 170°C (polypropylene melting) up to about 1 cm from the cold face:
254 it can be considered that all fibres were completely melted up to about 1 cm from the cold face. The
255 induced porosity due to the degradation of the fibres decreases the strength. However, after heating, a part
256 of polypropylene fibres is still present in the outer face side. The cold face temperature is only 140°C
257 after one hour, while the melting point is given at 170°C. Thus, the strength loss is limited. These results
258 are consistent with the results obtained in a preliminary study [29].



259

260

Figure 12: Test bed to punching shear.

261

262

Table 7: Residual punching shear effort of the plates after testing at flame.

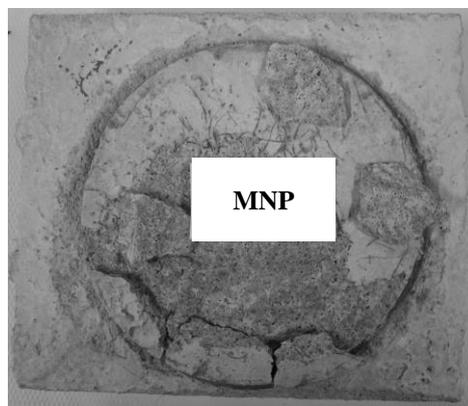
	Non-heated	Heated
Mortars	F_{\max} (kN)	F_{\max} (kN)
Non-fibre	20.3	7.2
Fibre	20.9	5.5

263

264 4.5. Spalling during heating

265 Induced porosity due to melting of polypropylene fibres is considered to facilitate the transfer of steam
 266 and avoid spalling [23, 30, 31]. It is reasonable to consider that concrete incorporating polypropylene
 267 fibre can provide a benefit to concrete so as to prevent it from explosive spalling, due to the fact that it is
 268 melted under temperature around 170°C and hence accumulated moisture pressure in concrete can escape
 269 through inter-connected pores to outside of concrete. Samples from mortars with and without fibre at a

270 water to cement ratio equal to 0.5 did not spall. However, other tests with polypropylene fibre reinforced
271 mortars with the same fibre volume ratio but a water/cement ratio of 0.4 spalled during testing (figure 13).
272 Similar observations were conducted in studies on concrete with low water/cement ratio (concrete with
273 0.26 water/cement ratio and 1 kg/m³ of polypropylene fibres spalled, but concrete with 0.26 water/cement
274 ratio and 0.6 kg/m³ of polypropylene fibres and 40 kg/m³ of steel fibres did not spall [32]) or on
275 lightweight concrete (concrete with 0.33 ratio spalled, and concrete with 0.42 ratio did not spall [5]).



276

277 **Figure 13:** Example of spalling of sample made with 0.58% polypropylene fibre and w/c=0.4.

278

279

7. CONCLUSION

280 This study highlights the contribution of polypropylene fibres in cement based building materials exposed
281 to an increasing temperature or exposed to flame. We have studied the mechanical behaviour of standard
282 mortars and fibre reinforced mortars heat-treated at 400°C, 500°C, 600°C, 700°C, 800°C and 1000°C.
283 Two types of treatment have been made: a heating furnace (low rate) and an extreme heated test with
284 flame (high rate).

285 At room temperature (before heating), the post peak stress clearly highlights the role of the fibres: the
286 stress transfer between the faces of the cracks by polypropylene fibres is important and gives samples
287 ductility.

288 After heating, below 400°C, the fibres have an uncracking effect by allowing the dissipation of fluid over
289 pressure in the matrix. This phenomenon disappears at a temperature over 500°C. The fibre samples have
290 greater young modulus compared to that of the non-fibred ones with an increasing gap until a temperature
291 of 400°C and decreases beyond this value. At 500°C, they are identical. After 500°C, the young modulus
292 becomes almost zero. The fracture energy at 20°C is 3 times greater for the fibred samples compared to
293 the non-fibred ones. This ratio drops to 1.5 at 400°C. Fibres effects are negative beyond the temperature
294 of 500°C.

295 It appears, from the flame test that the fibre mortar and non-fibre mortar have the same thermal
296 behaviour. After one hour, the unexposed side is about 140°C.

297 For the residual punching strength; the results show that polypropylene fibres are not so efficient: the
298 polypropylene fibres limit the cracking during heating but do not increase the punching strength.

299 By melting at 200°C the polypropylene fibres are considered to create a porosity which allows a
300 limitation of the pressure due to the evaporation of water treatment and thus a limitation of cracking. The
301 spalling phenomenon was not observed for all mortars having a water/cement ratio of 0.5. However,
302 spalling was observed for mortars with water/cement ratio of 0.4.

303 For design of concrete structures, it has to be noted that the temperature remains below 500°C after two
304 centimetres inside the concrete (i.e. after the cover over reinforcing steel). Up to 500°C, polypropylene
305 reinforced mortar gives a pseudo-ductile behaviour with a better strength, a better Young modulus, a
306 better fracture energy than mortar without fibre. Thus, the safety of concrete structures submitted to fire is
307 increased. After fire, the rehabilitation of concrete cover will be limited and associated cost decreased.

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