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1 **Impact of external biaxial compressive loading on the fire spalling**  
2 **behavior of normal-strength concrete**

3  
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16  
17 **Abstract:** Explosive spalling of concrete exposed to fire consists in the expulsion of shards  
18 from the heated face during rapid heating. The phenomenon can seriously jeopardize the  
19 integrity of reinforced concrete structures due to the reduction of the cross-sectional area of the  
20 structural elements and even leading to the direct exposure of reinforcing bars to flames. In the  
21 literature, it is shown that various parameters influence the occurrence of fire spalling, such as  
22 heating rate, specimens geometry and boundary conditions, concrete grade, and external loads.  
23 In this regards, the present study aims at highlighting the role of external loading in

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24 combination with the effects of pore pressure and thermo-mechanical stresses in triggering  
25 spalling in normal-strength concrete ( $f_{c_{28days}} \approx 45$  MPa). Unreinforced concrete slabs (size: 800  
26  $\times 800 \times 100$  mm<sup>3</sup>) were subjected to a standard (ISO 834-1) fire curve under seven different  
27 levels of external membrane biaxial compressive load. The experimental results clearly show  
28 that compressive loading significantly increases spalling propensity and severity.

29

30 **Keywords:** Concrete, Biaxial compression, Standard fire curve, High temperature, Pore  
31 pressure, Thermal stress, Fire spalling.

32

### 33 **1 Introduction**

34 Because of some significant accidents that occurred in the last decades, the safety of human  
35 beings in case of fire is one of the major issues in the design and construction of concrete  
36 structures and infrastructures, such as buildings, tunnels, nuclear power plants, and shelter  
37 structures. Therefore, it is necessary to attain an extended knowledge about the fire behavior of  
38 concrete in order to ensure adequate fire stability of the concrete structures.

39 Heat exposed concrete, in fact, experiences an overall decay of the mechanical properties (in  
40 terms of both compressive and tensile strength, and stiffness) due to the chemo-physical  
41 processes occurring in the material because of the high temperatures, that induce a generalized  
42 cracking and damaging in matrix and aggregates [1, 2]. Such condition can be worsened by fire  
43 spalling phenomenon, namely the sudden detachment of concrete layers or pieces from the  
44 surface of the concrete element when exposed to high temperatures. Such a phenomenon can  
45 significantly decrease the cross-section geometry and reinforcements can be even directly  
46 exposed to the flames (thus speeding up the deterioration of the mechanical properties of

47 reinforcement), thus considerably jeopardizing the structural load-bearing capacity [3, 4].

48 It is generally agreed that two physical mechanisms are associated with fire spalling: the  
49 build-up of pore pressure due to water vaporization (thermo-hygral mechanism) and the  
50 introduction of thermal stresses because of temperature gradients (thermo-mechanical  
51 mechanism).

52 Even though extensive experimental research has been conducted in the literature to explain  
53 the mechanisms behind fire spalling of concrete, a comprehensive explanation of the  
54 phenomenon is still to be given. Studies emphasize pore pressure as the main driving force [5].  
55 In contrast, others underline the importance of thermally induced stresses [6, 7] or consider their  
56 combination necessary to trigger spalling [3, 8, 9]. Some recent experimental studies corroborate  
57 the idea that pore pressure build-up alone is not sufficient, even though very high values can be  
58 attained during heating [10, 11, 12, 13]. In particular, Mindeguia et al. [11] observed several  
59 concrete specimens exposed to high temperature spalled with low pore pressure (lower than 0.5  
60 MPa). In comparison, other specimens did not spall even though they experienced high pressure  
61 values (higher than 2.5 MPa) [11].

62 Spalling phenomenon is made rather complex by the interaction of various parameters, such  
63 as material factors (porosity, permeability, types of aggregate, fibers, particle size distribution,  
64 moisture content, the strength of concrete, etc.), geometrical factors (shape and size of the  
65 specimens), and external factors (heating rate, applied external mechanical loading, and  
66 constraints), which influence the fire behavior of concrete [3-15]. Among the others, Ali et al.  
67 [16] investigated the effect of specimen size (testing 200 × 100 mm cylinders, 400 × 400  
68 columns, small slabs and large wall panels:), and aggregate types (granite and basalt aggregates)  
69 and size (maximum diameter of 7 mm, 14 mm, and 20 mm) on the fire spalling behavior of

70 concrete. It was observed that spalling depths were significantly higher for larger-size  
71 specimens than the smaller-size specimens [16], this being probably ascribable to the higher  
72 thermal stress induced in stiffer specimens by thermal gradients. Spalling depth dramatically  
73 increased for concrete cast with smaller-size aggregates [16], probably due to the lower porosity  
74 triggering higher values of vapor pressure in the pores. In contrast, a negligible spalling  
75 difference was observed for the concrete made with basalt and granite aggregates due to the  
76 similar thermal expansion coefficient of the aggregates [16]. Interestingly, Fernandes et al. [17]  
77 studied the fire spalling behavior of concrete made with different replacement percentages (0%,  
78 10%, 20%, 40%, and 100% by volume) of natural aggregate (NA) by recycled concrete  
79 aggregates (RCA) on prismatic specimens (20 cm × 20 cm × 10 cm). The samples were exposed  
80 to ISO 834-1 fire curve with a constant uniaxial compressive loading (2.5 and 5 MPa) [17]. The  
81 authors reported that concrete made with RCAs is more sensitive to fire spalling than NA with  
82 spalling severity increasing with aggregate replacement rate of up to 40%, while for higher  
83 values spalling depths and volumes remained almost constant [17].

84 From the literature, it can be also observed as already adding 0.2 kg/m<sup>3</sup> of polypropylene  
85 (PP) fiber can remarkably diminish spalling propensity, while 0.6 kg/m<sup>3</sup> can even be enough to  
86 avoid spalling [18], even though it is worth noting as such results strongly depends on fiber  
87 chemistry, melting temperature and aspect ratio. The beneficial role of PP fibers mainly  
88 depends on the mitigation of the build-up of the pore pressure due to an increase in the porosity  
89 and permeability of concrete caused by the melting of PP at around 165 °C, thus allowing the  
90 escape of the vapor pressure in the pores [19] and minimizing the risk of fire spalling. [18, 20].  
91 On the other hand, steel fiber cannot be considered an effective mean against spalling, since the

92 increased toughness in tension of fiber-reinforced concrete can have a negative effect leading to  
93 more violent spalling events [21].

94 It is worth mentioning that numerous experimental studies have been published in the  
95 literature on experimental tests conducted on unloaded specimens [3-4, 11-12, 22-26], while  
96 comparatively, there are few published data on loaded specimens [27-34]. Tests carried out in  
97 [27, 28, 29] highlighted that mechanically loaded specimens during heating are more susceptible  
98 to spalling than unloaded specimens. Other studies highlighted not only the role of the applied  
99 stress level, but also the way in which it is imposed [27-31]. Mohaine et al. [35] investigated the  
100 differences of five different spalling tests with different specimen geometries (cylinder, large  
101 ring, small ring, and intermediate scale slabs) and boundary conditions (mechanical load or  
102 restraint) in characterizing the behavior of a “spalling-sensitive” concrete. The authors' findings  
103 confirmed that the existence of mechanical load and/or restraint significantly affects the  
104 magnitude of spalling [35]. The maximum spalling depths were registered for the slab loaded  
105 during heating (e.g., spalling depth was more than twice for the loaded slab than the unloaded  
106 slab) and the restrained large rings [35]. Ozawa et al. [36] reported that pre-stressed concrete  
107 slabs experienced significantly higher spalling than ring-restrained concrete specimens and pre-  
108 stressed concrete beams. Despite the investigations mentioned above [27-31, 35, 36], however,  
109 the role of loading on concrete fire spalling behavior it has not totally clarified, demonstrating  
110 the need for a systematic study.

111 Finally, it can be observed as in the literature most of the researchers investigated concrete  
112 made with cement CEM I [4, 12, 13, 18, 19, 23, 26, 27, 28, and 36] or CEM II [4, 11, 17, 22, and  
113 28], while limited work deals with CEM III [35] (as CEM III/A 42.5 N CE CP1 NF, containing  
114 43% of slag). Within this context, this study attempted to fill the literature gap and better

115 understand the effect of slag content on the fire spalling behavior of concrete made with CEM II  
 116 (3% of slag) and CEM III (43% of slag). In this regard, it is also worth noting as CEM III is  
 117 attracting more and more attention in the last years thanks to the lower content of Portland  
 118 Cement (thanks to its partial replacement with slag), this being advantageous in the view of  
 119 concrete sustainability.

120 In order to cast some light on the abovementioned issues, namely role of external biaxial  
 121 compression and cement type, an extensive experimental campaign has been conducted  
 122 employing the test setup developed at the Politecnico di Milano [37] for the herein presented  
 123 experimental campaign developed within a research collaboration with Centre Scientifique et  
 124 Technique du Bâtiment – CSTB (France) and Université de Pau et des Pays de l’Adour–  
 125 SIAME (France). The following sections discuss the test methodology and experimental results  
 126 regarding fire spalling patterns, temperature, pore pressure, and cracking.

127

128 **2 Experimental investigation**

129 **2.1 Tests plan and concrete mixes**

130 The influence of biaxial compressive loading on fire spalling has been investigated on 15 mid-  
 131 size concrete slabs (800 x 800 x 100 mm<sup>3</sup>). The slabs were subjected to ISO 834-1 fire curve at  
 132 the bottom face under different levels of biaxial compressive loading ranging from 0 to 10 MPa.  
 133 Two experimental test campaigns were conducted in 2015 and 2016 [38], and the overview of the  
 134 testing program is shown in Table 1.

135 Table 1: Test plan (Note: “–” = No test).

Applied stress [MPa]		0	0.5	0.75	1.5	3	5	10
2015	B40-II	1	1	–	–	–	1	1
	B40-III	–	1	–	–	–	1	1

2016	B40-II	1	–	1	1	1	–	–
	B40-III	1	–	1	1	1	–	–

136

137 Two normal strength concretes have been investigated, namely B40-II made with CEM II  
 138 (CEM II/A-LL 42.5 R CE CP2 NF) cement and B40-III made with CEM III (CEM III/A 42.5 N  
 139 CE CP1 NF). It should be noted that the mix design of the two concretes was identical, with the  
 140 only difference of the cement type. CEM II cement contains 85% of clinker, 12% of calcareous  
 141 fillers, and 3% of slag, while CEM III cement contains 54% of clinker, 3% of calcareous fillers,  
 142 and 43% of slag. Compressive strength ( $f_c$ ) and splitting tensile strength ( $f_t$ ) of both concrete were  
 143 measured on cubic samples ( $100 \times 100 \times 100 \text{ mm}^3$ ) at the age of 28 and 90 days. The mixed  
 144 design of the two concretes is reported in Tab. 2, together with their main mechanical properties.

145

Table 2. Mix design and mechanical properties of the concrete mixes.

B40 Concrete	Unit	B40-II	B40-III
Cement	$\text{kg/m}^3$	350	350
Calcareous 8/12.5 gravel	$\text{kg/m}^3$	330	330
Calcareous 12.5/20 gravel	$\text{kg/m}^3$	720	720
0/2 siliceous sand	$\text{kg/m}^3$	845	845
Water	Liter/ $\text{m}^3$	189	189
Water/cement ratio (w/c)	–	0.54	0.54
Average cube $f_c$ at 28/90 days (2015)	MPa	54.4/63.4	52.4/62.8
Average cube $f_c$ at 28/90 days (2016)	MPa	46.8/61.8	48.1/64.8
Average cube $f_t$ at 90 days (2015)	MPa	4.9	4.6

146

## 147 2.2 Test setup and experimental procedure

148 Fifteen mid-size concrete slabs ( $800 \times 800 \times 100 \text{ mm}^3$ ) were subjected to ISO 834-1 fire curve  
 149 under different biaxial membrane compressive loading levels, according to the setup



150 characteristics and instrumentation system presented in Fig. 1. Concrete slabs were placed on the  
 151 top of the horizontal furnace within a loading system consisting of a restraining welded steel  
 152 frame fitted with eight hydraulic jacks. The thrust is applied via spherical metallic heads and thick  
 153 steel rectangular plates acting as load dividers (see Fig. 1b).

154

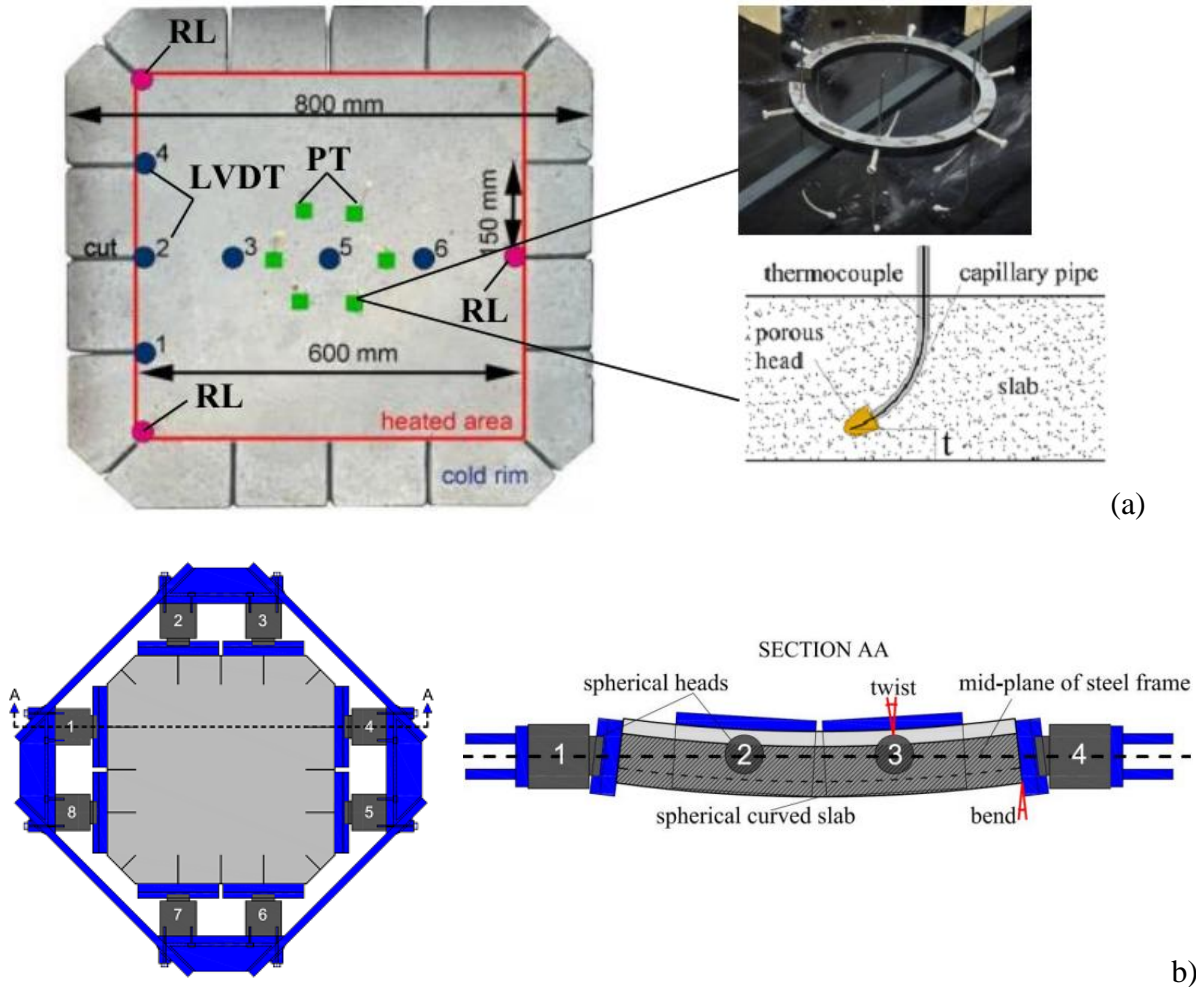


Fig. 1. Test setup for fire spalling test under external biaxial compressive loading: a) specimen, measurement points, and detail of the embedded pressure–temperature sensors and b) Concrete slab within the loading system and section AA in the deformed configuration. Note: PT = pressure-temperature sensors, LVDT = linear variable displacement transducers, RL = 3 rigid legs of the LVDT-holding frame [37].

155

156 The spherical heads are instrumental in allowing the rotation of the edges of the concrete slab  
 157 caused by thermal curvature. To limit the heat propagation into the metallic hydraulic jacks, only

158 the central portion ( $600 \times 600 \text{ mm}^2$ ) of the concrete slab is heated, thus keeping the 100 mm-thick  
159 external concrete rim colder. To decrease the confinement exerted by this concrete colder rim on  
160 the heated central portion of the slab, 16 radial slits (approximately 5 mm thick) are realized  
161 during casting, aimed at breaking its mechanical continuity [37] (see Fig. 1a).

162 The furnace consists in a propane burner with a control system able to follow the ISO 834-1  
163 fire curve, while the biaxial membrane compressive load is applied before heating and kept  
164 constant throughout the fire test. Seven different levels of biaxial compressive stresses (0, 0.5,  
165 0.75, 1.5, 3.0, 5.0, and 10 MPa) have been studied on both concrete mixes (B40-II and B40-III).

166 Since spalling progression is a function of time, in order to adopt the spalling depth as the main  
167 index in (1) comparing the two mixes and (2) quantifying the effect of biaxial compression, a  
168 unique fire duration of 30 min has been defined for all the tests. However, the collapse of the slab  
169 occurred before 30 min in the 2 tests at 10 MPa, while in one of the two tests at 5 MPa, the  
170 collapse occurred at 29 min.

171 The specimens were instrumented with six pressure gauges placed at 6 different depths from  
172 the exposed surface of the concrete slab (namely, 5, 10, 20, 30, 40, and 50 mm) for the  
173 simultaneous measurement of pressure and temperature (see Fig. 1a). Gas pore pressure and  
174 temperature were monitored according to the system described in Felicetti et al. [10]. During the  
175 tests, the flexural behavior was also monitored through 6 linear variable displacement  
176 transducers (LVDT) placed at the cold face along an axis of symmetry and along one edge line  
177 (of the heated area). It should be noted that the displacement of concrete slabs is not discussed in  
178 this paper, since continuous spalling progression makes the evolution of the deflection not  
179 interesting in comparing the different tests.

180 During the fire tests, a continuous visual observation of the exposed surface of the slab was  
181 implemented via a digital camera (placed in front of the glass windows of the furnace) to monitor  
182 and record the spalling events. After each test, the spalled surface is measured at room  
183 temperature using a laser profilometer. Mean spalling depths are presented in the following.

184

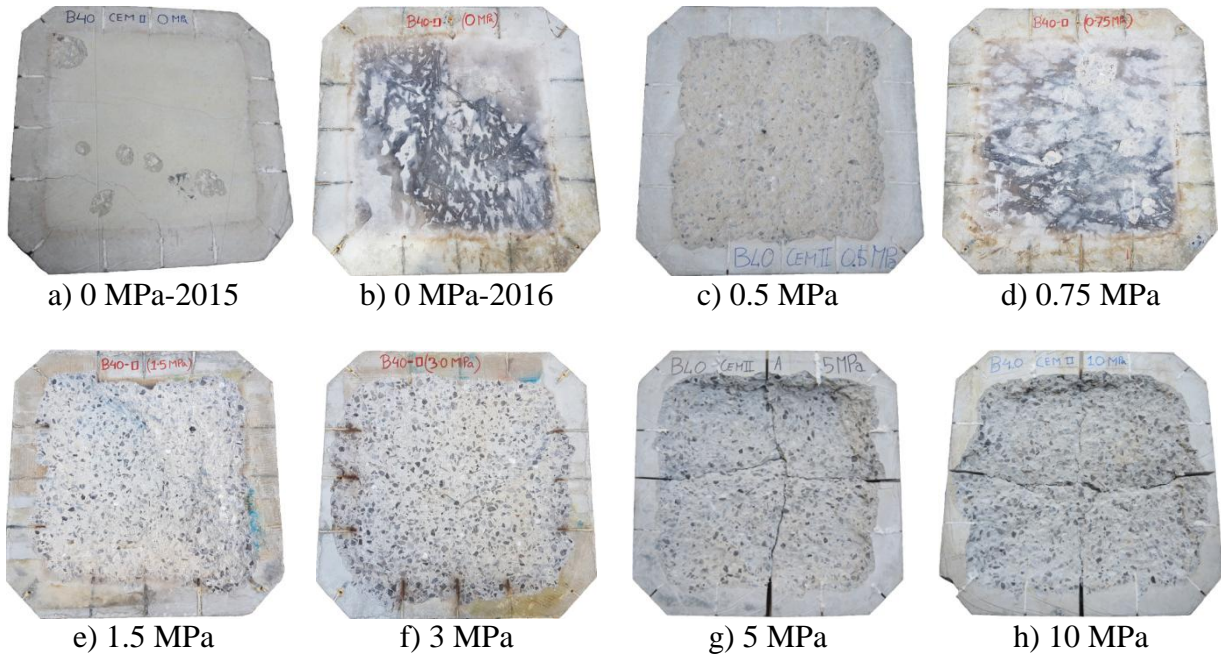
### 185 **3 Experimental results**

#### 186 **3.1 Fire spalling progression**

187 Figs. 2 and 3 present the pictures of the exposed face of all specimens after the fire tests. The  
188 experimental results have shown that spalling severity increases with load. This trend is  
189 consistent with what was observed in [31], where concrete cubes made with the same mix design  
190 herein presented have been exposed to ISO 834-1 while subjected to uniaxial compression. The  
191 results are also in good agreement with the fire spalling tests in Carré et al. [30], where none of  
192 the B40-II slabs spalled when exposed to ISO 834-1 fire curve in unloaded conditions.

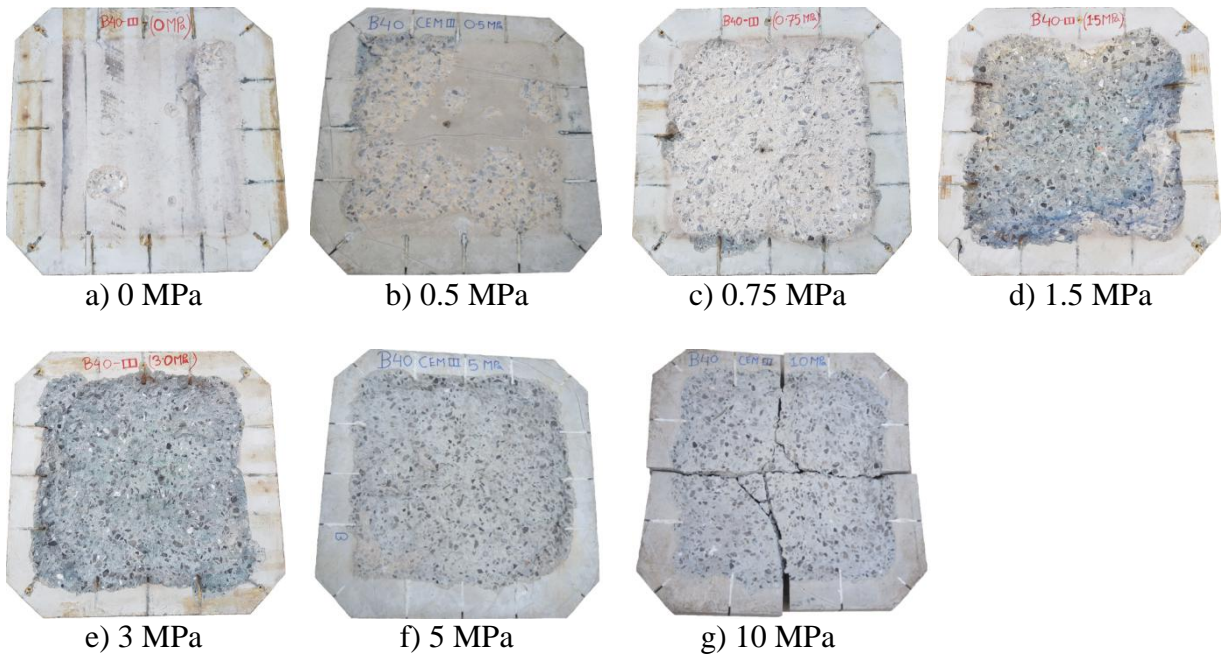
193 Fire spalling in biaxially loaded slabs was accompanied by a loud “popping” sound as  
194 concrete fragments were released layer-by-layer from the concrete surface. The first spalling  
195 events occurred in the range from 6 to 10 minutes, and the number (or intensity) of spalling  
196 events increased with the applied compressive stress (similar to spalling tests on uniaxially  
197 loaded concrete samples reported in Miah et al. [31]). At the onset of concrete spalling, concrete  
198 temperature measured at a depth of 5 mm from the exposed surface was around 150 °C to 200  
199 °C.

200



201 Fig. 2. Exposed faces of B40-II slabs after exposure to ISO 834-1 fire curve.

202



203 Fig. 3. Exposed faces of B40-III slabs after exposure to ISO 834-1 fire curve.

204

### 205 3.2 Effect of biaxial compressive loading on the fire spalling severity

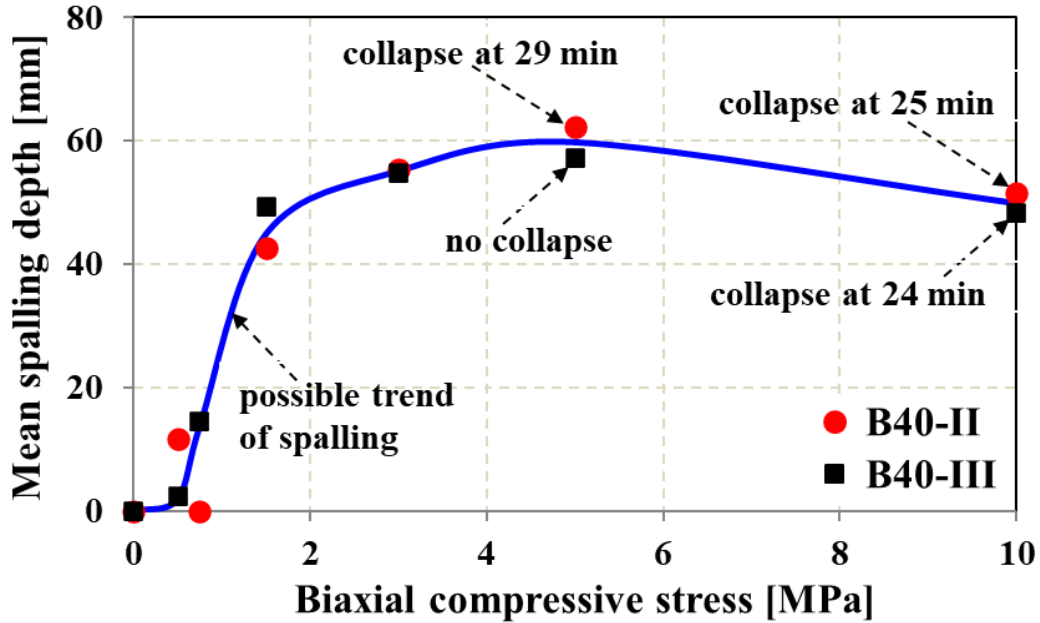
206 Since the edges of the heated face of the slab were disturbed by the presence of the cold rim  
207 (as discussed in [37]), the mean spalling depths have been calculated in the central area of 500 x  
208 500 mm<sup>2</sup> (smaller than the area of the exposed face, equal to 600 x 600 mm<sup>2</sup>). The average fire  
209 spalling depth of concrete as a function of external biaxial compressive stress is reported in Fig.  
210 4. The evolution of mean spalling depth induced by fire and external biaxial compressive stress  
211 can be differentiated into three main stages: low load level (0 to 0.5 MPa), intermediate load  
212 level (0.75 to 5 MPa), and high load level (5 to 10 MPa).

213 No spalling was observed for both concretes in unloaded specimens, while very limited or  
214 limited spalling was observed for loading levels of 0.5 and 0.75 MPa. In particular, a uniform  
215 spalling extended to the whole heated area has been observed at 0.5 MPa for B40-II and 0.75  
216 MPa for B40-III, with average spalling depths of 12 mm and 14 mm, respectively (see Figs. 2-4).  
217 Such an outcome proves that even very low levels of compressive loading (about 1% of the  
218 compressive strength at ambient temperature) during heating can affect the fire spalling behavior  
219 of concrete. This can be ascribed to the role played by permeability, which is linked to concrete  
220 cracking and micro-cracking (favored by thermal stresses and by the thermal mismatch between  
221 cement pastes and aggregates). The external in-plane compression, in fact, limits the formation  
222 of cracks perpendicular to the heated surface of the slab (and thus to the isothermal planes), thus  
223 limiting the increase of permeability. Hence, the limitation of cracking leads to a steeper build-up  
224 and higher pore pressure values (as discussed in section 3.4). These results agree with the  
225 measurement of gas permeability under confining pressure reported by Miah et al. [39]. A sharp  
226 decline in axial gas permeability was found when the radial confining pressure (perpendicular to  
227 the gas flow) was increased from 0.3 to 0.6 MPa [39], this being may be ascribable to the closure  
228 of micro-cracks in the matrix. Probably, this is the main reason why higher pore pressure was

229 observed at the loading levels of 0.5 and 0.75 MPA with respect to the unloaded specimens  
230 (discussed in section 3.4). This higher pore pressure in combination with the increased  
231 mechanical instability in the hot layer in the case of applied external compressive load increase  
232 the spalling severity.

233 Interestingly, the steepest increase in spalling depth was observed in both concretes when the  
234 external compression increased from 0.5 MPa to 5 MPa. As also described in [37], the possible  
235 explanation of this behavior can be related to the combined effects of (a) concrete mechanical  
236 instability triggered by cracking parallel to the heated face in the hottest layers and (b) higher  
237 vapor pore pressure because of the lower permeability due to the reduced cracking in the inner  
238 core (making reference, in this latter case, to the cracks formed in the inner core of the slab in the  
239 direction orthogonal to the exposed face due to the tension equilibrating the compression in the  
240 dilating hottest layers). When a concrete slab is heated at the bottom surface under biaxial  
241 compression, cracking in the hottest region (mostly under in-plane compression due to thermal  
242 stress and external load) increases with external membrane compression. Simultaneously,  
243 cracking decreases perpendicularly to the heated surface. Such a tendency increases with  
244 compressive load.

245



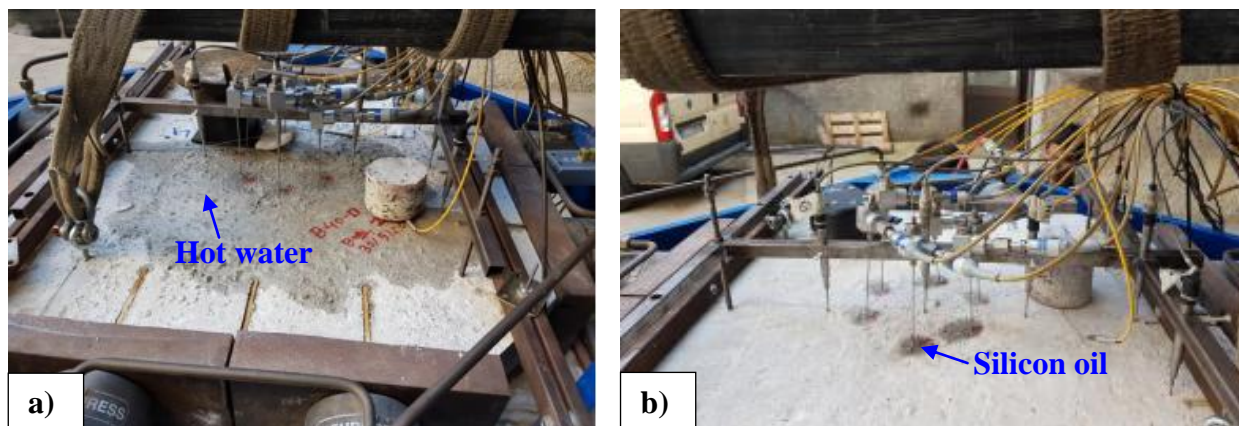
246 Fig. 4. Mean fire spalling depth of concrete induced by applied biaxial compressive stress.

247 In this regard, it is worth underlining that Miah et al. [39] showed as axial permeability in  
 248 concrete disks decreases if radial confining pressure increases, since the opening of the axial  
 249 cracks is reduced, while axial permeability increases if uniaxial compression is applied due to the  
 250 formation of cracks parallel to the direction of the load. As a result of such reduced permeability,  
 251 moisture and vapor can more hardly drain from the critical spalling zone, fostering higher pore  
 252 pressure values (as discussed in section 3.4). Higher pore pressure combined with the mechanical  
 253 instability in the hottest region dramatically increases the severity of fire spalling of concrete.

254 Conversely, in unloaded conditions, multiple cracks could more freely occur [40], smoothing  
 255 down the build-up of pore pressure and thermal stresses [41, 42].

256 During the fire tests, the appearance of water on the cold face of the specimens was observed.  
 257 This phenomenon was more evident in unloaded specimens since the cracks were free to open in  
 258 all directions (similar behavior was observed in uniaxially loaded tests [31]). After  
 259 approximately 13-16 minutes of heating, water started to appear on the cold surface of the slab

260 through multiple paths (see Fig. 5 a). In contrast, the appearance of water on the cold surface of  
261 the slabs was not seen for the loaded specimen, as shown in Fig. 5b.



262 Fig. 5. Release of hot moisture at the cold face during the fire tests on B40-II in an unloaded  
263 condition (a) and at the load level of 3 MPa (b), respectively.

264 As shown in Fig. 4, the mean spalling depth of both concretes decreased from 5 to 10 MPa.  
265 The main explanation for the lower values determined at 10 MPa is the premature collapse of  
266 the slabs, which led to the termination of the test (24-25 min, as shown in Figs. 2h and 3g,  
267 instead of the target fire duration of 30 min). The collapse was caused by the hogging bending  
268 moment acting on the unreinforced slab due to the negative eccentricity of the external load  
269 caused by the rise of the center stiffness of the specimen due to spalling-induced thickness  
270 reduction. The fire spalling depth of concrete at 10 MPa could be reasonably expected to be  
271 equal to or higher than the one observed at 5 MPa for the same fire duration. Assuming, for  
272 example, a linear progression of spalling depth with time, at 30 min, it would be 20% larger than  
273 at 25 min, hence around 60 mm for the load level of 10 MPa.

274 Regarding the effect of cement type, no significant difference in spalling depths was observed  
275 for all loading levels. At the low compressive load (0.5 MPa), lower spalling has been observed  
276 in B40-III (43% of slag) than the B40-II (3% of slag). On the contrary, the spalling differences

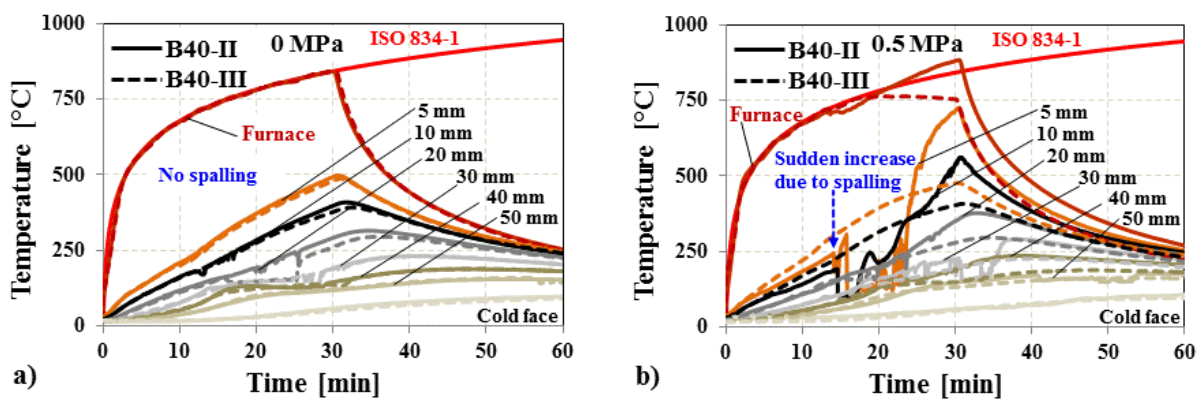


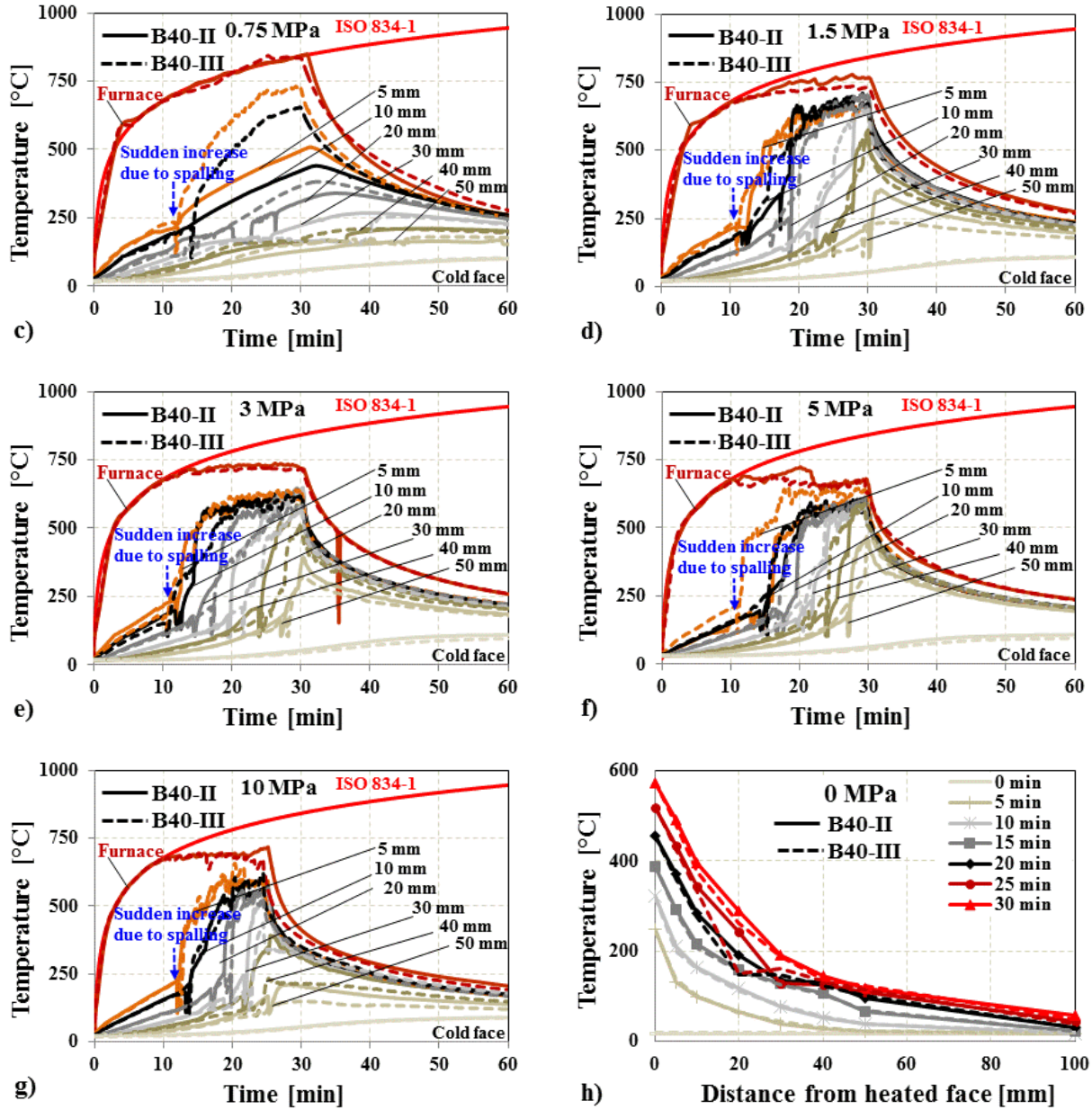
277 between the two concrete are much lower for external compression in the range 1.5-10 MPa.  
278 This behavior could be linked to the lower influence of the intrinsic permeability of the material  
279 (since crack-induced permeability is predominant).

280

### 281 3.3 Thermal response of the slabs

282 Figure 6a-g presents the evolution of temperature inside the specimens under the different  
283 levels of compressive load. The sudden rise of temperature in the plots indicates the direct  
284 exposure of the thermocouple to hot air when the concrete layer behind is spalled away. The  
285 furnace temperature was measured using a plate thermometer, and it is worth noting as the target  
286 ISO 834-1 fire curve is strictly followed up to the first spalling event. Afterward, the temperature  
287 was lower due to the increased thermal inertia of the furnace because of the presence of concrete  
288 debris collected close to the burner. Therefore, for homogeneity among the tests, the constant  
289 power of the burner was set after 15 minutes of heating. Almost a similar thermal response has  
290 been observed in both concretes in unloaded tests (see Fig. 6a).



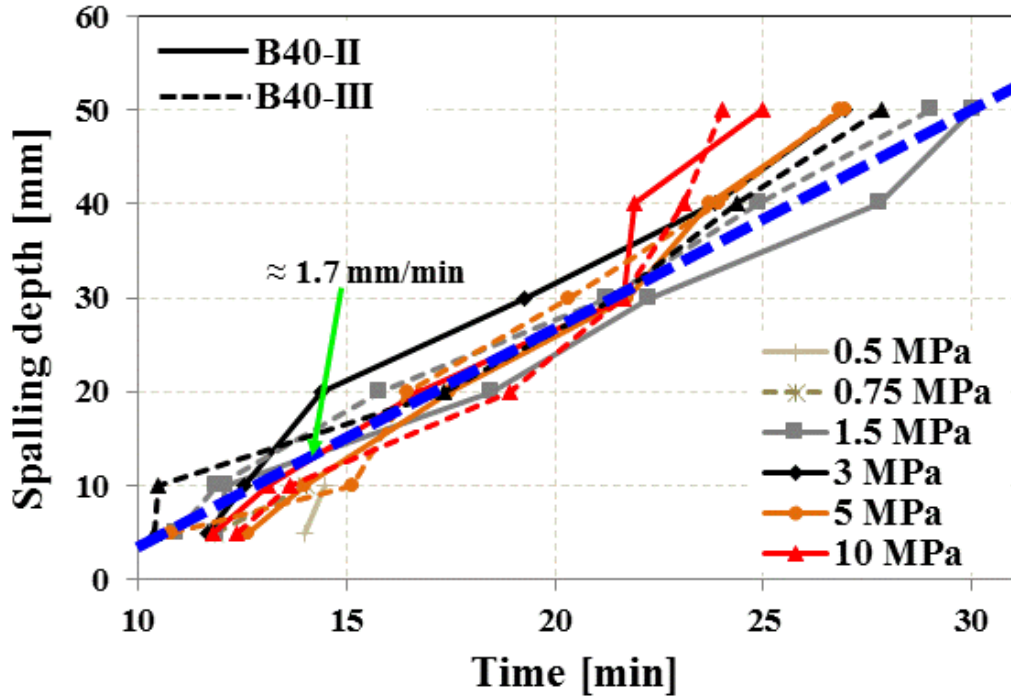


291 Fig. 6. Temperature as a function of time (a-g) and temperature profiles through the thickness  
 292 (h).

293 The temperature plateau occurred at approximately 100 °C (onset of water vaporization, with  
 294 the consequent significant absorption of energy). Once the plateau was reached, the temperature  
 295 almost remained constant until the water phase change was completed in the region surrounding  
 296 the thermocouple. It can be noticed that the plateau is more evident at higher distances from the

297 exposed face (see Fig. 6a). Water vaporization, in fact, induces pressure gradients, which push  
298 part of the vapor towards the hot face (where it can be released into the environment) and part  
299 towards the inner and colder core where the vapor can condensate, increasing the degree of  
300 saturation. The small plateau corresponds to higher pore pressure values in the hottest zones. In  
301 contrast, pore pressure is lower in the deeper zone (as discussed in section 3.4), which allows a  
302 more significant amount of vaporization. Furthermore, it needs to be kept in mind that pressure  
303 gauges may affect the permeability and that the measured pore pressures could be lower than in  
304 reality. Figure 6h presents temperature profiles along the slab thickness every 5 minutes as  
305 determined in the two unloaded slabs. In general, the temperature difference between B40-II and  
306 B40-III concretes is limited (as shown in Fig. 6a, h). After 10 min of heating, the temperatures at  
307 the hot face and at 5 mm are approximately 320 °C and 200 °C, respectively, typical temperature  
308 range for spalling.

309 Since spalling behavior involved rather homogeneously the whole central part of the exposed  
310 area (500 mm x 500 mm) for all the tests, spalling kinetics can be reasonably determined by  
311 monitoring the sudden rise of temperature measured by thermocouples (as shown in Fig. 7), this  
312 corresponding to the direct exposure of the thermocouples to fire. It can be observed that spalling  
313 rate with time is almost constant and has a very similar slope for all the levels of compression up  
314 to around 22 minutes of heating, with a rate which is approximately 100 mm/h ( $\approx 1.7$  mm/min,  
315 see the blue dashed line in Fig. 7). After 22 minutes, there is an increase in the spalling rate for  
316 the load levels of 3, 5, and 10 MPa. This increase is higher for increasing values of external  
317 compression.



318 Fig. 7. Concrete fire spalling kinetics based on the observed sudden temperature rise induced by  
 319 direct exposure of thermocouples to hot gases.  
 320

### 321 3.4 Build-up of pore pressure in the slabs

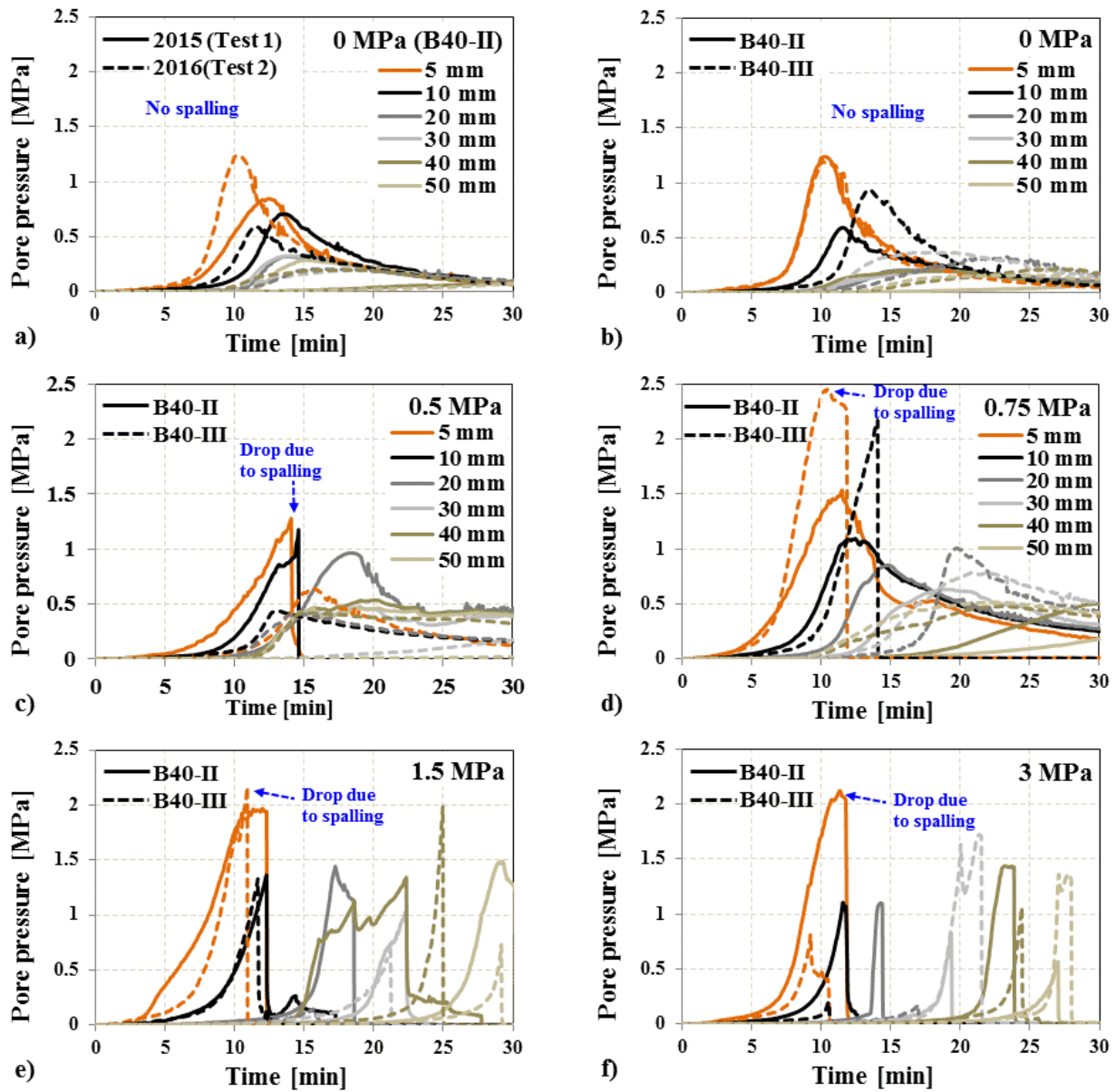
322 Figure 8 presents pore pressure development as a function of time for B40-II and B40-III  
 323 specimens under the different levels of biaxial compressive loading. Two general trends have  
 324 been observed. The curves show a bell shape in unloaded specimens and at 0.5 MPa for B40-III  
 325 and at 0.75 MPa for B40-II. This curve shape was observed when no spalling occurred. In  
 326 unloaded specimens, multiple cracks may occur inside concrete slabs (i.e., cracks parallel to the  
 327 isothermal planes in the hot region and orthogonal in the inner core) due to thermal stress and  
 328 thermal mismatch between cement paste and aggregates [40]. This significantly enhances  
 329 concrete permeability and releases the vapor and liquid water from the specimen (as shown in  
 330 Fig. 5a), thus considerably affecting the build-up of pore pressure, thereby developing a bell  
 331 shape curve (as shown in Fig. 8a and b). Later, the pressure drop occurs naturally, causing higher

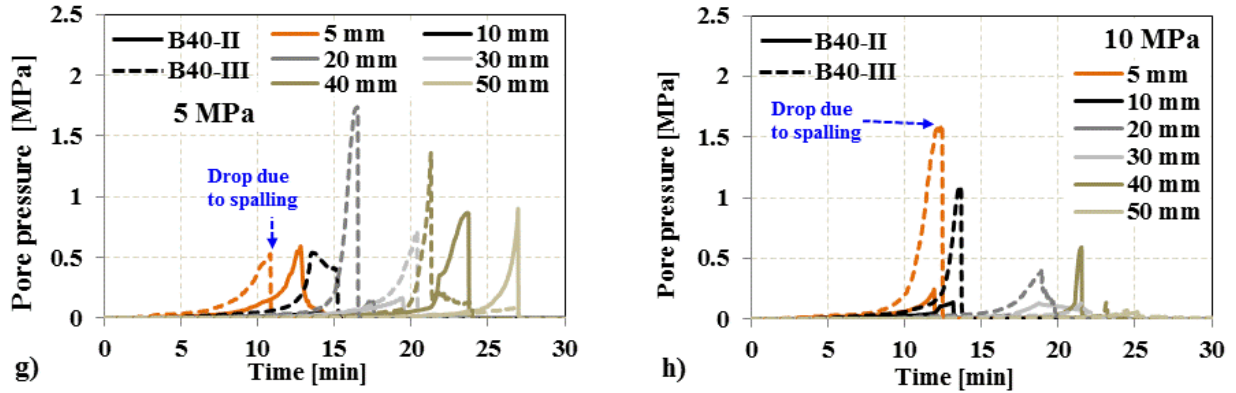
332 water vapor transport inside the concrete induced by the increased temperature and thermal  
333 cracks (i.e., permeability). In contrast, a sudden drop in pore pressure was observed when  
334 concrete spalled.

335 The maximum pore pressure values for a given depth from the heated face are presented in  
336 Fig.9a and b for all the loading levels. In unloaded samples, maximum pore pressures of B40-II  
337 and B40-III were 0.8 (B40-II – Test 1), 1.2 MPa (B40-II – Test 2), and 1.2 MPa (B40-III),  
338 respectively, and no spalling was observed. In the limited load range (0.75 to 3 MPa), maximum  
339 pore pressure increased when biaxial applied stress increased. At 1.5 MPa, the maximum pore  
340 pressures for B40-II and B40-III are 2.0 and 2.2 MPa, respectively, and spalling was observed in  
341 such cases. These results indicate that external compressive loading affects pore pressure build-  
342 up during heating. The mechanisms behind this behavior are the same as described in section 3.2  
343 regarding permeability evolution. In particular, biaxial compression fosters cracking next to the  
344 heated phase parallel to loading, while it reduces cracking in the core perpendicularly to the  
345 loading direction. Felicetti and Lo Monte [43], by implementing an innovative technique based  
346 on ultrasonic pulse-echo on the same biaxial fire spalling test herein discussed, have shown that  
347 damage is significantly reduced when concrete slabs are under in-plane compression, even for  
348 very low-stress levels (e.g., 0.5 MPa).

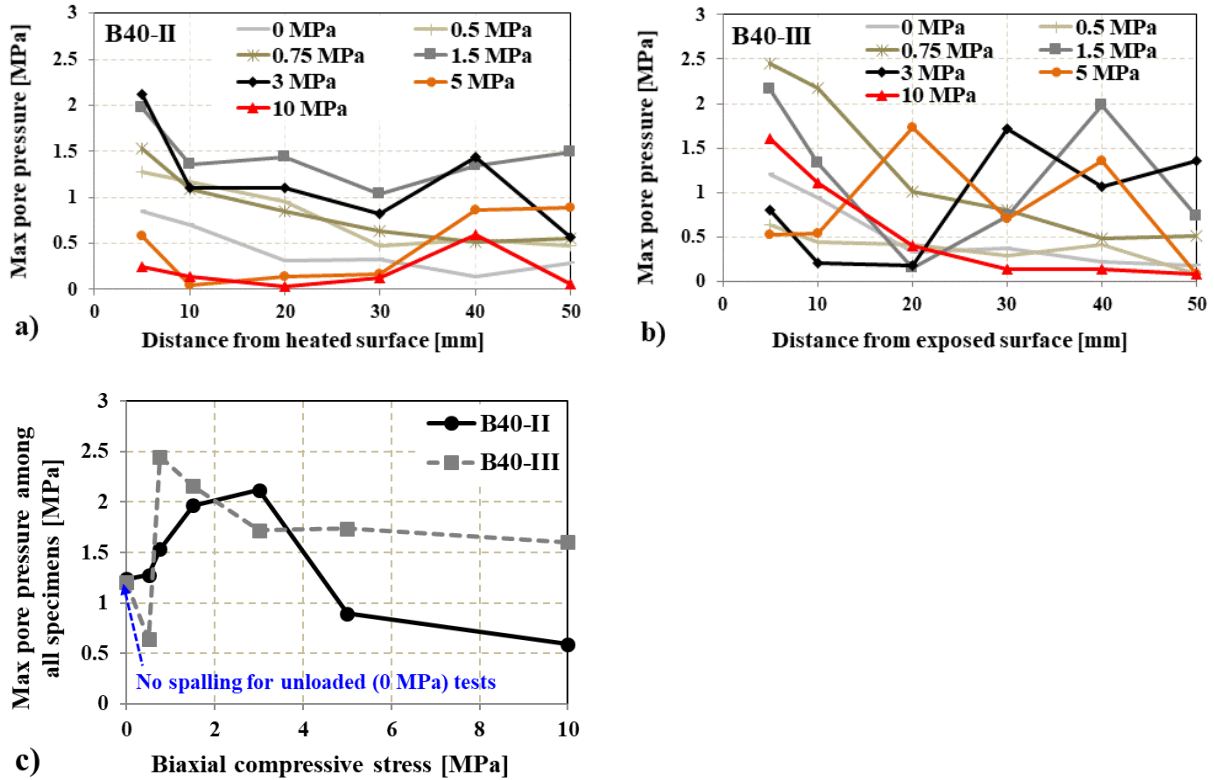
349 The maximum pore pressures of concrete slabs made with B40-II and B40-III subjected to the  
350 different applied compressive stress levels are presented in Figure 9c. It should be noted that no  
351 spalling occurred for the unloaded (0 MPa) test specimens made with both B40-II and B40-III, as  
352 indicated in Fig. 9c. Under low-stress levels, maximum pore pressure tends to increase with the  
353 applied stress. This is probably due to the above-mentioned decreased permeability in the  
354 concrete core. In the higher stress range (where spalling occurred), pore pressure decreases when

355 external compressive stress rises. This behavior could be attributed to the fact that the higher the  
 356 applied stresses, the lower the pore pressure needed to reach the conditions for spalling initiation.  
 357 It is to note that in most of the cases, pore pressure was increased when spalling occurred.





358 Fig. 8. Evolution of pore pressure inside B40-II and B40-III specimens subjected to heating and  
 359 different levels of external compressive stress.



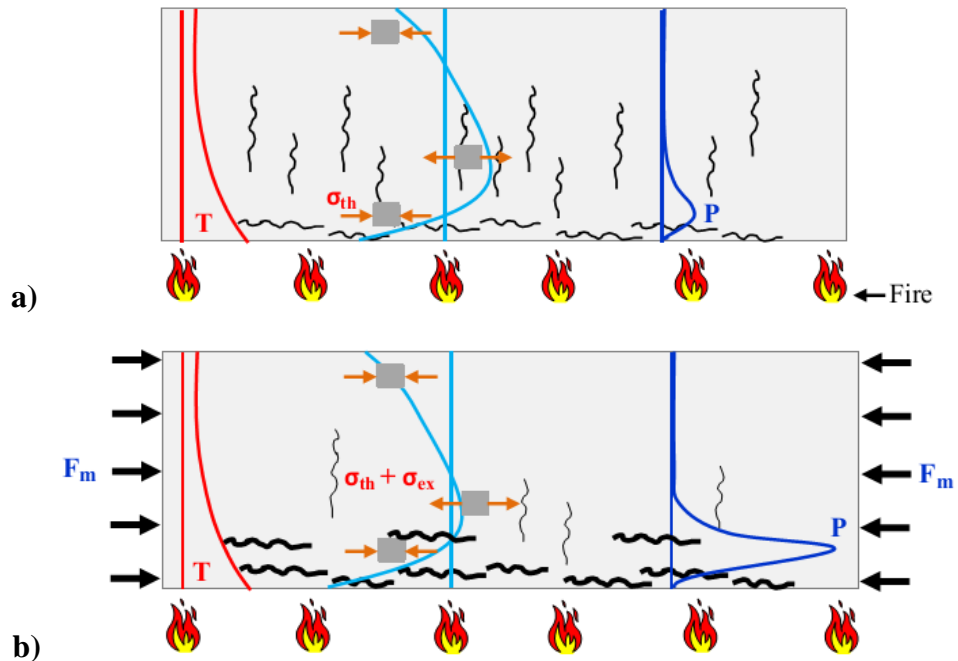
360 Fig. 9. Maximum pore pressure measured at different depths of slab made with B40-II and B40-  
 361 III (a, b), and maximum pore pressure observed in the whole specimen subjected to fire and  
 362 different levels of external compressive stress (c).

363

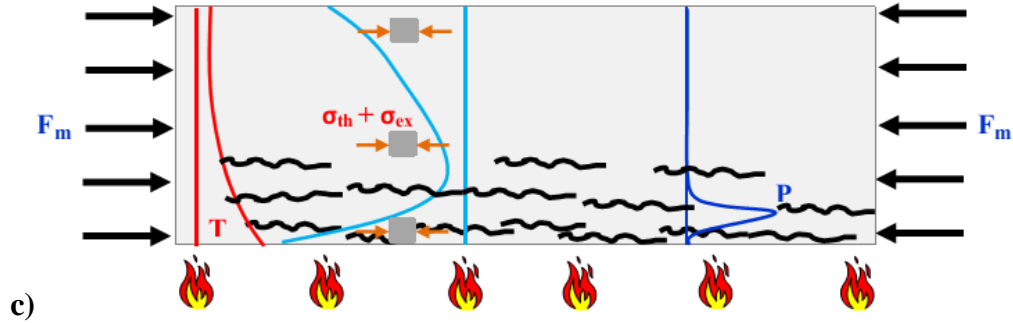
364 **3.5 Fire spalling mechanism in normal-strength concrete**

365 In order to deepen the role of external compression on fire spalling mechanism in normal-  
 366 strength concrete, a schematic diagram of a heated slab is drawn in Fig. 10. When a concrete slab  
 367 is heated at the bottom surface in unloaded condition, the hottest layer of the specimen is  
 368 compressed, while tensile stress propagates in the inner core. Finally, the layer next to the cold  
 369 face is again under compression for rotational equilibrium [37].

370 Therefore, numerous cracks may occur inside the slab, parallel to the isothermal planes in the  
 371 hot region and orthogonal in the inner part (Fig. 10a). These cracks are beneficial to limit the  
 372 further development of thermal stresses (due to the reduced sectional stiffness) and pore pressure  
 373 (due to the increased permeability). This is consistent with the slight rise of pore pressure for  
 374 increasing external compression in the lower-stress range (Fig. 10b). This aspect, together with  
 375 the increase in mechanical instability next to the hot layer with the increase of external  
 376 compression, makes spalling severity higher.





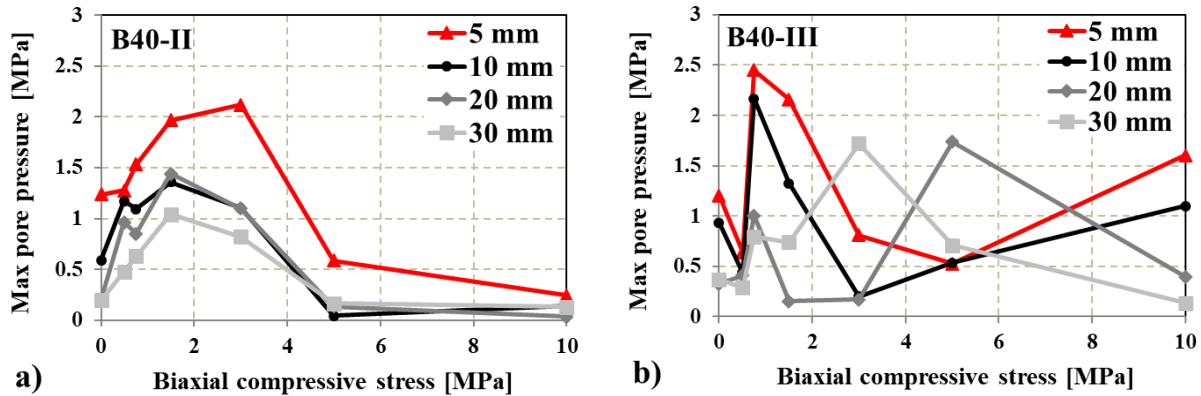


377 Fig. 10. Schematic diagram of cracking pattern, temperature, and pressure profiles in a concrete  
 378 slab heated at the bottom face, in unloaded (a) and under low (b) or high (c) in-plane compression  
 379 ( $F_m$  = external compression,  $T$  = temperature,  $p$  = pore pressure,  $\sigma_{th}$  = thermal stress, and  $\sigma_{ex}$  =  
 380 load-induced stress).

381 For the higher-stress range (Fig. 10c), the increase of cracking parallel to the isothermal  
 382 planes in the hot layer induces higher permeability, fostering lower pore pressure values.  
 383 However, despite the increased permeability, the concomitant increase in mechanical instability  
 384 makes spalling more severe. This is clear in Fig.11, where the maximum values of pore pressure  
 385 are observed for intermediate levels of external compression.

386 Zeiml et al. [44] assumed that cracks parallel to the isothermal plane induced by the in-plane  
 387 compression (because of thermal stress and external compression) are filled with vapor produced  
 388 by water vaporization in the pores. This vapor under pressure induces a tensile action within the  
 389 cracks orthogonal to the heated face. External compression can emphasize this process by  
 390 reducing cracks orthogonal to the heated face in the inner core, thus reducing the permeability  
 391 and fostering higher values of pore pressure [45]. The number and size of the cracks parallel to  
 392 the compressive load increase (see Fig. 10b-c) with the increasing heating up to the attainment of  
 393 the critical condition for spalling, namely when the layer between cracks and the heated face is  
 394 no longer able to bear the inner compressive stresses induced by external biaxial compressive

395 loading, and tensile stresses derived by the vapor pore pressure. This possibility gains with the  
 396 rising applied external compressive stress.



397 Fig. 11. Pore pressure envelopes for B40-II (a) and B40-III (b) concretes at different depths as a  
 398 function of applied biaxial compressive stress.

399 Since high pore pressure was measured for the intermediate level of compression (maximum  
 400 pore pressure was equal or higher than 2 MPa for both biaxial loads at 1.5 MPa and 3 MPa, see  
 401 Fig. 11), a less dense crack pattern is expected to be enough to trigger spalling. In contrast, in the  
 402 case of higher external compression (5 to 10 MPa), due to the lower pore pressure values, a more  
 403 severe crack pattern is expected to be needed to trigger spalling (see an example in Fig. 10c).  
 404 However, as reported earlier, it should be noted that the fire spalling of concrete is not only  
 405 induced by the increase in pore pressure, but also by the increase in compressive stresses due to  
 406 thermal stress and external compressive load and tensile stresses derived by the vapor pore  
 407 pressure.

408

409 **4 Concluding remarks**

410 The present study investigates fire spalling sensitivity of two normal strength concretes (B40-  
 411 II and B40-III) characterized by the same mix design but two different cement types, namely

412 CEM II (with 3% of slag) and CEM III (with 43% of slag). The main scope is to analyze the  
413 effect of biaxial compressive loading on the fire spalling behavior of normal strength concrete, to  
414 cast some light on the main mechanisms behind spalling. This is expected to contribute also in  
415 providing preliminary data useful for future modeling and for the development of appropriate  
416 design guidelines.

417 On the basis of the experimental results discussed in the paper, the following conclusion can be  
418 drawn:

419 I. External biaxial compressive stress significantly influences fire spalling behavior of  
420 concrete. Specimens are more prone to spalling when externally loaded with respect to  
421 unloaded specimens, even for a low level of external compression (0.5 MPa). In the  
422 present case, no spalling occurred in unloaded conditions, while remarkable spalling was  
423 observed under membrane compression.

424 II. For unloaded specimens, the formation of cracks increases the permeability, and pore  
425 pressure build-up is smoothed down, thus reducing spalling propensity.

426 III. A significant increase in spalling depth is observed going from 1.5 to 5 MPa. For higher  
427 compression, the effect of the load seems to be far less relevant. In the present case, the  
428 final spalling depth decreased, going from 5 to 10 MPa of external compression, most  
429 likely due to the premature collapse of the specimens in the latter case.

430 IV. Spalling progression can be identified from the sudden temperature increase measured  
431 by the thermocouples. It is noticeable that the spalling rate is nearly constant within the  
432 first 22 min of heating and very similar among the different tests. In this research project,  
433 the spalling rate was approximately 100 mm/h. Afterward, the spalling rate under 5 and  
434 10 MPa of compression increased with the external compression.

- 435 V. Under low external compressive stress, pore pressure tends to increase with the external  
436 compressive stress, while in the higher external compressive stress range, the highest  
437 pore pressure decreases with the applied stress. In the low-stress range, the main effect  
438 brought in by external compression is the reduction of the permeability because of the  
439 limitation of cracks. On the contrary, in the higher stress range, the main effect is the  
440 decreased mechanical stability in the hot layer due to the more severe crack pattern.
- 441 VI. At low compressive load (0.5 MPa), lower spalling has been observed in B40-III (43% of  
442 slag) than the B40-II (3% of slag). On the contrary, the differences in terms of spalling  
443 between the two concretes are much lower for external compression in the range from  
444 1.5-10 MPa. This phenomenon could be attributed to the lower influence of the intrinsic  
445 permeability of the material (since crack-induced permeability is predominant).

446 The experimental results clearly showed that the applied compressive stress is a crucial factor  
447 that should be considered for the fire resistance design of concrete structures/infrastructures and  
448 for the proper calibration of experimental tests regarding the final structural application. It is  
449 worth noting that concrete structural members are always loaded or restrained during a real fire.  
450 Hence, it is recommended that fire spalling tests should be carried out in loaded conditions,  
451 properly evaluating the load level on the base of the service life condition of the structure at  
452 hand.

453

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460

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