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Fiber content and curing time effect on the tensile characteristics of ultra high performance fiber reinforced concrete

Paschalis, Spyridon and Lampropoulos, Andreas (2017) Fiber content and curing time effect on the tensile characteristics of ultra high performance fiber reinforced concrete. *Structural Concrete*, 18 (4). pp. 577-588. ISSN 1464-4177

<http://dx.doi.org/10.1002/suco.201600075>

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- 1 **Fiber content and curing time effect on the tensile characteristics of Ultra**
- 2 **High Performance Fiber Reinforced Concrete (UHPFRC)**
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Photo of Spyridon Paschalis:



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- 9 **Running Head : Fiber content and curing time effect on UHPFRC**

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11

12 **Abstract**

13 Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is a concrete type with
14 superior mechanical properties and of a relatively high tensile strength. The tensile stress-
15 strain characteristics of UHPFRC are highly affected by the mixture design and the curing
16 regime. In the present study, an extensive experimental investigation has been conducted with
17 direct tensile tests on a number of specimens that contained different percentages of steel
18 fibers and different cement types were applied. Also, various curing regimes were
19 investigated. Different models depending on the steel fiber amount were proposed for the
20 simulation of the stress-strain and the stress-crack opening response of UHPFRC, while the
21 fracture energy was also calculated for the different fiber contents. Finally, the effect of fiber
22 content and curing time on the variation of the experimental results are discussed.

23 **Keywords**

24 UHPFRC, Direct Tensile Test, Fiber Content, Heat Curing, Stress-strain characteristics,
25 Fracture Energy

26 **1. Introduction**

27 Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is a material which is
28 characterized by enhanced properties in tension and compression and high energy absorption
29 in the post-cracking state. The behavior of the material, especially in tension, is highly
30 depended on the amount of fibers in the matrix and on the properties of the cementitious
31 matrix. The ultimate strength in tension depends on the effectiveness and orientation of the
32 fibers. When the post-cracking resistance is lower than the resistance of the matrix, strain-
33 softening occurs. If on the other hand, the post-cracking resistance of UHPFRC is higher than
34 the resistance of matrix and the fibers can sustain a higher load after the formation of the first

35 crack then multiple cracks appear and this behavior is known as strain-hardening behavior
36 [1]. This behavior normally characterizes the performance of UHPFRC at relatively high
37 fiber contents. The effect of different fiber contents on the tensile strength was investigated in
38 the present study through direct tensile tests, while the compressive behavior was evaluated
39 through standard compressive tests executed with cubes.

40 Another important parameter, which has been examined in the current study, is the effect of
41 curing time for different curing regimes on the compressive strength and the tensile stress-
42 strain characteristics of UHPFRC. Hence, different curing conditions were applied for which
43 the performance of the material was determined. Finally, the effects of different percentages
44 of steel fibers, and changing curing regimes on the variation of the experimental results were
45 studied.

46 Nicolaidis et al. [2] presented an experimental work which was focused on the development
47 of Ultra High Performance Cementitious Composites locally available in Cyprus. Different
48 parameters that can affect the strength and the workability of UHPFRC were investigated in
49 their study and an optimum mixture was proposed.

50 Kang et al. [3] and Yoo et al. [4] examined the effect of the steel fiber amount on the flexural
51 strength of UHPFRC and it was found that the flexural strength increased at increasing fiber
52 volume ratio, while the structural ductility was increased too. On the contrary, the post-peak
53 ductility at the softening region was decreased. Kang et al. [3] presented an inverse analysis
54 study to model the tensile fracture model of UHPFRC and a tri-linear tensile fracture model
55 of UHPFRC tensile softening behavior was proposed. Another inverse finite element analysis
56 method was proposed by Neocleous et al. [5] for deriving the tensile characteristics of Steel
57 Fiber Reinforced Concrete (SFRC). Kooiman et al. [6] carried out inverse analysis and
58 described a procedure for the development of a reliable bilinear stress-crack width model for
59 SFRC.

60 The orientation and distribution of the fibers in the mixture are important parameters
61 affecting the mechanical properties of UHPFRC. Kang and Kim [7] investigated the effect of
62 the fiber orientation on the tensile behavior of UHPFRC. According to this study, the effect
63 of the fiber orientation on the pre-cracking behavior was found to be negligible, but it
64 significantly affected the post-cracking behavior. The importance of fiber distribution on the
65 performance of UHPFRC was also highlighted by Ferrara et al. [8]. In this study, the effect of
66 different fiber orientations was examined and it was found that the orientation of the fibers
67 affected the mechanical performance of the fiber reinforced cementitious composites.
68 Paschalis and Lampropoulos [9] investigated the size effect on the flexural performance of
69 UHPFRC and it was found that as the depths of the prisms increased the flexural strength
70 decreased. The unique properties and the application of UHPFRC under monotonic and
71 cyclic loading in structural cases, where high mechanical properties are required, were
72 highlighted in a number of studies [10-14].
73 The superior performance of UHPFRC can be attributed to the enhanced tensile behavior.
74 However, until now, the effect of fibers and curing conditions on the tensile stress-strain
75 behavior have not been investigated thoroughly. The present study focused on both aspects
76 and an extensive experimental investigation has been conducted with dog-bone shaped
77 specimens tested in direct tension and standard cubes tested in compression.

78 **2. Experimental Investigation**

79 **2.1 Materials and preparation**

80 For the preparation of the specimens silica sand with a maximum particle size of 500 μ m was
81 used together with dry silica fume with a retention on a 45 μ m sieve of less than 1.5% and
82 Ground Granulated Blast Furnace Slag (GGBS). Silica fume was used in order to increase the
83 density of the matrix and to improve the rheological properties of the mixture. A low

84 water/cement ratio of 0.28 was applied together with polycarboxylate superplasticizer. The
85 steel fibers had a length of 13 mm, a diameter of 0.16mm and a tensile strength of 3000 MPa
86 while the modulus of elasticity was 200 GPa. Two different cement types were used in the
87 present study, which were a high strength cement 52.5 N type I and a 32.5 R CEM II. The
88 examined mixture (Table 1) was optimized in a previous study (Hassan et al. [15])
89 The mixing procedure was as follows: the dry ingredients were mixed first for three minutes.
90 Then, water and superplasticizer were added in the mixture and once the mixture reached the
91 wet stage, steel fibers were added gradually through sieving.

92 **2.2 Setup**

93 In the present study and for the investigation of the performance of UHPFRC, different
94 curing regimes and various fiber contents were tested; 76 dog bone specimens tested in
95 tension and 64 standard cubes in compression; (4 samples per mixture). The geometry of the
96 examined specimens is illustrated by Figure 1.

97 The tests were conducted using a servo-hydraulic testing machine. The extension was
98 recorded using a Linear Variable Differential Transformer (LVDT) that was connected to a
99 special steel frame; the displacement rate was 0.007 mm/sec (Figure 2a).

100 For the compressive tests, standard cubes with side lengths of 100 mm were used; the loading
101 rate was 0.6 MPa/s, according to BS EN 12390-3:2009 [16]. The experimental setup of these
102 tests is illustrated by Figure 2b.

103 **2.3 Experimental results**

104 **2.3.1 Effect of the cement type**

105 A preliminary study on the effect of cement type was conducted as a part of the current
106 research. Two different types of cement were used (32.5 R type II and 52.5 N type I cement);

107 direct tensile tests were conducted in order to evaluate the tensile stress-strain characteristics
108 and also compressive tests were executed. The percentage of steel fibers in the mixture for
109 this investigation was 3% per volume. After demoulding (two days after the casting) the
110 specimens were placed in a water curing tank for 26 days and tested after 28 days.

111 The results of 6 dog-bone shaped specimens tested in tension and prepared with cement 32.5
112 R type II are illustrated in Figure 3a together with the average curve. The maximum tensile
113 strength was 9.6 MPa and the modulus of elasticity was 53 GPa. The mean compressive
114 strength of 4 standard cubes was 125.6 MPa.

115 The respective results of the specimens prepared with cement class 52.5 N type I are
116 presented by Figure 3b. The average maximum tensile strength of this mixture was 11.3 MPa,
117 the modulus of elasticity was 56.2 GPa and the compressive strength was 150 MPa. A
118 comparison of the average curves is presented by Figure 4.

119 From the experimental results it is evident that due to the use of high strength cement a
120 significant higher tensile strength of UHPFRC was obtained; the tensile strength of the
121 specimens prepared with cement class 52.5 N type I was increased by 18% (Figure 4). Also,
122 the compressive strength of UHPFRC increased by 16% when 32.5 R type II cement was
123 replaced by 52.5 N type I cement.

124 Based on these results and in order to achieve the optimum performance, cement 52.5 N type
125 I was chosen for further investigation of the effect of different curing regimes and curing time
126 on the performance of UHPFRC.

127 **2.3.2 Effect of the curing regime on the tensile and compressive strengths of UHPFRC**

128 Crucial parameters that affect the performance of UHPFRC are the curing regime and the
129 curing duration. Heat curing is often applied for UHPFRC in order to accelerate the strength
130 development. The present study focuses on the effect of the curing regime and curing

131 duration on the tensile stress-strain characteristics of UHPFRC. Nicolaides et al. [2]
132 investigated the effect of different curing temperatures and concluded that the optimum
133 performance is achieved for a curing at 90 °C. This outcome also is in agreement with other
134 studies [17-18] and 90 °C was also adopted in the present study.

135 The specimens were demoulded 2 days after casting and some of the specimens were placed
136 in a water tank at a water temperature of 20 °C (± 2 °C), while other specimens were steam-
137 cured at 90 °C (± 2 °C). Testing was conducted at 3, 7, 14 and 28 days, while further
138 investigation at 90 days took place for specimens cured in the water tank (Table 2). For this
139 part of study, high strength cement 52.5 N was used together with 3 % per volume steel
140 fibers. The results of the direct tensile tests with the dog-bone shaped specimens for different
141 concrete ages and for different curing conditions are presented by Figures 5-9.

142 The development of the maximum tensile strength in time for the different curing conditions
143 is presented by Figure 10.

144 From the stress-strain results summarized in Figure 10 it can be noticed that the tensile
145 strength of the UHPFRC specimens placed in a water curing tank increased rapidly during the
146 first 28 days, while after this period an increase of only 5.8% can be observed. For the
147 specimens cured in the steam curing tank on the other hand, there is a clear strength increase
148 during the first 14 days, while after this period the tensile strength remains almost constant.
149 Also, it can be noticed that the 14 days tensile strength of the steam-cured specimens is
150 almost the same as the 90 days tensile strength of specimens cured under normal curing
151 conditions.

152 The compressive strength results for the different curing conditions are presented in the same
153 graph in Figure 11.

154 The results of Figure 11 indicate an upward trend of the compressive strength at increasing
155 age for the specimens cured in the water tank during the 90 days period. When comparing the

156 results for different curing conditions, it can be observed that the 7 days strength of the
157 steam-cured specimens is almost the same as the 90 days strength of the specimens cured
158 under normal conditions, which indicates the effectiveness of the steam curing on the
159 acceleration of the strength development. The maximum compressive strength was achieved
160 for steam-cured specimens after 14 days while further curing did not significantly affect the
161 compressive strength, which is comparable with the tensile behaviors.

162 **2.3.3 Investigation of the effect of heat curing on the variation of the experimental** 163 **results**

164 From the results presented in Figures 5-9 it is evident that there is a scatter of the
165 experimental results, which can be attributed to differences in the distribution and orientation
166 of the fibers and to the less developed bond strength between the fibers and the matrix. In
167 order to quantify this effect, the Coefficient of Variation (CV), was calculated for the steam-
168 cured specimens and the results are presented by Figure 12.

169 Figure 12 shows that the CV considerably decreases at increasing curing time. This reduction
170 in the CV values and the subsequent reduction in the scatter of the experimental results can
171 be attributed to the improvement of the strength of the concrete matrix at increasing curing
172 time.

173 **2.3.4 Study of the workability of UHPFRC for the different fiber contents**

174 The workability of UHPFRC has been investigated for different fiber contents. Therefore, the
175 workability of specimens without fibers, as well as with 3 Vol.-% and 6 Vol.-% steel fibers
176 was measured with a flow table, following the procedure proposed by BS 1015-3:1999 [19].
177 The applied cone had a height of 60 mm, a top diameter of 70 mm and a bottom diameter of
178 100 mm. The flow cone was filled in two layers and each layer was tamped ten times with a

179 tamper. Then the cone was lifted, and the table was jolted 15 times at a rate of one jolt per
180 second. The diameter of UHPFRC was determined as an average of perpendicular diameters.
181 The result of the measurement of the workability indicated that the volume of steel fibers in
182 the mixture affects the workability of UHPFRC. More specifically, while the flow diameter
183 of Ultra High Performance Concrete (UHPC) without fibers was 255 mm, the respective
184 values for the mixtures with 3 and 6 Vol.-% steel fibers were equal to 215 mm and 125 mm,
185 respectively. These results indicate a good workability for the mixture without fibers, as well
186 as for the mixture with 3 Vol.-%. On the contrary, the high volume of steel fibers in the
187 mixture prepared with 6 Vol.-% caused a pronounced reduction in flow.

188 **2.3.5 Effect of the steel fibers' content on the performance of UHPFRC**

189 In the present study, the effect of different fiber contents on the tensile response of UHPFRC
190 has been investigated. Five different fiber contents were examined, namely 1 Vol.-%, 2 Vol.-
191 %, 3 Vol.-%, 4 Vol.-% and 6 Vol.-%. and for the preparation of the specimens cement 32.5 R
192 type II was used. All the examined specimens were cured in a water tank and tested at 28
193 days.

194 Figures 13a-e present the results of the direct tensile tests of the examined specimens with
195 different fiber contents, together with the average curves.

196 The maximum tensile strengths for the different fiber contents are illustrated by Figure 14.

197 From the experimental results it is evident that as the amount of steel fibers in the mixture is
198 increasing, the ultimate tensile strength also increases. More specifically, while the elastic
199 part of the tensile response is not considerably affected by the volume fraction of steel fibers,
200 the post-elastic strength is highly affected by the fiber volume.

201 In addition to the tensile tests, compressive tests with standard cubes were executed for all the
 202 examined mixtures. The compressive strengths for the different fiber contents are presented
 203 by Figure 15.

204 The results of Figures 14 and 15 indicate that as the steel fiber content increased, both
 205 compressive and tensile strength increased too.

206 **2.3.6 Effect of the fiber content on the variation of experimental results**

207 The Coefficient of Variation (CV) has been calculated for the examined mixtures with the
 208 various amounts of steel fibers and the results are presented by Figure 16.

209 As the amount of steel fibers increased, the CV also increased; for the highest steel fiber
 210 content (6 Vol.-%), the CV was almost twice as high as specimens with 4 Vol.-% steel fibers.

211 As presented in the previous section, with higher percentages of steel fibers the workability is
 212 significantly reduced and subsequently this is affecting the distribution of the steel fibers in
 213 the mixture.

214 **2.3.7 The effect of fiber content on the fracture energy**

215 The amount of steel fibers in the mixture can affect apart from the strength, the fracture
 216 energy of UHPFRC. For this reason, and with the average tensile stress-strain curves for the
 217 different percentages of steel fibers, the fracture energy was calculated. The fracture energy
 218 has been investigated in a number of studies [20-22], for different fiber reinforced concretes,
 219 and it can be defined as the dissipated work which is necessary for the separation of two
 220 crack surfaces [20]. The fracture energy can be calculated by the following equation [20]:

$$221 \quad G = \frac{Q}{A_f} = \frac{\int_{w=0}^{w=w_u} F_t(w) dw}{A_f} \quad (1)$$

222 Where:

223 Q: the dissipated work needed for the generation of a crack

224 A_f : the new crack fracture area

225 F_t : the load applied in tension

226 w : the crack opening

227 w_u : the crack opening at the stage of complete separation

228 w_m : permanent crack opening

229 The fracture energy can be distinguished in the energy dissipated during the strain hardening
 230 (G_a) and the strain softening (G_b),.

231 The fracture energy is according to Equation 2 (Figure 17):

$$G = G_a + G_b \quad (2)$$

232 With the average stress-strain curves for the different percentages of steel fibers the fracture
 233 energy was calculated and the results are presented in Table 3.

234 The results of Table 3 indicate that very high values of fracture energy can be achieved for
 235 high percentages of steel fibers. For percentages of steel fibers between 1-3 Vol.-% the
 236 fracture energy presented a minor upward trend at increasing fiber dosage. Fracture energy
 237 values equal to 24.4 KJ/m² and 28.4 KJ/m² were obtained for specimens with 4 and 6 Vol.-%
 238 steel fibers respectively. These values are in the range of reported values in the literature for
 239 similar investigations. More specifically, the fracture energy of various UHPFRC mixes has
 240 been evaluated [20-22]. Benson and Karihaloo [22] recorded a value of fracture energy equal
 241 to 20 KJ/m² using 6 Vol.-% steel fibers, while for the same percentage of steel fibers, a value
 242 of 24 KJ/m² was recorded by Habel et al. [21]. Wille and Naaman [20], conducted a research
 243 on the improvement of the fracture energy of UHPFRC, and with an optimized UHPFRC

244 with a compressive strength of 200 MPa they found a fracture energy which exceeded 30
245 KJ/m² using 1.5 Vol.-% twisted steel fibers.

246 **2.4. Stress-Strain and Stress-Crack Opening Models for different fiber contents**

247 The experimental results of the investigation of the effect of different fiber contents on the
248 tensile performance and on the stress-strain response of UHPFRC, were used to model the
249 behavior of the material in tension. The behavior of the material is divided in two parts. The
250 parts are; first up to a maximum stress level and second after the maximum stress level is
251 reached, when the response of the material is governed by the formation of a single crack.
252 The direct tensile results show that the stress-strain behavior up to a maximum stress level
253 depend on the amount of steel fibers in the mixture. Hence, for the different fiber contents,
254 different ascending branches can be distinguished as presented by Figures 18a-c.

255 The tensile behavior of specimens with 1 Vol.-% steel fibers is characterized by strain-
256 softening behavior and the initial response is simulated with one linear branch up to a
257 maximum stress level (Figure 18a). Specimens with 2 and 3 Vol.-% steel fibers on the other
258 hand, presented strain-hardening behavior and two branches were used to represent the stress-
259 strain behavior up to a maximum stress level (Figure 18b). The first branch was limited to the
260 end of the elastic state ($\sigma_{u,1}, \epsilon_{u,1}$) and the second ended at the maximum stress ($\sigma_{u,max}, \epsilon_{u,max}$).
261 Finally, the incorporation of high percentages of steel fibers (4 and 6 Vol.-%) caused a
262 pronounced strain-hardening state. Hence, a third branch ($\sigma_{u,2}, \epsilon_{u,2}$) was inserted in the
263 ascending branch in order to simulate the behavior of the material up to the maximum stress
264 level (Figure 18c).

265 The effect of the fiber content in the post-elastic state, is shown by Figure 19. In this figure,
266 the strain-hardening of the average curves of specimens with 3, 4 and 6 Vol.-% steel fibers is
267 presented. As shown in this figure, the strain-hardening of the specimens with 3 Vol.-% can

268 be represented with one branch. However, for specimens with 4 and 6 Vol.-% steel fibers, a
269 second branch in the post-elastic state can be distinguished and is required in this state to
270 model the strain-hardening of the specimens with this fiber content.

271 Similar models for the modelling of the stress-strain behavior proposed by Habel et al. [10]
272 for UHPFRC and RILEM TC 162-TDF [1] for SFRC. The experimental results of the present
273 study indicate that the responses of specimens up to a fiber content of 3 Vol.-%, are in good
274 agreement with the shape of existing models available in the literature (Habel et al. [10]).
275 However, existing models could not accurately model the response of specimens with higher
276 fiber contents. Therefore, in the present study, the response of mixtures with fiber contents
277 higher than 3 Vol.-%, was modelled with a tri-linear model. The characteristic values of the
278 proposed models of Figure 18 are presented by Table 4. All the values for the elastic state
279 presented in Table 4 are based on the stress and strain results at the end of the initial linear
280 part which was identified graphically.

281 In all the examined cases, in which the tensile response was characterized by a strain-
282 hardening behavior (2-6 Vol.-%), the second modulus elasticity ($E_{U,hard}$) was calculated. This
283 can be defined as the ratio of the stress to strain in the hardening state (Figures 18b and 18c).
284 From the calculation of the second modulus of elasticity, it was evident that as the volume
285 fraction of the fibers increased the second modulus of elasticity also increased.

286 The stress-crack opening behavior can be modelled with a bi-linear curve, as illustrated by
287 Figure 20; the obtained characteristic values are presented by Table 5. The proposed values
288 of the present study in this state are in good agreement with the findings of other researchers
289 for similar models. Based on the model proposed by Habel et al. [10], it is considered that at
290 approximately half of the fiber length, no more stresses are transferred through the crack.
291 This assumption is in good agreement with the proposed values of the current study, which

292 are based on the experimental results, and have been found to be in the range of 5.3-6.6 mm,
293 for a fiber length of 13 mm.

294 **2.5. Existing models for the modeling of the tensile behavior of UHPFRC**

295 The fiber content is crucial for the tensile characteristics of UHPFRC after the formation of
296 the first cracks. According to AFGC-SETRA [23], three different types of tensile behavior
297 can be distinguished for UHPFRC. The first type is a strain-softening behavior (Figure 21a),
298 the second is a low strain-hardening behavior (Figure 21b), and the third is a high strain-
299 hardening behavior (Figure 21c).

300 In case of strain-softening (Figure 21a), the ultimate strength of UHPFRC is equal to the
301 strength of the concrete matrix. In cases of low and high strain-hardening the post-cracking
302 resistance of UHPFRC is higher than the resistance of matrix. However, for different fiber
303 contents, a different post-elastic behavior can be distinguished. Based on the experimental
304 results of the present research, for fiber contents higher than 4 Vol.-%, there is a clear
305 difference on the tensile response of the mixture compared to the respective results prepared
306 with fiber contents 2 and 3 Vol.-%. More specifically, in case of 2 and 3 Vol.-% fibers, and
307 based on the results of Table 4, the ratio $\frac{E_{u,hard}}{E_u}$ was found equal to 4%, while for the mixtures
308 with 4 and 6 Vol.-% steel fibers the respective ratio was found equal to 28% and 40%. This
309 indicates a clearly enhanced post elastic state for the mixtures with 4 and 6 Vol.-%, which is
310 defined as ‘high-strain’ hardening behavior. Consequently, specimens with 2 and 3 Vol.-%
311 steel fibers can be defined as “low strain-hardening” UHPFRCs (Figure 21b) and two
312 branches are required to represent the stress-strain behavior up to a maximum stress level
313 (Figure 18b). Specimens with 4 and 6 Vol.-% can be defined as “high strain-hardening”
314 UHPFRCs (Figure 21c) and a tri-linear model is required for the modelling of the tensile
315 behavior (Figure 18c). -

316 **3. Discussion**

317 In the present study, the tensile and compressive behavior of UHPFRC were investigated for
318 different curing regimes and different mixture compositions. The effect of different cement
319 types was also examined. The experimental results indicated that the use of high strength
320 cement can increase both the tensile and the compressive strengths of UHPFRC. Direct
321 tensile and compressive tests were conducted on a number of specimens that contained
322 different fiber contents. Based on the experimental results, it was evident that the steel fiber
323 content in the mixture affected the compressive strength, the tensile characteristics and the
324 fracture energy of the material. Therefore, different models, depending on the fiber content,
325 are required for the modelling of the material in tension. However, an aspect which should be
326 taken into consideration is that the big volume of fibers in the mixture (higher than 3 Vol.-%),
327 has a negative effect on the workability of the mixture. In this case, the good rheological
328 properties of UHPFRC should be secured, with higher water/cement ratio or the use of higher
329 quantity of superplactiser. From the study of different curing regimes on the mechanical
330 properties of UHPFRC, the effectiveness of the heat curing was proved and it accelerated the
331 strength development. However, heat curing for more than 12 days is not suggested as it has
332 not any further effect on the strength development.

333 **4. Conclusions**

334 From the results of the present study the following conclusions can be drawn:

- 335 • The use of 52.5 N type I cement instead of 32.5 R type II cement resulted in 18% higher
336 tensile strength and 16% higher compressive strength.
- 337 • The increase of the fiber content from 1 to 6 Vol.-% increased the tensile strength by 92%
338 and the compressive strength by 72%.

- 339 • Specimens with 1 Vol.-% steel fibers presented a strain-softening behavior; strain hardening
340 was achieved with a fiber dosage of at least 2 Vol.-%.
- 341 • The stress-strain response of specimens with 1 Vol.-%, up to the maximum stress level, was
342 simulated with one linear branch.
- 343 • Specimens with 2 and 3 Vol.-% steel fibers presented a low strain-hardening behavior and a
344 bi-linear model was used for the simulation of their response up to the maximum stress level.
- 345 • Specimens with 4 and 6 Vol.-% steel fibers presented a high strain-hardening behavior and a
346 tri-linear model was used for the simulation of their response up to the maximum stress level.
- 347 • The stress-crack opening behavior in all the examined cases was simulated with a bi-linear
348 model.
- 349 • High values of fracture energy were achieved for specimens with high strain-hardening
350 behavior in tension. Therefore, the fracture energy of the mixture with 4 Vol.-% was found to
351 be equal to 24.4 KJ/m², while for specimens with 6 Vol.-% steel fibers was equal to 28.4
352 KJ/m².
- 353 • From the investigation of the different curing regimes and the curing period, it was observed
354 that the 7 days strength of the steam-cured specimens was almost the same as the 90 days
355 strength of the specimens cured under normal conditions.
- 356 • The optimum properties of UHPFRC were achieved for steam-curing for 12 days.
- 357 • The Coefficient of Variation (CV) increased at increasing fiber content. Regarding the
358 effect of curing time, it was found that the CV was lower for a longer curing of UHPFRC in
359 the steam curing tank.

360 **Acknowledgements**

361 The authors would like to express their gratitude to David Pope for his assistance during the
362 testing, and they would also like to acknowledge Sika Limited and Hanson Heidelberg
363 Cement Group for providing raw materials.

364 **Notation**

365 $\epsilon_{u,1}$: strain at the end of the linear part

366 $\epsilon_{u,2}$: strain at the end of the second branch of the proposed stress-strain model for high strain
367 hardening behavior

368 $\epsilon_{u,max}$: strain at the maximum load

369 w : the crack opening

370 $w_{u,1}$: crack opening at the end of the descending part of the proposed stress-crack opening
371 model

372 $w_{u,2}$: maximum crack opening

373 w_u : the crack opening up to the complete separation

374 w_m : permanent crack opening

375 $\sigma_{u,1}$: stress at the end of the elastic part

376 $\sigma_{u,2}$: stress at the end of the second branch of the proposed stress-strain model for high strain
377 hardening behavior

378 $\sigma_{u,max}$: stress at the maximum load

379 σ_1 : stress at the end of the first linear part of the descending stress-crack opening model

380 E_u : modulus of elasticity

381 $E_{u, \text{hard}}$: second modulus of elasticity

382 Q : the dissipated work needed for the generation of a crack

383 A_f : the crack fracture area

384 F_t : the load applied in tension

385 G : the fracture energy

386 G_a : energy dissipated during the strain-hardening phase

387 G_b : energy dissipated during the strain-softening phase

388 l_f : length of the steel fibers

389

390

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