

On void structure and strength of foamed concrete made without/with additives

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Abstract

A study has been undertaken to investigate the effect of different additives on the strength of foamed concrete by characterising air-void size parameters and identifying the influence of these parameters and changes to cement paste microstructure on strength. Nine different mixes, made using a pre-formed foam, were investigated with varying density (nominally 1300, 1600 and 1900 kg/m³) without/with additives (silica fume, fly ash and superplasticizer), used either individually or together. Optical microscopy and scanning electron microscopy were used in this investigation. Compared to the conventional mixes, inclusion of additives (individually or in combination) helped to improve both the cement paste microstructure and air-void structure of foamed concrete. For a given density, although the additives in combination led to increased void numbers, higher strength was achieved due to reduced void size and connectivity, by preventing their merging and producing a narrow void size distribution. Furthermore, adding a superplasticizer on its own resulted in a void structure fairly similar to that from all additives in combination, implying that it is the superplasticizer that has the greatest influence on voids. Not only enhancement of void structure but also improved cement paste microstructure both contribute to the strength of the foamed concrete.

Keywords: Foamed concrete, Mineral additives, Superplasticizer, Pore structure, Strength.

1. Introduction

In aerated concrete, the structure is affected by the method of pore-formation (gas or foaming) and is characterised into a micro-porous matrix and macropores [1]. Foamed concrete is a particular example of aerated concrete in which addition pores have been

33 introduced by the introduction of either preformed foam or by chemical action after mixing.
34 In the study reported here, preformed foam was applied.

35 Ramamurthy et al. [2] and Nambiar and Ramamurthy [3], mentioned that air-void distribution
36 is one of the most significant micro-properties influencing strength of foamed concrete and
37 Ramamurthy et al. [2] found that foamed concrete with narrower air-void size distribution
38 shows higher strength.

39 The pore structure of foamed concrete is classified as gel pores, capillary pores and air-voids
40 (air entrained and entrapped pores) [2, 4]. In addition, the air-voids in the foamed concrete
41 may be characterized by parameters such as volume, size, shape, size distribution and spacing
42 between air-voids [3]. To investigate this, image analysis software was used on images of
43 specimens captured by using an optical microscope.

44 Although the compressive strength of porous materials has been expressed as a function of
45 porosity by many researchers, some have mentioned that determination of total air void
46 content (porosity) is not sufficient as shape, size and distribution of voids may affect the
47 strength and durability of foamed concrete [5].

48 Kearsley [5] investigated the microstructure of foamed concrete produced with the inclusion
49 of either classified (pfa) or unclassified (Pozz-fill) fly ash with nominal densities 1000, 1250
50 and 1500 kg/m³. It was found that, at any given density, there was no obvious effect of
51 *median* void diameter on the compressive strength.

52 Nambiar and Ramamurthy [3] determined the air void size distribution of foamed concrete
53 mixes with different added foam volumes (10%, 30% and 50%) and found that the size of the
54 larger voids increased sharply with an increase in foam volume, while for the same foam
55 volume they were smaller for a cement-fly ash mix compared to a cement-sand mix. In
56 addition, D₉₀ (90th percentile) correlated better with strength than D₅₀ (median pore size)
57 indicating that it was the larger pores that influenced the strength more than the smaller pores.
58 Thus, it is well known that with the same matrix and void volume (porosity), the strength of
59 material containing more large-size voids is lower. This paper aims to investigate, from pore
60 structural and cement paste microstructural points of view, the strength of foamed concretes
61 having the same air void contents, for a given density, but different matrices produced by
62 using different additives (individually and in combination). This will be achieved by:

- 63 • Determining and comparing the size distributions of air voids of the foamed concrete
64 mixes without/with different additives.
- 65 • Identifying the influence of size parameters on strength.
- 66 • Investigating the effect of cement paste improvement on foamed concrete strength.

67 **2. Materials, mix proportions and production**

68 Full details of the materials used, mix proportions and production process can be found in a
69 previous publication [6], but essential information can be summarized as follows:

70 **2.1 Materials**

71 To produce conventional foamed concrete, the following constituent materials were used in
72 this study.

- 73 • Portland cement, CEM I-52,5 N (3.15 S.G.) conforming to BS EN 197-1:2011 [7].
- 74 • Natural sand (2.65 S.G.) conforming to BS 882:1992 [8] with additional sieving to remove
75 particles greater than 2.36 mm.
- 76 • Fresh, clean and drinkable water.
- 77 • Foam (45 kg/m^3) was produced by blending the foaming agent, EABASSOC (1.05 S.G.),
78 water and compressed air in predetermined proportions (45 g water to 0.8 ml foaming
79 agent) in a foam generator, STONEFOAM-4.

80 Then, to improve the cement paste microstructure and the air-void structure, the following
81 additives were used individually or together depending on the desired mixes (see **Table 1**):

- 82 • Silica fume: Elkem Microsilica (2.2 S.G., 92% SiO_2 , mean particle size $0.15 \mu\text{m}$ and
83 specific surface $20 \text{ m}^2/\text{g}$).
- 84 • Fly Ash: CEMEX fly ash-class S (2.09 S.G.) conforming to BS EN 405-1:2005 [9].
- 85 • Superplasticizer : MIGHTY 21 EG made by Kao Chemical GmbH of density 1.1 g/cm^3 ,
86 compatible with the EABASSOC foaming agent.

87 **2.2 Mix proportions**

88 In this study, nine differently proportioned mixes were designed as follows: conventional
89 mixes FC and modified mixes using all additives together FCa at three nominal densities,
90 1300 (FC3 and FCa3), 1600 (FC6 and FCa6) and 1900 (FC9 and FCa9) kg/m^3 ; three further
91 mixes at 1600 kg/m^3 with individual additives, silica fume (FCs6), fly ash (FCf6) and
92 superplasticizer (FCp6), see **Table (1)**.

93 Mix proportioning began with the selection of the target density ($1300\text{-}1900 \text{ kg/m}^3$), the
94 cement content and the water to cement ratio. The mix was then proportioned by the method
95 of absolute volumes. For each mix the water/binder ratio required to produce a stable mix
96 (fresh density to target density ratio close to unity) was determined by trials while the
97 required foam volume was determined from the mix design. A dosage of superplasticizer
98 (1.5% of binder weight) was adopted for all relevant mixes. Silica fume was added to four of

99 the mixes at 10% of the cement weight (see **Table 1**). Fly ash replacement was limited to
100 20% by weight of sand.

101 **2.3 Production**

102 Component materials were added into the mixer in the following sequence: dry materials
103 (including additives, if any), water with dissolved admixture to produce the base mix (mortar)
104 and then foam to produce the foamed concrete. The foamed concrete mix was placed in cube
105 moulds in two approximately equal layers. The sides of the moulds were lightly tapped after
106 placing each layer until the surface of the layer had subsided approximately to level [10].
107 After levelling the specimens' surfaces, all specimens were covered with thick nylon to
108 prevent evaporation and then removed from moulds within 24 hours. Because sealed-curing
109 reflects typical industry practice for foamed concrete [11], all specimens were sealed-cured
110 (wrapped in cling film) and stored at about 20°C until testing.

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112 **3. Experimental details**

113 **3.1 Strength test**

114 For both foamed concrete and unfoamed (mortar) mixes, compressive strength testing was
115 carried out on 100 mm cubes in accordance with BS EN 12390-3:2002 [12] and in each case
116 the results quoted are the average of three specimens.

117 **3.2 Entrained air-void structure investigation**

118 For the void size investigation, three slices (50 × 50 × 15mm) were cut, perpendicular to the
119 cast face, from the centres of three cured foamed concrete specimens. To enhance the contrast
120 between the air voids and the matrix, the specimens were first polished and cleaned to
121 remove any residues and then treated by applying two coats of permanent marker ink to them.
122 Finally, after drying, a white powder (Sodium bicarbonate) with a minimum particle size of 5
123 µm was pressed into the surfaces of the specimens and forced into the voids leaving the
124 concrete surface with excellent properties for image analysis, namely a black surface and
125 white voids. This technique is described in details in BS EN 480-11 [13] and by Nambiar and
126 Ramamurthy [3].

127 A camera connected to an optical microscope and a computer was used to capture the images
128 of the foamed concrete mixes. From SEM images of both unfoamed and foamed concrete
129 mixes, it was shown that the smallest entrained air void diameter identified was about 20 µm
130 [14], also see **Figure (1)**. Therefore, a microscope magnification of (23×) was chosen in order
131 that air voids with diameters in excess of 20 µm could be easily identified. With this
132 magnification, a pixel represents 6 µm and the image area is 178.52 mm² (15.43mm ×

133 11.57mm). Ten images were captured for each mix and then digitized, converted into binary
134 form and analysed using the ImageJ software. For this study, only two phases, air voids and
135 solid, were of interest, **Figure (2)**.

136 To create the final binary image required for analysis, the threshold value, below which all
137 pixels were considered voids and above which they were considered as solid, was selected
138 from a histogram of grey levels. Although the grey-scale histograms did not have a sharp
139 boundary between the two phases (voids and matrix), there was always a minimum in the
140 boundary region and this was set as the threshold for analysis of the images in this study.

141 Since there is a sharp contrast between the white air voids and the surrounding black matrix,
142 for this study, it was found that the simple digital operation of hole filling was sufficient,
143 although software operations such as dilation, erosion, opening, closing as well as hole filling
144 have all been suggested by others as being useful in application to concrete microscopy [3].

145 **3.3 Microstructure investigation**

146 For microstructure investigation, the specimens were studied through secondary electron SE
147 and backscattered electron BSE images which were captured using a Scanning Electron
148 Microscope (SEM) in the form of 2D-images. For this technique, samples of about 20×20
149 mm size with a minimum thickness of about 12 mm were cut from the cubic specimens using
150 a diamond cutter. The faces of the specimens were cut perpendicular to the cast face (parallel
151 to the casting direction) [15]. After drying for 2 days at 105°C and to ensure the stability of
152 the air void walls during polishing, the cooled specimens were vacuum impregnated with a
153 slow setting epoxy. Then, the impregnated specimens were polished with 240#, 400#, 800#
154 and 1200# silicon carbide abrasive (58.5, 35, 21.8 and 15.3 micron, respectively) using a
155 rotating grinder and then a final stage made use of a 5 micron abrasive (4000#). In order to
156 avoid distortion of SE and BSE images due to a negative charge which may have built up on
157 the sample surface under the high energy incident electron beam, the samples, nonconductive
158 materials, were coated with a thin film of conductive material, carbon for BSE mode and gold
159 for SE mode, before investigating with the SEM.

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167 **4. Results and discussion**

168 **4.1 Effect of additives on air-void structure**

169 For each void, an effective diameter was calculated by measuring the void area and assuming
170 it to be perfect circle [5]. **Figure (3)** shows the resulting pore size distributions for FC and
171 FCa foamed concrete mixes with densities of 1300, 1600 and 1900 kg/m³. From the results,
172 sizes vary between approximately 20 and 2000 μm. It is clear that at higher density (less
173 added foam), the proportion of the larger voids decreases leading to a narrower air void size
174 distribution. In addition, for a given density, the additives in combination led to increased
175 void numbers by preventing their merging, see **Figure (2)**, and producing a narrower void
176 size distribution compared to a corresponding conventional mix. To investigate the effect of
177 additives, individually and in combination, on void structure, **Figure (4)** shows the void size
178 distributions of 1600 kg/m³ mixes.

179 In order to quantify and compare the air void distribution of selected mixes, the parameters
180 D₅₀ and D₉₀ were calculated on the basis of number of voids, see **Table (2)**. It can be seen
181 that both D₅₀ and D₉₀ increased with foam volume while they decreased significantly with
182 additives in combination (FCa mixes) suggesting that the inclusion of these additives helps in
183 achieving more uniform distribution of air voids (less merging) than for the FC mixes.
184 Compared to FC6, using the additives individually slightly decreased D₅₀, while D₉₀ was
185 significantly decreased, again implying that additives helped in reducing the merging of voids
186 and so reduced the areas of the larger voids. This is also clear from the SEM images of the
187 1600 kg/m³ mixes shown in **Figure (5)**. It can also be seen from **Figures 2 and 5** that adding
188 a superplasticizer on its own resulted in a void structure fairly similar to that when using all
189 the additives in combination, implying that it is the superplasticizer that has the greatest
190 influence on void sizes and size distribution.

191 **4.2 Effect of void structure characterisation on strength**

192 Foamed concrete is a porous material; therefore its pore structure plays a dominant role in
193 controlling its properties. **Figure (6)** shows the effect of void size distribution parameters on
194 the 28-day compressive strength of FC and FCa mixes, while **Figure (7)** illustrates the effect
195 for the 1600 kg/m³ mixes. It can be seen that for all mixes, a higher foam volume (nominally
196 1300 kg/m³) resulted in a greater degree of void merging, leading to large irregular voids
197 which resulted in a wide distribution of void sizes and lower strength. In addition, a reduction
198 in D₅₀ and D₉₀ is clearly linked to an increase in strength for each density implying that the
199 effect of additives (both individually and in combination) was significant. However, it is

200 known that changes to the cement paste microstructure due to additives, **Figures (8) and (9)**,
201 will also contribute to strength gain. Therefore for a given density, the questions are these;
202 does this strength improvement come from the enhancement of void structure or the paste
203 microstructure improvement due to additives and to what extent does each affect the
204 strength?

205 **4.3 Effect of microstructural changes on strength**

206 To answer the above questions, the compressive strengths of unfoamed mixes were
207 investigated and compared to those of foamed concrete, see **Figure (10)**. It is evident that the
208 compressive strengths of the most dense unfoamed mixes (FC9 and FCa9) are higher than
209 unfoamed FC3 and FCa3 mixes. The reason is the higher aggregate/binder ratio (a/b) in the
210 FC9 and FCa9 which may lead to reduced damage in the interfacial transition zone (ITZ)
211 between the aggregate and cement paste by reducing shrinkage and bleeding. In addition,
212 with high a/b ratio the cement paste would be less, resulting in, on the one hand, reduced
213 thermal changes from hydration of cement and, on the other hand, a smaller voids fraction
214 and so less adverse effect on strength [16]. In addition, some water may be absorbed by a
215 larger amount of aggregate in FC9 and FCa9 leading to reduce the effective w/b ratio. Neville
216 [16] also stated that strength of a mix decreases as the proportion of aggregate increases from
217 0 to 20% but it increases for aggregate proportions from 40% to 80%. He added that the same
218 behavior was noticed at different w/c ratios but the reason for this pattern of behavior is not
219 clear.

220 Similar strength increases is seen in the foamed concrete mixes FC9 and FCa9 being stronger
221 than the comparable FC3/6 and FCa3/a6 mixes, although the rate of strength increases with
222 density appears somewhat greater for foamed version compared to unfoamed version.

223 It can be seen from **Figure (10)** that inclusion of additives (individually or in combination)
224 helps to improve the strength of both unfoamed and foamed mixes. This is due to the
225 additional reduction in porosity of cement paste and an improved interface between it and the
226 aggregate by:

- 227 • A substantial reduction in the mixing water (using a superplasticizer);
- 228 • Forming calcium silicate hydrate (C-S-H) from a pozzolanic reaction of fly ash with
229 the lime produced from the hydration of cement and water;
- 230 • Acting as fine filler (silica fume).

231 See **Figure (8)**. This was noticed, firstly, from the difference between the vacuum saturation
232 porosity (entrained air voids and capillary voids) and the entrained ($> 20\mu\text{m}$) void content
233 calculated from analysis of optical microscopy images. It was found that the capillary

234 porosity of FCa is less than that of FC at all investigated densities. Secondly, micro-hardness
235 values of the ITZ at 30 μ m distance from the aggregate surface (five readings averaged from a
236 Vickers micro-hardness test, square base pyramid indenter, with test load 10g and contact
237 time 15s) were 39.66, 59.3 and 91.13 HV for FC3, FC6 and FC9 respectively while for FCa3,
238 FCa6 and FCa9 they were 54.83, 85.56 and 111.43, respectively (1 HV=1
239 kgf/cm³=0.09806650 MPa).

240 **4.4 General discussion**

241 The compressive strength reduction from unfoamed and foamed concrete for each mix is
242 shown in **Figure (11)**. It can be seen that this reduction decreases with increase in density for
243 both FC and FCa mixes. For the same density, the reduction was lower in the case of FCa
244 indicating that the void structure improvement helped in increasing the strength. This is also
245 evident from the results for individual additives (silica fume, fly ash and superplasticizer) at
246 the same density (1600 kg/m³).

247 A similar interpretation can be made from **Figure (12)** which illustrates the reduction for both
248 unfoamed and foamed concretes between a mix with additives (individual or in combination)
249 and a conventional mix. The difference between values of unfoamed and foamed concrete
250 reductions implies that not only the enhancement of cement paste microstructure but also
251 improvements in the void structure of foamed concrete both will contribute to strength gain.

252 In addition, the effect of each variable, i.e. mortar strength (changes to cement paste
253 microstructure) and void size parameters (D_{50} and D_{90}), were examined from a statistical
254 point of view using the Chi Squared Test which is the sum of the squared difference between
255 observed and expected data divided by the expected data. With a degree of freedom equal to
256 8 (the number of all categories minus 1) and a probability value $\alpha=0.1$ (which means that
257 there is a 10% probability that any deviation from expected results is due to change), the
258 value of χ^2 equals 13.362. It was found that the greatest effect was for D_{90} (with a power
259 relation with compressive strength, $\chi^2=6.535$) followed by mortar strength (with a linear
260 relation with foamed concrete strength, $\chi^2=10.101$). Meanwhile, with a power relationship,
261 $\chi^2=16.841$, D_{50} does not have any significant effect on the strength of the investigated foamed
262 concrete. These relationships are shown in **Figure (13)** which demonstrates that D_{90}
263 correlates better than D_{50} with strength of foamed concrete implying that it is the larger pores
264 that influence the strength. Similar behavior was noticed by Nambiar and Ramamurthy [3].

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268 **5. Conclusions**

269 Based on the results and discussion, the following conclusions are made:

- 270 • For all mixes, higher foam volume (1300 kg/m³) resulted in a greater degree of void
271 merging, leading to large irregular voids which resulted in a wide distribution of void
272 sizes (increased D₅₀ and D₉₀) and lower strength.
- 273 • For a given density, although the additives in combination led to increased void numbers,
274 higher strength was achieved due to reduced void size and connectivity, by preventing
275 their merging and producing a narrow void size distribution (decreased D₅₀ and D₉₀).
- 276 • Adding a superplasticizer on its own resulted in a void structure fairly similar to that
277 from all additives in combination, implying that it is the superplasticizer that has the
278 greatest influence on voids.
- 279 • A reduction in the D₅₀ and D₉₀ of air voids is clearly linked to an increase in strength for
280 each density implying that the effect of additives (both individually and in combination)
281 was significant.
- 282 • Proportional strength increase with density is greater for the foamed concrete mixes than
283 for comparable unfoamed concrete, apparently because a difference in their failure
284 mechanisms due to a presence of foam in the foamed concrete.
- 285 • Not only enhancement of void structure but also improvement to cement paste
286 microstructure of foamed concrete both contribute to strength gain.

287

288 **Acknowledgements**

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290 Development in Iraq (HCED) for the research scholarship enabling this work to be conducted
291 as part of a larger research project. The authors also wish to thank Dr Daniel Wells (E-A-B
292 Associates Company, UK) for providing the foaming agent. Finally, the valuable help and
293 comments of Mr Thomas Buss (University of Nottingham) during the microscopy
294 observation and Mr Martin Roe (University of Nottingham) during the SEM testing are
295 gratefully acknowledged.

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302 **Table 1.** Mix proportions of the all selected foamed concrete mixes.

	Mixes								
	FC3	FCa3	FC6	FCs6	FCf6	FCp6	FCa6	FC9	FCa9
Target density (kg/m ³)	1300	1300	1600	1600	1600	1600	1600	1900	1900
Cement content (kg/m ³)	500	450	500	450	500	500	450	500	450
Silica Fume (kg/m ³)	-	50	-	50	-	-	50	-	50
W/b ratio*	0.475	0.3	0.5	0.5	0.5	0.325	0.325	0.525	0.35
Superplasticizer (kg/m ³)	-	7.5	-	-	-	7.5	7.5	-	7.5
Water content (kg/m ³)	237.5	150	250	250	250	162.5	162.5	262.5	175
Sand content (kg/m ³)	562	514	850	850	680	930	744	1137.5	974
Fly Ash (kg/m ³)	-	128.5	-	-	170	-	186	-	243.5
Foam (kg/m ³)	19.4	19.4	13.3	13.3	13.3	13.3	13.3	7.6	7.6
Foaming agent (kg/m ³)	0.35	0.35	0.24	0.24	0.24	0.24	0.24	0.13	0.13
Foam (m ³)	0.424	0.424	0.295	0.295	0.295	0.295	0.295	0.166	0.166

303 *w/b ratios required to achieve a density ratio of about unity for the selected mixes

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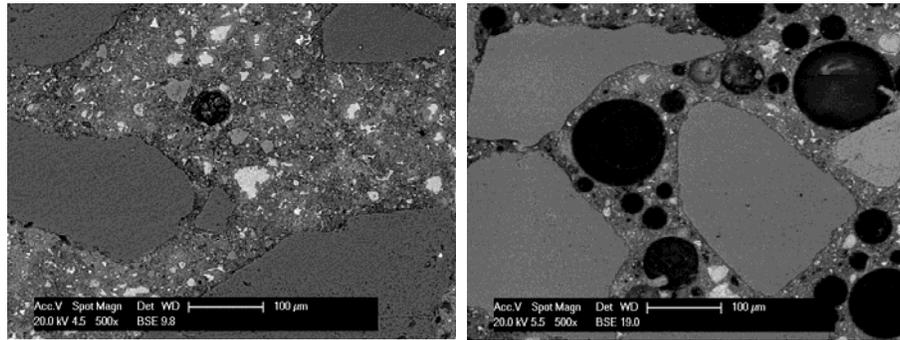
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314 Fig. 1. SEM images for 1600 kg/m³, (left) mix without foam, (right) foamed concrete mix

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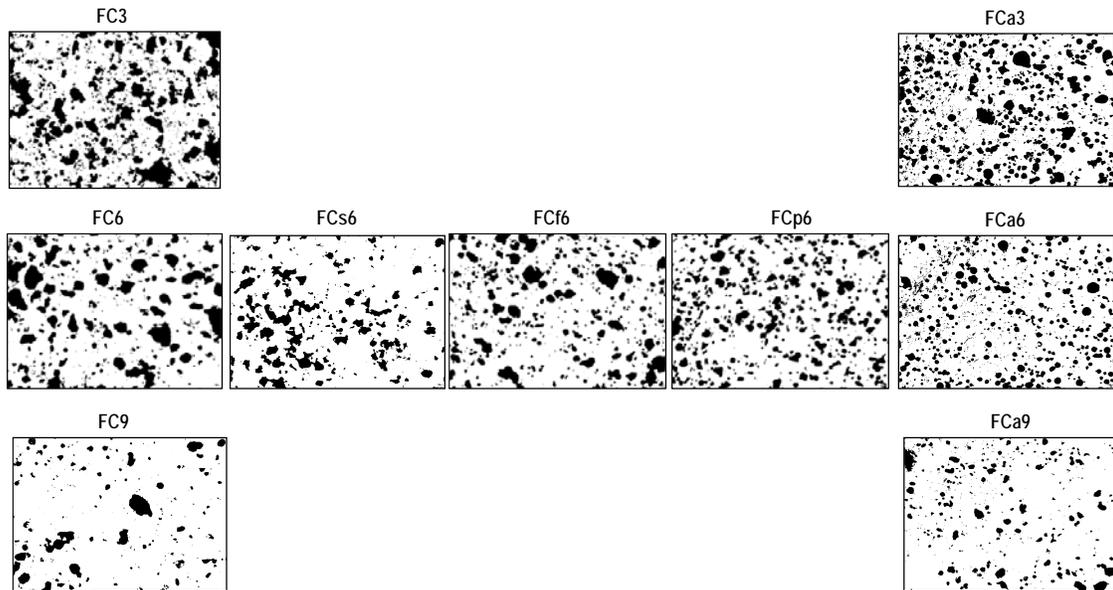
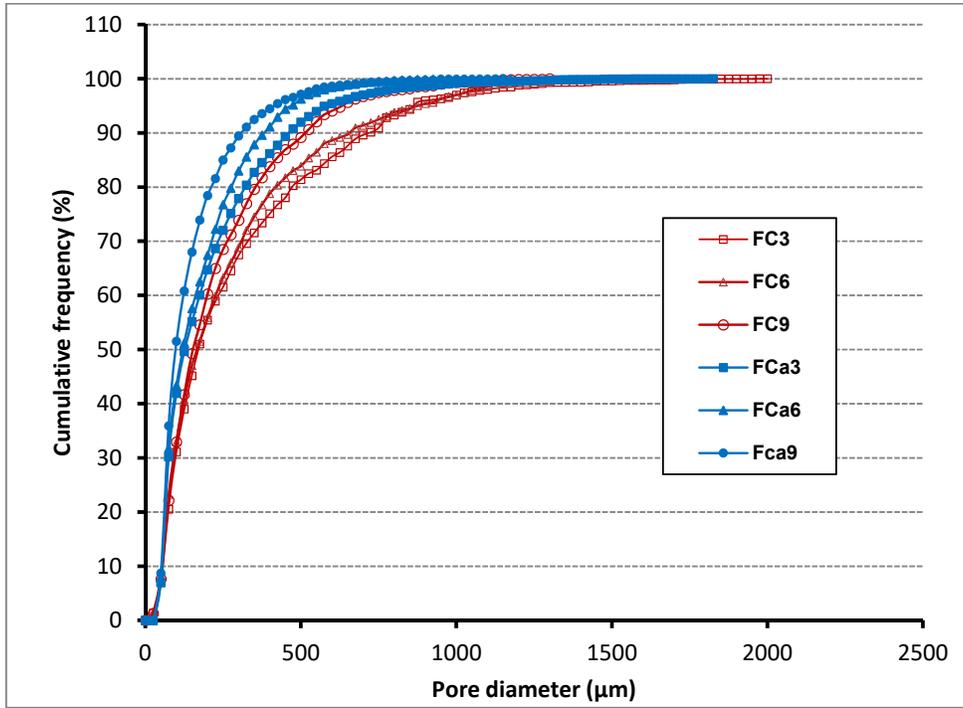


Fig. 2. Typical binary images [15.43mm × 11.57mm] for the selected mixes

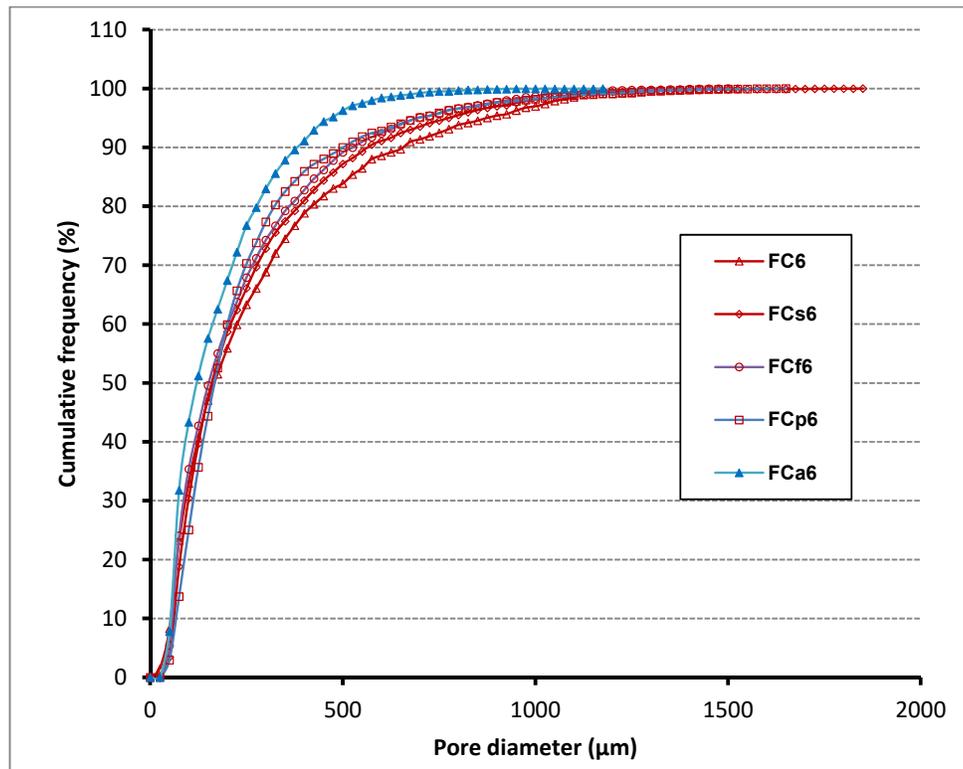


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Fig. 3. Cumulative frequency (%) of pore diameters of FC and FCa foamed concrete mixes



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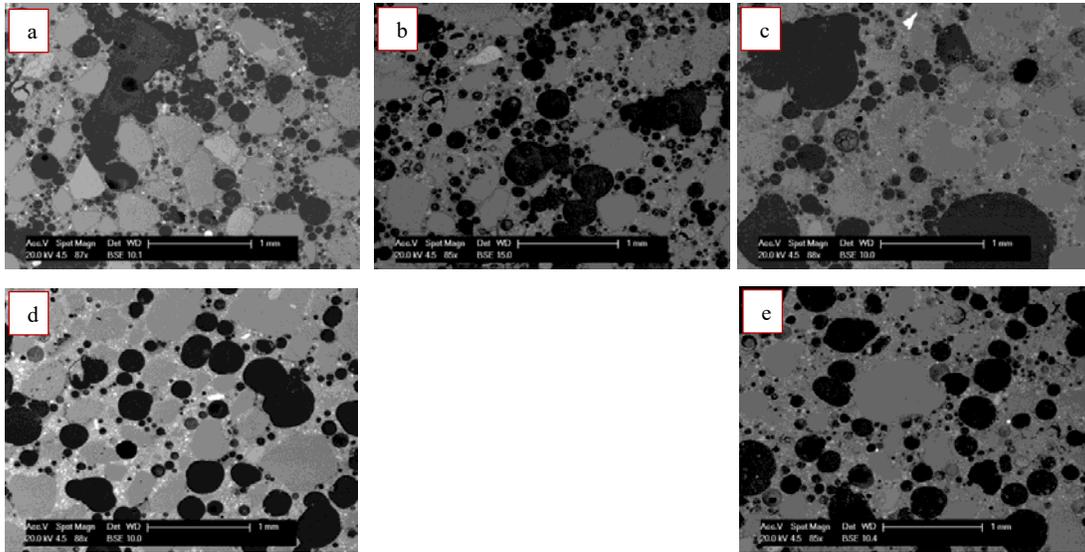
Fig. 4. Cumulative frequency (%) of pore diameters of 1600 kg/m³ mixes

337 **Table 2.** Parameters of pores sizes and circularity of selected foamed concrete mixes

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	FC3	FCa3	FC6	FCs6	FCf6	FCp6	FCa6	FC9	FCa9
D₅₀ (μm)	180	125	175	160	165	165	120	165	95
D₉₀ (μm)	750	465	650	565	510	500	385	525	315

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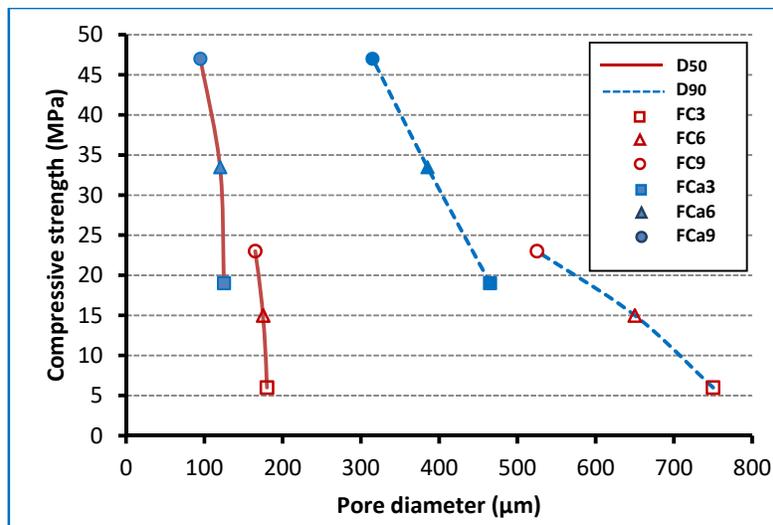


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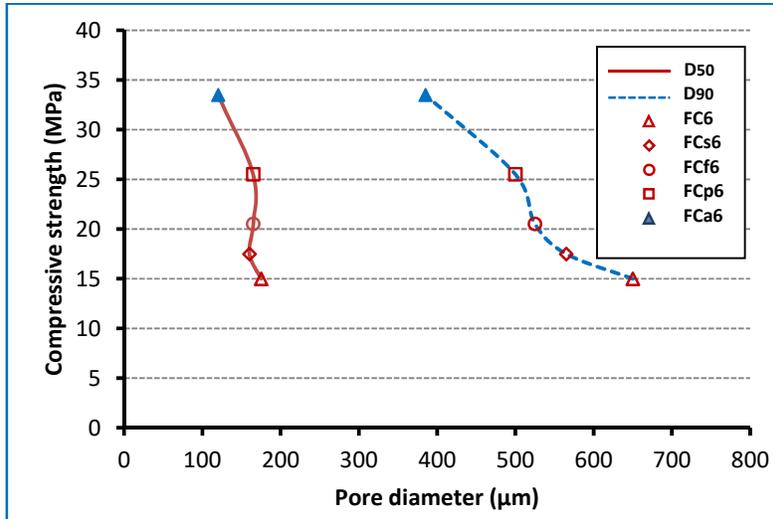
343 **Fig. 5.** SEM images for the selected 1600 kg/m³ mixes (a) FC6 (b) FCs6 (c) FCf6 (d) FCp6 and (e)
344 FCa6



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Fig. 6. Compressive strength versus void size parameters



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Fig. 7. Compressive strength versus void size parameters of 1600 kg/m³ mixes

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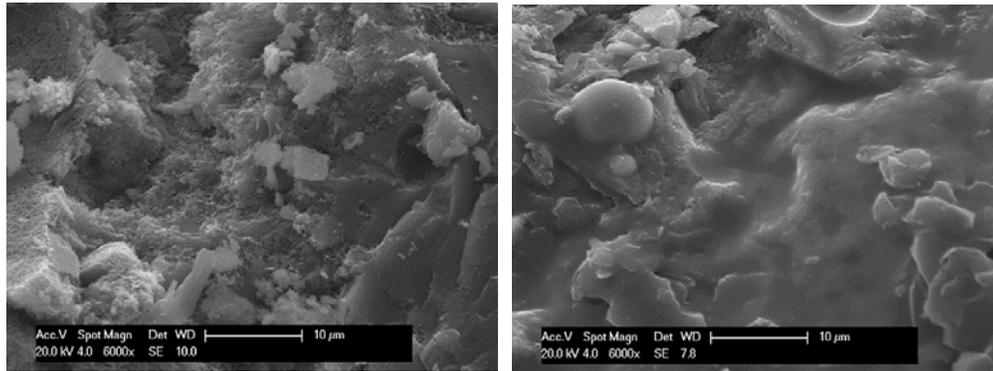
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Fig. 8. Effect of additives on the cement paste microstructure, left) FC6 mix, right) FCa6 mix

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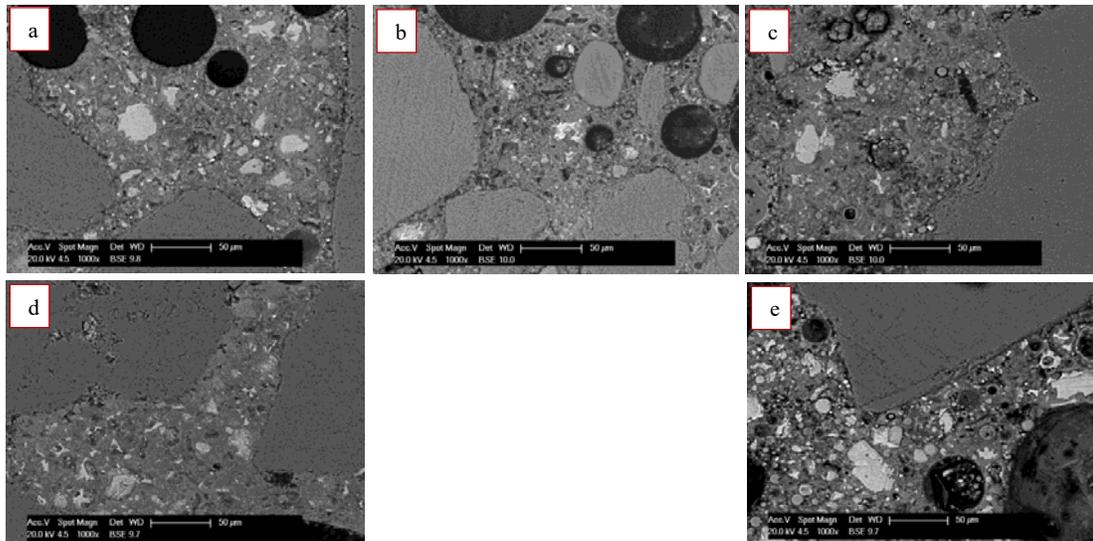
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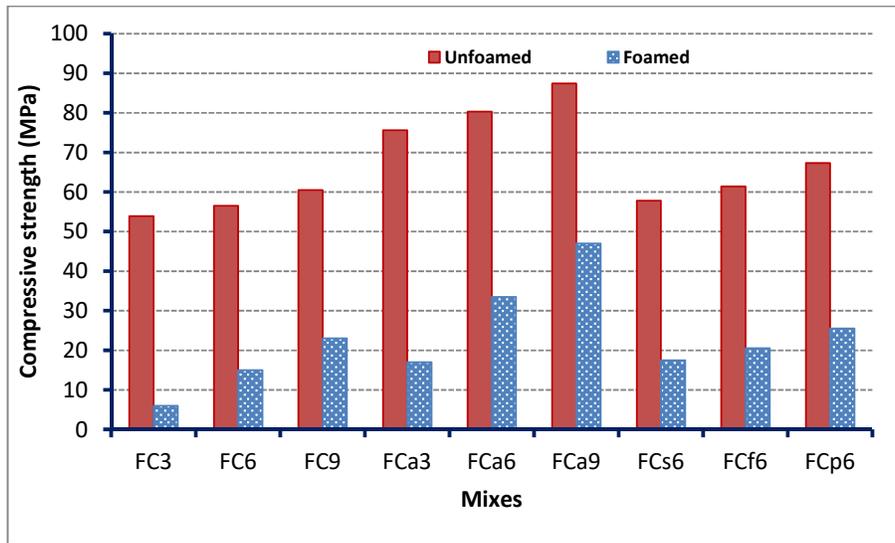


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Fig. 9. Effect of additives on the cement paste microstructure a) FC6 b) FCs6 c) FCf6 d) FCp6 and e) FCa6

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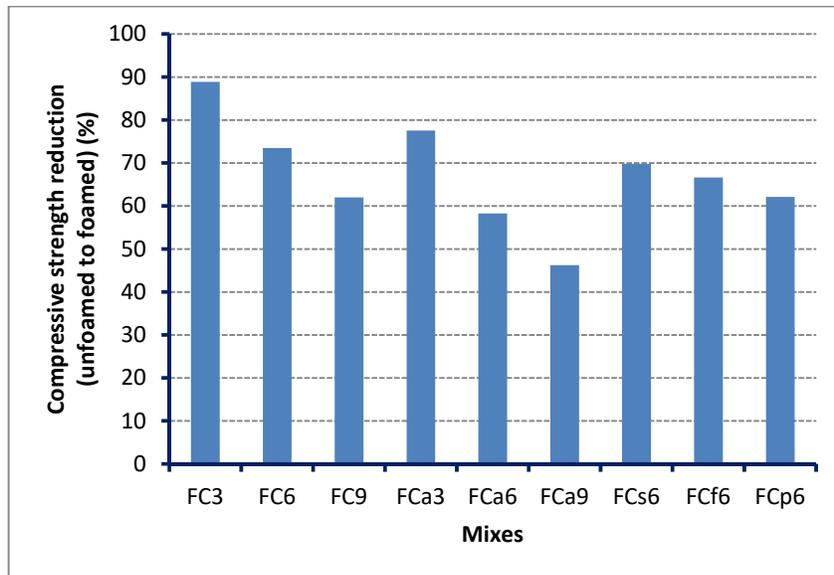
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Fig. 10. 28-day Compressive strength of unfoamed and foamed concrete mixes

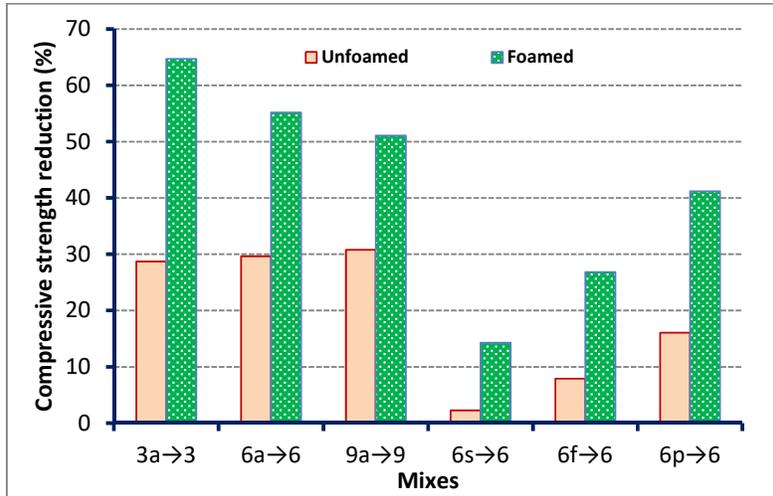


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Fig. 11. Compressive strength reduction (%) of unfoamed to foamed concrete for the same mixes

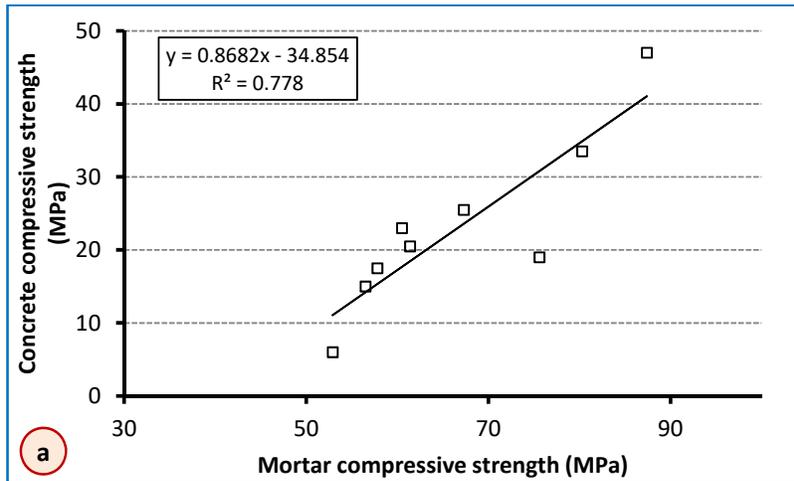
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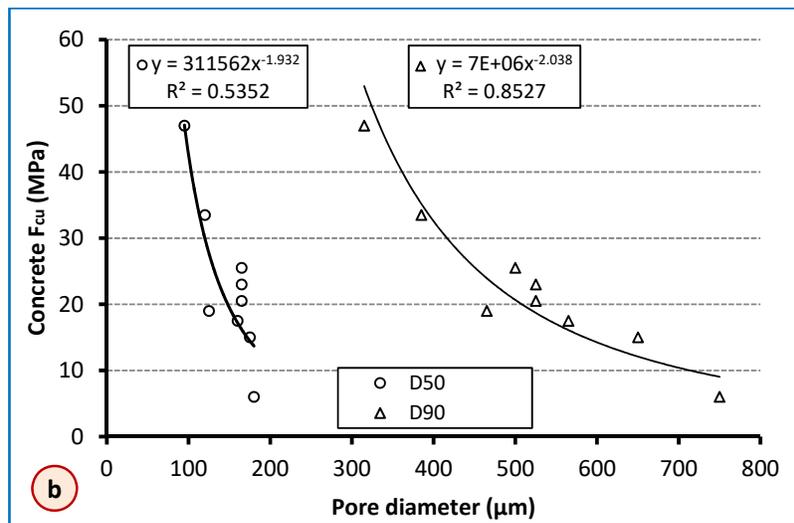
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Fig. 12. Compressive strength reduction (%) of unfoamed and foamed concrete mixes (from with additives to conventional)



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Fig. 13. (a) Mortar strength and (b) pore size parameters versus foamed concrete strength for all investigated mixes

389 **References**

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437 **Figures Captions**

438 **Fig. 1.** SEM images for 1600 kg/m³, left) mix without foam, right) foamed concrete mix

439 **Fig. 2.** Typical binary images [15.43mm × 11.57mm] for the selected mixes

440 **Fig. 3.** Cumulative frequency (%) of pore diameters of FC and FCa foamed concrete mixes

441 **Fig. 4** Cumulative frequency (%) of pore diameters of 1600 kg/m³ mixes

442 **Fig. 5.** SEM images for the selected 1600 kg/m³ mixes (a) FC6 (b) FCs6 (c) FCf6 (d) FCp6
443 and (e) FCa6

444 **Fig. 6.** Compressive strength versus void size distribution parameters

445 **Fig. 7.** Compressive strength versus void size distribution parameters of 1600 kg/m³ mixes

446 **Fig. 8.** Effect of additives on the cement paste microstructure (left) Mortar of FC6 mix (right)
447 Mortar of FCa6 mix

448 **Fig. 9.** Effect of additives on the cement paste microstructure (a) FC6 (b) FCs6 (c) FCf6 (d)
449 FCp6 and (e) FCa6

450 **Fig. 10.** 28-day Compressive strength of unfoamed and foamed concrete mixes

451 **Fig. 11.** Compressive strength reduction (%) of unfoamed to foamed concrete for the same
452 mixes

453 **Fig. 12.** Compressive strength reduction (%) of unfoamed and foamed concrete mixes (from
454 with additives to conventional)

455 **Fig. 13.** (a) Mortar strength and (b) pore size parameters versus foamed concrete strength for
456 all investigated mixes

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