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A simple optimized foam generator and a study on peculiar aspects concerning foams and foamed concrete

Devid Falliano^{1*}, Luciana Restuccia¹, Ernesto Gugliandolo²

¹ Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, Turin, 10129, Italy

² G. Gugliandolo s.r.l., Via Galileo Galilei, 98100, Messina, Italy

* Corresponding author: Devid Falliano, Politecnico di Torino. Email: devid.falliano@polito.it

ABSTRACT

This paper presents a study on peculiar aspects influencing foams and foamed concrete properties, starting from the foam generation up to the compressive strength of the lightweight and ultra-lightweight cementitious material. In particular, after a brief introduction on foam stability, this research work shows a simple and inexpensive foam generator used to produce the commonly used foams in concrete. The significant influence of the air pressure value, of nature and concentration of the foaming agents on density as well as the percentage drainages of the foams produced are therefore discussed. The results show that foams generated with the protein foaming agent have more suitable characteristics to produce foamed concrete, thanks to the significantly longer lifetime compared to foams produced with the synthetic foaming agent. The latter are characterized by very high drainage values even after a few minutes from their generation. Foams are then used to make lightweight (target dry density equal to 600 kg/m³ and 800 kg/m³) and ultra-lightweight (target dry density of 400 kg/m³) foamed concretes that show interesting results in terms of stability also when foams with high drainages are employed. The study provides explications of the differences between the compressive strength of lightweight foamed concrete obtained with foams generated using protein and synthetic foaming agents. Then, the significant influence of the increase in concentration of protein foaming agent on the compressive strength of ultra-lightweight foamed concretes is presented.

KEY WORDS: Foamed concrete; Foam stability; Foam lifetime; Lightweight concrete; Foaming agents; Compressive strength; Density; Foam generator.

35 1. INTRODUCTION

36 Many natural systems are mixtures, namely a physical combination of different substances
37 that continue to maintain their specific identity. When mixtures are characterized by the same
38 physical – chemical characteristics at each point, they are defined homogeneous; if
39 heterogeneous, their properties can vary from a point to another. Based on the size of the
40 particles, heterogeneous mixtures can be classified in the following categories: suspensions
41 (dimensions greater than 1000 nanometers) and colloids (dimensions in the range between 1
42 and 1000 nanometers). Liquid foams, in which small particles of a gas (in most cases air) are
43 scattered in a liquid, belong to the latter category. On the other hand, solutions composed of
44 particles smaller than 1 nanometer belong to the homogeneous mixture. The peculiarity of
45 foams is the capacity to diffuse a small amount of a liquid in an extremely large volume to
46 obtain a low density system: even up to 95% of the total volume can be occupied by gas.

47 Liquid foams can be classified in chemical foams and mechanical foams according to their
48 origins. The final ones, generated by a solution of water and surfactant expanded with
49 compressed air, are the most common and the cheapest. Foams can be also divided into wet
50 and dry foams [1]. The formers have a volumetric fraction of the liquid phase - generally
51 comprised between 10% and 20% - but also bubbles with approximately spherical shape and
52 high internal pressure. Dry foams are characterized by a volumetric fraction of the liquid
53 phase less than 10% and bubbles have an almost polyhedral shape.

54 Dealing with the dry foams' structure, it is possible to identify *Lamellae*, *Plateau borders*
55 and *Nodes*. The term *Lamella* identifies the region bordered by the two interfacial separation
56 surfaces between the gas and the liquid phase of two adjacent bubbles, therefore including the
57 thin liquid film region. The *Plateau borders* represent the liquid tubes in which three
58 *Lamellae* converge. The *Nodes* identify the points where four *Plateau borders* generally

59 meet.

60 In the building sector, the ideal material is characterized by low unit weight, high
61 mechanical performance, high durability, high service performance in terms of fire resistance,
62 thermal insulation and so on. Based on these considerations, it is common practice to use
63 foams in combination with concrete - the most used construction material in the world - to
64 create foamed concrete. This special material is characterized by extremely high flexibility of
65 use, since its density can be varied between 150 kg/m^3 and 2000 kg/m^3 . Although this
66 material could be suitable in civil engineering as it couples the antithesis properties of
67 concrete and foam, it actually exhibits very low mechanical strength and even instability [2],
68 from medium to low density range where the most desired properties like lightness, fire
69 resistance [3], sound absorption [4], thermal insulation [5] are emphasized. So, several
70 research works focused on how to develop lightweight foamed concretes not only
71 characterized by good physical properties but also appropriate mechanical strength. In order
72 to reach this goal, some authors modified the mix design employing sulfoaluminate cement
73 and water repellent [6] or including mineral addition with pozzolanic properties, such as
74 silica fume [7], [8] and fly ash [9], [10], or biochar to improve fracture energy [11], or carbon
75 nanotubes [12]. In other scientific experimentation the flexural capacity has been improved
76 with different kind of fibers' inclusion, namely polypropylene [13], [14], steel [15] or,
77 alternatively, with composite grids and fiber-reinforced meshes [16], [17].

78 However, all these strategies are useless if the foam used to make the lightweight concrete
79 is not characterized by good qualities in terms of density, lifetime (closely connected to the
80 drainage) and chemical properties.

81 For this reason this research paper will focus firstly on an optimized foam generator, then
82 on the characterization of the properties of foams produced with different foaming agents (i.e.
83 protein and synthetic) and finally on the assessment of the experimental results based on the

84 foam stability theory. The foams obtained will be employed to generate some foamed
85 concrete samples, whose characteristics will be combined with the properties of the
86 corresponding foams to explain their relevant differences in terms of compressive strength.
87 This allows to add new details to the actual knowledge of technical literature, in particular
88 with reference to the significantly different behavior of foams generated with protein and
89 synthetic foaming agents in the case of low w/c ratios. Furthermore, the study allows to
90 highlight the influence of the increase of protein foaming agents' concentration on
91 compressive strength of ultra-lightweight foamed concretes, although this increase does not
92 show appreciable differences in the properties of the foams themselves.

93 **2. FOAM STABILITY**

94 Peculiarities of colloids are certainly represented by the remarkable extension of the
95 separation surface between the scattered phase and the specific physical-chemical properties
96 of the molecules at the interphase. As well known, colloids can be divided into lyophilic and
97 lyophobic or, if the dispersing medium is water, into hydrophilic and hydrophobic
98 respectively. The latter types are characterized by a poor affinity between the two phases that,
99 over time, could try to separate in two distinct phases with different density after a
100 sedimentation process. Otherwise, they could be subjected to phenomena such as flocculation
101 or coalescence of the dispersed phase, with the consequent creation of dispersed particles
102 with greater mass and volume. These are spontaneous processes because the free energy of
103 the colloidal system tends to decrease reaching a minimum, in which the equilibrium state is
104 reached.

105 In order to obtain a more stable colloidal system, surface tension value is usually reduced.
106 From a thermodynamic point of view, it can be defined as the work per unit of area required
107 to create a new surface [18] and it depends on the greater or lesser inclination of the colloidal

108 system's phases to modify their structure in correspondence with the interphasic region. To
109 reach this aim, surfactants must be used. The amphiphilic structure of these molecules
110 promotes their adsorption at the interface, also determining a preferential orientation
111 characterized by the arrangement of the hydrophobic tail towards the gas and the hydrophilic
112 head in contact with the aqueous phase [19].

113 Surfactants can be classified in different ways, for example on the basis of their use (i.e.
114 emulsifiers, foaming agents, wetting agents, dispersants) or of their ionic character (i.e.
115 anionic, cationic, non-ionic, amphoteric), but also depending on their nature (i.e. natural,
116 synthetic). From the significant physical-chemical variances between the different types of
117 surfactants, it is theoretically possible to design an appropriate surfactant molecule based on
118 the specific needs of use by modifying the balancing between the hydrophilic and
119 hydrophobic groups and the properties of each group [20]. Hence, the purpose of this work is
120 to highlight that not all surfactants and foaming agents are appropriate for the production of
121 foamed concretes. As it will be clarified later, this is a fundamental reason to explain the
122 substantial differences between the experimental results of dissimilar research works focused
123 on the evaluation of foamed concrete properties and the possible explanation for low
124 mechanical strength of several foamed concretes, even from medium to high density,
125 discussed in other studies.

126 Two macro-phases can be distinguished during foam formation mechanism: the gas
127 encapsulation into the liquid and the lifetime of the generated foams. If a foaming agent
128 misses in the liquid phase, the air bubbles collapse almost instantly. On the contrary, the
129 foaming agent enhances system stability and its lifetime, as reported before; the presence of
130 the surfactant helps to identify further significant stages in addition to the two phases
131 previously reported: the formation of new interfaces, the adsorption of surfactant molecules
132 at these interfaces with a consequent reduction in the surface tension and, in the most

133 complex cases, the development of intramolecular and intermolecular bonds.

134 A crucial phenomenon in assessing the lifetime of a foam is the drainage (supported by the
135 force of gravity) which represents its most destabilizing cause [21]. As reported in the
136 introduction section, foams can be separated from wet and dry: actually, foams go from wet
137 to dry conditions during their lifetime because of the drainage. Indeed, a newly generated
138 foam is characterized by spherical bubbles and thick lamellae, which tend to become thinner
139 as the fluid drainage proceeds. This process causes a loss of foam density with the separation
140 between the fluid phase and the achievement of the dry condition characterized by polyhedral
141 bubbles [22]. In this situation, the lamellae generally become unstable causing the collapse of
142 the foam. From this point of view, it is possible to make a distinction between transient foams
143 characterized by a lifetime that lasts some seconds, and metastable or permanent foams,
144 whose lifetime is about tens of minutes or more (even days in some cases) [21]. Obviously,
145 useful foams in the field of foamed concretes belong to the last category.

146 Hence, the stability of a foam related to the drainage, is closely connected to the properties
147 of the film at the interface between the phases. These properties depend on the characteristics
148 of the foaming agent, on its concentration and on the interactions it gives rise to. Referring to
149 the Gibbs effect and the Marangoni effect [18], [23], a crucial role is played by the thickness
150 of the film and by the surfactant concentration. The optimal film should be characterized by a
151 high viscoelasticity (connected to its thickness) and an appropriate surfactant concentration,
152 which would guarantee the absorption of stresses and deformations. It is necessary to use
153 appropriate foaming agents or mixture of foaming agents, polymers, micro- or nano-particles
154 to reach this goal. The increase of the viscosity of the liquid, from which the foam is
155 generated, also affects the stabilization of the system positively reducing the drainage. This
156 can be attained by adding a viscous solution to the liquid phase [24], which would even
157 increase the confinement pressure on the bubbles, allowing the achievement of a stability

158 configuration of bubbles with higher internal pressure, so smaller dimensions. Indeed, the
159 smaller bubble's radius, the higher its internal pressure is.

160 A foam contains bubbles of different dimensions causing the diffusion of the gas from
161 smaller to larger bubbles [25]; this process facilitates the percolation of the liquid
162 immediately after foam's origin and it leads to the reduction of about 10% of the total number
163 of the bubbles.

164 Therefore, drainage and diffusion are the main causes of deterioration of a foam together
165 with coalescence. The last one represents the physical phenomenon whereby droplets of a
166 liquid, bubbles of a gas or particles of a solid merge to form a single larger element [26].
167 Total volume of the resulting element is the sum of the starting ones, while the resulting
168 surface area is much lesser than the sum of the starting ones. Thus, the coalescence leads to a
169 reduction of the total surface area at the interface between the two phases, resulting in a total
170 energy reduction of the entire system: this phenomenon is a spontaneous process. Due to the
171 drainage, if the films become thinner, the coalescence will be favored [27].

172 The main parameters to control foams' properties are: nature and concentration of the
173 foaming agents as well as internal pressure of the bubbles. Therefore, a proper foam
174 generator should be able to allow the correct regulation of all these parameters. Therefore, in
175 the following section a simple foam generator optimized for the purpose is described.
176 Subsequently, these parameters will be explored studying the properties of the generated
177 foams.

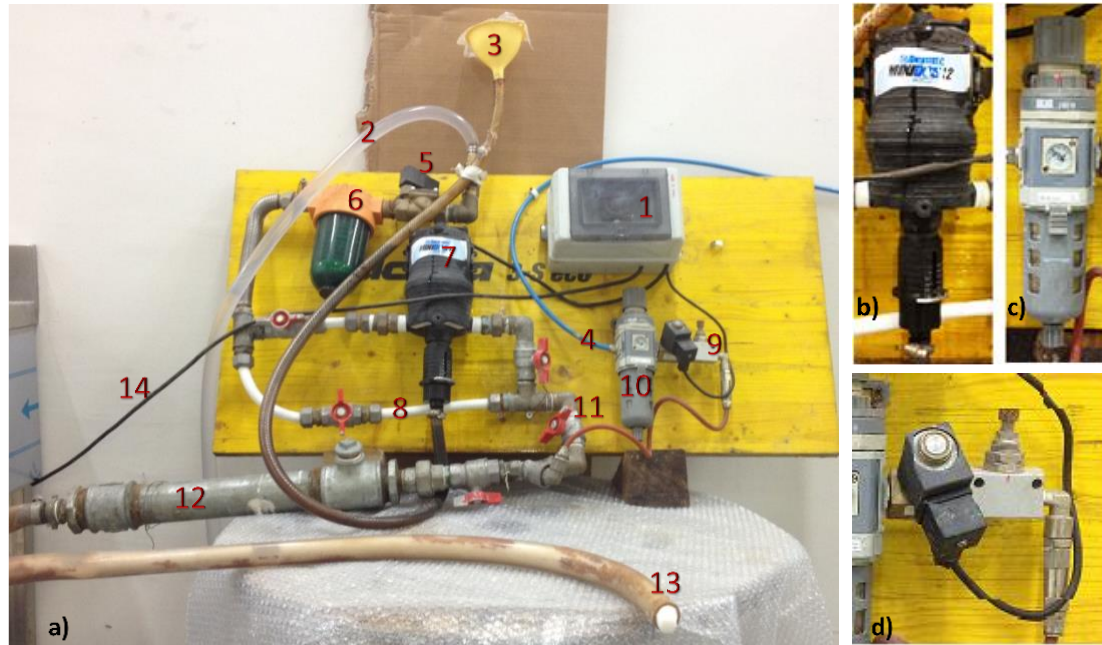
178 **3. A SIMPLE AND OPTIMIZED FOAM GENERATOR**

179 There are many strategies for making foam from a solution containing foaming agents:
180 mechanical stirring, emission of pressurized air through a nozzle, suitable chemical reactions
181 and so on. All these strategies have the common objective of introducing a gas (generally air)

182 in a liquid solution. Due to their simplicity and cost-effectiveness, the most conventional
183 ways to produce foams are certainly mechanical stirring with a high speed vertical mixer and
184 the use of a proper foam generator. The latter should be preferred because it allows to better
185 control all the parameters that come into play in the generation of a foam. Actually, a key
186 factor which significantly affects the quality of the foams in terms of bubble size, viscosity
187 and overall system stability, is the energy supplied to the system at this stage. It has been
188 shown that an increase factor of 3.3 in the mixing speed leads to a reduction of the bubble
189 size of about 4.5 times, but it also increases stability and viscosity of approximately 100%
190 [28]. Therefore, an appropriate foam generator must be able to produce foam through a
191 turbulent flow with high shear stresses. It is useful to highlight that the dynamic agitation of
192 the system reduces the time of adsorption of the surfactant molecules at the interfaces up to
193 the order of millisecond. In fact, unlike static systems where the migration of surfactant
194 molecules towards the interface is due to diffusion, in this case convection is significantly
195 predominant.

196 Regarding systems that use mechanical stirring to produce foams, a solution could be
197 represented by the exploitation of a gas injection into the liquid through a porous medium.
198 Another one could be use the rotor–stator system, which is commonly employed in different
199 foam generators already on the market, as the Top Mix produced by the Hansa Industrie-
200 Mixer for the food industry. However, the best solution is both extremely simple and very
201 effective: it consists of triggering the turbulent flow via a suitable pipe which the fluid is forced
202 to pass through. This is the most used system in the foamed concrete field.

203 Based on the foregoing parts of this study, to accurately verify all the parameters that play
204 a crucial role in foam production, the foam generator shown in Figure 1 was designed and
205 manufactured.



206 **Figure 1** Optimized foam generator: a) overall view; b) detail of the automatic dosing pump for the
 207 foaming agent concentration; c) detail of the air pressure reducer; d) detail for air flow regulation.

208 The operating principle is very simple: the foam is generated by the dispersion of gas
 209 under pressure (i.e. air) in a solution of water and surfactants with the subsequent triggering
 210 of the turbulent flow. In particular, the water and the foaming agents, whose concentration is
 211 regulated by a proper automatic dosing pump, are mixed together; subsequently, the mixture
 212 of water and surfactant meets the compressed air, whose pressure is regulated by a pressure-
 213 reducing valve. Lastly, the mixture of water and surfactant expanded with compressed air
 214 passes through the mixing pipe, which is filled with appropriate brass rings. These brass rings
 215 trigger turbulent flow conditions to obtain a homogeneous and stable foam. In particular,
 216 referring to the red numbers in Figure 1a), the foam generator is composed of:

- 217 1. Push-button panel for solenoid valves equipped with a timer to control the foam
 218 delivery time.
- 219 2. Water input, whose flow rate can be adjusted through a proper valve located
 220 upstream of the generator.
- 221 3. Foaming agent input.

- 222 4. Compressed air input: the blue tube is connected to a compressor.
- 223 5. Solenoid valve for synchronized entry of water and air in the circuit (the other
224 solenoid valve is clearly visible in the detail of Figure 1d).
- 225 6. Water filter.
- 226 7. Automatic dosing pump to regulate the foaming agent concentration from 1% to 5%
227 of the water content by volume (detail in Figure 1b).
- 228 8. Parallel circuit to bypass the foaming agent input.
- 229 9. Valve for regulating the compressed air flow entering the circuit (detail in Figure
230 1d).
- 231 10. Pressure reducer equipped with a pressure gauge to regulate the air pressure from 0
232 to 12 bar (detail in Figure 1c).
- 233 11. Valve for regulating the flow of the liquid solution (water plus foaming agent) to
234 be mixed with compressed air.
- 235 12. Mixing pipe in which turbulent flow is triggered via its filling with appropriate
236 brass rings.
- 237 13. Foam output.
- 238 14. Electricity input.

239

240 Compared to other foam generators, the one described so far allows to control all the key
241 parameters to be optimized to check the properties of the produced foams: water flow, air
242 pressure, foaming agents concentration, compressed air flow, flow of water plus foaming
243 agent before compressed air entry. Controlling all these parameters makes it possible to refine
244 the properties of the foams produced in any condition, ensuring the generation of a
245 continuous and uninterrupted flow of a stable foam.

246 **4. INVESTIGATION ON FOAM PROPERTIES**

247 **4.1. Testing conditions**

248 The influence of the key parameters on the properties of the foams produced by the
249 previously showed generator is now investigated. In particular, while the regulations of both
250 the flow of compressed air (that enters the circuit) and the flow of the liquid solution (water
251 plus foaming agent) to be mixed with compressed air are fundamental to guarantee a
252 continuous and an uninterrupted flow of stable foam, the concentration of foaming agents and
253 air pressure are the crucial parameters to check the quality of the foams produced. Hence
254 their choice is strictly connected to the water flow entering the circuit and the last two
255 parameters can be simply changed by means of the automatic metering pump and by the
256 pressure reducer.

257 Considering this topic more specifically, the properties of foams produced with a protein
258 foaming agent called Foamin C[®] (whose main properties are reported in Table 1) in terms of
259 density and percentage of drainage at 5, 10, 15 and 180 minutes after generation with
260 different concentrations of foaming agent (2%, 3%, 4% and 5% with respect to the water
261 volume) and with different air pressure values (1.5 bar, 2 bar, 2.5 bar, 3 bar, 3.5 bar, 4 bar,
262 4.5 bar and 5 bar) will be analysed.

263 As specified in Section 2, due to its importance, nature of foaming agents is also
264 investigated. In this regard, the influence of different air pressure values (2 bar, 2.5 bar, 3 bar,
265 3.5 bar, 4 bar, 4.5 bar and 5 bar) on the properties of the foams generated with the use of a
266 synthetic foaming agent, namely Sodium Laureth Sulfate (SLS, whose main properties are
267 reported in Table 1), with a concentration of 4% with respect to the water volume will be
268 illustrated; then, the properties of foams generated with foaming agents of different nature,
269 but other conditions being equal, will be examined.

270 **Table 1** Properties of foaming agents

Foaming agent	Nature	Ionic character	Color	Density	Acidity PH
Foamin C [®]	Protein	Anionic	Brown	1.15 g/ml	6.6
SLS	Synthetic	Anionic	Transparent	1.05 g/ml	9.5

271

272 The Foamin C[®] anionic protein foaming agent is produced by the Italian company Mibo
 273 s.r.l. and it is commonly used in building materials field to produce foamed concrete to make
 274 thermal insulating screeds and flat roofs or substrates of industrial and civil flooring. In
 275 addition to water, it is composed of 25% hydrolysed proteins and 4% mineral salts; 1.5% of
 276 the latter are metals like zinc chloride, magnesium chloride and iron sulphate.

277 The SLS anionic synthetic foaming agent is widely used in various industrial sectors.
 278 From a chemical point of view, it is obtained from the reaction between lauric acid and
 279 sulphuric anhydride together with sodium hydroxide.

280 Regarding the procedures, one of the greatest difficulty is the definition of a quick, simple,
 281 effective and easily repeatable way of filling the beakers with the foams produced. Indeed,
 282 the correct evaluation of the properties of the foam is strictly connected to its pouring into the
 283 beaker immediately after its generation in order to avoid the beginning of drainage even
 284 before positioning the sample, which will cause a consequent invalidation of the results. Any
 285 attempt to fill the beaker with the use of spatulas or spoons has proved to be unsuccessful
 286 especially because of the voids created during the filling phase.

287 To overcome these challenges, a procedure for filling the beaker directly from the rubber
 288 tube connected to the generator has been defined. In particular, the foam dispensing tube is
 289 initially put in touch with the base of the beaker; as soon as dispensing begins, the tube must
 290 be gradually raised until the container is filled with foam over the top; the last step consists of
 291 smoothing of the upper surface of the beaker by means of a proper metal spatula, in order to
 292 eliminate the excess of foam. This quick, simple and effective procedure prevents the

293 development of voids inside the beaker during the filling phase.

294 It should be emphasized that, the foam delivered during the first 5 seconds is rejected to
295 guarantee its total discharge that is already inside the tube; so, only freshly generated foam
296 will be used.



297 **Figure 2** Pyrex beakers used for tests on the foams produced.

298 After the filling phase, the weight of the foam W_f , is determined as the difference between
299 the weight of the beaker filled with the foam W_t , and the weight of the empty beaker W_b ; the
300 volume of the pyrex beaker (showed in Figure 2) is also required to determine the foam
301 density, γ_f . This one is evaluated through expression 1, where W_w represents the weight of the
302 pyrex beaker filled with deaerated water and evaluated after the removal of the air bubbles
303 possibly deposited on the walls of the container and γ_{wt} represents the density of water at the
304 measured temperature.

$$305 \quad V = \frac{W_w - W_b}{\gamma_{wt}} \quad (1)$$

306 The foam density γ_f , can be determined as the ratio between the weight of the foam W_f , and
307 its volume V .

308 In addition to the density, drainage is evaluated after 5, 10, 15 and 180 minutes. This
309 determination is carried out considering the weight of the solution of water and surfactant

310 drained from the foam at the selected time intervals previously specified. The drainage
311 quantity at the time x - Q_x - is hence evaluated as the difference between the weight of the
312 beaker with the liquid drained at the time x , W_{Q_x} , and the weight of the empty beaker. Once
313 the quantity of drainage at the time x , Q_x , is noted, it is possible to determine the percentage
314 drainage at the time x , D_x , by means of the expression 2.

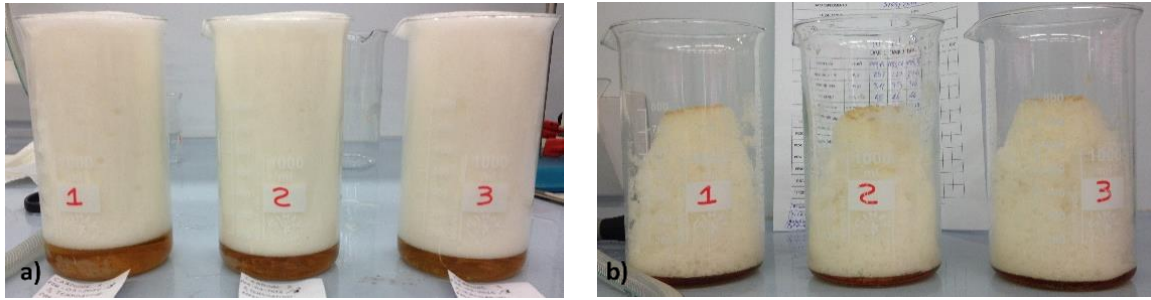
$$315 \quad D_x = \frac{Q_x}{W_f} \quad (2)$$

316

317 **4.2. Results and discussion**

318 This section reports the evaluation and the analysis of the effects of both Foamin C[®]
319 protein foaming agent concentration (ranging from 2% to 5% with respect to the water
320 volume) and pressure of the compressed air (ranging from 1.5 bar to 5 bar) on the density and
321 the percentage drainage at 5, 10, 15 and 180 minutes of the foams produced. Furthermore, the
322 same analysis for SLS synthetic foaming agents at a concentration of 4% with respect to the
323 water volume but also for a compressed air pressure that varies from 2 bar to 5 bar is reported
324 to highlight the effect of the foaming agents' nature.

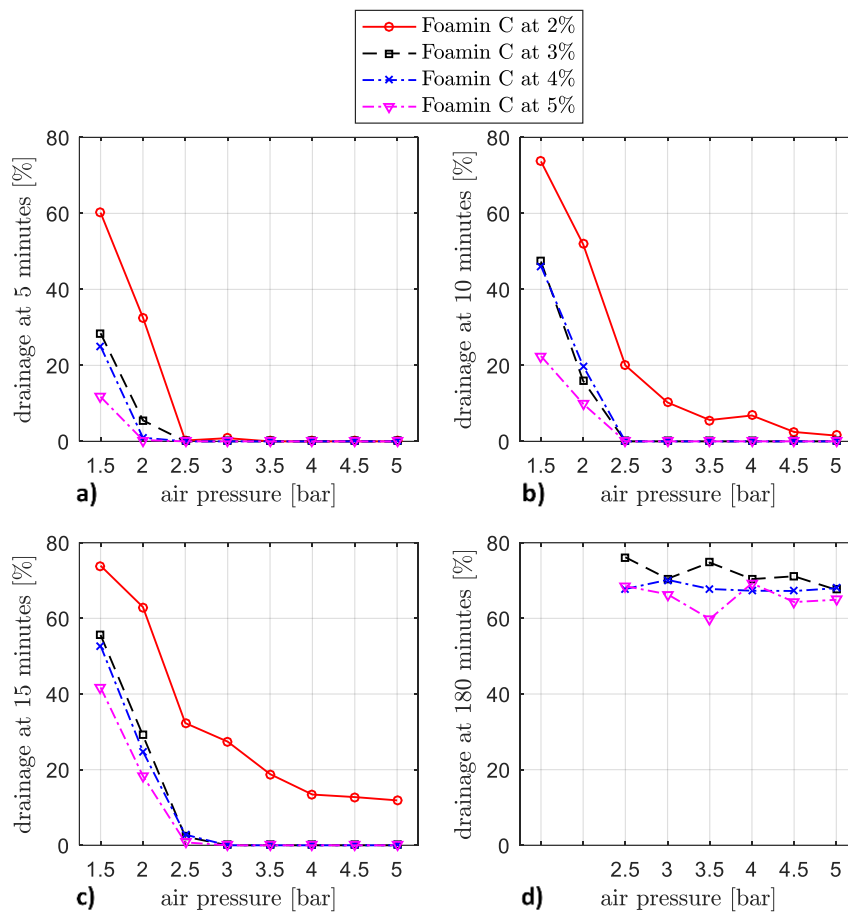
325 With regard to foams produced with Foamin C[®] protein foaming agent, a series of these
326 samples is reported in the photos of Figure 3 and their relative results are shown in Table 2 to
327 Table 9. In particular, 59 series were analysed; letter "P" reported for each serial number
328 stands for protein, while in Table 10 the series are indicated with letter "S" due to the
329 synthetic nature of the foaming agent and it refers to the properties of the foams produced
330 with SLS. It is important to remind that each value shown in the tables (namely density, γ ,
331 drainage at 5 minutes, D_5 , drainage at 10 minutes, D_{10} , drainage at 15 minutes, D_{15} , drainage
332 at 180 minutes, D_{180}) is given by the average value of three different determinations; thus, the
333 standard deviation and the coefficient of variation of the parameters evaluated are reported to
334 express the dispersion of the findings.



335 **Figure 3** Foam produced with Foamin C[®] protein foaming agent showing drainage a) and structural
336 collapse (showed by all the foams produced) at the selected time interval of 180 minutes b).

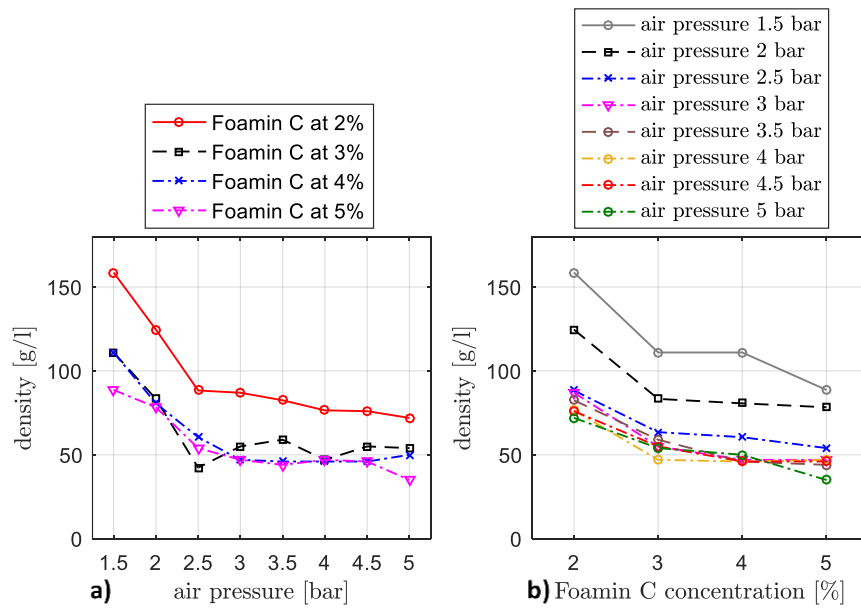
337 As for the foams generated with Foamin C[®] foaming agent at a concentration equal to 2%,
338 it is possible to notice that drainage increases significantly with a wider time interval for any
339 air pressure value, as it can be seen in Figure 4. Moreover, for lower air pressure values, i.e.
340 1.5 bar and 2 bar, the lifetime of the foams is very short, since most of the drainage is
341 concentrated within the first 10 minutes. This is due to the fact that the foams generated with
342 these low values of foaming agent concentration and air pressure are characterized by a too
343 high density value, in particular equal to 120 g/l, as can be seen by the inspection of Figure 5.

344 Despite the low foaming agent concentration, in case of air pressure values equal to or
345 greater than 2.5 bar, foam density decreases significantly (Figure 5) and it causes a greater
346 stability in terms of percentage drainages, which are around 10% to 30% at 15 minutes. The
347 improvement of foam characteristics is due to a better turbulent flow in the mixing tube,
348 triggered by a higher air pressure value. Moreover, the results show that it is possible to
349 improve the quality of the foams by increasing air pressure values only up to a certain point,
350 namely 4 bar; in any case, a 2% Foamin C[®] concentration makes the drainage null only at the
351 selected time interval of 5 minutes. Therefore, a further improvement in the quality of the
352 foams can only be obtained by increasing the concentration of the foaming agent so as to
353 enhance the presence of surfactant molecules at the interfaces and to improve consequently
354 the stability of the system.



355 **Figure 4** Influence of air pressure and Foamin C® protein foaming agent concentration on the
 356 drainage of foams produced at selected time intervals: 5 minutes a); 10 minutes b); 15 minutes c); 180
 357 minutes d).

358 Of course, for this foaming agent concentration, the foams generated with air pressure
 359 values lower than 2.5 bar are characterized not only by a very high drainage and high density
 360 values, but also by a greater variability of their properties with a small variation of the air
 361 pressure value. Therefore, it is impossible to produce foams with a satisfactory level of
 362 repeatability, as demonstrated by the high values of both the standard deviation and the
 363 coefficient of variation for the drainage and the densities of these foams, which are
 364 considerably higher than those referred to foams produced with a higher concentration of
 365 foaming agents.



366 **Figure 5** Influence of air pressure and Foamin C[®] protein foaming agent concentration on the density
 367 of foams produced: for fixed foaming agent concentration a); for fixed air pressure value b).

368 Going to the foams generated with 3% Foamin C[®] concentration, the percentage drainage
 369 remains very high for 1.5 bar and 2 bar air pressure values, although lower than the previous
 370 case, but from 2.5 bar onwards they become null or, at most negligible within 15 minutes. In
 371 this case as well, the air pressure value of 2.5 bar represents the discriminant between good
 372 and bad quality foams in terms of percentage drainage and lifetime. Thanks to Figure 4a), b)
 373 and c), it is possible to notice that this assumption is also valid for 4% and 5% protein
 374 foaming agent concentrations.

375 **Table 2** Density and percentage drainage at 5, 10 and 15 minutes for foams produced with air pressure value equal to 1.5 bar and for different Foamin C[®]
 376 foaming agent concentrations.

Foaming agent concentration [%]	n° series	Average density	Standard deviation	CoV	Average drainage 5 min.	Standard deviation	CoV	Average drainage 10 min.	Standard deviation	CoV	Average drainage 15 min.	Standard deviation	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$
2	#1P	152	23.84	0.15	60.2	9.96	0.17	-	-	-	-	-	-
	#2P	170	18.61	0.11	-	-	-	73.68	3.98	0.05	-	-	-
	#3P	154	14.60	0.09	-	-	-	-	-	-	73.93	2.48	0.03
3	#4P	110	2.33	0.02	28.46	2.92	0.10	-	-	-	-	-	-
	#5P	111	2.05	0.02	-	-	-	47.33	2.64	0.06	-	-	-
	#6P	112	1.39	0.01	-	-	-	-	-	-	55.61	1.61	0.03
4	#7P	113	2.62	0.02	25.01	3.81	0.15	-	-	-	-	-	-
	#8P	112	0.46	0.01	-	-	-	46.14	1.91	0.04	-	-	-
	#9P	108	7.76	0.07	-	-	-	-	-	-	52.76	1.80	0.03
5	#10P	93	0.55	0.01	11.74	0.85	0.07	-	-	-	-	-	-
	#11P	85	2.52	0.03	-	-	-	22.46	2.84	0.13	-	-	-
	#12P	88	2.19	0.02	-	-	-	-	-	-	41.75	3.28	0.08

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Table 3 Density and percentage drainage at 5, 10 and 15 minutes for foams produced with air pressure value equal to 2 bar and for different Foamin C® foaming agent concentrations.

Foaming agent concentration [%]	n° series	Average density	Standard deviation	CoV	Average drainage 5 min.	Standard deviation	CoV	Average drainage 10 min.	Standard deviation	CoV	Average drainage 15 min.	Standard deviation	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$
2	#13P	124	3.70	0.03	32.60	3.87	0.12	-	-	-	-	-	-
	#14P	124	4.16	0.03	-	-	-	51.86	2.83	0.05	-	-	-
	#15P	126	8.65	0.07	-	-	-	-	-	-	63.00	4.24	0.07
3	#16P	85	2.96	0.03	5.53	3.49	0.63	-	-	-	-	-	-
	#17P	83	2.15	0.02	-	-	-	15.92	0.80	0.05	-	-	-
	#18P	82	2.62	0.03	-	-	-	-	-	-	29.08	1.40	0.05
4	#19P	78	3.85	0.05	0.97	0.94	0.97	-	-	-	-	-	-
	#20P	86	2.12	0.02	-	-	-	19.82	1.64	0.08	-	-	-
	#21P	78	5.36	0.07	-	-	-	-	-	-	24.81	8.01	0.32
5	#22P	79	3.71	0.05	0.35	0.30	0.87	-	-	-	-	-	-
	#23P	80	3.12	0.04	-	-	-	9.88	1.83	0.19	-	-	-
	#24P	76	6.74	0.09	-	-	-	-	-	-	18.36	6.64	0.36

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381 **Table 4** Density and percentage drainage at 5, 10, 15 and 180 minutes for foams produced with air pressure value equal to 2.5 bar and for different Foamin
 382 C[®] foaming agent concentrations.

Foaming agent concentr. [%]	n° series	Av. density	St. dev.	CoV	Av. drain. 5 min.	St. Dev.	CoV	Av. drain. 10 min.	St. dev.	CoV	Av. drain. 15 min.	St. dev.	CoV	Av. drain. 180 min.	St. dev.	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$	D_{180} [%]	$\sigma_{D_{180}}$ [%]	$CoV_{D_{180}}$
2	#25P	84	0.55	0.01	0.24	0.22	0.94	-	-	-	-	-	-	-	-	-
	#26P	91	3.72	0.04	-	-	-	20.00	2.22	0.11	-	-	-	-	-	-
	#27P	90	3.90	0.04	-	-	-	-	-	-	32.32	2.86	0.09	-	-	-
3	#28P	61	0.93	0.01	0.00	0.00	0.00	0.00	0.00	0.00	2.28	1.54	0.68	-	-	-
	#29P	66	2.66	0.04	-	-	-	-	-	-	-	-	-	76.16	2.12	0.03
4	#30P	60	2.27	0.04	0.00	0.00	-	0.00	0.00	-	2.82	0.11	0.04	-	-	-
	#31P	61	1.40	0.02	-	-	-	-	-	-	-	-	-	67.76	2.32	0.03
5	#32P	53	1.79	0.03	0.00	0.00	-	0.00	0.00	-	0.77	0.75	0.97	-	-	-
	#33P	55	1.65	0.02	-	-	-	-	-	-	-	-	-	68.52	4.56	0.07

383 **Table 5** Density and percentage drainage at 5, 10, 15 and 180 minutes for foams produced with air pressure value equal to 3 bar and for different Foamin C[®]
 384 foaming agent concentrations.
 385

Foaming agent concentr. [%]	n° series	Av. density	St. dev.	CoV	Av. drain. 5 min.	St. Dev.	CoV	Av. drain. 10 min.	St. dev.	CoV	Av. drain. 15 min.	St. dev.	CoV	Av. drain. 180 min.	St. dev.	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$	D_{180} [%]	$\sigma_{D_{180}}$ [%]	$CoV_{D_{180}}$
2	#34P	88	4.80	0.05	0.86	0.84	0.98	-	-	-	-	-	-	-	-	-
	#35P	84	4.70	0.05	-	-	-	10.24	2.59	0.25	-	-	-	-	-	-
	#36P	89	5.51	0.06	-	-	-	-	-	-	27.41	3.61	0.13	-	-	-
3	#37P	55	3.83	0.07	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	70.48	1.32	0.02
4	#38P	47	0.80	0.02	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	70.18	5.01	0.07
5	#39P	47	1.71	0.04	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	66.37	5.58	0.08

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390 **Table 6** Density and percentage drainage at 5, 10, 15 and 180 minutes for foams produced with air pressure value equal to 3.5 bar and for different Foamin
 391 C[®] foaming agent concentrations.

Foaming agent concentr. [%]	n° series	Av. density	St. dev.	CoV	Av. drain. 5 min.	St. Dev.	CoV	Av. drain. 10 min.	St. dev.	CoV	Av. drain. 15 min.	St. dev.	CoV	Av. drain. 180 min.	St. dev.	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$	D_{180} [%]	$\sigma_{D_{180}}$ [%]	$CoV_{D_{180}}$
2	#40P	83	5.12	0.06	0.00	0.00	-	5.62	2.48	0.44	-	-	-	-	-	-
	#41P	82	2.96	0.04	-	-	-	-	-	-	18.83	2.91	0.15	-	-	-
3	#42P	59	0.86	0.01	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	74.76	0.91	0.01
4	#43P	46	2.20	0.05	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	67.77	2.03	0.03
5	#44P	44	2.42	0.05	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	59.83	1.11	0.02

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 393 **Table 7** Density and percentage drainage at 5, 10, 15 and 180 minutes for foams produced with air pressure value equal to 4 bar and for different Foamin C[®]
 394 foaming agent concentrations.

Foaming agent concentr. [%]	n° series	Av. density	St. dev.	CoV	Av. drain. 5 min.	St. Dev.	CoV	Av. drain. 10 min.	St. dev.	CoV	Av. drain. 15 min.	St. dev.	CoV	Av. drain. 180 min.	St. dev.	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$	D_{180} [%]	$\sigma_{D_{180}}$ [%]	$CoV_{D_{180}}$
2	#45P	78	2.28	0.03	0.00	0.00	-	6.82	0.77	0.12	-	-	-	-	-	-
	#46P	75	1.94	0.02	-	-	-	-	-	-	13.42	1.81	0.13	-	-	-
3	#47P	47	1.32	0.03	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	70.38	1.78	0.02
4	#48P	46	0.14	0.00	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	67.31	3.33	0.05
5	#49P	47	0.97	0.00	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	69.27	1.90	0.03

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396 **Table 8** Density and percentage drainage at 5, 10, 15 and 180 minutes for foams produced with air pressure value equal to 4.5 bar and for different Foamin
 397 C[®] foaming agent concentrations.

Foaming agent concentr. [%]	n° series	Av. density	St. dev.	CoV	Av. drain. 5 min.	St. Dev.	CoV	Av. drain. 10 min.	St. dev.	CoV	Av. drain. 15 min.	St. dev.	CoV	Av. drain. 180 min.	St. dev.	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$	D_{180} [%]	$\sigma_{D_{180}}$ [%]	$CoV_{D_{180}}$
2	#50P	77	4.48	0.06	0.00	0.00	-	2.48	1.49	0.60	-	-	-	-	-	-
	#51P	75	5.31	0.07	-	-	-	-	-	-	12.75	5.75	0.45	-	-	-
3	#52P	55	2.20	0.04	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	71.13	1.88	0.03
4	#53P	46	1.70	0.04	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	67.24	1.19	0.02
5	#54P	46	0.34	0.01	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	64.32	2.43	0.04

398 **Table 9** Density and percentage drainage at 5, 10, 15 and 180 minutes for foams produced with air pressure value equal to 5 bar and for different Foamin C[®]
 399 foaming agent concentrations.
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Foaming agent concentr. [%]	n° series	Av. density	St. dev.	CoV	Av. drain. 5 min.	St. Dev.	CoV	Av. drain. 10 min.	St. dev.	CoV	Av. drain. 15 min.	St. dev.	CoV	Av. drain. 180 min.	St. dev.	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$	D_{180} [%]	$\sigma_{D_{180}}$ [%]	$CoV_{D_{180}}$
2	#55P	73	2.21	0.03	0.00	0.00	-	1.52	0.61	0.40	-	-	-	-	-	-
	#56P	71	1.89	0.03	-	-	-	-	-	-	11.88	1.46	0.12	-	-	-
3	#57P	54	3.27	0.06	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	67.55	1.08	0.02
4	#58P	50	2.01	0.04	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	67.98	1.97	0.03
5	#59P	35	0.88	0.00	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-	64.92	5.05	0.08

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Table 10 Density and percentage drainage at 5, 10 and 15 minutes for foams produced with 4% SLS synthetic foaming agent concentration and for different air pressure values.

Air pressure [bar]	n° series	Av. density	St. dev.	CoV	Av. drain. 5 min.	St. Dev.	CoV	Av. drain. 10 min.	St. dev.	CoV	Av. drain. 15 min.	St. dev.	CoV
		γ [g/l]	σ_γ [g/l]	CoV_γ	D_5 [%]	σ_{D_5} [%]	CoV_{D_5}	D_{10} [%]	$\sigma_{D_{10}}$ [%]	$CoV_{D_{10}}$	D_{15} [%]	$\sigma_{D_{15}}$ [%]	$CoV_{D_{15}}$
2	#1S	61	7.36	0.12	40.90	13.80	0.34	-	-	-	-	-	-
	#2S	64	5.94	0.09	-	-	-	67.85	7.71	0.11	-	-	-
	#3S	63	6.29	0.10	-	-	-	-	-	-	77.17	5.86	0.08
2,5	#4S	40	3.94	0.10	22.10	2.82	0.13	-	-	-	-	-	-
	#5S	43	2.83	0.06	-	-	-	52.36	0.90	0.02	-	-	-
	#6S	42	4.24	0.10	-	-	-	-	-	-	64.88	1.15	0.02
3	#7S	33	1.95	0.06	20.30	1.33	0.07	-	-	-	-	-	-
	#8S	34	2.64	0.08	-	-	-	47.82	1.69	0.03	-	-	-
	#9S	32	2.52	0.08	-	-	-	-	-	-	61.41	2.13	0.03
3,5	#10S	34	2.83	0.08	14.33	4.27	0.30	-	-	-	-	-	-
	#11S	32	3.39	0.10	-	-	-	46.39	1.89	0.04	-	-	-
	#12S	33	3.53	0.10	-	-	-	-	-	-	60.74	1.78	0.03
4	#13S	31	4.34	0.14	2.72	3.26	1.20	-	-	-	-	-	-
	#14S	32	1.98	0.06	-	-	-	39.83	4.28	0.11	-	-	-
	#15S	30	3.46	0.11	-	-	-	-	-	-	56.50	3.03	0.05
4,5	#16S	34	2.41	0.07	18.34	2.18	0.12	-	-	-	-	-	-
	#17S	33	3.25	0.10	-	-	-	47.69	2.03	0.04	-	-	-
	#18S	34	3.39	0.10	-	-	-	-	-	-	63.52	2.71	0.04
5	#19S	32	4.66	0.14	11.32	6.59	0.58	-	-	-	-	-	-
	#20S	33	3.39	0.10	-	-	-	45.06	8.69	0.19	-	-	-
	#21S	32	2.82	0.09	-	-	-	-	-	-	56.27	8.10	0.14

410 Considering density, Figure 5 shows that all trends have a well-defined slope in
411 correspondence of the air pressure value of 2.5 bar, even if this property is highly variable for
412 air pressure values lower than 2.5 bar. There is no further significant reduction in foam
413 density if air pressure values increase among all the protein foaming agent concentrations
414 investigated (Figure 5 b). Furthermore, for fixed air pressure value, Figure 5 a) highlights that
415 the increase in the protein foaming agent concentration from 2% to 3% leads to a significant
416 reduction, of about 30%, in foam density, while a further increase in the Foamin C[®]
417 concentration up to 5% leads to negligible variations in the density of the foams produced.

418 Based on the experimental evidence, the reduction of the foam density and the limitation
419 of the drainage in short to medium time, so the increase in foams' lifetime, can be obtained in
420 two different ways: 1) by increasing the air pressure values up to 2.5÷3 bar for fixed
421 concentration of the foaming agent, as it can be seen in Figure 4 a), b) and c) and Figure 5 a);
422 2) by increasing the foaming agent concentration up to 3÷4% for fixed air pressure value, as
423 it is shown in Figure 4 a), b) and c) and Figure 5 b). Strategy 1) improves the quality of the
424 foams thanks to the better turbulent flow conditions inside the mixing tube of the generator,
425 while strategy 2) enhances the quality of the foams due to a greater quantity of surfactant
426 molecules, which give a better stability to foams by diffusing them to the interfaces.
427 Furthermore, the increase in air pressure and foaming agent concentration beyond the values
428 previously reported indicates completely negligible changes in the properties of the foams. In
429 fact, higher air pressure values negatively influence the correct flow of the water-surfactant
430 solution and its subsequent expansion inside the mixing chamber as it is evident because the
431 foams leave the generator in a discontinuous and intermittent way; moreover, higher
432 concentrations of foaming agents do not cause further improvements in the quality of the
433 foams since, a further increase in the foaming agent concentration does not correspond to a
434 further lowering of the surface tension beyond a specific value called critical micellar

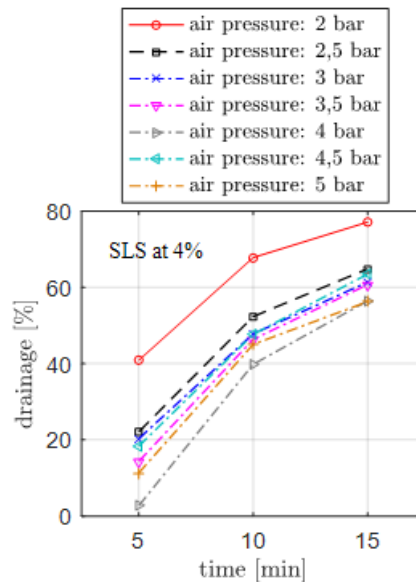
435 concentration, but to an increase of particular surfactant molecules configurations called
436 micelle [18].

437 As a consequence, all foams produced with a Foamin C[®] protein foaming agent
438 concentration equal to or greater than 3% and air pressure values equal to or greater than 2.5
439 bar are characterized by excellent properties in terms of percentage drainage within 15
440 minutes and a good repeatability of the obtained results. The last characteristic is fundamental
441 to be achieved in the field of foams for foamed concrete just thinking that a small change in
442 the density of the foams produced greatly affects the mix design of the concrete conglomerate
443 to be adopted.

444 To better understand the behaviour of the foams produced in case of significant rest time
445 too, the percentage values of the drainage at 180 minutes (at which cementitious
446 conglomerates generally entered the setting phase) was also evaluated for the best foaming
447 agent concentrations and air pressure values. Results are shown in Figure 4 d); it is evident
448 that the 180 minutes percentage drainage is characterized by very high values for all the
449 samples, so it is possible to conclude that neither the increase in the air pressure values nor
450 the same in protein foaming agent concentrations cause an improvement in the resistance to
451 drainage of the foams. A change of these factors does not affect the long-term percentage
452 drainage of the foams. For such a long rest time, the reduction of drainage and an increase in
453 foams' lifetime can be obtained only by means of suitable chemical modifications of the
454 foaming agent or by increasing the viscosity of the fluid phase due to an introduction of
455 proper viscosity modifying agents [24].

456 Figure 6 shows the influence of air pressure values on percentage drainage at selected time
457 intervals for foams generated with SLS synthetic foaming agent at a concentration of 4%. In
458 this case as well, the results indicate that an increase in air pressure values generally leads to
459 a decrease in the percentage drainage for all the samples. This reduction is greater for air

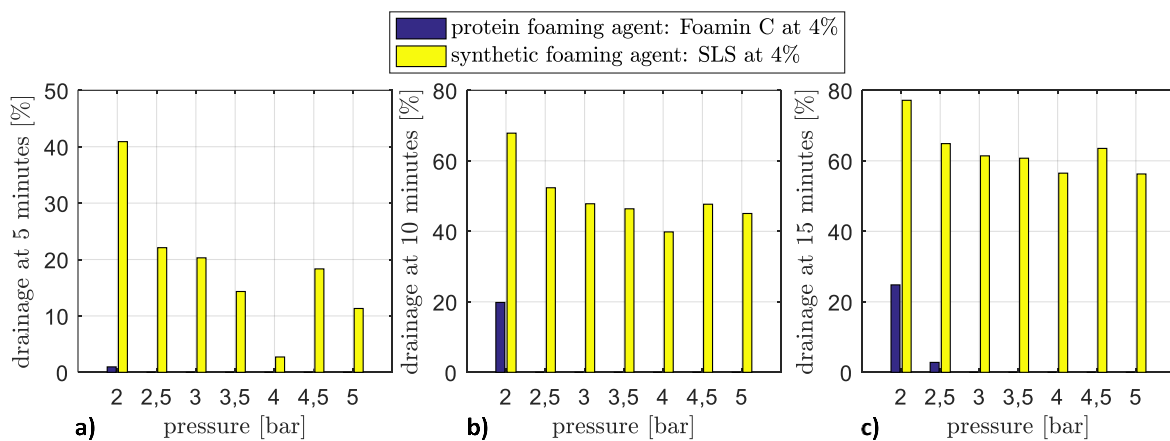
460 pressure values passing from 2 bar to 2.5 bar and it gradually becomes less evident for
461 subsequent increases in air pressure. The minimum percentage drainage is recorded for air
462 pressure value equal to 4 bar in all selected time intervals.



463 **Figure 6** Influence of air pressure value on drainage at selected time intervals of foams produced with
464 4% concentration SLS synthetic foaming agent.

465 The comparison between this condition and the percentage drainages at the same selected
466 time intervals of the foams produced with Foamin C[®] protein foaming agent at the same
467 concentration of 4% allows to frame the substantial differences of foams' lifetimes produced
468 with foaming agents having different nature, as it is evident in Figure 7. In all cases, the
469 percentage drainage of foams produced with synthetic foaming agent is vastly higher than
470 that of foams generated by means of protein foaming agent. As previously discussed, the last
471 foams have a percentage drainage at a concentration of 4% of protein foaming agent always
472 equal to zero, except for the lowest air pressure values. On the contrary, foams generated with
473 SLS synthetic foaming agent are characterized by a poor drainage resistance, even in case of
474 rest time of only 5 minutes. The justification of this different behaviour lies in the greater
475 stabilizing effect due to the presence of proteins: these macromolecules confer viscoelasticity
476 properties to the thin film between the air bubbles, thus contributing to their stiffening. In

477 particular, the molecular structure of the proteins is much more complex than the same of
 478 SLS synthetic surfactants (characterized by a low molecular weight) and this characteristic
 479 influences the way in which proteins are adsorbed at the interfaces: the different
 480 configurations can be distinguished in train, loop and tails [29]. The more complex the
 481 structure configuration of the protein molecules, the greater the reduction of foam drainage is,
 482 significantly increasing the lifetime of the system. This behaviour leads to a reduction in
 483 drainage speed phenomena and, consequently, in an increase of foams' lifetime as a
 484 consequence.

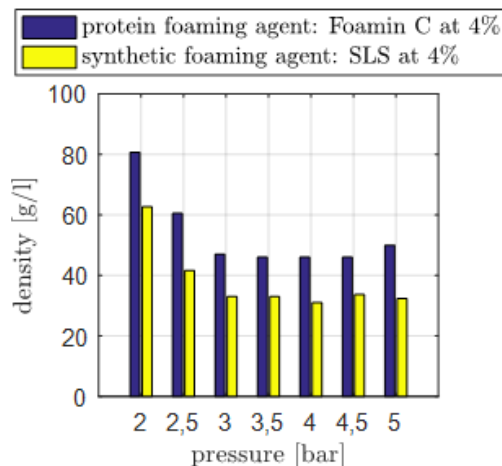


485 **Figure 7** Comparative histograms between the drainages of foams produced with Foamin C[®] protein
 486 foaming agent and SLS synthetic foaming agent for different air pressure values and at selected time
 487 intervals: 5 minutes a); 10 minutes b); 15 minutes c).

488 However, structure configuration also affects the bubbling capacity of a foaming agent,
 489 i.e. its ability to form large volumes of foam. From this point of view, the more complex the
 490 structure configuration, the lower the bubbling ability of the foaming agent is. Furthermore,
 491 foaming agents capable of generating high volumes of foam in a short time, are generally
 492 marked by a poor stability and a reduced lifetime, while the opposite is true for foaming
 493 agents with lower foaming ability [29]. This means a lower density of the foams generated
 494 using the synthetic foaming agent SLS compared to that of the foams produced with the
 495 protein foaming agent Foamin C[®], as it is clear from the analysis of Figure 8. Indeed, the

496 foams generated with the synthetic foaming agent are generally characterized by a decreasing
497 density of about 30% compared to the foams produced with an equal concentration of the
498 protein foaming agent: SLS is characterized by a greater foaming ability compared to Foamin
499 C[®]. This behavior is caused by the presence of the macromolecules in the protein surfactant;
500 in fact, they both contribute to reducing drainage and they are characterized by lower rates of
501 diffusion, adsorption and reorientation at the interfaces [30].

502 It is interesting to mention that an increase in air pressure above 3 bar does not lead to a
503 further decrease in the density of the foams produced, despite the different nature of the
504 foaming agent. As previously discussed, this is due to the optimization of the turbulent flow
505 in the mixing tube in correspondence of an air pressure value of about 3 bar, while a further
506 increase in air pressure leads to a foam obtained in a discontinuous and intermittent way.



507 **Figure 8** Comparative histograms between the density of foams produced with Foamin C[®] protein
508 foaming agent and SLS synthetic foaming agent for different air pressure values.

509 Given these results, it was decided not to extend the experimental campaign to other
510 concentrations of synthetic surfactants. however, in order to extend the understanding of
511 foamed concrete properties to foams with such different properties, the properties of foamed
512 concrete produced with foams generated with the SLS synthetic foaming agent will be also
513 studied in the following section: they will be compared to the properties of concretes made
514 using foams generated with the protein foaming agent Foamin C[®]. Unlike what might be

515 expected, despite the very significant drainage value at very short time intervals of synthetic
516 foams, the corresponding foamed concrete will not be characterized by instability.

517 **5. INVESTIGATION ON FOAMED CONCRETE PROPERTIES**

518 **5.1. Materials, specimen preparation and testing conditions**

519 Foams characterized by the best properties are used to produce foamed concrete samples
520 to evaluate their behavior after being mixed with cementitious paste, but also their influence
521 on the compressive strength of this lightweight material. With regard to the protein foaming
522 agent, the foams were produced with a Foamin C[®] concentration and an air pressure value of
523 3% and 3 bar respectively, in order to obtain acceptable repeatability and a good quality in
524 terms of lifetime. Furthermore, for a specific set of samples, it has been used foams generated
525 with an air pressure value of 3 bar, but with a protein foaming agent concentration of 5%.
526 Despite the poor quality in terms of drainage resistance manifested by foams generated with
527 synthetic foaming agents, this type of foam has also been used to produce foamed concrete in
528 order to widen this research field. Therefore, foamed concrete was also prepared using foams
529 generated with SLS synthetic foaming agents at a concentration of 4% and an air pressure
530 value of 3.5 bar.

531 In compliance with UNI EN 197-1 standard at the constituent proportion CEM I 52.5R
532 was used, while a water to cement ratio equal to 0.3 was selected. Three different target dry
533 densities were analyzed, namely 400 ± 50 kg/m³ (ultra-lightweight foamed concrete) 600 ± 50
534 kg/m³ and 800 ± 50 kg/m³ (lightweight foamed concrete). In addition, only in case of foams
535 generated with the protein foaming agent, the effect of the concentration (3% or 5%) of
536 protein foaming agent used for generating the foams on the compressive strength of ultra-
537 lightweight (400 ± 50 kg/m³) and lightweight (800 ± 50 kg/m³) foamed concrete was also
538 analyzed.

539 Foamed concrete paste was prepared according to the following steps: 1) mixing the
 540 correct amount of cement and water for about 1 minute; 2) foam generation; 3) gradual
 541 addition of the selected quantity of foam to the cementitious paste and contextual mixing for
 542 about 2 minutes or until a homogeneous lightweight paste is obtained. A vertical mixer with a
 543 mixing intensity of 1200 rpm was employed. The quantity of the constituent materials is
 544 selected on the basis of the mix proportion reported in Table 11. Specimens labeled #1.1 and
 545 #3.1 were prepared with a concentration of Foamin C[®] in the preformed foam equal to 5%,
 546 useful to highlight the possible influence of the foaming agent concentration on the
 547 compressive strength of the foamed concrete.

548 **Table 11** Mix design of foamed concrete

Foaming agent	series no.	Mix design					
		fresh density	cement	water	foam	ratio 1	ratio 2
		γ_f [kg/m ³]	c [kg/m ³]	w [kg/m ³]	f [kg/m ³]	w/c	f/c
FOAMIN C	#1	496	370	149	138	0.3	0.37
	#1.1 ¹	503	373	151	131	0.3	0.35
	#2	723	535	160	139	0.3	0.26
	#3	975	775	232	124	0.3	0.16
	#3.1 ¹	968	768	230	115	0.3	0.15
SLS	#4	513	379	114	76	0.3	0.20
	#5	731	540	162	70	0.3	0.13
	#6	953	765	229	61	0.3	0.08

549 ¹ Preformed foam prepared with a Foamin C[®] concentration equal to 5% (3% in other specimens).

550 Three cubic specimens of 5 cm side for each series were prepared. The choice to evaluate
 551 the compressive strength of the material by means of cubic specimens is not only due to save
 552 materials, but it is also justified by: 1) ASTM C109 standard; 2) absence of aggregate; 3)
 553 more conservative results (i.e. lower compressive strength) than 10 cm and 15 cm side cubic
 554 specimens, according to experimental results reported in [31].

555 After 48 hours, specimens were demoulded, wrapped in cellophane sheets (a typical
 556 strategy in the precast industry of foamed concrete artefacts [32]), then kept in laboratory
 557 conditions at environmental temperature of 20±3°C and relative humidity of 65÷70%. The 28

558 days compressive strength was assessed using a Controls test frame with a load capacity of
559 250 kN, in force-controlled mode (loading rate equal to 1000 N/s). As usually done in
560 foamed concrete field [33], [34], the dry density γ_{dry} was also evaluated after compression
561 tests, drying the samples in an oven at $105\pm 5^\circ\text{C}$ for at least 48 hours or until a constant
562 weight is reached.

563 **5.2. Results and discussion**

564 This section reports the results in terms of compressive strength of foamed concrete
565 specimens and the analysis concerning the properties of the different samples corresponding
566 to the foams generated with different foaming agents.

567 Table 11 clearly indicates that the increase in density leads to a decrease in the amount of
568 foam and in the f/c ratio consequently. However, in order to obtain the same target density,
569 the required amount of foam generated with the Foamin C[®] protein foaming agent is
570 interestingly much greater than the one produced with the SLS synthetic foaming agents,
571 approximately double. This behavior has been also observed in [35] and it can now be
572 justified through the results obtained from the investigation on the properties of the foams.
573 Indeed, the foams generated with SLS are characterized by lower densities and greater
574 foaming ability; in other terms, a smaller amount of this type of foam is sufficient to reach a
575 certain density. However, this is not enough to justify this remarkable difference. In fact, it is
576 necessary to add the different behavior of the two types of foams during the first moments of
577 the mixing phase with the cementitious paste. In case of foams generated with SLS, during
578 the mixing phase with a cement paste with a low w/c ratio, there is a macroscopic
579 flocculation of the cement particles probably due to the non-optimal interaction of the SLS
580 molecules with cement particles, which tend to agglomerate rather than dispersing. This
581 agglomeration causes a consistent decrease in the specific surface area and, consequently,

582 leads to a lower amount of foam to reach a target density. This behavior is emphasized by
583 low w/c ratios and it could be limited by increasing the distance between the cement particles
584 before introducing the foam; for example, an effective method could be to increase the fluid
585 phase of the cementitious paste. This may explain the significant increase in the compressive
586 strength of foamed concrete with the increase of w/c ratio evidenced in [36] for another type
587 of synthetic foaming agent.

588 On the contrary, if foams are generated with the protein foaming agent, there is a greater
589 affinity between surfactant molecules and cement particles. This allows a de-flocculation of
590 the cement particles, leading to a more homogeneous paste without creating cement lumps.
591 However, the adsorption of the foaming agent molecules on the surface of the cement
592 particles [37], much greater compared to the previous case where macroscopic flocculation
593 occurred, causes a significant reduction in the amount of surfactant molecules free to stabilize
594 the system by diffusion [18] during the mixing phase. In case of high-consistency
595 cementitious paste (i. e. with a low w/c ratio), where a substantial amount of surfactant
596 molecules is needed to confer the proper viscoelasticity properties to the thin film, it leads to
597 the collapse of the air bubbles introduced into the cementitious system with the first
598 introduction of foam. In other words, a certain amount of foams initially introduced into the
599 cementitious paste collapses during the mixing phase without an appreciable reduction in the
600 density of the system. However, this leads to an increase in the amount of surfactant
601 molecules inside the system allowing the incorporation of the air bubbles introduced with the
602 subsequent quantities of foams. The foregoing explanations also clarifies the slightly smaller
603 amount of foam in case of protein foaming agent concentration equal to 5% compared to 3%,
604 as it can be seen in Table 12. Obviously, this behavior causes an increase in the f/c ratio,
605 consequently in the fluid phase of the system if foamed concrete is produced with foams
606 generated with protein foaming agents.

607 Another interesting result is the lack of instability phenomena. Although this could be
608 expected for specimens prepared with foams generated with protein foaming agents, it was
609 certainly less predictable for the samples produced with foams generated using SLS foaming
610 agents due to the high drainage values even for short time intervals, as illustrated before. This
611 behavior is due to a crucial property of the fresh cementitious paste, namely the thixotropy: at
612 rest, a cementitious paste tends to build an internal network increasing its consistency with
613 the increase in rest time [38], [39]. The internal structure, gradually resistant due to the
614 progress of the flocculation and structuration processes [38], stabilizes the cementitious
615 system at rest thanks to the choice of a rapid cement with high mechanical performance
616 (CEM I 52.5 R),. Therefore, these results indicate that foams characterized by very high
617 drainage values at short time intervals do not necessarily lead to unstable foamed concrete.

618 Flocculation and structuration also explain another interesting phenomenon, which could
619 generally affects foamed concrete at the fresh state: the possible slight instability of the
620 system in case of a resumption of the mixing phase after an even limited period at rest; this
621 phenomenon could lead to an increase in final density of the material compared to what was
622 planned. In fact, during these phases, nucleation of hydrates occurs [38] and dispersed
623 surfactant molecules will tend to be adsorbed on the surfaces of these new products [40]; in
624 case of a new external disturbance (for example, the resumption of mixing phase) the amount
625 of surfactant molecules free to stabilize the system by diffusion [18] may not be sufficient
626 resulting in an increase in the density of the system.

627 Regarding the compressive strength of hardened foamed concrete, the results are reported
628 in Table 12 for lightweight and ultra-lightweight foamed concretes prepared with the foams
629 generated using the two different foaming agents and for lightweight and ultra-lightweight
630 foamed concretes prepared with the foams generated with two different concentration of
631 Foamin C® (3% and 5%).

632 **Table 12** Dry density and compressive strength of foamed concrete

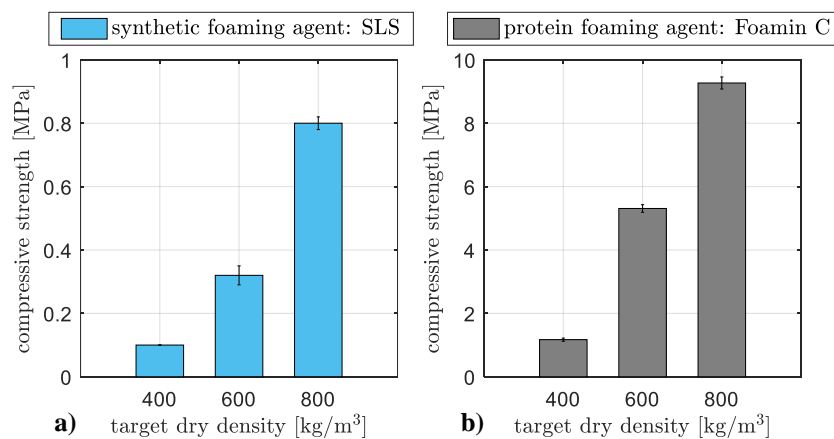
foaming agent	series no.	mean dry density	st. dev. dry density	COV dry density	mean compres. strength	st. dev. strength	COV strength
		γ_{dry} [kg/m ³]	$\sigma_{\gamma_{dry}}$ [kg/m ³]	$COV_{\gamma_{dry}}$	R_c [MPa]	σ_{R_c} [MPa]	COV_{R_c}
Foamin C	#1	403	12	0.03	1.17	0.05	0.04
	#1.1 ¹	408	16	0.04	1.87	0.05	0.02
	#2	605	12	0.02	5.31	0.12	0.02
	#3	816	16	0.02	9.27	0.19	0.02
	#3.1 ¹	808	11	0.01	9.61	0.20	0.02
SLS	#4	407	14	0.03	<0.1	-	-
	#5	611	17	0.03	0.32	0.03	0.09
	#6	803	20	0.02	0.80	0.02	0.03

633 ¹ Preformed foam prepared with a Foamin C[®] concentration equal to 5% (3% in other specimens).

634 The comparison between foamed concretes with the same target dry density but produced
635 with foaming agents of different nature shows significant differences at the fresh state, which
636 lead to very significant differences in terms of compressive strength. In fact, apart from the
637 obvious consideration that the compressive strength increase significantly with increasing
638 density, true for both foaming agents, the use of the protein foaming agent gives rise to a
639 remarkable increase in the compressive strength of the foamed concrete by approximately
640 1070%, 1550% and 1050% for a target dry density of 400 kg/m³, 600 kg/m³ and 800 kg/m³
641 respectively (Figure 9). These results are in line with another experimental campaign reported
642 in [35] and, in addition to the justifications reported therein, based above all on the mutual
643 influence of the air to cement ratio and water to cement ratio on the compressive strength. In
644 fact, for low density foamed concretes it may be possible to detect an increase in compressive
645 strength with the increase of the fluid phase [41], greater in the case of foamed concretes
646 prepared with foams generated using protein foaming agent. This is probably due to the
647 greater quantity of foam compared to the case of synthetic foaming agent and the explanation
648 of the different behaviour at the fresh state between the two different types of foams reported
649 here helps to better justify this important finding. The macroscopic flocculation of the cement
650 particles caused by the addition of the foam generated with SLS adversely affects the degree
651 of hydration of the cement leading to poor mechanical performance. On the contrary, the de-

652 flocculating action on the cement particles of the first protein foam added to the cementitious
 653 paste leads to excellent compressive strength values, which are quite in line with the
 654 experimental results of relevant literature. In fact, for example, in [42] the compressive
 655 strengths of the foamed concretes prepared with a protein foaming agent are approximately
 656 equal to 2.5 MPa, 4.9 MPa and 6.9 MPa for target dry densities of about 500 kg/m³, 600
 657 kg/m³ and 700 kg/m³, respectively. In [43] the compressive strengths of foamed concretes
 658 characterized by a plastic density of 500 kg/m³ and produced with a protein foaming agent
 659 are in the order of 0.3 MPa.

660 These results highlight the importance of the foaming agent used developing the
 661 knowledge discussed in [35] and [44] and it may explain the substantial differences in terms
 662 of mechanical properties that characterize the foamed concrete produced in different parts of
 663 the world; in fact, as any other raw material, it is common practise to use the foaming agents
 664 more readily available in a given area.



665 **Figure 9** Compressive strength of ultra-lightweight (400 kg/m³) and lightweight (600 kg/m³, 800
 666 kg/m³) foamed concrete produced with foams generated using the synthetic foaming agent SLS (a)
 667 and the protein foaming agent Foamin C[®] (b).

668 Due to the very low mechanical strength of the foamed concrete produced using the SLS
 669 foaming agent, the study on the possible influence of the foaming agent concentration in the
 670 preformed foam on the compressive strength of the foamed concretes was carried out only

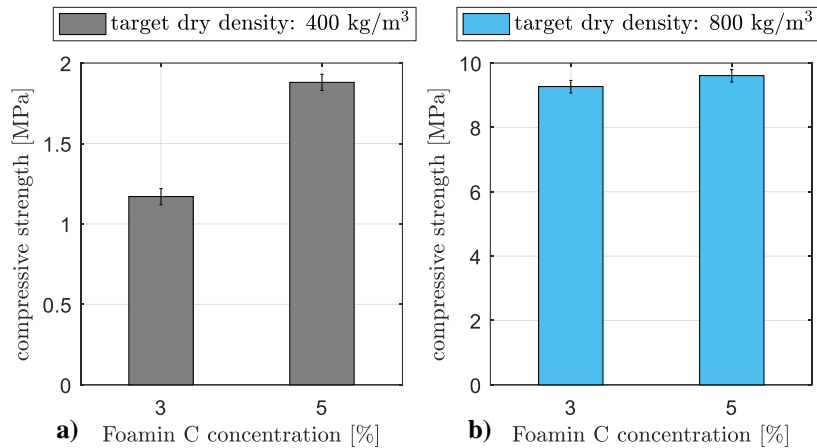
671 with foams generated with the protein foaming agent. Two additional series of foamed
672 concrete were prepared, labelled #1.1 and #3.1 in Table 11 and Table 12, to investigate the
673 possible influence of the protein foaming agent concentration on the compressive strength of
674 the material.

675 As depicted in Figure 10, the increment in the concentration of Foamin C[®] from 3% to 5%
676 leads to an increase in the compressive strength of the ultra-lightweight foamed concretes of
677 about 60%, despite the increase in the Foamin C[®] concentration has not led to appreciable
678 variations in the properties of the foams produced, as demonstrated in the previous section.

679 This trend is confirmed in the case of lightweight foamed concrete characterized by a
680 target dry density of 800 kg/m³, although the increase in the compressive strength is
681 significantly reduced, reaching 4%.

682 This interesting result can be explained by the following considerations. A greater amount
683 of foaming agent molecules introduced into the cementitious paste allows to obtain a more
684 homogeneous distribution of the air bubble in the system. In fact, in case of a lower amount
685 of surfactant molecules, some air bubbles tend to coalesce forming bubbles with larger
686 diameters; the presence of a greater amount of free surfactant molecules substantially reduced
687 this phenomenon, as in case of a concentration of foaming agent equal to 5%. The result is a
688 more homogeneous distribution of the dimensions of air bubbles in the system or, in other
689 words, the presence of larger diameter air bubbles drastically reduced.

690 Furthermore, the effect of the foaming agent concentration on the compressive strength is
691 much greater in the case of ultra-lightweight foamed concrete compared to the lightweight
692 one because the lower the density of the foamed concrete, the greater the average diameter of
693 the bubbles and the greater the possible presence of macro-bubbles [45]. Both of these
694 conditions emphasize the previously explained beneficial effect due to a higher concentration
695 of foaming agent.



697 **Figure 10** Comparative histogram between the compressive strength of foamed concrete, with target
 698 dry density equal to 400 kg/m^3 (a) and 800 kg/m^3 (b) produced with foams generated using the protein
 699 foaming agent (Foamin C[®]) at different concentrations.

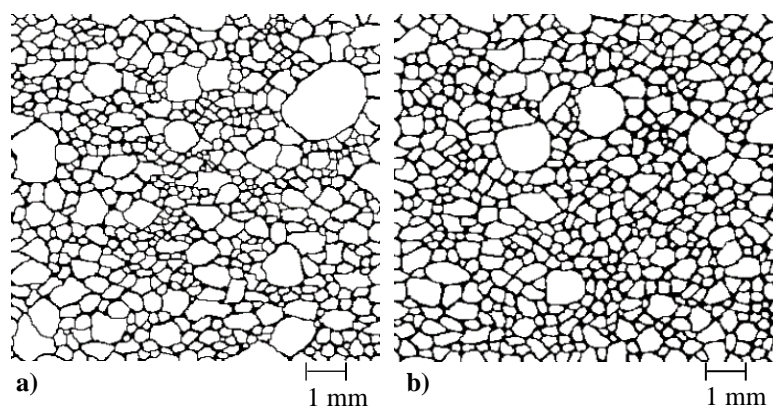
700 This interpretation is corroborated by the evaluation of the distribution of air bubbles
 701 diameters in the two cases, according to [45].

702 Figure 11 shows two representative binary images related to the cross section of two
 703 foamed concrete specimens characterized by a target dry density of 400 kg/m^3 and a
 704 concentration of the protein foaming agent in the preformed foam equal to 3%, Figure 11, a),
 705 and 5%, Figure 11, b), respectively.

706 Indeed, by indicating with D50 the equivalent diameter that represents the median of the
 707 cumulative frequency distribution and with D90 the equivalent diameter that is overcome
 708 only in 10% of the cases, the image analyzes showed that increasing the foaming agent
 709 concentration from 3% to 5% leads to negligible differences in terms of D50, but also in an
 710 appreciable reduction of about 11% in D90 in the case of ultra-lightweight foamed concrete
 711 with a target dry density of 400 kg/m^3 . On the other hand, in the case of foamed concrete with
 712 a target dry density of 800 kg/m^3 , also the reduction in D90 is negligible.

713

714



715 **Figure 11** Representative binary images of the cross section of two foamed concrete specimens with
 716 the same target dry density of 400 kg/m^3 but produced with two different concentration of the protein
 717 foaming agent in the preformed foam: 3% (a), 5% (b).

718

719 Therefore, especially at lower densities, a more homogeneous distribution of air bubbles
 720 diameters together with the reduction of larger diameter air bubbles lead to an improvement
 721 in the compressive strength of ultra-lightweight foamed concretes [46]. In addition to this, a
 722 greater amount of surfactant molecules, can also improve the stability of the system in case of
 723 need to resume the mixing phase of fresh foamed concrete paste after a certain period at rest
 724 due to a higher concentration of foaming agent in the foam.

725 6. CONCLUSIONS

726 This paper has presented an analysis on the characteristics of foamed concretes starting
 727 from the foam generation up to the compressive strength of the lightweight cementitious
 728 material. After a short introduction focused on the basic concepts of foams' stability, the
 729 design of an optimized simple and inexpensive foam generator has been presented because it
 730 allows to obtain excellent quality foams in various possible working conditions..
 731 Investigations on the properties of the foams generated using two different foaming agents,
 732 namely the protein Foamin C[®] and the synthetic SLS, have shown that: 1) the percentage
 733 drainage and the density of the protein foams can be reduced either by increasing the foaming

734 agent concentration or by increasing air pressure value up to 3% and 3 bar respectively; a
735 further increase in these parameters does not lead to appreciable variations in the foams
736 properties; 2) long-term (180 minutes) percentage drainage cannot be reduced simply by
737 changing these parameters; 3) due to the absence of macromolecules that hinder the drainage,
738 this one is very high even for short time intervals after the foam generation in case of the
739 synthetic foaming agents; 4) in case of synthetic foaming agents too, further increase of the
740 air pressure value beyond 3 bar does not lead to further decrease in the density of the foams;
741 5) the SLS foaming agent is characterized by a higher foaming ability than the Foamin C[®]:
742 the foams produced with the former foaming agent are characterized by an average decrease
743 in the density of approximately 30% compared to the corresponding ones generated with the
744 protein foaming agent.

745 The foams with the best properties have been used to produce lightweight and ultra-
746 lightweight foamed concretes (with a target dry density of 400 kg/m³ and 600 kg/m³). This
747 investigation showed a decidedly marked behavior of the foams generated with the two
748 different foaming agents when mixed with the cementitious paste. This different behavior
749 ascribed to the different interactions between the protein and synthetic surfactant molecules
750 with the cement particles is crucial to understand the enormous differences in terms of
751 compressive strength of the foamed concrete produced with different foaming agents used to
752 generate the foams (in case of Foamin C[®] there is an average increase in the 28 days
753 compressive strength of about 1070%, 1550% and 1050% for a target dry density of 400
754 kg/m³, 600 kg/m³ and 800 kg/m³ respectively). These considerations allow to better
755 understand the different properties of foamed concretes when foams have been generated
756 with protein or synthetic foaming agents. Furthermore, the results showed that the
757 corresponding foamed concretes have not shown instability phenomena, despite the very high
758 short-term drainage of the foams generated with SLS.

759 In addition, it is interesting to notice that an increase in the protein foaming agent
760 concentration from 3% to 5% leads to an increase of approximately 60% in the compressive
761 strength of ultra-lightweight foamed concretes (target dry density equal to 400 kg/m³) thanks
762 to a more homogeneous distribution of the size of the air bubbles in the system. Therefore,
763 higher foaming agent concentrations are desirable to improve mechanical performance and
764 stability in case of a resume of the mixing phase in the fresh state for ultra-lightweight
765 foamed concretes. This increase in the compressive strength is less marked (approximately
766 4%) in the case of foamed concrete characterized by a target dry density of 800 kg/m³. In this
767 case, an increase in the foaming agent concentration in the foam does not lead to appreciable
768 differences in the distribution of the air bubbles diameters within the foamed concrete
769 specimens.

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774

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