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

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

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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/m^3 and 800 kg/m^3) and ultra-lightweight (target dry density of 400 kg/m^3) 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.

1. INTRODUCTION

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

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

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

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

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

For this reason this research paper will focus firstly on an optimized foam generator, then on the characterization of the properties of foams produced with different foaming agents (i.e. protein and synthetic) and finally on the assessment of the experimental results based on the foam stability theory. The foams obtained will be employed to generate some foamed concrete samples, whose characteristics will be combined with the properties of the corresponding foams to explain their relevant differences in terms of compressive strength. This allows to add new details to the actual knowledge of technical literature, in particular with reference to the significantly different behavior of foams generated with protein and synthetic foaming agents in the case of low *w/c* ratios. Furthermore, the study allows to highlight the influence of the increase of protein foaming agents' concentration on compressive strength of ultra-lightweight foamed concretes, although this increase does not show appreciable differences in the properties of the foams themselves.

2. FOAM STABILITY

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

In order to obtain a more stable colloidal system, surface tension value is usually reduced. From a thermodynamic point of view, it can be defined as the work per unit of area required to create a new surface [18] and it depends on the greater or lesser inclination of the colloidal system's phases to modify their structure in correspondence with the interphasic region. To reach this aim, surfactants must be used. The amphiphilic structure of these molecules promotes their adsorption at the interface, also determining a preferential orientation characterized by the arrangement of the hydrophobic tail towards the gas and the hydrophilic head in contact with the aqueous phase [19].

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

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

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

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

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

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

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

3. A SIMPLE AND OPTIMIZED FOAM GENERATOR

There are many strategies for making foam from a solution containing foaming agents: mechanical stirring, emission of pressurized air through a nozzle, suitable chemical reactions and so on. All these strategies have the common objective of introducing a gas (generally air) in a liquid solution. Due to their simplicity and cost-effectiveness, the most conventional ways to produce foams are certainly mechanical stirring with a high speed vertical mixer and the use of a proper foam generator. The latter should be preferred because it allows to better control all the parameters that come into play in the generation of a foam. Actually, a key factor which significantly affects the quality of the foams in terms of bubble size, viscosity and overall system stability, is the energy supplied to the system at this stage. It has been shown that an increase factor of 3.3 in the mixing speed leads to a reduction of the bubble size of about 4.5 times, but it also increases stability and viscosity of approximately 100% [28]. Therefore, an appropriate foam generator must be able to produce foam through a turbulent flow with high shear stresses. It is useful to highlight that the dynamic agitation of the system reduces the time of adsorption of the surfactant molecules at the interfaces up to the order of millisecond. In fact, unlike static systems where the migration of surfactant molecules towards the interface is due to diffusion, in this case convection is significantly predominant.

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

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

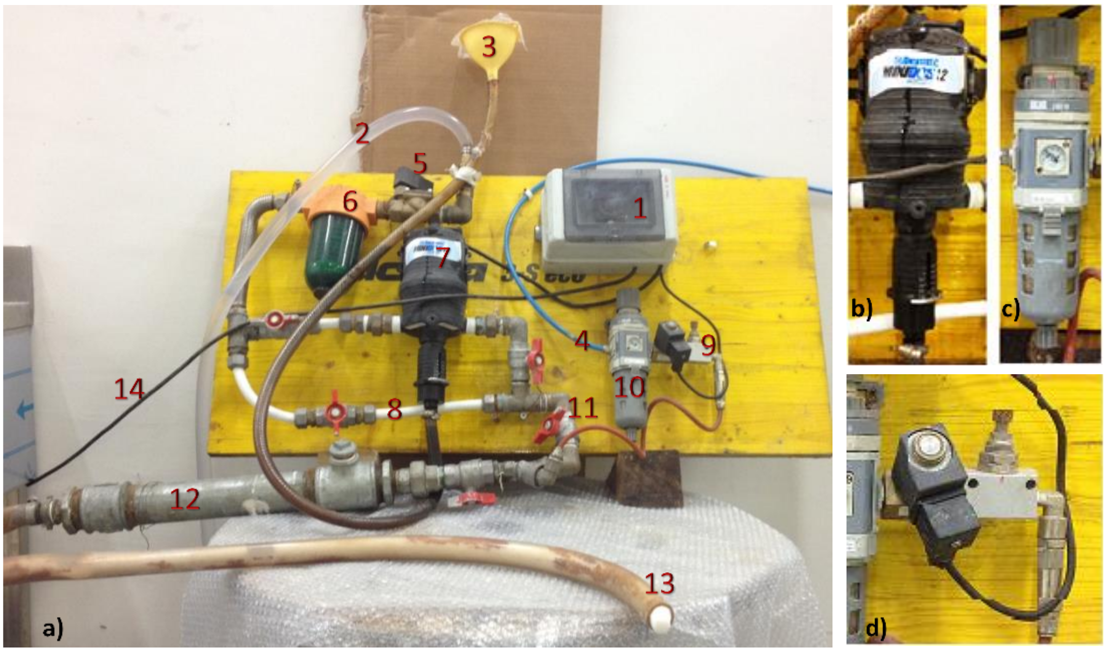

Figure 1 Optimized foam generator: a) overall view; b) detail of the automatic dosing pump for the foaming agent concentration; c) detail of the air pressure reducer; d) detail for air flow regulation.

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

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

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

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

4. INVESTIGATION ON FOAM PROPERTIES

4.1. Testing conditions

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

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

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

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

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

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

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

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

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

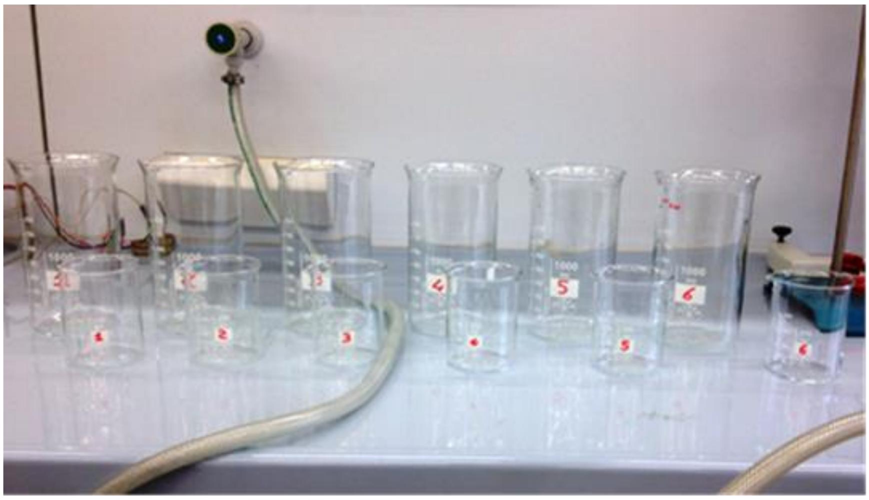

Figure 2 Pyrex beakers used for tests on the foams produced.

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

$$V = \frac{W_w - W_b}{\gamma_{wt}} \tag{1}$$

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

In addition to the density, drainage is evaluated after 5, 10, 15 and 180 minutes. This determination is carried out considering the weight of the solution of water and surfactant drained from the foam at the selected time intervals previously specified. The drainage quantity at the time x - Q_x - is hence evaluated as the difference between the weight of the beaker with the liquid drained at the time x, W_{Qx}, and the weight of the empty beaker. Once the quantity of drainage at the time x, Q_x, is noted, it is possible to determine the percentage drainage at the time x, D_x, by means of the expression 2.

$$D_x = \frac{Q_x}{W_f} \tag{2}$$

4.2. Results and discussion

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

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

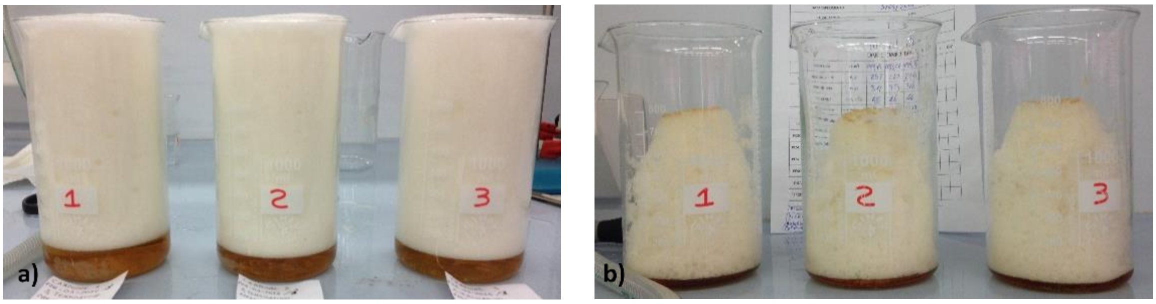

Figure 3 Foam produced with Foamin C® protein foaming agent showing drainage a) and structural collapse (showed by all the foams produced) at the selected time interval of 180 minutes b).

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

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

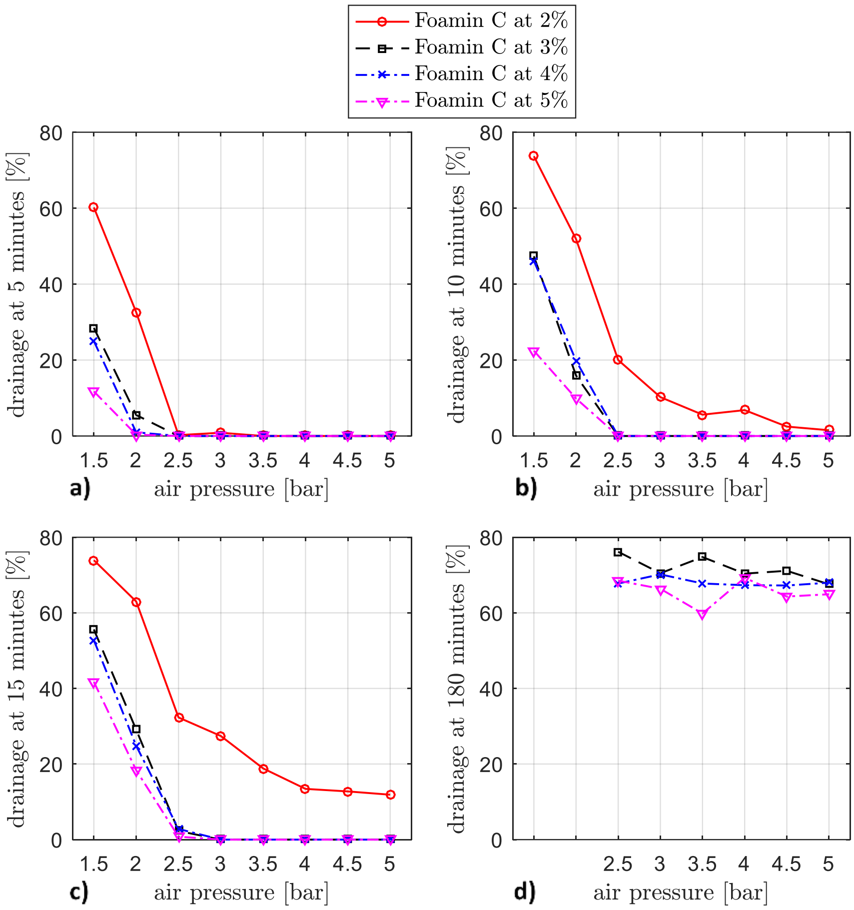

Figure 4 Influence of air pressure and Foamin C® protein foaming agent concentration on the drainage of foams produced at selected time intervals: 5 minutes a); 10 minutes b); 15 minutes c); 180 minutes d).

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

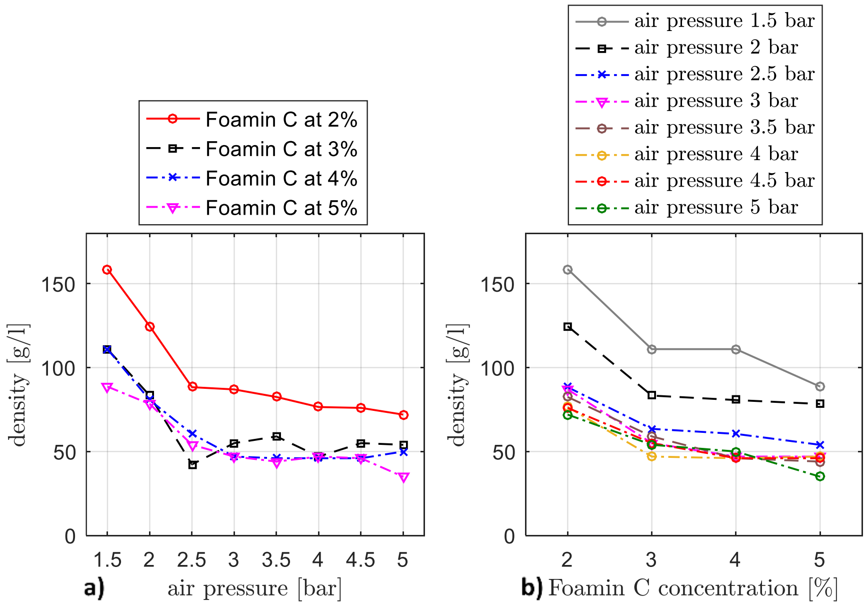

Figure 5 Influence of air pressure and Foamin C® protein foaming agent concentration on the density of foams produced: for fixed foaming agent concentration a); for fixed air pressure value b).

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

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® 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
		$\gamma [g/l]$	$\sigma_\gamma [g/l]$	CoV_γ	$D_5 [\%]$	$\sigma_{D_5} [\%]$	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

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
		$\gamma[g/l]$	$\sigma_\gamma[g/l]$	CoV_γ	$D_5[\%]$	$\sigma_{D_5}[\%]$	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

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 C® foaming agent concentrations.

Foaming agent concentr. [%]	n° series	Av. density $\gamma[g/l]$	St. dev. $\sigma_\gamma[g/l]$	CoV CoV_γ	Av. drain. 5 min. $D_5[\%]$	St. Dev. $\sigma_{D_5}[\%]$	CoV CoV_{D_5}	Av. drain. 10 min. $D_{10}[\%]$	St. dev. $\sigma_{D_{10}}[\%]$	CoV $CoV_{D_{10}}$	Av. drain. 15 min. $D_{15}[\%]$	St. dev. $\sigma_{D_{15}}[\%]$	CoV $CoV_{D_{15}}$	Av. drain. 180 min. $D_{180}[\%]$	St. dev. $\sigma_{D_{180}}[\%]$	CoV $CoV_{D_{180}}$
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

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® foaming agent concentrations.

Foaming agent concentr. [%]	n° series	Av. density $\gamma[g/l]$	St. dev. $\sigma_\gamma[g/l]$	CoV CoV_γ	Av. drain. 5 min. $D_5[\%]$	St. Dev. $\sigma_{D_5}[\%]$	CoV CoV_{D_5}	Av. drain. 10 min. $D_{10}[\%]$	St. dev. $\sigma_{D_{10}}[\%]$	CoV $CoV_{D_{10}}$	Av. drain. 15 min. $D_{15}[\%]$	St. dev. $\sigma_{D_{15}}[\%]$	CoV $CoV_{D_{15}}$	Av. drain. 180 min. $D_{180}[\%]$	St. dev. $\sigma_{D_{180}}[\%]$	CoV $CoV_{D_{180}}$
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

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 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
		$\gamma[g/l]$	$\sigma_\gamma[g/l]$	CoV_γ	$D_5[\%]$	$\sigma_{D_5}[\%]$	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

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® 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
		$\gamma[g/l]$	$\sigma_\gamma[g/l]$	CoV_γ	$D_5[\%]$	$\sigma_{D_5}[\%]$	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

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 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
		$\gamma[g/l]$	$\sigma_\gamma[g/l]$	CoV_γ	$D_5[\%]$	$\sigma_{D_5}[\%]$	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

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® 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
		$\gamma[g/l]$	$\sigma_\gamma[g/l]$	CoV_γ	$D_5[\%]$	$\sigma_{D_5}[\%]$	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

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

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

Based on the experimental evidence, the reduction of the foam density and the limitation of the drainage in short to medium time, so the increase in foams' lifetime, can be obtained in two different ways: 1) by increasing the air pressure values up to 2.5÷3 bar for fixed concentration of the foaming agent, as it can be seen in Figure 4 a), b) and c) and Figure 5 a); 2) by increasing the foaming agent concentration up to 3÷4% for fixed air pressure value, as it is shown in Figure 4 a), b) and c) and Figure 5 b). Strategy 1) improves the quality of the foams thanks to the better turbulent flow conditions inside the mixing tube of the generator, while strategy 2) enhances the quality of the foams due to a greater quantity of surfactant molecules, which give a better stability to foams by diffusing them to the interfaces. Furthermore, the increase in air pressure and foaming agent concentration beyond the values previously reported indicates completely negligible changes in the properties of the foams. In fact, higher air pressure values negatively influence the correct flow of the water-surfactant solution and its subsequent expansion inside the mixing chamber as it is evident because the foams leave the generator in a discontinuous and intermittent way; moreover, higher concentrations of foaming agents do not cause further improvements in the quality of the foams since, a further increase in the foaming agent concentration does not correspond to a further lowering of the surface tension beyond a specific value called critical micellar concentration, but to an increase of particular surfactant molecules configurations called micelle [18].

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

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

Figure 6 shows the influence of air pressure values on percentage drainage at selected time intervals for foams generated with SLS synthetic foaming agent at a concentration of 4%. In this case as well, the results indicate that an increase in air pressure values generally leads to a decrease in the percentage drainage for all the samples. This reduction is greater for air pressure values passing from 2 bar to 2.5 bar and it gradually becomes less evident for subsequent increases in air pressure. The minimum percentage drainage is recorded for air pressure value equal to 4 bar in all selected time intervals.

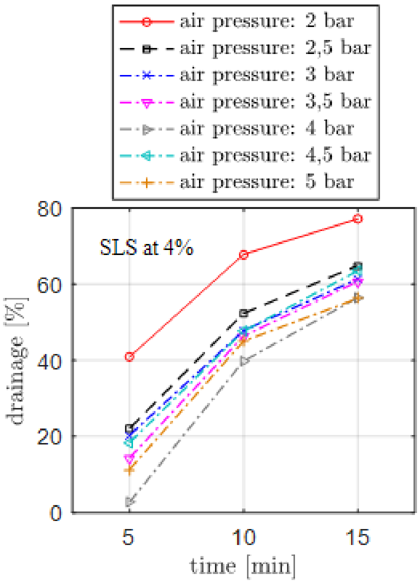

Figure 6 Influence of air pressure value on drainage at selected time intervals of foams produced with 4% concentration SLS synthetic foaming agent.

The comparison between this condition and the percentage drainages at the same selected time intervals of the foams produced with Foamin C® protein foaming agent at the same concentration of 4% allows to frame the substantial differences of foams' lifetimes produced with foaming agents having different nature, as it is evident in Figure 7. In all cases, the percentage drainage of foams produced with synthetic foaming agent is vastly higher than that of foams generated by means of protein foaming agent. As previously discussed, the last foams have a percentage drainage at a concentration of 4% of protein foaming agent always equal to zero, except for the lowest air pressure values. On the contrary, foams generated with SLS synthetic foaming agent are characterized by a poor drainage resistance, even in case of rest time of only 5 minutes. The justification of this different behaviour lies in the greater stabilizing effect due to the presence of proteins: these macromolecules confer viscoelasticity properties to the thin film between the air bubbles, thus contributing to their stiffening. In particular, the molecular structure of the proteins is much more complex than the same of SLS synthetic surfactants (characterized by a low molecular weight) and this characteristic influences the way in which proteins are adsorbed at the interfaces: the different configurations can be distinguished in train, loop and tails [29]. The more complex the structure configuration of the protein molecules, the greater the reduction of foam drainage is, significantly increasing the lifetime of the system. This behaviour leads to a reduction in drainage speed phenomena and, consequently, in an increase of foams' lifetime as a consequence.

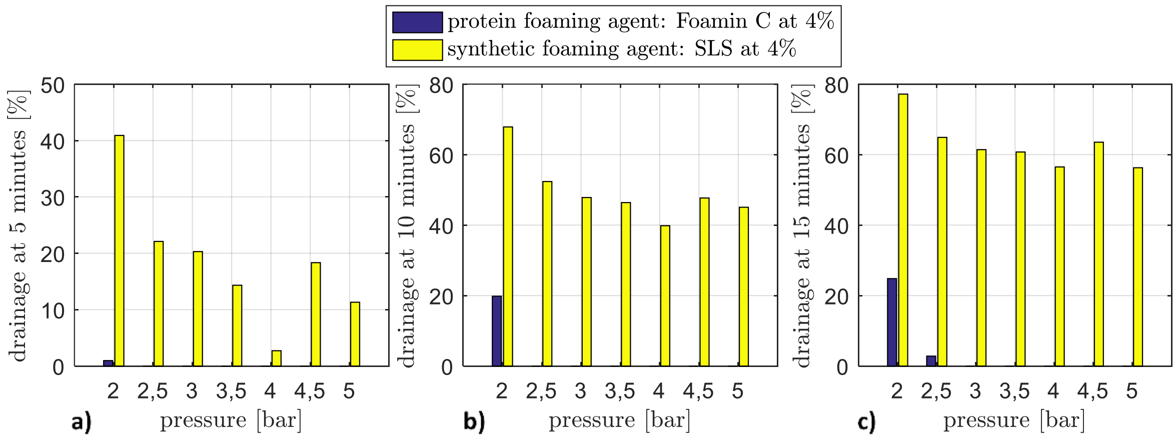

Figure 7 Comparative histograms between the drainages of foams produced with Foamin C® protein foaming agent and SLS synthetic foaming agent for different air pressure values and at selected time intervals: 5 minutes a); 10 minutes b); 15 minutes c).

However, structure configuration also affects the bubbling capacity of a foaming agent, i.e. its ability to form large volumes of foam. From this point of view, the more complex the structure configuration, the lower the bubbling ability of the foaming agent is. Furthermore, foaming agents capable of generating high volumes of foam in a short time, are generally marked by a poor stability and a reduced lifetime, while the opposite is true for foaming agents with lower foaming ability [29]. This means a lower density of the foams generated using the synthetic foaming agent SLS compared to that of the foams produced with the protein foaming agent Foamin C®, as it is clear from the analysis of Figure 8. Indeed, the foams generated with the synthetic foaming agent are generally characterized by a decreasing density of about 30% compared to the foams produced with an equal concentration of the protein foaming agent: SLS is characterized by a greater foaming ability compared to Foamin C®. This behavior is caused by the presence of the macromolecules in the protein surfactant; in fact, they both contribute to reducing drainage and they are characterized by lower rates of diffusion, adsorption and reorientation at the interfaces [30].

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

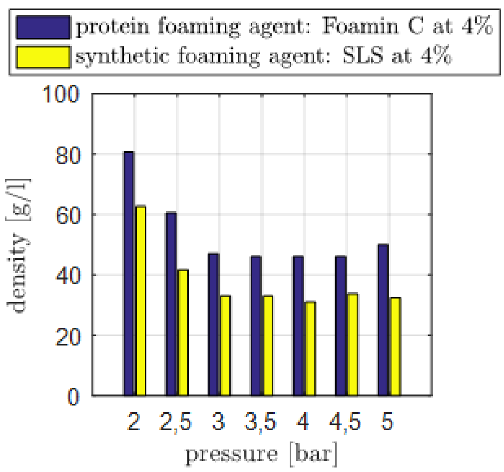

Figure 8 Comparative histograms between the density of foams produced with Foamin C® protein foaming agent and SLS synthetic foaming agent for different air pressure values.

Given these results, it was decided not to extend the experimental campaign to other concentrations of synthetic surfactants. however, in order to extend the understanding of foamed concrete properties to foams with such different properties, the properties of foamed concrete produced with foams generated with the SLS synthetic foaming agent will be also studied in the following section: they will be compared to the properties of concretes made using foams generated with the protein foaming agent Foamin C®. Unlike what might be expected, despite the very significant drainage value at very short time intervals of synthetic foams, the corresponding foamed concrete will not be characterized by instability.

5. INVESTIGATION ON FOAMED CONCRETE PROPERTIES

5.1. Materials, specimen preparation and testing conditions

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

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

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

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

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

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

After 48 hours, specimens were demoulded, wrapped in cellophane sheets (a typical strategy in the precast industry of foamed concrete artefacts [32]), then kept in laboratory conditions at environmental temperature of 20±3°C and relative humidity of 65÷70%. The 28 days compressive strength was assessed using a Controls test frame with a load capacity of 250 kN, in force-controlled mode (loading rate equal to 1000 N/s). As usually done in foamed concrete field [33], [34], the dry density γ_{dry} was also evaluated after compression tests, drying the samples in an oven at 105±5°C for at least 48 hours or until a constant weight is reached.

5.2. Results and discussion

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

Table 11 clearly indicates that the increase in density leads to a decrease in the amount of foam and in the *f/c* ratio consequently. However, in order to obtain the same target density, the required amount of foam generated with the Foamin C® protein foaming agent is interestingly much greater than the one produced with the SLS synthetic foaming agents, approximately double. This behavior has been also observed in [35] and it can now be justified through the results obtained from the investigation on the properties of the foams. Indeed, the foams generated with SLS are characterized by lower densities and greater foaming ability; in other terms, a smaller amount of this type of foam is sufficient to reach a certain density. However, this is not enough to justify this remarkable difference. In fact, it is necessary to add the different behavior of the two types of foams during the first moments of the mixing phase with the cementitious paste. In case of foams generated with SLS, during the mixing phase with a cement paste with a low *w/c* ratio, there is a macroscopic flocculation of the cement particles probably due to the non-optimal interaction of the SLS molecules with cement particles, which tend to agglomerate rather than dispersing. This agglomeration causes a consistent decrease in the specific surface area and, consequently, leads to a lower amount of foam to reach a target density. This behavior is emphasized by low *w/c* ratios and it could be limited by increasing the distance between the cement particles before introducing the foam; for example, an effective method could be to increase the fluid phase of the cementitious paste. This may explain the significant increase in the compressive strength of foamed concrete with the increase of *w/c* ratio evidenced in [36] for another type of synthetic foaming agent.

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

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

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

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

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_{Rc}
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

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

The comparison between foamed concretes with the same target dry density but produced with foaming agents of different nature shows significant differences at the fresh state, which lead to very significant differences in terms of compressive strength. In fact, apart from the obvious consideration that the compressive strength increase significantly with increasing density, true for both foaming agents, the use of the protein foaming agent gives rise to a remarkable increase in the compressive strength of the foamed concrete by approximately 1070%, 1550% and 1050% for a target dry density of 400 kg/m^3, 600 kg/m^3 and 800 kg/m^3 respectively (Figure 9). These results are in line with another experimental campaign reported in [35] and, in addition to the justifications reported therein, based above all on the mutual influence of the air to cement ratio and water to cement ratio on the compressive strength. In fact, for low density foamed concretes it may be possible to detect an increase in compressive strength with the increase of the fluid phase [41], greater in the case of foamed concretes prepared with foams generated using protein foaming agent. This is probably due to the greater quantity of foam compared to the case of synthetic foaming agent and the explanation of the different behaviour at the fresh state between the two different types of foams reported here helps to better justify this important finding. The macroscopic flocculation of the cement particles caused by the addition of the foam generated with SLS adversely affects the degree of hydration of the cement leading to poor mechanical performance. On the contrary, the deflocculating action on the cement particles of the first protein foam added to the cementitious paste leads to excellent compressive strength values, which are quite in line with the experimental results of relevant literature. In fact, for example, in [42] the compressive strengths of the foamed concretes prepared with a protein foaming agent are approximately equal to 2.5 MPa, 4.9 MPa and 6.9 MPa for target dry densities of about 500 kg/m^3, 600 kg/m^3 and 700 kg/m^3, respectively. In [43] the compressive strengths of foamed concretes characterized by a plastic density of 500 kg/m^3 and produced with a protein foaming agent are in the order of 0.3 MPa.

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

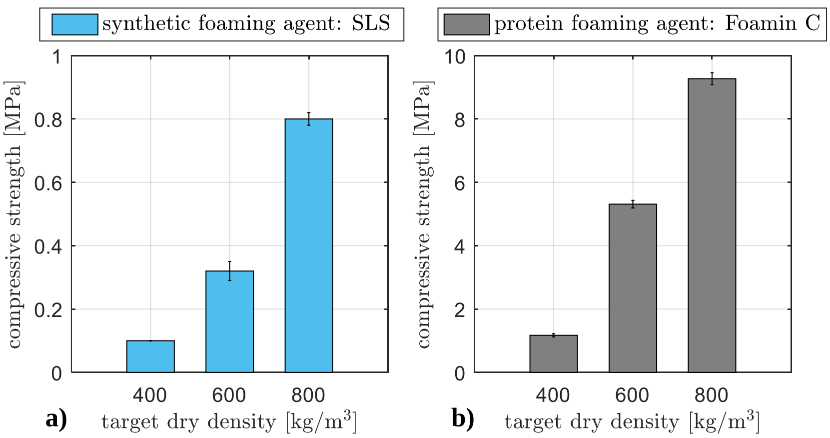

Figure 9 Compressive strength of ultra-lightweight (400 kg/m^3) and lightweight (600 kg/m^3, 800 kg/m^3) foamed concrete produced with foams generated using the synthetic foaming agent SLS (a) and the protein foaming agent Foamin C® (b).

Due to the very low mechanical strength of the foamed concrete produced using the SLS foaming agent, the study on the possible influence of the foaming agent concentration in the preformed foam on the compressive strength of the foamed concretes was carried out only with foams generated with the protein foaming agent. Two additional series of foamed concrete were prepared, labelled #1.1 and #3.1 in Table 11 and Table **12**, to investigate the possible influence of the protein foaming agent concentration on the compressive strength of the material.

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

This trend is confirmed in the case of lightweight foamed concrete characterized by a target dry density of 800 kg/m^3, although the increase in the compressive strength is significantly reduced, reaching 4%.

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

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

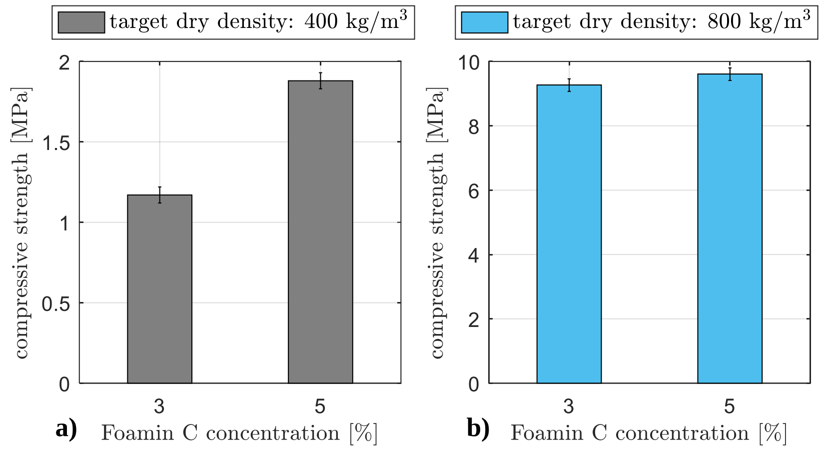

Figure 10 Comparative histogram between the compressive strength of foamed concrete, with target dry density equal to 400 kg/m^3 (a) and 800 kg/m^3 (b) produced with foams generated using the protein foaming agent (Foamin C®) at different concentrations.

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

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

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

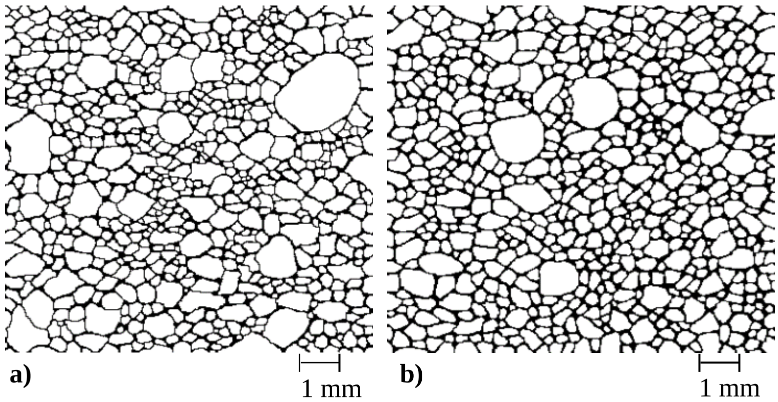

Figure 11 Representative binary images of the cross section of two foamed concrete specimens with the same target dry density of 400 kg/m^3 but produced with two different concentration of the protein foaming agent in the preformed foam: 3% (a), 5% (b).

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

6. CONCLUSIONS

This paper has presented an analysis on the characteristics of foamed concretes starting from the foam generation up to the compressive strength of the lightweight cementitious material. After a short introduction focused on the basic concepts of foams' stability, the design of an optimized simple and inexpensive foam generator has been presented because it allows to obtain excellent quality foams in various possible working conditions.. Investigations on the properties of the foams generated using two different foaming agents, namely the protein Foamin C® and the synthetic SLS, have shown that: 1) the percentage drainage and the density of the protein foams can be reduced either by increasing the foaming agent concentration or by increasing air pressure value up to 3% and 3 bar respectively; a further increase in these parameters does not lead to appreciable variations in the foams properties; 2) long-term (180 minutes) percentage drainage cannot be reduced simply by changing these parameters; 3) due to the absence of macromolecules that hinder the drainage, this one is very high even for short time intervals after the foam generation in case of the synthetic foaming agents; 4) in case of synthetic foaming agents too, further increase of the air pressure value beyond 3 bar does not lead to further decrease in the density of the foams; 5) the SLS foaming agent is characterized by a higher foaming ability than the Foamin C®: the foams produced with the former foaming agent are characterized by an average decrease in the density of approximately 30% compared to the corresponding ones generated with the protein foaming agent.

The foams with the best properties have been used to produce lightweight and ultra-lightweight foamed concretes (with a target dry density of 400 kg/m^3 and 600 kg/m^3). This investigation showed a decidedly marked behavior of the foams generated with the two different foaming agents when mixed with the cementitious paste. This different behavior ascribed to the different interactions between the protein and synthetic surfactant molecules with the cement particles is crucial to understand the enormous differences in terms of compressive strength of the foamed concrete produced with different foaming agents used to generate the foams (in case of Foamin C® there is an average increase in the 28 days compressive strength of about 1070%, 1550% and 1050% for a target dry density of 400 kg/m^3, 600 kg/m^3 and 800 kg/m^3 respectively). These considerations allow to better understand the different properties of foamed concretes when foams have been generated with protein or synthetic foaming agents. Furthermore, the results showed that the corresponding foamed concretes have not shown instability phenomena, despite the very high short-term drainage of the foams generated with SLS.

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

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