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Key factors affecting the compressive strength of foamed concrete

Devid Falliano ^{1,*}, Dario De Domenico ¹, Giuseppe Ricciardi ¹, Ernesto Gugliandolo ²

¹ Department of Engineering, University of Messina, Contrada Di Dio, 98166 Sant'Agata, Messina, Italy

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

*Corresponding author, email: dfalliano@unime.it

Abstract. This contribution aims to highlight, from an experimental point of view, the key factors affecting the compressive strength of foamed concrete. An experimental campaign has been conducted on a broad group of cubic specimens made of foamed concrete under compression tests at 28 days. In addition to the obvious influence of the density on the achievement of the compressive strength, other factors have been studied. In particular, three different curing conditions, three foaming agents with either synthetic or protein nature, two different cement types, and three water/cement ratios have been included in this experimental investigation. As a result of this experimental campaign, it has been found that the not only the density, but also the foaming agent and the water/cement ratio play a major role in the strength achievement of the foamed concrete. It is also demonstrated that the combination of the foaming agent with a particular water/cement ratio is a crucial parameter affecting the compressive strength of this material.

1. Introduction

Foamed concrete is a composite material including cement, water, preformed foam, fine sands, and other mineral additions e.g. fly ash or silica fume and, if necessary, chemical additives [1]. The presence of the foam in the cement past produces a system of air voids in the material microstructure, which are responsible for the increased porosity, and consequently, for the following resulting features: lower weight, higher thermal and acoustic insulation, good resistance against fire, flotation, excellent workability [2]. Furthermore, there may be additional advantages in terms of environmental sustainability when recycled materials are used in the cement paste as replacement of natural aggregates for example electric arc furnace slag [3], [4], [5], recycled glass, foundry slag [6], fly ash and ground granulated blast-furnace slag [7], [8]. Considering the higher porosity of foamed concrete as compared to conventional concrete [9], the associated mechanical properties are generally poorer, especially at the lower densities. As a result this lightweight material is commonly utilized in non-structural portions of the buildings and only for density values $>1600 \text{ kg/m}^3$ could be employed also for structural purposes. The determination of the mechanical characteristics of foamed concrete is an interesting research subject. More importantly, the identification of the key factors affecting the compressive strength of this material is essential to properly adjust the mix design so as to achieve a trade-off between lightweight properties and mechanical performance. In this research context, the aim of this paper is to present the



results of a broad experimental campaign on the compressive strength of foamed concrete. In order to highlight which are the most important factors that influence the compressive strength values, the experimental campaign has included different cement types, curing conditions, foaming agents, dry densities and water/cement ratios, with more than 100 foamed concrete cubic specimens tested at 28 days. The most important results of this experimental campaign will be outlined in the following sections.

2. Experimental campaign and specimen preparation

The experimental investigation is focused on the compressive strength of foamed concrete. A set of more than 100 cubic specimens having 5 cm side were prepared in accordance to ASTM C109 standards. The choice of this specimen dimensions is justified by other research works from the relevant literature [10], in addition to being more convenient for obvious saving of material and times for the specimen preparation. The tests were carried out with a CONTROLS test frame model 65-L1301/FR with 250kN load capacity. The foam was a preformed one, and was prepared with an appropriate foam generator with a surfactant concentration of 3% in volume, air pressure of 3 bar and a final density of 80 ± 5 g/l. The foam was introduced into the cement + water mix.

The amount of cement ranged from about 350 kg/m^3 for the lowest densities up to about 780 kg/m^3 for the highest ones, while the amount of foam varied from about 30 kg/m^3 (for the highest densities) up to nearly 150 kg/m^3 (for the lowest densities) and it was strictly related to the water/cement ratio of the mix design. Indeed, for a target density, increasing the water/cement ratios led to a lower foam content. This is ascribed to the higher stability of the foam during the mixing phase with a more fluid cement paste. The dry density was determined by drying the specimens after the test within an oven at 120°C for two days and until the specimen reached a constant weight. The mix design proportion are listed in Table 1.



Figure 1 Curing conditions of the tested specimens in air at environmental temperature (top left), wrapped in a cellophane sheet at environmental temperature (top right), and in water at controlled temperature (bottom left and right)

Two types of cement were used, namely Portland CEM I 52,5 R, and limestone Portland CEM II A-L 42,5 R. Moreover, 2 different synthetic based foaming agents (SLS and FoamTek) and 1 protein-based foaming agent (Foamin C[®]) were used for comparison purposes. The specimens were prepared in order to achieve three target dry densities, namely 400, 600 and 800 kg/m^3 . The specimens were cured in three different conditions during the 28 days before testing, namely in air at environmental temperature of $20 \pm 3^\circ \text{C}$, in cellophane at the same conditions, and in water at a controlled temperature of 30°C , Fig. 1

Table 1. Mix design proportions of the foamed concrete specimens.

ceme nt type	foami ng agent	Mix design							
		fresh density	dry density	cement	water	foam	rati o 1	rati o 2	ratio 3
		γ_f [kg/m ³]	γ_{dry} [kg/m ³]	c [kg/m ³]	w [kg/m ³]	f [kg/m ³]	w/c	f/c	$(w+f)/c$
CEM I 52,5 R	Foami n C [®]	510	407	381	114	145	0.30	0.38	0.68
		818	624	588	176	143	0.30	0.24	0.54
		855	613	574	287	101	0.50	0.17	0.68
		1046	820	779	234	117	0.30	0.15	0.45
	FoamT ek	497	394	363	109	68	0.30	0.19	0.49
		722	600	534	160	68	0.30	0.13	0.43
		756	588	511	255	38	0.50	0.07	0.57
		774	539	501	351	37	0.70	0.07	0.77
		973	840	730	219	55	0.30	0.08	0.38
		SLS	691	564	517	155	76	0.30	0.15
CEM II A- L 42,5 R	Foami n C [®]	470	367	354	106	127	0.30	0.36	0.66
		831	640	579	174	120	0.30	0.21	0.51
		986	774	741	222	93	0.30	0.13	0.43
	FoamT ek	503	406	375	113	65	0.30	0.17	0.47
		732	597	543	163	63	0.30	0.12	0.42
		947	817	710	213	50	0.30	0.07	0.37
		SLS	722	584	529	159	58	0.30	0.11

Considering 2 cement types, 3 foaming agents, 3 curing conditions and 3 target dry densities, we obtain an overall number of 54 configurations. For each configuration, two samples were prepared for repeatability purposes. For all the above-mentioned samples a constant water/cement ratio equal to 0.3 was utilized. Additionally, in some configurations, two further water/cement ratios were explored, namely equal to $w/c = 0.5$ and 0.7 . Consequently, this experimental campaign has included more than 100 foamed concrete specimens.

3. Results and discussion

In this section we present in a graphical format the main results of the experimental investigation. Only a limited set of results are discussed, and more details on this experimental campaign are reported in [11]. The influence of the foaming agents on the compressive strength of foamed concrete specimens with $w/c=0.3$, CEM I 52,5 R for the three curing conditions specified above is shown in Figure 2.

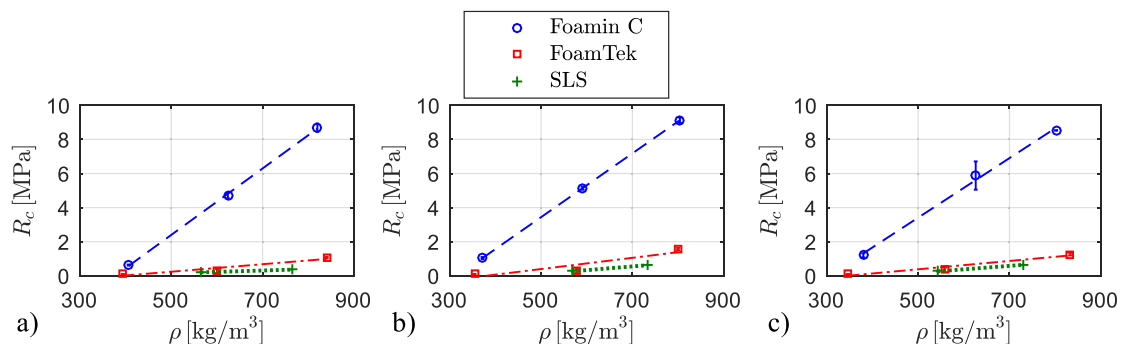


Figure 2 Effect of the foaming agent on the compressive strength of foamed concrete specimens with $w/c=0.3$: a) air conditions; b) cellophane conditions; c) water conditions with CEM I 52,5 R cement type

It is noted that the compressive strength is considerably affected by the nature of the foaming agent for the medium-to-low densities here analyzed. This is in contrast to what reported in [12], where negligible influence of the foaming agent was reported for medium-to-high densities.

By inspection of Figure 2, the best results were obtained with the protein-based foaming agent (Foamin C[®]) for the fixed $w/c=0.3$. This is strictly connected to the stability of the different foams. Indeed, the synthetic-based foams (FoamTek and SLS) are significantly more stable than the protein-based ones (Foamin C[®]), and give rise to the achievement of a lower $(w+f)/c$ ratio (with f denoting the foam content). It is well known in the literature that, unlike ordinary concrete in which the increased w/c ratio is detrimental for the compressive strength, the development of the compressive strength in low-density concrete specimens is directly affected by the volume of entrained and entrapped air and, thus, by the (air+water)/cement ratio [13]. In these cases, the increase of the w/c ratio is therefore advantageous for the achievement of a higher compressive strength, especially for lower densities and up to a maximum (critical) (air+water)/cement ratio [13]. In this experimental campaign, the higher stability of the synthetic foams led to a reduced fluid phase in the cementitious paste as compared to the air/cement ratio, which is the justification of the lower strength values obtained.

In order to assess the validity of this qualitative interpretation of the results, a set of specimens were replicated with a different w/c ratio equal to 0.5 and 0.7 in place of 0.3 for the FoamTek foaming agent. Relevant comparisons are illustrated in the histogram of Figure 3. As expected, increasing the water-to-cement ratio generates a remarkable increase of the compressive strength values. Moreover, there is a particular critical (air + water)-to-cement ratio for which increasing the w/c ratio further does not generate an increase of the compressive strength (this behaviour resembles that of the ordinary concrete). This is a novel result that has not been reported in [11].

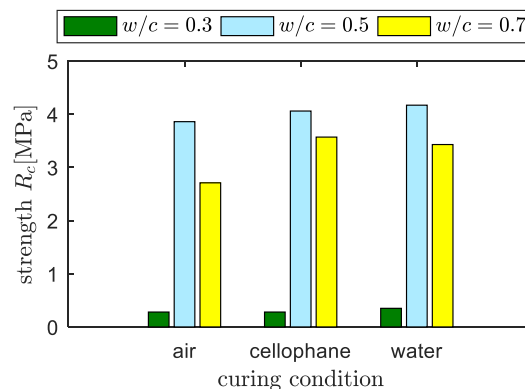


Figure 3 Effect of water/cement ratio on the development of the compressive strength for foamed concrete with FoamTek foaming agent and target dry density 600 kg/m^3 for different curing conditions

As a second novel research contribution of this paper, in addition to what already reported in [11] a more detailed study of the effect of the water-to-cement ratio for the protein-based Foamin C[®] foaming agent has been performed. In Figure 4 the compressive strength values for two water-to-cement ratios are reported. As a first remark, it is worth noting that the influence of the w/c ratio on compressive strength is completely different from that observed for the FoamTek foaming agent. Indeed, in this second case the achievement of the compressive strength is strictly related to the different curing conditions of the specimens. In particular, only in the air curing conditions the increase of the w/c ratio leads to a moderate increase of the compressive strength, while in the other two curing conditions a decrease of the compressive strength with increasing the w/c ratio is observed. This is motivated by the fact that an increase of the w/c ratio improves the hydration of the cement in the worst curing condition (air) where the specimens are subject to a premature dehydration, which surely causes a decrease of their mechanical resistance. These effects of a premature dehydration are surely mitigated by a higher fluid phase in the case of increased w/c ratio equal to 0.5 in place of 0.3.

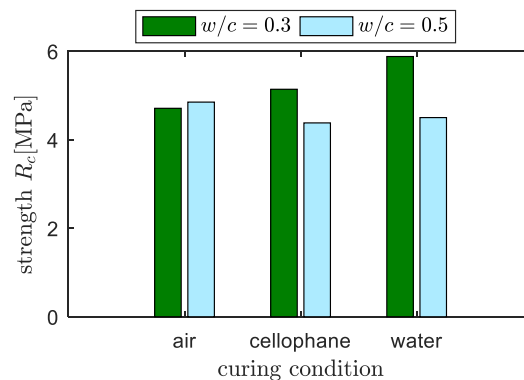


Figure 4 Effect of water/cement ratio on the development of the compressive strength for foamed concrete with Foamin C[®] foaming agent and target dry density 600 kg/m³ for different curing conditions

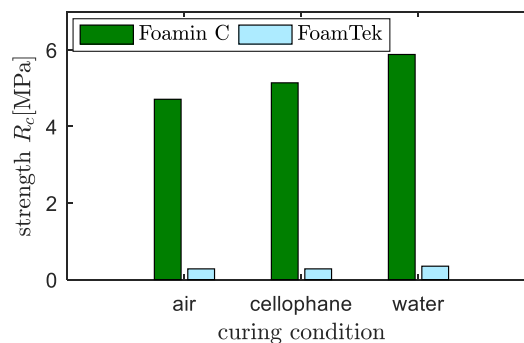


Figure 5 Effect of foaming agent on the development of the compressive strength for foamed concrete with $w/c=0.3$ and target dry density 600 kg/m³ for different curing conditions

When comparing the values reported in the two histograms of Figure 3 and 4, as illustrated in Figure 5 and 6, the following conclusions can be drawn: for the w/c ratio equal to 0.3 the compressive strength associated with the Foamin C[®] is disproportionately larger than that with FoamTek foaming agent for all the curing conditions analysed, cf. Figure 5; on the contrary, the differences of the strength values for $w/c = 0.5$ are far less pronounced, although the qualitative trend outlined before (i.e., specimens with Foamin C[®] have higher compressive strength than specimens with FoamTek) is confirmed, cf. Figure 6.

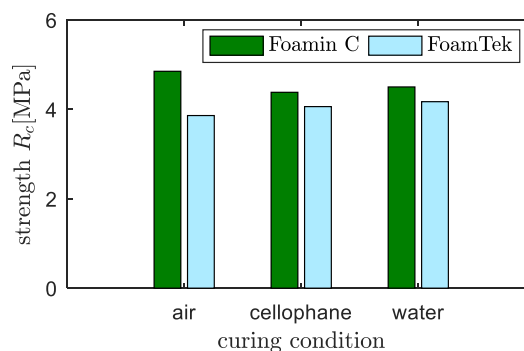


Figure 6 Effect of foaming agent on the development of the compressive strength for foamed concrete with $w/c=0.5$ and target dry density 600 kg/m³ for different curing conditions

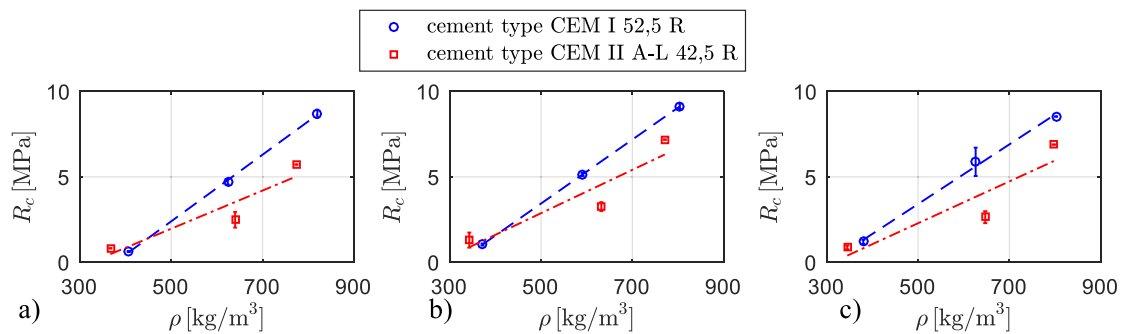


Figure 7 Effect of the cement type on the compressive strength of foamed concrete specimens: a) air conditions; b) cellophane conditions; c) water conditions with Foamin C[®] foaming agent

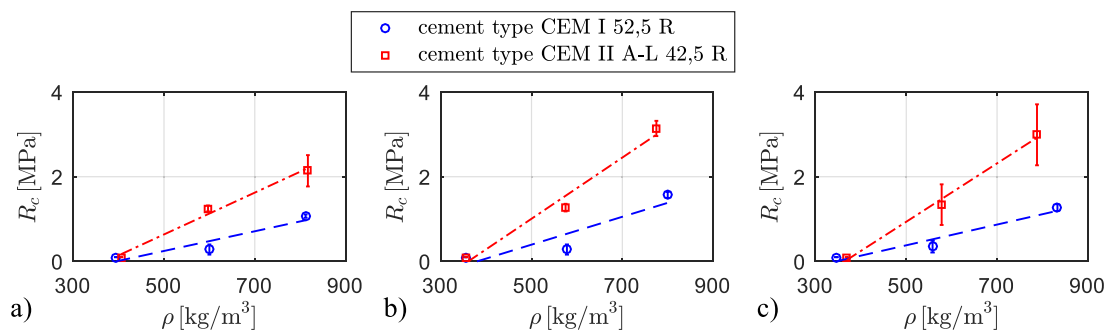


Figure 8 Effect of the cement type on the compressive strength of foamed concrete specimens: a) air conditions; b) cellophane conditions; c) water conditions with FoamTek foaming agent

The influence of the cement type on the compressive strength is closely connected to the nature of the foaming agent employed. Indeed, as expected, in the case of protein-based Foamin C[®] foaming agent the best results were obtained for the higher-strength CEM I 52,5 R in comparison to the CEM II A-L 42,5 R, as can be seen in Figure 7. Conversely, in the case of the synthetic-based FoamTek foaming agent, the highest strength values were obtained, for all the curing conditions, in the lower-strength CEM II A-L 42,5 R, cf. Figure 8. This may be justified from a microstructural point of view: indeed, in the case of synthetic foaming agents with CEM I 52,5 R type a lower hydration degree was achieved as compared to the case of the same synthetic foaming agents with CEM II A-L 42,5 R for the examined water-to-cement ratio equal to 0.3. Moreover, not only the value of the compressive strength, but also the rate of increase of the compressive strength with the density is different in the two foaming agents analyzed: in the Foamin C[®] foaming agent this rate is higher for CEM I 52,5 R, whereas in the FoamTek foaming agent is higher for CEM II A-L 42,5 R.

In all the analyzed cases, the increase of the compressive strength with the dry density is nearly linear as can be seen by the regression curves superimposed in the graphs reported in Figure 2, 7 and 8.

4. Concluding remarks

The present contribution has highlighted the key factors affecting the compressive strength of foamed concrete, at least in the low-to-medium density range explored in this experimental campaign. It has been found that foaming agents having different nature (protein versus synthetic) lead to a completely different mechanical behavior, hydration conditions, and sensitivity to the other ingredients of the mix design (e.g., the cement type and the overall fluid content). The highest strength values are obtained for the protein-based foaming agent and cellophane curing conditions. For a water-to-cement ratio equal to 0.3, the compressive strength of the specimens with protein-based foaming agents and CEM I 52,5 R is, on average, ten times higher than the strength of the specimens with synthetic foaming agents. This is ascribed to the overall fluid phase and to the effect of the combined (air+water)/cement ratio in foamed

concrete specimens with low densities. The curing conditions in cellophane and in water lead to an improved mechanical behavior in comparison with specimens cured in air.

Moreover, a specific aspect that has been in-depth analyzed is the influence of the w/c ratio. This ratio has a different influence depending on the foaming agent employed and, in the case of protein-based ones, on the different curing conditions. Indeed, in the synthetic-based foaming agents increasing the w/c ratio from 0.3 to 0.5 leads to a dramatic increase of the compressive strength (nearly 10 times higher), but a further increase from 0.5 to 0.7 does not produce an additional increase of the strength, but instead a moderate decrease. On the contrary for the protein-based foaming agents the increase of the w/c ratio does not yield significant differences of the compressive strength for all the curing conditions except for air. Indeed, for air curing conditions it is reasonably expected that the premature dehydration of the specimen has contributed to a poorer mechanical behaviour, and the addition of the water content seems to mitigate this negative effect of the sudden dehydration of the specimen.

Finally, the different nature of the foaming agents plays a key role also in the different compatibility with the cement type. Indeed, it has been found that the protein-based foaming agents lead to specimens with higher strength values when the CEM I 52,5 R is employed in comparison with CEM II A-L 42,5 R, whereas for the synthetic foaming agents the opposite behaviour has been observed.

The present experimental campaign is part of a wider research programme focused on the development of an innovative extrudable foamed concrete [14].

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