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Strategies to increase the compressive strength of ultra-lightweight foamed concrete

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Abstract

Foamed concrete is a special lightweight concrete characterized by the presence of a stable preformed foam in the mix proportion that give rise to the development of a system of air voids in the material. Its physical and mechanical properties are strongly influenced by microstructural properties, in turn linked to various parameters such as the amount of foam, the presence of mineral additions or chemical additives, the characteristics of the mixing process and so on. Since ultra-lightweight foamed concrete is characterized by excellent functional properties (thermal insulation, sound absorption, fire resistance) but very poor mechanical properties (compressive strength), in this contribution three different ways to improve the compressive strength of this material without worsening its lightness are discussed. More specifically, the three different strategies (improve the consistency of the fresh lightweight cementitious paste through the addition of a viscosity enhancing agent, add silica fume and increase the rotational speed of the vertical mixer) lead to appreciable improvement in the compressive strength of the produced foamed concrete. The most significant increases in compressive strength are associated with the addition of silica fume in the mix, in proportion to 10% of the cement weight.

Keywords: foamed concrete; compressive strength; silica fume; mixing intensity; lightweight concrete.

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1. Introduction

Foamed concrete belongs to the wider category of lightweight concrete. The roughly spherical air voids in the material microstructure are obtained through the addition of preformed foam in the mix design. Therefore, the elements forming this special lightweight concrete are simple, affordable and readily available: cement, water, fine sand, stable foam and, if necessary, additives.

Foam is the ingredient that characterizes this cementitious material and is formed by trapped pockets of a gas (in most cases air) in a liquid: indeed, liquid foams are composed by a solution of water and surfactants, which play the fundamental role of increasing the lifetime of a foam, expanded with compressed air [Falliano et al, 2018a].

It is possible to obtain cementitious conglomerates with density ranging from 150 kg/m^3 to 2000 kg/m^3 simply by appropriately varying the mix design. This is a key feature of foamed concrete, as density plays a crucial role in defining properties of foamed concrete: it can be designed according to the needs for both structural and non-structural use. In the latter case, especially when very low densities are employed, this material is characterized by properties that are of increasing importance in the building field: fire resistance [Valore, 1954], sound absorption [Kim et al, 2012], thermal insulation [Falliano et al, 2019a; Wei et al, 2013] and, obviously, lightness.

Evidently, if, on the one hand, an increase in porosity of foamed concrete is associated with improved physical properties, on the other hand, is accompanied by a significant reduction in mechanical performances. The utopia in the building sector is to obtain a material characterized by all the physical properties that characterize lightweight foamed concrete, associated, however, also with good mechanical strength.

All this has led many researchers to concentrate their efforts to determine ways to improve the mechanical properties of lightweight and ultra-lightweight foamed concrete, the latter characterized by a target dry density lower than 500 kg/m^3, without worsening the lightness. A usual solution present in the relevant literature to improve the compressive strength is to include mineral addition such as fly ash [Kearsley et al, 2001] and silica fume [Gökçe et al, 2019], while biochar is used to improve fracture energy [Falliano et al, 2020a]. Fibers of different nature [Falliano et al, 2019b; Kayali et al, 2003] and composite grids [Falliano et al, 2019c; Falliano et al, 2019d; Hulimka et al, 2017] are commonly employed to improve the indirect tensile strength.

The present paper fits into this field of research and presents three different strategies aimed to improve the compressive strength of ultra-lightweight foamed concrete. In particular, while two strategies are associated with changes in the mix design of the cementitious mixes, the third strategy allows improving the compressive strength by simply modifying the production process, keeping the same mix proportion.

2. Materials and methods

Foamed concrete specimens are prepared using Portland cement CEM I 52.5R, a water to cement ratio equal to 0.3 and a foam generated using a protein foaming agent called Foamin C®. The density of the preformed foam was equal to 80±5 g/l. The study focuses on ultra-lightweight foamed concrete, indeed the target dry density of the produced foamed concrete was equal to 400±50 kg/m^3.

Tests to evaluate the compressive strength of the ultra-lightweight cementitious material are performed on cubic specimens of 5 cm side, according to ASTM C-109 standard, after 28 days of curing conditions. In particular, three different curing conditions are investigated, namely in air, wrapped in cellophane and in water. As demonstrated in recent study [Falliano et al, 2019e] these different curing conditions play a crucial role in the fracture behaviour of lightweight foamed concrete.

It is important to point out that, compared to ordinary concrete, the mix proportion of foamed concrete is much more complicated because, in addition to conventional parameters (such as water to cement ratio, amount of cement, granulometric assortment of aggregates and so on) its properties are influenced by other factors: nature and amount of foaming agent [Falliano et al, 2018a] and mixing procedure [Falliano et al, 2020b].

In literature, regarding nature of the foaming agent, it is shown that the best results in terms of compressive strength of foamed concrete are associated with the use of a protein foaming agent in the generation of the preformed foam [Falliano et al, 2018a; Panesar, 2013]. This is the reason why a protein foaming agent was used also in this study. Therefore, the main objective of this research is to define which strategies can be used to further improve the compressive strength of ultra-lightweight foamed concrete produced with a protein foaming agent.

As already mentioned, the first two strategies are related to changes in the mix proportion of the foamed concrete, while the third strategy relates to changes in the mixing process, more precisely in the mixing intensity.

With regard to the first strategy, the modification of the foamed concrete mix design consists in adding a viscosity enhancing agent in the mix in order to obtain a more consistent and viscous fresh lightweight cementitious paste. A more common way to increase the compressive strength is employed in the second strategy presented in this study: the introduction of silica fume in the mix in proportion to 10% of the cement weight. The last strategy consists instead in increasing the mixing intensity of the vertical mixer from 1200 rpm (employed in the case of the first two strategies) to 3000 rpm.

3. Results and discussion

The main results of this study are presented in this section in three different subsection, in order to simplify their presentation and comprehension. The reported compressive strength values are the average values of three different experimental findings.

3.1. Strategy 1: increase the consistency of the fresh lightweight cementitious paste

The introduction of a viscosity enhancing agent into the mix design of ultra-lightweight foamed concrete leads not only to a more consistent and viscous lightweight cementitious paste [Falliano et al, 2020c], but, also, to a change in the microstructure of the material [Falliano et al, 2018a] as is evident from the inspection of the comparative photos reported in Fig.1. Indeed, the presence of a viscosity enhancing agent allows to obtain a foamed concrete characterized by air bubbles of smaller dimensions and more uniformly distributed in the cementitious matrix. The higher confinement pressure, due to the greater consistency of the fresh cementitious paste in the presence of a viscosity enhancing agent, justifies the better microstructural configuration; indeed, this improves stability and prevents the expulsion of air bubbles, enhancing the stability of the mixture [Jones et al, 2016].

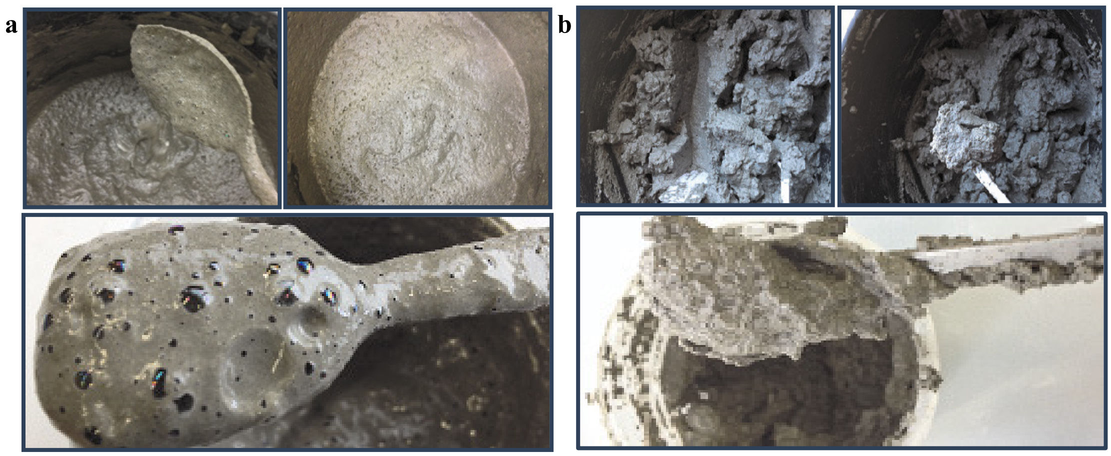

Fig. 1. Effect of viscosity enhancing agent (VEA) on the fresh lightweight cementitious paste: (a) without VEA; (b) with VEA.

As illustrated in the comparative histogram shown in Fig.2, these microstructural differences lead to an increase in the compressive strength of ultra-lightweight foamed concrete, especially in the case of the most unfavorable curing condition, i.e. air.

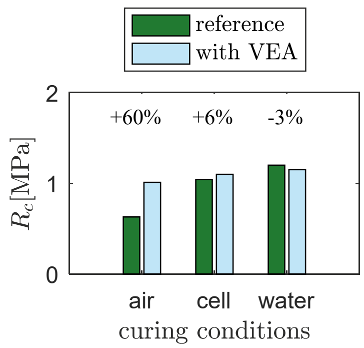

Fig. 2. Effect of viscosity enhancing agent (VEA) on the compressive strength of ultra-lightweight foamed concrete with a target dry density of 400 kg/m^3.

In addition to this, interestingly, the rheological modification in the lightweight cementitious paste allows to apply this special concrete through cutting-edge technologies, such as 3D printing, giving rise to an ultra-lightweight 3D printable foamed concrete.

3.2. Strategy 2: add silica fume

As already mentioned, a more common strategy to increase the mechanical performance of foamed concrete is to introduce silica fume in the mix proportion of the material. Indeed, this mineral addition allows an improvement in compressive strength due to its smaller dimensions than those that characterize the cement particles and to its pozzolanic activity. Silica fume used in this study is characterized by particles having an average dimension of 0.25 μm and a specific surface of approximately 200 m^2/g.

Due to the potential use of foamed concrete produced with viscosity enhancing agent in the field of 3D printing, this strategy is applied to 3D printable foamed concrete. Therefore, in addition to the previously presented 3D printable foamed concrete specimens, 9 additional samples, 3 for each curing conditions, were prepared introducing silica fume into the mixture in proportion to 10% of the cement weight. The mixing intensity was set at 1200 rpm.

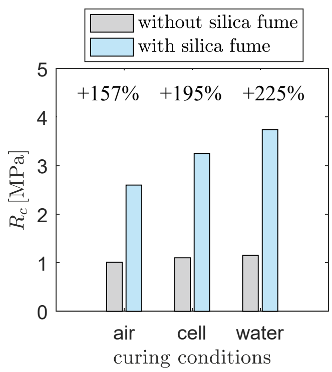

Fig. 3. Effect of silica fume on the compressive strength of ultra-lightweight foamed concrete with a target dry density of 400 kg/m^3.

The comparative histogram illustrated in Fig. 3 highlights a significant improvement in the compressive strength of ultra-lightweight foamed concrete of approximately 157%, 195% and 225% for air, cellophane and water curing conditions respectively. Given the curing time of 28 days, this improvement is mainly due to the densification of the cementitious matrix produced by the presence of silica fume particles. Moreover, the increase in compressive strength with the improvement of the curing conditions can be explained with a better hydration degree of the cement particles in cellophane and, even more, in water, which leads to a greater effectiveness of the pozzolanic activity of the silica fume.

3.3. Strategy 3: increase mixing intensity

The mixing phase strongly influence properties of foamed concrete. In particular, not only the type of mixer, but also the mixing intensity - namely the rotational speed of the mixer - is a crucial parameter in the field of foamed concrete. As demonstrated in literature [Hanselmann et al, 1998], an increase of the mixing intensity from 500 to 2000 rpm can lead to a decrease in the average diameter of the bubbles of a foam by approximately 75%. A reduction in the air voids dimensions into the cementitious matrix is related to an improvement in mechanical strength of foamed concrete [Sang et al, 2015]. Based on these considerations, an additional batch of 9 specimens, three for each curing conditions, were prepared with the use of viscosity enhancing agent, as in the strategy 1 (therefore without the use of silica fume) but with a mixing intensity equal to 3000 rpm (rather than 1200 rpm as in the previous cases).

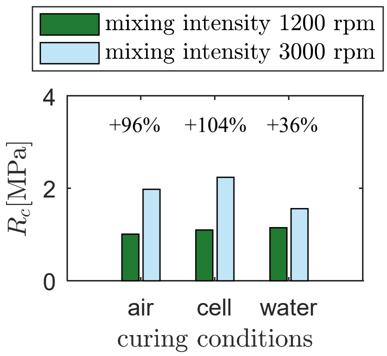

Fig. 4. Effect of mixing intensity on the compressive strength of ultra-lightweight foamed concrete with a target dry density of 400 kg/m^3.

As illustrated in the comparative histogram shown in Fig. 4, specimens produced with a rotational speed of the vertical mixer equal to 3000 rpm are characterized by an increase in compressive strength of 96%, 104% and 36% for air, cellophane and water curing conditions respectively, compared to specimens produced with a rotational speed equal to 1200 rpm. This important result is justified in light of the smaller dimensions and the more homogeneous distribution of the air bubbles into the cementitious matrix and of the mechanical deflocculation effect that a higher speed of the mixer in the mixing phase certainly has on the cement particles.

Therefore, it is possible to improve the compressive strength of ultra-lightweight foamed concrete simply by increasing the rotational speed of the mixer regardless of mineral or chemical additions.

4. Conclusions

The primary goal in the construction field is to realize a material characterized by lightness, very good mechanical properties and excellent performance in terms of fire resistance and thermal insulation. Excellent functional features but poor mechanical strength characterize ultra-lightweight foamed concrete, so many researchers focus their efforts on determining ways to improve the mechanical properties of ultra-lightweight foamed concrete.

In this study, three different strategies to improve the compressive strength of ultra-lightweight foamed concrete through the modification of its microstructure have been presented: increase the consistency of the fresh cementitious paste, add silica fume and increase the mixing intensity.

The first strategy not only leads to an appreciable increase of the compressive strength in air and cellophane curing conditions, but also gives rise to a stabilization of the lightweight cementitious system allowing to exploit this interesting material through cutting-edge technologies such as 3D printing.

The addition of silica fume is associated with the most important increase in the compressive strength of ultra-lightweight foamed concrete: 192% on average over the three different curing conditions analysed.

The increase in the mixing intensity leads to an average increase in the compressive strength over the three different curing conditions of about 79%. The main advantage linked to this strategy is due to the fact that the improvement in the compressive strength is related only to a modification of the mixing phase and not to a mineral or chemical addition in the mix proportion.

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