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Increase the fracture energy of foamed concrete: two possible solutions

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Abstract

The aim of the present paper is to investigate the influence of the curing conditions and the addition of an eco-friendly filler, biochar, on the flexural strength and fracture energy of a "green" special concrete characterized by lightness, high thermal and acoustic insulation properties and excellent fire resistance: foamed concrete. The study aims to highlight the properties of this promising material that, depending on its density, can be used for both structural and non-structural purposes. In fact, if the material is designed with a density not exceeding 800 kg/m^3, it can be employed in interior partitions or in high energy-efficiency building envelopes; on the other hand, if the material is designed with a density greater than 1400 kg/m^3, it can be used for structural purposes. All this makes it legitimate to state that it is a material that can be engineered according to specific needs. In this contribution the possibility to improve the fracture energy through biochar addition in this special concrete is also analyzed and presented. In particular, two different dry density were investigated: 800 kg/m^3, and 1600 kg/m^3. The first one for non-structural applications, the second for structural purposes. With regard to the biochar, used for 1600 kg/m^3 density, two different percentages, 2% and 4%, were investigated. Two different curing conditions were analyzed, namely in air at 20°C, wrapped in cellophane at the same room temperature and cured in water at 20 °C. Three-point bending tests in CMOD (crack mouth opening displacement) mode and compressive tests on the two-halves of the broken specimens have shown interesting results. Curing conditions significantly affect the fracture energy and the addition of biochar at 2% concentration seems to be beneficial in improving the fracture behavior of foamed concrete.

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1. Introduction

A type of special concrete which is gaining increasing interest in the construction sector is represented by lightweight concretes, which can be characterized by a density ranging from 100 kg/m^3 to 2000 kg/m^3.

There are several ways to produce lightweight concrete. One solution is to replace traditional aggregates with lightweight aggregates [Cui et al, 2012], another one is to eliminate the fine fraction of the aggregates, thus obtaining the so called no-fines concrete [Carsana et al, 2013]. In case the density reduction is obtained through the addition of air bubbles in the cementitious matrix, the lightweight special concrete is called cellular concrete. More in particular, if the air bubbles are obtained through the addition of preformed foam into the matrix, the resulting special concrete is called foamed concrete.

Compared to ordinary concrete, the mix design of the foamed concrete is much more complicated because, in addition to conventional parameters, such as the water to cement ratio, the granulometric assortment of aggregates, the amount of cement, the mineral additions, its properties are influenced by other factors: the nature and the amount of the foaming agent [Panesar, 2013], the mixing process [Falliano et al, 2020a], namely the type of mixing, the mixing intensity and the duration of mixing.

It is possible to improve the mechanical properties of foamed concrete thanks to the use of mineral additions, such as silica fume [Gökçe et al, 2019; Falliano et al, 2020b] or fly ash [Kearsley et al, 2001], or by increasing its consistency [Falliano et al, 2020b; Falliano et al 2020c], or including fibers of different nature, employed to improve the flexural capacity of this material [Kayali et al, 2003; Falliano et al, 2019a].

In this paper some solutions are proposed to improve the fracture energy of foamed concrete. In particular, two different target dry densities will be considered: 800 kg/m^3, a typical density for non-structural applications and 1600 kg/m^3, typical for possible structural applications. Results relating to non-structural density will highlight the significant influence of curing conditions on the fracture energy of foamed concrete. Instead, although the use of biochar gives promising results in terms of increasing fracture energy, further studies will be needed to limit the negative effect on the compressive strength.

2. Materials and methods

All the specimens were prepared using Portland cement CEM I 52.5 R; the chosen water to cement ratio was equal to 0.3. The foam was generated through an appropriate foam generator [Falliano et al, 2021], using a protein foaming agent. In fact, as well established in the relevant literature, the use of a protein foaming agent gives rise to better mechanical properties compared to synthetic ones [Falliano et al, 2018a]. Moreover, since the increase in the concentration of foaming agent improve the lifetime of a foam [Falliano et al, 2021], a 5% concentration of protein foaming agent was used for the production of both non-structural, 800 kg/m^3, and structural, 1600 kg/m^3, specimens. The resulting foam was characterized by a density of 85 ±5 g/l. In case of non-structural density, the foam to cement ratio was equal to 0.3, while for structural density this ratio was equal to 0.08. Indeed, an increase in foam's volume in the mix proportion leads to a decrease in cementitious material's density and, correspondingly, to an increase in its porosity, since air bubbles occupy a larger portion of the volume.

The 800 kg/m^3 foamed concrete specimens refer to the first possible strategy to increase the fracture energy: the choice of the best curing condition. In particular, two different series of four prismatic specimens each have been considered. The size of specimens, in accordance with JCI-S-001 standard [Japan Concrete Institute, 2003], was 20 mm x 20 mm x 80 mm. The two different curing conditions considered were: in accordance with UNI en 12390-2, namely in water at a temperature equal to 20°C; in air at a temperature of 20±3°C and a relative humidity equal to 70±5%.

The 1600 kg/m^3 foamed concrete specimens refer to the second possible strategy to increase the fracture energy of foamed concrete: the addition of biochar, a solid rich in carbon obtained through thermal decomposition and molecular cracking of organic matter, called biomass. Indeed, as already stated in the relevant literature, the biochar addition can improve the fracture energy of cementitious materials [Restuccia et al, 2016]. Three different series of four prismatic specimens each have been considered: reference (without the addition of biochar), 2% biochar addition (with reference to cement weight), 4% biochar addition (with reference to cement weight).

All the specimens were tested under crack mouth opening displacement-controlled three-point-bending tests using a Zwick-Line testing equipment, Fig. 1. A displacement rate of 0.005 mm/min was used. After this test, the two broken halves of each specimen were tested in compression. In this case the displacement rate used was equal to 0.5 mm/min.

Fig. 1. Zwick testing equipment.

The fracture energy G_F was computed through the following formula reported in JCI-S-001:

$$G_F = \frac{0.75 W_0 + W_1}{A_{LIG}} \tag{1}$$

Where $A_{LIG}[mm^2]$ represents the area of broken ligament, $W_0[Nmm]$ represents area below CMOD curve up to rupture of sample while $W_1[Nmm]$ represents the work done by deadweight of specimen and loading jig, given by:

$$W_1 = 0.75 \cdot \left(\frac{S}{L} m_1 + 2m_2\right) g \cdot CMOD_c \tag{2}$$

Being in the latter: S $[mm]$ the loading span, L $[mm]$ and $m_1[kg]$ the total length and the mass of the specimen respectively, $m_2[kg]$ the mass of the jig not attached to testing machine and placed on specimen, g $[m/s^2]$ the gravitational acceleration, $CMOD_c[mm]$ the crack mouth opening displacement at the time of rupture.

3. Results and discussion

To make the results clearer and more comprehensible, they will be presented in two different subparagraphs, relating to the two different strategies previously introduced.

3.1. Strategy 1: choice of the best curing condition

Curing conditions affect the properties of foamed concrete. The experimental finding illustrated in Fig. 2 highlight the significant differences in terms of fracture energy of samples cured in the two different curing conditions previously explained: samples cured in air showed a percentage increase of over 235% compared to those cured in water. Contrarily, compressive strength does not show such a marked influence of the curing conditions, in accordance with other studies [Falliano et al, 2018a].

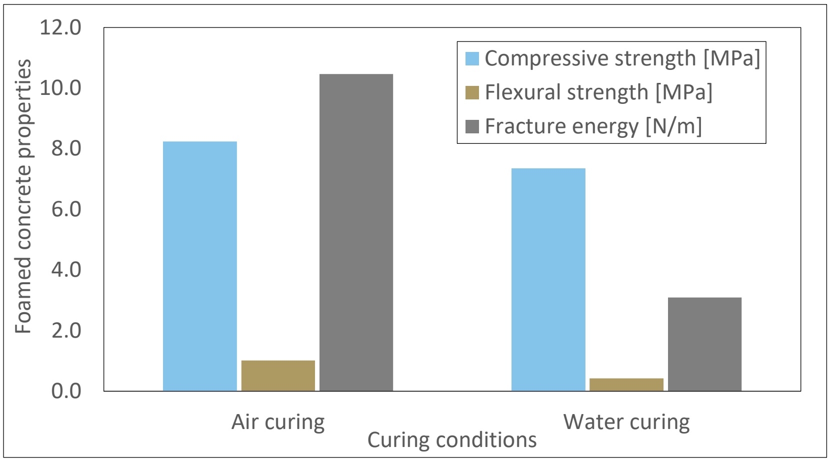

Fig. 2. Influence of curing conditions on 800 kg/m^3 density foamed concrete specimens properties.

From a macroscopic point of view this surprising result is justified by the greater tortuosity of the rupture surface in the case of air-cured samples. To better explain this important result, some FESEM micrographs are presented in Fig. 3. These micrographs highlight how the curing conditions affect the development of different hydration products.

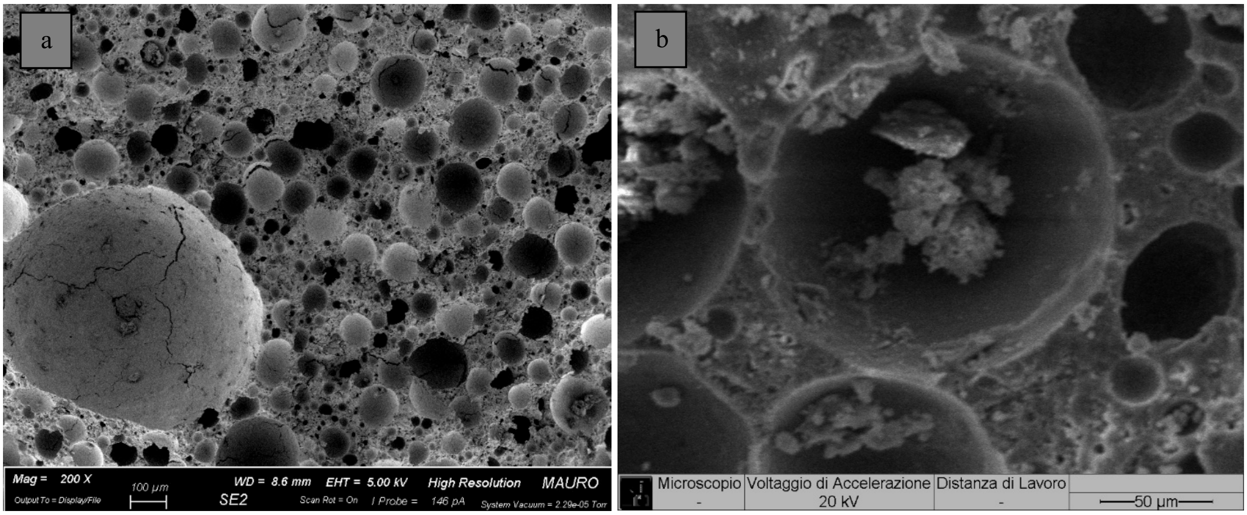

Fig. 3. SEM micrographs of foamed concrete specimens cured in air (a) and in water (b)

In particular, samples cured in air are characterized by products with an elongated and mono-oriented shape, characteristic of flattened crystals, contrarily, water-cured specimens, are marked by the presence of flower-like crystals. The different fracture behavior between the two curing conditions could be due to these significant morphological and microstructural differences, which give rise to a different crack path: a significant number of widespread microcracks that develop over the entire fracture surface for air curing condition and less widespread microcracks and less tortuous crack surface for water curing condition.

3.2. Strategy 2: addition of biochar

Strategy 2 consists of an eco-friendly addition to the cementitious matrix. Two different concentrations of biochar were studied: 2% and 4% of the cement weight. Compared to the previous mix design, as already reported previously, in this case the chosen target dry density was equal to 1600 kg/m^3, in fact studies concerning lightweight foamed concrete with the addition of biochar are currently in progress and will be shown in future works.
The results of the experimental tests in terms of flexural strength, fracture energy and compressive strength are reported in Fig. 4.

The use of 2% biochar concentration gives rise to an increase of the fracture energy of about 10% with respect to the lean samples (without biochar); however, this trend is not so evident in specimens with 4% biochar concentration, where there is a slight decrease of about 4% in the fracture energy values, compared to the lean samples. These results must be related on the one hand to the ability of the biochar particles to attract the crack, as they represent defects in the cementitious matrix, thus modifying the crack path so as to make it more tortuous and giving rise to advantages regarding the fracture energy of the material and, on the other hand, to the worsening of the resistance of the material, always greater as the percentage of biochar in the mixture increases. Although the results in terms of fracture energy are interesting, further studies are needed regarding the use of biochar in foamed concrete in order to limit, as much as possible, the negative effect on the compressive strength.

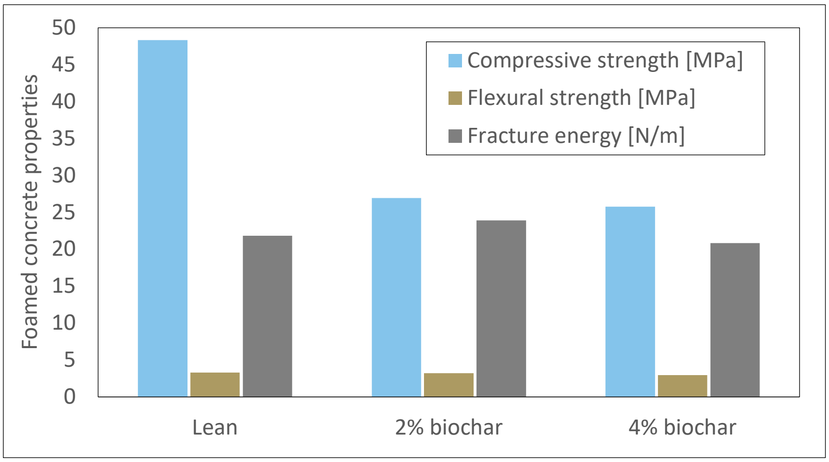

Fig. 4. Influence of biochar addition on 00 kg/m^3 density foamed concrete specimens properties.

4. Conclusions

In this contribution, two different strategies to improve the fracture energy of foamed concrete have been presented: choice of the best curing condition and addition of biochar.

With regard to the first strategy, it was highlighted that air curing condition results in a significant increase in both the fracture energy (over 235% compared to water curing condition) and the flexural strength (over 135% compared to water curing condition). Instead, the compressive strengths with the two different curing conditions are comparable. This different fracture behavior between the samples cured in air and those cured in water has been explained by the significant morphological and microstructural differences found in the samples cured in the two different curing conditions.

With regard to the second strategy, the addition of biochar at 2% concentration with respect to the cement weight, results to an increase of the fracture energy of about 10%. Further biochar additions do not translate into increases in fracture energy. In fact, the beneficial action of biochar in modifying the crack path is opposed by its negative influence on the mechanical properties of the material, which is increasingly evident as the concentration of biochar increases.

References

Carsana, M., Tittarelli, F., Bertolini, L., 2013. Use of no-fines concrete as a building material: Strength, durability properties and corrosion protection of embedded steel. Cement and Concrete Research; 48: 64-73.

Cui, H.Z., Lo, T.Y., Memon, S.A., Xu, W., 2012. Effect of lightweight aggregates on the mechanical properties and brittleness of lightweight aggregate concrete. Construction and Building materials; 35: 149-158.

Falliano, D., De Domenico, D., Ricciardi, G., Gugliandolo, E., 2018a. Experimental investigation on the compressive strength of foamed concrete: Effect of curing conditions, cement type, foaming agent and dry density. Construction and Building Materials; 165: 735-749.

Falliano, D., De Domenico, D., Ricciardi, G., Gugliandolo, E., 2019a. Compressive and flexural strength of fiber-reinforced foamed concrete: Effect of fiber content, curing conditions and dry density. Construction and Building Materials; 198: 479-493.

Falliano, D., De Domenico, D., Ricciardi, G., Gugliandolo, E., 2020a. 3D-printable lightweight foamed concrete and comparison with classical foamed concrete in terms of fresh state properties and mechanical strength. Construction and Building Materials; 254: 119271.

Falliano, D., Restuccia, L., Ferro, G.A., Gugliandolo, E., 2020b. Strategies to increase the compressive strength of ultra-lightweight foamed concrete. Procedia Structural Integrity; 28: 1673-1678.

Falliano, D., Crupi, G., De Domenico, D., Ricciardi, G., Restuccia, L., Ferro, G., Gugliandolo, E., 2020c. Investigation on the Rheological Behavior of Lightweight Foamed Concrete for 3D Printing Applications. In: RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2020, RILEM Bookseries, vol 28, pp. 246-254. Springer, Cham, DOI: 10.1007/978-3-030-49916-7_25.

Falliano, D., Restuccia, L., Gugliandolo, E., 2021. A simple optimized foam generator and a study on peculiar aspects concerning foams and foamed concrete. Construction and Building Materials; 268: 121101.

Gökçe, H.S., Hatungimana D., Ramyar K., 2019. Effect of fly ash and silica fume on hardened properties of foam concrete. Construction and Building Materials; 194: 1-11.

JCI-S-001: Method of Test for Fracture Energy of Concrete by use of Notched Beam, Japan Concrete Institute, Tokyo, Japan, 2003.

Kayali, O., Haque, M.N., Zhu, B., 2003. Some characteristics of high strength fiber reinforced lightweight aggregate concrete. Cement and Concrete Composites; 25(2): 207-213.

Kearsley, E.P., Wainwright, P.J., 2001. The effect of high fly ash content on the compressive strength of foamed concrete. Cement and concrete research; 31(1): 105-112.

Panesar, D.K.. 2013. Cellular concrete properties and the effect of synthetic and protein foaming agents. Construction and Building Materials; 44: 575-584.

Restuccia, L., Ferro, G.A., 2016. Promising low cost carbon-based materials to improve strength and toughness in cement composites. Construction and building materials; 126: 1034-1043.