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Fiber-reinforced lightweight foamed concrete panels suitable for 3D printing applications

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Abstract. This contribution presents a set of experimental results on fiber-reinforced innovative lightweight panels (FRIL-panels) having thickness of 12mm. These panels are prepared with a peculiar foamed concrete that has a high viscosity and cohesion in the fresh state, which makes it particularly suitable for 3D printing applications. The FRIL-panels can be used for internal partitions, external infills, and suspended ceilings of buildings as more effective solutions than conventional plasterboard ones, with better thermal insulation and acoustic absorption properties due to the internal air-void microstructure. The aim of this work is to investigate the out-of-plane resistance of FRIL-panels, prepared with a density of 800kg/m^3, under displacement-controlled three-point bending tests. In view of potential use in the precast industry, the FRIL-panels were placed into an accelerated concrete curing tank so as to speed up the overall production process. Modulus of rupture, ultimate deflection and collapse mode of FRIL-panels are critically analysed and discussed.

1. Introduction and motivations

In the field of construction materials, research is currently directed towards environmentally friendly solutions making use of materials that ensure good mechanical strengths in combination with efficient thermal insulation properties. Foamed concrete could be a viable solution that guarantees the achievement of the above-mentioned goals. Indeed, a portion of this material is occupied by air bubbles that replace cement or aggregates, thus lowering the self-weight (or density) significantly and allowing considerable saving of raw materials. The microstructural air-voids embedded in the cementitious matrix make this material particularly advantageous in comparison with ordinary concrete from different perspectives, including thermal insulation, acoustic absorption and fire resistance [1-3]. Additionally, the low self-weight is another interesting property that facilitates applications in situ when precast elements are considered, diminishes the overall weight in the structural assembly, and consequently, leads to lower inertial force in earthquake-prone areas.

The aforementioned advantageous characteristics are more pronounced in the low-to-medium density range (say <1200 kg/m^3), therefore a bulk of research was focused on the mechanical, physical and rheological characterization of lightweight foamed concrete (LWFC) characterized by different densities, foaming agents, cement types, curing conditions, mix designs [4-6]. Other research studies were focused on improving the mechanical characteristics of LWFC through either mineral additions such as fly ash, silica fume, or slags and by-products [7, 8], or reinforcement strategies involving fibers of different nature [9-12] or reinforcement grids [13].

Considering these peculiar characteristics, LWFC can also be used directly in situ for the realization of lightweight slabs, filling material in cavities, strengthening of soils, etc. On the other hand, in the precast industry LWFC can be usefully employed to realize blocks and panels for use in internal partitions of buildings, external environmentally-friendly infills, suspended ceilings and false walls. Although these are non-structural elements, adequate in-plane and out-of-plane strength and stiffness are required in such applications [14]. A particular type of LWFC was recently developed by the authors, which is called extrudable LWFC (E-LWFC) [11]. The E-LWFC is featured by a high cohesion and viscosity at the fresh state, which is achieved through the addition of a proper viscosity enhancing agent (VEA) in the mix design [11]. This specific characteristic allows the preparation of blocks or panels through an automated extrusion process (3D printing technology), thus optimizing the industrialization, eliminating the need of formworks and speeding up the overall production times in the precast industry. Additionally, the new material E-LWFC can be processed through 3D printing technology directly in situ.

This contribution aims to present the bending behavior of 12 mm thick fiber-reinforced innovative lightweight panels (FRIL-panels) realized with E-LWFC at a dry density of 800kg/m^3. The high viscosity of the material at the fresh state permits a low-cost and rapid preparation, as illustrated in the sequel of the paper. Motivated by the increasingly stringent requirements of short yet efficient production times in the precast industry, the FRIL-panels here investigated are placed in an accelerated concrete curing tank and ready to be tested within a couple of days from the preparation. This would allow their implementation in the construction market in very short times. A set of 5 FRIL-panels are subject to displacement-controlled three-point bending test and the corresponding force-displacement curve is recorded. Modulus of rupture, ultimate deflection and collapse mode are critically analysed and discussed.

2. Materials and methods

Five E-LWFC FRIL-panels having dimensions 60 x 225 x 12 mm are realized using a Portland CEM I 52.5 R, complying with the mix proportions of EN 197-1 standards. The dimensions are set in compliance with UNI EN 12467, which indicates the following limitations: i) span-to-thickness ≥ 15, ii) total length of the panel ≥ span + 40mm; iii) panel width ≥ 5 × panel thickness.

A water/cement ratio equal to 0.3 is adopted throughout. The lightweight features of the FRIL-panels are obtained through the addition of a preformed foam into the cement matrix. The preformed foam is realized by a proper foam generator mixing tap water, air (pressure 3 bar) and foaming agent (concentration of 5% of the water volume). A protein-based foaming agent called Foamin C® is employed, whose peculiar properties were reported in [4]. The resulting foam density is around 85 ± 5 g/l. The mix design also incorporates a VEA with a concentration of 5% of the cement weight.

The foamed concrete material is produced by mixing water, cement and VEA and gradually introducing a proper amount of foam (foam-to-cement ratio equal to 0.3) and mixing the resulting paste at a speed of 3000 rpm with a vertical mixer, so as to achieve a value of fresh density of the cementitious mix equal to 1050 kg/m^3, which corresponds to a dry density (evaluated after oven-dry the samples) roughly equal to 800 ± 50 kg/m^3.

In the preparation of the E-LWFC a bi-directional grid reinforcement is used, using alkali-resistant glass fiber mesh produced by Fassa Bortolo (trademark name Fassanet 160). The mesh has specific mass per unit surface of 160 g/m^2, square unit cell of 4.0mm side, a tensile strength ≥ 35N/mm and an ultimate elongation of 5%.

In figure 1 we report the main phases of the specimen preparation. Firstly, lateral metallic blocks acting as guides are located to define the in-plan dimensions of the panels. Secondly, the bottom reinforcement grid is placed and the E-LWFC fresh paste is poured for the entire thickness of the panel. Thirdly, the top reinforcement grid is placed and the upper surface is polished and smoothed out. Finally, the metallic guides are immediately removed after polishing the surface, so as to exploit them for the preparation of the subsequent samples. In this way, the green strength of the E-LWFC at the fresh state is conveniently exploited to speed up the overall production times because there is no need of waiting for the initial setting of foamed concrete before removal of the guides. In figure 2 it is possible to notice the absence of any settlement of the sample after removal of the lateral guides (i.e., the material is able to keep its shape without lateral expansions). This peculiar characteristic is particularly convenient in view of possible applications in the 3D printing field.

Figure 1. Preparation of samples of FRIL-panels: a) realization of guides and placement of the bottom bi-directional grid reinforcement; b) pouring of fresh E-LWFC paste; c) polishing of the upper surface and placement of the top bi-directional grid reinforcement; d) final samples before removal of guides.

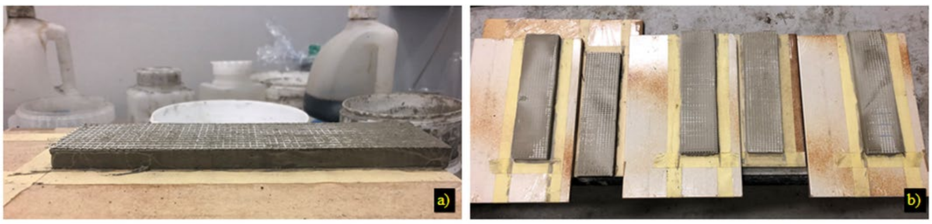

Figure 2. Final samples of FRIL-panels: a) removal of lateral guides and assessment of the self-supporting capacity immediately after the pouring phase: b) series of 5 FRIL-panels left at environmental conditions (pre-curing phase) for 12 hours.

After removal of the metallic guides, the samples undergo a pre-curing phase of 12 hours in air at environmental laboratory conditions (temperature 20 ± 3°C, relative humidity 65-75%). The reason why the specimens are not immediately placed into the water tank for the accelerated curing process is related to the internal microstructure of the E-LWFC samples themselves. Indeed, at this stage (material at the fresh state) an imposed temperature increase would cause an expansion of the air bubble volume within the cement matrix, thus yielding diffused cracking phenomena in the external concrete layer. A pre-curing time of 12 hours at environmental conditions leads to a higher hydration degree of the cement paste that prevents the aforementioned cracking phenomena. After the pre-curing phase of 12 hours, the samples are then introduced into the accelerated concrete curing tank (cf. figure 3) and subject to the following accelerated curing cycle: a) in the first 6 hours there is an increase from the environmental temperature up to 70°C; b) in the subsequent 4 hours the temperature is kept constant at 70°C; c) to avoid thermal shocks in the cooling phase, the temperature is gradually reduced (for at least 2 hours) until achievement of the initial environmental value. This particular curing process has been selected to speed up the overall production time thus making the introduction of the E-LWFC in the construction market easier and more rapid. However, the attainment of the minimum modulus of rupture (MOR) prescribed in the EN 12467 regulations with such accelerated curing process must be verified afterwards, which represents the motivation of the present experimental campaign.

Figure 3. Curing conditions: a) accelerated concrete curing tank; b) 5 FRIL-panels immersed in water.

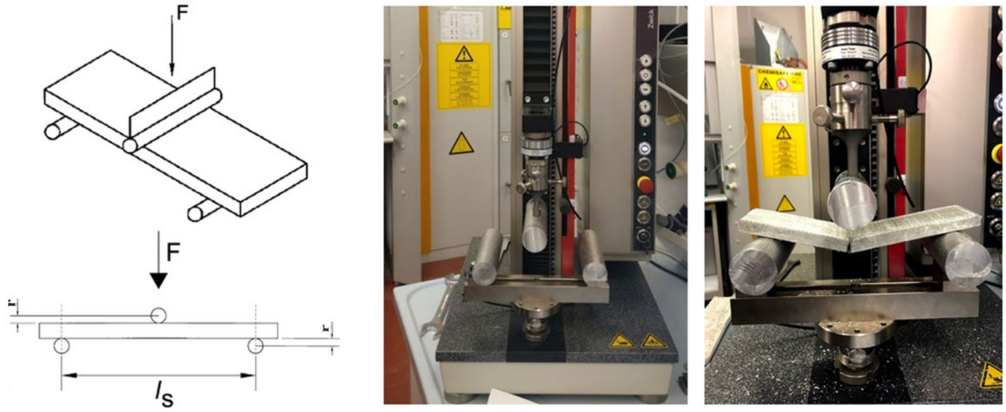

Figure 4. Schematic of the testing condition (left), actual testing equipment for MOR determination (centre) and final collapse of a representative FRIL-panel (right).

Three-point-bending tests are carried out with a ZWICK testing equipment having a 2.5kN load capacity, as shown in figure 4. The UNI EN 12467 prescribes that the failure of the specimen should occur within a range between 10 sec and 30 sec, therefore a preliminary sensitivity study has been carried out with a displacement rate of 6 mm/min (panel L1). The failure for this panel occurred in 78 sec (therefore exceeding the maximum value recommended by the regulations), this is why the subsequent tests have been performed with a displacement rate of 10 mm/min, thus obtaining compliance with the requirements of the UNI EN 12467. As to the roller supports, steel cylinders with a radius of 20mm have been used in accordance with UNI EN 12467. The span of the panels is 185 mm, and satisfies the geometrical requirements of the standards.

3. Results and discussion

From the force registration, the formula for computing the modulus of rupture (MOR) corresponding to the peak force is adopted, following UNI EN 12467, which is reported below

$$\mathrm{MOR}=\frac{3F_{\max}l_s}{2be^2} \tag{1}$$

where $F_{\max}$ is the peak load [N], l_s is the span between the axes of supports [mm], b is the width of the specimen [mm], e is the panel thickness [mm]. Corresponding load-displacement curves for the 5 FRIL-panels are shown in figure 5, while a representative collapse mode (for panel L4) is illustrated in figure 6. In figure 5, we purposely separated the results of the panels L1, L2, L4 from those of the panels L3, L5. This is motivated by the different failure behaviour of the two classes of specimens, as will be clarified below. From the left part of figure 5 we observe that the displacement rate has a certain influence on the peak load (which affects the MOR) because the L1 specimen was tested with a displacement rate of 6 mm/min, in contrast to the other specimens where a higher velocity was adopted (10 mm/min) to meet the requirements of the UNI EN 12467, as said above. Moreover, the displacement rate also influences the first-crack load, which corresponds to the first abrupt change of slope in the force-displacement curve. The first-crack load is ascribed to the tensile strength of the E-LWFC (without fiber reinforcement) and is recorded at the appearance of the first crack at the panel soffit propagating upwards, as depicted in figure 6a)-b). Subsequently, a moderate decrease of the load is observed until the glass-fiber reinforcement is engaged in the load bearing capacity. At this stage, the load increases progressively while additional cracks may develop in the E-LWFC, as illustrated in figure 6c). The final collapse takes place with a detachment in the tensile zone of the glass-fiber reinforcement mesh from the overlying foamed concrete, figure 6d). This typical collapse mode was observed in all the 5 FRIL-panels. Although all the specimens had a qualitatively similar collapse mode, specimens L3 and L5 are characterized by a MOR drastically lower than the other 3 samples. This is due to a premature detachment of the glass-fiber reinforcement mesh from the foamed concrete owing to a non-perfect preparation of the specimens. Indeed, we noticed that the detached mesh was not fully covered by foamed concrete. Careful attention must be paid to this issue during the preparation of the samples, otherwise the mesh should be more effectively placed adopting a certain concrete cover.

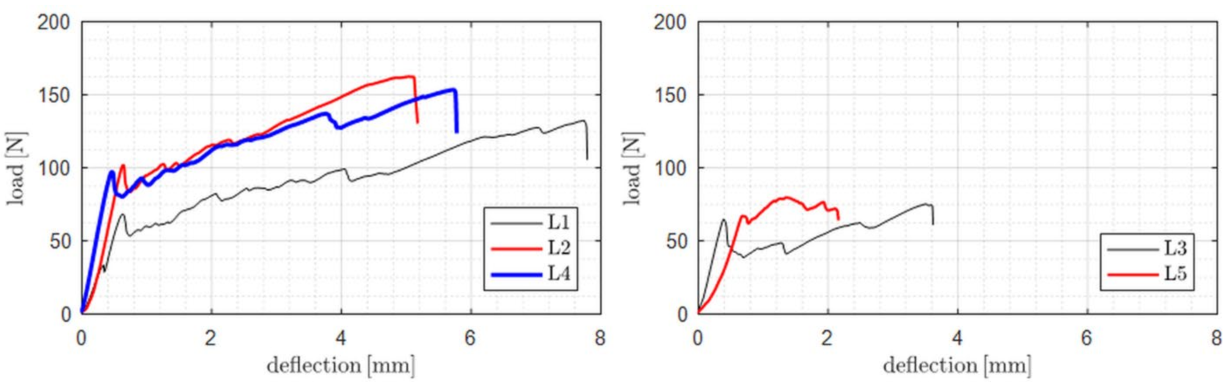

Figure 5. Force-deflection curves for the five FRIL-panels under three-point-bending test.

As to the specimens L1, L2, L4 the average MOR value is 4.44 MPa. According to table 6 of UNI EN 12467, these specimens can therefore be classified as class 1 (because the MOR > 4 MPa).

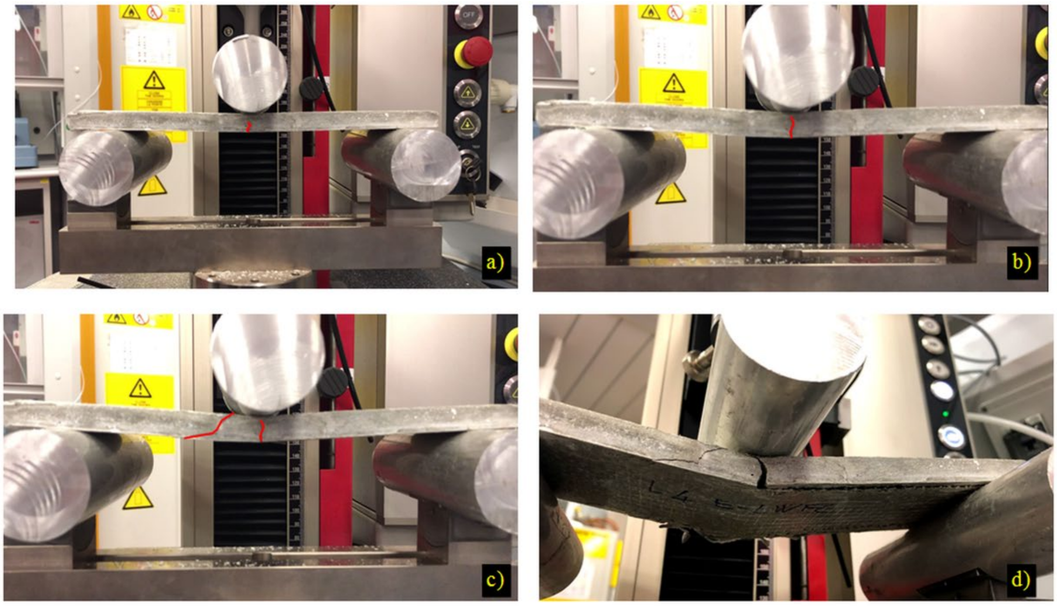

Figure 6. Typical collapse mode of FRIL-panels under three-point-bending test.

4. Conclusions

In this work, the modulus of rupture and the collapse mode of a series of fiber-reinforced E-LWFC panels have been evaluated from an experimental point. The possibility of using the innovative E-LWFC as construction material leads to several advantages in the production process, because of its high cohesion and viscosity at the fresh state. Indeed, these peculiar properties eliminate the need of formworks and speed up the preparation of the specimens in the precast industry, as well as enable potential use in 3D printing applications. Additionally, in order to shorten the production times as much as possible for the straightforward introduction in the construction market, these panels have been subject to an accelerated curing process in water tank. The overall production times are thus limited to within 2 days. The resulting force-displacement curves extracted from the three-point-bending tests have revealed that the lightweight foamed concrete panels abide by the requirements of the UNI EN 12467 in terms of MOR value and falls into class 1 (MOR > 4 MPa).

This experimental work paves the way for new perspectives in the realization of economic blocks and panels with high thermal efficiency and acoustic absorption, reasonably good mechanical strength and rapid production process. Further research will be aimed at extending the present work by investigating other densities and curing conditions.

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