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Structural foamed concrete: preliminary studies for applications in seismic areas

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Abstract

The experimental research presented in this contribution highlights the possibility of producing foamed concretes with target dry densities of 1550±50 kg/m^3 and 1750±50 kg/m^3 for the use in structural applications, thanks to compressive strengths greater than 25 MPa. The lower structural weight compared with ordinary concrete suggests the idea of using this material in seismic areas to exploit its advantages in relation to inertial forces. However, the reduced elastic modulus compared with ordinary concrete of equal compressive strength must be considered. In addition to demonstrating the beneficial effect of reducing the maximum diameter of the fine sand used to produce the foamed concrete, this contribution also shows how the behavior of a reinforced concrete frame changes (increase in the main vibration mode and decrease of the maximum shear at the base of the frame) if the foamed concrete presented in this study is used instead of ordinary concrete of equal compressive strength.

Keywords: Structural foamed concrete; compressive strength; lightweight concrete; reinforced concrete frame.

1. Introduction

Foamed concrete belongs to the category of lightweight concrete; this material is characterized by a system of air voids that can be interconnected (open-cell structure) or not interconnected (closed-cell structure); the presence of the pores makes it possible to achieve low density values, between 100 kg/m^3 (Falliano et al, 2022) and 2000 kg/m^3, when compared with those of a traditional concrete. The void system, within the mixture, can be achieved in different ways.

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One of the most widely used, also employed in the present study, is to mix a preformed foam to the cementitious mortar. Foamed concrete, because of the wide range of densities achievable, can be used for several purposes; in fact, depending on the density reached, it can be used in both non-structural and structural applications. There are a large number of studies in the relevant literature related to the application of foamed concrete for non-structural purposes, mainly focused on evaluating the influence of certain key parameters on the rheological (Falliano et al, 2020a), mechanical and physical properties of the material, such as: type of foaming agent (Panesar, 2013), (Falliano et al, 2021), presence and dosage of fibers (Raj et al, 2020), (Falliano et al, 2019), water-to-cement and air-to-cement ratios (Tam et al, 1987). On the other hand, there are very few studies concerning the application of this material in the structural field. Among the few studies in the literature on foamed concrete for structural applications, the effect provided by the complete replacement of sand with coarse fly ash was investigated in (Jones et al, 2005). In all the mixtures presented, with densities of 1400 kg/m^3, 1600 kg/m^3, and 1800 kg/m^3, a 56-days compressive strength greater than or equal to 25 MPa was achieved; moreover, the strength values achieved were up to 2.5 times higher than those for mixtures with sand. (Hilal et al, 2015) investigated the effect of replacing part of the cement with silica fume (10% by weight) and part of the sand with fly ash (20% by weight) and obtained a 28-days compressive strength of approximately 33 MPa, with a density of 1600 kg/m^3. To accelerate the development of compressive strength in a foamed concrete, Ordinary Portland cement can be replaced with magnesium phosphate cement (Ma et al, 2017). In particular, magnesium phosphate cement, made it possible to obtain a foamed concrete mixture capable of developing in just three hours 70% of the 28-days compressive strength. The compressive strength achieved at 28 days, with a density of 1300 kg/m^3, was slightly lower than 25 MPa. In order to obtain foamed concrete with less environmental impact, some authors have proposed using oil palm shells as coarse aggregate (Alengaram et al, 2013). Oil palm shell is a waste material produced during the extraction of palm oil, and millions of tons of this material are produced annually worldwide. The resulting mixture, using both sand as fine aggregate and oil palm shell as coarse aggregate, achieved a 28-day compressive strength of 20.2 MPa, with a density of 1600 kg/m^3. In the present research work, based on the authors' experience in the field of low-density foamed concretes, efforts were made to produce a foamed concrete mixture with suitable mechanical properties for the use in the structural field, trying to obtain a compressive strength of at least 25 MPa. The advantages that could result from using the material introduced in this research work for the construction of a reinforced concrete building in a high seismicity zone are also preliminarily presented. In fact, the use of lightweight concrete in the structural field allows, in seismic areas, for the significant advantage of reducing structural masses. A structure characterized by lower masses will result in lower stresses on structural elements due to seismic action with benefits at several levels.

2. Materials and methods

To produce the foamed concrete mixtures, Portland CEM I 52.5 R and tap water were used. This type of cement is in compliance with UNI EN 197-1 standard in terms of the mixing proportions of the main constituent ingredients. Four different maximum diameters of the fine quartz sand were selected to highlight the effect of maximum diameter of the fine sand on the mechanical performance of foamed concrete: 0.25 mm; 0.5 mm; 2 mm; 4 mm. Based on previous studies on low-density foamed concretes, foaming agent of protein nature (Falliano et al, 2018), superplasticizer, and viscosity enhancing agent (Falliano et al, 2020b) were selected. The protein foaming agent was used to produce preformed foam with density equal to 85±5 g/l. In fact, in accordance with most experimental studies in the pertinent literature, foam concrete specimens were prepared by the preforming procedure. Mixing was performed using a vertical mixer for minimum 2 minutes and, in any case, until a homogenous paste was reached, Fig.1. Two different target dry densities were addressed in this study, namely 1550±50 kg/m^3 and 1750±50 kg/m^3. Six series each consisting of three prismatic samples of dimensions 40 mm x 40 mm x 160 mm were produced. All series were realized using the same sand-to-cement ratio, equal to 2.3, and vea-to-cement ratio, equal to 0.05. The complete mix proportion is shown in Table 1, where *w* stands for water, *c* for cement, *s* for sand, *v* for viscosity enhancing agent, *sp* for superplasticizers, *f* for foam; moreover, the sample denomination in Table 1 reports the target dry density, and the maximum diameter of the fine sand used.

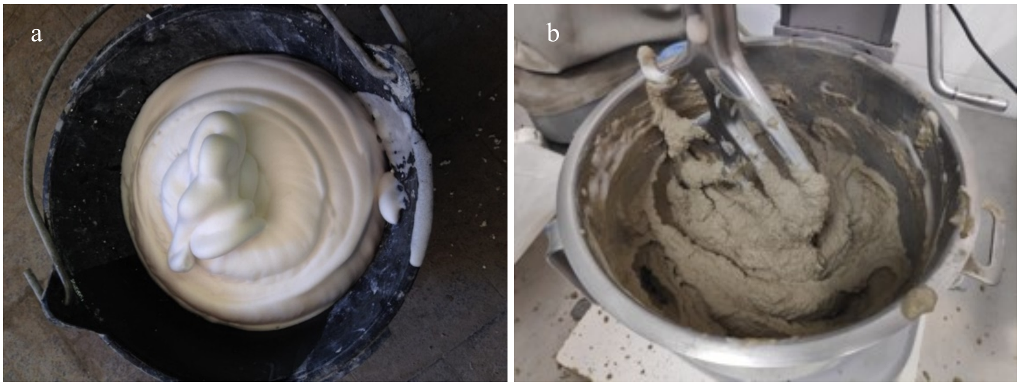

Fig. 1. (a) preformed foam; (b) foamed concrete.

The specimens were demolded after 24 hours and cured in water. Three point bending test and compressive test were carried out after 28 days according to UNI EN 196-1. As mentioned, the best result obtained from this experimental campaign is used to carry out a comparative study in terms of main vibration modes and maximum shear at the base of a reinforced concrete frame realized with the material here presented or with ordinary concrete characterized by the same compressive strength.

Table 1. Mix proportions

Specimen class	*w*/*c*	*s*/*c*	*v*/*c*	*sp*/*c*	*f*/*c*
1750_0.25	0.33	2.3	0.05	0.02	0.21
1750_0.5	0.33	2.3	0.05	0.03	0.12
1750_2	0.33	2.3	0.05	0.02	0.12
1750_4	0.33	2.3	0.05	0.02	0.12
1550_0.25	0.45	2.3	0.05	0.03	0.12
1550_2	0.33	2.3	0.05	0.03	0.12

3. Results and discussions

The results obtained in terms of 28-days flexural strength and compressive strength are shown in Figures 2 and 3. In particular, Fig. 2 shows the influence of the maximum diameter of the fine sand used on the flexural (Fig. 2a) and compressive (Fig. 2b) strengths of foamed concretes characterized by a target dry density equal to 1750±50 kg/m^3. It is pointed out that, although it falls (even if only slightly) outside the target dry density range considered, it was decided to maintain the series produced with maximum aggregate diameter of 4 mm, as it is useful for the discussion of the results and it is consistent with the findings of the experimental campaign. It can be seen that the best results are obtained in the case of the smaller maximum diameters, namely 0.25 and 0.5 mm. In fact, as the maximum particle diameter increases, and particularly for the diameter of 4 mm, there is a marked decay in mechanical performance. This result is due to the disturbance caused by these larger-diameter particles during the mixing stages of the material, with the effect of increased instability of the system that adversely affects the microstructure of the material in the hardened state. The drastic reduction in compressive strength (about 58% passing from a maximum diameter of 0.25 mm to a maximum diameter of 4 mm) makes it clear the importance of design of a stable system at the fresh state that will result in an excellent pore microstructure of foamed concrete at the hardened state, and, from this point of view, how crucial is the design parameter maximum diameter of the aggregate in this type of special concretes.

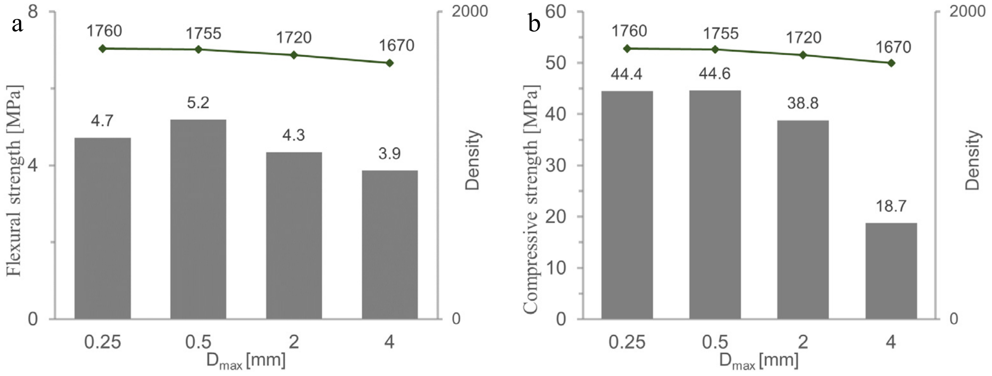

Fig. 2. (a) influence of the maximum aggregate diameter on the flexural strength of foamed concrete with a target dry density equal to 1750±50 kg/m^3; (b) influence of the maximum aggregate diameter on the compressive strength.

These results are also confirmed at the target dry density of 1550±50 kg/m^3, Fig. 3. In particular, what was previously stated is emphasized at lower densities. In fact, at 1750±50 kg/m^3, the reduction in compressive strength, passing from a maximum diameter of 2 mm to a maximum diameter of 0.25 mm, was about 13%, while at 1550±50 kg/m^3, this reduction is much more significant, about 33%. In fact, as density decreases, an increasing influence of this design parameter on the mechanical performance of the material can be expected, given the increasing amount of air voids in the cementitious conglomerate.

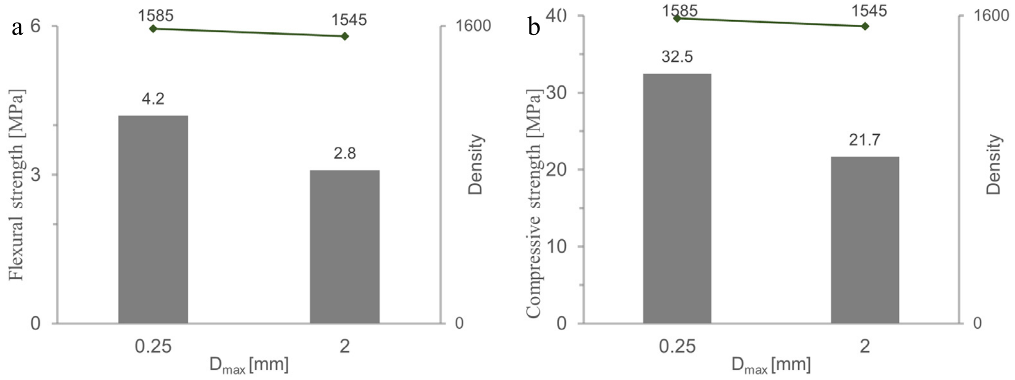

Fig. 3. (a) influence of the maximum aggregate diameter on the flexural strength of foamed concrete with a target dry density equal to 1550±50 kg/m^3; (b) influence of the maximum aggregate diameter on the compressive strength.

It is very interesting to note the excellent compressive strength (more than 44 MPa and more than 32 MPa for 1750 and 1550 kg/m^3 target dry density, respectively) associated with the series produced with the smaller maximum diameters of the fine sand presented in this study. In fact, the results presented here are well comparable with the compressive strengths related to a material that is not only much better known, but also standardized, namely lightweight concrete made from lightweight aggregates, particularly expanded clay. This result is even more surprising when considering that it can be improved in future work by the use of mineral additions such as, for example, silica fume.

4. Outlook: applications in seismic areas

In order to highlight the beneficial effect that can be obtained from the application of the foamed concrete named 1550_0.25 presented in this work (compressive strength of 32.5 MPa) in a seismic area, this section compares the main vibration modes and the maximum shear at the base of a reinforced concrete frame in the case of using this material or a conventional concrete (density equal to 2400 kg/m^3; elastic modulus equal to 30867 MPa) of the same compressive strength for its realization. This is a preliminary analysis that will be presented in more detail in a forthcoming study, after also determining the actual elastic modulus of the material. An elastic modulus (equal to 16120 MPa) determined on the basis of the experimental compressive strength through an empirical relationship presented in (Jones et al, 2005) was used for this preliminary analysis. A reinforced concrete frame consisting of six floors, regular in both plan and height, and located in a high seismic hazard area (pick ground acceleration equal to 0.25g) was considered. The structure is characterized by a rectangular plan and a number of spans equal to five in x-direction and equal to three in y-direction; the spans have lengths equal to 5 m, Fig. 4.

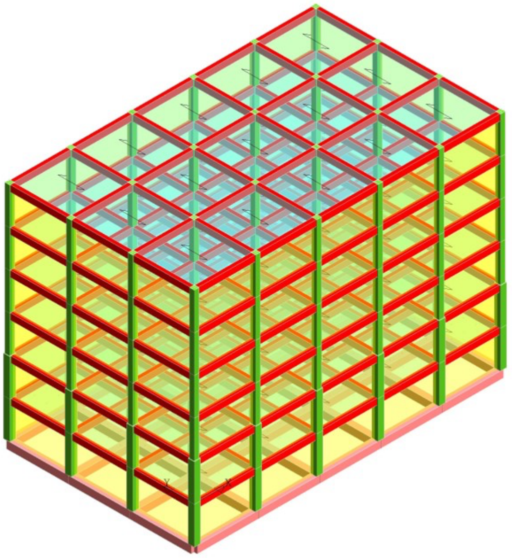

Fig. 4. Reinforced concrete frame consisting of six floors considered in the analysis.

The structure is characterized by square-section pillars of 50 cm side for the first two floors, and 40 cm side for the remaining floors. The analysis performed shows that the use of foamed concrete instead of ordinary concrete of equal compressive strength results in an increase of about 20% in the main vibration mode and in a significant decrease of the maximum shear at the base of the frame of about 38%. As expected, the use of foamed concrete gives a significant benefit in seismic areas due to the reduction in mass that leads to consequential reductions in earthquake actions on structural elements. However, the assessment of the actual benefit cannot take into account mass alone, as changes in terms of the stiffness of the structures are also crucial. In fact, as highlighted by the results of the analysis, the use of structural foamed concrete also results in changes in the fundamental period of vibration of the structures. In fact, since this material is characterized by a lower elastic modulus than ordinary concrete of equal compressive strength, it will result in greater deformability, which will result in greater vibration periods.

5. Conclusions

This paper has presented foamed concrete mixtures characterized by mechanical properties suitable for the use in the structural field. In particular, the best mixture at the target density of 1750 kg/m^3 is characterized by flexural strength of 5.2 MPa and compressive strength of 44.6 MPa, while the best mixture at the target density of 1550 kg/m^3 is characterized by flexural strength of 4.2 MPa and compressive strength of 32.5 MPa. Experimental findings have revealed that reducing the maximum diameter of the fine sand results in beneficial effects on the mechanical properties of foamed concrete. Mixture optimization and the use of mineral additions will make it possible to obtain foamed concretes characterized by even better mechanical performance than those presented here. Considering these improvements, it will be possible to define the lowest density that can be used for structural purposes. The use of this type of concrete for the construction of structures in seismic areas can have significant advantages. A preliminary analysis performed on a six-story reinforced concrete frame revealed that the use of the foamed concrete of compressive strength equal to 32.5 MPa and effective density equal to 1585 kg/m^3 presented in this study, instead of ordinary concrete of equal compressive strength, results in an increase of about 20% in the main vibration mode and in a significant decrease of the maximum shear at the base of the frame of about 38%. These advantages coupled with the peculiarities of lower raw materials exploitation and lower environmental impact of foamed concrete lead to a growing interest in the possibility of exploiting this material not only for non-structural purposes, but also for structural aims.

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