Mechanical Characterization of Extrudable Foamed Concrete: An Experimental Study

D. Falliano, D. De Domenico, G. Ricciardi, E. Gugliandolo

***Abstract*—**This paper is focused on the mechanical characterization of foamed concrete specimens with protein-based foaming agent. Unlike classic foamed concrete, a peculiar property of the analyzed foamed concrete is the extrudability, which is achieved via a specific additive in the concrete mix that significantly improves the cohesion and viscosity of the fresh cementitious paste. A broad experimental campaign was conducted to evaluate the compressive strength and the indirect tensile strength of the specimens. The study has comprised three different cement types, two water/cement ratios, three curing conditions and three target dry densities. The variability of the strength values upon the above mentioned factors is discussed.

***Keywords*—**Cement type, curing conditions, density, extrudable concrete, foamed concrete, mechanical characterization.

I. Introduction

FOAMED concrete is increasingly studied owing to the resulting lightweight properties, economic implications and for the higher availability of its constituting ingredients: cement, water, preformed foam and, in some cases, fine sand and other additions like silica fume and/or fly ash [1]-[3]. Investigating the mechanical strength of foamed concrete under a range of conditions that may occur during the preparation and casting process is highly interesting and important research subject [4]-[8].

In this contribution, an experimental campaign focused on the evaluation of the mechanical characteristics of foamed concrete specimens with protein-based foaming agent [9] is discussed. Unlike classic foamed concrete, this material can be extruded via the introduction of a specific additive in the concrete mix that significantly improves the cohesion and viscosity without worsening the workability of the fresh cementitious paste [10]-[12]. This unconventional characteristic is advantageous for applications of this material in the context of prefabricated elements. In this study, a set of specimens were prepared with this variant of foamed concrete, using a protein-based foaming agent. These specimens were tested at 28 days to determine the compressive strength and the tensile strength via three-point-bending tests. The examined class of specimens comprised dry densities ranging from 300 kg/m^3 up to 850 kg/m^3 (corresponding to three target dry densities of 400, 600 and 800 kg/m^3) and involved different curing conditions, namely in air at environmental temperature, in cellophane at environmental temperature and in water at controlled temperature of 30 °C. Additionally, three different cement types were used to prepare the specimens: Portland CEM I 52,5 R, limestone Portland CEM II A-L 42,5 R and pozzolanic cement CEM IV/A. Finally, two water/cement ratios have been analyzed, namely $w/c = 0.3$ and $w/c = 0.5$.

Despite the different rheological behavior of the extrudable foamed concrete, the corresponding compressive strength values were comparable to values obtained with classic foamed concrete mixes in an earlier experimental campaign [4]. As normally expected, the compressive strength as well as the tensile strength increases with increasing density. Among the three curing conditions, it has been found that the water curing conditions lead to the highest strength values. The influence of the water content on the attainment of the strength is also investigated for some specimens. In line with other research works from the relevant literature, the final strength of the specimens is affected by the combined action of both water and air, and not on the individual water/cement ratio [13]. These preliminary encouraging results on this type of foamed concrete motivates the authors to further extend the investigation in order to analyze other specimens, including real scale structural elements for civil engineering applications.

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II. Experimental Campaign

A wide class of foamed concrete specimens was prepared to investigate different factors affecting their strength. For the assessment of the compressive strength a set of 5 cm side cubes were prepared as shown in Fig. 1. Moreover, a set of prismatic 4x4x16 cm specimens were also prepared to perform indirect tensile strength from three-point-bending tests, as illustrated in Fig. 1. The choice to prepare cubes of 5 cm side is motivated by savings of times and materials, but is also justified by earlier experimental studies in the literature [14].

A. Materials

The specimens were prepared with three types of cement, namely Portland CEM I 52,5 R, limestone Portland CEM II A-L 42,5 R and pozzolanic CEM IV/A 42,5 R. Composition of these cement types is set in accordance with EN 197-1 (2006) standards. The foaming agent employed to generate the foam is a protein-based one called Foamin C® (trademark name), which is usually adopted in the field of cellular concrete.

Fig. 1 Preparation of extrudable foamed concrete specimens

B. Specimen Preparation, Mix Proportions and Curing Conditions

At first, a foam with density of 80 g/l was generated through an appropriate foam generator with a foaming agent concentration equal to 3% in volume and an air pressure of 3 bar. This foam was then introduced into the water + cement + additive mix. The additive used to give rise to the extrudability characteristics of the foamed concrete specimens is a chemical agent able to increase the viscosity and the cohesion of the fresh cementitious paste. The mix proportions were calibrated in order to achieve target dry densities equal to 400, 600 and 800 kg/m^3. Two fixed water/cement ratios are adopted, and the foam content is adjusted to obtain the target dry density. The amount of cement ranged from about 330 kg/m^3 for the lowest densities, up to 670 kg/m^3 for the highest ones. The water content ranged from about 100 kg/m^3 to about 210 kg/m^4 for the $w/c = 0.3$ ratio, and from about 160 kg/m^3 to about 340 kg/m^4 for the $w/c = 0.5$ ratio. The latter $w/c = 0.5$ ratio was investigated to assess the influence of the water/cement ratio on the strength, but it was found that only the specimens with $w/c = 0.3$ can be extrudable, i.e., exhibited a dimensional stability in the green strength that denotes the capacity of the specimen to retain the shape of the mould at fresh state after de-moulding. This is illustrated in Fig. 2.

For each series of tested specimens (having identical cement type and water/cement ratio) three different curing conditions were analyzed as depicted in Fig. 3, namely in air at environmental temperature, wrapped in cellophane and in water at controlled temperature of 30 °C. Wrapping the specimens in cellophane minimizes the evaporation and thus reduces de-hydration of the foamed concrete specimens, which leads to an improved hydration of the cement paste.

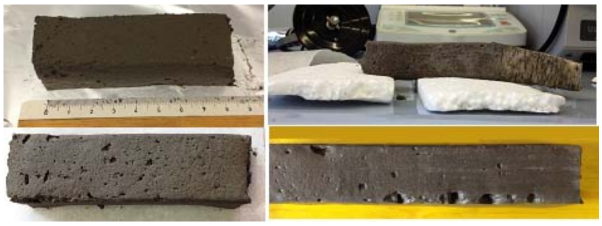

Fig. 2 Dimensional stability of extrudable foamed concrete at fresh state (green strength)

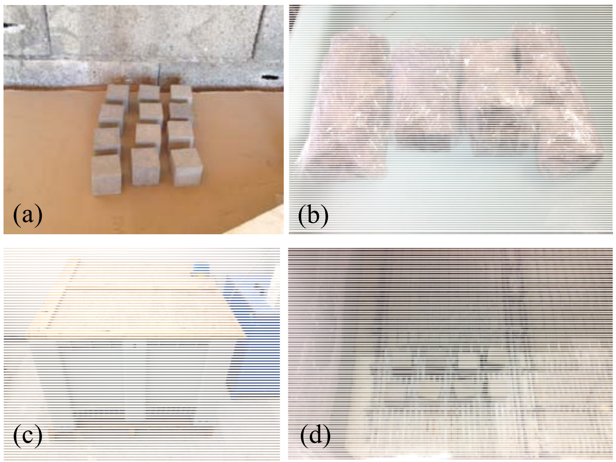

Fig. 3 Curing conditions of the specimens: (a) in air at environmental temperature; (b) wrapped in a cellophane sheet at environmental temperature; (c) and (d) in water at controlled temperature

Fig. 4 Photograph of the test frame with twin columns used in the experimental campaign for the compressive and indirect tensile tests

C. Testing Conditions and Standards

The testing equipment is a CONTROLS test frame model 65-L1301/FR and consists of a twin column rigid steel construction as shown in Fig. 4, which is devoted to both compressive and indirect tensile strength tests. The compressive strength was measured according to ASTM C109 standards. The pertinent column has 250 kN load capacity. The tensile strength was measured according to the UNI EN 196-1:2005 standards with the same testing frame. In the latter case the column has a 15 kN load capacity. In the former case the load rate employed was equal to 1000 N/s, with a set point of 0.10 kN and for each specimen the peak load was recorded and then the maximum compressive stress was computed. For the tensile strength the load rate was of 50 N/s.

III. Results

The compressive and tensile strength values were determined at 28 days after casting in the different curing conditions specified above. A limited set of results that are more relevant to this comparative study are presented.

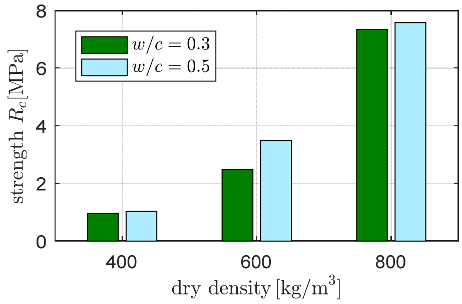

Fig. 5 Effect of w/c ratio on the compressive strength (cement type CEM II A-L 42,5R, air curing conditions)

In Figs. 5 and 6 the effect of the w/c ratio on the achievement of the compressive strength is illustrated for air and cellophane curing conditions, respectively. It can be noticed that the w/c ratio has a different influence in the analyzed curing conditions. More specifically, for air curing conditions the compressive strength is found to slightly increase with increasing w/c. This can be motived in connection with the premature de-hydration of the specimen in this specific curing condition, which in general proved to be the worst one among the three analyzed. For a higher w/c than 0.3 the effects of such premature de-hydration of the specimens are mitigated due to a higher fluid phase in the cementitious paste, which allowed the achievement of a better hydration degree of the cement. These statements are opinions of the authors, and further investigation on the microstructural properties of the specimens is currently being performed to validate this hypothesis. On the contrary, as normally expected, increasing the w/c ratio in the other two curing conditions (water curing conditions are qualitatively similar to those of the cellophane curing and are not reported for brevity) led to a decrease of the compressive strength values, as can be seen in Fig. 6.

A unified comparison of the compressive strength values for the three analyzed curing conditions is reported in Fig. 7 for the CEM IV/A 42,5R and $w/c = 0.3$. In this case, the highest strength values are found when the specimens cured in water. Values of compressive strength found for cellophane and air are more or less comparable with each other.

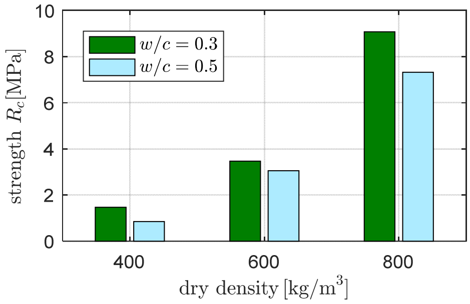

Fig. 6 Effect of w/c ratio on the compressive strength (cement type CEM II A-L 42,5R, cellophane curing conditions)

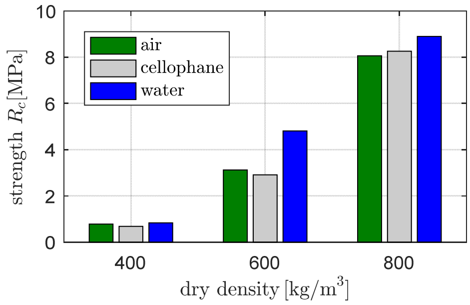

Fig. 7 Effect of curing conditions on the achievement of the compressive strength (CEM IV/A 42,5R, $w/c = 0.3$)

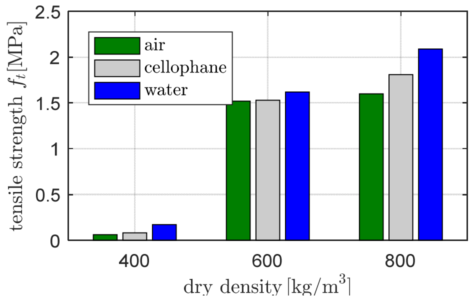

Fig. 8 Effect of curing conditions on the achievement of the tensile strength (CEM I 52,5R, $w/c = 0.3$)

Results in terms of indirect tensile strength confirmed the qualitative conclusions drawn above for the compressive strength. As an example, in Fig. 8 the tensile strength values for the CEM I 52,5R and $w/c = 0.3$ are shown, with a comparison among the three curing conditions. The strength associated with water curing conditions is the highest one, while cellophane and air are comparable. Moreover, it is noted that the tensile strength significantly increases with increasing density in the range between 400 kg/m^3 to 600 kg/m^3, but in the range between 600 kg/m^3 to 800 kg/m^3 the increase is considerably less pronounced. This trend, here shown for CEM I 52,5R, water curing conditions and $w/c = 0.3$, has been observed also in other types of cement.

Finally, the increasing trends of tensile and compressive strength values with dry density are also illustrated in Fig. 9.

The values of both f_t and R_c have been normalized to a unit max value at the dry density of 800 kg/m^3. It can be seen that, according to the remarks made above, the tensile strength f_t increases considerably in the range between 400 kg/m^3 to 600 kg/m^3, but the gradient of increase is lower in the range between 600 kg/m^3 to 800 kg/m^3. On the contrary, the compressive strength R_c increases almost linearly over the entire range of dry density investigated in this research work. The latter linear increase of the compressive strength with the dry density is in line with earlier research findings published by the authors in the context of classic (non-extrudable) foamed concrete specimens [4].

The ratios between tensile and compressive strength f_t/R_c range between 0.05 (for very low density specimens) and 0.30. These values are in line with other literature studies [15]. Indeed, Valore [15] reported values of the f_t/R_c ratio to vary from 0.22 to 0.27, and found very low values for low density specimens. These values are approximately consistent with the ones obtained in the present experimental campaign, although in the case of the present extrudable foamed concrete specimens, the experimentally detected ratios are a bit higher than those reported in [15].

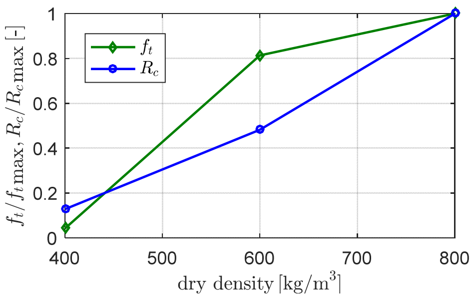

Fig. 9 Increasing trend of tensile and compressive strength with dry density for $w/c = 0.3$, water curing conditions and CEM I 52,5R

An approximated formula for determining the indirect tensile strength f_t once the compressive strength R_c has been measured is provided as follows:

$$f_t = R_c^{0.4591} - 0.91571 \quad (1)$$

which is valid in the range of densities analyzed (400-800 kg/m^3), for CEM I 52,5R cement type and for water curing condition. The coefficient of determination R^2 associated with (1) is 0.9132. Similar correlation formulae can be derived for other cement types and curing conditions. The predictive trend of (1) against the experimental data is illustrated in Fig. 10.

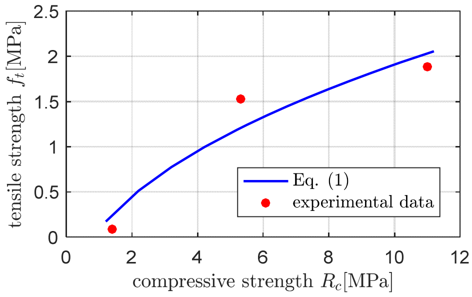

Fig. 10 Correlation between tensile and compressive strength for $w/c = 0.3$, water curing conditions and CEM I 52,5R

IV. Conclusions

A type of foamed concrete featuring a peculiar property of extrudability has been analyzed in this paper. In particular, this contribution deals with a preliminary experimental characterization of this foamed concrete in terms of compressive and tensile strength values. Based on the broad experimental campaign carried out by the authors, these strength values have been found to depend upon several factors, mainly the water content (in terms of the w/c ratio) and the curing conditions. In particular, the w/c ratio has a different influence depending on the analyzed curing condition. Indeed, the higher w/c values lead to higher compressive strength values for air curing conditions, while in other scenarios (cellophane and water curing conditions) specimens with increased w/c exhibit a poorer mechanical performance.

The compressive strength increases almost linearly with the dry density, which is consistent with results relevant to classic foamed concrete found by the authors in earlier investigations [4]. On the other hand, the tensile strength increases more sharply in the range of low densities, while the increase is far less pronounced in the medium-to-high density range.

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