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Impact of perlite, vermiculite and cement on the Young modulus of a plaster composite material: Experimental, analytical and numerical approaches

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A B S T R A C T

The mechanical behavior of a new composite material used in building construction is studied in this work. The composite panel results of combination of a calcium sulfate hydrates matrix mainly water and inorganic mineral additives. The effective young modulus of the composite is measured by three bending test. Analytical and numerical models are used to determine the composite young modulus which can be expected vs the type and rate of additives. The experimental values are compared with analytical and numerical results. The results from models are near or lightly lower than the experimental values and allow an estimation of the effective properties which can be expected for the new composite developed.

1. Introduction

More and more restrictive standards as environmental materials, energy consumption and/or fire protection in building construction need to develop new composites [1–5]. Good mechanical and thermal properties will be expected in standard condition. In this study, it will be used as a fire protection for construction building. These new composite are generally based from a gypsum matrix [6–9]. The main advantages of gypsum are its availability, its low cost, its ease of production and its quality as fire barrier. Indeed, when gypsum is subjected to fire, the endothermic dehydration process consumes a part of fire energy [10–12]. Nevertheless, the main disadvantage of gypsum is its brittleness at room temperature and its poor resistance to crack opening and propagation when it is subjected to fire conditions as described in the standard curve ISO 834 [13]. To improve its fire resistance, the addition of additives is introduced in the gypsum matrix. For fire protection, the additives usually used are vermiculite, mica, alumina, perlite, ceramic hollow sphere [14–17] to improve the thermal insulator properties. To improve the mechanical properties, the addition of fibers (inorganic or vegetables) is generally proposed [18–21].

A characteristic of these composites is the high rate of porosity present in the matrix part. Indeed, gypsum matrix is elaborated from calcium sulfate hemihydrate, which can occur under two forms: α- or β-hemihydrate. The α form is very limited in construction due to its brittleness behavior [22]. The β form of hemihydrates needs a water excess during the preparation of the composite (due to the high specific area) [23]. During the material drying stage, the departure of excess water will be responsible of the high rates of porosity in the material. The consequences are a lightweight material with good insulation properties but poor mechanical properties which can leads to the falling down of the structure.

In the case of this study, a new composite based on gypsum matrix is developed. To improve the properties of the material, three different additives, vermiculite, perlite and cement has been chosen. The choice has been done to obtain the best compromise between thermal and mechanical properties and a lower coast for the final composite. In a previous work, the evolution of the thermal properties with the rate of each additive added has been detailed [24]. This paper described the impact of these additives on the mechanical properties and especially the Young modulus. This work proposes three approaches. First of all, analytical models will be used to describe the evolution of the Young modulus versus the rate of each additive. Moreover, two different numerical models based on the finite element method have been developed to

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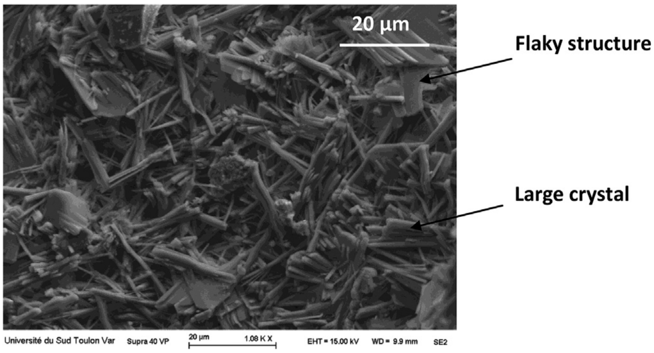

Fig. 1. SEM observation of the plaster matrix.

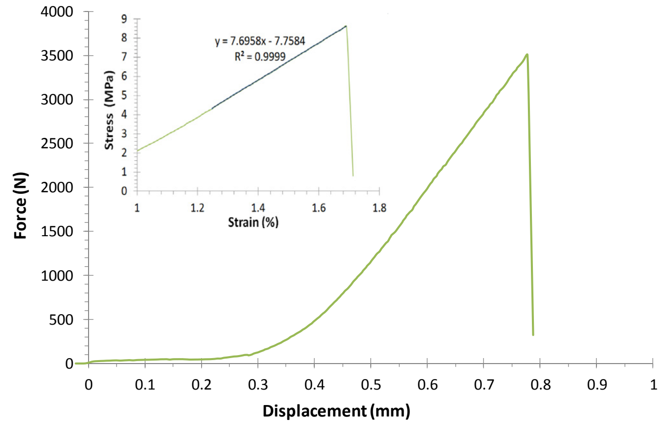

Fig. 2. Force-elongation curve characteristic of the mechanical behavior of plaster samples obtained by a three-point bending test.

calculate the effective Young modulus of these new composites. Finally, experimental measurement will be done with different composites to confirm the results obtained by the analytical and numerical approaches.

2. Material and methods

2.1. Matrix materials

An industrial gypsum plaster (from Algiss) has been chosen for the composite matrix. In a previous work [24], the chemical characterization of this plaster has been fully described. A flaky structure has been observed from scanning electron microscopy (SEM) observation (Fig. 1). This structure is characteristic of β-hemihydrates form [22]. Moreover a large crystal has been observed which could be attributed to residual dehydrate after the incomplete dehydration of dehydrate extracted from quarries. The identification of the chemical composition of the plaster has been done from thermo gravimetric and differential thermal analysis (TGA and DTA) analysis. The results have been reported in Table 1.

The correlation between the performance of composite materials and their porosity rates in relation with the particle size distributions and their compaction are widely described in the literature [19].

The mechanical properties of the plaster have been obtained from experimental measurements about plaster samples. The effective Young modulus is calculated from a three bending test (Appendix A1). The plaster samples used have the standard dimensions (i.e. 160 $\times$ 40 $\times$ 40 mm3). As expected, a brittle behavior is observed for the plaster (Fig. 2). A Young modulus equal to 770 $\pm$ 40 MPa has been calculated from the experimental measurements. The bulk density is measured from gravimetric measurements (Appendix A2). The values are reported in Table 2.

2.2. Additives

Additives have been chosen to obtain the best compromise between thermal and mechanical properties and a lower cost for the final materials. The three commercial additives are vermiculite under exfoliated form (GRANUTEC® E), perlite (P10) and cement (Portland 32,5R).

Vermiculite results from the exfoliation of volcanic rock of the family of phyllosilicates (silicates iron and aluminum magnesium hydrated). The expansion of this rock exfoliation can reach 10 to 30 times its original volume. During the exfoliation stage, the bulk density of the rock decrease from 0.825 to 0.097 g cm^3. It comes in the form of brown silver sequins, crystallizing in the monoclinic system. The lamellar structure of the vermiculite contains a large amount of air (porosity of about 90%) which can explain it excellent thermal insulation property (Fig. 3). It is widely used in the construction industry to achieve sound and heat insulation panels, but also as a firebreak. Its main disadvantage is its low mechanical strength. Compression slips easily tabulated and especially when the stresses are perpendicular to the sheets, the tensile sheets delaminating phenomenon is prominent leading the material to fracture [34].

In the literature, many values of Young modulus have been proposed [25–28]. A value around 14 GPa is measured without taking into account the anisotropic behavior of the vermiculite [27,28]. Goodall et al. [25] have measured the comportment of exfoliated vermiculite particles, which exhibit a stiffness nearly 20 times greater in-plane than in the through-thickness direction. They explain it by the opening of the exfoliated structure (Table 3). Martias et al. [21], by a finite element study, have shown than a value of 14 GPa for the Young modulus of the vermiculite will be overestimate the mechanical properties of a gypsum/vermiculite composite. When the authors applied a value of Young modulus equal to 1 MPa, the finite element model underestimate the mechanical properties of their composite. The evolution between the effective Young modulus of the composite versus the volume fraction of vermiculite added, is well describe when a value of 20 MPa has been used in the numerical models. So, in the next of this work the Young modulus used in the analytical and numerical models will be equal to 20 MPa in agree with the previous results [21].

Table 1
Chemical composition of the industrial plaster from experimental measurements.

Measures	D $CaSO_4$, $2H_2O$ (w%)	H $CaSO_4$, $1/2H_2O$ (w%)	C $CaCO_3$ (w%)	I impurities (w%)
1	5	90	5	0
2	4	90	5	1
3	4	89	5	2
4	4	89	6	1