Energy and Buildings 70 (2014) 135–144

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Properties of gypsum composites containing vermiculite and polypropylene fibers: Numerical and experimental results

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ARTICLE INFO

Article history:
Received 31 May 2013
Received in revised form 7 November 2013
Accepted 13 November 2013

Keywords:
Gypsum composite
Vermiculite
Polypropylene fibers
Thermal conductivity
Mechanical strength
Response surface methodology
Finite element modeling

ABSTRACT

We have added expanded vermiculite and polypropylene fibers with low thermal conductivity to lightweight gypsum. Thermal conductivity of the composites decreases on addition of vermiculite as pore-maker. Physical and mechanical properties of the composites are improved by incorporating polypropylene fibers. A nonlinear finite element model of a three point bending model and a design of experiments analysis have been developed to evaluate and optimize the additive concentrations and also to understand the effects provided by the additives on the mechanical strength. Statistical response surface method with three-level factorial was employed to evaluate the effect of addition of vermiculite and polypropylene fibers on gypsum composites. Our methodology can be applied to other nonlinear materials for property optimization.

1. Introduction

Gypsum plaster and board along with composites based on them have been increasingly used in building construction [1–14]. Thermal and sound-proofing properties of the gypsum building materials can be improved by increasing the porosity, e.g. by foaming [5] or by adding pore-forming agents such as inorganic ones [6–8]. Different clay minerals can be added to gypsum plaster in order to modify the physical properties [6]. Physical and thermal conductivity properties were improved by the addition of expanded silica gel granules introduced into the gypsum [8]. Also, reinforcing materials such as fibers or aggregates with different sizes are added to the gypsum plaster and board to improve certain mechanical properties [1,2,15–17]. Several different types of polymeric fibers such as glass fiber, carbon fiber, polypropylene fiber, polyamide fiber, polyester fiber have been extensively used in gypsum boards for their specific advantages [1–5,18–20]. The use of fiber reinforcement materials in gypsum mix allows increasing the materials strength. Existing studies use different fiber type, while no results have been reported for using both vermiculite and polymeric fibers.

The expanded vermiculite used by us as a mineral additive to obtain a low thermal conductivity is one of the natural clay minerals that have phyllosilicate groups [$(Mg, Fe, Al)_3(Al, Si)_4O_{10}(OH)_2{\cdot}4H_2O$] composed of shiny flakes, resembling mica in appearance. When vermiculite is heated to elevated temperatures, its flakes expand as much as 8–30 times with respect to their original size due to the removal of their interlayer and structural water. Expanded vermiculite has a very low density and low thermal conductivity, high fire resistance and strong sound absorption, what makes it attractive for use as a lightweight construction aggregate, thermal insulation filler and soil modifier. Due to its lower density, such vermiculite is used as a constituent of concretes and plasters [9,21]. The use of expanded vermiculite in gypsum mix should allow a reduction of the density and thermal conductivity values of the gypsum composites.

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0378-7788/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2013.11.047

Polypropylene (PP) fibers were added to the gypsum composite mixtures to improve the mechanical properties. According to Tazawa [19], the local response of fiber/matrix interface during fracture is of great importance. The most important effect of fibers is to act as bridging ligaments in the crack plane in order to limit crack propagation and opening, increasing the deformation energy needed to reach fracture. However, the stress transfer between matrix and fibers is complicated and models dealing with effects of the different fiber ratios on the mechanical properties of gypsum-reinforced composite were not available.

Numerical studies of laboratory results have become a useful tool for both engineers and researchers, as shown by the ever-growing number of books and articles published and the conferences dedicated to this subject. Much can be learned from the engineering of Simulation and Testing (or Hybrid Engineering) that can later be applied to improvements in the field of structural and thermal design and analysis in the form of new theories, concepts or details [18,22–25].

Along these lines, there are models dealing with analytical modeling of strength in fiber reinforced gypsum composites [18], the effect of self-stress on flexural resistance [19], the effect of longitudinal reinforcement on glass fiber reinforced gypsum [20]. However, most of the studies related to gypsum composites have concentrated on analytical or laboratory tests and very few pay attention to numerical models based on the finite element modeling (FEM) and the design of experiments (DOE) methodology play [26–28].

We have prepared lightweight gypsum composites containing expanded vermiculite and polypropylene fibers to examine their thermal conductivities and physical and mechanical properties. In order to understand the effect on mechanical resistance of vermiculite and polypropylene fibers, a nonlinear three point bending FEM analysis is performed. The structural nonlinearity is due to the possibility of cracking and crushing.

With the basis in this nonlinear structural numerical model, a search for optimal value based on the designs of experiments (DOE) [19,20,28,29] and goal optimization analysis have been performed to define the optimized fiber concentration [30,31].

2. Experimental studies

2.1. Gypsum

A commercially available gypsum plaster mix characterized according to TS EN 13279-1 [32] was used in this study. The properties of gypsum used were given in Table 1.

2.2. Vermiculite

Exfoliated vermiculite was supplied from the Demircilik vermiculite deposit in Yıldızeli, Sivas, Turkey. The vermiculite was obtained by heating raw vermiculite at 600 °C for 10 s. Then the vermiculite was ground and fine sized particles smaller than sieving intervals of 100-mesh (149 μm) were used for plaster mixes. The chemical and physical properties of exfoliated vermiculite are presented in Table 2. Exfoliated fine vermiculite was added to the plaster mixtures at ratios of 10 wt.% and 20 wt.%. The amount of vermiculite listed is the ratio of the vermiculite mass to the total dry mass.

Table 1
The properties of gypsum used.

Workability time (min)	60–90
Final setting time (min)	150
Compressive strength (MPa)	2.5
Flexural strength (MPa)	1
Dry density (kg/m^3)	650–1000
1000 μm (% passing)	100
150 μm (% passing)	60
Chemical formulation	$CaSO_4 \cdot 1/2H_2O$

Table 2
Properties of additives used for gypsum composites.

	Exfoliated vermiculite	Polypropylene fiber
Physical properties		
Color	Silver	White
Shape	Accordion shaped granule	–
Water holding capacity	240 wt.%	–
Cation exchange capacity	90 meg/100 g	–
pH (in water)	6.1	–
Thermal conductivity (W/mK)	0.063	–
Combustibility	Non-combustible	–
Specific heat (kcal/kg K)	0.22	–
Bulk density (g/cm^3)	0.140	0.91
Tensile strength (N/mm^2)	–	300–400
Aspect ratio (L/D)	–	545 (12 mm/0.022 mm)
Chemical composition (%)		
SiO_2	34.1	
Al_2O_3	17.2	
K_2O	4.52	
CaO	6.4	
MgO	16.3	
Fe_2O_3	14.7	
Loss on ignition	6.4	

2.3. Polypropylene fibers

Polypropylene fibers with 22 μm diameter and 12 mm length were used, their properties listed in Table 2. The fibers were added to the mixtures in the ratios of 0.5 wt.% and 1.0 wt.%. The amount of fibers is counted as a ratio to the total dry mass.

2.4. Response surface method

We have used a multi-objective simultaneous optimization technique to optimize gypsum composites, to which the response surface method (RSM) is incorporated. The RSM uses statistical techniques for empirical model building; it comprises regression surface fitting to obtain approximate responses, design of experiments to obtain minimum variances of the responses and optimizations using the approximated responses. The RSM also aims to reduce the cost and save time [33,34]. This approach has been widely used to optimize products and processes in manufacturing, chemical and other industries, but it has had very limited use in the construction industry. In one such study, Simon et al. [35] optimized high performance concrete mixtures. Bayramov et al. [36] optimized the fracture parameters of steel fiber reinforced concrete to obtain a more ductile behavior. Some of us [37] optimized abrasive wear of concrete.

In the experiments, the mixture ratios were defined by the use of a statistical experimental design technique. A RSM with three-level factorial was employed to study the effect of two factors (vermiculite and polypropylene fiber) on samples of gypsum composites. Three response variables were measured: dry unit weight, compressive strength and thermal conductivity. This experimental design referred 13 experiments with four replicates in the center point. These factors were investigated at three levels; low (−), medium (0) and high (+) level as shown in Table 3. The Analysis of Variance (ANOVA) test for response surface quadratic model was used to determine the impact of independent variables on all dependent response variables in a regression analysis.