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Lightweight gypsum composite with plastic waste incorporation for building construction applications

Compozit ușor din ghips cu încorporarea deșeului de plastic pentru aplicații în construcția clădirilor

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Abstract. *Aiming at making lightweight gypsum-based composite whose mechanical strength to be acceptably high, the current work tested the combined use of some recycled plastic waste (polyethylene terephthalate-PET, polypropylene, and expanded polystyrene) as well as silica fume, a very fine powder as by-product in metallurgical industry, having the ability to improve the composite mechanical properties. The optimal combination of fillers included PET (1 wt. %) and polypropylene (1 wt. %) whose fibrous structure influenced the decrease of bulk density up to 540 kg·m^{-3} as well as especially the increase of flexural strength up to 4 MPa.*

Key words: *lightweight gypsum composite, plastic waste, aluminum powder, fiber, polymer.*

Rezumat. *Vizând fabricarea compozitului ușor pe bază de ghips a cărui rezistență mecanică să fie acceptabil de înaltă, lucrarea curentă a testat utilizarea combinată a* *unor deșeuri reciclate de plastic polietilenă tereftalata-PET, polipropilenă și polistiren expandat), precum și nanosilica, o foarte fină pulbere ca produs secundar al industriei metalurgice, având capacitatea de a îmbunătăți proprietățile mecanice ale compozitului. Combinația optimă a materialelor de umplutură a inclus PET (1 wt. %) și polipropilenă (1 wt. %) a căror structură fibroasă a influențat reducerea densității în vrac până la 540 kg·m^{-3}, precum și, în mod special, creșterea rezistenței la încovoiere până la 4 MPa.*

Cuvinte cheie: compozit ușor din ghips, deșeu de plastic, pulbere de aluminiu, fibră, polimer.

1. Introduction

Calcined gypsum plaster known also as ”plaster of Paris” is a building sulfate material mainly used for protective or decorative coating of walls and ceilings. Gypsum is a water-containing calcium silicate. After calcination processes the water of crystallization is partially removed, resulting in calcined gypsum ($CaSO_4 \cdot 0.5H_2O$) [1]. Gypsum plaster is a replacement for sand cement plaster more expensive. The main properties of gypsum plaster are: light weight, less water-curing, insulation for temperature control, and eliminates shrinkage cracks. According to [2], perlite and vermiculite are lightweight minerals, being suitable for their application in making gypsum composites. They have excellent properties that improve gypsum plaster characteristics. Perlite, that is a volcanic glass, is one of the most effective natural minerals. Water is absorbed into the raw perlite matrix developing its ability to expand when heated. The properties of perlite are: light weight, insulating properties, without organic contaminants, non-flammable, and pest-proof. Vermiculite is a hydrated magnesium aluminum silicate mineral. Vermiculite is a hydrated magnesium aluminum silicate mineral. Subjected to heat, vermiculite expands forming particles. Its main properties are: light weight, fireproof, compressible, strongly absorbent, non-reactive, and increases its volume in water up to three times.

A method of reducing the weight of gypsum-based materials is the use of light inorganic or organic fillers. The inorganic fillers most often used are perlite and wollastonite. According to [3], a mixture of fly ash-lime-gypsum including 5-10 % perlite and very low microsilica addition allowed to obtain a composite with the bulk density of 730 kg·m^{-3} and compression strength of 2.3 MPa. Another combination of materials that led to acceptable results was the use of vermiculite (20 wt. %) together with polypropylene fibers [4]. The bulk density was reduced by about 10 % and simultaneously the thermal conductivity by 30 %. However, the decrease in the mechanical strength by up to 30 % at the same time was the negative aspect of the test.

Two variants of making composites based on lightweight gypsum were tested [5], containing foamed gypsum matrices with low density using aggregates with higher density as well as matrices with higher density using aggregates with low density. The method with higher density matrix and lightweight aggregates was the optimal option. Using 5 wt. % expanded perlite the test led to a bulk density of 547 kg·m^{-3}, heat conductivity of 0.12 W·m^{-1}·K^{-1} and compression strength of 2 MPa. On the other hand, composites with low density of the foamed matrix and higher density of aggregates had good thermal properties, but too low compression strength.

Authors of the current paper have performed experiments on making lightweight gypsum-based materials using calcined gypsum, $Ca(OH)_2$, fly ash, perlite, silica fume, carboxy-methyl cellulose, and aluminum powder [6]. Bulk density had relatively low values (530-600 $kg \cdot m^{-3}$), heat conductivity was between 0.129-0.184 $W \cdot m^{-1} \cdot K^{-1}$, compression strength within the limits of 1.2-2.2 MPa, and water-absorption up to 3.9 vol. %.

In terms of energy, the use of perlite and vermiculite as aggregates for lightweight gypsum has a negative influence on the environment due to the relatively high energy consumption during processing. The incorporation of polystyrene wastes (both extruded and expanded polystyrene) substituting perlite and vermiculite is a viable solution]7]. Expanded polystyrene is used in constructions to insulate walls and floors, while extruded polystyrene is used to insulate the roof.

The addition of cork waste and other fillers such as cellular glass, expanded polystyrene, extruder polystyrene or polyurethane wastes showed a reduction in bulk density. However, the mechanical strength was affected, being also reduced [8]. As a conclusion of this work, polystyrene wastes can be used as alternative aggregates in the gypsum mass, replacing perlite and vermiculite.

Other experiments reported in the literature [9] used polystyrene beads (2 wt. %) and polypropylene fiber (2 wt. %), obtaining a reduction of about 50 % of bulk density, while the tensile strength increased by 23 %.

The attempt of some researchers to extremely reduce the bulk density (up to 200 $kg \cdot m^{-3}$) led to the serious damage of mechanical strength.

According to the paper [10], the physical and mechanical properties of gypsum-based composites can be favourably influenced by recycled non-degradable materials (e.g. wet wipes). The experimental results showed that more effective materials can be manufactured with a small decrease in density compared to ordinary gypsum. The improvement of mechanical properties is worth noting. In the case of starting mixtures with 2.5 wt. % recycled fibers, flexural strength value increased by 19 %. One of the most widely used polyethylene plastics is polyethylene terephthalate (PET). Plastic foam waste such as extruded polystyrene, expanded polystyrene and polyurethane foam were used as lightweight aggregates in gypsum-based composites with better thermal properties.

Polypropylene fiber as textile waste with a very high annual generation rate worldwide has led to the increase of plastic waste reserves. Recently, recycling this waste for construction applications has become a viable solution. The paper [11] presents different fiber contents (between 0.25-0.55 wt. %) and water/powder ratios (between 0.6-0.9 %) in the gypsum-based composite experimentally manufactured. Different thicknesses of flexural plates (9-18 mm) incorporating recycled fibers, reinforced with different mesh types were produced. The results showed that the density of the composite decreased by up to 26 % as the fiber content increased. Compression and flexural strength decreased with the increase of the fiber content and the water/powder ratio, still remaining within the acceptable limits of 1 and 2 MPa, respectively.

A study on the effect of including plastic fiber waste on mechanical and durability characteristics of foamed gypsum was carried out in the work [12]. The fibers were introduced in proportions within the limits of 0.25-1 wt. %. The experimental results showed that by this addition, the workability of gypsum foam decreased. However, the samples with up to 0.75 % plastic fibers reached the highest flexural and compression strength values. The water-absorbing of these samples increased with the increase in the proportion of added fibers.

The influence of the content of polypropylene fibers and their length on physico-mechanical characteristics of gypsum particleboard were analyzed in [13]. The effect of the quantity and length of fibers is felt by values of internal bond resistance and modulus of rupture of the composite. The highest value levels of fiber content (9 %) and fiber length (9 mm) were experimentally determined. A high content of polypropylene fiber reduces the internal bond strength, modulus of rupture and modulus of elasticity.

In the work [14] hemp and sheep wool fibers were used for the reinforcement of gypsum composite. The aim of the research was to evaluate the ability of these bio-materials to enhance the fracture toughness of gypsum matrix. The results showed that wool fibers improved the mechanical performance more effectively compared to hemp fibers due to the high adhesion at the interface of the fiber and the gypsum matrix.

To reduce the open structure of expanded polystyrene particles, a modern technique was tested in [15]. Their heat treatment at low temperature (120-130 °C) improved the performance of polystyrene by reducing the volume and increasing its density. Expanded polystyrene with bulk density between 40-100 $kg \cdot m^{-3}$ was incorporated as filler material for making the gypsum composite. According to the measurement results, the compression strength had very low values (between 15-136 kPa) and the material density was also reduced (between 48-194 $kg \cdot m^{-3}$). The noise reduction coefficient had values between 600-800 Hz and the sound absorption coefficient reached 0.88.

The present work started from the need to increase the mechanical strength of gypsum foam composites. Different fiber types incorporated in the mixture of materials as fillers can represent the viable technical solution considering the previous results of their application as reinforcement of other material types (e.g. concrete, cement). Using usual components of the gypsum foam making process (calcined gypsum, fly ash, hydrated lime, aluminum powder as a foaming agent), polyethylene terephthalate fiber, polypropylene fiber, expanded polystyrene, and silica fume (as an ultrafine powder) were incorporated. These materials were grouped into three combinations, each representing an experimental version as follows: polyethylene terephthalate-silica fume, polypropylene fiber-polyethylene terephthalate, and expanded polystyrene-silica fume. The use of experimental association of two types of materials each with reinforcing role constitutes the originality of this work.

2. Materials and methods

Calcined gypsum ($CaSO_4 \cdot 0.5H_2O$) is available on the market in granulated state below 1mm. For its use in experiment, the material was ground in a ball mill, being selected after sieving the grain size under 100 μm.

Fly ash was provided by Paroseni-Thermal power plant (Romania) being captured from electrofilters of the plant's energy boiler. Under the conditions of using lignite as a solid fuel, the fly ash composition included 46.5 % SiO_2, 23.7 % Al_2O_3, 10.1 % (Na_2O + K_2O), 8.6 % Fe_2O_3, 3.2 % MgO, and 7.9 % CaO. The initial grain size of the ash was under 250 μm, and it was necessary to grind it to reduce the dimensions under 80 μm. By using fly ash, the weight proportion of gypsum as a binder could be slightly reduced.

Polyethylene terephthalate was recycled from post-consumer PET packaging waste, cut and ground in the form of particles below 2 mm. Due to its fibrous structure, this waste has a major role in reinforcing the final product to increase the mechanical strength to an acceptable level.

Polypropylene fiber and expanded polystyrene fiber were recycled from plastic waste existing among the residual materials of a building site. Wastes were cut, ground, and selected after sieving at the grain size below 1.5 mm.

The chosen foaming agent was the fine aluminum powder (below 10 μm) previously produced through own nitrogen jet atomization technique of recycled aluminum waste melted by microwave irradiation [6].

Hydrated lime ($Ca(OH)_2$), known also as slaked lime, was adopted for developing the corrosion reaction of aluminum in aqueous solution.

Silica fume with SiO_2 content more than 93 % is a by-product of metallurgy industry. It is a highly pozzolanic material being usually used to increase mechanical and durability properties of concrete. Silica fume is an ultrafine material with spherical particles less than 1 μm diameter. It is available on the market, the main supplier being China.

Three compositional variants were adopted for the experiment including calcined gypsum, fly ash, hydrated lime, and aluminum powder maintained in constant weight proportion as well as polyethylene terephthalate + silica fume (version 1), polypropylene fiber + polyethylene terephthalate (version 2), and expanded polystyrene + silica fume (version 3). The composition of the three experimental versions is presented in Table 1.

Table 1

Composition of experimental versions

Composition	Version 1 ($kg \cdot m^{-3}$)	Version 2 ($kg \cdot m^{-3}$)	Version 3 ($kg \cdot m^{-3}$)
Calcined gypsum	79.0	79.0	79.0
Fly ash	6.0	6.0	6.0
Hydrated lime	10.0	10.0	10.0
Aluminum powder	3.0	3.0	3.0
Polyethylene terephthalate	1.2	1.0	-

Composition	Version 1 ($kg\cdot m^{-3}$)	Version 2 ($kg\cdot m^{-3}$)	Version 3 ($kg\cdot m^{-3}$)
Silica fume	0.8	-	0.9
Polypropylene	-	1.0	-
Expanded polystyrene	-	-	1.1
Water addition	30.0	30.0	30.0

The method adopted for obtaining gypsum foam is based on the use of gaseous hydrogen as a foaming gas resulting from the corrosion process of fine aluminum particles in aqueous solution of $Ca(OH)_2$. The process takes place at room temperature, being efficient in terms of energy, unlike the foaming techniques of silicate materials using an expanding agent that releases the necessary gas at high temperatures (800-1100 °C).

The basic chemical reaction of foaming with fine aluminum powder forming katoite ($Ca_3Al_2(OH)_{12}$) that enters the gypsum mass and hydrogen is the following:

$$2Al + 3Ca(OH)_2 + 6H_2 = Ca_3Al_2(OH)_{12} + 3H_2 \qquad (1)$$

It was experimentally applied by authors of the current paper [16] in the cold foaming process of glass waste for producing glass foam.

According to [17], the reaction mechanism is complex including several stages (2-5) that occur at the aluminum particle/aqueous solution interface.

$$Al_2O_3 + H_2O = 2AlOOH \qquad (2)$$

$$AlOOH + H_2O = Al(OH)_3 \qquad (3)$$

$$Al(OH)_3 + OH^- = Al(OH)_4 \qquad (4)$$

$$3Ca^{2+} + 2Al(OH)_4 + 3H_2O = Ca_3Al_2(OH)_{12} + 6H_2 \qquad (5)$$

The paste was prepared into a cylindrical metal mold by stirring with a rate of 800 rpm up to it began the expansion process.

Usual methods were used to characterize the gypsum foam samples. The determination of bulk density and porosity was carried out by applying the water intrusion method (Archimedes' method), according to ASTM D792-20 standard. Heat conductivity was measured by heat-flow method-ASTM E1225-04 [18]. Compression strength was determined with TA.XTplus Texture analyzer and flexural strength was investigated by conducting the three-point bend test on the specimen (ASTM D790) [19]. Using the usual technique of immersing the specimen under water (ASTM D570) the water-absorbing capacity was determined. Microstructural particularities of samples were observed with ASONA 100X Zoom Smartphone Microscope.

3. Results and discussion

The amount of wet starting mix of 300 g was used in all versions tested. The making process with an average duration of around 10 min was carried out at room temperature (24 °C).

The three experimental versions were made with calcined gypsum, fly ash, hydrated lime, aluminum powder, and water addition in weight proportions shown in Table 1 kept constant, to which different combinations of plastic waste and silica fume were added in order to improve the mechanical strength of gypsum foam.

The three gypsum foam specimens (shown in Fig. 1) were subjected to investigations to determine the physico-mechanical and thermal characteristics. The results are presented in Table 2.

a b c

Fig. 1. Appearance images of gypsum-based composite
a – version 1; b – version 2; c – version 3.

Table 2

Physico-mechanical and thermal characteristics

Characteristic	Version 1	Version 2	Version 3
Bulk density ($kg \cdot m^{-3}$)	570	540	590
Porosity (%)	72.7	74.0	71.6
Heat conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.178	0.169	0.180
Compression strength (MPa)	2.4	1.9	2.5
Flexural strength (MPa)	3.2	4.0	3.1
Water-absorbing (vol. %)	3.6	3.3	3.5
Pore size (mm)	0.3-0.6	0.4-0.9	0.1-0.3

The data in Table 2 show modifications of physical, mechanical, and thermal characteristics influenced by the additions of fibrous plastic waste as well as silica fume as a by-product of the metallurgical industry. Two important effects of using fibers are the decrease of bulk density (540-590 $kg \cdot m^{-3}$) that determines also decreasing the heat conductivity (0.169-0.180 $W \cdot m^{-1} \cdot K^{-1}$) and increasing the porosity (71.6-74.0 %), i.e. improving insulation properties as well as the increase of mechanical strength of composite, especially of flexural strength (3.1-4.0 MPa). These effects have already been previously observed by researchers in the field and numerous works have published these conclusions [20-22].

The most effective combination of fibers in gypsum foam was polyethylene terephthalate (PET)-polypropylene (version 2), because the insulation properties were the best (bulk density of 540 kg·m^{-3}, heat conductivity of 0.169 W·m^{-1}·K^{-1}, and porosity of 74.0 %), while the flexural strength clearly had the highest value of 4.0 MPa. The combinations that included silica fume together with plastic wastes (versions 1 and 3) were less porous, the flexural strength was lower compared to version 2 and only the compression strength was slightly higher (2.4-2.5 MPa) compared to the optimal version.

The microstructural appearance of composite foam specimens is shown in Fig. 2.

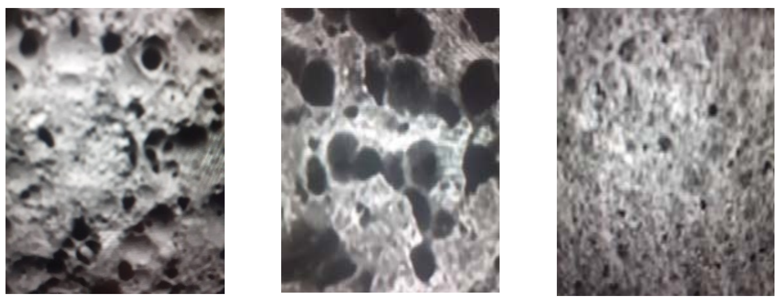

Fig. 2. Microstructural appearance of composite samples
a – version 1; b – version 2; c – version 3.

The pore size range in the optimal version (no. 2) had the highest values (0.4-0.9 mm) among the three tested versions. The gypsum foam specimen corresponding to version 3 had the lowest pore size values (0.1-0.3 mm), thus explaining the highest bulk density value.

The research presented in this paper aimed at improving the mechanical properties of gypsum foam, characterized mainly by its porous and lightweight structure. The use of fibrous material additions is a method recently applied in several types of dense composites to increase their strength and durability to very high limits. In the case of lightweight composites, low-density fillers are necessary and the most well-known light inorganic materials are perlite and vermiculite, but their large-scale application raises problems with ecological impact. Therefore, the search for optimal solutions of preparing lightweight composites (including gypsum foam) was oriented towards plastic waste containing fibers.

Nanomaterials of the silica fume type are also known due to their ability to improve the mechanical properties of any type of composite. For this reason, silica fume was included among the materials used in this experiment.

The most favourable corelation between thermal insulation properties and mechanical strength of the gypsum composite was obtained in the case of using the combination of polyethylene terephthalate (PET) fiber with polypropylene fiber (in equal weight proportions of 1 % of the total amount of dry gypsum composite). Bulk density was minimal (540 kg·m^{-3}) and flexural strength reached the highest value (4 MPa).

4. Conclusions

The work aimed at the production of a lightweight gypsum-based composite whose mechanical strength should be acceptably high despite its porous structure. Except for calcined gypsum, fly ash, and hydrated lime, the specific ingredients of the material mixture as well as aluminum powder as an expanding agent, combinations of plastic waste (polystyrene terephthalate, polypropylene, and expanded polystyrene) and a micromaterial (silica fume) were used alternatively in the three experimental versions. The results showed the tendency to decrease the bulk density (540-590 kg·m^{-3}) by comparison with gypsum foam without the addition of fibers and to increase the flexural strength (especially), but also the compression strength. Flexural strength had values within the limits of 3.1-4.0 MPa and compression strength in the range of 1.9-2.5 MPa. The pore size of specimen microstructure was influenced by the nature of plastic wastes in combination with silica fume, however, the dimensions had low values from 0.1 to 0.9 mm. Water-absorbing of samples was influenced to a small extent, the values being maintained in the limited range of 3.3-3.6 vol. %. The work originality was the simultaneous combination of two fiber-supplier fillers into the material mixture. The optimal version was chosen that of combination polyethylene terephthalate and polypropylene, which led to obtaining bulk density of 540 kg·m-3 and flexural strength of 4.0 MPa. The ecological and economic product based on gypsum is suitable for applications mainly in the building construction. Lucrarea se va încheia cu un paragraf de concluzii în care vor fi menţionate rezultatele originale obţinute şi eventualele posibilităţi de aplicare ale acestora.

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