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Recycling of polystyrene waste in the composition of ecological mortars

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Abstract

As part of sustainable development, an important objective of constructors is the elaboration of a technology that may lead to the manufacture of new building materials and their implementation so as to contribute to the protection of the environment and natural resources, as well as to the creation of healthy living conditions. This study presents technologies for the manufacture of new building materials by polystyrene waste recycling. The following are produced: an ecological plastering mortar whose thermal conductivity is three times lower than that of ordinary mortar, which recommends it as a thermal insulation plastering mortar; three thermal insulation fillers, of which one is also recommended to be used as panels for external thermal insulation systems. All these are supported by the results obtained following the laboratory determinations presented in the paper.

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Keywords: Ecology; recycling; building materials; polystyrene; mortar.

1. Introduction

The very high consumption of materials in the construction industry by modern society leads to the exhaustion of the ecosystem resources, producing at the same time high amounts of waste and pollution.

In this context, waste recycling has a particular importance in waste management, contributing to the reduction of raw material requirements and to the conservation of natural resources, as well as to the reduction of environmental degradation [1, 2].

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Polystyrene, which is the object of the study, is a material used in various fields such as the packaging of industrial and food products [3]. On the Romanian market, in particular, it has gained ground in the construction industry, for the thermal insulation and rehabilitation of buildings. It is not recyclable, generating huge amounts of waste at the end of the life cycle (Fig. 1).

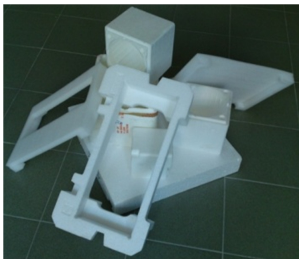

Fig. 1. Polystyrene residues.

Expanded polystyrene is a stiff cell plastic material produced from the molding of little spheres or pearls of expansible polystyrene that shows a closed structure made of this thermoplastic which contains trapped air in a 96-98% proportion of the volume of the pearls [3].

Expanded polystyrene has a thermal conductivity coefficient λ = 0.03 W/mK, which has led to the wide use of polystyrene panels for the rehabilitation and thermal insulation of buildings [4].

Polystyrene is a material whose thermal insulation performance is recognized, but its use in the insulation systems of buildings generates a number of inconveniences. It is in the first place a high energy-consuming material, with a high embodied energy 88.6 MJ/kg [5].

The great problem posed by the use of polystyrene in thermal insulation systems is its inflammability. To illustrate this, Figure 2 presents the fire behavior of polystyrene waste. This figure shows that under the action of the flame, polystyrene ignites almost instantly, burns with an intense flame, maintains combustion, and releases strong toxic black smoke emissions. This is why, according to European standards, polystyrene insulations are allowed in buildings that are not higher than 12 meters, which is about four floors high [6].

a b

Fig. 2. Fire behavior of the polystyrene

Another disadvantage of polystyrene is that the water vapor diffusion resistance factor is extremely high and can reach 100 [7], which in time, may create an unhealthy indoor climate by the appearance of moisture, dampness and mould [8, 9, 10].

The application of ecological materials has become increasingly important as a consequence of the increasing need to conserve energy, use natural materials, incorporate architecture and construction into sustainable development processes, and the recently promulgated discussions on appropriate disposal of used insulation materials such as polystyrene (EPS) [11, 12].

Recent studies, regarding the development of lightweight cement mortars, from Ferrandiz-Mas and Garcia-Alcocel [13] indicate that the presence of expanded polystyrene in mortar results in a decrease in the capillary absorption coefficient, the mortars had low thermal conductivity and low bulk density compared to control samples [1] and mechanical strength decreases with increasing content of expanded polystyrene [14].

The paper presents the study on polystyrene waste recycling in order to obtain ecological mortar.

The aim of the study is to determine a modality not only for recycling polystyrene waste, but also for obtaining ecological materials to reduce the disadvantages of polystyrene in thermal insulation systems.

The research problem is to establish a recipe and to develop a technology for the manufacture of a new ecological mortar with good thermal insulation properties, which can ensure the recovery of the high embodied energy of polystyrene waste following its recycling.

2. Material and Method

Although polystyrene is not a recyclable material in the true sense of the word, it is a material that can be reused in the composition of building materials, which ensures the recovery of its manufacturing energy and the reduction of negative environmental effects [15, 16].

The research on the use of polystyrene waste for the manufacture of ecological mortars fits in this context.

The materials used for the experimental part were Portland cement 42.5, lime, sand with a 0-4 mm granularity, water, commercially available polystyrene granules, as well as polystyrene waste.

The study was carried out on six mortar recipes:

- Recipe I – standard mortar based on cement, sand with a 0-4 mm granularity and water;
- Recipe II – 50% of the sand volume in the recipe of standard mortar was replaced with polystyrene granules;
- Recipe III – 100% of the sand volume was replaced with commercially available polystyrene granules;
- Recipe IV – having the same composition as recipe III, but the commercially available polystyrene granules were replaced with granules derived from different types of polystyrene waste;
- Recipe V – having the same composition as recipe IV, but 30% of the cement was replaced with lime;
- Recipe VI – having the same composition as recipe IV, but 50% lime was added to the existing cement amount.

The composition of the recipes is presented in Table 1.

Table 1. Mortar recipes.

Recipe	Cement 42,5	Lime	Sand	Polystyrene	Water
	[kg]	[kg]	[kg]	[kg]	[l]
I	1,7	-	6,21	-	1,3
II	1,7	-	2,94	0,013	1,3
III	1,7	-	-	0.49	1,1
IV	1,7	-	-	0.12	1,1
V	1,2	0,5	-	0.12	1,1
VI	1,7	0,85	-	0.12	1,7

The methods for the manufacture of mortars are the following:

- for recipe I (standard mortar), the classical method for the manufacture of mortar was used;
- for the recipes using polystyrene, in order to produce the necessary amount for the test samples, due to the very small density of polystyrene granules, the transformation of mass recipes into volume recipes was needed. This required the determination of the density of the component elements in order to establish the volume proportions of the recipes.
- the commercially available materials used required no special preparation; the polystyrene waste was ground to obtain granules with a diameter ranging between 2-4 mm. This was done using an electric knife device.

- the manufacture of mortars with polystyrene addition involved weighing the materials, mixing the component materials with the mixer, and casting the test samples (4x4x16 cm prisms and 5x30x30 cm plates).

3. Results and Discussions

Physico-mechanical and fire behavior determinations were performed after 28 days in test tubes cast and stored according to standards during this period.

3.1 Physico-mechanical characteristics

The following physico-mechanical characteristics were determined in the test tubes: the apparent density of set mortar, bending and compressive strength, adhesion to the support layer, water absorption by capillarity, thermal conductivity.

The results obtained following the physico-mechanical determinations are synthesized in Table 2.

Table 2. Technical characteristics obtained.

Recipe	Apparent density	Bending strength	Compressive strength	Adhesion to the support layer	Water absorption by capillarity	Thermal conductivity
	[kg/m^3]	[N/mm^2]	[N/mm^2]	[N/mm^2]	[Kg/(m^2*min$^{0.5}$)]	[W/mK]
I	1838	3,79	14,83	0,25	0,48 / W0	0,93
II	1291	3,56	13,35	0,2	0,4 / W1	0,3276
III	232.1	0,26	0,29	-	0,22 / W1	0,06483
IV	225.3	0,22	0,22	-	0,17 / W2	0,06469
V	217.5	0,23	0,19	-	0,17 / W2	0,06524
VI	341.3	0,39	0,42	-	0,26 / W1	0,09914

By comparing the technical characteristics of the mortar produced based on recipe II with the characteristics of the standard mortar (recipe I), the following conclusions can be drawn:

- the value of apparent density decreases following the replacement of 50% of the sand of recipe I with polystyrene waste granules, which places this mortar in the class of light mortars;
- the compression and bending strengths decrease, but not significantly;
- adhesion to the support layer also decreases, but is sufficient to allow its use as a plastering mortar;
- water absorption by capillarity decreases from 0.48 to 0.4, which places it in the category of mortars W1;
- thermal conductivity decreases to 35% compared to standard mortar, which means a significant improvement of thermal resistance, demonstrating better thermal insulation properties compared to standard mortar.

Polystyrene is a material that is used almost in all rehabilitation and thermal insulation works. It is most frequently used for the thermal insulation of buildings as polystyrene panels.

New recipes for the use of polystyrene have appeared on the market, such as thermal insulation fillers for the thermal insulation of attics, floor filling, or under the floors.

Recipe III uses such a material having the recipe provided by the manufacturer, which includes ground polystyrene with special additives and cement. It can be seen that in this composition, 100% of the sand was replaced with commercially available polystyrene granules.

Recipes IV, V and VI are similar, except that they use granules obtained following the grinding of polystyrene waste.

In all these recipes, apparent density and mechanical strengths decrease considerably compared to recipe I.

An important problem is posed by the fact that adhesion to the support layer is so low that it cannot be determined. This means that they cannot be used as plastering mortars, but they could be used as insulation panels or as a resilient layer under the finishing pavement layer [17].

Compared to recipe III with the commercially available product, in the case of recipe IV with polystyrene granules, it can be seen that water absorption by capillarity decreases from 0.22 to 0.17 [$Kg/(m^2*min^{0.5})$], which places it in class W2.

From the point of view of thermal conductivity, recipe IV is somewhat better than recipe III, conductivity decreasing from 0.06483 to 0.06469 [W/mK].

In recipe V, the same binder amount as for recipe IV was maintained, but 30% of the cement amount was replaced with lime.

The influence of lime manifests in the first place by the decrease of apparent density and compression strength compared to recipe IV. Water absorption by capillarity remains the same, but thermal conductivity increases insignificantly from 0.06469 to 0.06524 [W/mK].

Recipe VI has a composition identical to that of recipe IV, but the binder is enriched with lime representing 50% of the cement amount. This entails the increase of the water amount from 1.1 to 1.7 liters.

Compared to recipe IV, the apparent density of mortar increases by approximately 51%. This entails a significant increase of mechanical strengths (bending strength from 0.22 to 0.39 N/mm^2, compression strength from 0.22 to 0.42 N/mm^2). A significant increase is also found in the case of water absorption by capillarity, which assigns it to class W1. Thermal conductivity increases from 0.06469 to 0.09914 [W/mK], this value maintaining the material in the category of thermal insulation materials.

Figure 3 presents the break of the test samples cast according to recipes III, IV, V and VI following the determination of the bending strength.

Recipe III Recipe IV Recipe V Recipe VI

Fig. 3. Breaking section during bending

The figure shows that breaking is plastic, the surface has no elastic deformation, but the polystyrene granules are rather removed from the breaking plane.

3.2 Fire behavior

The fire behavior of recipes II, III, IV, V and VI was determined according to SR EN ISO 11925-2. Reaction to fire tests. Ignitability of building products subjected to direct impingement of flame [18].

The test samples were cast under the same conditions as the test samples for physico-mechanical determinations having a 5x30x30 cm size.

Given that there are no organic materials in the composition of recipe I, mortar is assigned to fire reaction class A1, according to SR EN 998-1 [19].

The test samples in recipes II-VI subjected to the direct flame test present the following common phenomena:

- the area under the direct action of the flame gradually turned red;
- the adjacent areas changed their color and appearance under the influence of heat (Fig. 4a);

- at 60 s there were no detachments of the material, only a deformation of the surface following the volatilization of polystyrene granules; no flames or smoke were seen, but a malodorous gas emission was felt, which means that the polystyrene granules decomposed;
- after 300 s, following the removal of the flame, it can be seen that the material did not maintain combustion, the reddened area affected by the direct flame progressively changed its color in a relatively short time (Fig. 4b);
- during the 300 s over which the material was exposed to the action of the direct flame, the part of the material opposite to the flame did not heat.


a b

Fig. 4. Fire behavior of the polystyrene mortar

Figure 4b shows that after the removal of the flame and the cooling of the test sample, there remained a circular dark area surrounded by an area with a different appearance from the initial appearance of the test sample, circled by a brownish oval belt. These areas were affected by the heat emitted by the open flame; it was found that due to the high temperature within the range of the flame, the polystyrene granules decomposed over a great depth and the areas around the direct flame were less affected as the distance from the flame increased (Figs. 5a and 5b).

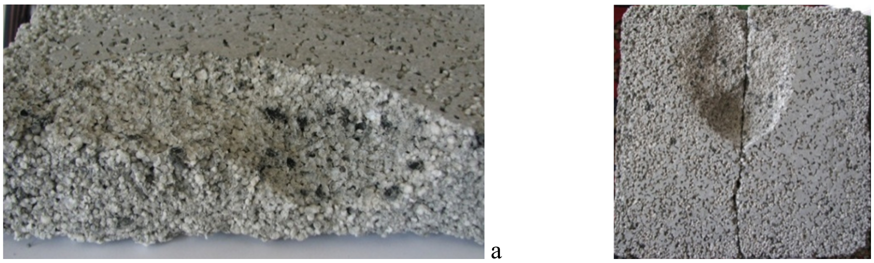
a b

Fig. 5. Effects following the fire test (recipe III)

The depth and the surface area of the direct flame varied depending on the composition of the mortar (Fig. 6).

The diagram of Figure 6 shows that in recipe III, in which commercially available polystyrene was used, following the removal of the affected layers and the sectioning of the test sample (Fig. 5), the maximum depth at which the flame penetrated was 36 mm and the area of the affected frontal surface was 111 cm^2.

In recipe IV, in which ground polystyrene waste granules were used, while keeping the same volume proportions as in recipe III, the depth of the layer affected by the flame decreased to 29 mm and the affected frontal surface area increased to 120 cm^2. The explanation is that the density of the granules obtained from polystyrene waste is lower, which leads to the decrease of the density of granules per surface area unit. Under the direct action of the flame, when the polystyrene granules decompose up to a certain depth, the cement stone alveoli are maintained, which prevent the flame from advancing. This leads to the increase of the affected surface area due to the lateral propagation of temperature.

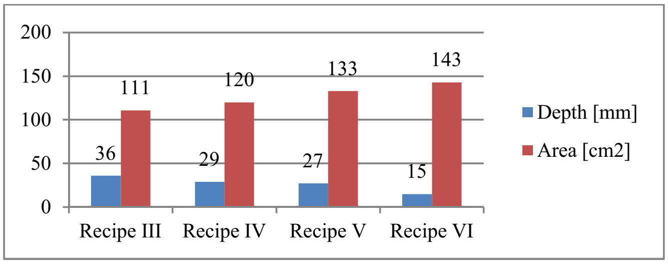

Fig. 6. Diagram of the size of the area affected by fire

In recipe V, when 30% of the cement amount was replaced with lime, a 2 mm decrease of the depth penetrated by the flame compared to recipe IV occurred, as well as an increase of the affected surface area. These phenomena are due to the lime in the composition, which increases the thermal conductivity of the material; this leads to the dissipation of thermal energy in the test sample mass, resulting in the increase of the affected area and hindering the in-depth propagation of heat.

In recipe VI, in which a lime amount equivalent to 50% of the cement amount was added to the binder composition of recipe IV, a 50% decrease of the flame penetration depth and a considerable increase of the area affected by the dissipated heat were seen. This can be explained by the much larger volume amount of the binder, which after homogenization and setting results in a thickening of the cement stone and lime coat that covers the polystyrene granules.

4. Conclusions

The research demonstrates that there are multiple possibilities for the reuse of polystyrene waste in the construction industry by the manufacture of various building materials.

Following the study on the manufacture of ecological materials based on polystyrene waste, it was found that polystyrene granules can successfully replace sand in classical mortars in a proportion of up to 100%.

The mortar produced based on recipe II, with 50% of the sand volume of the standard mortar recipe replaced by polystyrene granules, is, compared to classical mortar, a light material with an apparent density of 1291 kg/m^3, and can be assigned depending on compression strength to class CS IV and from the point of view of water absorption by capillarity, it is categorized as class W1. Its thermal conductivity is about three times lower than that of standard mortar, which recommends it as a plastering mortar.

As the other recipes included in the study do not have adhesion to the support layer, they cannot be used as plastering mortars; in contrast, they can be used as thermal insulation fillers for the thermal insulation of attics, floor filling or under the floors, given that they belong to the category of thermal insulation materials with thermal conductivity coefficients ranging between 0.06469 and 0.09914 W/mK.

Of these, the material produced based on recipe VI, which in addition to the thermal conductivity coefficient 0.09914W/mK that assigns it to the category of thermal insulation materials, also has adequate physico-mechanical characteristics and good fire behavior (it does not conduct flame), is recommended to be used as panels for the thermal insulation systems of the building envelope.

The technologies developed as part of this study ensure the manufacture of new ecological building materials, without involving high energy consumption, allowing to recover the embodied energy of the reused polystyrene.

The study presented in the paper is finalized with the development of technologies for the fabrication of two types of ecological building materials: a plastering mortar and three thermal insulation fillers, of which one is also recommended to be used as panels for external thermal insulation systems.

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