Power System Technology
ISSN:1000-3673

Received: 06-01-2026 Revised: 15-02-2026 Accepted: 12-03-2026

Thermo-Physical and Mechanical Properties of a New Insulating Material Based on Plaster Mortar and Expanded Polystyrene Beads

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Abstract: The aim of this work is to study the effect of the incorporation of different percentages and particle sizes of expanded polystyrene beads (EPS) on the thermo-physical and mechanical properties of plaster mortars. Thermal conductivity, thermal diffusivity and heat capacity are measured using the TPS-technique (Transient Plane Source) in this research. The analysis of the results indicates that the increasing of percentage of PSE beads incorporated decreases the bulk density, the mechanical strengths, thermal conductivity and thermal diffusivity compared to the plaster mortar control. With polystyrene bead proportions ranging from 0 to 60%, density and thermal conductivity decreased by up to 60% and 42%, respectively. Even a decrease for the specific heat is recorded for certain percentage of expanded polystyrene beads (EPS). So the novel insulating material based gypsum, dune sand and polystyrene beads can be used with advantage in the construction purpose.

Keywords: Plaster mortar, dune sand, expanded polystyrene, physical properties, thermal properties, compressive strength, flexural strength.

1. Introduction

In recent year, the repurposing of waste materials has gained increasing attention to address sustainability challenges. Polystyrene waste, commonly discarded after its initial use, offers potential for producing lightweight construction materials. Expanded polystyrene (EPS) beads have been identified as effective aggregates to enhance thermal insulation while reducing material density.

Previous studies have highlighted the trade-offs between mechanical and thermal properties when incorporating EPS beads into building materials. For instance, Herihiri et al. [1] demonstrated that EPS incorporation reduces mechanical strength while improving thermal insulation in dune sand mortars. Similar trends were reported for gypsum based composites by San-Antonio-González et al. [2]. This study builds on existing work by analyzing the influence of EPS bead proportions and particle sizes on the thermo-physical properties. An experimental work [3] has been elaborated on the use of recycling potential of waste rubber coming from pipe foam insulation by adding it to a gypsum matrix and the analysis of

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ISSN:1000-3673
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the obtained results shows that the waste foam rubber could be used forming part of core plaster boards, meaning a low density environmentally friendly materials. Gypsum mortars made with 75 % of waste brick should be recommended for the rehabilitation of the architectural monuments [4]. Energy demand reduction up to 16 % is obtained with 30 % of polystyrene content for composites made of Moroccan natural gypsum plasters with polystyrene balls [5]. Bicir and Kar [6] show that the gypsum plaster mixed with expanded polystyrene and tragacanth as insulation plaster and decoration material in building applications. Zaragaza- Benjel et al. [7] develop a new lightened plaster material with dissolved recycled expanded polystyrene and end of life tires fibers obtained with a 66,7 % lower thermal conductivity and 33,% higher flexural strength. The study [8] shows that the maximum thermal comfort of gypsum plaster was achieved with phase change material (PCM) light granulates compared to cement blocks with PCM. Bicer [9] improves that, if we use EPS aggregate, we can produce plasters with thermal conductivity coefficients of (0.058-0.335W/mK (non resinous with a grain diameter of 0-3 mm), 0,045 – 0,250 W/mK (resinous; 2%), 0,039-0,290 W/mK (non resinous with a grain diameter of 0-6 mm), and 0,035-0,240 W/mK. Different gypsum matrix composites were produced with varied proportions of cellulose fiber and expanded polystyrene, to analyze the influence of residues on the properties of this composite, the thermal conductivity obtained for composites with greater amount of PSE was (0.18 W/mK) [10]. The expanded polystyrene residues reduce the final density of mortars, improving their behavior against water absorption and reducing the final thermal conductivity of plaster [11]. The applications of thermal insulating plaster with a thickness of 5 cm on the walls of the analyzed building with other partitions of good thermal quality reduced its energy demand by over 20% [12]. Maaroufi et al. showed that adding recycled polystyrene beads to a cement paste improves its hygro-thermal properties [13]. In the present work and taking into account the parameter related to expanded polystyrene beads, such as, their proportions and their geometries, we have study the influence of the percentage by weight of this aggregates on the thermo- physical and mechanical properties of plaster mortars. The properties obtained from the experiments were compared with theoretical evaluations.

2. Materials and methods

The binder used in this experimental work was a commercial gypsum with a calcium sulfate dihydrate (CaSO4, 2H2O) content approximately 96%, which permitted us to classify it in class 1[14]. The chemical analysis mentioned on the table1, shows the presence of the elements S, O, and Ca with significant atomic percentages compared to the other elements, which confirms that the most essential constituent of this binder is the calcium sulphate. The hydration of plaster gives a crystalline porous product consisting of prismatic and tabular particles (figure 1). Instead of an industrial additive, air lime was chosen as a plaster setting retarder; siliceous sand 0 to 2 mm with continuous granulometry was used in

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ISSN:1000-3673
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this investigation. As lightweight aggregates, expanded polystyrene (EPS) beads manufactured in an Algerian local company (Figure 2). Two sizes of EPS were studied. Table 2 gathers the thermo-physical properties of the polystyrene (EPS) beads with different diameter D_1 = 3.15 mm and D_2 = 4 mm.

Table1. Chemical analysis of the plaster used by SEM.

Element	Wt(weight)%	Atomic%	Wt(weight)Error%
CK	2.31	3.77	± 0.17
OK	63.55	77.80	± 0.08
Mgk	0.61	0.49	± 0.13
Al K	0.24	0.18	± 0.31
SK	12.20	7.45	± 0.04
CaK	21.10	10.31	± 0.05

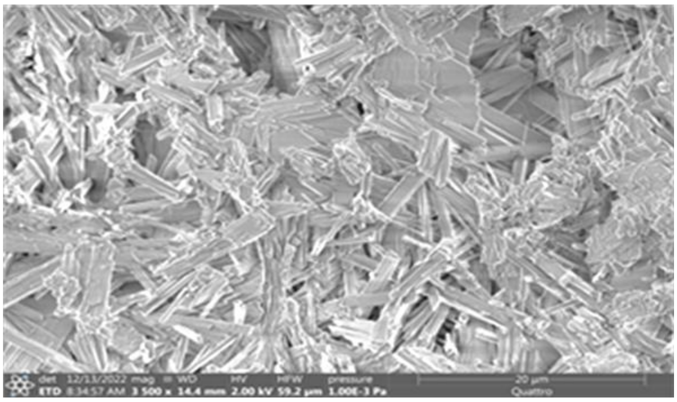

Figure1. SEM image of the plaster microstructure

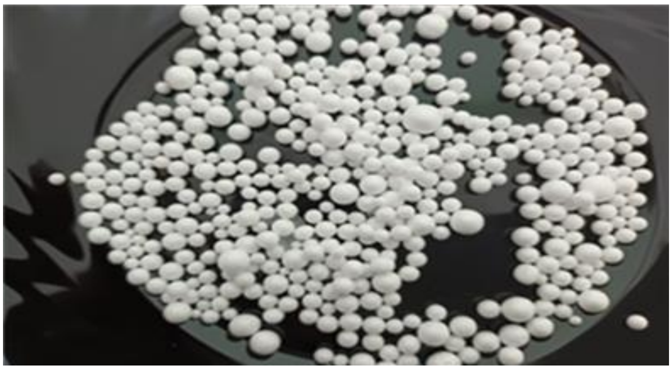

Figure 2. Expanded polystyrene (EPS) beads with different diameter.

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Table 2. Thermal and physical properties of the used expanded polystyrene beads.

Physical characteristics	EPS	
	D_1=3.15mm	D_2=4mm
Apparent density (kg/m^3)	22.3	18,7
Specific density (kg/m^3)	36.2	29.2
Compactness (%)	61	64
Porosity (%)	39	36
Thermal conductivity λ (W. m^{-1}.K^{-1})	0.028	0.028
Thermal diffusivity a (mm^2/s)	1.24	1.24
Specific heat c (MJ. m^{-3}.K^{-1})	0.022	0.022

The proposed mix designs were based on the recommendations of regulatory technical document for plaster construction published by CNERIB [14]:

- The Water/Plaster ratio (W/P= 0.60) was taken equal to the saturation mixing ratio of plaster.
- The sand / plaster ratio (S / P = 0.50) by weight, because an excess in the sand quantity reduces the mechanical properties of the plaster based materials.
- Regarding the lightweight aggregates, the EPS beads were incorporated into a mortar matrix (plaster + sand); the percentages by weight of the expanded polystyrene (relative to the mass of sand) varied from 25 to 60% with steps of 5%.
- The composition with 0% of EPS was taken as a reference mortar.

For the thermo-physical and mechanical characterization, a sample size of 4x4x16 cm^3 was chosen. The mold was filled with the material in three layers without vibration in order to avoid any segregation problems affecting the homogenization of the samples. After 24 hours, samples were stored under the following conditions (which are similar to those of the local construction sites):

• Temperature (C°): 20° ± 5°;

• Humidity (%): 45% ± 5%.

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The density of EPS mortar elaborated was calculated by measuring the weight and the volume of samples. Thermal properties were measured using the Transient Plane Source (TPS) technique (Figure 3) [15]. The test involved placing a TPS probe-hot-disk between two sample parts in a sandwich configuration, then connecting it to an electrical circuit, as shown in Figure 3. The resistance variation, ΔU, across a Wheatstone bridge provides the potential difference, ΔE(t), across the TPS element. This enables establishing a relationship between ΔE(t) and the temperature variation in the TPS component. Since the temperature variation depends on the thermal diffusivity 'a' and thermal conductivity 'λ,' suitable mathematical calculation provides values for 'λ', 'a' and specific heat 'c'(eq.1);

$$\lambda = a \cdot \rho \cdot c \quad (1)$$

Where:

- λ: thermal conductivity (W/(mK);

- a: thermal diffusivity (m^2/s);

- ρ: density (kg/m^3);

- c: specific heat capacity (J/(kgK).

Each test was repeated three times to calculate an average of the three measured values.

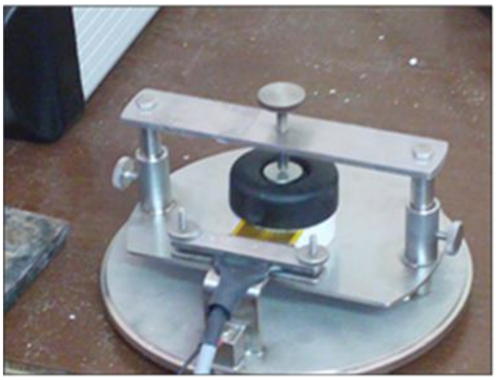

Figure 3. Clamping device, probe, test sample for the measurement of the thermal properties of the EPS-plaster mortar.

The flexural strength was measured on $4x4x16cm^3$ prisms and the compressive strength on $4x4x4cm^3$ cubes using an universal press of type ‘‘Controls’’ (EN196-1) (Figure 4a,b).

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(a)

(b)

Figure 4. The used experimental techniques, (a) Measurement of the flexural strength of the EPS-plaster mortar., (b)Measurement of the compressive strength of the EPS-plaster mortar.

3. Results and discussion

Generally, the main properties of a lightweight concrete or mortar that must be identified are its density, its mechanical strength and its thermal characteristics. It is therefore primordial and essential to begin in this study by identifying these three pa-rameters.

3.1. Density

The measured values at 28 days are illustrated by the Figure 5. It is clear that the bulk density of the control plaster mortar (0% EPS), which is about of 1380kg/m^3, is much lower than that of cement mortar which is of about 2300kg/m^3. So even without expanded polystyrene, a plaster mortar is much lighter than cement mortar.

By increasing the quantity of the expanded polystyrene aggregates in the mortar (and by decreasing the quantity of sand), the density of the mortar decreased further. This is quite normal since the density of this kind of aggregate is lower than that of mineral aggregates such as dune sand. Indeed, this density reduction is due to the partial substitution of dune sand by lightweight aggregates. Compared to the control mortar (0% EPS), a reduction of density of approximately 20-65% was achieved by the introduction of 25-60% of EPS beads respectively. Let us note that these findings are consistent with those obtained with the introduction of the expanded polystyrene aggregates in cementitious matrices.

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Herki and al. [16] studied a cement lightweight concrete using different proportions of expanded polystyrene aggregates and also showed that the increase of the proportion of the EPS decreased the density of the concrete. Petlitckaia et al. [17] found that the addition of the cork aggregates to the plaster matrix reduces the apparent density and the Virgin cork – plaster composites with density 1.312–0.878 g/cm^3 were produced. Djoudi [18] showed that the density decreases for the plaster mortars based on recycled polyethylene particles coming from plastic bottles waste. Our results are also in agreement with the works of Ouakarrouch et al. [19] on the addition of waste chicken feathers to the plaster leads, a remarkable reduction in apparent density of about 12.3%. The increase of EPS percentages of substitution up to 50% decreased significantly the density of the dune sand mortar composites [1].

3.2. Mechanical strength

The mechanical strength of concretes and mortars depends on many factors such as the nature and dosage of the binder, the Water/Binder ratio, the particle size and the nature of the aggregates, the energy of mixing and implementing, the preservation medium, etc. The variations of the flexural and compressive strengths at 28 days of the studied plaster mortar according to the “EPS/S” ratio are shown in Figure 6.

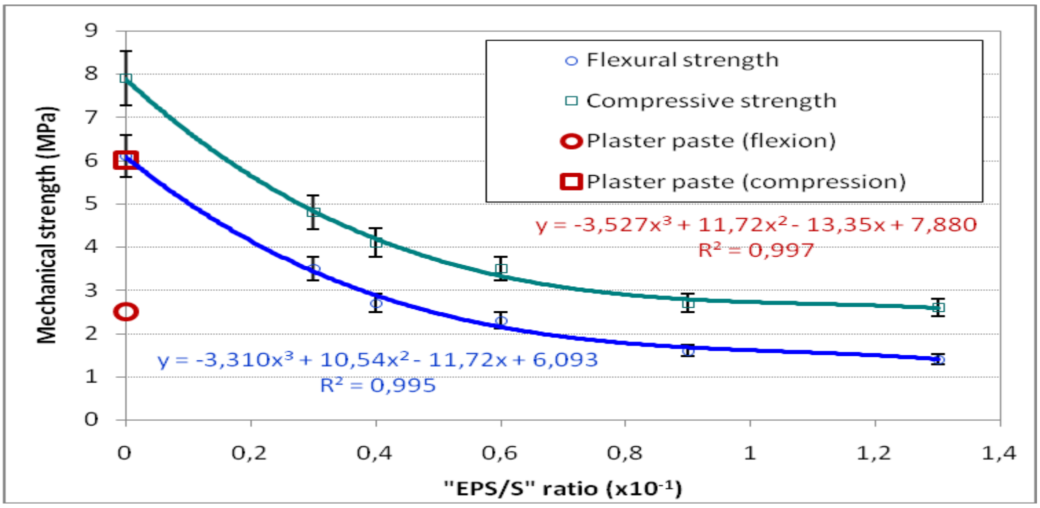

Figure 6. Variation of the mechanical strength according to the “EPS/Sand” ratio.

It is clear that the mechanical strength (in compression and flexion) decreases with the increase of the content of the EPS beads, i.e. with the decreases of the content of dune sand. With an EPS content of 60%, the flexural strength falls from 6.2 to 1.2 MPa and the compressive strength falls from 7.8 to 2.6 MPa. These values correspond to densities situated between 1380 and 480kg/m3.

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This reduction of compressive strength is due to the direct consequence of replacing rigid mineral aggregate (dune sand) with highly compressible, low-density EPS beads, which increases the material's porosity and reduces its structural integrity. Regarding the decrease in bending strength, it can be attributed to the poor adhesion between polystyrene beads and the gypsum matrix mortar. Our results are in agreement with the works [18] for the plaster mortars based on recycled polyethylene particles coming from plastic bottles waste. In the case where higher mechanical strength is required, the problem of low mechanical properties of lightweight mortar containing EPS aggregates can be solved by the use of a mineral addition, natural or artificial fibers. In the case of the use of EPS with binders other than the plaster, Babu et al. increased the strength by mixing the fly ash into the EPS concrete and the silica fume into the EPS concrete [20, 21]. Chen et al. introduced a premix method to avoid the segregation of the expanded polystyrene particles during casting and reinforced their concrete by the addition of steel fibers [22].

3.3. Thermal properties

The thermal test was carried out firstly on the expanded polystyrene itself, then on the plaster mortars containing different rates of EPS beads (0, 25, 30, 35, 40, 45, 50, 55 and 60%).

3.2.1. Expanded polystyrene

The introduction of the EPS aggregates in concretes or mortars considerably improves their thermal insulation. In our case, the thermal properties of the used EPS have been measured and the obtained results are presented in Table2. It is clear that the obtained results are consistent with those of the literature λ=0.028 $W.m^{-1}.K^{-1}$ is well included in the interval (0.027 - 0.037) $W.m^{-1}.K^{-1}$) [16].

3.2.2. Plaster mortar

For the plaster mortar containing different proportions of expanded polystyrene beads and dune sand, the thermal properties have been measured according to the devise shown in Figure 3. The obtained results of the thermal conductivity are shown in Figure 7 and the results of the thermal diffusivity and the specific heat are given in Table 3.

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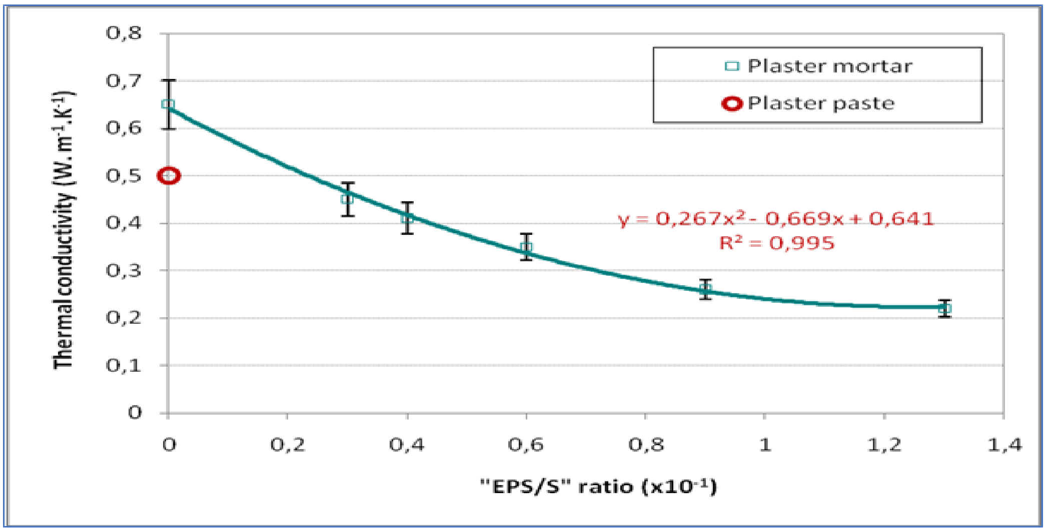

Figure 7. Variation of the thermal conductivity (λ) according to the “EPS/Sand” ratio.

Table 3. Thermal properties of the plaster mortar based on expanded polystyrene beads and dune sand.

Percentage of EPS	Thermal diffusivity a (mm^2/s) (±0.002)	Specific heat c (MJ. $m^{-3}.K^{-1}$) (±0.03)
0%	0.62	1.1
25%	0.48	1.3
30%	0.43	1.2
35%	0.40	1.5
40%	0.39	1.2
45%	0.43	0.6
50%	0.42	0.6
55%	0.38	0.7
60%	0.36	0.8

According to Figure 8, it is clear that the thermal conductivity decreases as the percentage of expanded polystyrene increases (i.e. as the percentage of dune sand decreases). The lowest thermal conductivity, which is 0.22 $W.m^{-1}.K^{-1}$, is obtained with an addition of 60% of

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expanded polystyrene beads; this represents a decrease of about 68% compared to the control mortar. That is normal because the mineral aggregates (dune sand) were replaced with EPS beads which are characterized by lower thermal conductivity. The obtained values are in agreement with those of the literature. Chen and Liu [22] as well as Sotehi and Chaker [23] made the same observation in the case of the addition of expanded polystyrene to the cement concrete and to the cement paste [13]. The high proportions of expanded polystyrene beads gave thermal conductivities less than 0.30 W.m-1.K-1. This finding is in agreement with many studies conducted on cement composites based on the expanded polystyrene aggregates [22, 24].

The thermal conductivity also decreases with the decreasing of the density; in fact, the decrease of the composite density means the increase of the proportion of the voids in the material. The higher expanded polystyrene beads content (i.e. less sand), lower is the density of mortar. According to the obtained results, the density of the material decreases from 1380 kg/m3 to 480 kg/m^3, when the content of the expanded polystyrene beads increases from 0 to 60%.

The measured thermal diffusivity values are shown in the Table 3. As for the thermal conductivity, it is clear that this property decreases as the quantity of the expanded polystyrene beads in the mortar increases (i.e. the decrease of sand). With 60% of expanded polystyrene beads, a decrease in the thermal diffusivity of about 42% compared to the control mortar (0% of EPS) was recorded. This decrease, which can be attributed to the specific texture of the used aggregates, is in good agreement with the literature [25].

The specific heat of the studied composite has also been measured. The obtained values are shown in Table 3. These latter vary in an irregular manner with the increase in the EPS content, which is in contradiction with some works made of materials other than EPS. By way of illustration, Binici et al. [26] as well as Bouguerra et al. [27] showed that the increase of vegetable fibers regularly decreased the specific heat-capacity of their composite. Maaroufi et al. [13] show that the presence of EPS beads improves the specific heat capacity of the cement paste. At last the specific heats of the plaster mortar with expanded polystyrene beads still lower than that of plant based materials; our results are in agreement with the study on cement mortar with expanded polystyrene beads [28].

4. Conclusions

This research proposed studying the possibility use of expanded polystyrene beads (EPS) for the production of a light weight plaster mortars susceptible to be used in building domains. Based on the obtained results, we can conclude:

- The partial substitution of dune sand by EPS beads led to low densities which were between 480 and 1380 kg /m^3 for EPS contents ranging from 0 to 60%; compared to

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ISSN:1000-3673
Received: 06-01-2026 Revised: 15-02-2026 Accepted: 12-03-2026

the control mortar (without EPS beads), a decrease in the bulk density of about 65% was recorded.

- A reduction of about 66% was recorded with a content of 60% of EPS beads for the compressive strength and about 80% for the flexural strength because EPS is an ultra-lightweight material composed of about 98% air. By replacing dune sand (a dense and rigid aggregate) with EPS beads, macroscopic structural "voids" are introduced into the matrix. The density of the mixture decreases, which mechanically reduces the structure's ability to bear loads. Furthermore the mechanical performance of a composite depends heavily on the bond between the aggregate and the binder. EPS beads are hydrophobic and possess a very smooth surface, which results in a poor bond with the plaster paste. This creates a weak Interfacial Transition Zone where micro-cracks can easily initiate and propagate under flexural or compressive stress compared to the rougher, more compatible surface of dune sand.
- The thermal conductivity of the composite is decreased by the increase of the EPS/S ratio (i.e. by addition of the EPS beads). With a percentage of 60% expanded polystyrene (EPS/S=0.13), it was possible to obtain thermal conductivities lower than 0, 30W.m^{-1}.K^{-1}.
- Increasing the Expanded Polystyrene (EPS)/S ratio in mortar reduces its thermal diffusivity; enhancing insulation by slowing heat transfer, as EPS replaces denser materials and increases insulating pores. While this lowers thermal conductivity and density, the specific heat capacity exhibits irregular, non-linear variations, often depending on the complex interplay between the matrix, EPS inclusions, and moisture content.

Finally the experimental results of this study demonstrate the suitability of incorporating the expanded polystyrene beads into plaster mortars in order to the diversification of their uses in building.

Acknowledgments

This research was sponsored by the General Directorate for Scientific Research and Technological Development (DGRSDT) of the Algerian Minister of Higher Education and Scientific Research.

Conflicts of Interest

The authors declare no conflicts of interest.

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