An investigation on the physical, mechanical and thermal properties of dune sand mortars lightened by expanded polystyrene beads (EPS)

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Abstract

As the idea of sustainable development has been involved in all fields including construction and civil engineering, a huge amount of researches has focused on reducing energy use and protecting the environment, while at the same time ensuring the comfort of inhabitant. Taking on this viewpoint, the current work focuses on replacing natural materials with recycled and synthetic materials, to produce a new eco-material that satisfies the binary concept; minimizing cost and constructing light elements with complex geometry that promotes architectural innovation. The present work aims to mix design and study a mortar based on mixture of fine siliceous dune sand and crushed limestone sand lightened by expanded polystyrene (EPS). Sand was substituted by EPS with percentages of 0, 5, 10, 15, 20, 25 and 100%. The physical, mechanical and thermal properties of composite mortars were assessed according to the dry density, compressive strength, flexural strength, porosity, and conductivity. The obtained results show that, the use of EPS decreases the mechanical properties and the density of mortars. However, the thermal properties of mortars incorporating EPS were improved and meet the requirement for lightweight concrete constructions and insulation applications.

Keywords: EPS, dune sand, crushed sand, physic-mechanical properties, porosity, thermal properties

Kulcsszavak: EPS, dűne homok, zúzott homok, fizikai-mechanikai tulajdonságok, porozitás, hőtani tulajdonságok

1. Introduction

Concrete is the most widely used material in building construction despite its relatively high weight and limited thermal performance in which thermal conductivity ranges between 1.4 and 3.6 W/mK [1-3]. Lightweight concrete (LWC) offers a considerable advantage in terms of its unit weight which encourages its use in the construction industry where savings made in the weight of structures are a major factor [4]. Several researchers have exploited natural, artificial and recycled lightweight aggregates in order to enhance their importance in modern construction [5]. Expanded polystyrene (EPS) is one of the artificial lightweight aggregates that provide concrete lightening, and a wide range of density choices and is used in thermal insulation. The introduction of this material therefore contributes to the efficient management of solid waste while saving landfills, conserving natural resources and protecting the environment [6]. Herki et al [7] Examined the effect of using EPS waste and fly ash in concrete. The results showed that the compressive strength and ultrasonic velocity decreases with increasing amounts of EPS and fly ash in the concrete. Ferrandiz-Mas et al [8] investigated the effect of EPS on the thermal conductivity of lightweight mortars; the results showed that the increase in the percentage of EPS beads decreases the thermal conductivity, thus increasing the thermal insulation. Sayadi et al [9] found that the strength of lightweight concrete made with

EPS beads decreases as the amount of replacement EPS increases. Ali et al [10] have carried out some tests on concretes made of polyethylene balls; the results showed that regardless of the EPS balls content, the shrinkage of EPS concrete is greater than that of the control concrete. In the context of sustainable development, the Algerian Minister of Housing and Urban Planning has banned the exploitation of river and sea sand, as a justified way to preserve the environment; this is a major environmental challenge due to the increasing need for sand. In order to balance the country's need for sand in construction field and the preservation of the environment, researchers have started to introduce new ideas and innovative solutions for this complicated problem in one hand. On the other hand, the improved thermal performance of lightweight aggregate concrete is considered as the most appropriate, particularly in reducing the energy used in heating and air conditioning of buildings. Among the steps suggested by researchers is to use the quarry limestone crushed sand and to evaluate the economy of the aggregates sector. The approach alone, however, cannot satisfy the growing demand for development programs of construction projects. Nevertheless, the search for other alternatives to deal with the lack of materials especially the sand remains increasingly important. Recently, a shift in research towards new construction materials has taken place through the reuse of local materials for the construction of high-performance concrete from a mechanical and economic point of view as well as

its durability. A local available dune sand which covers more than 60% of the Algerian territory is practically unexploited until now [11]. Many researches have been done on the use of dune sand in the field of construction in Algeria, due to the availability of this material in huge quantities especially in the southern zones [12-16]. The main objective of this work is to investigate the effect of EPS beads and plasticizer on the properties of mortar made with a mixture sand of dune and crushed sand, in order to meet the concern of preserving the natural resources, and enhance the thermal insulation of buildings. The physical, mechanical and thermal properties of mortar were evaluated according the dry density, compressive, flexural strength, porosity and thermal conductivity.

2. Experimental program

2.1 Material

2.1.1 Cement

The cement used in this work is a Portland Limestone Cement of type CPJ CEM/II which conforms to the standard EN 197-1:2000 [17]. Its specific density is 3.1 g/cm³ and its Blaine specific surface area is 3100 cm²/g.

2.1.2 Sand

As fine aggregates, a mixture of 44% of siliceous dune sand (DS) and 56% limestone crushed sand (CS) were used. The physical properties and sieve analysis results of these sands are given in Table 1 and Fig. 1 respectively.

Physical properties	DS	CS
Apparent density (kg/m ³)	1440	1530
Absolute density (kg/m ³)	2610	2630
Finesse modulus	0.74	3.88
Sand equivalent (%)	62	88
Absorption coefficient (%)	1	2
Compactness (%)	54.9	58.1
Porosity (%)	45.1	41
Empty index	0.82	0.72

Table 1 Physical properties of sand used
1. táblázat A felhasznált homok fizikai tulajdonságai

Fig. 1 Particle size distribution of sand used
1. ábra A felhasznált homok szemcseméret eloszlása

2.1.3 Expanded polystyrene (EPS)

The manufacture of polystyrene is obtained by polymerizing the basic product, which is styrene. The EPS balls with diameters ranging from 1.5 to 4 mm were used to substitute sand by percentage of 0, 5, 15, 25, 50, 75 and 100 % to lighten the mortar. The properties of the EPS balls used are given in Table 2.

Properties	Value
Particles' size (mm)	1.5 - 4
Absolute density (kg/m ³)	28
Apparent density (kg/m ³)	18
Dry thermal conductivity (W/m.K)	0.045

Table 2 Properties of EPS
2. táblázat EPS tulajdonságai

2.1.4 Plasticizer

A plasticizer with a specific gravity of 1.04 ± 0.01 g/cm³, solid content of 35% and pH of 7.9, was used to ensure the suitable workability of mortar mixtures.

2.2 Mix proportions and mixing procedure

To assess the effect of EPS on the physical, mechanical and thermal properties of lightweight mortar, seven mixtures were prepared. In order to determine the quantity required for each ingredient of lightweight mortar, the general method is used according to the standard EN 196-1 [18]. Cement/sand (S/C) ratio is maintained constant (1/3). Sand was substituted by EPS with percentages of 0, 5, 10, 15, 20, 25 and 100%. In order to reach suitable workability, varying amounts of plasticizer (PL) and water/cement (W/C) ratio were used. The mixture proportions of all lightweight mortar mixes are given in Table 3.

Mixtures	1	2	3	4	5	6	7
Cement (kg/m ³)	450	450	450	450	450	450	450
Sand (kg/m ³)	1302.50	1237.38	1107.13	976.88	651.25	325.63	0.00
EPS (%)	0	5	15	25	50	75	100
EPS (kg/m ³)	0.00	0.82	2.45	4.09	8.17	12.26	16.34
W/C *	0.55	0.5	0.48	0.44	0.38	0.33	0.27
W/C **	0.5	0.47	0.43	0.4	0.34	0.29	0.26
PL *	0.5	0.5	0.5	0.5	0.5	0.5	0.5
PL (%) **	1	1	1	1	1	1	1

Table 3 Mix proportions of different EPS mortars
3. táblázat Habarcs keverékek összetétele

The mixing procedure for making control mortar mixtures takes three steps. Firstly, the cement and sand were mixed for 1 min, and then 80% of the mixing water was added and mixed for 1 min. The remaining 20% of water containing the PL was then added and mixed for 1 min. Finally, the procedure continued for another 2 min. For the mixture containing EPS, with an additional mixing time of 2 min.

2.3 Testing

- The workability was measured according to the standard NF P 15-437 [19].
- The air content in the mortars was measured by aerometer according to the standard NF P 18-353 [20].
- The dry density of the composites was measured according to the standard NF P18-435[21].
- The flexural strength and compressive strength are measured 28 days according to ASTM C348 [22] and ASTM C349 [23] standards, respectively.
- The measurements of the thermal properties were carried out according to the standard ISO 8497-1 [24].
- The porosity accessible to water was measured according to standard NFEN18-459 [25].
- The dynamic elastic modulus of composites was determined at 28 days, using the ultrasonic pulse velocity (UPV) test according the standard ASTM C597-97 [26].
- To understand the developing of microstructure of hardened mixtures, a scanning electron microscopy analysis (SEM) was performed.

3. Results and Discussion

3.1 Fresh properties

3.1.1 Workability

Table 3 shows that the values of the W/C ratio decrease with the increase in the dosage of EPS beads, due to the polystyrene properties, it is a material that does not absorb water through a closed cellular structure [27]. These results are confirmed by the studies carried out by Bengin et al [28]. Kim et al [29] investigated the effect of polystyrene on the workability of lightweight mortars; and found that the increase in polystyrene content causes an increase in workability. Madandoust et al [30] showed that the use of EPS decreased the demand for high range water reducer, while higher slump flow was achieved. The plasticizer was added to the mixture in order to improve the consistency class of mortar with the fluidity time less than 10 s. The optimization of the percentage of PL consists in developing the best characteristics of mortar at the fresh state to ensure better performance at the hardened state. In this study, two percentages of PL were used; 0.5% and 1% by weight of cement.

Fig. 2 shows the variation of the workability of mortars with different percentages of EPS. As shown in Fig. 2, the flow time for all mixes was between 7 and 11 s, which indicates good consistency and compliance with flow time limitation so that requirement is less than 10 s in order to have a similar fluidity. It was noted that, mortars with 1% of PL have a high fluidity compared to those with 0.5% of PL [31]. For visual control, the setting is easy without any tendency to segregation or bleeding for the high percentages of EPS beads. This is due to the increase in the percentage of EPS, which is characterized by a hydrophobic behavior.

Fig. 2 Workability of mortars made with different EPS contents
2. ábra Különböző EPS tartalommal készített habarcsok bedolgozhatósága

3.1.2 Air content

The variation of the air content of the composite as a function of the EPS content, is illustrated in Fig. 3. According to this figure, the air content of mortars with EPS is more important than that of reference mortar with 0% of EPS. Up to 15% of EPS substitution, the air content increases with increasing the EPS content from 6.2% for mortar with 0% of EPS to 9.1% for mortar with 100% of EPS. However, the incorporation of 5% of EPS decreases the air content in the mixture by 20% compared to the control mortar. The decrease is due to the increase in compactness of the composite, it can be confirmed by the results of the workability test of this mixture. These results seem to be similar for the both plasticizer percentages used. The increase in the air content is explained by the increase in porosity, which can be attributed to the morphology of EPS, which is characterized by a hydrophobic nature. This explains that the EPS composite is less compact, and therefore it is more porous compared to the control mortar and that EPS balls can trap air, thus significantly increasing the air volume in composites. Increasing the air content in fresh mixture is practically identical with increasing the porosity of the composite at hardened state to the detriment of mechanical strength and the durability of the composite in general.

Fig. 3 Air content of mortars made with different EPS contents
3. ábra Különböző EPS tartalommal készített habarcsok levegőtartalma

3.2 Hardened properties

3.2.1 Density

The evolution of the density of the composite with various EPS content is given in Fig. 4; the figure shows that the density

varies from 2227.5 kg/m³ to 944.01 kg/m³ for mixtures with 1% of PL. For the control mortar, the density was 2204.98 kg/m³, and it decreased to 962.66 kg/m³, when incorporating 100 % of EPS and 0.5% of PL in the mixture. This low density can also facilitate the implementation of concrete in construction sites [32]. In addition, the decrease in the density is related to the increase of the air content in the matrix, which increases with the increase of EPS content [33-35]. Therefore, the substitution of sand by EPS has a negative effect on the density of the all mixtures, whereas the increase in the percentage of plasticizer causes an increase in density. These results were expected because the density of EPS is lower than that of the control mixture.

Fig. 4 Density of mortars made with different EPS contents
4. ábra Különböző EPS tartalommal készített habarcsok sűrűsége

3.2.2 Compressive Strength

The variation of the compressive strength of the mixtures with different substitution rates of EPS is shown in Fig. 5. From the figure, it can be seen that the compressive strength considerably decreases with the increase in the content of EPS, but it remains acceptable, even for mortars with a content of 100% of EPS as used in semi-solid insulators manufacture.

Fig. 5 Compressive strength at 28 days of mortars made with different EPS contents
5. ábra Különböző EPS tartalommal készített habarcsok 28 napos nyomószilárdsága

The compressive strength of mortar with 100% of EPS decreases from 31.58 MPa to 12.4 MPa and from 29.47 MPa to 10.34 MPa, compared to the control mixture, when using 1% and 0.5% of PL respectively. This reduction in strength is attributed to the stiffness of polystyrene, which is much lower compared to that of natural aggregates on one hand. On the

other hand, the porosity percentage of the produced composites increases with the increase of the percentage of the EPS balls [36, 37]. However, a slight increase in the compressive strength of mortars is noted with the incorporation of 5% of EPS; this is due to the decrease in the W/C ratio as well as to the small percentage of the porosity of mixture.

3.2.3 Flexural tensile strength

Fig. 6 shows the 28 days flexural tensile strength of mortars made with different percentages of EPS. It is found that, the flexural strength of mortar decreases when adding EPS. for example, the flexural strength decreases from 4.51 to 2.79 MPa for mortars with EPS content of 0% and 100% respectively, which represents a reduction rate of about 40%, whatever the percentage of PL used. This decrease in the flexural strength is probably due to the microstructure of mortar, which is characterized by high porosity and low adhesion between the EPS beads and the cement paste [38, 39]. These results are similar to those previously obtained by some authors on lightweight aggregate-based mortars [36, 37]

Fig. 6 Flexural tensile strength at 28 days of mortars made with different EPS contents

6. ábra Különböző EPS tartalommal készített habarcsok 28 napos hajlítószilárdsága

3.2.4 Dynamic modulus of elasticity

Fig. 7 shows the evolution of the dynamic modulus of elasticity at 28 days of the composites as a function of the EPS content. The figure illustrates that the modulus of elasticity of mortar varies in the same way as the flexural tensile strength and decreases with the increase of EPS content. The reduction rate of dynamic modulus of elasticity is about 85% when incorporating 100% of EPS in mixture compared to that with 0% of EPS, whatever the percentage of PL used. The weak bond between the matrix and the EPS balls may have contributed to this reduction. In addition, the presence of air bubbles in the matrix may accentuated this reduction. The waves must pass through these air bubbles in order to be propagated in the cement paste [40]. This highlights the capacity to mitigate the ultrasonic waves as well as the damping of vibrations, which indicates the good sound insulation behavior.

Fig. 7 Dynamic modulus of elasticity of mortars made with different EPS contents
7. ábra Különböző EPS tartalommal készített habarcsok dinamikus rugalmassági modulusa

3.2.5 Porosity

Fig. 8 shows the porosity accessible to water of different mortar mixtures as function of EPS aggregates percentages. From this figure, it can be noticed that, the two series of composites have the same behavior of the evolution of porosity versus the incorporated volume of EPS; the porosity of mixtures increases as the EPS content increases. For example, for mixtures with 0.5% of PL, the porosity increases from 8% to 27% when the EPS content increases from 0% to 100%. For composites with 1% of PL, the porosity varies from 7% to 24% when the EPS content varies from 0% to 100%. This increase is due to the low adhesion between the cement matrix and the EPS beads, which are characterized by hydrophobic nature in which the alveolus-shape cells are closed and remove of a part of the matrix resulting in a more complex porous structure [12]. These results are similar to those found by other researchers [41, 42]. G. Babu and S. Babu [43] studied the effect of EPS content on the porosity of concrete. The results showed an increase in porosity with the inclusion of high EPS content compared to control mixtures.

Fig. 8 Porosity of mortars made with different EPS contents
8. ábra Különböző EPS tartalommal készített habarcsok porozitása

3.3 Thermal properties

The results of the thermal properties: conductivity, diffusivity, effusivity and resistance of composites with different EPS proportions are shown in Figs. 9, 10, 11 and 12 respectively.

Fig. 9 Thermal conductivity of mortars made with different EPS contents
9. ábra Különböző EPS tartalommal készített habarcsok hővezető képessége

Fig. 10 Thermal diffusivity of mortars made with different EPS contents
10. ábra Különböző EPS tartalommal készített habarcsok hőterjedési képessége

Fig. 11 Thermal effusivity of mortars made with different EPS contents
11. ábra Különböző EPS tartalommal készített habarcsok hőkibocsátó képessége

Fig. 12 Thermal resistance of mortars made with different EPS contents
12. ábra Különböző EPS tartalommal készített habarcsok termikus ellenállása

Fig. 9 shows the thermal conductivity variation of composites with different EPS contents. It can be noted that the thermal conductivity of mortar decreases with the increase in the percentage of EPS beads compared to that of the composite control. This corresponds to a reduction of about 80% for the composite with 100% of EPS compared to the composite without EPS. This reduction in thermal conductivity is due to the morphology of EPS, which represents an amorphous structure and its low thermal conductivity is $0.4 \text{ W/m}^\circ\text{C}$ compared to natural aggregates that represent a crystalline structure and a thermal conductivity more than $1.5 \text{ W/m}^\circ\text{C}$ [44]. The RILEM recommendations reported that all mixtures studied, except the control, are classified in the “class II” of lightweight concrete of construction and insulation, based on their range of thermal conductivity less than $0.75 \text{ Wm}^{-1}\text{K}^{-1}$ [45]. Laoubi et al [46] found that the conductivity of the lightweight plaster decreased with the increase in the quantity of EPS, due to the insulating effect of the EPS.

Figs. 10 and 11 show the results of the thermal diffusivity and the thermal effusivity of the different composites. It is observed that, the diffusivity and effusivity values are in the range between $(3.454 - 4.743) \times 10^{-7} \text{ m}^2/\text{s}$ and $(2637.244 - 435.592) \text{ J/m}^2\text{s}^\circ\text{C}$ respectively. From this result, it can be concluded that, the incorporation of EPS beads decreases these parameters, due to the insulating effect of the EPS beads, which makes the produced composite more efficient thermally.

The results of thermal resistance of mortars with different percentages of EPS is shown in Fig. 12. The figure reveals the positive effect of adding EPS beads in improving the thermal resistance of composites. For control mortar, thermal resistance is $0.026 \text{ m}^2\text{C/W}$ which increases to $0.133 \text{ m}^2\text{C/W}$ for mortar prepared with 100% of EPS and 0.5 % of PL. According to the standard NFP 75-101 [47], if the thermal resistance of product is at least equal to $0.50 \text{ m}^2\text{C/W}$, it can be classified as a good thermal insulator in the building. This classification shows that all mortars were belonged to the NFP 75-101 limitation standard.

3.4 Microstructure analysis using SEM

The analysis of the specimens' morphology was carried out using a scanning electron microscopy (SEM) in order to highlight the interaction between cement-aggregates zones and the eventual changes of the microstructure of the composites within the incorporation different EPS contents. Fig. 13 shows some SEM images for samples of EPS composite mortars after 28 days of maturity.

Fig. 13 a shows that the specimen has an alveolar structure of the EPS beads, which explains the lightness of the produced composites. Figs. 13 b, c show a poor adhesion of interfacial transition zone (ITZ) between cement-aggregates, which can significantly reduce the strength. This may be because that EPS beads have surface electrostatic charges that move the paste on EPS ball-paste contact area and known as the aggregate paste interaction.

Fig. 13.a SEM appearance of the porous EPS beads structure
13a. ábra A porózus EPS szerkezetének felépítése pásztázó elektronmikroszkópos felvételen

Fig. 13.b Interfacial transition zone between EPS beads and the cement matrix
13b. ábra Felületi átmeneti zóna az EPS gyöngyök és a cementmátrix között

Fig. 13 d reveals that, the adhesion between EPS and the cement matrix is weak; this is because the EPS beads form agglomerations. The analysis of the interface “cement-aggregate” showed the bad adhesion between the EPS and the cement matrix. Indeed, some gaps have been observed between these two components as shown in Fig. 13 e. The incorporation of EPS beads seems affect the total pore volume in the mixture, which results in high porosity and producing a more complex pore network in the composite.

Fig. 13.c Interfacial transition zone EPS beads and the cement matrix
13 c. ábra Felületi átmeneti zóna az EPS gyöngyök és a cementmátrix között

Fig. 13.d SEM observation of the grouping of EPS beads in the mass of the cement matrix
13d. ábra Pásztázó elektronmikroszkopos felvételen az EPS gyöngyök csoportosulása a cement mátrixban

Fig. 13.e Interfacial transition zone EPS beads and the cement matrix
13.e ábra Felületi átmeneti zóna az EPS gyöngyök és a cementmátrix között

3.5 Relationships between the properties of ESP composites

The relationship between the compressive strength and density is illustrated in Fig. 14. The figure indicates that the compressive strength of composite decreases proportionally with density; the decrease in compressive strength of the EPS composite is associated with a decrease in density with a good coefficient of correlation ($R^2 > 0.8$). This decrease was about 60% for both strength density. In this aspect, Sayadi et al [9] have found that the evolution of the compressive strength of concretes and mortars decreases with the increase of polystyrene substitution. An improvement of the resistance is obtained for the substitution of 5% in EPS; it is related to the decrease of the percentage of the density of this composite.

Fig. 14 Correlation between compressive strength and density of EPS composites
14. ábra EPS kompozitok nyomószilárdságának és sűrűségének összefüggése

Fig. 15 shows the correlation established between the compressive strength and thermal conductivity. According to this figure, it is noted that, a decrease in the compressive strengths is associated with a decrease in thermal conductivity. A good non-linear correlation for all mixtures ($R^2 > 0.9$) is found between the two properties.

Fig. 15 Correlation between compressive strength and thermal conductivity of EPS composites
15. ábra EPS kompozitok nyomószilárdságának és hővezető képességének összefüggése

Figs. 16 and 17 illustrate the relationship between the thermal conductivity, density and porosity for all mixtures, respectively. It can be seen that, a good linear correlation is therefore observed between the parameters studied with high coefficients of correlation.

Fig. 16 Correlation between thermal conductivity and density of EPS composites
16. ábra EPS kompozitok hővezető képességének és sűrűségének összefüggése

Fig. 17 Correlation between thermal conductivity and porosity of EPS composites
17. ábra EPS kompozitok hővezető képességének és porozitásának összefüggése

4. Conclusions

The present experimental study investigated the physico-mechanical and thermal performances of dune sand mortars containing EPS as aggregate, the following conclusions can be drawn:

- The incorporation of EPS beads as aggregate improved the workability of mortar.
- An increase in the percentage of EPS beads is accompanied by the increase of the air content of the composites, which increases the voids inside the matrix and consequently increases its porosity.
- The compressive strength and flexural tensile strength decreased as the quantity of EPS beads increased, except the mixture with 5% of EPS that gives the best mechanical performance compared to other mixtures.
- The modulus of elasticity of the composites lightened by EPS relatively decreases according to the increase in the percentage of EPS, which means greater deformability in the reference matrices and therefore less risk cracking.
- The increase of EPS percentages of substitution up to 50% decreased significantly the density of the composites.
- The microstructure analysis showed that the use of EPS in mixtures caused an increase in porosity as well as a weak adhesion zone between cement and aggregate.
- The thermal properties of all mixtures are significantly decreased by the addition of the EPS; it was possible to obtain a thermal conductivity equal to $0.30 \text{ Wm}^{-1}\text{C}^{-1}$ for when 100% of EPS is used. It should be noted that the obtained values of the thermal conductivity meet the RILEM recommendations, which suggest a coefficient of thermal conductivity less than $0.75 \text{ Wm}^{-1}\text{C}^{-1}$ for lightweight concrete construction and insulation applications.
- Finally, the EPS composites could be the subject of several applications, and can be used to reduce the heat transfer and thus to save energy.

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