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Research Article

Recycling waste expanded polystyrene as aggregate in production of lightweight screed mortar

Serhat Çelikten [1], *, İsmail İ. Atabey [2], Zehra A. Özcan [3], Uğur Durak [4], Serhan İlkentapar [5] Okan Karahan [6] Cengiz D. Atiş [7]

[1] Department of Civil Engineering, Nevşehir Hacı Bektaş Veli University , Nevşehir (Türkiye); scelikten@nevsehir.edu.tr
[2] Department of Civil Engineering, Nevşehir Hacı Bektaş Veli University , Nevşehir (Türkiye); ismailatabey@nevsehir.edu.tr
[3] Tomarza Mustafa Akıncıoğlu Vocational College, Kayseri University, Kayseri (Türkiye); zehraozcan@kayseri.edu.tr
[4] Department of Civil Engineering, Erciyes University , Kayseri (Türkiye); ugurdurak@erciyes.edu.tr
[5] Department of Civil Engineering, Erciyes University , Kayseri (Türkiye); serhan@erciyes.edu.tr
[6] Department of Civil Engineering, Erciyes University , Kayseri (Türkiye); okarahan@erciyes.edu.tr
[7] Department of Civil Engineering, Erciyes University , Kayseri (Türkiye); cdatis@erciyes.edu.tr
*Correspondence: scelikten@nevsehir.edu.tr

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Abstract: The potential use of waste-expanded polystyrene (EPS) beads in the production of lightweight screed mortar (LSM) was investigated. LSM specimens were produced by replacing waste EPS with normal weight aggregate at 20%, 40%, 60%, 80%, and 100% proportions by volume. Workability, unit weight, capillarity, flexural and compressive strength, abrasion resistance, drying shrinkage, and thermal conductivity of the LSMs were determined. Waste EPS replacement by the normal weight aggregate reduced the abrasion resistance and strength properties of LSMs. Waste EPS also caused the LSMs to have lower unit weight and thermal conductivity, significantly. It was concluded that substitution of waste EPS by normal weight aggregate up to 60% can be proposed for adequate strength and heat-insulating properties of LSMs. LSM produced with 60% waste EPS (M60) has 16.3 MPa 28th-day compressive strength with 0.4562 W/m.K thermal conductivity and 1.35 g/cm^3 unit weight. Moreover, the recovery of waste EPS contributes to both reducing environmental pollution and storage problems.

Keywords: Waste EPS, recycling, lightweight screed mortar, strength, thermal insulation.

1. Introduction

Nowadays, the concept of sustainability emphasizes the importance of energy saving as well as reducing raw material consumption in order to prevent global warming by reducing greenhouse gas emissions. Utilizing the resource efficiency of construction materials is one of the important current issues facing the industry. There are problems in many parts of the world in the disposal of urban solid waste and various industrial wastes. In recent years, intensive studies carried out to valourize waste materials instead of cement and aggregate as traditional building materials (Khankhaje,et al., 2023; Moreira et al., 2014).

In this context, many waste products such as silica fume, fly ash, rice husk ash and blast furnace slag have been utilized as alternative binders to cement (Kaya and Köksal, 2022; Görhan and Bozkurt, 2022; Yurt, 2022; Bayer Öztürk, Z. and Çam, T, 2023). Similarly, the use of various waste products as an alternative to aggregate is being also investigated. One of the waste products considered to be used instead of aggregate is EPS. Waste EPS foams, which take a long time to disappear in nature, are a material widely used in the industrial field. The recycling and reuse options of EPS-derived waste products are very limited. Waste EPS is generally disposed of by incineration that results serious environmental problems. On the other hand, waste EPS can be replaced with normal weight aggregate in mortar to produce lightweight concrete (Kar and Biçer, 2016, Colangelo et al., 2018).

Polystyrene, an industrial product, is a thermoplastic polymer that is expanded by steam or a chemical agent. EPS is a hydrocarbon thermoplastic and inert material with a very low density. EPS aggregates are used in the manufacture of panels, flooring applications, laminated walls. EPS has very good heat and sound insulation properties due to its porous microstructure. The use of EPS in cement-containing composites increases the insulating properties of the mortar/concrete (Köksal et al., 2020; Becker et al., 2022).

EPS accounts for 0.1% of total municipal solid waste. Recycling polymeric solid waste as concrete and mortar components requires further research that improves the incorporation of polymers into cementitious materials and increases the added value. (Ferrándiz-Mas and García-Alcocel, 2013). In the literature, three methods are proposed for recycling EPS. The first is to produce new raw materials in different forms by dissolving them with heat or solvents for use in different sectors. The second is chemical conversion. The third is thermal recycling. The use of the high amount of EPS in the heat and sound insulation of buildings causes a large amount of waste EPS (Noguchi et al., 1998; Mounanga et al., 2008; Ben Fraj et al. 2010; Meddage at al. 2022).

Lightweight aggregates are used in screeds, concretes, and mortars to reduce weight and increase thermal and acoustic performance (Mounanga et al., 2008; Ben Fraj et al., 2010; Benkreira et al., 2011; De-Carvalho et al., 2013). A conventional screed mix usually consists of water, cement, and fine aggregate. As acoustic and thermal insulation regulations impose more severe restrictions, special attention has been paid to the development of new products that can compete with traditional products in terms of performance (Juenger et al., 2011). EPS mortars are lightweight composites that have been widely used in building construction in recent years (Cui et al., 2016). There are various studies in which EPS is used instead of aggregate in mortar. Particularly, the strength properties of such concrete were characterized and the effect of using EPS, organic additives, fly ash, silica fume, and other additives in different grain sizes was evaluated. Other laboratory studies have characterized the thermal and mechanical properties of mortar containing non-waste EPS aggregate. However, the studies performed on the use of waste EPS as aggregate in mortars are limited (Ferrándiz-Mas et al., 2016).

When the literature was reviewed; Koksal et al. (2020) used the waste EPS by replacing the expanded vermiculite by volume. The authors stated that mortars containing waste EPS have lower water absorption capacity than that of vermiculite. Sayadi et al. (2016) investigated the effect of EPS particles on the compressive strength and thermal conductivity of foamed concrete. They concluded that the increase in EPS volume caused a decrease in strength, however, it provided a significant decrease in thermal conductivity. Ferrándiz-Mas et al. (2016) experimented with lightweight mortars containing waste EPS and designed mortars with statistical optimization methods. They reported that EPS-containing mortar was suitable for use in wall plasters. In another work, Ferrándiz-Mas et al. (2014) aimed to develop lightweight mortars with adequate thermal insulation characteristics by using waste EPS and waste paper sludge ash. They stated that mortars containing up to 60% waste EPS were suitable for use in plaster and plaster applications. In addition, in another study, the same researchers Ferrándiz-Mas et al. (2013) investigated the durability properties of both commercial and waste EPS in Portland cement mortars. They stated that EPS used in different sizes reduced the capillary water absorption coefficient of the masonry mortars and provided an improvement in residual compressive strength after freeze-thaw cycles.

Demirboğa and Kan (2012) investigated the effect of waste EPS on the workability, density, thermal conductivity, and drying shrinkage of lightweight concrete. They replaced the waste EPS and river sand at proportions of 25, 50, 75 and 100%. They stated that the thermal conductivity decreases by about 70% at the 100% replacement ratio. Kar and Bicer (2016) investigated the potential of using EPS in lightweight concrete production. In their study, they investigated the strength and thermal properties of concretes made with EPS aggregates. The results of the study showed that as the EPS ratio increases in concrete, the compressive and tensile strength decreases. Kilincarslan et al. (2019) investigated the effects of using EPS on properties of foam concrete containing fly ash. They stated that the expansion ratios decreased with the increase in EPS ratio. They also stated that the use of EPS in foam concrete greatly reduced the capillary cracks on the concrete surface caused by shrinkage. Bicer and Kar (2017), investigated the strength and thermal properties of EPS-Cement-Marble powder composites and stated that the thermal conductivity improves as the EPS ratio increases in the mixture. Liu and Chen (2014), in their study investigating the effect of EPS particle size on the mechanical properties of EPS-containing lightweight concrete, stated that as a result of the improvement of plastic deformation with the increase in EPS volume ratio, lightweight concretes experienced a different fracture process than normal concrete in compressive strength. Cui et al. (2016) in their study, investigated the usability of EPS in concrete. According to the results of the study, they stated that EPS can be used in structural concrete applications.

In the literature, there are studies on the thermal properties and compressive strength of lightweight mortar containing EPS. However, there are limited studies investigating the engineering properties that include durability, thermal conductivity, and strength properties of LSM. It is very important to reduce the screed mortar specific gravity that brings additional load to the building, both in terms of earthquake and in terms of heat and sound insulation between floors. In this study, an attempt was made to develop building materials with high sensitivity to waste recycling and energy efficiency, which are especially important in order to minimize global environmental problems. This work also For this purpose, the thermal, strength, and physical properties of LSMs produced by using waste EPS particles as a replacement for sand were experimentally investigated in this study. In this context, workability, unit weight, capillary water absorption, flexural and compressive strength, abrasion resistance, drying shrinkage, and thermal conductivity tests were conducted on the mortars produced. Properties obtained from EPS-containing mortar were compared with normal-weight mortar made without EPS.

2. Materials and methods

2.1. *Materials*

CEM I 42.5 R type Portland Cement specified in the TS EN 197-1 (2012) standard was used for LSM production. Specific surface area, the specific gravity, initial and final setting times of the cement were determined as 3.15, 3468 cm²/g, 162 minutes, and 215 minutes, respectively. In addition, the chemical oxide composition, physical, and strength properties of cement are presented in Table 1. Waste EPS was obtained from Koyuncu Kimya, an EPS recycling plant in Turkey. Waste EPS consisted of irregularly shaped residual EPS particles as shown in Figure 1. Waste EPS aggregates were grained with the size of 0-4 mm by using a grinder. The density of waste EPS foams was 16 kg/m^3.

Table 1. Chemical composition, physical and strength properties of cement

Blaine specific surface area, cm²/g	Specific Gravity, g/cm^3	Remaining (40 Micron), %	Remaining (90 Micron), %	Initial setting time, min	Final setting time, min	Volume expansion, mm	2 days, MPa	7 days, MPa	28 days, MPa
3468	3.15	10.3	0.9	162	215	1.0	26.5	39.0	49.7
				Chemical Composition, %					
CaO	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	MgO	SO_3	Cl	LOI
65,08	19,25	4,23	3,02	0.38	0.93	1.73	3.47	0.02	1.87

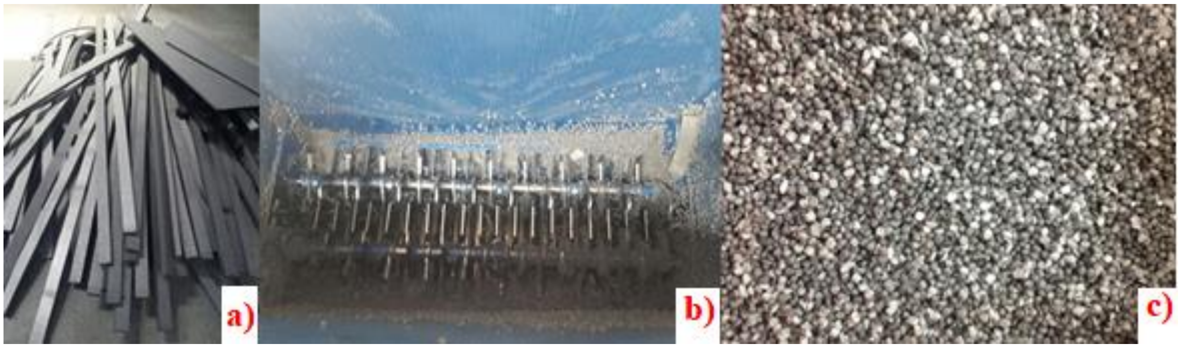

Figure 1. Pictures of waste EPS a) the waste EPS pieces b) graining process c) waste EPS aggregates.

In the experimental study, fine river sand with 0-4 mm grain size was used as aggregate. The river sand supplied from a low flow river in Kayseri, Turkey. Sieve analysis was performed for the sand in accordance with TS EN 933-1 (2012) and was presented in Table 2. The fineness modulus of the fine aggregate was 1.88, dry volume-specific gravity, and saturated surface dry density were measured as 2.60 and 2.64 g/cm³, respectively. The water absorption capacity of sand was 1.70%. The agent was added to distribute EPS foams in the mortar. Its properties are given in Table 3. In the production of lightweight screed with waste EPS, an agent was used to form a bond between the EPS granules and the cement mortar. The agent was resistant to cracking and provided complete integrity with the cement. The admixture had no negative influence on the strength properties of LSMs. The properties of the admixture are presented in Table 3. In the production of LSM, potable tap water was used. Additionally, a plasticizer was added to improve the consistency of the mortar. The plasticizer in complies with EN 934-1 was used to obtain constant workability (110±10).

Table 2. Sieve analysis of river sand.

Sieve Size (mm)	Pan	0.25	0.5	1.0	2.0	4.0
Remaining on Sieve (%)	0	16.1	47.0	66.6	82.4	100

Table 3. The properties of chemical agent.

Properties	Appearance	Color	Specific Gravity	pH	Resolution	Freezing Point	Fire Reactivity
	Liquid	Brown	1.15	7.0	Unlimited	-10ºC	Fireproof

2.2 Methods

Six different mortar mixtures were designed as illustrated in Table 4. The mixtures were coded concerning the waste EPS replacement ratio by the sand. EPS was replaced by sand by volume as 0%, 20%, 40%, 60%, 80% and 100% to obtain LSM. The water-to-cement ratio of the LSMs was 0.50 and the cement dosage was determined as 300 kg/m^3. Plasticizer was added in appropriate proportions so that the flow workability values of LSMs containing waste EPS aggregate were 115±5 mm. The mortar mixtures were prepared in a Hobart mixer in accordance with TS EN 196-1 (2009). The mixtures were placed in the molds in two stages and compacted by a vibrating table. Mortar specimens with dimensions of 40×40×160 mm, 70×70×70 mm, 100×100×100 mm, 25×25×285 mm, and 500×500×50 mm was obtained. The pictures of the specimens are presented in Figure 2. The specimens were cured in water chamber at 21±1°C for 7 and 28 days, separately. Workability tests were performed on LSMs at fresh state. The unit weight, capillary water absorption, flexural and compressive strength, abrasion resistance and drying shrinkage tests were performed on the specimens, separately. In addition, the thermal conductivity coefficients of the LSMs containing waste EPS were measured. The results obtained from the waste EPS-incorporated LSMs were compared with the traditional sandy screed mortar (M0).

The workability test was carried out on the fresh LSMs in accordance with the TS EN 1015-3 (2000) standard. The spread value of each LSM mixture was determined by measuring the average diameter of two readings from the mixture. The unit weights of LSM specimens were calculated after 28 days of water curing. For the capillary water absorption test firstly, the specimens were dried in the oven and then covered with an aluminum foil tape so that only the bottom surface touched the water. Capillary water absorption test was performed according to ASTM C 1585. The amount of water absorption at 1, 5, 10, 20, 30, 60, 120, 240, 300, and 360. minutes and at 1, 2, 3, 4, 5, 6, 7, and 8 days were evaluated. A third point flexural strength test in accordance with TS EN 1015-11 (2000) standard was carried out on the 40×40×160 mm specimens. The loading rate of the test was 50 N/s. The flexural strength test was performed on three specimens for each mixture and the arithmetic average of the obtained values was recorded as the flexural strength value. Compressive strength test was carried out in accordance with TS EN 1015-11 (2000) standard. The test was performed on the six semi-specimens. The six semi-specimens were the broken specimens during the flexural strength test. The loading rate of the test was 500 N/s The compressive strength value of each LSM mixture was the arithmetic average of six semi-specimens. Abrasion resistance of the LSM specimens was determined by Böhme device on 71×71×71 mm3 cube specimens in accordance with TS 2824 EN 1338 (2005). Abrasion resistance was determined as the reduction in mass and volume of the specimens. To observe the effect of lightweight screeds with waste EPS aggregates on drying shrinkage, shrinkage test was carried out in accordance with ASTM C157/C157M (2017) standard. For the experiment, 25×25×285 mm LSM bar specimens were employed. During the experiment, the specimens were cured in a climatic chamber at 23±2ºC temperature and 50±5% relative humidity. The length changes of the specimens were recorded up to 120 days.

In order to determine the thermal conductivity coefficients, with size of 500×500×50 mm lightweight screed specimens were used (Figure 2). The prepared specimens were cured in a curing pool at 21±1ºC for 28 days. After water curing, lightweight screed specimens were dried in an oven at 105±5ºC for 24 hours and placed in the enclosed hot plate device shown in Figure 3. The heat transfer coefficient values were obtained by using a computer program. In the plate method, the thermal conductivity value of a material was determined with the configuration in Figure 4 according to the principles outlined in the TS ISO 8302 (2002) "Determination of Thermal Conductivity with the Plate Method" standard. The thermal conductivity coefficient was calculated on two specimens for each mixture, and the average of two values obtained was recorded as the thermal conductivity coefficient.

Figure 2. View of the prepared specimens a) the mortar mixture placed in the prism mold b) the 100×100×100 mm cube c) the 40×40×160 mm prism specimens d) the 500×500×50 mm plate.

Figure 3. Hot plate device.

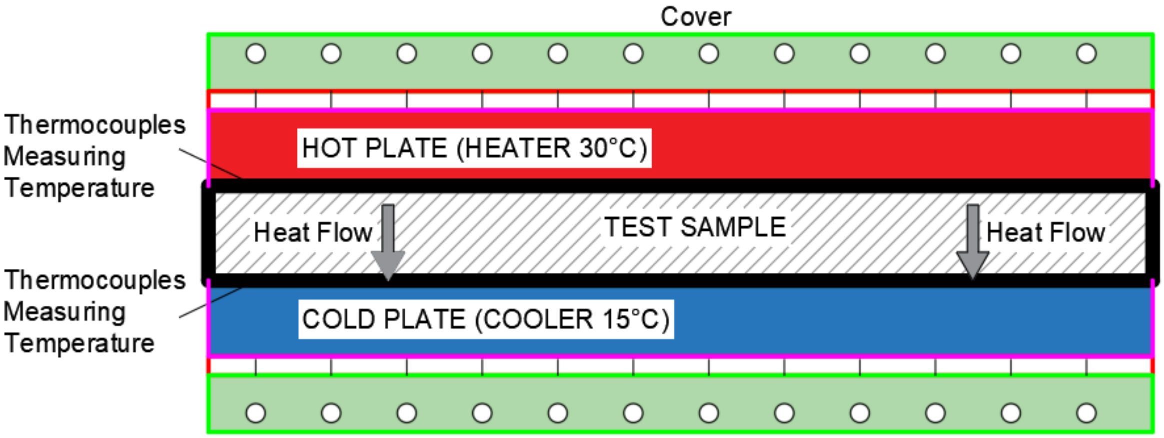

Figure 4. Hot plate device graphic configuration.

Table 4. Mix proportion of mortars produced.

Mixture Code	Water	Cement	Aggregate	EPS	Agent	Plasticizer
	kg/m^3					
M0	0.5	300	1936	0	0.00	4.5
M20	0.5	300	1549	2.38	0.20	3.0
M40	0.5	300	1162	4.77	0.40	1.5
M60	0.5	300	775	7.15	0.60	0.0
M80	0.5	300	387	9.53	0.80	0.0
M100	0.5	300	0	11.92	1.00	0.0

3. Results and discussions

3.1. *Workability and unit weight*

The spread values of LSMs were presented in Figure 5. The spread values measured were between 110 and 120 mm as targeted. The improved workability with increasing replacement levels of fabricated EPS employed as aggregate in cementitious composites was reported by many researchers (Hilal et al., 2021; Assaad and Abdulkader, 2020; Laoubi et al., 2019). On the other hand, the irregular grain shape of waste EPS as seen on the Fig. 1, limited the workability enhancement of the LSMs as increasing EPS content. The 28-day dry unit weights of the LSMs were presented in Figure 6. It was observed that the unit weights of LSMs decreased as the increase of the replacement ratio. While unit weight of control mortar (M0) was 1.93 g/cm^3, the unit weights of LSMs made with waste EPS aggregates varied between 0.42-1.80 g/cm^3 the decrease in unit weight values was attributed to replacement of waste EPS. Sayadi et al. (2016) stated that the use of EPS significantly affects the density of the concrete. Higher polystyrene volume resulting in lower density and unit weight in mortar was found to be parallel to literature. Besides, with the replacement of river sand waste EPS, the dead load of the elements can be reduced, that means a saving in the reinforcement and the foundation dimensions.

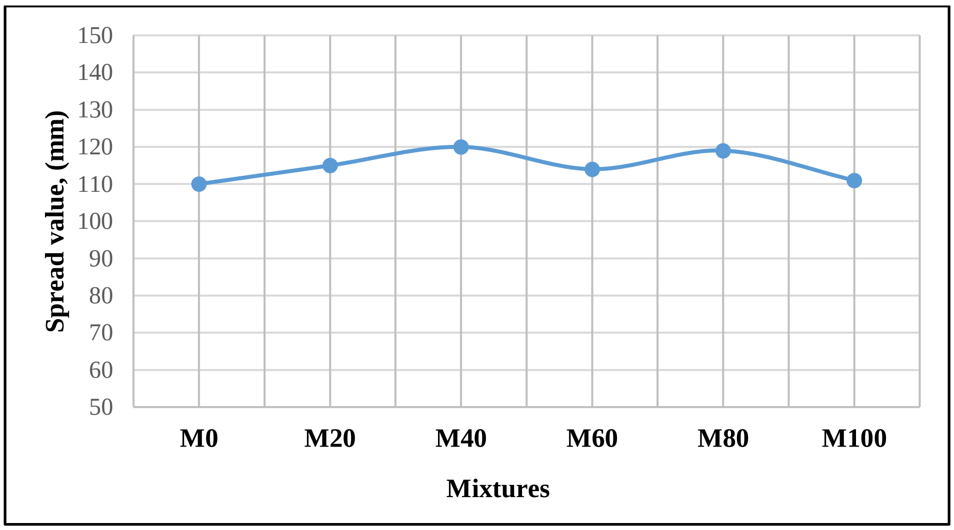

Figure 5. Workability results.

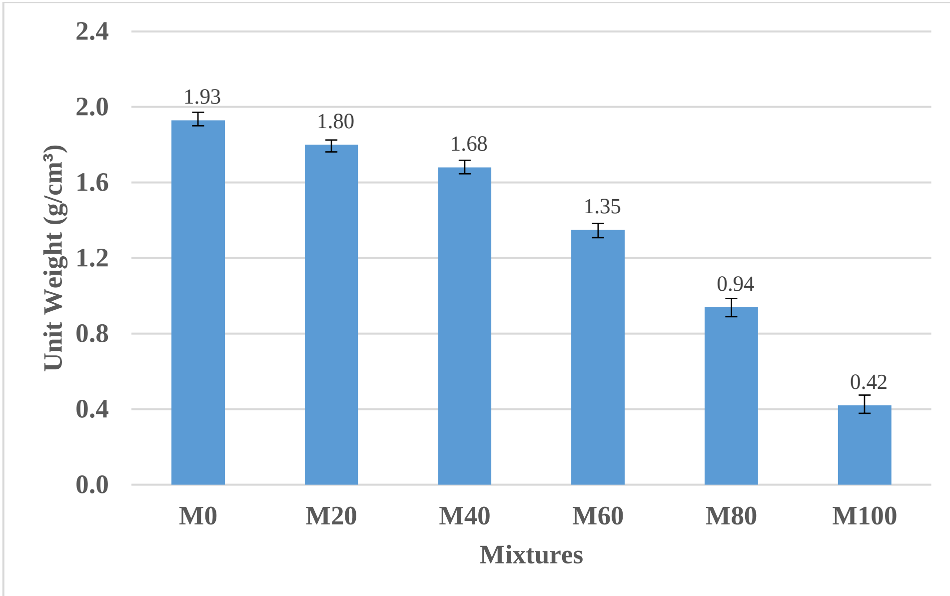

Figure 6. Unit weights results.

3.2. *Capillarity*

Capillary water absorption coefficients are presented in Figure 7. Coding was made according to capillary water absorption duration. For example, initial capillary water absorption was abbreviated as M0-1, and secondary capillary water absorption as M0-2. Initial (6-hour) and secondary (8-day) capillary water absorption values for M0, M20, M40, M60, M80 and M100 were 2.17, 3.22, 3.42, 4.64, 5.09, 8.17 mm/s^{½}, (for 6-hour) and 5.38, 6.63, 7.06, 8.70, 9.56, and 10.17 mm/s^{½}, (for 8-days), respectively. As the waste EPS inclusion rate increased, an increase was observed in the capillary water absorption. It can be attributed to the highly porous structure of waste EPS. In addition, a typical pore structure of EPS can be seen in the previous work of Bouvard et al. (2007). The pore structure of EPS illustrates that irregular pores are available between the cellular voids of EPS. The capillary movement of water from these irregular pores is another reason for the increased capillary water absorption of LSMs. Moreover, the interfacial transition zone between the EPS aggregate and cement paste is more porous than the zone between river sand and cement paste (Bakhshi and Shahbeyk, 2019). The movement of water from the surface of LSM sample to inner regions is easier due to the porous zone.

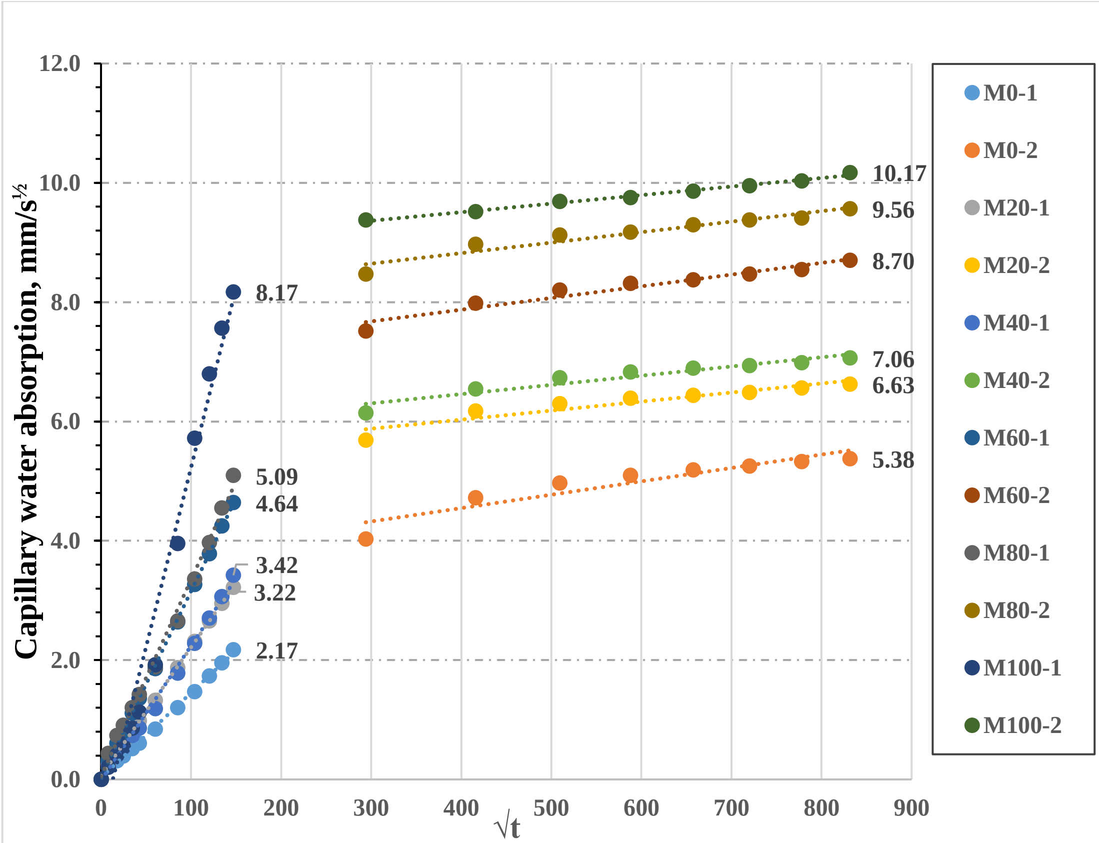

Figure 7. Capillary water absorption test results.

3.3. *Flexural and compressive strength*

The flexural strength values of the LSMs are given in Figure 8. According to the results, flexural strengths of M20, M40, M60, M80, and M100 LSMs were about 12%, 20%, 40%, 70% 88%, and 7%, 16%, 43%, 71%, 88% lower than the reference mixture (M0) at 7 and 28 days, respectively. It was seen that substitution of EPS by sand decreased the flexural strength values of the LSMs, significantly. In addition, the increase in the curing time (from 7 days to 28) increased the flexural strength of the specimens up to 40% waste EPS usage, however, it did not provide a significant increase by the use of waste EPS over 40%. The compressive strength values of the LSMs are presented in Figure 9. Compressive strength values of M20, M40, M60, M80, and M100 LSMs were about 22%, 53%, 64%, 85%, 97% and 31%, 45%, 60%, 86%, 97% lower than the reference mixture at 7 and 28 days, respectively. The 28-day compressive strengths were generally slightly higher than that of the 7-day compressive strengths. The decrease in the compressive strength with the increase of waste EPS ratio is explained by the fact that the specimens have a more porous microstructure as well and waste EPS aggregate has much lower density and thus compressive strength than normal aggregate. Similar results were also concluded and published in other studies in the literature (Sayadi et al., 2016). In addition, the degree of interfacial bonding between the cement paste and aggregate is one of the most important parameters of the strength performance of the mortars and concretes. The decrement in the strength properties of the LSMs can also be attributed to the weak bonding of EPS with cement paste (Milling et al., 2020). Additionally, Figure 10 illustrates the relationship between the strength properties of the LSMs. The R^2 value of 0.92 indicates a strong relationship between the flexural and compressive strength of the LSMs.

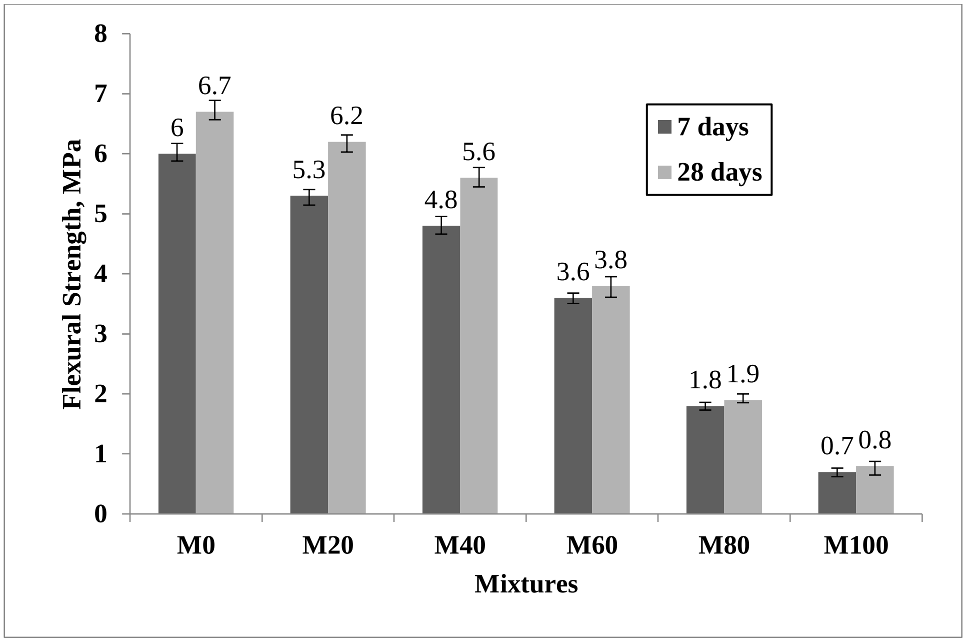

Figure 8. Flexural strength results.

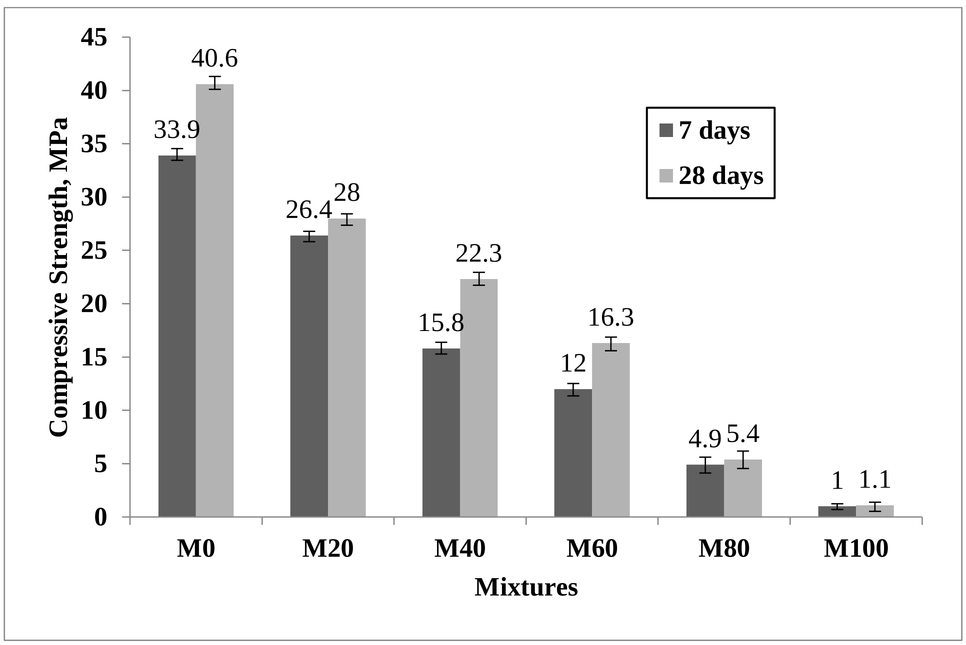

Figure 9. Compressive strength results.

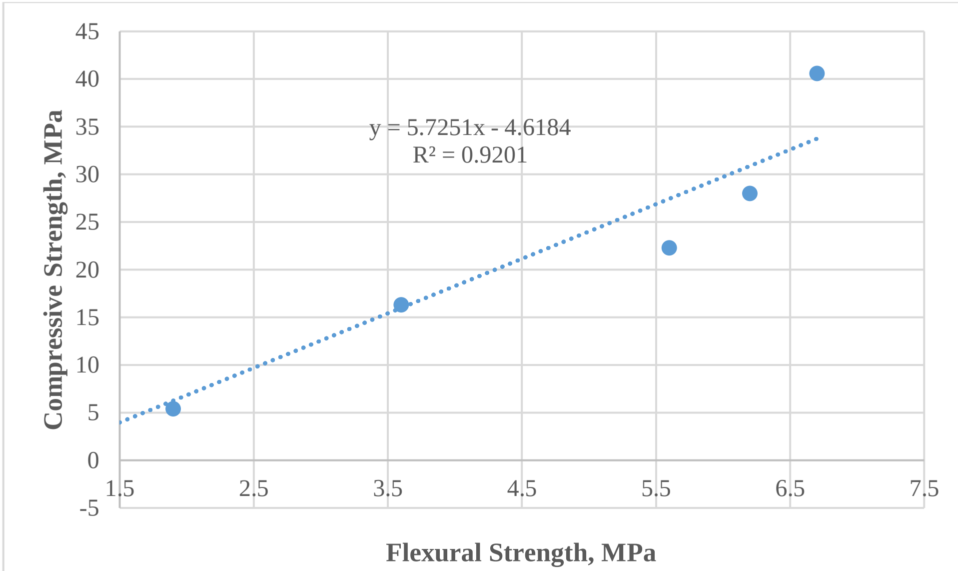

Figure 10. The relationship between compressive and flexural strength.

3.4. *Abrasion resistance*

Abrasion test results of the LSMs are presented in Table 5. Mass loss in the reference sample (M0) was 26.9 g. EPS-incorporated LSMs had the higher mass loss concerning the M0. M20, M40, M60, M80, and M100 mortars exhibited 16%, 37%, 59%, 70%, 104% higher mass loss than the reference sample (M0), respectively. Volume loss in the reference sample (M0) was 17933 mm3/5000 mm^2. Similar to the mass loss results, substitution waste EPS at the ratio of 20%, 40%, 60%, 80%, and 100% resulted in more than 16%, 48%, 90%, 144%, and 500% volume losses compared to reference sample, respectively. This decrease is compatible with the strength losses.

Table 5. Abrasion test results.

Specimen	Mass loss (g)	Volume loss ($mm^3/5000mm^2$)
M0	26.9	17933
M20	31.3	20816
M40	36.8	26619
M60	42.9	34129
M80	45.9	43811
M100	55.1	108996

3.5. *Drying shrinkage*

The drying shrinkage test results obtained are presented in Figure 11. M0 specimen exhibited 0.012% and 0.058% shrinkage at 7 and 120 days, respectively. It was observed that the substitution of waste EPS caused to increase in the drying shrinkage of the LSMs. The main factors affecting shrinkage are cement paste quality, cement paste amount, and aggregate type. When hard and dense fine aggregate is used in concrete, less shrinkage is generally observed as the mobility of the cement is restricted. However, in lightweight concretes where weaker and less hard aggregates are used, fewer restrictions are placed on the cement paste, resulting in higher drying shrinkage in concretes (Demirboga and Kan, 2012). Therefore, as the amount of river aggregate decreased and the rate of EPS increased (from 20% to 100%), the shrinkage measured in the specimens increased. The increase in the shrinkage results was much more significant at 80% EPS content and above. These results can be mainly attributed to the low elastic modulus and mechanical properties of the EPS (Maghfouri et al. 2022).

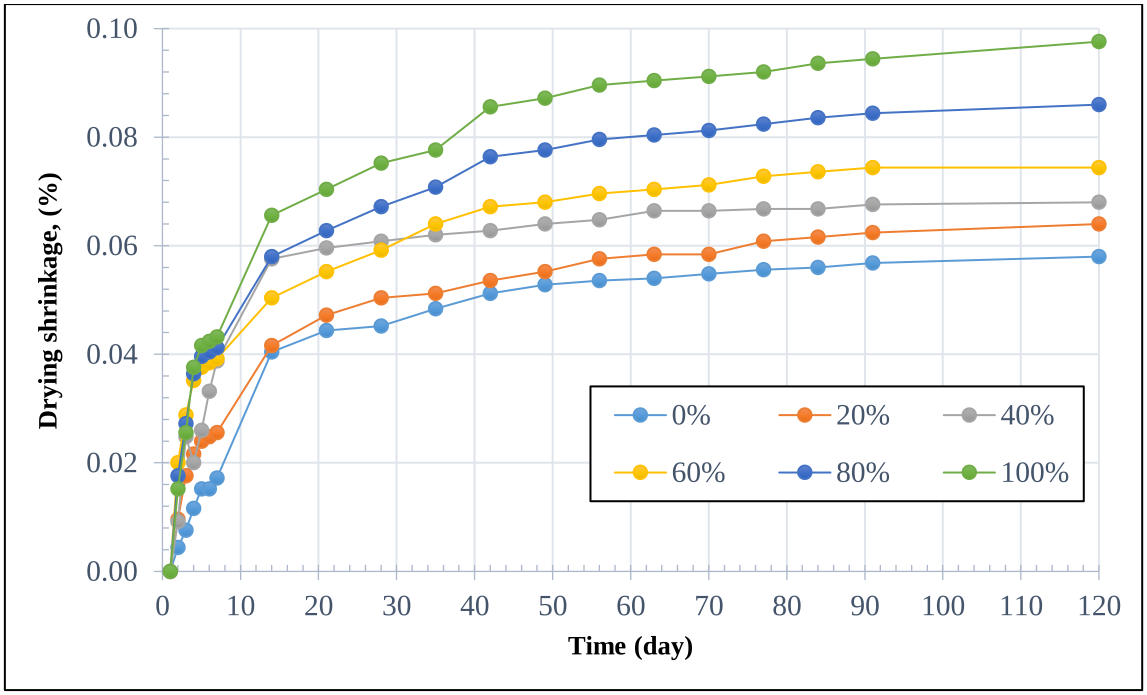

Figure 11. Drying shrinkage results.

3.6. *Thermal conductivity*

Thermal conductivity test results are presented in Figure 12. Thermal conductivity coefficient of the M0 sample was 0,6299 W/m.k. While the highest thermal conductivity coefficient belonged to the M0 specimen, the lowest coefficient was seen on the M100 LSM. The thermal conductivity coefficients of M20, M40, M60, M80 and M100 LSMs were 11%, 20%, 28%, 54% and 72% lower than the M0, respectively. It can be claimed that the material obtained with a decrease in the thermal conductivity coefficient turns into a product that conducts less heat, thus, it can be used as a thermal insulation material. In a similar study, Sayadi et al. (2016) stated that the thermal conductivity decreases with the increase in EPS volume. Demirboğa and Kan (2016) demonstrated the relationship between thermal conductivity and unit weight of lightweight concrete. They showed that as the unit weight decreases, the thermal conductivity decreases. Similar with the previous results and statements, Figure 13 demonstrates a highly strong relationship between the unit weight and thermal conductivity of the RSMs. In addition, compatible with the present work, Colengelo et al. (2016) revealed that sustainable lightweight heat-insulated building materials can be produced using waste EPS.

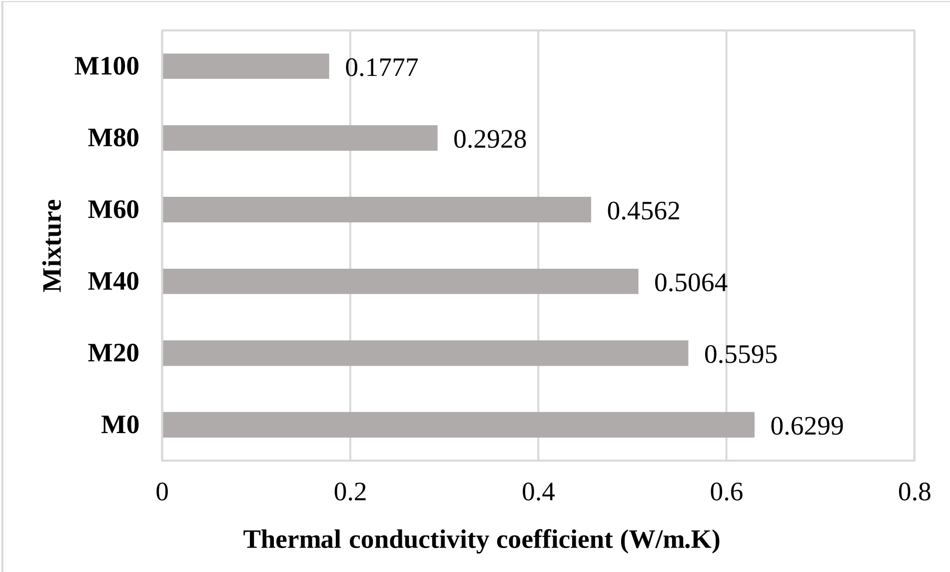

Figure 12. Thermal conductivity results.

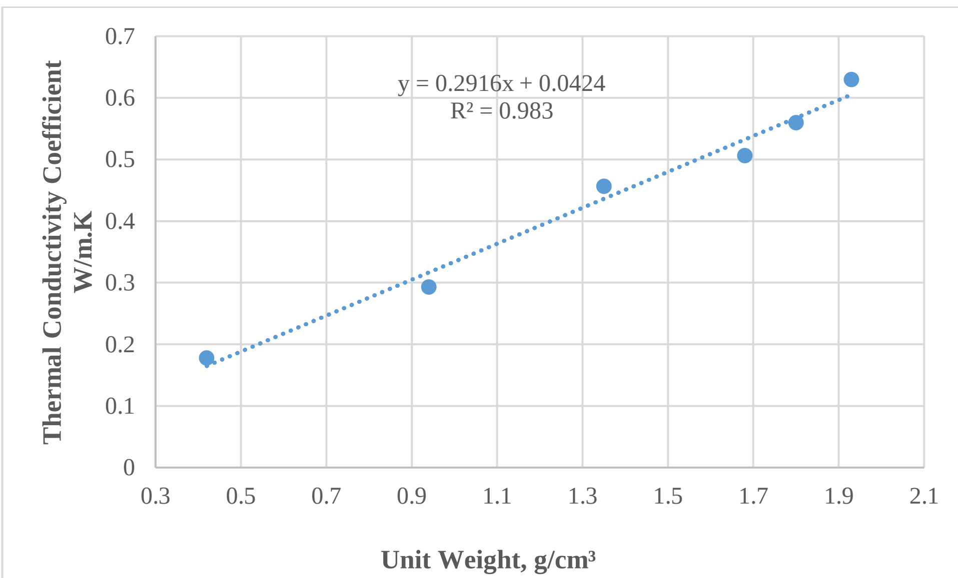

Figure 13. The relationship between thermal insulation and unit weight.

4. Conclusions

1. Using waste EPS instead of sand in LSM production increased the workability of the LSM.
2. While the unit volume weight of the control screed mortar was 1.93 kg/m^3, the unit weight decreased to up to 0.42 kg/m^3 with the use of waste EPS.
3. With the replacement of waste EPS, the flexural and compressive strength of LSMs decreased. Besides, 40% waste EPS incorporated LSM had still a 28^{th}-day compressive strength of 22.3 MPa.
4. Waste EPS replacement increased the capillary water absorption and drying shrinkage of LSMs.
5. Abrasion resistance was decreased with the waste EPS replacement ratio in LSM specimens.

6. The use of waste EPS has improved the thermal insulation performance of LSMs. While the thermal conductivity coefficient of the control sample was 0.6299 W/m.K, the thermal conductivity coefficients decreased up to 0.1777 W/m.K with the use of waste EPS.
7. Recycling of waste EPS in LSM production has benefits such as reducing dead load and energy consumption of the buildings and also the environmental impacts of the waste EPS.

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