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# Evaluation of Thermal and Mechanical Properties of Cement Mortar Containing Expanded Polystyrene Waste

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## Abstract

In recent years, there has been an increasing interest in the thermal properties of building materials to increase comfortability, low energy consumption, and sustainability when used the Expanded Polystyrene Waste (EPSw) as a filler substance. Using this non-biodegradable waste in cement mortar represents a solution to minimize 2 its negative impact on our environment as well as to reduce the CO2 emission due to cement manufacturing. Five groups of cement mortar containing chopped EPSw (20, 30, 40, 50, and 60 volume percentage) in addition to the reference mix were poured to investigate the density, thermal conductivity, water absorption, compressive strength, and flexural strength. The distribution of the non-homogeneous ingredients was controlled by using a superplasticizer admixture and using chopped EPSw of 1 mm maximum size particles. Results show a high reduction in the thermal conductivity (70.5%) of the mortar containing 60% EPSw compared with the control mix. However, other mechanical properties had acceptable values for many building applications, even for the masonry products of compressive strength of 5 MPa.

**Keywords:**

Mechanical properties lightweight cement mortar • Thermal conductivity KD2 pro • Expanded polystyrene waste

## Introduction

A sustainable lightweight composite of cement mortar filled with EPSw involves two environmental benefits. Firstly, using EPSw as a filler material in concrete production represents a reduction of cement consumption (reduction of CO2 emission due to Cement manufacture). Secondly, storing non-biodegraded plastic waste away from our environment represents a solution against the pollution due to EPSw. There have been several studies involving the effect of EPS ratio on the density and compressive strength of conventional concrete. EPS was used as a replacement part of the aggregate in concrete, it can reduce the dry density up to 55%, while the reduction in thermal conductivity reduced more than 87%. The density and the compressive strength were affected by the percentage of EPS beads 1940 to 464 kg/m$^3$ and 38.5 to 0.11 MPa, respectively. Workability of the fresh mixture was decreased significantly when increased EPS ratio, therefore high range water reduction or super-plasticizer is preferable to keep the constant water-cement ratio. On the other hand, the segregation of EPS (the agglomeration on the top of the mold) happened either when increasing the workability or exceeding the duration of the compaction (vibration process). The compressive strength and other mechanical properties were very sensible when increased EPS ratio due to the number of voids and their distribution. The pore structure and distribution have a direct effect on the compressive strength of OPC mortar, Bhattacharjee model was the nearest approach to the experimental data. Lightweight concrete of EPS aggregate showed a less reversible shrinkage/dry shrinkage ratio than the normal concrete. A study on the absorption characteristics mentioned that the water absorption and capillary water absorption increased proportionally if increased EPS replacement. The capillary water absorption is increased due to the composite shrinkage causing continuous micro-pores. The effect of EPS quantity on the compressive strength was more pronounced than other mechanical or physical properties due to the absence of chemical bonds between EPS beads and cement matrix. The durability of cement mortar filled with EPS against the freezing-thawing resistance has been modified by the presence of EPS, which can permit to absorb a part of the internal pressure due to the water expands. In general, compressive strength decreases dramatically when increases the porosity as well as its. size. The pore structure, mean diameter, cement content, and hydration degree possessed a direct influence on cement mortar strength which was suggested by an empirical approach. In this research, EPSw was chopped to a very small particle size of less than 1 mm, which would allow the particles

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to better distribute inside the mixture, as well as, the rough texture of EPSw particle will permit better mechanical interlocking with cement matrix [1].

## Materials and Methods

The experimental work included the investigation of the thermal and mechanical properties of lightweight cement mortar containing different percentages of Expanded Polystyrene waste (EPSw). Cement mortar of 1:2 (cement: sand) mix proportion was prepared after mixed with 0.45 W/C ratio. EPSw was chopped and added to the mixture as a fourth substance to guard constant mortar mix proportion even when adding a higher percentage of EPSw. The mixtures were nominated according to the EPSw volume percentage 0% of EPS as a control specimen; 20% EPSw; 30% EPSw; 40%EPSw; 50% EPSw; 60% EPSw. The workability was approximately fixed by using a superplasticizer. Physical properties like density, water absorption, and thermal conductivity also mechanical properties like compressive strength and modulus of rupture were investigated for each mix [2].

### Material properties

**Cement:** Ordinary portland cement (type I) manufactured according to the ASTM C150 was used for all the mortar specimens. It has 41 min and 560 min for initial and final setting time, respectively. It has a specific density of 3.15 [3].

**Sand:** Natural sand of a maximum size of 4.75 mm was used as fine aggregate. The granular distribution was checked according to the ASTM C778 for the sieve analysis. It has a fineness modulus of 2.4 and a specific density of 2.6.

**Water:** Tap water is filtered and treated by the municipal water treatment plant, It was used for the mixture preparation and curing processes [4].

**Expanded polystyrene waste:** The expanded Polystyrene waste used for insulation purposes was collected from a destructive multi-story building site. It was cleaned and chopped by a universal cutting mill to get particles size of less than 1 mm, as shown in Figure 1. The chopped EPSw has a unit weight of 10.2 kg/m3. In the EPS mortar, the volume percentage of EPSw can be calculated by using a combination of weight and density of the constituents, see equation [5].

$$\%\,Volum\,of\,EPS = \frac{\frac{Weight\ of\ EPS}{EPS\ density}}{\frac{Weight\ of\ EPS}{EPS\ density}+\frac{Weight\ of\ Cement}{Cement\ density}+\frac{Weight\ of\ Sand}{Sand\ density}+\frac{Weight\ of\ water}{water\ density}} * 100\% \quad (Eq.1)$$


**Figure 1.** a) Huge quantity of EPS used for external insulation b) Collection of EPSw from the destructive building site c) Universal cutting mill d) Size of chopped EPSw.

### Superplasticizer (SP)

Due to the use of chopped EPSw with cement mortar, the workability was decreased when increasing the dosage of EPSw. Therefore, Superplasticiser ADMIX CF 570 formulated from a synthetic polymer is designed to retain concrete workability for a longer time at a low W/C ratio [6].

### Sample preparation

After many trials to adjust the SP quantity, adopting the flow table test according to ASTM C230, the percentage of flowability was about 90 ± 10 for each mix, as shown in Figure 2.

Five EPSw mixtures of cement mortar in addition to the control mix (Table 1) were poured into special molds for compressive strength (cubic of 50 mm length), Modulus of rupture (prism of 50 mm width, 50 mm height, and 170 mm length), and thermal conductivity (cylinder of 25 mm diameter and 120 mm height) [7].

**Figure 2.** a) Chopped EPSw before the mixing b) Flow table test c) Cubic, prism, and cylinder specimens.

| Group designation | Cement (kg/m3) | Sand (kg/m3) | Water (l) | SP (kg/m3) | EPSw (kg/m3) | Volume of EPSw | Flow ability (%) |
|---|---|---|---|---|---|---|---|
| 40%EPSw | 390 | 780 | 176 | 6.42 | 22.1 | 40 | 85 |
| 50%EPSw | 325 | 650 | 146 | 8.12 | 33.15 | 50 | 80 |
| 60%EPSw | 260 | 520 | 117 | 10.24 | 51.27 | 60 | 95 |

**Table 1.** Mix proportion of control mix and five EPSw mixtures of cement mortar.

The constituent volume percentage for each mix was illustrated in Figure 3. The mixture of 60% of EPS has equivalent cement content in the lean mortar of 1 cement: 8 sand.

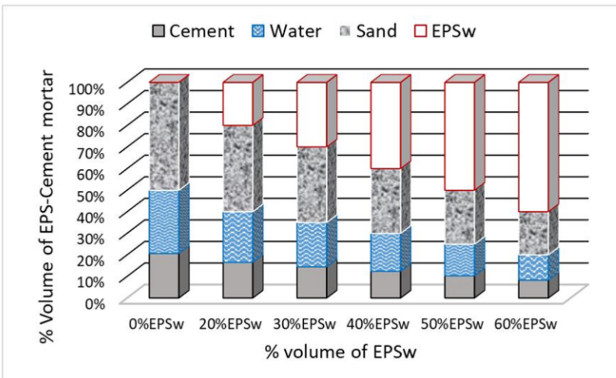


**Figure 3.** Shows the volume percentage of the ingredients for each mixture.

## Results and Discussion

### Density of hardened mortar

The dry apparent density was calculated according to the ASTM C905 when divided the mass of the dried specimen (for 72 hrs at 80°C (regarding the collapse of EPSw particles)) by its proper volume, then the average of 5 cubic specimens was recorded for each mix, as shown in Figure 4.

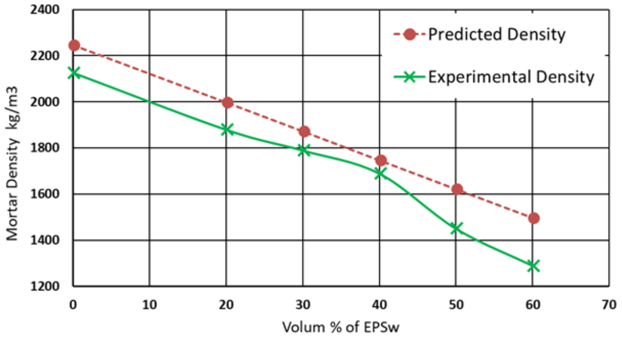


**Figure 4.** States the effect of the EPSw on the mortar density.

The mortar density decreased when increased the dosage of EPSw within the mix, the reductions in the average density relative to the reference mix were 11.6, 15.8, 20.5, 31.7, and 39.3% for 20% EPSw, 30% EPSw, 40% EPSw, 50% EPSw, and 60% EPSrespectively.

There is a slight difference between the predicted (theoretical) density and the experimental one due to the presence of air voids.

There is no segregation even with the highest EPSw percentage due to the use of very fine chopped EPSw (≤ 1 mm) as well as due to the use of superplasticizer which may restrict EPSw particles by the cement matrix.

Moreover, the rough surface of chopped EPSw enhances the mechanical interlocking over the interface with the cement matrix [8].

Water absorption of hardened mortar

After dry mass measurement (w1) for density calculation, the cubic specimens were immersed in water for 30 minutes and reweighted (w2) to calculate their water absorption according to the BS 1881-122: 2011, the results shown in Figure 5.

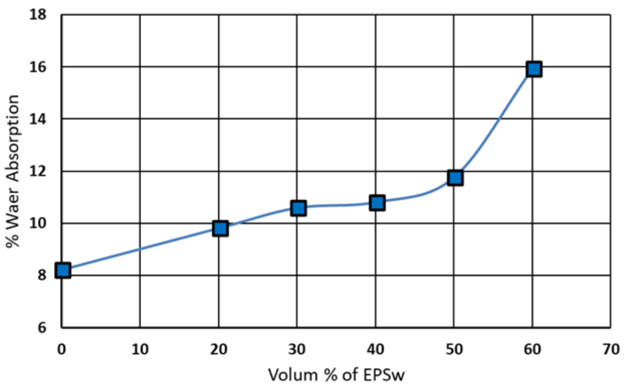


**Figure 5.** Represents the effect of the volume % of EPSw on the mortar absorption.

The water absorption increased when increased the dosage of EPSw within the mix, the increments in the average of water absorption relative to the control mix were 19.6, 29, 31.7, 43.3, and 94.1 % for 20% EPSw, 30% EPSw, 40% EPSw, 50% EPSw, and 60% EPSw respectively.

High water absorption is one of the worst factors which can affect mortar durability due to the alkali movements and reactions with hydrated cement products as well as freezing-thouing resistance. It mainly depends on the continuous pores which depend on the constituent's morphology [9].

Thermal conductivity of hardened mortar

18 cylindrical specimens of 25 mm in diameter and 125 mm in length were prepared, it had a central hole of 3mm in diameter and 100mm in length, which was made by a steel bar as similar as the sensor bar dimensions (probe) of the KD2 pro thermal properties analyzer, shown in Figure 6.

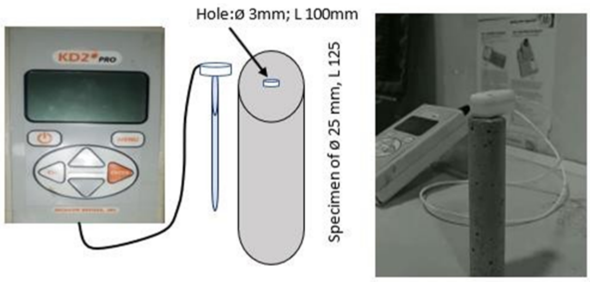


**Figure 6.** Illustrates the KD2 pro thermal properties analyzer and mortar specimen during the test.

The top surfaces of the cylindrical specimens were cleaned and smoothed to ensure proper contact with the sensor foot. The thermal conductivity (K value) based on the ASTM D5334 was measured for each mix at a constant laboratory temperature of 25°C, as shown in Figure 7.

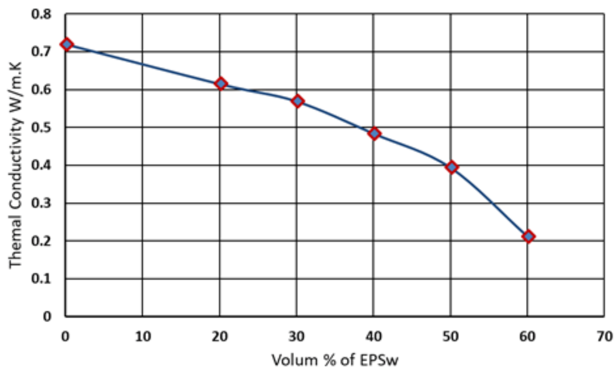


**Figure 7.** Represents the thermal conductivity value of cement mortar versus the Volume % of EPSw.

The thermal conductivity decreased when increased the dosage of EPSw within the mix, the reductions in the average thermal conductivity relative to the control mix were 14.5, 20.9, 32.7, 45.2, and 70.5% for 20% EPSw, 30% EPSw, 40% EPSw, 50% EPSw,and 60% EPSw respectively. These reductions in k-value are in agreement with the finds of other researchers based on the density value for each mortar [10].

Compressive strength of hardened mortar

30 cubic specimens were tested after 28 days of water curing by using the ELE Universal Testing Machine (UTM) of 1000 kN (compressive load capacity) according to the ASTM C109. The average of 5 specimens was calculated for each mix, as shown in Figure 8.

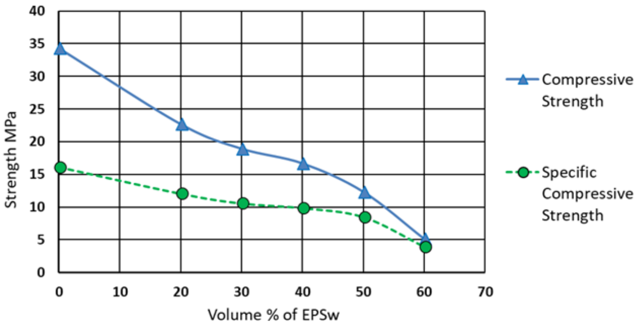


**Figure 8.** Represents the effect of EPSw proportion on the compressive strength and the specific compressive strength.

The compressive strength decreased proportionally when increased EPSw in the mix. The decrements were 33.8, 44.8, 51.4, 64.1, and 85.1% for 20% EPSw, 30% EPSw, 40% EPSw, 50% EPSw, and 60% EPSw respectively. These expected results (or behavior) were due to the EPSw (void) quantity which can create a continuous path for the failure. However, the specific compressive strength represents an important indicator factor, especially for insulation works. The convergence or the intersection between these two curves represents the ideal mortar components because it exhibits interesting physical properties with acceptable compressive strength. Therefore, the mortar that contains 60 volume percent of expanded polystyrene waste (EPSw60%) represents the best mix with an average compressive strength of 5.11 MPa, it can be affirmed for many applications even for masonry products [11].

Flexural strength of hardened mortar

18 prism specimens were tested after 28 days of water curing by using three-point of loads of Universal Testing Machine (UTM) according to the ASTM C348-21, as shown in Figure 9.

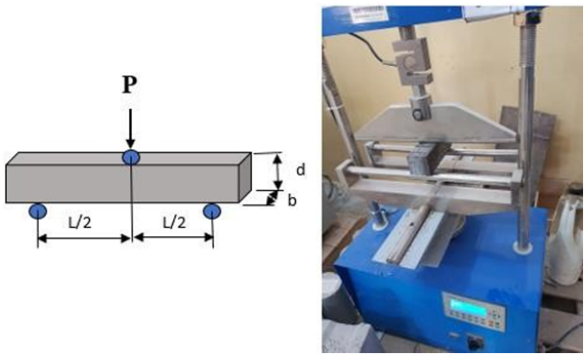


**Figure 9.** Shows the prism specimen during the flexural test by the universal testing machine.

The average of 3 specimens was calculated for each mix by using the bending formula (eq.2), as shown in Figure 10. M.O.R refers to the modulus of rupture, P represents the fracture load, L is the distance between the two supports, b represents the width of the specimen while d is the depth of the sample.

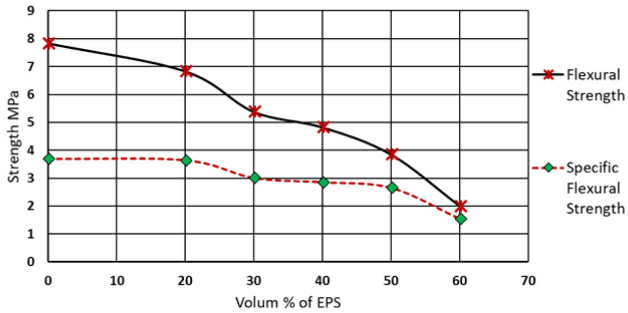


**Figure 10.** Represents the effect of EPSw proportion on the flexural strength and the specific flexural strength.

The flexural strength decreased when increased EPSw in the mix. The decrements were 12.7, 31.3, 38.4, 50.8, and 74.4% for 20% EPSw, 30% EPSw, 40%EPSw, 50% EPSw, and 60% EPSw respectively. This decrease was due to the EPSw (void) quantity which represents the defect points that create non-uniform stress distribution over the failure plane. However, the specific flexural strength represents an important property, especially for cement board manufacture. The slight difference between the results of the specific flexural strength of different mixes refers to the equivalent decrease proportion of the density and/ or the flexural strength while the sharp drop in the curve represents an irregular decrease in the flexural strength. In general, it exhibits interesting physical properties with acceptable flexural strength. Therefore, the mortar that contains 60 volume percent of expanded polystyrene waste (EPSw60%) represents an attractive mix with an average flexural strength of 2.0 MPa, it can be affirmed for many applications even for lining works [12].

## Conclusion

Our environment needs critical attention and efforts to reduce the negative impact of a huge quantity of Expanded Polystyrene waste. Therefore, conserving it inside an Eco- friendly building composite, instead of the incineration or the damping into the landfall will decrease cement consumption consequently reducing CO2 emissions due to cement manufacturing.

The highest volume dosage of chopped EPSw was 60% of the total mortar volume, after this proportion, the segregation takes place.

Due to the weight reduction and the volume increment of the EPSw60% mortar, the density decreased by 39.3% to be 1290 kg/m$^3$, the thermal conductivity decreased by 70.5% to be 0.212 watt/k.m, the compressive strength decreased by 85.1% to be 5.11 MPa, the flexural strength decreased by 74.4% to be 2 MPa. These physical and mechanical properties are acceptable for many civil engineering works and especially for cement board manufacturing (outdoor utilization) to improve its heat insulation causing less electrical consumption. The author suggests further experimental solutions to overcome the segregation problem when increased the chopped EPSw in the mortar.

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