*Kufa Journal of Engineering*
*Vol. 17, No. 2, April 2026, P.P. 346-361*
*Article history: Received 24 May 2025, last revised 1 July 2025, accepted 22 July 2025*

# SUSTAINABLE CEMENT MORTAR USING RICE HUSK ASH AND SOLVENT-TREATED EXPANDED POLYSTYRENE AS PARTIAL REPLACEMENTS

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**https://doi.org/10.30572/2018/KJE/170220**

## ABSTRACT

The research work is intended to develop sustainable cement mortar by means of partial substitution of cement with rice husk ash (RHA) at 4%, 8%, 12%, 16%, and 20% by weight and replacement of mixing water with solvent, treated expanded polystyrene (EPS) at 3%, 6%, 9%, and 12% by volume. The mortar was prepared by using 1:3 cement, to, sand and 0.5 water, to, cement ratios. The mix with 8% RHA and 6% EPS produced the highest mechanical performance at the age of 28 days with compressive strength and flexural strength of 34.72 MPa and 2.34 MPa, respective 22.16% and 5.88% increments over the control mix. At the highest substitution, drying shrinkage was reduced from 0.008% to 0.006%, and thermal conductivity was lowered by 24%, from 0.927 W/mK to 0.704 W/mK. Water absorption rose slightly by 8.2%. Although higher replacement levels reduced strength, the combination of 20% RHA and 12% EPS produced the best insulation and shrinkage performance. The results demonstrate that combining RHA and treated EPS improves durability and thermal efficiency, making the mortar suitable for non-load-bearing applications.

## KEYWORDS

Rice husks ash, Expanded polystyrene, Sustainability, Cement mortar, Compressive strength, Thermal insulation.

## 1. INTRODUCTION

The large-scale expansion of infrastructure has made us more dependent on concrete. Worldwide, more than 25 billion tons of concrete are used every year (Zareei et al., 2019). The cement industry currently producing approximately 4.1 billion tons of concrete annually, and this increase in demand has put significant pressure on it to increase that capacity (Koushkbaghi et al., 2019). Additionally, one major source of greenhouse gas emissions, especially CO2 emissions, is the cement sector. About 1.7 Gt of $CO_2$ emissions are produced annually by the cement industry worldwide as a result of the manufacturing of cement clinker, a process that can produce up to 1000 kg $CO_2$/t due to carbonate breakdown and heat emissions (Thiedeitz et al., 2024). Consequently, numerous researchers have directed their efforts towards the recycling of various waste materials with the objective of reducing the environmental impact and compensating for the excessive consumption of cement (Abdulkarem et al., 2024; Rasool et al., 2022; Al-Wazni et al., 2024; Khalil and Al-Daebal, 2018; Hasan, 2024).

In contrast, RHA's CO2 emissions are regarded as zero, as it doesn't cause global warming (Pode, 2016). In concrete technology, rice husk cinders are used as a highly valued interactive pozzolanic material that creates contacting surface layers (between the cement matrix and the aggregate). The RHA testing in concrete showed that the particle grading of cement and RHA admixtures also affected the blending adequacy (He et al., 2017), in addition to the interaction of pozzolanic RHA.

Huge numbers of researchers have really tried to use the RHA waste generated from rice mills to make sustainable and thermally enhanced mortar for wall plasters (Sanou et al., 2019). The use of RHA is being investigated in many countries as a method of reducing the total amount of cement used in mortar or concrete applications because of its high reactive potential with pozzolans (Park et al., 2016, Thiedeitz et al., 2022). (Muthukrishnan et al., 2019) showed that utilizing 20% treated RHA in-place of cement made early-age strength comparable to control mortar. Then a later research by (Thiedeitz et al., 2022) demonstrated that mortar samples, consisting of 25% cement substitution by RHA, have higher strength than the control samples at the ages of hydration from 7 to 90 days. (Fernando et al., 2020) demonstrated that both materials (rice husk ash (RHA) and nylon fibre) in cement mortar were effective in improving properties of cement mortar. The results of the tests showed that RHA can provide an increase in the flexural and compressive strength of cement by as much as 10% by weight. (Muwashee, 2020) focused on evaluating cement-based products where 10% of the cement was substituted with RHA and the water was substituted also with raw sewage sludge. The results indicate that compared to the control mix, the incorporation of additional components into mixes improves performance results. (Noori et al., 2023) investigated that 10% is the ideal ratio of RHA to boost compressive strength as a partial cement substitution rate for days 3, 7, and 28.

Recycled expanded polystyrene (EPS) is an intriguing option because it helps the environment and economy. The structure of EPS beads comprising 98% air is a defining feature of this commercial insulation material (Ranjbar and Mousavi, 2015). These EPS wastes are usually disposed of in landfills or burned in incinerations; material loss is the result of the former , which also causes environmental pollution, as they are not biodegradable (Chaukura et al., 2016), and it is not cost-effective, whereas the latter damages the environment and human health by releasing harmful and cancer-causing compounds into the atmosphere (Prathiba et al., 2018). Therefore, recycling activities are thought to be crucial for improving the material sustainability that is transformed into a secondary raw material mixture, a new resource (Petrella et al., 2020, Rasool et al., 2023).

A lack of research has been done on the use of chemically modified expanded polystyrene in concrete mixes, especially on the adhesion between the expanded polystyrene and the cement. A significant amount of recycled polystyrene can dissolve in a small amount of thinner, resulting in a substantial volume reduction (exceeding 100 times) and, consequently, a reduction in transportation expenses (García et al., 2009, Gutiérrez et al., 2013). There are studies of EPS dissolution in different solvents, such as alcohol, acetone, chloroform, etc. (Selukar et al., 2014). (Abu Alfoul et al., 2021) have proposed that paint thinner can easily dissolve discarded polystyrene to produce a viscous solution. There is ample evidence to support the effectiveness of this new substance as a coating sealer in lowering the permeability of concrete. However, its effectiveness as an admixture remains to be elucidated. Whereas (Patle et al., 2018) obtained from the primary results of the combination influence of thermocol waste and thinner in concrete, used as an additive, can be employed well in concrete composites. The purpose of this research is to look at the possibility of using rice husks ash (RHA) with expanded polystyrene waste (EPS) solvent treated by paint thinner as an eco-friendly substitute admixture to the cement mortar and its effect on the physical and mechanical performance. The cement mortar will undergo specific tests in accordance with ASTM standards to accomplish this purpose.

## 2. METHODOLOGY

### 2.1. Cement

Throughout this study, all mixes used Ordinary Portland Cement type I. Type CEM I is produced in Iraq by Al-Mass Company. Tables 1 and 2 display the cement's chemical and physical characteristics, respectively. According to test results, the selected cement meets ASTM-C150-21 and Iraqi Standard Specification for Cement IQS 5/2019.

**Table 1. The chemical composition of cement, fine aggregate and RHA**

| Chemical composition | Cement (%) | Fine aggregates (%) | RHA (%) |
|---|---|---|---|
| $SiO_2$ | 19.9 | 83.56 | 82.72 |
| $Al_2O_3$ | 4.95 | 0.54 | 0.56 |
| $Fe_2O_3$ | 3.24 | 0.53 | 0.18 |
| CaO | 63.3 | 5.4 | 1.16 |
| MgO | 1.25 | 0.81 | 0.48 |
| $Na_2O_3$ | - | - | 1.41 |
| $K_2O$ | 0.51 | - | 1.48 |
| $SO_3$ | 2.48 | 2.57 | 2.05 |
| L.O.I. | 3.56 | 5.56 | 1.82 |
| I.R. | 0.81 | 1.03 | 8.14 |

**Table 2. The physical characteristics of cement**

| Characteristics | Results | Specification limit |
|---|---|---|
| specific surface area | 291.4 (m2/kg) | 230 (m2/kg) |
| compressive strength: | | |
| for 7-days | 22.4 (MPa) | 15 (MPa) |
| for 28- days | 28.2 (MPa) | 23 (MPa) |
| setting time (Vicat): | | |
| Initial setting time | 75 (min) | 45 (min) |
| Final sitting time | 285 (min) | 600 (min) |

### 2.2. Fine aggregates (sand)

In this investigation, fine aggregates were derived from local construction material stores in Iraq. Tables 1 and 3 outline the fine aggregate grading system that correlates to the No. 45/1984 Zone 3 Iraqi Specification criteria.

**Table 3. Standard sand gradation**

| Sieve size (mm) | Percent passing (%) | Specification limit (%) |
|---|---|---|
| 4.75 | 97 | 90-100 |
| 2.36 | 81 | 75-100 |
| 1.18 | 56 | 55-90 |
| 0.6 | 35 | 35-59 |
| 0.3 | 10 | 8-30 |
| 0.15 | 1 | 0-10 |

### 2.3. Water

Every mixing and curing step uses clean water.

### 2.4. Rice husks ash (RHA)

The RHA used in this investigation is leftover material from "Karbala." To get the ash, the rice husks were initially burned in an electrical oven at a regulated temperature in accordance with ASTM C311-05. The furnace utilized in this investigation is shown in Fig.1(a), and the received ash was combusted at 600 °C for 2 hours. The ash had then been crushed until the cinders (75µm) could pass through the sieve. After grinding, the color of RHA changed from blackwhite to gray, as shown in Fig.1(b). According to Table 1, chemical analysis of RHA shows that silica ($SiO_2$) makes up 82.72% of the ash, with small oxides and other chemicals also present.

**a)** **b)** **c)**


**Fig. 1. RHA Productions: (a) The furnace used, (b) Raw rice husks, (c) RHA after grinding**

## 2.5. Admixture (EPS dissolved in paint thinner)

Admixture was prepared using expanded polystyrene (EPS) and paint thinner solution (10 % of EPS in thinner). Table 4 displays characteristics of polystyrene, which has been gathered as garbage from local shops and broken into little pieces, as seen in Fig.2. The small pieces of EPS were then added to the paint thinner, which has the technical details in Table 5 and was purchased from nearby retailers. It was stirred for 1 minute and left for 5 minutes at room temperature (25 ± 2 °C). Thinner has been brought from local stores, as shown in Fig. 3. The reason for choosing this kind of paint thinner was that it dissolves polystyrene into a viscous liquid. Other kinds of thinners have just decreased the polystyrene's volume. In varying amounts, the viscous liquid has been employed as an additive to replace water in cement mortar. Table 6 displays the parameters of the combination.

**Fig. 2. EPS**


**Fig. 3. Paint Thinner**

**Table 4. Properties of EPS**

| Characteristics | Description/Value |
|---|---|
| chemical composition | polystyrene $(C_8H_8)n$ |
| density (g/cm$^3$) | 0.052 |
| particle diameter (mm) | <3 |
| particle geometry | spherical |
| colour | white |

**Table 5. Technical information of paint thinner**

| Characteristics | Description/Value |
|---|---|
| color | transparent |
| product weight | 0.85 ± 0.02 kg/lt |
| distillation range | 100-180°C At 101.3kpa |
| evaporation rate | 2.1 (nBuoAc = 1) |
| surface tension | 29 Dyne/cm |
| refractive index | 1.453 ± 0.002 at 25°C |
| V.O.C. | 870 gm/liter |
| flash point | 4-10°C |

**Table 6. Properties of EPS dissolved in thinner solution**

| Properties | The value | Unit |
|---|---|---|
| flash point | 35 | ˚C |
| volatile | 82.03 | % |
| non volatile | 18.77 | % |
| density | 0.9418 | $g/cm^3$. |
| specific gravity | 0.95 | - |
| pH | 7.2 | - |

## 3. MIXTURE PROPORTION

Slurry samples were prepared according to ASTM C305 in the slurry mixing process. Specimen casting and curing were performed according to ASTM C109. As shown in Table 7, the mortar mixtures were created using Portland cement and fine aggregate that were combined in a 1:3 and w/c ratio of 0.5. Specimens of the modified mortar were created by substituting RHA for cement in amounts of 4%, 8%, 12%, 16%, and 20%, while the water was replaced through dissolved EPS in proportions of 3%, 6%, 9%, and 12%.

**Table 7. Legend of specimens and mix gradient**

| Legend | RHA | | Cement (gm) | Sand (gm) | Water (ml) | Dissolved EPS | |
|---|---|---|---|---|---|---|---|
| | % | gm | | | | % | ml |
| Ref. | 0 | 0 | 600 | 1800 | 300 | 0 | 0 |
| A4E3 | 4% | 24 | 576 | 1800 | 291 | 3% | 9 |
| A8E3 | 8% | 48 | 552 | 1800 | 291 | 3% | 9 |
| A12E3 | 12% | 72 | 528 | 1800 | 291 | 3% | 9 |
| A16E3 | 16% | 96 | 504 | 1800 | 291 | 3% | 9 |
| A20E3 | 20% | 120 | 480 | 1800 | 291 | 3% | 9 |
| A4E6 | 4% | 24 | 576 | 1800 | 282 | 6% | 18 |
| A8E6 | 8% | 48 | 552 | 1800 | 282 | 6% | 18 |
| A12E6 | 12% | 72 | 528 | 1800 | 282 | 6% | 18 |
| A16E6 | 16% | 96 | 504 | 1800 | 282 | 6% | 18 |
| A20E6 | 20% | 120 | 480 | 1800 | 282 | 6% | 18 |
| A4E9 | 4% | 24 | 576 | 1800 | 273 | 9% | 27 |
| A8E9 | 8% | 48 | 552 | 1800 | 273 | 9% | 27 |
| A12E9 | 12% | 72 | 528 | 1800 | 273 | 9% | 27 |
| A16E9 | 16% | 96 | 504 | 1800 | 273 | 9% | 27 |
| A20E9 | 20% | 120 | 480 | 1800 | 273 | 9% | 27 |
| A4E12 | 4% | 24 | 576 | 1800 | 264 | 12% | 36 |
| A8E12 | 8% | 48 | 552 | 1800 | 264 | 12% | 36 |
| A12E12 | 12% | 72 | 528 | 1800 | 264 | 12% | 36 |
| A16E12 | 16% | 96 | 504 | 1800 | 264 | 12% | 36 |
| A20E12 | 20% | 120 | 480 | 1800 | 264 | 12% | 36 |

Note: Ref. refers to the control sample, while A represents (RHA substitute Cement) with varying replacement, E represents (dissolved EPS substitute water) with varying replacement.

## 4. TEST METHODS

### 4.1. Water absorption test

The water absorption test is a method for determining cement mortar's ability to absorb water, per ASTM C1403. The procedure involves immersing a particular cement slurry sample in water for a predetermined amount of time and then monitoring any weight changes in the sample. The calculation of the amount of water absorbed by the cement mortar is performed by comparing its wet and dry weights with each other. The measurement of the amount of water absorbed by a material is known as absorption and may be computed using a very specific formula:

$$\text{Water absorption} = \frac{\text{Weight after immersion (Kg)} - \text{Dry weight (Kg)}}{\text{Dry weight (Kg)}} \times 100 \qquad (1)$$

### 4.2. Drying shrinkage test

Refers to the length reduction of a test sample caused by environmental factor such as temperature, moisture and rate of evaporation. It is one of the major components of material testing as per the ASTM C596 requirement. The testing method uses samples with the dimensions 25x25x285 mm. The experimental drying shrinkage is determined using the below formula as per the ASTM C490 requirement:

$$\text{Shrinkage of specimen \%} = \frac{\text{length after drying} - \text{initial length before drying}}{\text{effective length } (250\ mm)} \times 100 \qquad (2)$$

### 4.3. Thermal conductivity test

The thermal conductivity (k) of the 40 mm × 40 mm × 160 mm prism was determined using the hot wire method, specifically the method for using a platinum resistance thermometer, as specified in ASTM-C1113/C1113M-09, after a curing period of 28 days. The QTM 500 was utilized to expedite the measurement of thermal conductivity, accompanied by a probe consisting of a hot wire and a thermocouple. Three replicates were prepared for each blend, and each sample underwent three tests, with the mean of the results being selected. The experiment was conducted at the National Center for Structural Laboratories in Baghdad.

### 4.4. Flexural strength

To evaluate the flexural strength of cement mortar, a 40 x 40 x 160 mm prism made in accordance with ASTM C348 guidelines was used. When the specimens were 28 days old, they were taken out of the storage water and tested right away as shown in Fig. 4. The following formula is used to determine the flexural strength:

Flexure strength (MPa) = 3PL/2bd, (3)

Where: P = maximum applied load (N), L = span's length (mm),

b = sample width (mm), d = sample depth (mm).

Compressive strength test

Employing cubic specimens (50 mm × 50 mm × 50 mm) were subjected to compressive strength testing in accordance with the guidelines established by ASTM C109/C109M-23, as shown in Fig.5. The testing procedure was initiated immediately following the removal of the specimens from storage water at specific ages, namely 7 and 28 days, as determined by the protocol. During the test, the maximum load capacity as indicated by the testing machine was recorded. Next, the compressive strength of the specimens was determined using the formula:

Compressive strength (MPa) = P/A, (4)

Where: P = total maximum load (N), A = area of loaded surface ($mm^2$).

**Fig. 4. Flexural strength test**

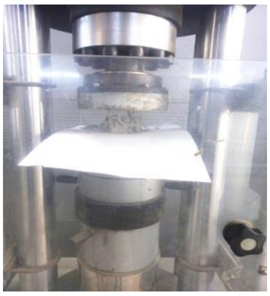

**Fig. 5. Compressive strength test**

## 5. RESULTS AND DISCUSSION

### 5.1. Water Absorption

As shown in Fig. 6, it was noticed that when the amount of RHA content was increased, the water absorption also increased. This means that RHA has a greater water, absorption capacity than cement. Based on a previous study, the reason for this is that RHA concrete has more pores than control concrete (Park et al., 2016). The water absorption of the mortar samples containing different proportions of RHA (Rice Husk Ash) was lowered when EPS, dissolved percentages (3%, 6%, 9%, and 12%) were introduced. It is possible to attribute such an effect to the presence of EPS, which acts as a water, repellent agent (Ferrándiz-Mas and García-Alcocel, 2013). The high levels of EPS present in the mix will negatively affect the mortar properties, adjusting the % of EPS content will help in balancing reduced water absorption and maintain its structural integrity (Horma et al., 2022).

### 5.2. Drying Shrinkage

As seen in Fig.7, the RHA replacement ratio rises to 20%, and drying shrinkage generally tends to decrease. Filler effects and pozzolanic interaction provide an explanation for this (Noori et al., 2023). According to the data, dry shrinkage consistently decreases as RHA dosages are increased. Additionally, when the ratios of EPS solution replacement increase, the cement mortar's dry shrinkage gradually decreases. The primary cause of dry shrinkage in cement mortar, which causes volume contraction and cracking, is water evaporation. Unlike water, EPS is a polymer and does not evaporate. Replacing some of the water with the EPS solution may decrease the total shrinkage because there will be less water to evaporate (Petrella et al., 2020)

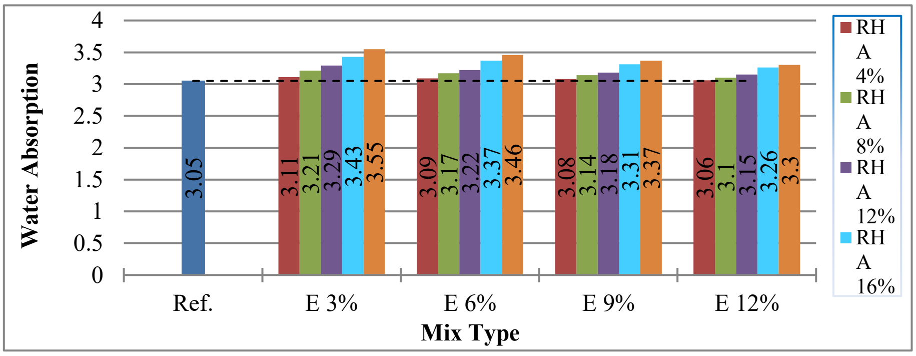


**Fig. 6. Water absorption for cement mortar samples with various ratios of RHA as well as dissolved EPS.**

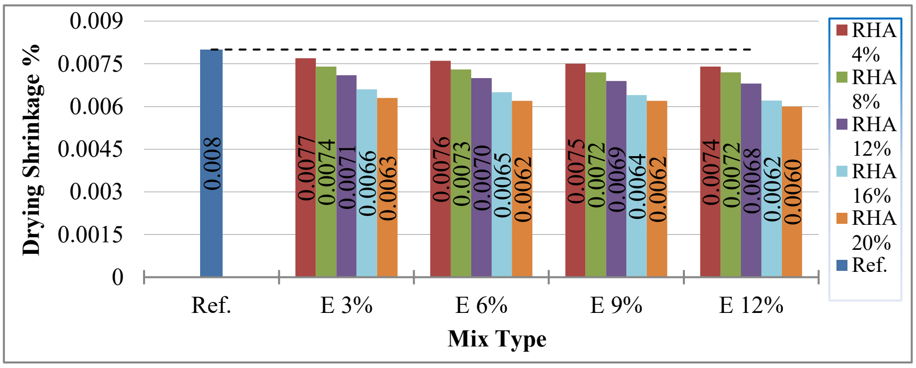


**Fig. 7. Drying shrinkage results for cement mortar samples with different ratios of RHA and dissolved EPS.**

## 5.3. Thermal Conductivity

As illustrated in Fig.8, good thermal insulation properties are produced when the ratio of adding RHA to the mortar matrix instead of cement increases because it lowers the mortar's thermal conductivity. RHA mortar with a greater dissolved EPS ratio has a poorer thermal conductivity. The higher the mortar's RHA content, the larger and more numerous the pores were. When the RHA content rises, the mortar's density falls and its thermal conductivity falls (Selvaranjan et al., 2021). Owing to its low density and superior thermal insulation, it was also noted that the thermal conductivity reduced as more EPS solution was added to the cement mortar in place of water (Ezdiani Mohamad et al., 2022). Thermal conductivity will often decrease when fluid or dissolved polymers are added to cement mortar or concrete. The additional polymers' enhanced porosity and insulating properties are mainly responsible for this result. However, the particular polymer employed and its concentrations determine how much of an impact this has. Numerous investigations into how fluid or dissolved polymers affect the thermal conductivity of cement mortar and concrete have shown that a higher polymer content might result in a lower thermal conductivity (Bicer et al., 2024, Bicer, 2019).

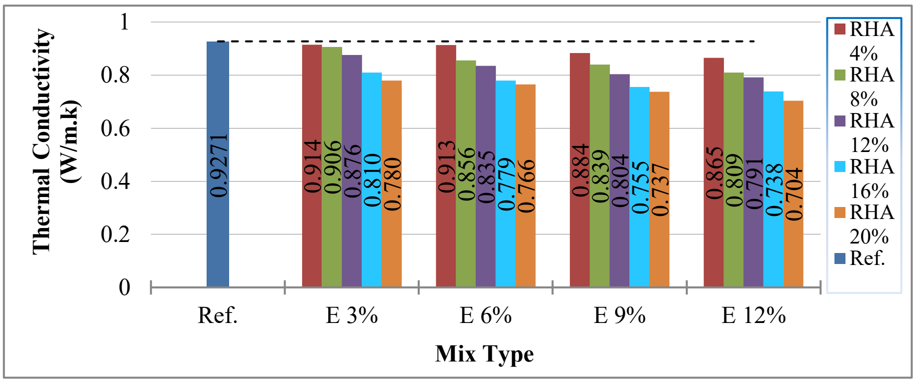


**Fig. 8. Thermal conductivity results for cement mortar samples with different ratios of RHA and dissolved EPS.**

### 5.4. Flexure Strength

As seen in Fig.9, the highest amount of flexural strength was produced when using 4% and 8% replacement proportions for RHA combined with an EPS solution of 3% and 6%, respectively. The enhanced bending resistance resulting from the pozzolanic reactivity of the RHA (Al-Alwan et al., 2024), which reduces the porosity and increases the structural density. However, if the proportions of the dissolved EPS solution are increased beyond 9%, the flexural strength of the cement mortar will decrease progressively. This is because high levels of dissolved EPS cause the structure to be weak, thus pozzolanic reactivity is limited, and cohesion is negatively affected by the presence of unreacted materials which, in turn, impact the flexural strength (Patle et al., 2018). High replacement ratios (16% and 20%) of RHA resulted in significant decreases in flexural strength performance; due to its larger surface area, RHA tends to stick together through physical bonding rather than play an active role in the hydration process, which reduces flexural strength of the mortar (Fernando et al., 2020).

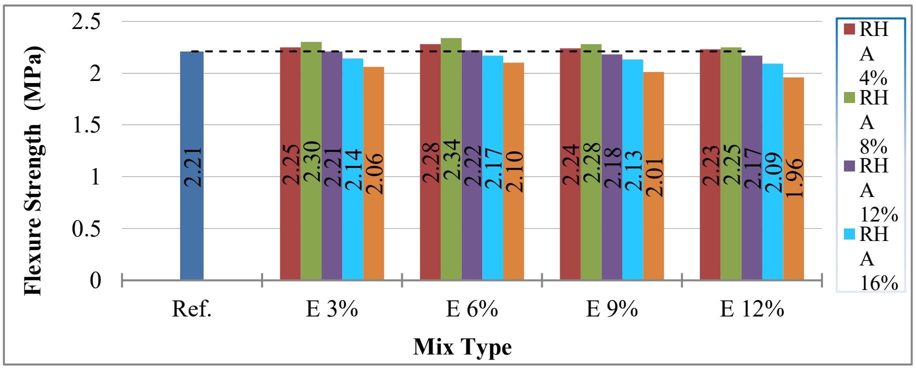


**Fig. 9. Flexure strength findings for cement mortar samples with various ratios of RHA and dissolved EPS in thinner after 28 days.**

### 5.5. Compressive Strength

Figs. 10 and 11 clearly show that the maximum compressive strength is attained at 4%, 8%, and 12% RHA replacement levels, along with dissolved EPS solution proportions of 3%, 6%, and 9%, over the periods of 7 and 28 days. The reason for the improved compressive strength at low RHA replacement levels is basically the contribution of reactive silica, which upon reaction with calcium hydroxide from the cement hydration, yields more (C, S, H) compounds resulting in increased mechanical strength (Fernando et al., 2020). The remarkable performance at small replacement levels of polystyrene solution is probably due to its ability to prevent a water loss to the surroundings in the curing process thus allowing the cement to rehydrate. Besides that, the pairing of extreme levels of RHA mixtures (16% and 20%) with dissolved EPS (9% and 12%) caused the performance to go down. The drop in performance was due to a decrease in effective cement, lack of water for rehydration, increase of pores, and decrease of the total mixture density resulting in it being less workable (Sharma and Dubey, 2023).

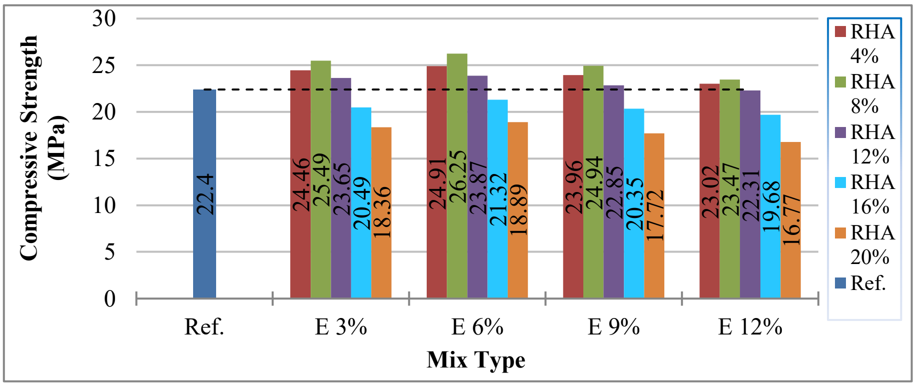


**Fig. 10. Compressive strength findings for cement mortar samples with various ratios of RHA and dissolved EPS after 7 days.**

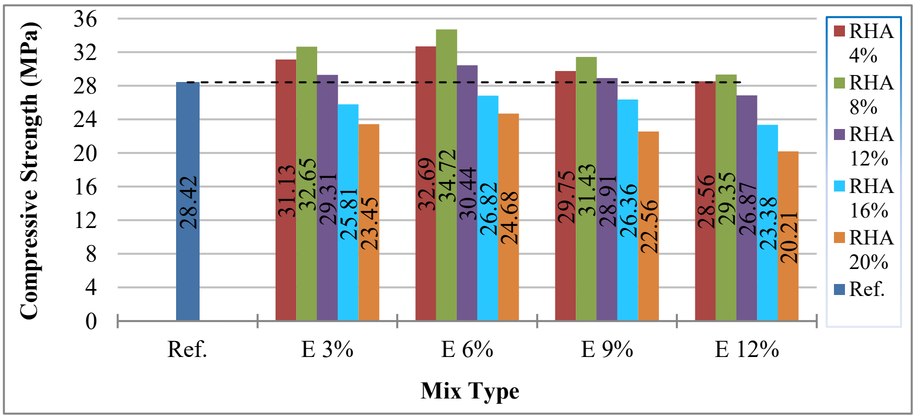


**Fig. 11. Compressive strength findings for cement mortar samples with various ratios of RHA and dissolved EPS after 28 days.**

According to the data from Table 8, the quantity of RHA and dissolved EPS used in a mix determines its behaviour across all the characteristics tested. Specifically, those mortar mixes made with 8% RHA and 6% dissolved EPS produced the greatest compressive strength (34.72

MPa) as well as flexural strength (2.34 MPa); therefore, this indicates that at moderate levels of replacement, mechanical performance is optimal due to improved quality of particle-packing and internal bonding within the mixture. Conversely, mortar mixes produced with the greatest relative percentages of RHA (20%) and dissolved EPS (12%) exhibited the lowest thermal conductivity (0.704 W/m·K) and the lowest drying shrinkage (0.006%). This suggests that such mortar mixes are suitable only for non-load-bearing applications where thermal insulation and dimensional stability take precedence over strength.

**Table 8. Summary table of optimal mixes and their performance**

| Notes | Legend | Drying shrinkage (%) | Water absorption (%) | Thermal conductivity (W/m·K) | Flexural strength (MPa) | Compressive strength (MPa) |
|---|---|---|---|---|---|---|
| control sample | Ref. | 0.008 | 3.05 | 0.927 | 2.21 | 28.42 |
| best (compressive + flexural) | A8E6 | 0.0073 | 3.17 | 0.856 | 2.34 | 34.72 |
| best thermal insulation + lowest drying shrinkage | A20E12 | 0.006 | 3.30 | 0.704 | 1.96 | 20.21 |
| lowest water absorption | A4E12 | 0.0074 | 3.06 | 0.865 | 2.23 | 28.56 |

## 6. CONCLUSIONS

This research focused on the effects of simultaneous replacement of cement and water by RHA and EPS dissolved in thinner, respectively, on the mechanical and physical properties of cement mortar. The testing outcomes of both the conventional and modified cement mortar were the basis for the following conclusions:

1. Substituting cement with RHA caused an increase in water absorption because of its highly porous microstructure. On the other hand, the use of dissolved EPS as a water substitute partly counteracted this effect by bringing a water, repellent agent into the matrix.
2. With increasing RHA and EPS levels, drying shrinkage was invariably lessened. This decrease was ascribed to the filler effects of RHA and the non, evaporative property of EPS polymers, which restrict moisture loss.
3. Thermal conductivity in the mixture containing 20% RHA and 12% EPS dropped by 24%, which reflects how both materials contribute to insulation improvement. Such a mixture is perfect for nonload, bearing parts of a building where thermal performance is prioritized over strength.
4. The blend with 8% RHA and 6% EPS seemed to provide the optimum combination of mechanical and physical performances. It recorded 22. 16% and 5. 88% more compressive and flexural strengths respectively than the control. At dosages higher than this, the strength properties started to deteriorate because of the reduction in cement content and the presence of an excess polymer that interferes with hydration.

### 6.1. Further researches should focus on:

- Microstructural validation of the cement matrix
- Long-term aging, thermal cycling, as well as durability under real conditions
- Scaling up for field applications in wall insulation and non-structural panels

**ACKNOWLEDGMENTS**

The authors thank Mustansiriyah University (www.uomustansiriyah.edu.iq) in Baghdad, Iraq and Structural Materials Laboratory /Civil Engineering Department for their support in this work.

**CONFLICTS OF INTEREST**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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