Performance Assessment of EPS and XPS Waste in Cement Composites for Sustainable Construction Applications

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Abstract. The growing number of nonbiodegradable waste materials presents a significant environmental issue, especially when synthetic polymers such as expanded polystyrene (EPS) and extruded polystyrene (XPS) are among the most enduring pollutants. These materials are widely used in packaging and construction, yet their disposal remains a challenge as they build up in landfills and marine environments, contributing to long-term pollution. Transforming this waste into valuable resources offers an opportunity to mitigate environmental impacts while promoting the use of sustainable materials in construction.

This study investigates the use of EPS and XPS waste as partial sand replacements in cementitious mortars. The aim is to develop lightweight composites with adequate mechanical properties for structural or nonstructural applications, while promoting the reuse of persistent plastic waste materials sourced from construction and marine environments. Five mortar series were prepared for each material with 0%, 20%, 40%, 60% and 80% volumetric replacement of sand using EPS or XPS waste particles and were tested for flowability, compressive and flexural strength and hardened density. The results showed that both EPS and XPS effectively reduce mortar density, with EPS achieving a greater reduction across all replacement levels. Compressive and flexural strength decreased with increasing replacement percentage, although XPS modified mortars retained higher mechanical performance. At 80%, XPS mortars exceeded 32 MPa compressive strength, compared to just over 10 MPa for EPS mortars. These findings suggest that EPS is more suitable for lightweight, insulating, non-load-bearing applications, whereas XPS may be employed in structural or semi-structural elements requiring reduced weight and acceptable strength.

Keywords: EPS, XPS, waste, sustainability, cement composites, polystyrene waste, repurposing, lightweight, thermal insulation.

1 Introduction

Polystyrene-based plastics pose a significant and persistent environmental challenge on a global scale [1-2]. Expanded polystyrene (EPS) and extruded polystyrene (XPS), commonly used in packaging and building insulation, are non-biodegradable and widely distributed in land and marine environments [3]. Around 200,000 tons of polystyrene foam are estimated to end up in construction and demolition waste streams in Europe each year, with recycling still at low levels [4-3]. The rest of the material is driven to incineration or burial, contributing significantly to the production of microplastics and the release of harmful additives. Foamed polymers occupy a large volume in relation to their mass, making them disproportionately heavy for landfills [5]. As environmental regulations tighten and landfill space becomes increasingly limited, the need to repurpose these wastes into valuable, long-lasting products is more urgent than ever [6].

Incorporating waste materials into construction practices presents an opportunity to mitigate environmental impacts while conserving natural resources [7-9]. The use of recycled aggregates and industrial by-products in concrete and mortar has been extensively studied [10-13]. The inclusion of EPS as a lightweight aggregate in cementitious composites has been explored, with studies indicating improvements in thermal insulation and reductions in density [14-15]. EPS has been studied as a light-weight aggregate replacement in the last decade and studies have shown that its inclusion can reduce density and improve thermal insulation, but eventually with some compromise in mechanical performance [15-19]. On the other hand, XPS, despite its widespread use in thermal insulation systems and its superior mechanical and moisture resistance properties compared to EPS [20-21], has received considerably less attention in cementitious applications. In a recent study conducted by the authors [22] XPS waste collected from construction and demolition sites was shown to successfully replace sand in mortar production, producing materials with low thermal conductivity and adequate mechanical strength. These findings suggest that XPS waste has considerable potential in the development of lightweight structural or non-structural composites.

Research on the use of EPS and XPS derived from waste in cement-based materials is still limited, despite the growing need for sustainable construction practices [15]. Given the distinct characteristics of EPS and XPS, a comparative analysis is crucial to identify the optimal application of each waste material in mortar and concrete. This study investigates experimentally the replacement of sand with EPS and XPS waste in cement mortar mixtures. Considering that both types of waste differ significantly in origin, morphology, and physical properties [20], a side-by-side investigation is also essential to understand the relative advantages and potential applications of each waste material in sustainable construction practices. The current study investigates the experimental substitution of sand with EPS and XPS waste in cement mortar mixtures. Several replacement percentages are tested, and the resulting materials are evaluated in terms of fresh properties, mechanical behavior, and density. The research seeks to evaluate the suitability of these cement-based composite materials for both structural and non-structural applications. The results are expected to contribute to the development of sustainable construction materials and the effective management of polystyrene waste [23].

2 Materials and Methods

The experimental procedure closely followed the methodology previously presented by the authors [22]. The binder used was CEM II/B-M (P-W-L) 42.5 N Portland composite cement, and the fine aggregate was standardized EN 196-1 sand with a controlled granulometry suitable for mortar production. Two distinct polystyrene waste types were incorporated as sand substitutes: expanded polystyrene (EPS) and extruded polystyrene (XPS). EPS waste was collected from coastal and marine environments, while XPS waste was sourced from insulation offcuts and residues collected during demolition and renovation works. Both types were manually shredded into particles and sieved to ensure compatibility with the granulometry of standard sand. A visual representation of the EPS and XPS particles after shredding is provided in Fig. 1.

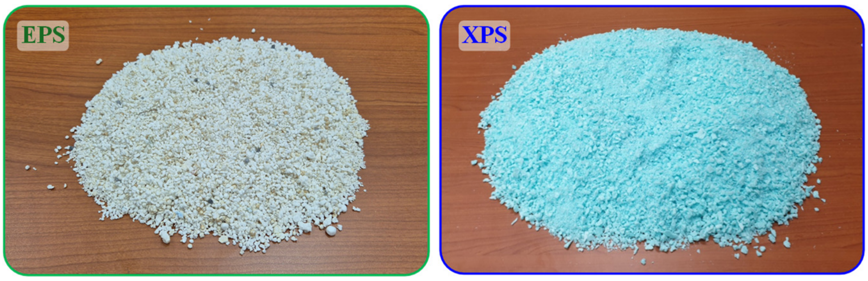

Fig. 1. EPS and XPS waste particles granulometry after shredding.

A reference mortar was prepared using a cement-to-sand ratio of 1:3 by weight and a constant water-to-cement ratio of 0.5. In modified mixtures, sand was replaced by EPS or XPS waste at volumetric levels of 20%, 40%, 60% and 80%. EPS and XPS modified mixes were prepared independently to assess the effect of each type of waste.

All mixtures were produced in a laboratory rotary mixer following a consistent dry–wet mixing sequence. First, the dry components (cement and sand or polystyrene waste) were mixed to ensure homogeneity and then gradually water was added. Fresh mortar was poured into standard prismatic molds measuring 40 mm × 40 mm × 160 mm, compacted in two layers using a vibrating table and covered with plastic sheets to prevent moisture loss. After 24 hours, the specimens were demolded and transferred to a curing tank maintained at 20 ± 2°C, where they remained until the day of testing at 28 days.

The workability of fresh-state mortar was assessed using the flow table method according to EN 1015-3. Hardened dry density was determined following EN 1015-10. The flexural and compressive strength measurements were carried out at 28 days using a universal testing machine, in accordance with EN 196-1. For each mix, at least three specimens were tested and average values were reported.

3 Results and discussion

In this section, the experimental findings are reported and analyzed with respect to the fresh and hardened properties of cement mortars incorporating EPS and XPS waste. Workability, density, flexural strength, and compressive strength were measured for each mixture and compared with the reference. The influence of increasing replacement levels was examined, and differences between EPS and XPS were evaluated to assess their respective suitability for structural and non-structural applications.

3.1 Visual Inspection of Polystyrene Distribution

To assess the internal distribution of EPS and XPS particles, specimen cross section were cut after hardening. This allowed visual observation of the dispersion quality of the shredded waste within the cement matrix. The inspection revealed that in all cases the polystyrene particles were distributed relatively uniformly throughout the volume of the specimen, without significant signs of agglomeration, sedimentation, or clustering of voids near the top or bottom surfaces. A representative image of the cross sections is provided in Fig. 2.

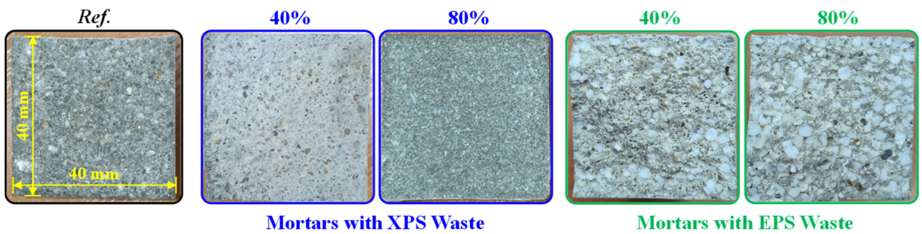

Fig. 2. Cross-sectional views of hardened mortar specimens incorporating EPS and XPS waste, showing the internal distribution of the polystyrene particles.

3.2 Flow of fresh mortar

The workability of mortars incorporating EPS and XPS waste as sand replacements was evaluated using the flow table test, with results presented in Fig. 3. For EPS modified mortars, an increase in flow was observed up to a replacement level of 60%, with a maximum enhancement of approximately 9.5% at 40% replacement compared to the reference mix. This improvement in workability can be attributed to the low density and spherical shape of the EPS particles, which reduce internal friction and facilitate better particle movement within the mix. However, at an 80% replacement level, a reduction in flow was observed with respect to the reference mortar, possibly due to the insufficient sand content to maintain cohesion and uniform wetting, leading to a less stable mix.

In contrast, XPS-modified mortars exhibited a gradual decrease in flow with increasing replacement levels, which became more pronounced beyond 60%, reaching nearly 19% lower than the reference at 80% replacement. This trend is consistent with the morphology of shredded XPS particles, which tend to be flake-like, irregular, and rough-surfaced. Such characteristics result in higher internal friction and increased water demand, possibly due to the larger surface area and the ability of water to adhere to the crumbled particle surface. These factors collectively contribute to the reduction in workability observed at higher XPS contents.

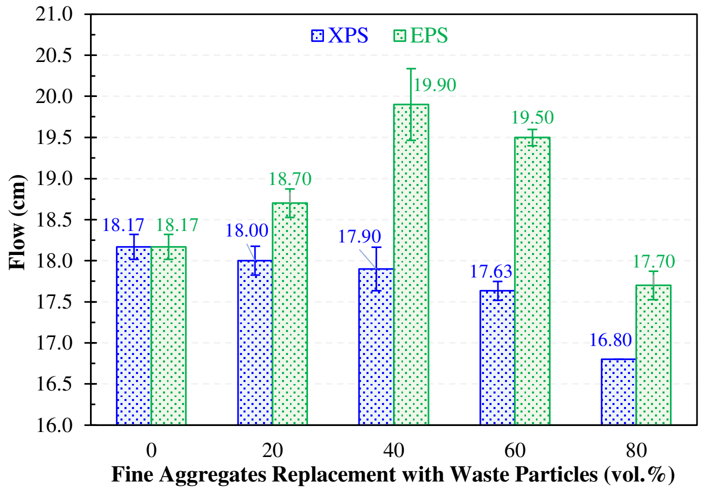

Fig. 3. Flow values of mortars incorporating EPS/XPS waste at different levels of sand replacement.

3.3 Compressive and Flexural Strength

The results of the 28-day compressive strength tests for mortars containing EPS and XPS waste are shown in Fig. 4. A continuous decline in strength was observed with increasing replacement levels for both types of waste materials. However, the rate of reduction varied significantly between the two series. In mortars containing EPS, the strength loss was more pronounced. At 20% replacement, a reduction of 27.6% was recorded compared to the reference, while at 80% replacement the compressive strength decreased by 81.0%. On the contrary, XPS-modified mortars exhibited a more gradual decline in compressive strength. At 20% replacement, the reduction was almost insignificant, while at 80%, a total loss of 38.9% was observed. Although in both cases the compressive strength is reduced, the extent of reduction remains within acceptable ranges for several applications, since in both cases mortars maintain strength way above the 3.5- 7.5 MPa that is indicated for rendering and plastering mortars. XPS-modified mortars, due to their more moderate strength reductions, may even be appropriate for structural applications.

Flexural strength values at 28 days for mortars incorporating EPS and XPS waste are shown in Fig. 5. A reduction in strength was observed with increasing sand replacement for both materials, following a trend similar to that of compressive strength. For EPS modified mortars, the strength decreased from approximately 7.4 MPa in the reference mix to 3.2 MPa at 80% replacement. XPS-modified mortars exhibited a more moderate decline, with strength remaining above 5.5 MPa at the same level of substitution. Across all replacement levels, mortars containing XPS retained a higher flexural strength than those with EPS.

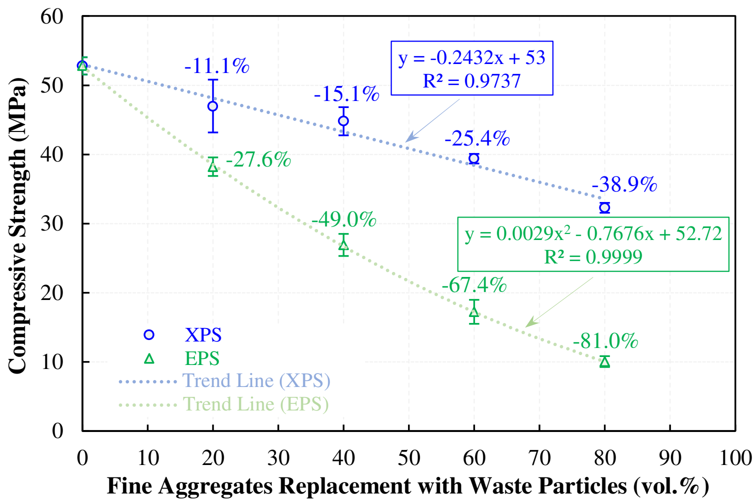

Fig. 4. Compressive strength of cement mortars incorporating EPS and XPS waste at varying sand replacement levels.

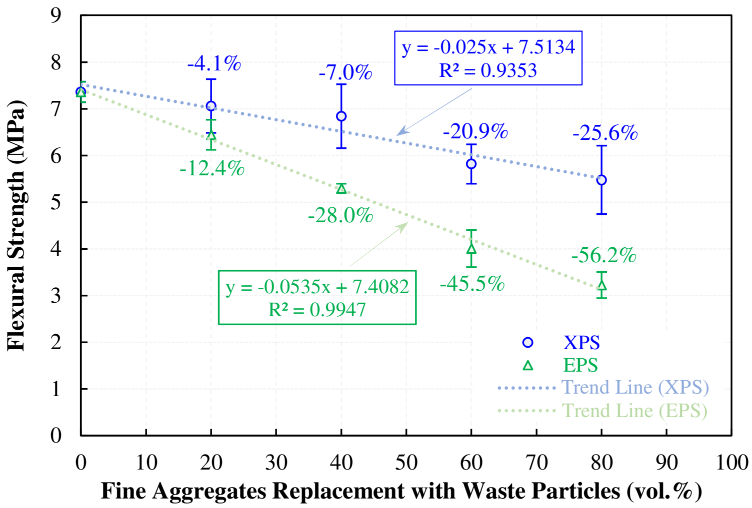

Fig. 5. Flexural strength of cement mortars incorporating EPS and XPS waste at varying sand replacement levels.

3.4 Density

The hardened density values at 28 days for mortars incorporating EPS and XPS waste are shown in Fig.6. As the level of replacement of the sand increased, both EPS and XPS mortars exhibited a progressive reduction in density, consistent with the significantly lower bulk density of polystyrene waste compared to natural sand. At 20% replacement, the density reduction was comparable for both materials: 4.1% for EPS and 3.4% for XPS. However, beyond this point, the reduction in EPS-modified mortars was approximately twice that observed in XPS mortars at each level. At 40%, EPS led to a 16.3% reduction versus 8.0% for XPS. Similarly, at replacement levels of 60% and 80%, the reductions were 31.6% and 43.6% for EPS, compared to 15.8% and 24.8% for XPS, respectively. These results indicate that, while both EPS and XPS effectively lower the weight of cementitious materials, EPS has a more substantial impact on bulk density, which is consistent with the typically higher density of XPS compared to EPS as a material.

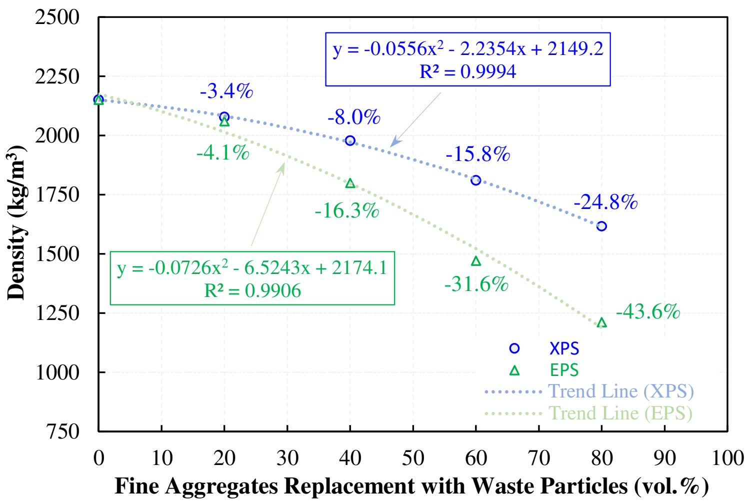

Fig. 6. Hardened density at 28 days of cement mortars incorporating EPS and XPS waste at varying sand replacement levels.

3.5 Relationship between Density and Compressive Strength

Fig. 7 presents the relationship between 28-day compressive strength and hardened density for mortars incorporating EPS and XPS waste. In both series, a clear correlation is observed, indicating that as density decreases as a result of increasing polystyrene content, compressive strength also decreases. This trend is consistent with the lower mechanical contribution of lightweight aggregates and the greater air volume introduced into the matrix.

In the case of EPS mortars, the relationship is nonlinear, with a sharper strength reduction at lower densities. At 80% replacement, the density falls below 1250 kg/m^3, while the strength remains slightly above 10 MPa. In contrast, XPS modified mortars show a near-linear correlation, maintaining compressive strengths above 32 MPa even at 80% replacement and a density of 1616 kg/m³. This distinction highlights the more gradual performance decline and the higher mechanical retention of XPS at comparable density levels.

These results are particularly relevant in the context of the development of lightweight cement-based composites for construction. Reduced density contributes not only to weight savings and easier handling, but also improves thermal insulation properties, an effect widely recognized in the literature as being associated with a higher air content and lower material compactness [17, 22]. XPS-based mixes offer a more favorable strength-to-density ratio, while EPS-based mixes provide greater density reduction for applications where thermal performance is prioritized.

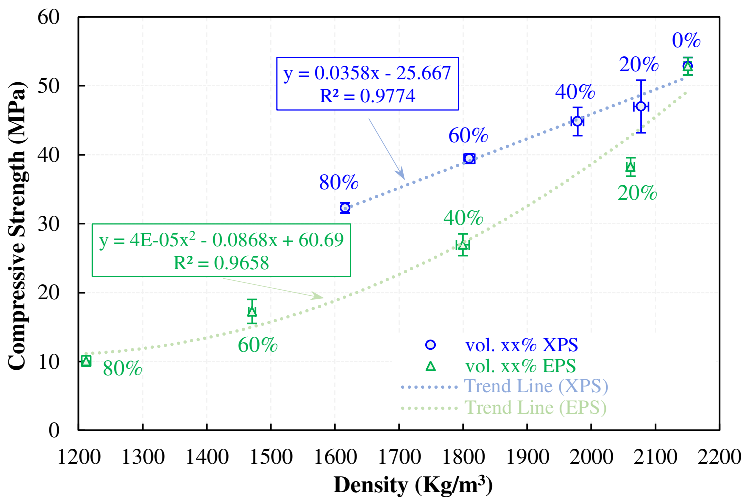

Fig. 7. Correlation between 28-day compressive strength and hardened density for EPS- and XPS-modified cement mortars at various sand replacement levels.

4 Concluding Remarks

This experimental study assessed the feasibility of using EPS and XPS waste as partial sand replacements in cementitious mortars. The primary aim was to develop lightweight mortars with acceptable mechanical properties, offering potential for both structural and non-structural applications.

- Compressive and flexural strength decreased with increasing sand replacement. However, mortars with XPS waste retained considerably higher strength. At 80% replacement, XPS mortars exceeded 32 MPa in compressive strength, while EPS mortars remained just above 10 MPa.
- Both EPS and XPS waste led to significant reductions in mortar density, and EPS achieved greater decreases at each replacement level. At 80% replacement, EPS reduced density by approximately 44% and XPS by 25%.

- The strength-to-density performance suggests that XPS waste can be used to produce lightweight mortars suitable for structural or semi-structural use. EPS-modified mortars are better suited for non-load bearing or thermally insulating applications, where weight and energy performance are prioritized over strength.
- Both types of waste were successfully incorporated into cement composites, supporting the circular use of materials that otherwise persist in landfills or marine environments. This contributes to waste reduction and aligns with the goals for more sustainable construction practices.

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