

Optimization of the Compressive and Split Tensile Strength of Lightweight Concrete Containing Recycled Expanded Polystyrene Using Response Surface Methodology

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Abstract This study optimized the compressive and split tensile strengths of lightweight concrete containing recycled expanded polystyrene (EPS) using Response Surface Methodology (RSM). EPS, a non-biodegradable polymer commonly used in packaging, was recycled from computer packaging waste and used as a partial replacement for coarse aggregates. A central composite design with three factors—EPS particle size (12, 16, 19 mm), replacement level (25%, 35%, 45%), and density—was generated using Design Expert (v.11). Ten experimental runs with five replicates each for compressive and split tensile strength were conducted. Results showed that compressive strength decreased from 8.52 MPa for the control (clay balls) to 3.78–5.80 MPa for EPS concretes, while split tensile strength ranged from 1.02–1.42 MPa compared with 1.162 MPa for the control. Replacement level significantly affected both properties, while particle size showed an interaction effect with replacement level for compressive strength. The optimal mix consisted of 13.53 mm EPS at 25% replacement and a density of 1.73 g/cc, achieving 5.80 MPa compressive strength and 1.33 MPa split tensile strength values suitable for non-structural lightweight concrete. These findings demonstrate the potential of recycled EPS for sustainable construction and highlight the effectiveness of RSM in

optimizing lightweight concretes.

Keywords Compressive Strength, Split Tensile Strength, Recycled Expanded Polystyrene, Lightweight Concrete, Response Surface Methodology

1. Introduction

In the Philippines, lightweight concrete is widely used to reduce dead loads and improve material efficiency in construction. Replacing natural aggregates with recycled expanded polystyrene (EPS) offers dual benefits: it diverts plastic waste from the environment and produces concrete that is lighter and potentially more economical [1]. However, studies consistently show that high EPS contents reduce strength due to weak bonding and increased voids. For instance, Sadrmomtazi et al. [2] reported a 69% reduction in compressive strength at 55% replacement, while Nikbin and Golshekan [3] observed losses of up to 73% at 40% replacement. Conversely, Rosca and Corobceanu [4] found that with a proper mix design, EPS concretes can achieve compressive strengths above 25 MPa at 35% replacement.

Similar results have been reported in recent works. Matsuo [5] showed that EPS waste used as fine aggregate in lightweight concrete reduced strength but achieved acceptable performance at moderate replacement levels. Gyawali [6] also demonstrated that tensile and compressive strengths decreased as EPS content increased, though lightweight properties were consistently achieved. More recent advances combine EPS with fibers or hybrid binders to mitigate strength loss. For example, steel fiber reinforcement improved EPS self-compacting concrete [7], while hybrid binders incorporating EPS with expanded clay and alkaline cements produced sustainable lightweight concretes with balanced strength and density [8]. These studies highlight the ongoing innovation in EPS concrete but also confirm the persistence of strength reduction challenges.

According to ACI 213R-14, structural lightweight concrete must have a density of 1120–1920 kg/m³ and compressive strength above 17 MPa, while lower strengths are acceptable for non-structural applications such as partitions and insulation [9]. Achieving this balance remains a challenge, particularly when recycled EPS is used as coarse aggregate. Researchers have investigated particle size reduction, fiber reinforcement, and chemical treatments to improve bonding [10, 11]. The use of densified EPS also shows potential to reduce water absorption and enhance concrete's durability [12].

Optimization techniques, particularly Response Surface Methodology (RSM), have proven effective in modeling and predicting the performance of concretes with multiple interacting variables. Prior studies successfully applied RSM to concretes incorporating fly ash, plastic waste, palm oil clinker, and silica fume [13–16]. However, limited work has applied RSM to EPS-based lightweight concretes, leaving a gap in systematic optimization of EPS particle size, replacement level, and density.

EPS sourced from computer packaging typically has a bulk density of 10–35 kg/m³ and is classified as ASTM Type I or II [17, 18]. Its low density makes it highly effective in reducing unit weight. Beyond technical advantages, EPS recycling contributes to sustainability: Alqahtani et al. [19] reported that plastic waste concretes reduce embodied energy by 21% and carbon emissions by 13%, while Yu et al. [20] showed its suitability for porous insulation concretes. Collectively, recent studies confirm EPS's potential for sustainable construction, but optimization is necessary to achieve broader acceptance.

Recent studies have extended EPS reuse to hybrid cement systems and optimized formulations through RSM

to achieve better strength-to-weight ratios [21, 22, 23]. These advancements highlight EPS's potential for sustainable construction, yet systematic optimization of both compressive and tensile strength parameters remains limited.

Although several studies have investigated the mechanical behavior of EPS concretes, many have relied on empirical mix trials, which are limited in capturing the combined effects of multiple variables. This research distinguishes itself by employing Response Surface Methodology (RSM) to systematically optimize EPS particle size, replacement level, and density—an approach that enhances statistical accuracy and reduces the number of experimental trials. Moreover, by utilizing recycled EPS from packaging waste, this study contributes to both sustainable material innovation and circular construction practices.

2. Materials and Methods

2.1. Materials

The following materials were used in the experimental work: Ordinary Portland Cement (Type I), river sand as fine aggregate, expanded clay balls for control mixes, and recycled EPS beads as lightweight aggregate replacement. All materials were characterized in accordance with relevant ASTM standards to ensure reliability and consistency.

Ordinary Portland Cement (Type I) conforming to ASTM C150 was used as the primary binder. River sand with a fineness modulus of 2.7 served as the fine aggregate. Expanded clay balls were used as coarse aggregates in the control mix. Recycled EPS was sourced from discarded computer packaging waste and manually cut into three nominal particle sizes: 12 mm, 16 mm, and 19 mm. The EPS bulk density ranged from 10–25 kg/m³, consistent with ASTM C578 Type I. Potable water was used for mixing and curing.

2.2. Mix Design

A Class A mix proportion of 1:2:4 with a constant water–cement ratio of 0.5 was adopted. EPS was introduced as a partial replacement for coarse aggregates at 25%, 35%, and 45% by volume, while the control mix used expanded clay balls. Table 1 presents the mix proportions for all experimental runs.

2.3. Experimental Design

Response Surface Methodology (RSM) with a central composite design was applied using Design Expert (v.11) to evaluate the effects of EPS particle size, replacement level, and density. The software generated 10 experimental runs, each with five replicates for compressive and split tensile strength, resulting in 50 specimens per test. Design Expert is a widely used statistical tool for experimental design and optimization, particularly in engineering and material science studies. It provides efficient techniques for modeling and analyzing the relationships between multiple variables and responses, allowing researchers to identify optimal conditions with fewer experimental trials compared to conventional methods. Its ability to generate regression models, surface plots, and diagnostic statistics made it particularly useful for this study, where interaction effects and nonlinear relationships between EPS properties

and concrete strength needed to be evaluated.

2.4. Sample Preparation

Mixing was performed according to ASTM C192. EPS particles were gradually incorporated into the fresh mix to ensure uniform dispersion. The concrete was cast into 150 × 300 mm cylindrical molds, compacted using a vibrating table, and cured in water until testing.

2.5. Testing Procedures

Compressive Strength: Determined at 28 days following ASTM C39 using a 2000 kN testing machine. **Split Tensile Strength:** Conducted at 28 days in accordance with ASTM C496, where specimens were loaded diametrically until failure. The test of specimens for compressive and split tensile strength tests is shown in Figure 1.

Table 1. I-optimal design of experiment used for modeling the effects of EPS particle size, replacement level, and EPS concrete density on the mechanical properties of lightweight concrete

Runs	1	2	3	4	5	6	7	8	9	10
A: EPS size (mm)	16	16	19	12	19	12	12	16	19	16
B: EPS Replacement (%)	35	45	35	35	45	25	35	35	25	25
C: EPS concrete Density (g/cc)	1.93	1.77	1.88	1.85	1.73	1.92	1.83	1.92	1.94	1.90



Figure 1. Testing setup for compressive (left) and split tensile strength (right) showing specimen positioning, applied load direction, and measurement configuration for EPS-based concrete specimens

3. Results and Discussion

3.1. Mechanical Performance

Table 2 summarizes the compressive and split tensile strengths of EPS-based concretes. Increasing EPS content reduced strength, although smaller particle sizes and lower replacement levels performed better. These results reflect the inherent trade-off between lightweight performance and mechanical capacity observed in previous studies [2, 3, 5].

3.2. Compressive Strength

The control mix achieved a 28-day compressive strength of 8.52 MPa, while EPS concretes ranged from 3.78 MPa (19 mm, 45% replacement) to 5.80 MPa (12 mm, 25% replacement). Strength reduction at higher replacement levels was attributed to poor bonding and increased voids caused by the hydrophobic nature of EPS beads. These findings are consistent with earlier reports [2, 3, 6], and closely align with Matsuo [5], who observed similar losses with EPS waste aggregates.

Although compressive strength decreased, certain EPS mixes met the minimum requirements for non-structural lightweight concrete [9]. Recent innovations, such as hybrid cement systems combined with EPS, have been shown to mitigate strength loss while preserving lightweight properties [8].

These findings highlight the trade-off between mechanical strength and density reduction. The results indicate that the inclusion of EPS effectively reduces unit weight but compromises compressive strength due to poor interfacial bonding and the hydrophobic surface of EPS beads. Nevertheless, the optimized mixture achieved adequate strength for non-structural applications, aligning with the requirements of ACI 213R-14 for lightweight concrete.

3.3. Split Tensile Strength

The control mix attained an average split tensile strength of 1.162 MPa, whereas EPS concretes showed values between 1.02 and 1.42 MPa. Mixes with 12 mm particles at 25% replacement achieved the highest tensile strength, marking an improvement of up to 8.78% over the control. Similar improvements in tensile resistance were reported when EPS was combined with fibers [7]. Larger particles and higher replacement levels reduced tensile strength, confirming the role of the interfacial transition zone [11]. Densified EPS also shows promise in enhancing bond strength and reducing water absorption [12].

3.4. Statistical Modeling with RSM

The compressive strength model achieved $R^2 = 0.9609$, while the split tensile model attained $R^2 = 0.7996$. ANOVA confirmed that replacement level was the most significant factor ($p < 0.05$), while particle size alone was less influential but showed interaction effects with replacement level. These results validate RSM as an effective optimization tool, consistent with its use in other sustainable concretes [13–16].

The regression equations derived from Design Expert are presented below. Each model quantifies the relationship between EPS variables and corresponding strength properties.

The regression equations for both Compressive and Split Tensile Strengths in actual terms are shown below:

- $f_c = 121.447 - 9.879A + 0.126B - 47.161C + 0.052AB + 4.359AC - 0.536BC$
- $f_t = 1.65 + 0.005A - 0.015B - 0.008C$

where f_c is the Compressive Strength, f_t is the Split Tensile Strength, **A** is EPS particle size, **B** is EPS replacement level, and **C** is EPS concrete density.

Table 2. Comparison of 28-day compressive and split tensile strengths between the control mix and EPS-based lightweight concrete mixes, highlighting the influence of EPS particle size, replacement level, and density

Run No.	EPS Size (mm)	EPS Replacement (%)	Density (g/cc)	Average Compressive Strength (MPa)	Average Split Tensile Strength (MPa)
1	16	35	1.93	4.54	1.20
2	16	45	1.77	3.78	1.08
3	19	35	1.88	4.60	1.17
4	12	35	1.85	4.00	1.25
5	19	45	1.73	3.92	1.02
6	12	25	1.92	5.80	1.25
7	12	35	1.84	4.18	1.10
8	16	35	1.92	4.00	1.18
9	19	25	1.94	4.78	1.35
10	16	25	1.90	4.78	1.42

3.4.1. Analysis of Variance

ANOVA results for both compressive and split tensile strength models (Table 3) showed that the quadratic models were statistically significant ($p < 0.05$). The models achieved R^2 values of 0.9609 for compressive strength and 0.7996 for split tensile strength, confirming strong agreement between experimental and predicted values.

The adequacy, fitness, and consistency of the created models were tested using the R^2 values. Table 4 demonstrates that all models have strong R^2 values on average. The correlation among the two independent variables and their outcome responses was established and presented in 3-D response surface diagrams depicted in Figures 2 and 3 for compressive strength and split tensile strength, respectively, of concrete mixes containing recycled EPS. As can be seen, smaller EPS particle size (12 mm) and lower replacement level (25%) had relatively

higher positive impacts on compressive strength, while split tensile strength showed a slight increase with larger particle sizes and lower replacement levels. These results are consistent with the experimental observations.

3.5. Optimization

Numerical optimization identified the optimum mix at 13.53 mm EPS particle size, 25% replacement, and 1.73 g/cc density, yielding 5.80 MPa compressive strength and 1.33 MPa split tensile strength. These values meet the requirements for non-structural lightweight concrete. Few studies have applied RSM to EPS concretes, further underscoring the contribution of this work. Optimization of the EPS concrete mixtures was carried out by maximizing compressive strength and split tensile strength, while simultaneously minimizing density, as summarized in Table 5.

Table 3. ANOVA results for compressive and split tensile strength models, indicating factor significance, interaction effects, and model adequacy statistics

Response	Variables	Sum of Squares	D.F.	Mean Square	F-value	P-value
Compressive Strength	Model	3.15	6	0.5249	12.30	0.0322
	A-size	0.0758	1	0.0758	1.78	0.2749
	B-%	0.1565	1	0.1565	3.67	0.1514
	C-Density	0.0158	1	0.0158	0.3705	0.5857
	AB	0.4793	1	0.4793	11.23	0.0440
	AC	0.2547	1	0.2547	5.97	0.0923
	BC	0.1601	1	0.1601	3.75	0.1482
Split-Tensile Strength	Model	0.1071	3	0.0357	7.98	0.0162
	A-size	0.0019	1	0.0019	0.4213	0.5403
	B-%	0.0327	1	0.0327	7.30	0.0355
	C-Density	9.425E-07	1	9.425E-07	0.0002	0.9889

Where A is EPS size, B is EPS % replacement, C is Density, AB/AC/BC is Interaction effects, D.F. is Degree of freedom, F-values are Fisher-statistical test values, and P-values are Probability values.

Table 4. Validation of response surface methodology (RSM) models by comparing predicted and experimentally measured compressive and split tensile strengths

Response	R^2	Adj R^2	Pred. R^2	Mean	S.D.	CoV(%)	AP
Compressive	0.9609	0.8828	0.7678	4.44	0.2066	4.65	11.5370
Split Tensile	0.7996	0.6994	0.4610	1.20	0.0669	5.57	7.4774

Design-Expert® Software
Factor Coding: Actual

Compressive (MPa)
3.78 5.8

X1 = A: Size
X2 = B: %

Actual Factor
C: Density = 1.83415

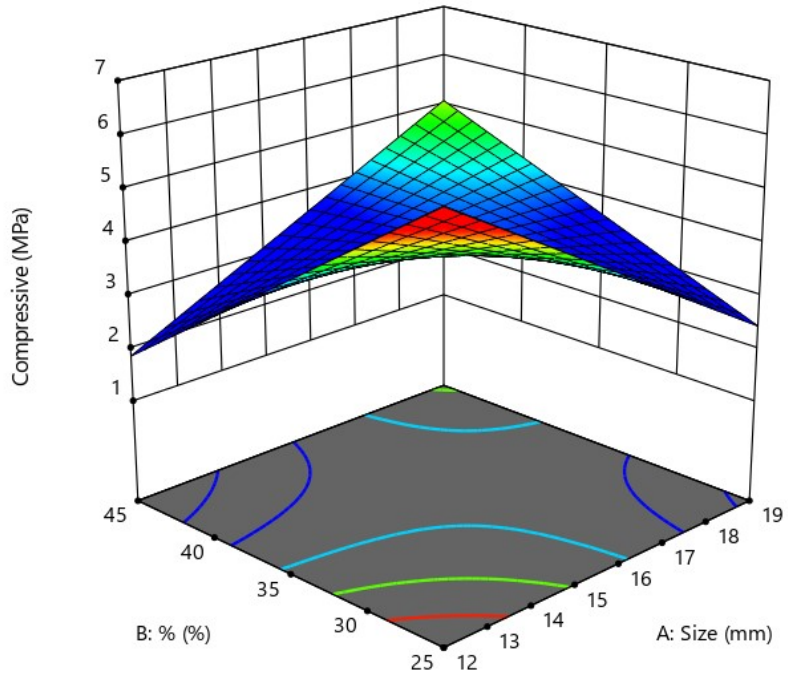


Figure 2. Response surface plot showing the interaction between EPS particle size and replacement level on Compressive Strength

Design-Expert® Software
Factor Coding: Actual

Split Tensile (MPa)
1.02 1.42

X1 = A: Size
X2 = B: %

Actual Factor
C: Density = 1.83415

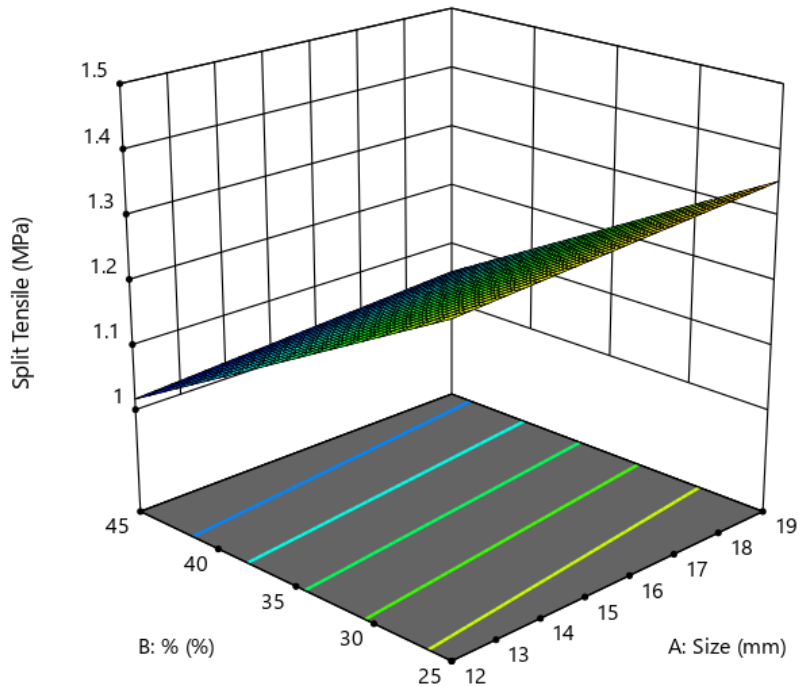
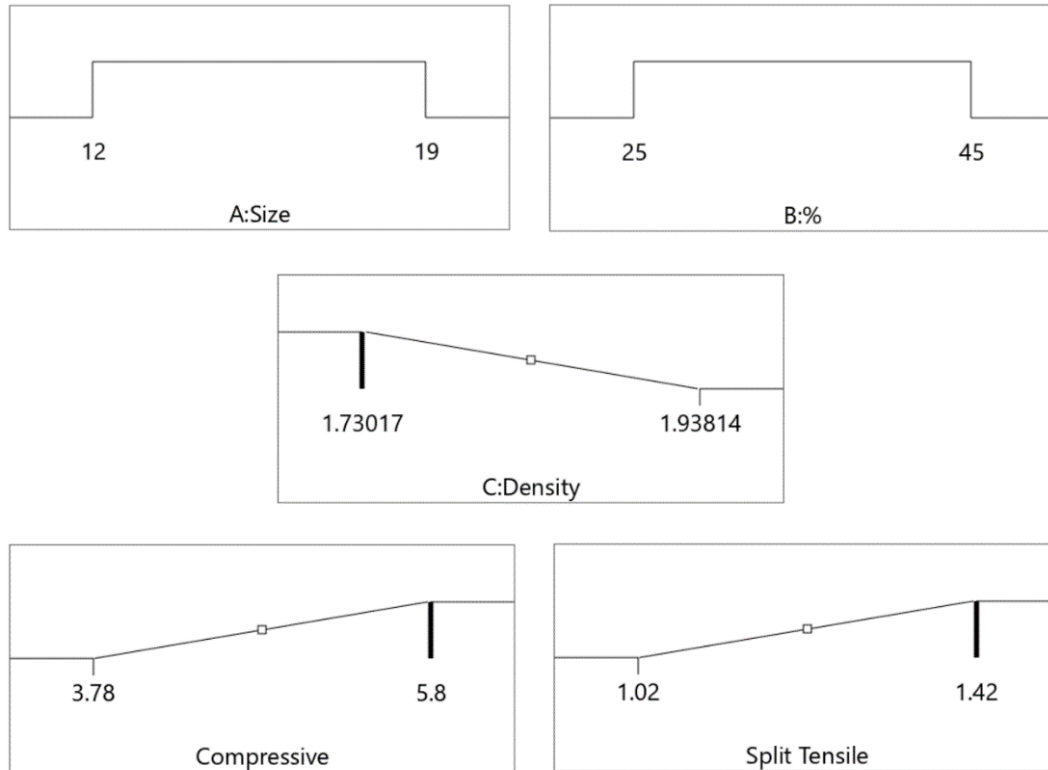


Figure 3. Response Surface plot showing the interaction between EPS particle size and replacement level on Split Tensile Strength

Table 5. Optimization benchmark for EPS-based lightweight concrete summarizing optimal EPS particle size, replacement percentage, and predicted mechanical performance based on RSM

Independent and Dependent Variables	Sign	Goal	Lower Limit	Upper Limit
EPS size (mm)	A	in range	12	19
EPS Replacement (%)	B	in range	25	45
EPS Concrete Density	C	Minimize	1.73017	1.93814
Compressive Strength	Compressive	Maximize	3.78	5.8
Split-Tensile Strength	Split Tensile	Maximize	1.02	1.42



$$Desirability = 0.916$$

Figure 4. Desirable plot showing optimal combination of EPS particle size, replacement percentage, and concrete density based on multi-response optimization criteria

Table 5 presents the optimization benchmark for EPS-based lightweight concrete, where compressive and split tensile strengths were maximized, density was minimized, and EPS size and replacement levels were kept within range. The desirable combination of variables is shown in Figure 4, with an optimized mix yielding 5.8 MPa compressive strength, 1.42 MPa split tensile strength, and a minimized density of 1.73017 g/cm³, achieving an overall desirability of 91.6%. The 3D response surface plot in Figure 5 further illustrates that the optimal region corresponds to smaller EPS particle sizes and lower replacement levels, which provided the best balance

between strength and density.

While this study focused primarily on optimizing mechanical properties, durability aspects such as water absorption, shrinkage, and long-term strength retention were not investigated. These factors are critical for assessing service life performance. Future studies should address these aspects to ensure that EPS concretes perform reliably under field conditions. For potential structural applications, integrating fiber reinforcement, hybrid aggregates, chemical treatment of EPS, or densification and surface modification could enhance bond strength and stiffness.

Design-Expert® Software

Factor Coding: Actual

Desirability

○ Design points below predicted value

0.000  1.000

X1 = A: Size

X2 = B: %

Actual Factor

C: Density = 1.73017

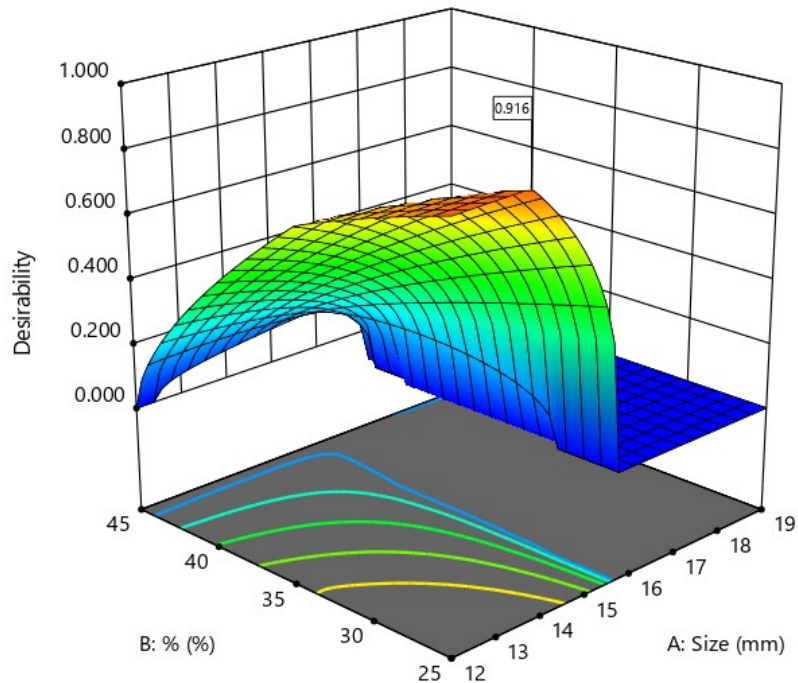


Figure 5. Three-dimensional optimization plot illustrating the combined effects of EPS particle size and replacement level on the overall desirability score for EPS lightweight concrete

4. Conclusions

This study evaluated the use of recycled EPS as a partial replacement for coarse aggregates in lightweight concrete and optimized its performance using RSM.

- EPS replacement reduced compressive strength compared with the clay ball control mix (8.52 MPa), with EPS concretes ranging from 3.78–5.80 MPa.
- Split tensile strength ranged from 1.02–1.42 MPa, with the best mix (12 mm, 25% replacement) exceeding the control (1.162 MPa) by 8.78%.
- Replacement level was the most significant factor, while particle size had weaker individual effects but interacted with replacement level for compressive strength.
- The optimal mix was 13.53 mm EPS at 25% replacement, producing 5.80 MPa compressive strength and 1.33 MPa split tensile strength at a 1.73 g/cc density, acceptable for non-structural lightweight applications.

These findings confirm EPS's potential for lightweight, non-load-bearing concretes, consistent with recent studies [5,6]. Fiber reinforcement [7], hybrid aggregate systems [8], and densified EPS [12] offer promising directions for further improvement. The successful application of RSM to EPS concretes also bridges a gap in the optimization of

sustainable concrete materials.

The experimental optimization confirmed that EPS can effectively reduce concrete density while maintaining acceptable strength for non-structural uses. However, long-term durability tests and microstructural analyses were not included, representing areas for future research.

Future work should focus on durability testing, fiber reinforcement for structural adaptation, and life cycle assessment to evaluate environmental benefits.

The optimized EPS mix can be used in non-structural elements such as wall panels, façade blocks, and insulating layers. Its reduced self-weight and recycling potential align with sustainable construction practices, directly supporting SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production).

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