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Mechanical Characteristics of Concrete Elements Incorporating Waste-Derived Expanded Polystyrene (EPS) Spheres at The Neutral Zone

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Abstract

This study experimentally investigates the use of waste-derived expanded polystyrene (EPS) spheres as discrete core formers in M20 concrete. Spherical Thermocol formers were positioned centrally within cube specimens and around the theoretical neutral axis region of three-point-bending beam specimens at nominal volume ratios of 0%, 4%, 5%, and 6%. Workability, 24-h water absorption, density, compressive strength, and flexural strength were evaluated at 28 days. Increasing EPS content reduced density from 2403.65 kg m⁻³ for the control mixture to 2314.47 kg m⁻³ at 6% EPS, while compressive strength decreased from 20.260 to 18.630 MPa. Flexural strength decreased from 5.835 MPa to 4.189 MPa over the same range. One-way ANOVA indicated that the overall effect of EPS ratio on compressive strength was not statistically significant at the 5% level, $F(3,8)=3.90$, $p=0.055$, although the Tukey comparison between 0% and 6% was reported as significant ($p=0.040$). In contrast, the flexural-strength effect was statistically significant, $F(3,8)=22.33$, $p\approx 0.0003$. The results therefore indicate a measurable reduction in self-weight accompanied by strength penalties that become more pronounced in flexure. The study does not establish an optimum EPS ratio or structural/seismic performance; instead, it provides an initial materials-level assessment of discrete waste-EPS core formers and identifies the need for controlled placement, larger datasets, reinforced-member testing, and direct structural and durability investigations.

Keywords: EPS embedded concrete, Expanded polystyrene, Thermocol, Neutral-zone core former, Dead load reduction, Compressive strength, Flexural strength

29 1 **Introduction**

30 Concrete is the most widely used construction material in the world, but its high self-weight
31 increases the size of structural members and foundations and raises overall project cost [1]. A
32 substantial share of this dead weight is structurally redundant: in a conventional reinforced
33 concrete slab or beam, the material near the neutral zone carries little bending stress and serves
34 mainly to maintain the lever arm between the tension and compression reinforcement [2].
35 Replacing this structurally redundant concrete with a lightweight, non-structural core former—an
36 approach generally described in the literature as voided or biaxial slab construction—reduces dead
37 load, seismic mass, and material consumption while largely preserving flexural capacity [3].

38 The rationale for utilizing waste expanded polystyrene (EPS), commonly known as Thermocol, as
39 a core-former material stems from its combination of structural and environmental advantages.
40 Recent reviews show that EPS has been investigated extensively in lightweight concrete, mainly
41 as beads or particles replacing mineral aggregate, with resulting reductions in density and generally
42 accompanying changes in workability and mechanical performance [4]. Other work has examined
43 recycling waste EPS into construction materials and has highlighted its potential contribution to
44 waste management and lightweight construction, while also emphasizing the need to control the
45 associated mechanical penalties and processing requirements [5]. Voided slab systems originated
46 in Europe in the nineteenth century and were commercialized through proprietary biaxial systems
47 such as Bubble Deck, Cobiax, U-Boot Beton, and Air Deck from the 1990s onward; these systems
48 typically use manufactured plastic or hollow spherical/ellipsoidal void formers embedded within
49 the slab depth, and their performance has been documented under controlled industrial fabrication
50 conditions that are not readily accessible in many developing regions.([6]; [7]) In parallel, EPS is
51 a synthetic, non-biodegradable polymer that persists in the environment for centuries and is
52 frequently disposed of through open burning, releasing toxic styrene gas [8]. Encapsulating this
53 waste material within concrete simultaneously sequesters it from the waste stream and exploits its
54 low density (approximately 13.5 kg m^{-3}) for structural benefit. The seismic vulnerability of heavy
55 load-bearing structures in Nepal, highlighted in recent post-earthquake assessments [9], further
56 motivates lightweight construction approaches suited to locally available materials rather than
57 imported proprietary systems.

Hollow or biaxial voided slabs reduce structural weight and material cost by embedding voids within the slab depth while aiming to preserve load-bearing capacity. El-Behairy et al. [10] found that decreasing the void-depth ratio improved load distribution across voided slabs and that deflection decreased as the reinforcement ratio increased. Chung et al. [11] reported that donut-type voided slabs achieved flexural strengths equivalent to 98–105% of an equivalent solid slab, with stiffness reduced by only 8–9% relative to the solid case. Lee et al. [12] showed that slabs voided by circular tubes exhibited smaller long-term deflections and at least 10% longer maximum span lengths than solid slabs of equal depth.

Recycled waste materials have also been explored as void formers. Rajab et al. [13] used steel mesh tubes packed with waste plastic bottles and found enhanced flexural capacity and reduced deflection relative to solid one-way slabs. Mahdi and Ismael [14] tested hollow-core slabs with longitudinal voids and reported ultimate strength reductions of 6.5–17.1% alongside self-weight reductions of 15–30% and cost savings of 12–23%, with CO₂ emission reductions of 16–32% depending on void ratio. Shetkar and Hanché [15] used elliptical hollow balls in a bubble-deck configuration and observed up to 6% higher load-carrying capacity when shear links were added, alongside dead load reductions of up to 50%. Khan et al. [16] investigated waste bottle caps as a partial coarse-aggregate replacement and found a 5.97% increase in compressive strength and a 19.01% increase in flexural strength at 10% replacement, illustrating that not all waste-derived modifications reduce strength. Cho et al. [17] studied the shear capacity of one-way voided slabs and found that higher hollow-core ratios introduce vulnerability under shear loading, underscoring the importance of void placement and ratio. Riad and Shoeib [18] examined polystyrene foam concrete flat slabs under fire exposure and noted reduced tensile strength and bond with reinforcement due to the presence of the foam, despite the use of polypropylene fibers for crack control. Khedikar et al. [19] used waste Thermocol with a thinner waste as an admixture and reported improved workability and a reduced water–cement ratio requirement. Ingeli et al. [20] studied the thermal performance of expanded-polystyrene-voided slabs and found equivalent thermal conductivity to air-voided systems, alongside construction cost reductions of up to 20%.

Closely related to the present work, Gyawali [21] assessed lightweight concrete containing EPS beads extracted from Thermocol waste and found that increasing EPS content reduced workability, density, compressive strength, flexural strength, split tensile strength, and Young's modulus, while

confirming that up to 30% EPS content remains usable for structural applications. Al-gasham et al. [22] tested one-way slabs voided with polystyrene balls of varying diameter and found that balls sized at 50% of the slab thickness produced negligible loss in ultimate strength, while larger balls caused strength reductions of 17.7–21.3%, recommending the smaller diameter ratio as a practical design guideline.

Collectively, the reviewed literature establishes that internal void or core formers, whether proprietary plastic systems, recycled plastic waste, or EPS in bead or foam form, can substantially reduce concrete dead load and, in several cases, water absorption, with manageable strength penalties provided the void ratio, geometry, and placement are controlled. Nevertheless, the specific configuration examined here has not previously been reported. Proprietary biaxial systems and recycled-former studies using plastic bottles or bottle caps ([16]; [13]) rely on manufactured or pre-shaped void formers rather than hand-fabricated waste material, so their performance data cannot be directly transferred to Nepalese material and construction conditions. Gyawali [21] distributed EPS beads throughout the entire cementitious matrix as a partial aggregate replacement, so the resulting loss of stiffness and strength is spread uniformly across the section rather than confined to a defined zone, while Al-gasham et al. [22] and Riad and Shoeib [18] embedded discrete polystyrene formers or foam layers within reinforced slab sections without specifically isolating the neutral-zone zone as the sole target for material removal. The present study is, to the authors' knowledge, the first to combine three elements: (i) an indigenous, waste-derived spherical core former hand-fabricated from factory-reject Thermocol sheet rather than a manufactured or pre-formed product; (ii) deliberate placement of the former exclusively at the neutral zone of plain M20 cube and beam specimens, a zone that theoretically carries negligible bending stress, so that any measured strength loss can be attributed to local geometric stress concentration rather than to a reduction of the load-bearing matrix itself; and (iii) inferential statistical validation, by one-way ANOVA, Tukey's HSD post-hoc comparison, and linear regression, of the dose–response relationship between core-former ratio and each measured property, rather than reliance on descriptive means alone, which is not reported in any of the reviewed Thermocol- or EPS-based voided concrete literature.

A systematic evaluation was conducted to determine the influence of core-former ratio (0–6% by volume) on the workability, water absorption, density, compressive strength, and flexural strength

of M20-grade concrete, and to identify the statistically defensible optimum ratio for dead-load reduction. The specific objectives were to: (i) fabricate concrete specimens containing 0% (control), 4%, 5%, and 6% spherical Thermocol core formers by volume; and (ii) experimentally quantify, and statistically compare, the measured properties across core-former ratios. The scope of the study is bounded in several respects: only 28-day behavior was evaluated; long-term durability and time-dependent performance were outside the present scope; only Thermocol was investigated as a core-former material; only M20-grade concrete was tested; and factors such as chemical composition, curing environment, and reinforcement detailing were held constant rather than varied as independent parameters. These boundaries are revisited as directions for further research in Section 4.

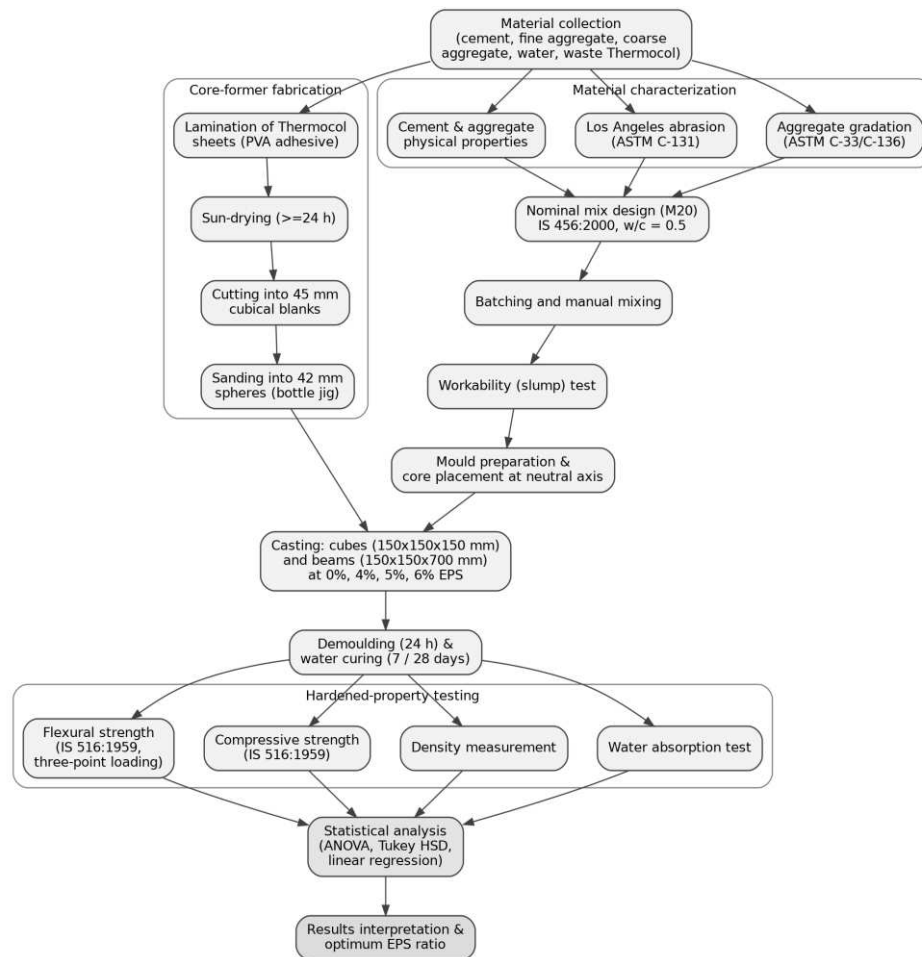


Fig. 1: Schematic diagram of the overall experimental workflow, from raw material collection and core-former fabrication through casting, curing, hardened-property testing, and statistical analysis.

2 Experimental program

2.1 Materials, resources, and characterization

Ordinary Portland Cement (OPC, 43-grade) was used after verifying fineness, setting time, standard consistency, and specific gravity. Well-graded granite coarse aggregate of maximum size 20 mm was sourced from the Nepal, Solti River, Manglabare area, and tested for aggregate impact value, Los Angeles abrasion resistance, water absorption, and specific gravity (Table 1). Clean, well-graded river sand passing a 4.75 mm sieve served as fine aggregate. Potable water was used at a water–cement ratio of 0.5. Thermocol (EPS), of density approximately 13.5 kg m^{-3} , was sourced as factory waste from a local panel manufacturer, so that the core-former material itself carried no procurement cost beyond collection and fabrication labor. The nominal mix design followed IS 456:2000 [23] for M20-grade concrete using a maximum aggregate size of 20 mm under sunny atmospheric conditions (Table 2).

Table 1: Materials properties against IS standard requirements.

Material	Property	Observed	IS requirement
Cement	Fineness (% retained, 90 μm)	8	$\leq 10\%$
	Standard consistency	31%	26-33%
	Initial setting (min)	31	≥ 30
	Final setting (min)	266	≤ 600
	Specific gravity	3.15	3.10-3.15
Fine aggregate	Specific gravity	2.70	2.6-2.7
	Water absorption (%)	1.20	≤ 2.0
	Fineness modulus	2.63	2.3-3.1
Coarse aggregate	Specific gravity	2.66	2.5-2.9
	Water absorption (%)	1.36	≤ 2.0

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Table 2: Mix design parameters.

Parameter	Value
Concrete grade	M20
Cement type	OPC (43-grade)
Nominal mix ratio (cement : FA : CA)	1 : 1.5 : 3
Water–cement ratio	0.5
Cement	372 kgm ⁻³
Water	186 kgm ⁻³
Fine aggregate	703.84 kgm ⁻³
Coarse aggregate	1131.35 kgm ⁻³

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148 2.2 Preparation of spherical Thermocol core formers

149 Standard Thermocol sheets (1 m × 1 m, ≈ 0.02 m thickness) were laminated together using
 150 polyvinyl acetate adhesive to build up the required block thickness, then sun-dried for a minimum
 151 of 24 hours to ensure complete curing of the adhesive bond and prevent delamination. The
 152 consolidated block was cut into 45 mm cubical blanks using a utility knife, chosen to minimise
 153 crushing of the foam cell structure relative to coarser cutting tools. Each cube was then shaped into
 154 a sphere by continuous, uniform sanding against a jig fashioned from a half-cut plastic bottle,
 155 whose curvature guided the abrasion and controlled the final radius, producing finished spheres of
 156 approximately 42 mm diameter (Fig. 2). This low-cost, manually controlled fabrication route was
 157 deliberately chosen over a manufactured or molded former to demonstrate that the technique
 158 remains accessible without specialized industrial equipment, though it introduces a degree of
 159 dimensional and volumetric variability that is discussed further in Section 3.3.



Fig. 2: Fabrication of spherical Thermocol core formers: shaping the half-cut-bottle jig (left) and sanding cubical blanks into uniform spheres (right).

2.3 Mix design and specimen preparation

The experimental programme evaluated the effect of spherical Thermocol core formers on M20-grade concrete across four core-former ratios: 0% (control), 4%, 5%, and 6% by volume, replacing an equal volume of the mix. Concrete was manually batched and mixed, with dry mixing repeated 2–3 times followed by wet mixing to a uniform consistency. Mold interiors were lightly greased prior to casting. A total of 16 cubes (150 mm × 150 mm × 150 mm) and 12 beams (150 mm × 150 mm × 700 mm) were cast across the four core-former ratios (Table 3), with Thermocol spheres positioned by hand at the mid-height (cubes) or mid-depth (beams) of each mold prior to placing the surrounding concrete, so that the former's center coincided with the theoretical neutral zone of the section. Manual compaction was applied using 25–30 tamping strokes per layer to minimize entrapped air while preserving sphere position; an allowance of 1% entrapped air void was assumed in the mix design to account for the limits of hand compaction relative to mechanical vibration. Specimens were demolded after 24 hours and water-cured at ambient temperature for 7 and 28 days depending on the test schedule.

Table 3: Number of specimens cast per core-former ratio.

EPS percentage	No. of cubes	No. of beams
0% (control)	4	3
4%	4	3
5%	4	3
6%	4	3

2.4 Testing program

Fresh concrete workability was assessed via the standard slump cone test [23] (Fig. 3). Coarse aggregate gradation followed ASTM C-33/C-136 [24], and abrasion resistance was determined via the Los Angeles Abrasion Test ASTM C-131 [25]. Water absorption was computed from the oven-dry weight (W_1) and 24-hour saturated weight (W_2) of each specimen as:

$$\text{Water absorption}(\%) = \frac{(W_2 - W_1)}{W_1} \times 100$$

Compressive strength testing followed IS 516:1959 [26], applying load at a constant rate of $140 \text{ kg cm}^{-2} \text{ min}^{-1}$ on a compressive strength testing machine until failure, with strength computed as the peak load divided by the cube's cross-sectional area (Fig. 5). Flexural strength was determined via a three-point central-point-loading test on a Universal Testing Machine following IS 516:1959 [26], with the modulus of rupture computed as:

$$\text{Flexural strength } (F) = \frac{3PL}{2BD^2}$$

where P is the peak load, L is the effective span (600 mm for the 700 mm mould), and B and D are the breadth and depth of the beam cross-section (150 mm each) (Fig. 6).



Fig. 3: Slump cone test on fresh concrete.



Fig. 4: Thermocol placement at the core of the Beam and cube



Fig. 5: Compressive strength testing of cube specimens during and after the test.



Fig. 6: Three-point flexural strength testing of beam specimen during and after the test.

2.5 Statistical analysis

To determine whether apparent differences across the four core-former ratios reflected genuine effects rather than random specimen-to-specimen variation, each property was analyzed using one-way analysis of variance (ANOVA), with Tukey's honestly significant difference (HSD) post-hoc test applied to identify which specific pairs of ratios differed significantly, and simple linear regression used to quantify the strength of the dose-response trend across the 0–6% EPS range. Effect sizes were reported as η^2 , and a significance threshold of $\alpha = 0.05$ was adopted throughout.

3 Results and discussion

3.1 Workability

Fresh-concrete workability returned slump values of 56 mm for the 0% (control) batch, 60 mm for 4% EPS, 53 mm for 5% EPS, and 48 mm for 6% EPS (Table 4). All four batches fall within, or at the border of, the “medium workability” classification (50–100 mm) defined in IS 456 (IS 456: 2000), confirming that the mix remained of consistent, placeable quality across all four batching operations regardless of core-former content. The slight, non-monotonic dip in slump beyond 4% EPS is consistent with the increasing surface area of embedded spheres per unit volume as the core-former ratio rises: although the spheres themselves absorb negligible water, their presence

locally displaces the flowable cement–aggregate matrix near the specimen mid-depth, marginally reducing the effective flow path measured by the test. The magnitude of this effect, a fall of only 8 mm between the 4% and 6% batches, is small relative to typical batch-to-batch slump variation and indicates that hand compaction quality, rather than any change in the concrete’s intrinsic flow characteristics, was the dominant influence on the final compaction of the cast specimens.

Table 4: Slump (workability) values across core-former ratios.

Batch	EPS ratio	Slump (mm)	IS 456 classification
1	0% (control)	56	Medium
2	4%	60	Medium
3	5%	53	Medium
4	6%	48	Medium

3.2 Water absorption

Water absorption decreased monotonically with increasing EPS ratio: 1.835% (0%), 1.816% (4%), 1.757% (5%), and 1.664% (6%) (Fig. 7). This inverse relationship, though counter-intuitive at first, is explained by a volumetric substitution mechanism rather than by any improvement in the porosity of the surrounding cement paste itself. Thermocol is a closed-cell material with a bulk density of only about 13.5 kg m^{-3} ; its cell walls are essentially impermeable to liquid water over the 24-hour immersion period used in this test. As the volumetric proportion of Thermocol increases from 0% to 6%, an increasing fraction of each specimen’s total volume is occupied by material that cannot absorb water at all, so the volume of porous cement–aggregate matrix available to absorb water necessarily falls. Because the result is expressed as a percentage of the specimen’s own dry weight, and because that dry weight itself falls with increasing EPS content (Section 3.3), the observed percentage decline is best interpreted as a dilution effect superimposed on an essentially unchanged matrix-level permeability, rather than as a genuine improvement of the cement paste’s pore structure. This interpretation is consistent with Ingeli et al. [20], who reported that EPS-filled voided slabs achieve equivalent or superior performance to conventional air-voided systems precisely because the EPS itself contributes no additional absorption pathway. All recorded values remained well below the 3–5% upper limit generally accepted for durable, dense concrete, indicating that the neutral-zone core-former strategy used here does not introduce

a durability penalty, in contrast to hollow-core systems where poor former–concrete bonding at the void perimeter has been reported to increase local ingress [18].

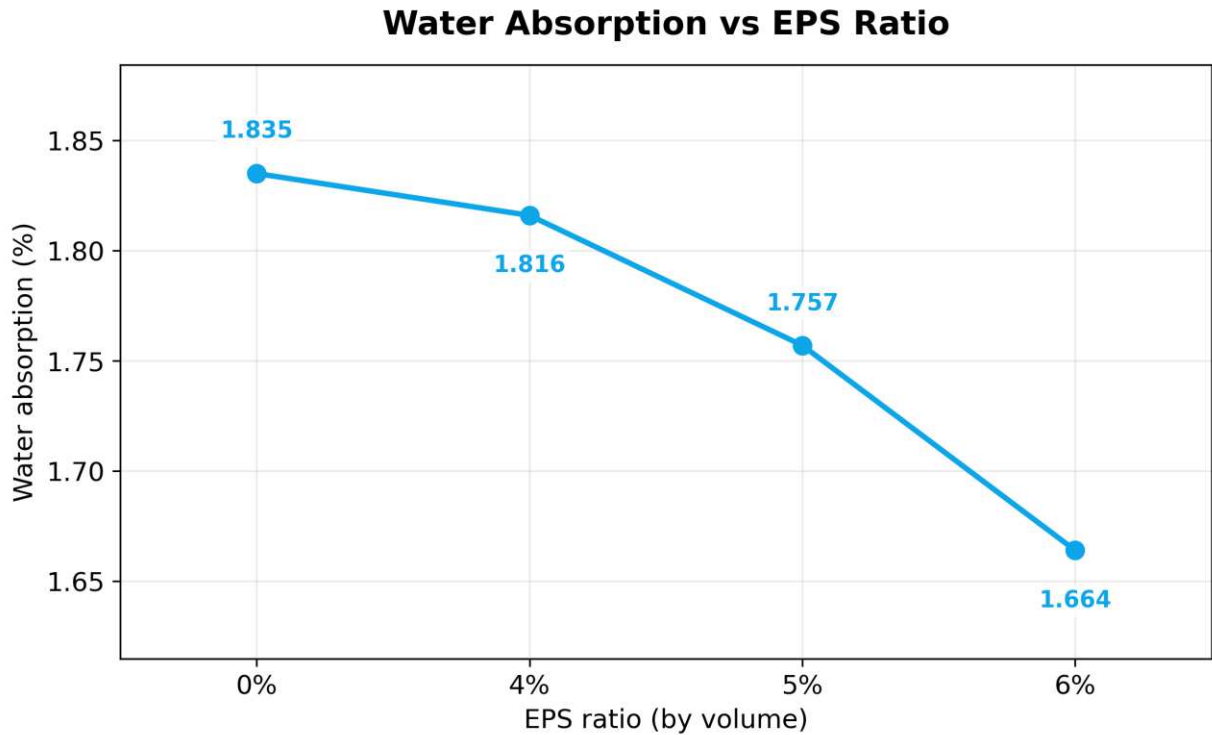


Fig. 7: Water absorption (left) and absorption trend (right) across EPS percentages.

3.3 Density

Average density decreased from $2403.65 \text{ kg m}^{-3}$ at 0% EPS to $2374.62 \text{ kg m}^{-3}$ at 4%, $2336.79 \text{ kg m}^{-3}$ at 5%, and $2314.47 \text{ kg m}^{-3}$ at 6% EPS (Fig. 8), corresponding to reductions of approximately 1.2%, 2.8%, and 3.7% relative to the control. The 0% EPS density closely matches the standard theoretical value for normal-weight concrete ($\approx 2400 \text{ kg/m}^3$), confirming a well-compacted control mix free of significant entrapped air beyond the 1% allowance assumed in the mix design. A simple mass-balance estimate, substituting a near-massless material (13.5 kg m^{-3}) for a matrix of approximately 2400 kg m^{-3} – 2450 kg m^{-3} , predicts a density reduction at 6% substitution of approximately 6.0%, noticeably higher than the 3.7% actually measured. This discrepancy indicates that the true in-situ core-former volume fraction achieved during casting was likely lower than the nominal 6% target, most plausibly because hand compaction locally displaced or partially deformed some spheres, or because the effective sphere volume was slightly overestimated during mix design; this is an inherent limitation of manual core placement that a

fixed positioning jig would help resolve in future work. Even so, a measured reduction of up to 89 kg m⁻³ translates, when scaled to a full structural slab or multi-storey frame, into a meaningful reduction in the dead load transmitted to beams, columns, and foundations. This reduction is comparatively modest next to the 15–50% dead-load savings reported for larger-diameter or more numerous void formers ([14]; [27]); the difference reflects the deliberately conservative 4–6% core-former ratio adopted here to protect flexural capacity (Section 3.5), rather than any inherent limitation of the spherical Thermocol former itself.

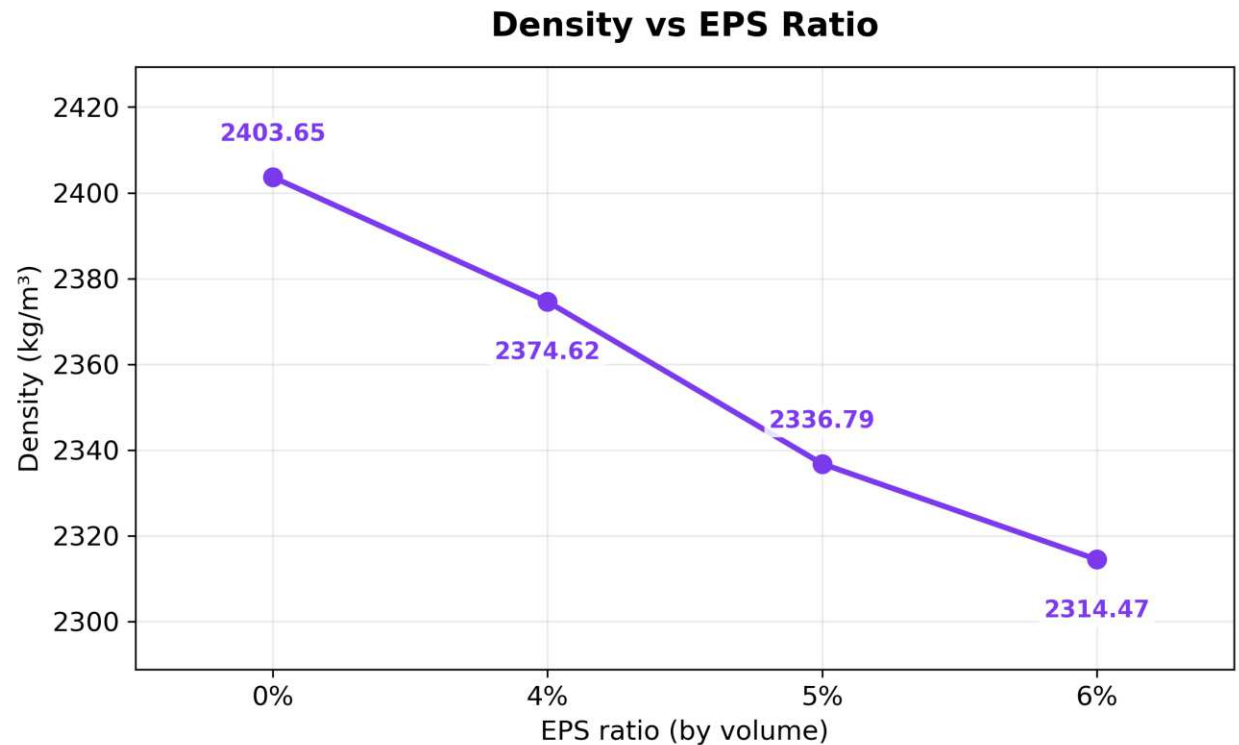


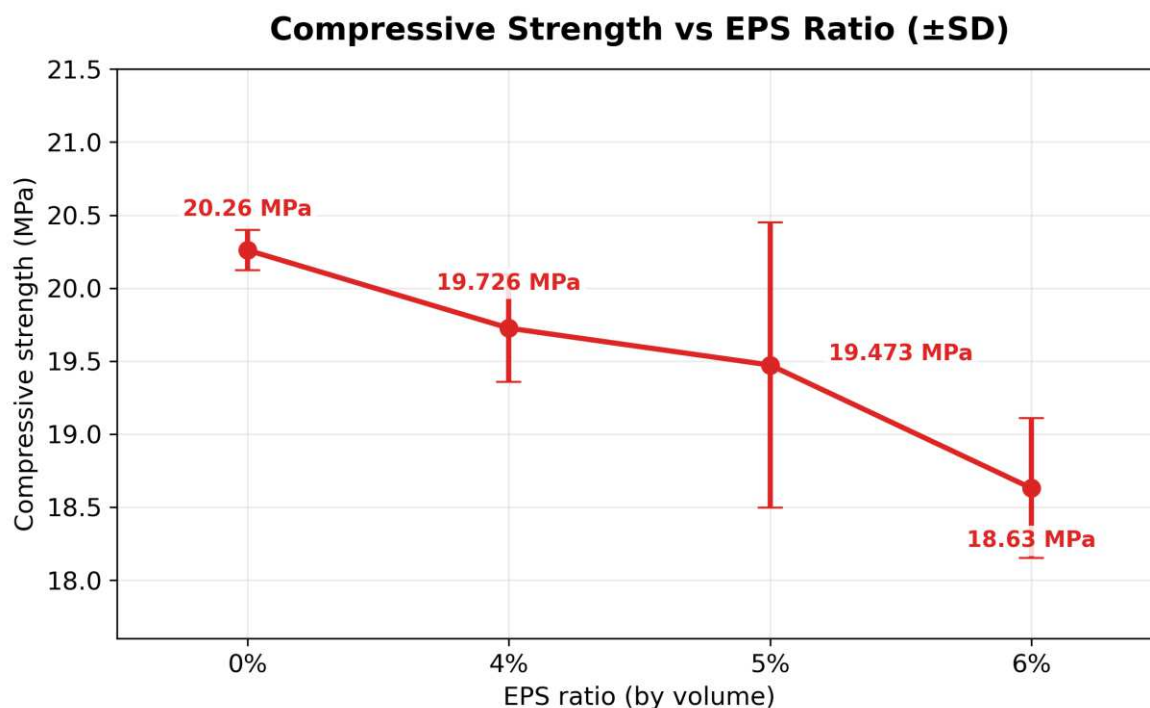
Fig. 8: Average density and density reduction trend across EPS percentages.

3.4 Compressive strength

The 28-day compressive strength of the control mix (20.260 ± 0.138 MPa) satisfied the M20 characteristic strength target, with a coefficient of variation of only 0.68%, indicating a well-controlled control batch. Strength decreased to 19.726 ± 0.368 MPa (4% EPS), 19.473 ± 0.978 MPa (5% EPS), and 18.630 ± 0.479 MPa (6% EPS) (Table 5; Fig. 9), corresponding to reductions of 2.63%, 3.95%, and 8.05% relative to the control.

Table 5: Compressive strength of cube specimens by EPS percentage.

EPS (%)	Avg. strength (MPa)	SD	SE	CV (%)
0	20.260	0.138	0.079	0.68
4	19.726	0.368	0.213	1.87
5	19.473	0.978	0.565	5.02
6	18.630	0.479	0.287	2.66



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Fig. 9: Compressive strength and strength reduction trend across EPS percentages.

One-way ANOVA indicated a marginally non-significant overall effect of EPS content on compressive strength ($F(3,8) = 3.90$, $p = 0.055$, $\eta^2 = 0.594$; Table 6; Fig. 10), and Tukey's HSD post-hoc comparisons confirmed that only the 6% EPS group differed significantly from the control ($p = 0.040$; Table 7; Fig. 11); the 4% and 5% groups were statistically indistinguishable from the control ($p = 0.688$ and $p = 0.405$, respectively) despite their numerically lower mean strength. Linear regression nonetheless confirmed a strong overall negative trend across the full range ($R^2 = 0.797$, slope -0.231 MPa per 1% EPS; Table 8; Fig. 12). This distinction is important for design interpretation: at 4–5% EPS, the apparent strength loss lies within the range

attributable to ordinary specimen-to-specimen variability rather than to a genuine, reproducible weakening of the mix, whereas the loss at 6% EPS is a statistically confirmed effect.

Table 6: One-way ANOVA of cube compressive strength.

Source	SS	df	MS	F	p
Between groups	3.978	3	1.326	3.90	0.055
Within groups	2.718	8	0.340	–	–
$\eta^2 = 0.594$					

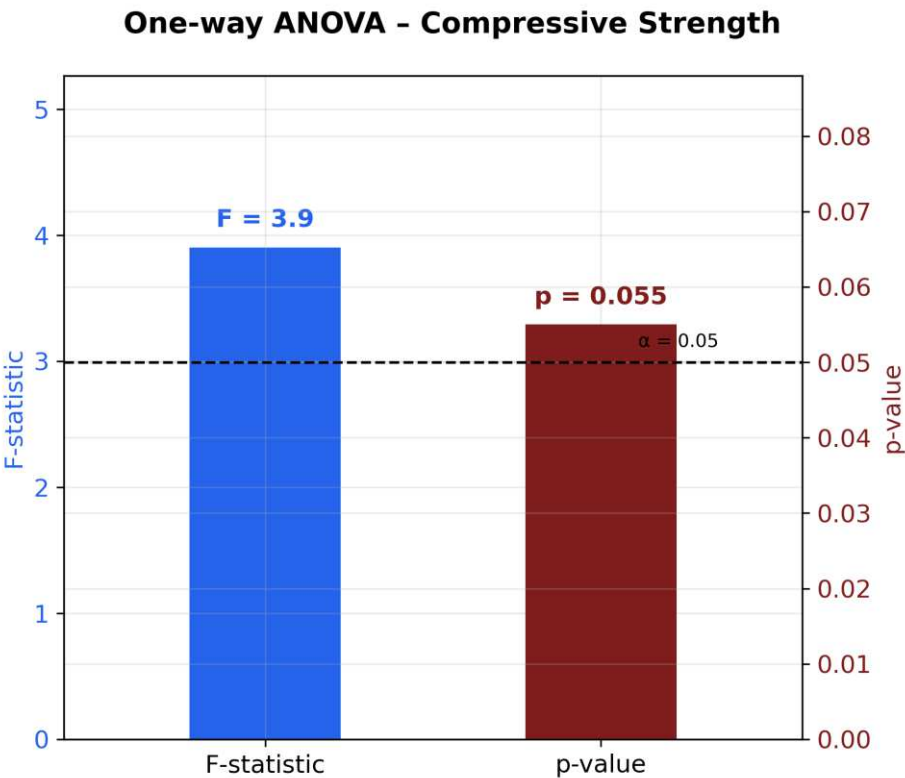


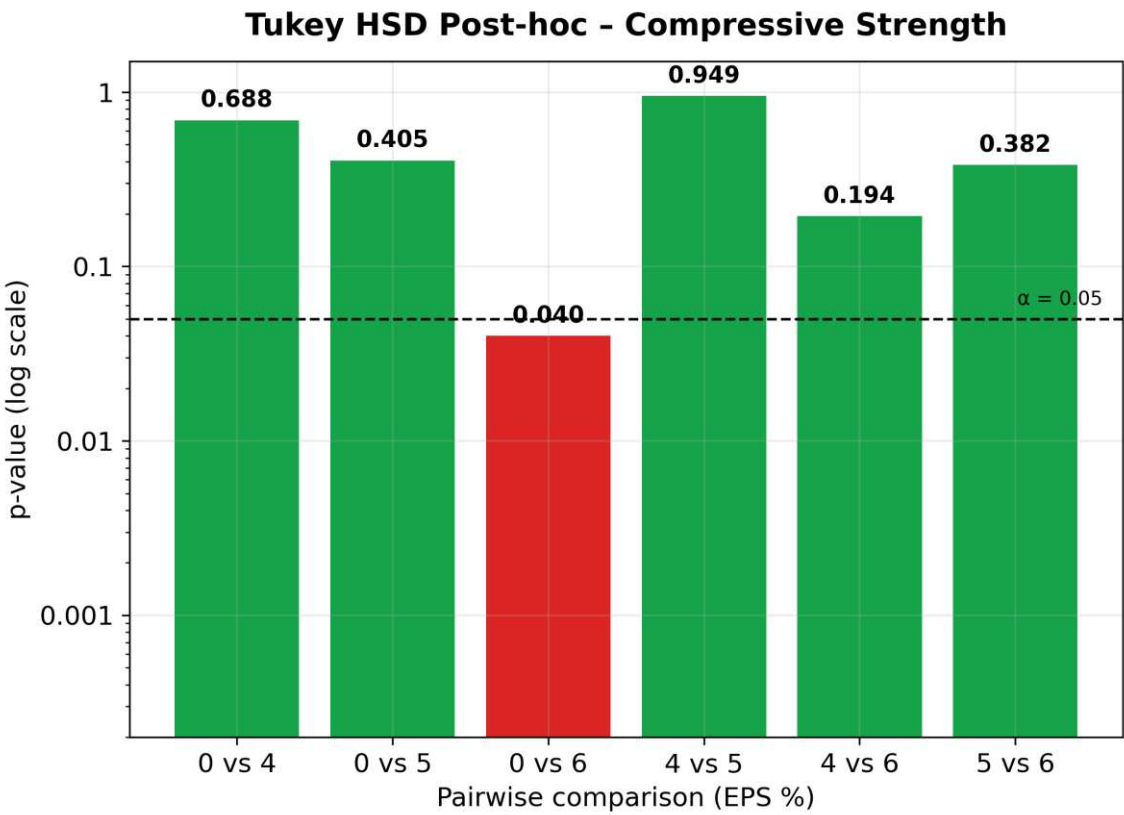
Fig. 10: One-way ANOVA of cube compressive strength

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Table 7: Tukey HSD post-hoc comparisons of cube compressive strength.

Comparison	Mean diff. (MPa)	<i>p</i>	Sig.
0% vs 4%	0.533	0.688	ns
0% vs 5%	0.787	0.405	ns
0% vs 6%	1.597	0.040	*
4% vs 5%	0.253	0.949	ns
4% vs 6%	1.063	0.194	ns
5% vs 6%	0.810	0.382	ns



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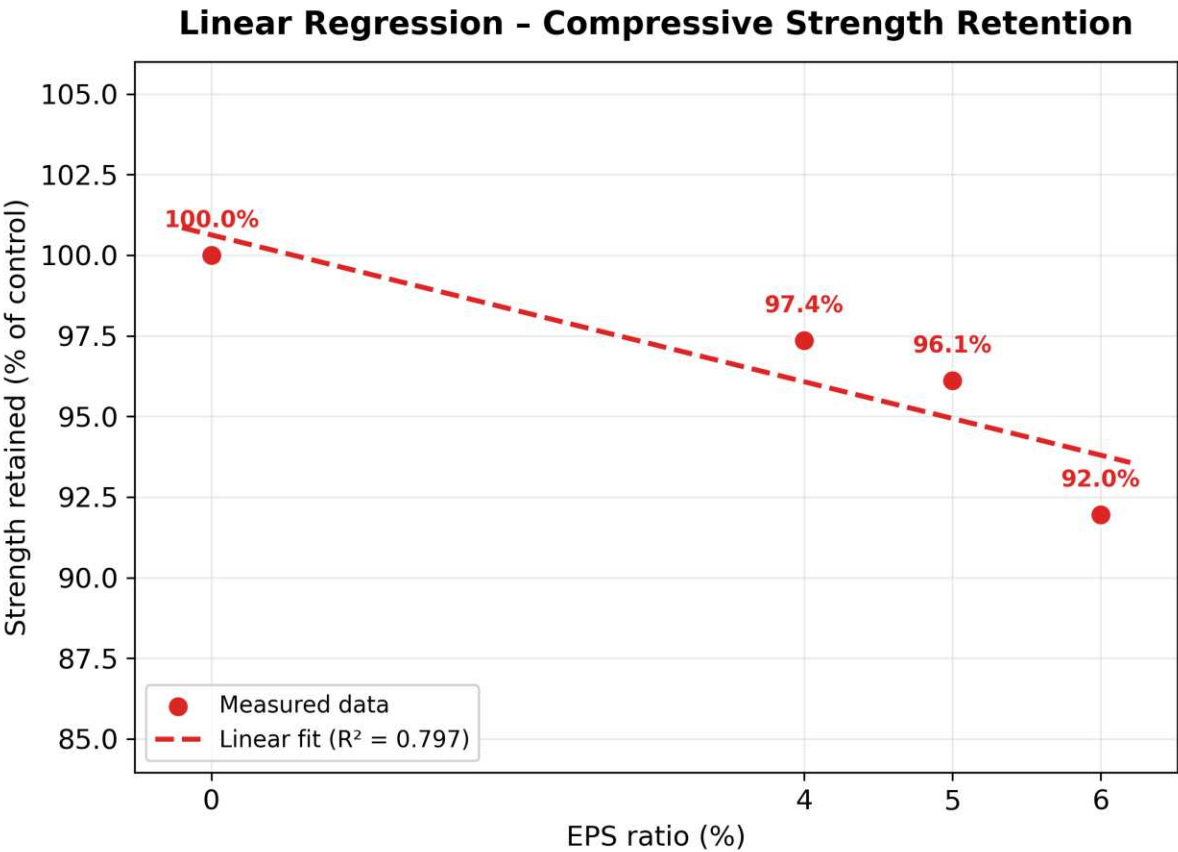
Fig. 11: Tukey HSD post-hoc comparisons of cube compressive strength.

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Table 8: Linear regression of compressive strength on EPS content.

Slope	Intercept	R^2	p
-0.231	20.387	0.797	0.107



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Fig. 12: Linear regression of compressive strength on EPS content.

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The mechanism underlying this pattern is the progressive loss of effective load-bearing cross-section and the introduction of a geometric stress raiser at the sphere–matrix interface. Under uniaxial compression, load is transferred through the dense cement–aggregate matrix; the presence of a rigid-but-far-more-compliant Thermocol sphere forces the principal compressive stress trajectories to detour around its equator, producing a local stress concentration that initiates micro-cracking earlier than in a homogeneous section. Because the spheres in the cube specimens are positioned at mid-height, close to the primary diagonal shear-compression failure planes typical of cube crushing tests, they intersect the dominant failure mechanism more directly than an

equivalent former would in an unreinforced beam under pure bending, which is one reason compressive strength is more sensitive to core placement than neutral-zone theory alone would suggest. This finding is broadly consistent with Al-gasham et al. [22], who found negligible ultimate-strength loss for polystyrene balls sized at 50% of the member depth but reported 17.7–21.3% reductions for larger balls, and with Mahdi and Ismael [14], who reported ultimate strength reductions of 6.5–17.1% with increasing longitudinal void diameter; the 8.05% reduction observed here at 6% EPS falls within this same range despite the difference in loading configuration (cube crushing versus slab bending), suggesting that the ball-to-specimen-depth ratio, rather than the loading type, is the dominant geometric parameter governing strength retention. It is also markedly smaller than the reductions reported by Gyawali [21] for EPS bead-mixed lightweight concrete, in which EPS is dispersed throughout the entire matrix rather than confined to a single, defined location; this comparison supports the central premise of the present study, that concentrating the core former exclusively at the neutral zone preserves substantially more compressive capacity than distributing an equivalent EPS volume throughout the mix.

3.5 Flexural strength

The 28-day flexural strength (modulus of rupture) of the unreinforced control beam averaged $5.835 \pm 0.118 \text{ N/mm}^2$. Flexural strength decreased to $5.382 \pm 0.445 \text{ N/mm}^2$ (4% EPS, –7.8%), $4.419 \pm 0.312 \text{ N/mm}^2$ (5% EPS, –24.3%), and $4.189 \pm 0.060 \text{ N/mm}^2$ (6% EPS, –28.2%) (Table 9; Fig. 13).

Table 9: Flexural strength of beam specimens by EPS percentage.

EPS (%)	Avg. (N/mm^2)	SD	SE	CV (%)
0	5.835	0.118	0.068	2.03
4	5.382	0.445	0.257	8.27
5	4.419	0.312	0.180	7.07
6	4.189	0.060	0.034	1.42

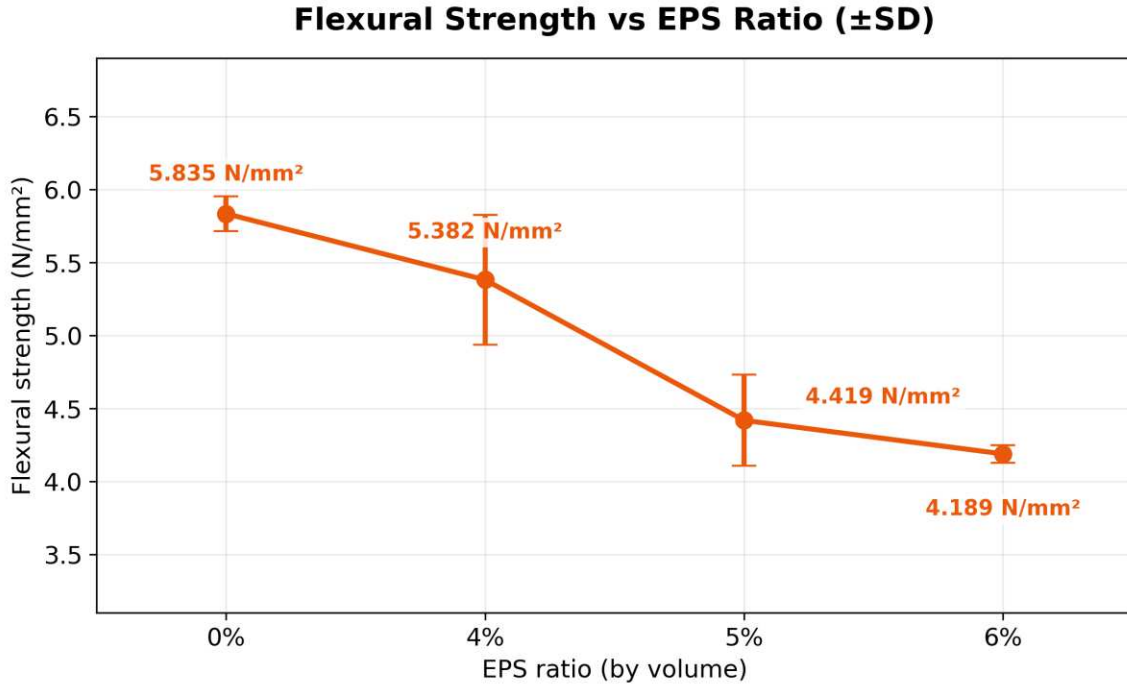


Fig. 13: Flexural strength and strength reduction trend across EPS percentages.

Unlike the compressive strength result, one-way ANOVA revealed a highly significant overall effect of EPS content on flexural strength ($F(3,8) = 22.33, p < 0.001, \eta^2 = 0.898$; Table 10; Fig. 14), and Tukey's HSD post-hoc comparisons confirmed that flexural strength at 5% and 6% EPS was significantly lower than the control ($p = 0.001$ and $p < 0.001$, respectively), and that even the 4% EPS group differed significantly from both the 5% and 6% groups ($p = 0.013$ and $p = 0.004$); only the 0% vs 4% and 5% vs 6% comparisons were non-significant (Table 11; Fig. 15). Linear regression confirmed a strong negative trend ($R^2 = 0.822$, slope -0.269 N/mm^2 per 1% EPS; Table 12; Fig. 16), a rate proportionally steeper than the corresponding compressive-strength slope once each is normalised against its own control-specimen mean.

Table 10: One-way ANOVA of beam flexural strength.

Source	SS	df	MS	F	p
Between groups	5.492	3	1.831	22.33	< 0.001
Within groups	0.656	8	0.082	–	–

$$\eta^2 = 0.898$$

One-way ANOVA - Flexural Strength

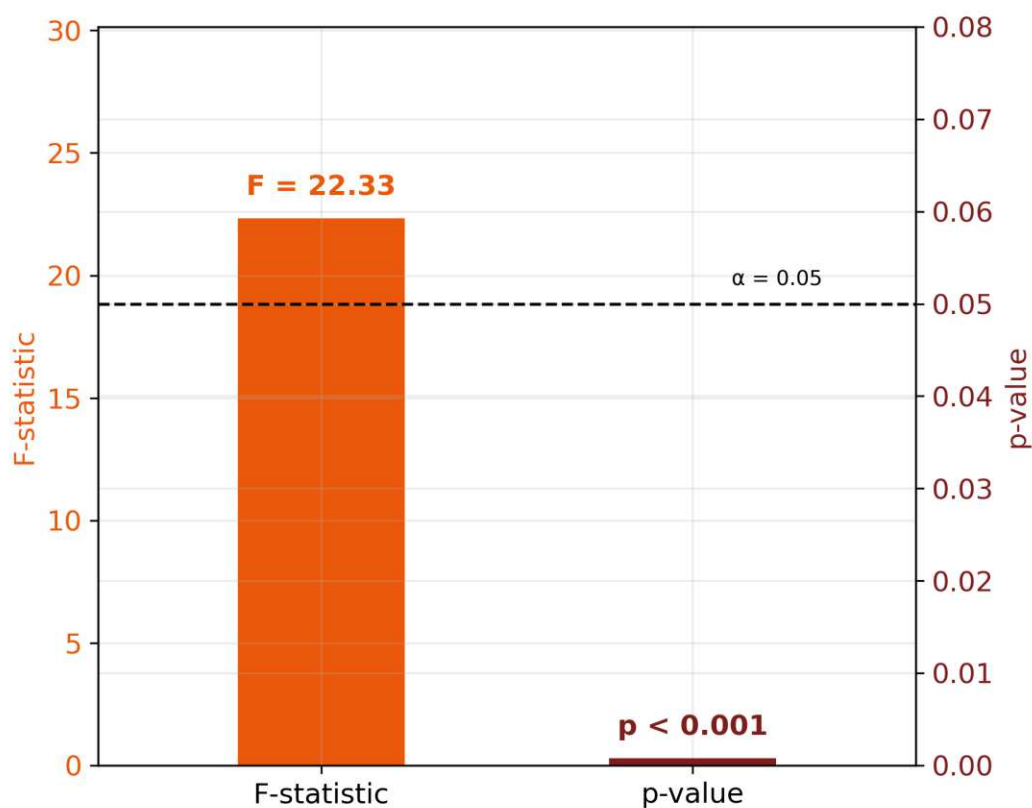


Fig. 14: One-way ANOVA of beam flexural strength.

Table 11: Tukey HSD post-hoc comparisons of beam flexural strength.

Comparison	Mean diff. (N/mm^2)	p	Sig.
0% vs 4%	0.453	0.270	ns
0% vs 5%	1.416	0.001	**
0% vs 6%	1.646	< 0.001	***
4% vs 5%	0.963	0.013	*
4% vs 6%	1.193	0.004	**
5% vs 6%	0.229	0.752	ns

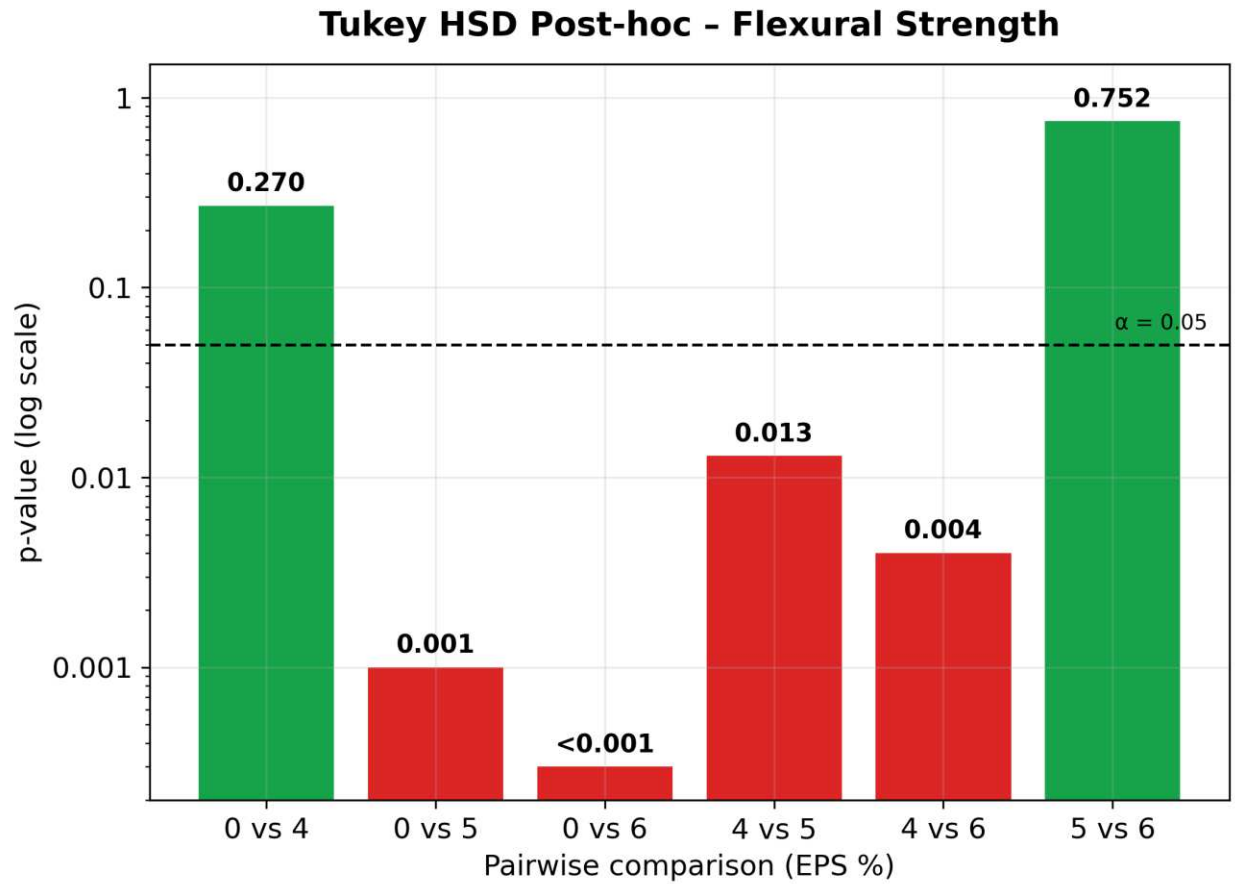


Fig. 15: Tukey HSD post-hoc comparisons of beam flexural strength.

Table 12: Linear regression of flexural strength on EPS content.

Slope	Intercept	R^2	p
-0.269	5.966	0.822	0.094

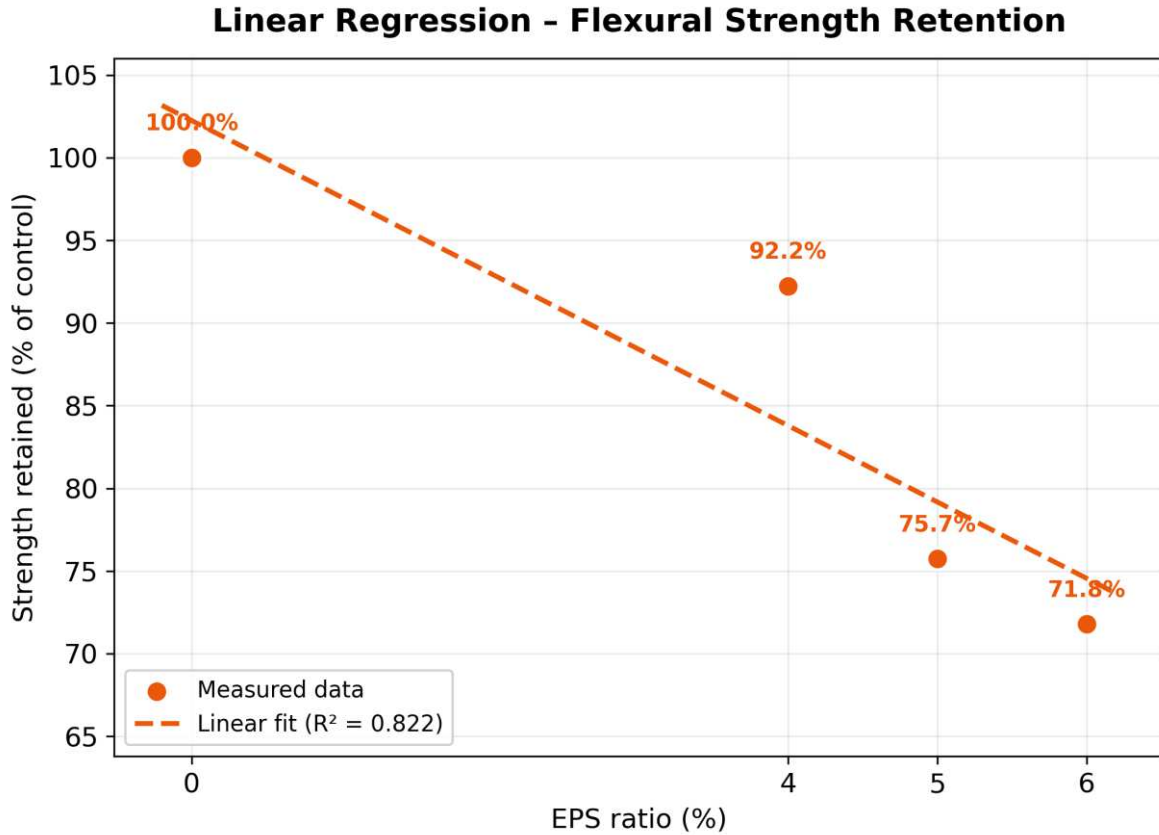


Fig. 16: Linear regression of flexural strength on EPS content

This steeper, statistically robust decline reflects the specific mechanics of the three-point bending test rather than a failure of the neutral-zone placement strategy. Although pure bending stress is theoretically zero exactly at the neutral zone, the beam geometry tested here—150 mm depth over a 600 mm effective span, loaded centrally—generates substantial vertical shear stress and diagonal tension in the region immediately surrounding the load point, a zone that necessarily overlaps the neutral-zone core formers positioned along the beam’s mid-length. The Thermocol spheres therefore act as shear-plane stress concentrators exactly where diagonal cracking is most likely to initiate, which explains why flexural capacity is lost more steeply, and more reproducibly, than compressive capacity. This is consistent with Cho et al. [17], who found that higher hollow-core ratios specifically increase vulnerability under shear loading, and with Mahdi and Ismael [14], who reported ultimate flexural strength reductions of 6.5–17.1% and corresponding deflection increases of 8.7–28.3% with increasing void diameter in one-way hollow-core slabs, a pattern of accelerating loss at larger void fractions that mirrors the disproportionate jump observed here between 4% (–7.8%) and 5% EPS (–24.3%). Nonetheless, from a design-code perspective the result remains

favourable: even the weakest EPS-embedded beam (6% EPS, 4.189 N/mm^2) exceeded the IS 456 (IS 456: 2000) theoretical flexural strength requirement for M20 concrete ($0.7\sqrt{f_{ck}} \approx 3.13 \text{ N/mm}^2$) by a margin of over 33%, and in practical construction these members would be reinforced with steel rebar carrying the primary tensile load, so the plain-concrete flexural reduction reported here represents a conservative, worst-case bound on the behaviour of a reinforced voided member.

3.6 Flexural-to-compressive strength ratio and structural significance

The flexural-to-compressive strength ratio declined from 28.80% at 0% EPS to 27.28% (4%), 22.69% (5%), and 22.49% (6%) (Table 13; Fig. 17), confirming numerically what the differing statistical significance of the two properties already indicated: flexural strength is substantially more sensitive to neutral-zone EPS incorporation than compressive strength. The ratio falls sharply between 4% and 5% EPS, a drop of 4.6 percentage points, but is essentially flat between 5% and 6%, a drop of only 0.2 percentage points, mirroring the plateau in the raw flexural data and the non-significant 5% vs 6% Tukey comparison ($p = 0.752$, Table 11). This plateau is engineering-significant: it suggests that once the core former's shear-plane interference effect is fully mobilised, at or before 5% EPS, further modest increases in core-former ratio impose comparatively little additional flexural penalty, even though compressive strength continues to decline with EPS content. This asymmetry is the practical basis for identifying 4–5% EPS as the optimal design range: below this range dead-load savings are limited, while above it, additional core-former content yields disproportionately little flexural benefit relative to the compressive strength surrendered.

Table 13: Flexural-to-compressive strength ratio across EPS percentages.

EPS (%)	Flexural (N/mm^2)	Compressive (MPa)	Ratio (%)
0	5.835	20.260	28.80
4	5.382	19.726	27.28
5	4.419	19.473	22.69
6	4.189	18.630	22.49

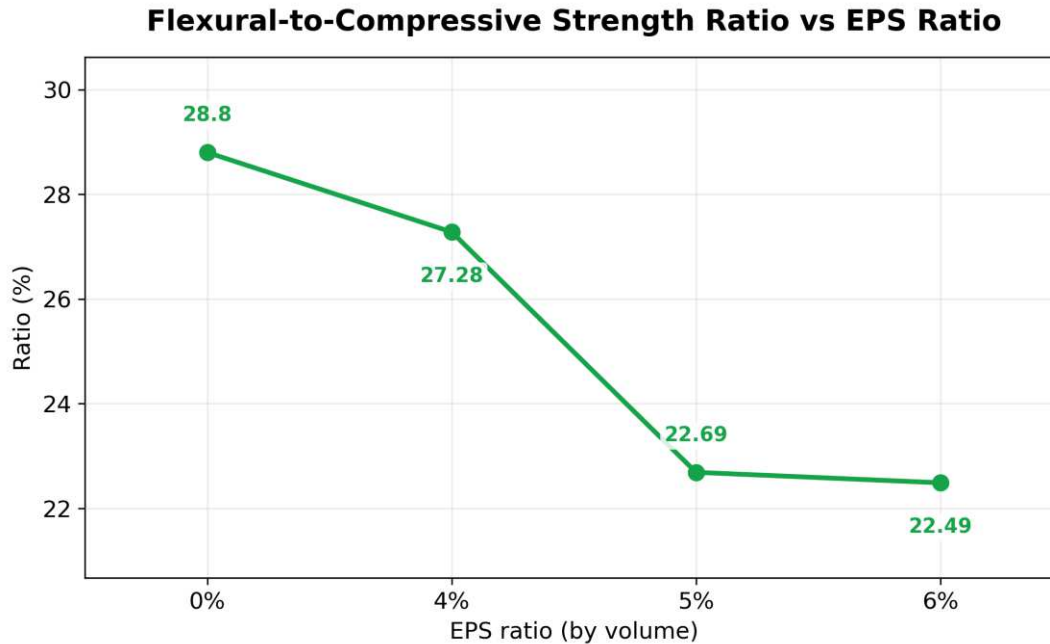


Fig. 17: Flexural-to-compressive strength ratio across EPS percentages.

3.7 Engineering significance, practical implications, and limitations

Taken together, the results support the use of spherical, waste-derived Thermocol core formers confined to the neutral zone as a mechanically efficient alternative to both proprietary biaxial void systems and EPS-bead-mixed lightweight concrete. Compared with proprietary systems such as Bubble Deck or Cobiax, which rely on manufactured plastic components not economically accessible in Nepal, the present approach uses freely available factory-reject Thermocol and simple hand tools, at the cost of a less tightly controlled core-former geometry, evidenced by the discrepancy between the nominal and mass-balance-inferred core-former volume fractions noted in Section 3.3. Compared with EPS bead-mixed concrete [21], which reported substantial reductions in workability, density, compressive strength, flexural strength, split-tensile strength, and Young's modulus even at moderate EPS contents, the neutral-zone placement strategy evaluated here retains statistically indistinguishable compressive strength up to 5% EPS, and flexural strength that, while significantly reduced, remains comfortably above the IS 456 (IS 456: 2000) design threshold at every tested ratio. Because the core former displaces concrete from a zone that theoretically carries minimal bending stress, its structural cost is paid disproportionately in the shear-affected zones near point loads rather than uniformly across the whole section—a distinction that is only visible when compressive and flexural behaviour are examined, and

statistically tested, separately, as done here. For practical slab or beam design in seismically vulnerable regions [9], a 4–5% EPS ratio can reduce structural dead load by several percent without a statistically confirmed compressive strength penalty, while requiring that conventional steel reinforcement be detailed with awareness of the locally reduced shear capacity near core formers positioned close to point loads or support regions.

Several limitations bound the interpretation and motivate further work. First, the manual core-placement method introduced variability between the nominal and achieved core-former volume fractions; a fixed positioning jig or spacer frame is recommended to eliminate this discrepancy. Second, only plain, unreinforced specimens were tested, so the flexural reductions reported here represent conservative bounds on reinforced member behavior. Third, long-term durability, creep, thermal performance, and seismic response under cyclic loading remain unquantified, and a detailed cost-efficiency analysis against proprietary voided systems is required before field deployment.

4 Conclusions

This study experimentally evaluated the use of waste Thermocol spheres as a structural core former positioned at the neutral zone of M20-grade concrete cubes and beams across EPS ratios of 0%, 4%, 5%, and 6%, and is, to the authors' knowledge, the first to combine an indigenous waste-derived spherical core former, deliberate neutral-zone placement, and inferential statistical validation of the resulting dose–response relationships. The principal findings are as follows.

(1) Density decreased progressively with EPS ratio, from $2403.65 \text{ kg m}^{-3}$ (0%) to $2314.47 \text{ kg m}^{-3}$ (6%), confirming effective dead-load reduction without altering external specimen dimensions, while water absorption decreased from 1.835% to 1.664% over the same range, indicating that the closed-cell, hydrophobic Thermocol spheres do not compromise, and may marginally assist, resistance to moisture ingress. (2) Compressive strength decreased progressively with EPS content, from $20.260 \pm 0.138 \text{ MPa}$ at 0% to $18.630 \pm 0.479 \text{ MPa}$ at 6%, but one-way ANOVA and Tukey's HSD testing showed that only the 6% EPS group differed significantly from the control ($p = 0.040$); the 2.63% and 3.95% reductions observed at 4% and 5% EPS were not statistically distinguishable from ordinary specimen variability. (3) Flexural strength declined more steeply and significantly ($F(3,8) = 22.33, p < 0.001$) by 7.8%, 24.3%, and 28.2% at 4%, 5%, and 6%

EPS respectively, a pattern attributed to shear-plane stress concentration around the core formers near the beam's load point rather than to a failure of the neutral-zone placement strategy; even so, every tested EPS ratio exceeded the IS 456 (IS 456: 2000) theoretical flexural strength requirement for M20 concrete by a comfortable margin. (4) On the basis of the statistically confirmed compressive strength retention and the flattening of the flexural-to-compressive strength ratio between 5% and 6% EPS, a 4–5% EPS ratio is identified as the statistically optimal balance between dead-load reduction and retained mechanical capacity.

These findings support neutral-zone Thermocol core formers as a viable, low-cost, and environmentally beneficial lightweight construction technique, particularly relevant to regions such as Nepal, where EPS packaging waste is abundant and structural dead-load reduction is a priority for seismic safety. Nevertheless, future work must address the long-term durability and creep performance of EPS-embedded concrete under sustained load; the behavior of reinforced, rather than plain, EPS-embedded slabs and beams, including shear and punching-shear resistance in the presence of steel reinforcement; thermal performance and energy-efficiency implications; seismic performance under cyclic loading; and a detailed cost-efficiency analysis comparing Thermocol-EPS-embedded construction with conventional and proprietary voided slab systems.

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Author Contribution:

Rojan Subedi: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Suraj Khanal:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Suman Shrestha:** Investigation, Data curation. **Sulav Dhamala:** Investigation, Data curation. **Sumesh Pathak:** Investigation, Visualization. **Sandip Kumar Shrestha:** Investigation, Visualization. **Paribesh Timsina:** Supervision, Conceptualization, Methodology, Writing-review and editing **Bishwash Poudel:** Supervision, Conceptualization, Methodology, Writing – review & editing.

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