

Mechanical Characterization of Concrete Reinforced with Sisal Fibers and Expanded Polystyrene Aggregates

Mercy S. OMEIFE^{1*}, Toyin Y. AKANBI², Peace D. PAUL³

^{1*,2,3}Department of Civil and Environmental Engineering, Faculty of Ground and Communication Engineering, Air Force Institute of Technology, Kaduna, Nigeria

^{1*}mercysomhtoh@gmail.com, ²tyakanbi@afit.edu.ng, ³peacefdpaul@gmail.com

Abstract

Concrete remains the backbone of construction because nothing else carries compressive load as reliably, but two weaknesses persist: it is heavy, and it fails suddenly once its tensile capacity is exceeded. These weaknesses limit its use where a lighter dead load and better crack tolerance matter. This study evaluated the mechanical properties of concrete reinforced with sisal fiber and modified with Expanded Polystyrene (EPS) lightweight aggregate to determine whether a fixed dosage of a cheap, locally available natural fiber could offset the strength lost to EPS substitution. Seven concrete mixes (C0 to C5) were produced at a constant 0.5% sisal fiber dosage while EPS replaced coarse aggregate by volume at 0, 5, 10, 15, 20, and 25%. The fine aggregate was first characterized, returning a fineness modulus of 1.84 and a specific gravity of 2.56, before the mixes were cast and tested for slump, fresh and hardened density, water absorption, and compressive strength at 7, 14, and 28 days. Workability fell from 73 mm (S2 class) in the control mix to 42 mm (S1 class) at 25% EPS replacement, a 42% reduction, while 28-day hardened density declined from 2403 kg/m³ to 1848 kg/m³, a 23.1% reduction that placed the two highest-replacement mixes within the lightweight concrete classification. Water absorption more than doubled, from 2.5% to 5.9%, and 28-day compressive strength dropped from 27.2 MPa to 19.6 MPa, a near-linear loss of about 1.5 MPa for every 5% increment of EPS added. The 0.5% sisal fiber addition produced only minor effects on workability and absorption and did not measurably offset this strength loss at any replacement level tested. Concrete containing 5–10% EPS is therefore recommended for semi-structural, lightly loaded elements, while mixes above 15% EPS are better suited to non-structural applications such as partition panels and insulation blocks.

Keywords: Sisal fiber, expanded polystyrene, lightweight concrete, compressive strength, water absorption.

1.0 Introduction

Concrete is produced by binding fine and coarse aggregate together with a hydraulic cement paste activated by water, and once hardened it carries compressive load well while remaining brittle in tension [1]. Because of this imbalance, most structural applications pair it with steel reinforcement, a combination that underpins the bulk of the world's buildings, bridges and pavements [2]. Plain concrete nonetheless carries real drawbacks: it is heavy, it fails abruptly once its limited tensile capacity is exceeded, and cement production accounts for a significant share of global industrial carbon emissions [3], [4]. These concerns have pushed research in two directions at once - reinforcing the cement matrix with dispersed fibers to improve toughness and crack resistance, and replacing part of the aggregate with lightweight materials such as Expanded Polystyrene (EPS) to reduce density and improve thermal performance.

Sisal (*Agave sisalana*) is among the most widely studied natural fibers for cement composites because it is cheap, locally available across much of the tropics, and offers a reasonable strength-to-weight ratio. As short discrete fibers, sisal bridges microcracks as they form and improves tensile and flexural behavior, though it is vulnerable to alkaline attack from the cement paste over time and its performance depends heavily on dosage and dispersion quality [5]. EPS, by contrast, works by removing weight rather than adding tensile capacity: replacing a portion of the coarse aggregate with EPS beads lowers density and improves thermal insulation, but EPS is far softer than natural aggregate, and stiffness and strength fall as its proportion in the mix rises [6], [7].

These two strategies are rarely studied together. Shah et al. combined EPS with steel fiber and found that fiber addition shifted the density-strength trade-off in the mix's favor, identifying 15% EPS with 2% steel fiber as an optimal balance point [8]. Whether a low-cost natural fiber such as sisal can achieve a comparable effect at a much lower dosage has not been established. Maghfouri et al., reviewing EPS lightweight concrete broadly, identified weak bonding at the EPS-paste interface, rather than the intrinsic weakness of the EPS material itself, as the dominant mechanism behind strength loss [9], a finding echoed by El-Mir et al. [6] and Hameed et al. [7], who positioned EPS-modified material specifically for masonry-unit and infill-wall applications rather than primary structural use.

Acosta-Calderon et al., comparing sisal and polypropylene fiber reinforcement under otherwise identical mix conditions, found that sisal fiber concrete showed reduced workability relative to plain concrete but delivered a toughness benefit broadly comparable to synthetic fiber at an equivalent dosage [10]. Beskopylny et al. similarly

reported that dispersed sisal fiber enhanced mechanical performance up to an optimal dosage of 1% by weight of cement, beyond which the added fiber's water demand outpaced the available cement paste and strength gains declined [11]. What the existing literature does not establish is how sisal fiber's crack-bridging contribution behaves as the surrounding matrix becomes progressively more compressible with increasing EPS content, and at what replacement level, if any, the combination stops making practical sense.

This study addresses that gap directly. The specific objectives were to determine the physical properties of the constituent materials; to determine the fresh properties of concrete produced with a fixed 0.5% sisal fiber dosage and EPS aggregate at 0, 5, 10, 15, 20, and 25% replacement; and to determine the hardened mechanical properties of the resulting mixes at 7, 14, and 28 days of curing.

2.0 Materials and Methods

2.1 Materials

Water was sourced from the Air Force Institute of Technology campus supply and was visually clear and free of suspended solids. Ordinary Portland cement was used throughout and stored in a dry environment before use. Fine aggregate consisted of natural river sand passing a 4.75 mm sieve, sourced locally and air-dried before use, and was free of clay and organic matter. Coarse aggregate was crushed granite of 12 mm maximum nominal size, obtained locally and used dry. Recycled EPS, cleaned and dried before use, was substituted for a portion of the coarse aggregate by volume. Sisal fiber was sourced from Kawo market, Kaduna State, and cut into 10-20 mm lengths for uniformity during mixing; the fiber was used raw and untreated.

2.2 Mix Design

Seven mixes were prepared at a 1:1.5:3 ratio (cement: fine aggregate: coarse aggregate) for M20 concrete, with cement content fixed at 3.5 kg and fine aggregate at 5.25 kg per batch. Sisal fiber was held constant at 0.5% by weight of cement across six of the seven mixes, while EPS replaced coarse aggregate by volume at 0, 0, 5, 10, 15, 20, and 25% for mixes C0, C0₁, C₁, C₂, C₃, C₄, and C₅, respectively, as summarized in Table 1.

Table 1: Concrete mix proportions

Mix	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Sisal fiber (%)	Eps (%)
C0 (Control)	3.5	5.25	10.50	0	0
C0 ₁	3.5	5.25	10.50	0.5	0
C ₁	3.5	5.25	9.98	0.5	5
C ₂	3.5	5.25	9.45	0.5	10
C ₃	3.5	5.25	8.93	0.5	15
C ₄	3.5	5.25	8.40	0.5	20
C ₅	3.5	5.25	7.88	0.5	25

2.3 Physical Property Tests

2.3.1 Sieve Analysis

Sieve analysis determined the particle size distribution of the fine aggregate in accordance with BS 812-103.1:1985 [12], using a 500 g air-dry sample passed through sieves from 4.75 mm to 75 μ m. The fineness modulus was computed as the sum of cumulative percentages retained divided by 100.

2.3.2 Specific Gravity Test

The specific gravity of the fine aggregate was determined using the pycnometer method in accordance with BS 1377:1990[23], from the weights of the empty pycnometer, the pycnometer with sand, the pycnometer with sand and water, and the pycnometer with water alone.

2.4 Fresh Property Test

2.4.1 Workability (Slump) Test

The slump cone test was used to assess the workability of the fresh concrete in accordance with BS EN 12350-2:2019 [13]. The cone was filled in three layers, each tamped 25 times, struck off level, and lifted vertically; the vertical drop of the slumped mortar from the original cone height was recorded as the slump value.

2.4.2 Density Test (Fresh and Hardened)

Fresh density was determined by weighing a container of known volume filled with compacted fresh concrete, while hardened density was determined at 7, 14, and 28 days by weighing cured cube specimens of known volume, both in accordance with BS EN 12390-7:2019 [14].

2.5 Hardened Mechanical Property Tests

2.5.1 Water Absorption Test

Water absorption was assessed on 100 mm cube specimens in accordance with BS 1881-122:2011 [15]. Specimens were oven-dried to constant weight, the dry weight recorded, then submerged in water for 24 hours before the saturated surface weight was recorded. Water absorption was calculated as the percentage increase in weight relative to the dry weight.

2.5.2 Compressive Strength Test

Compressive strength was determined on 100 mm cube specimens at 7, 14, and 28 days of water curing in accordance with BS EN 12390-3:2019 [16], with load applied gradually until failure and strength computed as the failure load divided by the specimen's cross-sectional area.

3.0 Results and Discussion

3.1 Physical Properties of the Fine Aggregate

3.1.1 Sieve Analysis

The fine aggregate returned a fineness modulus of 1.84, placing it within the fine grading classification under BS 882:1992, where FM typically spans 1.6 to 2.4 for fine river sands [17], and consistent with the range reported by Wilson *et al.* for aggregates sourced across Kaduna State [18].

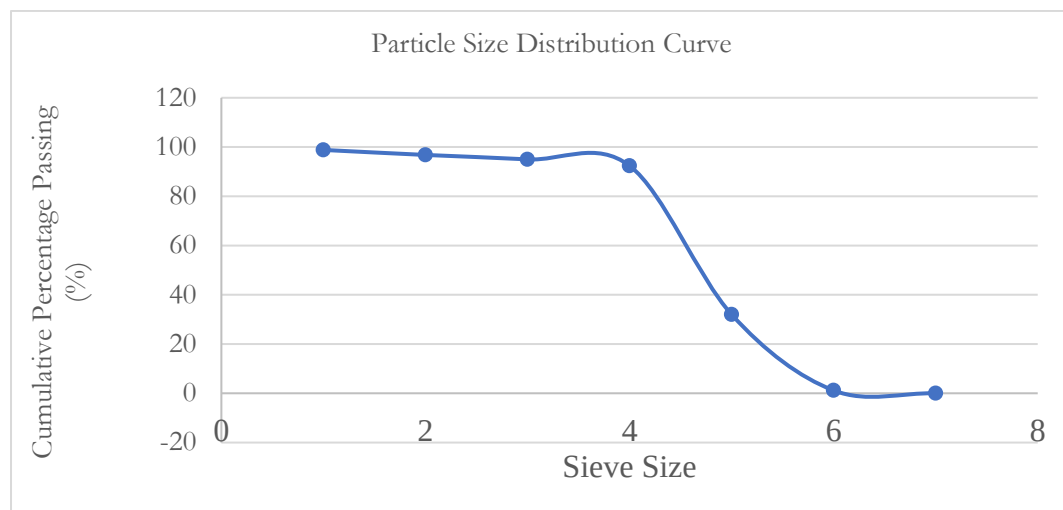


Figure 1: Particle size distribution curve for the fine aggregate

3.1.2 Specific Gravity Test

The fine aggregate averaged a specific gravity of 2.56 across three trials (Table 2), within the normal 2.5–2.7 range for natural sand under BS 882:1992 and consistent with quartz-dominated river sands typical of Nigerian river basins [19]. This value is the density reference point against which the EPS-driven density reductions discussed in Section 3.3 are measured, since EPS beads sit close to two orders of magnitude below it.

Table 2: Specific gravity results for the fine aggregate

Test Number	1	2	3
Weight of pycnometer jar (W_1)	31.20g	31.30g	31.40g
Weight of jar + fine aggregate sample (W_2)	59.20g	71.10g	65.40g
Weight of jar + fine aggregate sample + water (W_3)	100.00g	107.70g	103.90g
W_4 (Weight of jar + water)	83.00g	83.20g	83.30g
Specific Gravity	2.55	2.60	2.54
Average Specific Gravity		2.56	

3.2 Fresh Concrete Tests

3.2.1 Workability of Fresh Concrete

Workability fell steadily as EPS content increased, moving the mix from BS EN 206 class S2 down to class S1 by the highest replacement level tested (Table 3). The control mix, C0, returned a slump of 73 mm; adding 0.5% sisal fiber alone (C01) reduced this to 68 mm, a drop attributable to the fiber's hydrophilic surface absorbing part of the free mixing water and to physical interlocking within the fresh paste, consistent with the mechanism reported by Acosta-Calderon *et al.* [10]. From C1 (5% EPS) onward, EPS content became the dominant variable:

slump fell to 63, 57, 54, 48 and 42 mm at 5, 10, 15, 20 and 25% EPS respectively, a 42% overall reduction from the control. The drop into class S1 at 10% EPS reflects the beads' irregular, low-density character increasing internal friction in the fresh mix, an effect also reported by He *et al.* [20] and Maghfouri *et al.* [9]. Overall, EPS content was clearly the dominant variable governing workability, while the fixed sisal fiber dosage contributed a smaller, roughly constant reduction on top of whatever the EPS content already imposed.

Table 3: Slump values for all concrete mixes

Mix	Eps (%)	Sf (%)	Slump (mm)	Workability class	Classification
C0 (Control)	0	0	73	S2	Medium
C0 ₁	0	0.5	68	S2	Medium
C ₁	5	0.5	63	S2	Medium
C ₂	10	0.5	57	S1	Low-Medium
C ₃	15	0.5	54	S1	Low-Medium
C ₄	20	0.5	48	S1	Low-Medium
C ₅	25	0.5	42	S1	Low-Medium

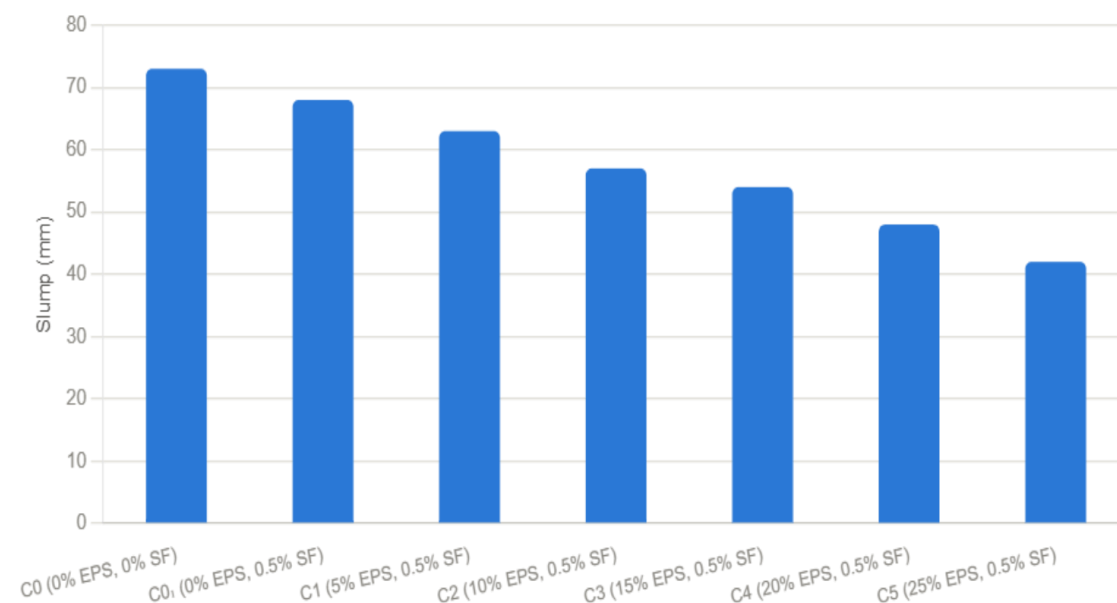


Figure 2: Slump test results showing the effect of EPS and sisal fiber on workability

3.2.2 Fresh and Hardened Density

Density decreased progressively with increasing EPS content at every curing age tested, confirming the lightweight nature of the EPS-modified mixes. At 28 days, density fell from 2403 kg/m³ in the control mix to 1848 kg/m³ at 25% EPS, a 23.1% reduction (Table 4 and Figure 3). Sisal fiber alone (C0₁) reduced density by only 10 kg/m³ relative to C0, an amount within normal specimen-to-specimen variation, since the fiber displaces too little volume of the denser constituents to meaningfully affect density on its own. Mixes C₄ and C₅ (20 and 25% EPS) fell below the 2000 kg/m³ threshold generally used to distinguish lightweight from semi-lightweight concrete. Shah *et al.* reported density reductions of 20% and 35% at 15% and 30% EPS replacement, respectively, in a comparable EPS-fiber hybrid system [8]; the reduction observed here at 15% EPS (13.0%) is somewhat more modest, plausibly because sisal and steel fiber affect fresh-mix compaction differently, though both datasets agree on the underlying trend.

Table 4: Hardened density of concrete specimens at 7, 14, and 28 days (kg/m³)

Mix	Eps (%)	Sf (%)	7-day (kg/m ³)	14-day (kg/m ³)	28-day (kg/m ³)
C0 (Control)	0	0	2266	2347	2403
C0 ₁	0	0.5	2190	2233	2393
C ₁	5	0.5	2168	2193	2295
C ₂	10	0.5	2126	2182	2214
C ₃	15	0.5	2001	2053	2091
C ₄	20	0.5	1924	1937	1989
C ₅	25	0.5	1743	1824	1848

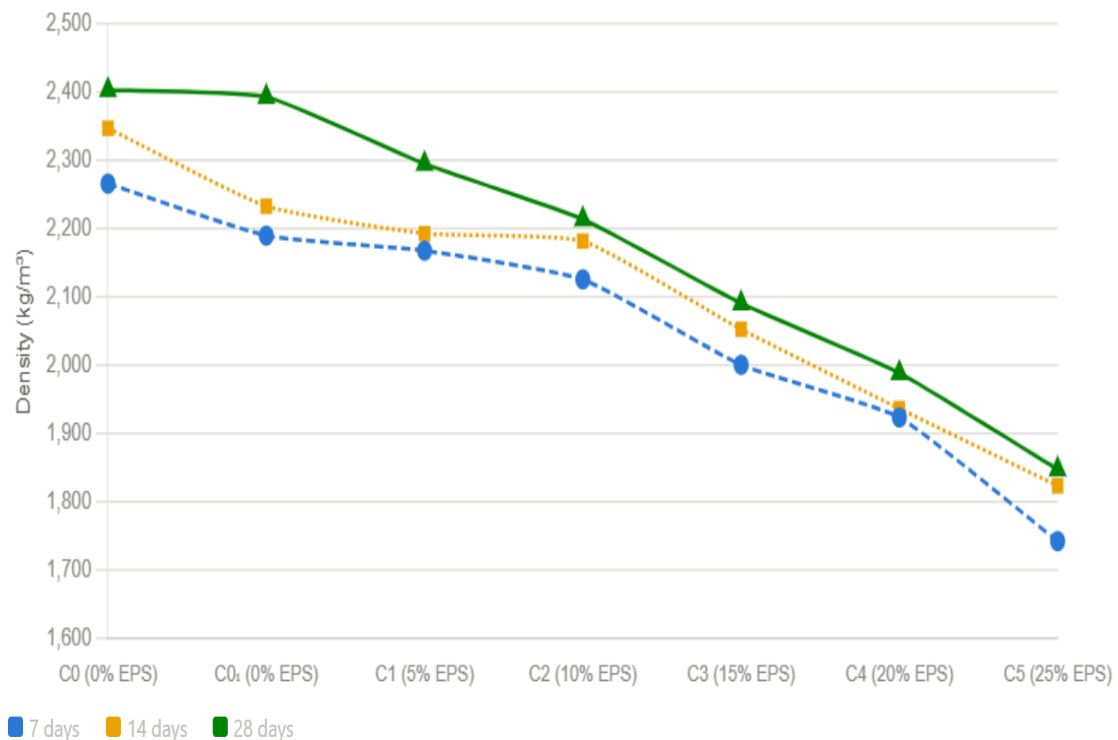


Figure 3: Fresh and hardened density test

3.3 Hardened Mechanical Property Tests

3.3.1 Water Absorption

Table 5 and Figure 4 indicate that the twenty-eight-day water absorption rose from 2.5% in the control mix to 5.9% at 25% EPS, more than doubling across the replacement range. The rise from C0 to C0₁ (2.5% to 2.8%) reflects additional micro-voids forming at the fiber-cement interface, consistent with the mechanism reported by Antwi-Afari *et al.* for natural fibers' hydrophilic surface locally weakening bond quality [5]. From C1 onward, absorption increased steadily with EPS content, matching the mechanism identified by El-Mir *et al.* and Maghfouri *et al.*: EPS beads do not chemically bond with cement paste the way mineral aggregate does, so each bead's surface becomes a small zone of elevated porosity, and as more beads are added, these zones connect into more continuous water-ingress pathways through the matrix [6], [9].

Table 5: Water absorption of concrete specimens at 28 days

Mix	EPS (%)	SF (%)	28-Day Water Absorption (%)
C0	0	0	2.5
C0 ₁	0	0.5	2.8
C1	5	0.5	3.1
C2	10	0.5	3.7
C3	15	0.5	4.4
C4	20	0.5	5.1
C5	25	0.5	5.9

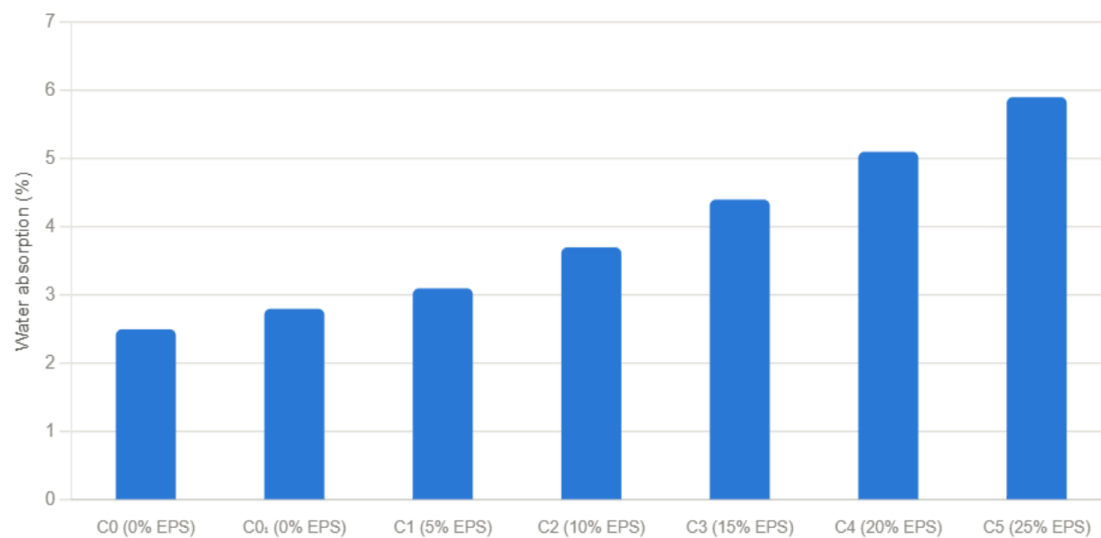


Figure 4: Water absorption test

3.3.2 Compressive Strength

The compressive strength developed predictably with curing age across all seven mixes (Table 6). The control mix, C0, gained strength from 19.5 MPa at 7 days to 27.2 MPa at 28 days, a 39% gain typical of ordinary Portland cement under standard water curing [21]. Sisal fiber alone (C01) produced a marginal 28-day strength penalty of 1.8% relative to C0 (26.7 MPa), consistent with sisal fiber's known effect on compressive strength at low dosage; this contrasts with both Acosta-Calderon *et al.*, who reported a 6% strength increase from sisal fiber alone, and Beskopylny *et al.*, who reported a 22% compressive strength gain at an optimal 1% sisal fiber dosage, suggesting the present mix's fixed 0.5% dosage may sit below the threshold needed for sisal fiber to meaningfully improve, rather than merely preserve, compressive strength [10], [11].

Strength fell progressively with EPS content: 26.0 MPa at 5% EPS, 24.6 MPa at 10%, 23.4 MPa at 15%, 21.8 MPa at 20%, and 19.6 MPa at 25%, a 28% reduction from the control at the highest replacement level. The near-linear loss of roughly 1.5 MPa per 5% EPS increment matches the pattern reported by He *et al.* for EPS lightweight concrete generally and sits within the same order of magnitude as the reductions reported by Salahaldeen *et al.* [20], [22], both pointing to the same underlying cause: EPS's low stiffness turns each bead into a weak inclusion under compressive load, disrupting the continuity of the load path through the matrix. Comparing C01 against C1 through C5 mix by mix shows that the 0.5% sisal fiber dosage did not measurably offset EPS-driven strength loss at any replacement level tested, since the rate of reduction per 5% EPS increment is essentially unchanged whether fiber is present or not. Shah *et al.* found that steel fiber at a higher 2% dosage did shift the strength-density trade-off measurably in EPS concrete's favor [8]; the absence of a comparable effect here suggests that dosage, rather than fiber type, may be the limiting factor, and is a direct, testable direction for further work.

Table 6: Compressive strength of concrete mixes

Mix	Eps (%)	7-day (MPa)	14-day (MPa)	28-day (MPa)
C0	0	19.5	22.9	27.2
C01	0	19.4	22.8	26.7
C1	5	18.8	22.5	26.0
C2	10	17.6	20.5	24.6
C3	15	16.3	20.4	23.4
C4	20	14.2	18.8	21.8
C5	25	13.3	16.8	19.6

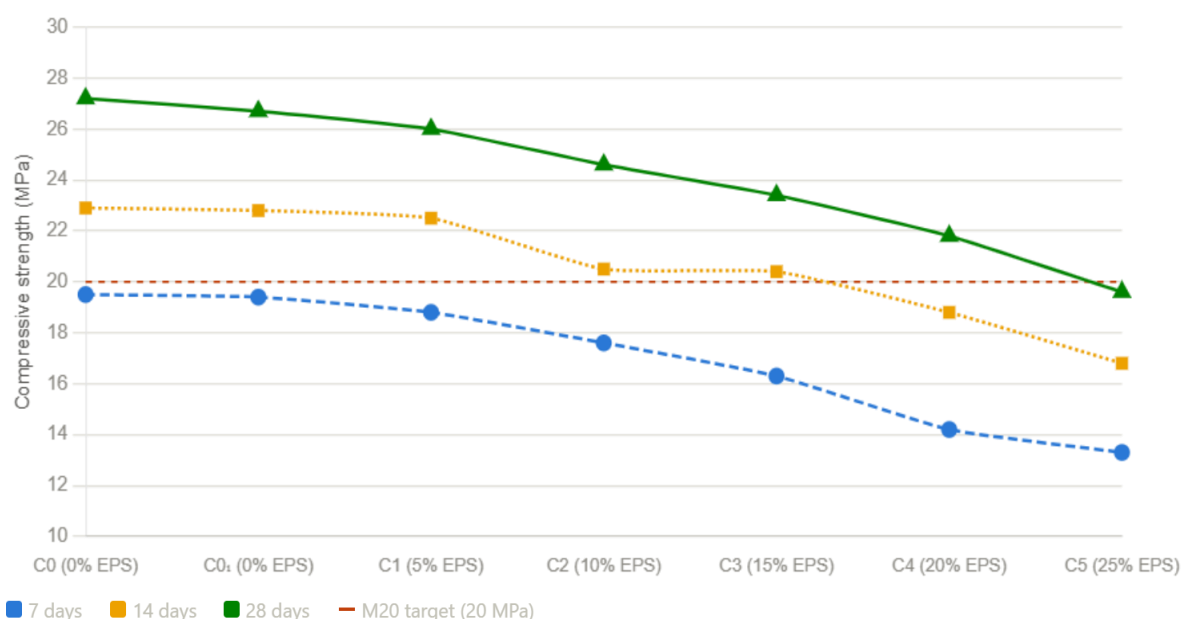


Figure 5: Compressive strength test

4.0 Conclusion

This study investigated the potential of developing a lightweight, eco-friendly concrete composite by incorporating natural sisal fibers as micro-reinforcement alongside Expanded Polystyrene (EPS) beads as partial aggregate replacement. After laboratory testing, the following conclusions have been made:

- The natural river sand used in this study exhibited a fineness modulus of 1.84 and a specific gravity of 2.56, confirming a well-graded fine aggregate suitable for producing a dense concrete matrix.
- Slump fell progressively with EPS content, from 73 mm in the control mix to 42 mm at 25% EPS replacement, a 42% reduction, while the addition of sisal fiber alone caused a comparatively small initial drop attributable to water absorption by the hydrophilic fiber.
- Hardened density fell from 2403 kg/m³ to 1848 kg/m³ across the replacement range, a 23.1% weight reduction, with the 20% and 25% EPS mixes crossing into true lightweight concrete classification.
- Water absorption more than doubled, from 2.5% to 5.9%, driven by interfacial porosity at the EPS-paste boundary and by micro-voids introduced by the untreated sisal fiber.
- Compressive strength dropped from 27.2 MPa to 19.6 MPa at 28 days, a loss of roughly 1.5 MPa for every 5% increment of EPS, and the 0.5% sisal fiber dosage did not measurably compensate for this loss at any EPS replacement level tested.

Overall, these results suggest that concrete with 5–10% EPS replacement is best suited for semi-structural precast elements and floor screeds, while concrete with 15–25% EPS is better kept to non-structural uses such as insulation and cladding. Going forward, it would be worth testing alkali pre-treatment of the sisal fibers and higher dosages, between 1.0% and 2.0%, together with a superplasticizer, to see whether a stronger fiber-matrix bond and greater fiber volume can better offset the strength lost to EPS without hurting workability.

References

- [1] N. Makul, *Introduction to the Principles of Cement and Concrete Composites*. Cham, Switzerland: Springer, 2021.
- [2] S. Abdal et al., "Application of ultra-high-performance concrete in bridge engineering: Current status, limitations, challenges, and prospects," *Buildings*, vol. 13, no. 1, p. 185, 2023.
- [3] R. M. Andrew, "Global CO₂ emissions from cement production, 1928–2018," *Earth Syst. Sci. Data*, vol. 11, no. 4, pp. 1675–1710, 2019.
- [4] G. Habert et al., "Environmental impacts and decarbonization strategies in the cement and concrete industries," *Nat. Rev. Earth Environ.*, vol. 1, pp. 559–573, 2020.
- [5] B. A. Antwi-Afari, R. Mutuku, C. Kabubo, J. Mwero, and W. K. Mengo, "Influence of fiber treatment methods on the mechanical properties of high-strength concrete reinforced with sisal fibers," *Heliyon*, vol. 10, no. 8, e29760, 2024.
- [6] A. El-Mir, E. Fayad, J. J. Assaad, and H. El-Hassan, "Multi-response optimization of semi-lightweight concrete incorporating expanded polystyrene beads," *Sustainability*, vol. 15, no. 11, p. 8757, 2023.
- [7] S. Hameed et al., "Investigating lightweight recycled brick aggregate concrete incorporating EPS beads: Application to masonry units," *Results Eng.*, vol. 25, 104019, 2025.

- [8] S. J. Shah et al., “Experimental investigation of the mechanical properties of a concrete mix with lightweight EPS and steel fibers,” *CivilEng*, vol. 5, no. 1, pp. 209–223, 2024.
- [9] M. Maghfouri et al., “Drying shrinkage properties of expanded polystyrene (EPS) lightweight aggregate concrete: A review,” *Case Stud. Constr. Mater.*, vol. 16, e00919, 2022.
- [10] S. Acosta-Calderón, P. Gordillo-Silva, N. García-Troncoso, D. V. Bompá, and J. Flores-Rada, “Comparative evaluation of sisal and polypropylene fiber-reinforced concrete properties,” *Fibers*, vol. 10, no. 4, p. 31, 2022.
- [11] A. N. Beskopylny et al., “Enhanced performance of concrete dispersedly reinforced with sisal fibers,” *Appl. Sci.*, vol. 12, no. 18, p. 9102, 2022.
- [12] British Standards Institution, *Testing Aggregates – Methods for Determination of Particle Size Distribution: Sieve Tests*, BS 812-103.1:1985. London, U.K.: BSI Group, 1985.
- [13] British Standards Institution, *Testing Fresh Concrete, Part 2: Slump Test*, BS EN 12350-2:2019. London, U.K.: BSI Group, 2019.
- [14] British Standards Institution, *Testing Hardened Concrete, Part 7: Density of Hardened Concrete*, BS EN 12390-7:2019. London, U.K.: BSI Group, 2019.
- [15] British Standards Institution, *Testing Concrete, Part 122: Method for Determination of Water Absorption*, BS 1881-122:2011. London, U.K.: BSI Group, 2011.
- [16] British Standards Institution, *Testing Hardened Concrete, Part 3: Compressive Strength of Test Specimens*, BS EN 12390-3:2019. London, U.K.: BSI Group, 2019.
- [17] British Standards Institution, *Specification for Aggregates from Natural Sources for Concrete*, BS 882:1992. London, U.K.: BSI Group, 1992.
- [18] U. N. Wilson, I. Balarabe, O. C. Eze, A. A. Adefila, and S. O. Odeyemi, “Assessment of compressive strength of concrete produced with fine aggregate from different locations in Kaduna State,” *FUTA J. Eng. Eng. Technol.*, vol. 16, no. 1, pp. 8–19, 2022.
- [19] S. S. Omopariola and A. A. Jimoh, “The evaluation of engineering properties of some selected aggregates in southwestern Nigeria for concrete production,” *Niger. J. Technol.*, vol. 42, no. 1, pp. 92–98, 2023.
- [20] D. He et al., “Influence of paste strength on the strength of expanded polystyrene (EPS) concrete with different densities,” *Polymers*, vol. 14, no. 13, p. 2529, 2022.
- [21] P. K. Mehta and P. J. M. Monteiro, *Concrete: Microstructure, Properties, and Materials*, 4th ed. New York, NY, USA: McGraw-Hill, 2014.
- [22] A. S. Salahaldeen and A. I. Al-Hadithi, “The effect of adding expanded polystyrene beads (EPS) on the hardened properties of concrete,” *Eng. Technol. Appl. Sci. Res.*, vol. 12, no. 6, pp. 9692–9696, 2022.
- [23] British Standards Institution, *Methods of Test for Soils for Civil Engineering Purposes*, BS 1377:1990. London, U.K.: BSI Group, 1990.