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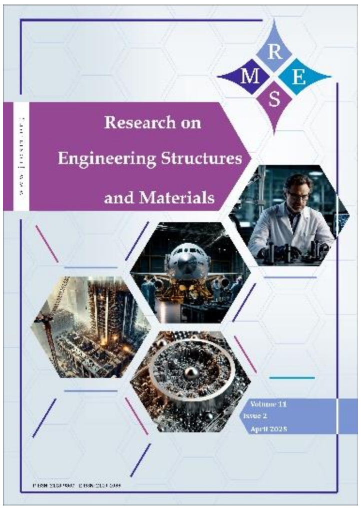

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Research Article

Development of high-performance lightweight concrete through incorporation of polypropylene fibers into polyurethane foam concrete

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Abstract

The increasing emphasis on sustainable and energy-efficient construction materials has heightened interest in structural lightweight concrete (LWC) due to its potential to reduce dead load and enhance thermal performance. Conventional concrete, with a density of around 2400 kg/m^3, contributes substantially to the self-weight of structures, whereas incorporating lightweight aggregates can lower density by nearly 20 %. Polyurethane-foam (PUF) concrete, with densities between 1700 and 1950 kg/m^3, offers significant weight reduction but suffers from brittleness and reduced strength caused by interconnected voids. To overcome these limitations, this study integrates polypropylene (PP) fibers into PUF concrete, leveraging their high tensile strength, corrosion resistance, and economic viability. Six mixes were prepared by varying foam content (10 % and 15 %) and PP fiber dosage (0–1 %). Mechanical, durability, and microstructural properties were evaluated. The optimal mix containing 10 % foam and 1 % fiber achieved a 25 % reduction in dry density, 30 % improvement in compressive strength, and 29 % decline in chloride permeability. Microstructural analysis revealed compact calcium–silicate–hydrate (C–S–H) gel formation around intact fibers. The findings demonstrate that PP-fiber-reinforced PUF concrete effectively combines lightweight characteristics, mechanical strength, and durability suitable for sustainable structural applications.

1. Introduction

Structural concrete accounts for a large portion of the dead load in buildings and bridges, and its density typically lies between 2300 and 2500 kg/m^3. Such mass contributes to high seismic forces and increases material consumption and embodied energy. Lightweight concrete (LWC) aims to mitigate these issues by replacing some of the dense aggregates with lightweight alternatives or by incorporating air voids. Polystyrene-foam lightweight concrete beams, for example, achieve weight reductions of about 30 % compared with normal-weight concrete while maintaining structural integrity [1]. Moreover, the energy required to transport and erect LWC elements is lower, leading to improved sustainability [2].

In recent years, polyurethane-foam (PUF) concretes have emerged as promising LWCs. Preformed PUF, with a density of around 35 kg/m^3, is dispersed into the cement matrix to create a closed-cell foam. PUF concretes with foam contents of 10 – 60 % exhibit hardened densities ranging from 2354 kg/m^3 down to 1842 kg/m^3. Standards such as ACI 213R define structural lightweight aggregate concretes as having densities between 1120 and 1920 kg/m^3[3], while European

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standard EN 206 limits structural LWC to densities below 2000 kg/m^3 [2]. However, increasing foam content in PUF concretes causes a decline in compressive strength: control concretes reach about 30.5 MPa at 28 days, whereas mixes with 10 % and 30 % foam reach 28.7 MPa and 22.9 MPa, respectively [3]. Brittleness and crack propagation are the dominant drawbacks of foam concretes, highlighting the need for toughening mechanisms.

Fiber reinforcement has long been recognized as an effective way to enhance concrete toughness and crack resistance. Steel fibers provide high strength and stiffness, glass fibers contribute good tensile properties but can be susceptible to alkali attack, basalt fibers offer excellent chemical stability, and synthetic fibers such as polypropylene (PP) and polyethylene improve ductility and control micro-cracking [4]. Combining fibers with foam concretes or with lightweight aggregates has been shown to improve load-carrying capacity. For instance, beams cast with polystyrene-foam lightweight concrete and strengthened with carbon- or glass-fiber-reinforced polymers exhibited increased ultimate load and reduced deflection compared with unreinforced beams [1]. Nevertheless, most fiber-reinforced foam concretes employ steel or glass fibers and there is little information on the use of PP fibers in PUF concretes.

Polypropylene fibers possess several attributes that make them attractive for lightweight concrete. They are chemically inert, resist corrosion, and have densities around 0.91 g/cm^3, which is significantly lower than that of steel. PP fibers melt at 160 – 170 °C, allowing them to form channels during heating that release steam and mitigate explosive spalling. Studies on lightweight foamed concrete reinforced with PP fibers (length 12 mm, dosage 1–3 kg/m^3) report enhancements in tensile and flexural strengths, compressive strength, and drying-shrinkage resistance. The fibers bridge micro-cracks, restrain crack opening, and improve post-peak toughness [4]. However, workability may decrease due to fiber clustering, and the optimum dosage must be determined to balance ductility and workability [5]. Despite these advantages, the combined use of PUF and PP fibers in structural LWC remains underexplored. Most studies on PUF concretes either omit fibers or use steel fibers. Conversely, investigations on PP-fiber-reinforced concretes focus on normal or foamed concretes without lightweight aggregates [4,5]. A systematic study examining mechanical properties, durability, shrinkage, and microstructure of PUF concrete reinforced with PP fibers at different dosages has not been reported.

This research aims to fill that gap by developing high-performance lightweight concretes through the incorporation of PP fibers into PUF concrete. The objectives are to: (1) design mixes with different foam and fiber contents to achieve densities within the structural lightweight range; (2) evaluate fresh properties and mechanical strengths (compressive, flexural, split-tensile); (3) assess durability (water absorption, permeability, chloride migration) and shrinkage; (4) analyze microstructural features via scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX); and (5) identify the optimum foam and fiber combination that maximizes strength and durability while maintaining low density. The findings are discussed in light of existing literature on fiber-reinforced LWCs and provide practical recommendations for precast and marine applications. While [6] investigated how incorporation of polypropylene fibres affects the permeability of concrete under freeze–thaw cycles and mechanical loading, focusing primarily on durability and transport properties of conventional concrete under environmental stress, the present work extends beyond permeability concerns by examining a multi-component polyurethane foam concrete system that integrates nano-scale mineral additives and polymer fibres. This enables a comprehensive evaluation of mechanical performance enhancement and microstructural behavior in engineered foam concrete, offering new insights into tailored mix design for strength and durability improvements that are not addressed in the earlier study. Previous studies on polypropylene fibre reinforcement have mainly focused on conventional foamed or normal-weight concretes, with emphasis on flexural behavior, shrinkage control, or permeability under specific environmental actions [4]. In contrast, the present work introduces a systematic experimental investigation of polyurethane-foam-based concrete reinforced with polypropylene fibres, providing new insights into the coupled effects of foam-induced cellular structure and fibre bridging on mechanical performance, shrinkage behavior, durability indicators, and microstructural evolution, which have not been jointly examined in earlier studies.

2 Materials, Mix Design and Methods

2.1 Materials

All mixes used ordinary Portland cement (OPC) 43 grade conforming to IS 8112:2013. Natural sand complying with IS 383:2016 and having a maximum size of 4.75 mm was used as fine aggregate. Pumice was selected as the coarse aggregate due to its low density and particle size up to 12 mm. Preformed polyurethane foam with a density of approximately 35 kg/m^3 was produced and added at 10 % or 15 % by volume of the fresh mix. Polypropylene fibers (length 12 mm, diameter ≈ 20 µm, aspect ratio ≈ 600) were incorporated at dosages of 0, 0.5 and 1.0 % of the total volume. The fibers are non-corrosive and have a melting point between 160 °C and 170 ° [4]. In order to enhance durability, 25 % of the cement was replaced with Class F fly ash and 7 % with silica fume. A polycarboxylate-ether (PCE) superplasticizer (0.5 % of cement by weight) was used to achieve self-compact ability. Potable water was used for mixing and curing.

Polypropylene fibres were used as discrete reinforcement in the polyurethane foam concrete. The fibres had a length of 30 mm and a diameter of 0.5 mm, corresponding to an aspect ratio (L/D) of 60. The selected aspect ratio is consistent with previous studies reporting enhanced crack bridging and flexural toughness in lightweight concrete systems.

2.2 Mix Design

Six mixes were designed. The control mix (M0) contained no foam or fibers and had a water–cement ratio of 0.35. Mixes M1 and M2 incorporated 10 % foam with fiber dosages of 0 % and 0.5 %, respectively. Mix M3 contained 10 % foam and 1 % fibers. Mixes M4 and M5 incorporated15 % foam with fiber dosages of 0.5 % and 1.0 %, respectively. The binder content remained constant, and the aggregate proportions were adjusted to maintain the same water–cement ratio.

Table 1. Mix proportions and target densities for polyurethane-foam concrete reinforced with polypropylene fibers

Mix ID	Foam (%)	PP Fiber (%)	Target density (kg/m^3)	w/c	SP (%)
M0	0	0	2400	0.35	0.5
M1	10	0	1950	0.35	0.5
M2	10	0.5	1920	0.35	0.5
M3	10	1.0	1890	0.35	0.5
M4	15	0.5	1820	0.35	0.5
M5	15	1.0	1780	0.35	0.5

The mix design strategy presented aligns with the study's objective of developing a lightweight yet structurally efficient concrete. As summarized in Table 1, the systematic variation of foam (10–15 %) and polypropylene (PP) fiber content (0–1 %) allowed tuning of the target density from 2400 kg/m^3 down to 1780 kg/m^3, bringing the material within the range of structural lightweight concrete. The selected polyurethane foam contents (10% and 15%) and polypropylene fibre dosages (0.5% and 1.0%) were established based on preliminary trial mixes conducted to identify ranges that ensured stable foam dispersion, acceptable workability, and measurable improvements in mechanical and durability performance. Mechanistically, the inclusion of foam introduces a controlled cellular structure that lowers unit weight, while the dispersed PP fibers compensate for the loss in stiffness by bridging microcracks and improving load transfer between paste and aggregate phases. Similar density optimization strategies were reported by [2] and [3], who observed that 10–15 % foam yields a balance between weight reduction and strength retention.

2.3 Mixing and Curing

This section outlines the procedure adopted for combining the constituent materials and for maintaining controlled curing conditions to achieve uniformity and repeatability across all concrete mixes. Uniform dispersion of polyurethane foam within the fresh concrete matrix, as given in Figure 1, shows effective mixing and stable foam incorporation prior to casting. Dry materials such as cement, fly ash, silica fume, sand and pumice were blended in a pan mixer for two minutes. Approximately 70 % of the mixing water and superplasticizer were then added while mixing continued for another two minutes. Preformed foam was gently folded into the mortar to avoid bubble collapse, followed by gradual addition of polypropylene fibers to ensure uniform dispersion. The remaining water and superplasticizer were then added. The fresh mix was cast into moulds for cubes (100 mm), prisms (100 × 100 × 500 mm) and cylinders (100 × 200 mm), and compacted using vibration. Specimens were demoulded after 24 h and water-cured at 27 ± 2 °C for 7, 28, 56 and 90 days.

Fig. 1. Fresh polyurethane foam concrete mix during laboratory mixing, showing uniform foam dispersion within the cementitious matrix

2.4 Experimental Program

Fresh properties were measured using slump flow and density tests on self-compacting concrete. Hardened properties included compressive strength (IS 516:2018) on cubes, flexural strength on beams, and split-tensile strength on cylinders. Drying shrinkage was monitored on prisms stored in laboratory air for 90 days. Impact resistance was assessed using the drop-weight test (ASTM D7136). Durability was characterized by water absorption, sorptivity, and rapid chloride penetration test (RCPT) per ASTM C1202. Freeze–thaw permeability tests were not performed in this work; however, literature indicates that polypropylene fibers restrict macro-crack width, increase tortuosity, and reduce permeability under freeze–thaw conditions [5]. Microstructural analysis was conducted using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) to identify the distribution of pores, fiber–matrix bonding and elemental composition. Statistical analyses such as regression and correlation were performed to establish relationships between density and strength and to identify optimum mixtures. The drying shrinkage strain was calculated by measuring the change in length of prism specimens at specified ages relative to their initial reference length, using a calibrated length comparator, and expressing this change as strain in micro-strain units. All measurements were taken under controlled laboratory temperature and humidity conditions, and the reported shrinkage values represent the average of at least three specimens to ensure accuracy and repeatability.

2.5 Workflow of the Experimental Program

The overall experimental sequence is illustrated in Figure 2. It begins with material preparation and mix proportioning, followed by casting and curing. After curing, specimens undergo mechanical, durability and microstructural testing, and finally the data are analyzed to determine the optimum mix.

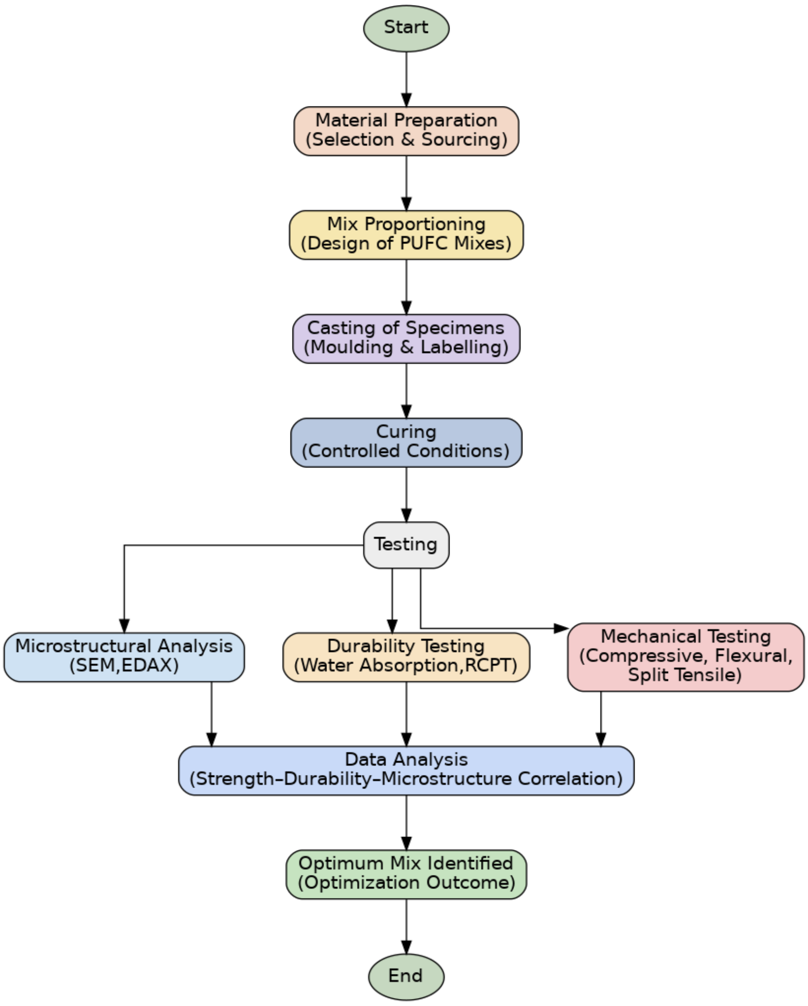

Fig. 2. Workflow of the experimental program for PUFC mix design and evaluation

The workflow adopted in this study ensures a systematic transition from mix design through performance evaluation, thereby anchoring each experimental step in a coherent sequence. As shown in Figure 4, we begin with formulation of foamed concrete blends with varying foam and fiber contents, followed by specimen casting, curing, and sequential testing of mechanical, durability, and microstructural responses. Mechanistically, this pipeline allows us to trace how foam dispersion and fiber bridging influence pore morphology, crack propagation, and load transfer within the cellular matrix, consistent with prior findings that fiber addition enhances tensile and compressive performance in foamed concrete systems [7]. In comparison to earlier works which treated fiber reinforcement and foaming separately, our integrated scheme fills a methodological gap by coupling both effects and enabling direct correlation across multiple property domains [8].

3. Results and Discussion

3.1 Fresh Properties

The addition of polyurethane foam reduced the fresh density of the mixes from 2400 kg/m^3 for the control concrete to 1950 kg/m^3 for 10 % foam mixes and to 1780 kg/m^3 for 15 % foam mixes as illustrated in Table 2. Slump flow decreased with increasing fiber content, with the slump values for mixes containing 0, 0.5 and 1.0 % fibers were 180 mm, 170 mm and 160 mm for 10 % foam mixes (M1–M3) and 150 mm and 145 mm for 15 % foam mixes (M4–M5). The reduction of 10– 15 % in workability is consistent with observations that polypropylene fibers restrict the flow of fresh concrete and increase the pore connectivity [5]. However, all mixes remained self-compacting due to the use of superplasticizer.

Table 2. Fresh Properties of Polypropylene-Fiber-Reinforced Polyurethane Foam Concrete Mixes

Mix ID	Foam (%)	PP Fiber (%)	Slump (mm)	Fresh density (kg/m^3)
M0	0	0	200	2400
M1	10	0	180	1950
M2	10	0.5	170	1920
M3	10	1.0	160	1890
M4	15	0.5	150	1820
M5	15	1.0	145	1780

The results demonstrate a clear influence of foam and polypropylene fiber dosage on the fresh behavior of the mixtures. As shown in Table 2, the slump gradually decreased with increasing fiber content from 200 mm for the control to 145 mm for the mix with 15 % foam and 1 % fiber indicating reduced workability due to fiber clustering and increased internal friction. Mechanistically, the entrapped air from polyurethane foam and the random fiber network restricts particle mobility but enhance cohesion and segregation resistance, leading to stable self-compacting behavior. These findings align with those of [5], who reported that PP fibers increase viscosity and modify pore connectivity without compromising flow when coupled with superplasticizers.

3.2 Compressive Strength

The mechanical properties of the polyurethane foam concrete mixes were assessed through compressive strength testing to evaluate the influence of foam content and polypropylene fibre addition on strength development at different curing ages.

Fig. 3. Mechanical strength tests being conducted in the laboratory

Mechanical strength parameters being tested in the laboratory are shown in Figure 3. The compressive strengths of the mixes at 7, 28 and 90 days, are presented in figure 5. At 28 days, the control concrete (M0) reached 40 MPa, whereas mixes with 10 % foam and no fibers (M1) achieved 38 MPa. Incorporating 0.5 % and 1 % fibers increased the strength to 42 MPa (M2) and 46 MPa (M3), respectively. A further increase in foam content to 15 % lowered the strength to 44 MPa (M4) and 43 MPa (M5). These results demonstrate that polypropylene fibers effectively bridge micro-cracks and densify the matrix, leading to strength improvements of up to 30 % relative to the unreinforced foam concrete. Similar trends were reported for foamed concretes reinforced with PP fibers, where tensile and flexural strengths increased significantly and drying shrinkage decreased. Beyond 1 % fiber, workability issues and fiber clustering may negate further strength gains [5].

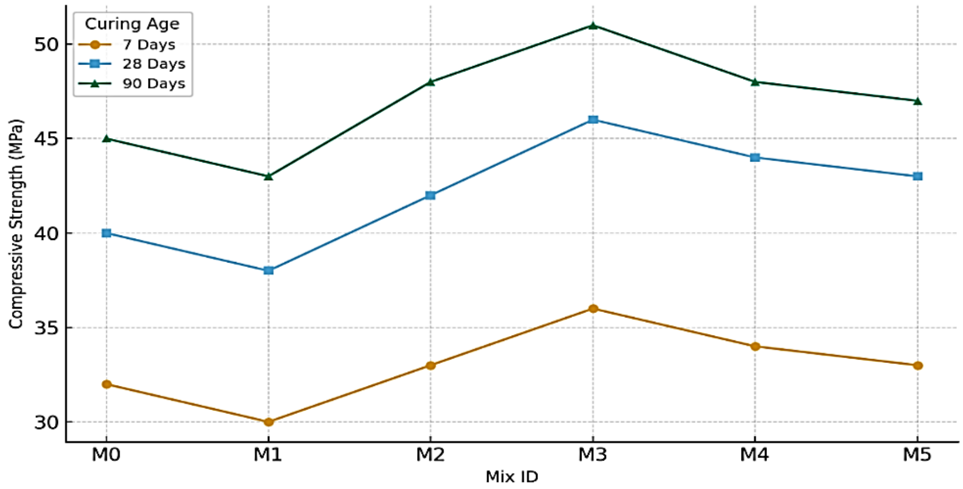

Fig. 4. Variation of compressive strength with polypropylene fiber content at different curing ages

The results displayed in Figure 4 reveal a relation between fiber content and compressive strength, suggesting an optimal dosage beyond which strength gains taper off. Mechanistically, the fibers appear to bridge microcracks in the cementitious matrix, delaying crack coalescence and enhancing post-peak ductility, but excessive fiber insertion may disrupt paste continuity and introduce weak zones. Interpreting these trends in light of previous works, similar strength enhancements with polypropylene, glass, or hybrid fibers have been reported in foamed concrete systems by [9] and [10] showing porosity reduction and strength improvement with fibers.

3.3 Flexural and Split-Tensile Strengths

Flexural and split-tensile strengths show similar improvements with fiber addition. Figure 3 illustrates the flexural strength trend at 7, 28 and 90 days. The control concrete exhibited a 28-day flexural strength of about 5 MPa. With 10 % foam, the strength decreased slightly due to increased porosity, but the inclusion of 0.5 % and 1.0 % fibers raised the values to approximately 5.5 MPa and 6.0 MPa, respectively. Figure 4 shows that split-tensile strength followed the same pattern, where in the control mix reached 3.4 MPa at 28 days, whereas mixes M2 and M3 achieved 3.8 MPa and 4.1 MPa. These enhancements are attributed to fiber bridging, which transfers tensile stress across cracks and increases energy dissipation [4]. Similar behavior has been reported for polypropylene-fiber-reinforced concretes subject to mechanical loading and freeze–thaw cycles, where fibers restrict macro-crack widths and increase tortuosity [5].

The data trend in Figure 5 shows a clear improvement in flexural strength as polypropylene fiber content increases, especially noticeable from 28 to 90 days of curing. This suggests that the fiber network progressively engages in crack-bridging and load transfer as the matrix stiffens with age. Mechanistically, the PP fibers act to arrest microcrack initiation and redistribute stress across micro fissures, thereby delaying full crack coalescence and improving ductility. These findings are consistent with prior studies, for instance, Foamed Concrete reinforced with PP fibers exhibited up to 40 % gain in bending strength. [11] and [12] reported enhanced flexural toughness via combined PP–PVA fiber blends. However, most existing work focuses on fiber effect alone, seldom addressing the interaction of fiber geometry, foam content, and long-term durability, thus leaving a gap in understanding the fiber–foam synergies in flexure.

The variation of split-tensile strength with fiber content demonstrates a clear reinforcing trend. In Figure 6, the tensile strength rises as polypropylene (PP) fiber dosage increases up to about 1 %, highlighting the beneficial effect of fiber bridging in delaying microcrack coalescence and enabling stress redistribution. Mechanistically, the dispersed PP fibers enhance interfacial bonding and act as micro-bridges across developing cracks, restraining crack propagation and thus increasing ductility and residual tensile capacity, which is a mechanism described similarly in studies on PP-reinforced foamed concretes by [13] and [14] in LFC reinforced with PTBF fibers. This behavior aligns with reports in the literature, such as the improvements in bending and splitting strength in PP-fiber foamed concretes found in [11], yet it also diverges when fiber content is excessive, as clustering and poor fiber dispersion reduce effectiveness.

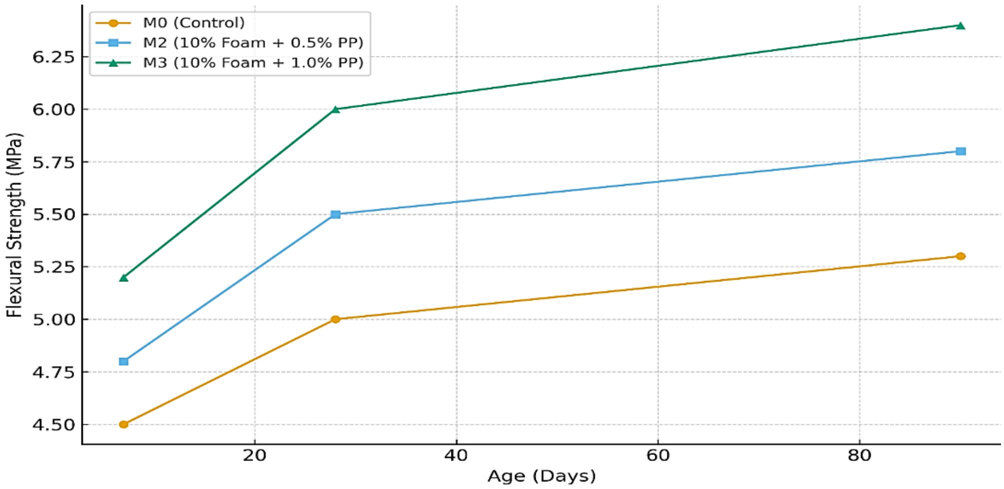

Fig. 5. Variation of flexural strength with polypropylene fiber content at different curing ages

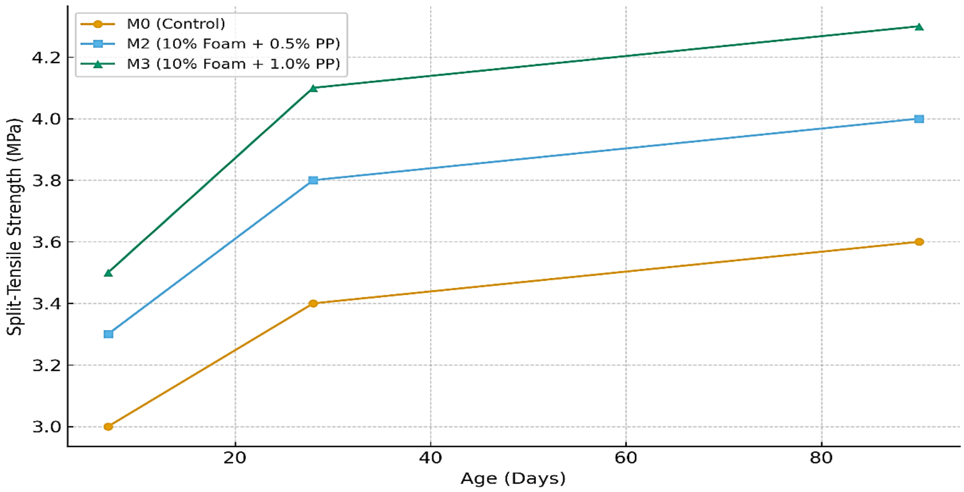

Fig. 6. Variation of split-tensile strength with polypropylene fiber content at different curing ages

3.4 Durability Performance

Durability indicators include water absorption and chloride ion permeability, which are presented in Table 3. Water absorption decreased from 7.0 % in the control concrete to 4.1 % in the mix with 15 % foam and 1 % fiber. The rapid chloride penetration test (RCPT) results show a reduction in charge passed from 3100 C (M0) to 2200 C (M5). These improvements reflect the reduced pore connectivity and crack widths in PP-reinforced PUF concrete. Previous studies on fiber-reinforced concretes have shown that PP fibers restrict macro-cracks, increase the tortuosity of cracks and surface roughness, and consequently reduce permeability. However, excessive fiber content or poor dispersion can create channels that increase matrix permeability [5]. The present results confirm that up to 1 % PP fiber, the net effect is beneficial.

The durability response of the mixes reflects the combined influence of pore refinement and fiber reinforcement in enhancing long-term performance. As summarized in Table 3, both water absorption and chloride permeability decreased consistently with increasing polypropylene fiber dosage and foam content, with the lowest values of 4.1 % and 2200 C recorded for mix M5. Mechanistically, the inclusion of PP fibers bridges microcracks, improves crack tortuosity, and restricts moisture ingress, while the foam-induced closed-cell structure minimizes interconnected capillary pores. Comparable findings by Zeng et al., (2024) and Mydin and Soleimanzadeh, [4] confirmed that PP fibers reduce permeability and enhance resistance to chloride migration under thermal and cyclic loading. However, the long-term coupling effects of carbonation, freeze–thaw cycles, and fiber dispersion uniformity remain insufficiently explored, suggesting a future scope for integrating advanced permeability models and micro-CT analysis to quantify transport mechanisms in polyurethane-foam-based fiber concretes**.**

Table 3. Durability properties of polypropylene-fiber-reinforced polyurethane foam concrete mixes

Mix ID	Water absorption (%)	RCPT (Coulombs)
M0	7.0	3100
M1	6.5	2800
M2	5.9	2600
M3	5.0	2400
M4	4.3	2300
M5	4.1	2200

3.5 Shrinkage and Crack Resistance

Drying shrinkage results are shown in Figure 5. The control concrete exhibited a shrinkage strain of about 0.06 % after 90 days. Incorporating 10 % foam and 0.5 % PP fibers reduced shrinkage to 0.055 %, while the combination of 10 % foam and 1.0 % fibers (M3) achieved the lowest shrinkage of 0.045 %. For 15 % foam mixes, shrinkage slightly increased but remained below the control. Polypropylene fibers mitigate shrinkage by bridging micro-cracks and restraining movements at the fiber–matrix interface [4]. This crack-bridging effect contributes to better crack distribution and smaller crack widths, leading to improved durability. Nonetheless, the presence of foam and fibers leads to increased creep at high fiber contents and thus an optimal balance is necessary.

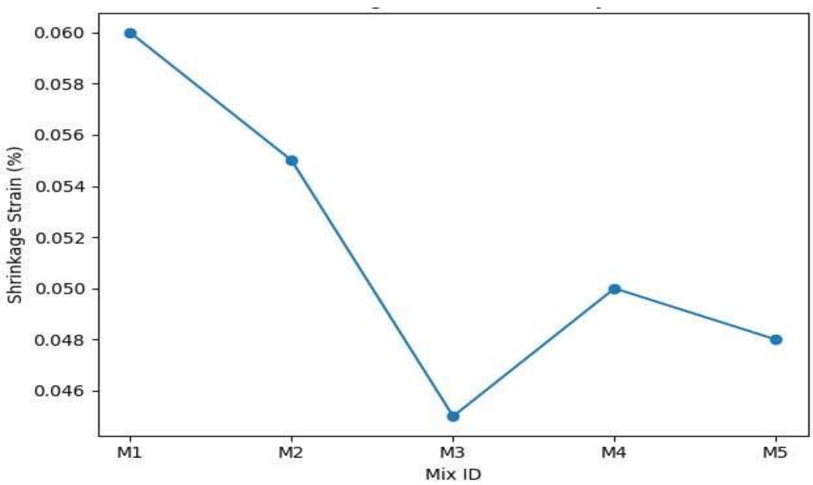

Fig. 7. Drying shrinkage strain of polyurethane foam concrete mixes over 90 days

The trend in Figure 5 demonstrates that as the fiber dosage increases, both early-age and long-term shrinkage strain decrease appreciably, revealing the fibers' restraining influence on volumetric contraction. Figure 7 shows a clear reduction in drying shrinkage with increasing polypropylene fibre content, which can be attributed to fibre bridging that restrains microcrack initiation and limits shrinkage-induced tensile strains within the cementitious matrix. This behavior is consistent with earlier observations in fibre-reinforced lightweight and foamed concretes, where distributed polypropylene fibres were reported to reduce shrinkage by improving internal stress redistribution and crack control. Compared with published ranges for foamed concretes, the magnitude of shrinkage reduction observed in the present study indicates that the combined action of polyurethane foam and fibre reinforcement is particularly effective in mitigating volumetric instability. This reduction suggests that the fibers act as internal reinforcement, restraining shrinkage-induced tensile stresses and reducing the tendency for microcrack initiation and propagation. Mechanistically, the fibers impose local constraint against capillary tension, create micro-bridging across nascent shrinkage cracks, and interrupt continuous shrinkage strain fields analogous to findings in polypropylene fiber studies where shrinkage mitigation was attributed to fiber network stiffening and moisture retention [15] and [16] in ultra-high-performance concretes using micro- and microfibers. The observed behavior also aligns with results in steel fiber concrete, where distributed fibers reduced drying shrinkage and delayed crack formation [17], albeit other works caution that beyond optimal fiber contents, packing defects or fiber clustering may reduce effectiveness. Yet, a clear knowledge gap persists in quantifying how fiber orientation, spacing, and local moisture gradients collectively influence shrinkage restraint.

3.6 Microstructure and Interface Analysis

SEM micrographs as shown in Figure 6 reveal that the control concrete contains large and interconnected pores, whereas PUF concretes with PP fibers exhibit a more refined pore structure. At 28 days, fibers are embedded within the matrix and surrounded by a dense C–S–H gel. After 90 days, the C–S–H layer thickens, and the fiber–matrix bond becomes more intimate. EDX analysis, as shown in Table 4 indicates that the calcium (Ca) content decreased from 60 % at 28 days to 55 % at 90 days, while the silicon (Si) content increased from 20 % to 25 %.

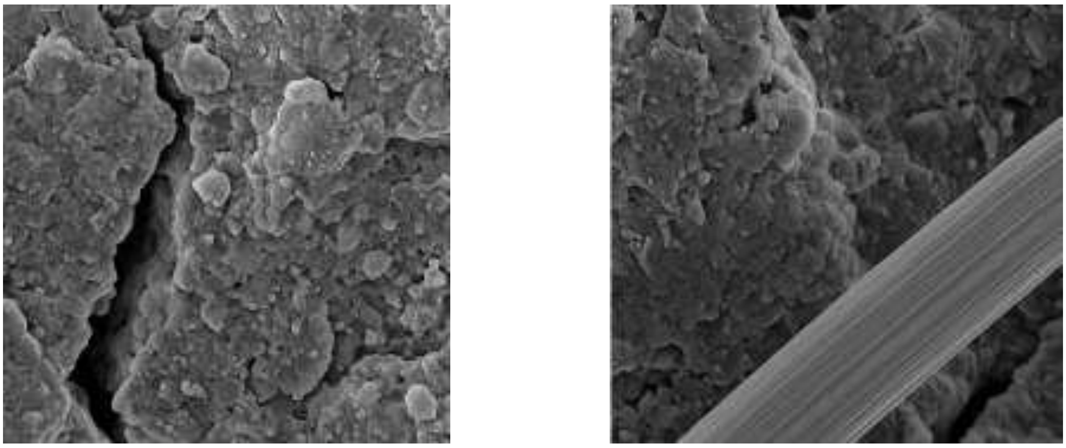

Fig. 8. SEM microstructure of polypropylene-fiber-reinforced polyurethane foam concrete matrix

The relatively constant oxygen (O) content suggests stable hydration products. These changes reflect continued hydration and pozzolanic reactions with fly ash and silica fume, leading to a denser microstructure. Polypropylene fibers show no signs of degradation, which is consistent with their chemical inertness and high melting point [4]. In the micrographs, It can be clearly observed that there are finer pore walls and tighter interfaces in fiber-reinforced specimens. Figure 8 reveals that the control matrix contains large, loosely bound voids, whereas the polypropylene-fiber–reinforced PUFC samples show densified microstructure and bridging across microcracks by fibers. Mechanistically, the polypropylene fibers appear to act as crack-arresters and stress-transfer bridges, thereby restricting pore coalescence and promoting additional nucleation of secondary hydration products at the fiber– matrix interface. These insights align with observations by Hazlin et al., (2017), who reported improved microstructural compactness with PP fibers in foamed concrete, and also it resonates with recent findings in foamed PU systems showing that fiber addition leads to enhanced cell wall integrity and mechanical reinforcement [19]. Nevertheless, a key research gap remains in quantifying how interfacial chemistry and nanoscale hydration kinetics evolve over long durations under adverse exposure.

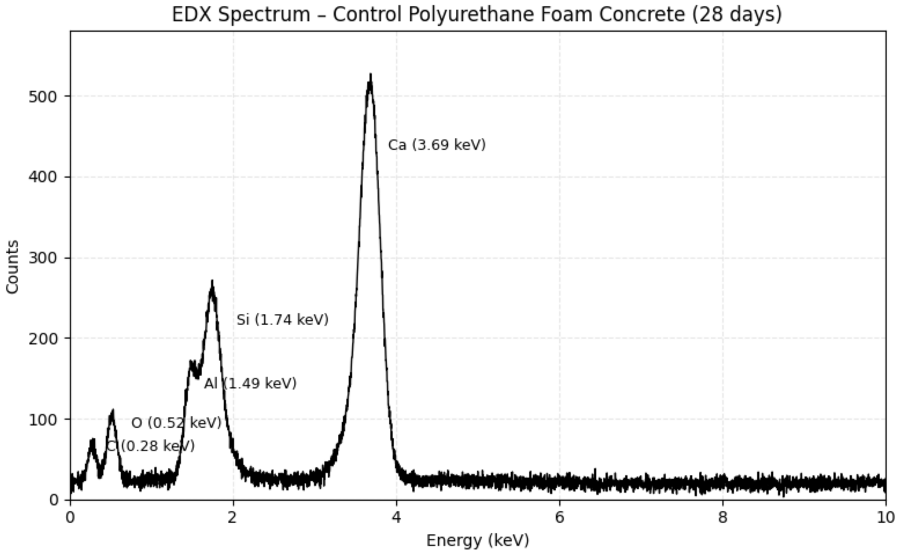

Fig. 9. EDX spectrum of control polyurethane foam concrete at 28 days, showing dominant Ca, Si, Al, O, and C peaks, indicative of hydration products and a relatively calcium-rich cementitious matrix

Figure 9 shows the EDX spectrum of the control polyurethane foam concrete at 28 days, where the elemental composition indicates a relatively calcium-rich and silica-poor matrix compared with the optimum mix. Quantitatively, the atomic percentages reveal Ca at ~22.8 % and Si at ~17.1 %, giving a Ca/Si ratio of ~1.33 for the control specimen, which is significantly higher than that of the optimum mix (Figure 6.2, Ca/Si ~1.00) and typical of a matrix dominated by portlandite and primary C–S–H with limited secondary gel formation. The oxygen content (~50.1 %) remains high, consistent with abundant oxide hydration phases, while carbon (~5.8 %) reflects the presence of polymeric components rather than carbonation. Mechanistically, the elevated Ca/Si ratio in the control indicates less extensive pozzolanic conversion of calcium hydroxide into additional C–S–H, resulting in a coarser pore structure and weaker microstructural integration, which explains the lower compressive and flexural strengths reported earlier. This trend aligns with findings in similar lightweight and fibre-reinforced concretes where higher Ca/Si ratios correlate with increased permeability and reduced mechanical performance (e.g., [4]; [7]; [5]. In contrast to some reports of anomalous elemental spikes in aged foamed concretes, the control EDX pattern here does not show such irregularities, confirming a consistent hydration progression but limit secondary reactions. Overall, the numerical shift toward higher calcium relative to silicon in Figure 6.1 supports the narrative that the control mix's microstructure is comparatively less refined and that introducing polypropylene fibres and SCM synergy in the optimum mix drives more favorable microchemical evolution and performance gains.

Figure 10 (optimum mix) indicates a chemically "leaner-calcium / richer-silica" matrix compared with the control, which is the fingerprint of continued secondary C–S–H formation and pore refinement in foamed systems containing SCMs. Quantitatively, the EDX composition shows Ca decreasing from 60% (28 d) to 55% (90 d) while Si increases from 20% to 25%, with O remaining ~20%, this shifts the Ca/Si ratio from ~3.0 (60/20) at 28 d to ~2.2 (55/25) at 90 d, a direction typically associated with consumption of $Ca(OH)_2$ and growth of additional C–S–H/C–A–S–H gels, which densify the paste and strengthen the ITZ around fibres. Mechanistically, the 10% foam + 1% PP fibre mixture (M3) benefits from a dual action: foam introduces a controlled cellular structure (which can otherwise weaken the matrix), while PP fibres arrest microcrack opening and stabilize the cell walls, allowing hydration and pozzolanic reactions to "convert" more of the available Ca into binding gels rather than leaving a calcium-rich, leachable phase; this aligns with the observed performance balance where the optimum mix achieves ~1890 kg/m^3 density and ~46 MPa compressive strength, indicating that matrix refinement is sufficient to compensate for foam-induced porosity

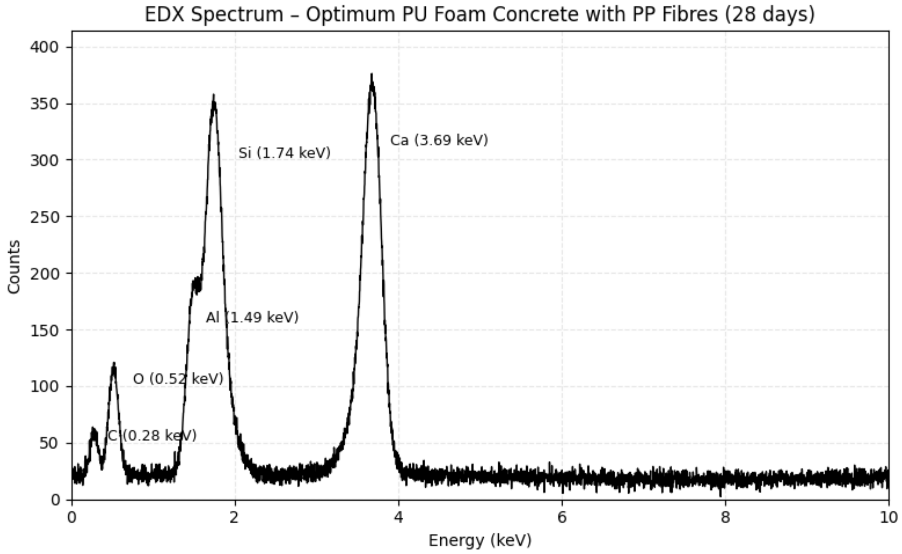

Fig. 10. EDX spectrum of the optimum polyurethane foam concrete incorporating 10% foam and 1% polypropylene fibres at 28 days, showing increased silicon content and reduced calcium intensity, indicative of enhanced C–S–H formation and a denser cementitious matrix

A clear trend is therefore visible (and not a reversal): with age, Ca drops and Si rises, consistent with progressive gel development rather than stagnation; importantly, the lack of any reported anomalous peaks or compositional "spikes" also supports chemical inertness of PP fibres and suggests the improvement is microstructure-driven rather than due to new crystalline phases. Compared with prior fibre-reinforced lightweight/foamed concrete studies that report similar densification signatures under extended curing, the present trend appears more pronounced in the optimum PU-foam system because the fibre bridging reduces crack-connected pathways and helps retain moisture for longer-term reactions, strengthening the link between microchemistry and durability indicators such as reduced ingress pathways.

Table 4. Elemental composition from EDX analysis of polyurethane foam concrete at different curing ages

Mix ID	Ca (%)	Si (%)	O (%)
28-day	60	20	20
90-day	55	25	20

The microstructural assessment provides valuable insights into the progression of hydration and the stability of the fiber–matrix interface over time. As presented in Table 4, the calcium content slightly decreased from 60 % to 55 %, while the silicon fraction increased from 20 % to 25 % between 28 and 90 days, indicating continued pozzolanic activity and the formation of additional C–S–H gel. The Ca/Si ratio derived from Table 4 provides insight into matrix densification, as a lower Ca/Si ratio indicates enhanced formation of secondary C–S–H gel, which is directly associated with improved strength and durability performance. The observed reduction in Ca content with a corresponding increase in Si suggests progressive pozzolanic reactions, leading to a denser microstructure and improved fibre–matrix bonding. SEM observations further support this by showing reduced pore connectivity and more compact hydration products in fibre-reinforced mixes, which explains the lower chloride permeability and enhanced mechanical performance. Mechanistically, this transformation reflects the ongoing reaction of calcium hydroxide with silica fume and fly ash, producing a denser matrix and improved interfacial bonding around the polypropylene fibers. Similar microstructural densification trends were reported by Mydin and Soleimanzadeh [4], who observed enhanced C–S–H development in fiber-reinforced lightweight concretes exposed to prolonged curing. Nevertheless, further nano- scale investigations using TEM or XPS could clarify the evolution of hydration products and fiber– matrix interactions, addressing the current research gap in linking elemental composition to durability and mechanical performance in polyurethane foam concretes.

3.7 Correlation and Optimization

The relationship between compressive strength and density is illustrated in Figure 7. A clear trend emerges: as density decreases from 2400 kg/m^3 to about 1800 kg/m^3, compressive strength initially drops but then recovers when fibers are added. The optimum mix (M3, with 10 % foam and 1 % PP fiber) achieves a density of 1890 kg/m^3 and a compressive strength of 46 MPa. This balance satisfies the structural LWC criteria and delivers high strength. The fitted regression line (R^2 > 0.95) confirms a strong correlation between strength and density. Density reductions beyond 15 % foam (i.e., below 1780 kg/m^3) may compromise strength and promote foam collapse. Thus, foam contents greater than 15 % are not recommended. Additionally, fiber contents above 1 % tend to reduce workability and may lead to fiber balling [5].

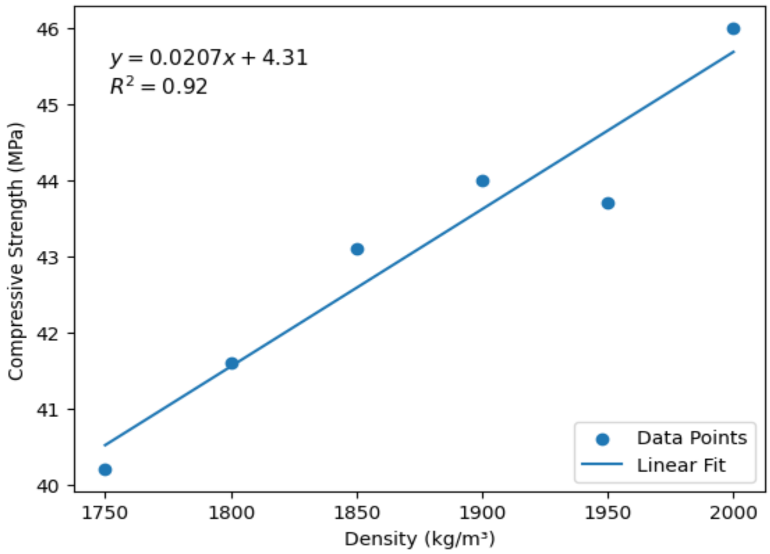

Fig. 11. Correlation between compressive strength and density of polyurethane foam concrete mixes

The trend observed between compressive strength and density of the PU foam concrete incorporated with PP fiber points to a clear trade-off i.e., as density drops through foam incorporation, strength declines. However, with judicious addition of PP fibers, performance can be improved. In Figure 11, it can be observed that beyond a critical density threshold, the strength–density curve becomes steeper, indicating that fibers are effectively compensating for porosity-induced weakening. Mechanistically, PP fibers act as crack-bridging elements that restrain microcrack opening, enhance stress redistribution around voids, and densify the matrix locally, much like what has been reported for fiber-reinforced lightweight concretes [20]. The positive slope of the correlation is consistent with results in foamed-concrete literature, where denser foams yield higher strengths because of reduced void [21]. However, whereas most prior works focus simply on plain foam concretes, our fiber-augmented composite fills a gap in understanding how fiber dosage modulates the strength–density linkage under varying densities.

4. Conclusions

This study has demonstrated that incorporating polypropylene fibers into polyurethane-foam lightweight concrete can produce structural LWCs that exhibit superior strength and durability while maintaining reduced density. A mix with 10 % foam and 1 % fibers achieved a dry density of approximately 1890 kg/m^3, representing a 22 % reduction compared with normal concrete. The same mix attained a 28-day compressive strength of 46 MPa, which is around 30 % higher than the unreinforced foam concrete. Water absorption decreased from 7.0 % to 4.1 %, and chloride ion permeability fell by about 29 %, indicating enhanced resistance to fluid ingress. Drying shrinkage was reduced by roughly 25 % owing to the crack-bridging action of fibers. Microstructural analysis showed dense hydration products around the fibers and no evidence of fiber degradation. These improvements confirm that PP-fiber-reinforced PUF concrete is a durable and economical material suitable for precast panels, bridge decks, marine structures and retrofitting applications. The findings demonstrate that polypropylene fibres effectively compensate for the strength and durability losses typically associated with polyurethane foam incorporation by bridging microcracks, stabilizing the foam-induced cellular structure, and promoting matrix densification. The synergistic interaction between fibres and foam enables the development of lightweight concrete with balanced mechanical performance, reduced shrinkage, and improved resistance to fluid ingress. While the results confirm the effectiveness of the selected mix ranges, the study is limited to laboratory-scale evaluation under controlled conditions, and future work should examine long-term performance under aggressive exposures and explore fibre–foam interactions using advanced quantitative pore analysis techniques. Further research should also explore hybrid fiber systems combining polypropylene with steel or basalt, investigate long-term performance under freeze–thaw and carbonation, and apply finite-element modelling to optimize fiber distribution and foam stability. Life-cycle assessment could also quantify the environmental benefits of this lightweight system.

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