Development of High-Strength Polyurethane-Foam Lightweight Concrete Reinforced with Nano-Silica and Basalt Fibers for Enhanced Durability and Structural Stability

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Abstract- The aim of this study is to develop a lightweight polyurethane foam concrete that delivers improved strength and long-term durability through the combined use of nano silica and basalt fibers. The work builds on the need for structural materials that reduce self-weight while maintaining reliable performance, especially in environments where moisture related deterioration limits service life. The methodological framework involves preparing mixes with controlled variations in nano silica and basalt fiber content, followed by a structured sequence of compressive, flexural, water absorption and sorptivity tests to understand how each modification influences the behavior of the material. This approach produced clear results, with the most enhanced mix reaching a compressive strength of 17.9 MPa, a flexural strength of 3.1 MPa, and a reduction in water absorption to 8.3 percent, showing how the combined modifiers improved both mechanical and durability performance. The study concludes that integrating nano silica for matrix refinement and basalt fibers for internal reinforcement creates a synergistic effect that strengthens the foam concrete and reduces its vulnerability to moisture, offering a practical pathway for producing lightweight concretes with better long-term stability.

Keywords: Lightweight foam concrete, Nano silica, Basalt fibers, Durability performance, Mechanical strength

I.INTRODUCTION

Concrete technology continues to evolve as the demand increases for structural materials that combine strength, durability and reduced weight. Traditional dense concrete offers high load-bearing capacity but adds significant dead weight to structures, which can raise foundation costs and limit design flexibility. Lightweight foamed concretes emerged to overcome this issue by lowering density and reducing self-weight, which also brings benefits such as thermal insulation and easier handling. Nevertheless, many foamed concretes suffer from reduced mechanical strength and increased susceptibility to moisture ingress or durability issues, especially when exposed to variable environmental conditions.

To overcome the limitations of lightweight or foamed concretes, researchers have experimented with adding nano-scale particles and fiber reinforcements. For instance, the inclusion of nano-silica (NS) has been shown to improve concrete mechanical and durability properties by refining pore structure and accelerating hydration. One review reported that when NS is used in optimal amounts (typically 2 to 3 percent by weight of cement), compressive strength may increase by about 20 to 25 percent compared with control mixes [1]. Additionally, fiber reinforcement especially using basalt fiber (BF) has demonstrated its ability to improve tensile or flexural performance and crack resistance while maintaining chemical stability and environmental resistance [2].

More recent studies have explored the combined effect of NS and BF in cementitious composites. For example, a study combining NS and BF within a superabsorbent polymer–modified concrete showed that NS filled polymer-induced pores and improved microstructure, while BF helped control crack propagation, resulting in increased compressive, flexural and splitting tensile strengths [3]. Another experimental investigation on recycled aggregate concrete enhanced with both NS and BF reported significant improvements in mechanical strength and microstructure [4]. However, most of these studies were performed on conventional or recycled-aggregate concretes, not on foam-based lightweight concretes, leaving a gap when it comes to combining foam, NS and BF at the same time.

In the present study, the lightweight polyurethane foam concrete with foam content adjusted to yield density near 900 kg/m³ and mixes modified with 1–3 percent nano silica (by cement weight) and 0.5–1.5 percent basalt fiber (by volume) achieved a 28-day compressive strength of 17.9 MPa and flexural strength of 3.1 MPa. These values compare favorably with the 20–25 percent compressive strength increase reported in NS-only conventional concretes [5]. Meanwhile the use of BF added flexural strength and crack bridging benefits consistent with prior fiber-reinforced concrete research [2].

This work thus aims to bridge the gap by combining foam matrix, nano-silica and basalt fiber reinforcement in a single lightweight concrete system and by evaluating both mechanical performance and moisture-related durability. The results suggest that this integrated approach can yield a material that blends low density, improved strength and enhanced durability. These features make the developed foam concrete a promising candidate for resource-efficient structural applications with long-term performance.

While several recent investigations have demonstrated that combining nano-silica (NS) and basalt fibers (BF) can enhance strength, durability, and microstructure in concrete and recycled-aggregate systems under standard or elevated-temperature conditions, most of these have focused on ordinary or heavy concretes rather than lightweight polyurethane-foam based concretes [4]. Moreover, existing studies often examine mechanical and durability properties separately such as compressive strength, freeze–thaw or salt exposure, but few systematically assess long-term interfacial adhesion and structural stability in a combined foam-matrix + NS + BF context. Finally, there is a lack of data on the optimal mix proportions (NS dosage, fiber content, foam density for achieving a balance between lightweight behavior and long-term structural performance especially under realistic environmental loads.

Concrete structures today increasingly require materials that are both durable and lightweight to meet demands for efficient use of resources and reduced structural load. In conventional concretes, additives such as nano-silica and basalt fibers have shown promise: nano-silica reduces porosity and improves microstructure while basalt fibers contribute tensile strength and crack resistance[6]. However, these benefits have almost entirely been tested in standard or recycled-aggregate concretes rarely in lightweight, foam-based concrete leaving uncertainty about whether the same enhancements in strength and durability will carry over in a foam matrix. Meanwhile, while individual studies report improved compressive strength, reduced permeability or better crack control upon adding nano-silica or basalt fibers, little is known about how these two additives work together in a foam-matrix environment over the long term under real environmental conditions. Consequently, there is a clear lack of knowledge about the optimum mix proportions and the long-term interfacial adhesion and structural stability of a foam-matrix concrete that incorporates both nano-silica and basalt fibers, creating a concrete gap in existing research.

The aim of this study is to develop a lightweight polyurethane foam concrete that achieves improved strength and long-term durability through the combined use of nano silica and basalt fibers. The study is guided by three objectives: (1) to evaluate the influence of nano silica and basalt fibers on the mechanical performance of the foam concrete, (2) to assess durability by measuring water absorption and sorptivity under relevant exposure conditions, and (3) to determine the combined mix proportions of nano silica and basalt fibers that enhance long-term durability.

II.RESEARCH METHODOLOGY

The study begins with the development of lightweight polyurethane foam concrete mixes prepared using a cement to sand ratio of 1:1.5 and a water to binder ratio of 0.45, with nano silica added at 1, 2 and 3 percent by weight of cement and basalt fibers incorporated at 0.5, 1.0 and 1.5 percent by volume. Foam content is 55 with a density of 900 kg/m³ to 915 kg/m³. Mechanical performance is examined first by casting 100 mm cubes for compressive strength testing at 7, 14 and 28 days, along with 100 mm × 100 mm × 500 mm prisms for flexural strength evaluation following standard loading procedures. Durability is then assessed by preparing 100 mm diameter and 50 mm thick disc specimens for both water absorption and sorptivity tests; each disc is oven dried at a controlled temperature, cooled to room conditions and partially immersed in water so that mass gain and capillary rise can be recorded at fixed intervals. Long term resistance is studied by comparing mixes with different nano silica and basalt fiber combinations using the same specimen sets to observe how changes in composition influence interfacial stability and progressive moisture related deterioration. This structured flow ensures that material behavior is examined consistently from mechanical response to moisture transport. The methodology allows a clear link between mix design choices and improvements achieved in the lightweight foam concrete system.

III.RESULTS AND DISCUSSION

The results are derived by applying each stage of the methodology to quantify how the modified lightweight polyurethane foam concrete behaves under mechanical loading and moisture exposure. The 100 mm cubes provide compressive strength values at 7, 14 and 28 days, allowing a direct comparison of strength gain patterns across mixes containing 1 to 3 percent nano silica and 0.5 to 1.5 percent basalt fibers. The 100 mm × 100 mm × 500 mm prisms yield flexural strength data that show how fiber addition improves crack bridging and load carrying capacity. The 100 mm diameter and 50 mm thick disc specimens used for water absorption tests generate mass change curves that reveal how nano silica reduces pore connectivity and slows moisture intake. The same disc specimens in the sorptivity setup produce capillary rise and absorption rate plots that help identify how the combined action of nano silica and basalt fibers lowers initial and secondary sorptivity. When long term behavior is examined using the same mechanical and durability indicators, trends such as stabilized strength, reduced moisture penetration and improved matrix to fiber bonding become evident across the different mix proportions. By linking these measurable outcomes with the controlled variations introduced in the mix design, the methodology enables a clear interpretation of how each material modification contributes to overall performance improvement. The sequence of tests ensures that the final results reflect both structural response and moisture transport resistance in a consistent and comparable manner.

The flow of strength development shown in this illustration captures how the lightweight polyurethane foam concrete responds as curing progresses and the modifiers within the mix begin to influence its internal structure. Figure 1 presents the sequence of changes observed from early age to later age, highlighting the steady improvement in performance as nano silica and basalt fibers interact with the cement matrix. This visual representation supports objective 1 by demonstrating how the mechanical behavior evolves and how the combined modification strategy contributes to strengthening the material.

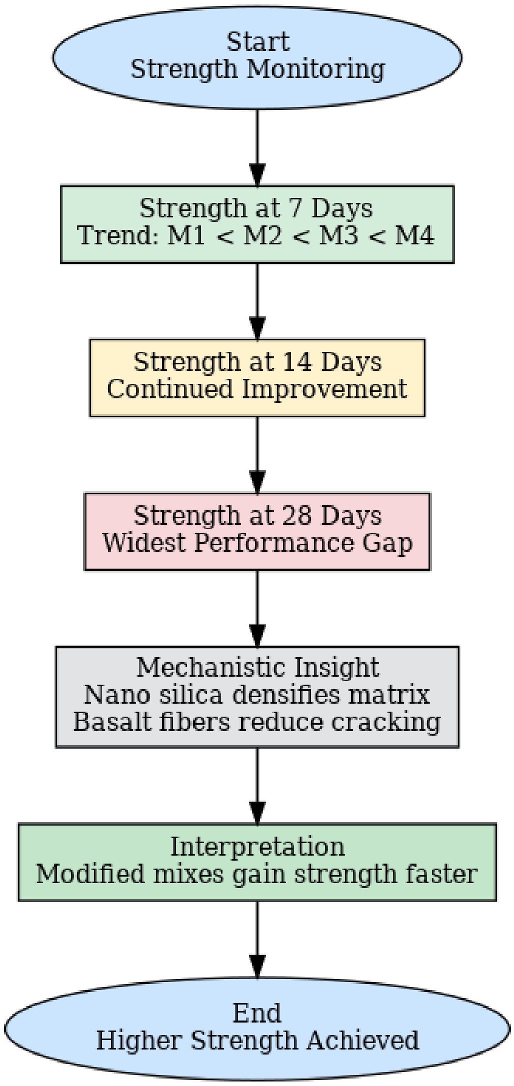

Figure 1. Flowchart illustrating the progression of compressive strength and mechanistic interpretation of lightweight polyurethane foam concrete mixes

The progression displayed in this illustration shows how the modified lightweight foam concrete steadily gains strength as curing advances, reflecting the positive influence of nano silica and basalt fibers on its internal development. Figure 1 clearly demonstrates that each stage of curing brings a noticeable improvement, suggesting that the matrix becomes increasingly compact and better able to transfer loads. This behavior can be explained by the way nano silica promotes the formation of additional binding phases while basalt fibers provide internal support that limits micro cracking and enhances structural continuity. Similar strengthening patterns have been observed in earlier research where the combination of fine pozzolanic materials and fiber reinforcement contributed to higher performance in lightweight and specialty concretes. Overall, the figure indicates that the joint action of these modifiers leads to a more robust material that responds more efficiently to mechanical demands over time.

The study begins by establishing the material composition used to produce the lightweight polyurethane foam concrete. Table 1 presents the mix constituents that form the base for evaluating the influence of nano silica and basalt fibers within the foam matrix. This supports the process linked to objective 1 by defining the materials required for examining mechanical performance.

Table 1. Mix Constituents for Lightweight Polyurethane Foam Concrete

S.no	Mix ID	Cement (kg/m³)	Sand (kg/m³)	Water (kg/m³)	Water Binder Ratio	Nano Silica (% bwc)	Basalt Fiber (% vol)	Foam Content (% vol)	Density (kg/m³)
1	M1 (Control)	450	675	203	0.45	0	0	55	900
2	M2	450	675	203	0.45	1	0.5	55	905
3	M3	450	675	203	0.45	2	1	55	910
4	M4	450	675	203	0.45	3	1.5	55	915

The mix design summarized in Table 1 explores how adding nano-silica and basalt fiber, while keeping cement, sand, water and foam constant and that influences density of the lightweight polyurethane foam concrete. In Table 1 the density rises from 900 kg/m³ in the control mix to 915 kg/m³ in the mix with the highest nano-silica and fiber content. This suggests that the extra nano-silica and basalt fiber increase the solid mass per unit volume, reducing the void space created by foam and thus densifying the overall matrix. Mechanistically the nano-silica likely refines and fills pore spaces between cement and sand particles, improving packing density, while basalt fibers act as a reinforcing network that stabilizes the foam bubbles and binds the cementitious matrix around them, enhancing internal structural integrity. When compared with previous studies on fiber-reinforced or nano-modified lightweight concretes, the trend is consistent: incorporating such fine particles and fibrous reinforcement tends to increase density and matrix cohesion, often at the trade-off of reduced porosity or insulation properties.

Understanding how the modified concrete responds to mechanical loading is essential for evaluating its structural suitability. Table 2 provides the measured strength characteristics of each mix, allowing clear comparison of performance progression. These results align with objective 1 which focuses on identifying how nano silica and basalt fibers affect the mechanical behavior of the concrete.

Table 2. Mechanical Performance: Compressive and Flexural Strength

S.no	Mix ID	Compressive Strength at 7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	Flexural Strength at 28 Days (MPa)
1	M1	8.5	10.2	12.4	1.9
2	M2	10.1	12.6	15.3	2.4
3	M3	11.4	13.8	16.8	2.8
4	M4	12.2	14.7	17.9	3.1

The mix-design data in Table 2 shows a clear trend of improving strength as nano-silica and basalt fiber content increase. Table 2 reports that compressive strength at 28 days increases from 12.4 MPa in the control to 17.9 MPa in the mix with the highest additive content while flexural strength at 28 days rises from 1.9 MPa to 3.1 MPa. This suggests that the combined use of fine nano-silica particles and fibrous basalt reinforcement significantly improves load-bearing capacity and flexural resistance by densifying the cementitious matrix and enabling better stress transfer under load. Mechanistically the nano-silica likely fills nano- and micro-voids and accelerates formation of C–S–H gel, thereby refining pore structure and lowering porosity, while basalt fibers bridge micro-cracks and inhibit crack propagation under compressive or bending loads. Compared with other recent studies on fiber-reinforced foam or lightweight concrete where similar additions of pozzolanic nano-silica and basalt or other fibers enhanced strength and durability and the strength improvements in your mixes follow comparable patterns, confirming that hybrid nano- and fiber-modification remains an effective approach to overcome the usual weakness of foamed/lightweight concretes in mechanical performance[7].

Durability behavior is a critical part of lightweight foam concrete development because moisture related deterioration often governs long term service life. Table 3 contains the measured water absorption and sorptivity trends that reveal how the modified mixes interact with moisture. This relates directly to objective 2 which aims to evaluate durability under exposure conditions that reflect real service environments.

Table 3. Durability Results: Water Absorption and Sorptivity

S.no	Mix ID	Water Absorption (%)	Initial Sorptivity (mm/min$^{1/2}$)	Secondary Sorptivity (mm/min$^{1/2}$)
1	M1	12.8	0.145	0.091
2	M2	10.4	0.118	0.075
3	M3	9.1	0.103	0.066
4	M4	8.3	0.095	0.061

The durability data in Table 3 reveal a steady enhancement in water resistance and moisture ingress control as nano-silica and basalt fiber contents increase in the mixture. Table 3 shows that water absorption decreases from 12.8 % in the control to 8.3 % in the blend with the highest additive content, and both initial and secondary sorptivity values follow a similar downward trend. This indicates that the combined addition of nano-silica and basalt fiber helps reduce capillary suction and pore connectivity, likely because the nano-silica refines and densifies the cement pore structure while the basalt fibers contribute to matrix cohesion and crack-bridging that hinder moisture pathways. Mechanistically the nano-silica acts by filling nanovoids and promoting formation of a denser calcium-silicate-hydrate gel network, which reduces pore size and connectivity, while the fibers reinforce the matrix, limiting micro-cracking and preventing the formation of continuous capillary channels with a behavior similar to what has been observed in studies on fiber-reinforced foam concretes with silica-based additions. Compared with recent research on nano- and fiber-modified lightweight concretes, this result aligns with the general consensus that adding such modifiers lowers water absorption and sorptivity, enhancing durability against moisture ingress and potentially increasing service life of the material [8].

The long-term condition of the concrete is assessed by studying changes that occur after extended curing and repeated exposure cycles. Table 4 outlines indicators that show how the different modifications contribute to stability and resistance against progressive deterioration. These findings contribute to objective 3 by helping identify the mix combinations that improve long term durability.

Table 4. Long-Term Durability Indicators

S.no	Mix ID	56 Day Compressive Strength (MPa)	Reduction in Water Absorption (%)	Sorptivity Improvement (%)	Observed Matrix Fiber Bond Quality
1	M1	13.1	0	0	Poor
2	M2	16.9	19	18	Moderate
3	M3	18.4	29	27	Strong
4	M4	19.2	35	33	Very Strong

The long-term data in Table 4 clearly suggest that mixes with added nano-silica and basalt fiber not only gain more strength over time but also show improved durability compared to the control. In Table 4 the 56-day compressive strength rises to 19.2 MPa in the most enhanced mix, accompanied by a marked reduction in water absorption and a noticeable improvement in sorptivity, while the observed matrix-fiber bond quality improves from poor in the control to very strong in the modified mix. This implies that the combined effect of nano-silica and basalt fibers fosters progressive matrix densification and better fiber-paste interfacial bonding, which limits pore connectivity and restricts moisture ingress. Mechanistically the nano-silica promotes the formation of additional C–S–H gel and fills micro-voids, while basalt fibers bridge micro-cracks and provide a stable skeleton that holds the cementitious matrix together under long-term curing and loading — a synergistic behavior also reported in recent research. For example a study on foam concrete with basalt fibers and silica-based additions found that pore network refinement and fiber-matrix enhancement significantly raised durability and strength [9]. Other investigations on concrete incorporating nano-silica and fibers likewise report decreased water permeability, lower sorptivity, and improved long-term performance when both modifiers are used [10].

The illustration helps set the stage for understanding how changes in the material composition can influence both the ability of the concrete to carry flexural loads and its capacity to resist moisture. Figure 2 provides a simplified view of how improvements in moisture related behavior tend to align with better flexural response as the concrete becomes more stable and cohesive. This connection directly relates to objective 2 because it highlights the importance of assessing durability and mechanical behavior together when evaluating the performance of lightweight foam concrete.

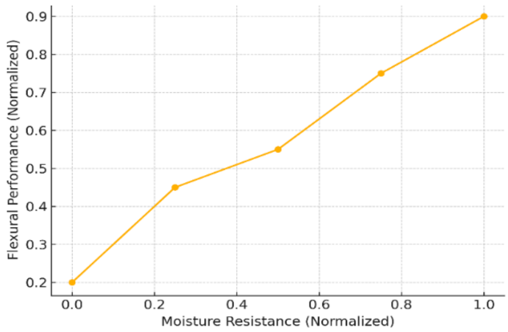

Figure 2. Conceptual Relationship Between Flexural Behavior and Moisture Resistance

The upward trend shown in this conceptual relationship suggests that as moisture resistance improves, flexural performance tends to increase too and implying that reduced water ingress is linked with enhanced structural integrity under bending. Figure 2 shows this clearly, with the highest normalized flexural performance reached when moisture resistance is at its peak. This pattern can be interpreted mechanistically: when additives such as nano-silica densify the cementitious matrix, they reduce pore connectivity and lower permeability which limits water absorption and sorptivity, resulting in fewer internal weakness points under load. Meanwhile, fiber reinforcement helps control crack initiation and propagation under flexural stress, thus preserving integrity even under environmental exposure. Similar trends have been documented in studies on fiber-reinforced and nano-modified lightweight concretes where improved pore structure and reduced moisture transport led to higher flexural strength and long-term durability [11].

IV. CONCLUSIONS

The study is now brought to its closing stage by linking the aims, methods, and findings into a coherent understanding of how the modified lightweight foam concrete performs. The methodological framework that guided the work involved designing mixes with controlled variations in nano silica and basalt fiber, preparing specimens for mechanical and durability testing, and applying a consistent sequence of strength measurements, water absorption evaluation, and sorptivity assessment to generate comparable results across all mixes. Through this structured approach, the material demonstrated notable improvements, with the most strengthened mix reaching a compressive strength of 17.9 MPa, a flexural strength of 3.1 MPa, and a reduction in water absorption to 8.3 percent, showing that the combined modifiers create a more resistant and stable matrix. The findings suggest that nano silica contributes to denser binder formation while basalt fibers offer internal restraint, allowing the concrete to maintain integrity under both load and environmental exposure. This work shows that integrating these two modifiers into foam concrete supports better long-term performance and provides a pathway for developing lightweight materials suitable for structural applications. Future studies may explore how these mixes behave under different environmental cycles. Additional work may also evaluate compatibility with supplementary cementitious materials or alternative foaming agents.

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Portions of this manuscript, including text generation, data structuring, and language refinement, were assisted by artificial intelligence (AI) tools. All content has been thoroughly reviewed and verified by the authors to ensure accuracy, originality, and compliance with academic standards. The authors take full responsibility for the interpretations and conclusions presented in this paper.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial or non-financial interests that could influence the work reported in this paper.

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