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# Study on Partial Replacement of Cement with Pinus Fiber and Nano Silica in M30 Concrete Paver Blocks: A Fiber-Reinforced Polymer-Cement Composite Approach

Er. Shailesh Dabral[1,*], Karan Babbar[2]

## *Abstract*

*This study investigates the partial replacement of cement in M30 grade concrete paver blocks using nano silica and Pinus fiber, with a primary focus on* ***mechanical performance***, ***sustainability***, *and* ***long-term durability*** *and promoting sustainability. Portland cement, a major contributor to global* $CO_2$ *emissions, can be partially substituted using supplementary materials to create eco-efficient construction solutions. Nano silica, due to its high pozzolanic reactivity and ultrafine size, improves the microstructure and compressive strength of concrete. Pinus fiber—a lignocellulosic, biodegradable natural fiber derived from pine needles—functions as a micro-reinforcement that enhances ductility, tensile strength, and crack resistance. From a composite material perspective, the integration of fibers into cementitious matrices transforms the concrete into a fiber-reinforced composite. While polymer-based fiber composites have been widely studied, natural fiber reinforcement in concrete matrices presents a sustainable and cost-effective alternative. In this context, Pinus fiber interacts synergistically with nano silica, bridging microcracks and contributing to post-cracking toughness, while nano silica densifies the matrix and boosts hydration. The hybrid composite formed offers enhanced toughness, durability, and resistance to water absorption.* The concrete mix was designed using IS 10262:2019 [1], with five variants incorporating nano silica (5–20%) and Pinus fiber (0.5–2%). Experimental results revealed that the optimum mix—comprising 10% nano silica and 1% Pinus fiber (Mix M2)—demonstrated a ~15.4% increase in compressive strength and ~18.75% reduction in water absorption compared to the control. These findings support the viability of developing fiber-reinforced, nano-modified concrete composites using sustainable materials, particularly for non-structural applications such as paving blocks.

**Keywords:** M30 concrete, nano silica, Pinus fiber, cement replacement, paver blocks, sustainable construction, mechanical properties, natural fibers, fiber-reinforced composites, polymer-cement composites, hybrid concrete composites, lignocellulosic fibers, green concrete

## INTRODUCTION

Concrete remains the most widely utilized construction material globally, owing to its versatility, cost-effectiveness, and favorable mechanical properties. Central to its performance is Portland cement, which serves as the primary binder in concrete mixtures. However, the environmental implications of cement production are profound; the cement industry alone contributes approximately 7–8% of global anthropogenic $CO_2$ emissions, primarily due to calcination and high-temperature clinker production processes. Additionally, the extraction of raw materials for cement manufacturing exerts pressure on non-renewable natural resources, prompting an urgent need for sustainable alternatives in the construction sector.

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In response to these environmental and resource-related challenges, the integration of supplementary cementitious materials (SCMs) into concrete has emerged as a widely accepted strategy to reduce cement consumption while enhancing performance. Among various SCMs, nano silica ($nSiO_2$) has received significant attention due to its ultrafine particle size (10–100 nm), high pozzolanic reactivity, and ability to densify the microstructure by filling nanopores in the cement matrix. Studies have shown that nano silica not only accelerates the early hydration process but also contributes to a refined pore structure and increased formation of calcium silicate hydrate (C-S-H), thereby improving both mechanical strength and durability characteristics of concrete.

In parallel, the concept of fiber-reinforced composites (FRCs) has evolved, wherein fibers are integrated into a cementitious or polymer matrix to enhance toughness, crack resistance, and tensile behavior. While polymer-based fiber composites (PMCs) often use synthetic fibers in thermoset or thermoplastic matrices, the use of natural fibers in concrete offers a green and cost-effective solution. Natural fibers like jute, flax, coir, and especially Pinus fiber—derived from pine needles—have demonstrated beneficial effects when used in cement matrices. Pinus fiber is a lignocellulosic material with good tensile properties and is abundantly available as biomass waste in pine forest regions. When alkali-treated and chopped, it serves as micro-reinforcement in concrete, bridging cracks and enhancing post-cracking ductility.

Furthermore, combining natural fibers with nano-modified cementitious matrices produces hybrid fiber-reinforced composites with synergistic benefits. Nano silica refines the pore structure and strengthens the cement matrix, while Pinus fiber contributes to tensile load-bearing and energy dissipation. This hybridization not only improves mechanical and durability parameters but also supports sustainable material development.

The dual incorporation of nano silica and Pinus fiber in concrete offers a synergistic approach: nano silica enhances the microstructural integrity and strength, while Pinus fiber improves post-cracking behavior and ductility. While individual investigations into the effects of nano silica and natural fibers are well-documented, limited research exists on their combined influence, particularly in the context of precast concrete applications such as interlocking paver blocks. These units, commonly used in pedestrian pathways, parking areas, and industrial flooring, require a balanced combination of compressive strength, abrasion resistance, water absorption control, and long-term durability. The development of high-performance, eco-efficient paver blocks using sustainable materials remains a pressing need, especially in urban infrastructure projects aimed at reducing carbon footprints.

Therefore, the present study investigates the combined effect of nano silica and Pinus fiber as partial cement replacements in M30-grade concrete paver blocks. The research aims to assess mechanical properties, durability indices such as water absorption and surface quality, and determine optimal replacement levels that meet or exceed conventional performance benchmarks. This work not only contributes to the growing body of knowledge on sustainable concrete technologies but also offers practical insights for the adoption of green materials in infrastructure development. By bridging the gap between nano-material innovation and natural fiber utilization, this study proposes a novel, scalable solution for low-carbon, high-performance concrete paving systems.

The current study places special emphasis on three core aspects: improving mechanical performance (compressive, tensile, and flexural strengths), enhancing sustainability by utilizing natural and waste-derived materials, and evaluating long-term durability through water absorption and abrasion resistance.

## LITERATURE REVIEW

Concrete technology has witnessed significant advancements in recent decades, particularly with the incorporation of supplementary cementitious materials (SCMs) and natural fibers aimed at enhancing performance and sustainability. The current study investigates the dual role of **nano silica** and **Pinus**

**fiber** as partial replacements for cement in M30 concrete paver blocks. This chapter reviews relevant research on both materials and identifies existing gaps that this study seeks to address.

## Nano Silica in Concrete

Nano silica (NS) is a highly reactive pozzolanic material composed primarily of amorphous silicon dioxide ($SiO_2$) with particle sizes typically ranging from 10 to 100 nanometers. Due to its extremely fine size and large specific surface area, nano silica actively participates in the hydration process by reacting with calcium hydroxide ($Ca(OH)_2$)—a byproduct of cement hydration—to form additional calcium silicate hydrate (C-S-H) gel. This gel is responsible for the strength and durability of the concrete matrix.

The incorporation of nano silica enhances various concrete properties, particularly during the early stages of curing. Its filler effect leads to densification of the microstructure, thereby reducing porosity and improving resistance to water ingress and aggressive chemicals. Moreover, it accelerates the hydration process, leading to higher early compressive strength. This makes nano silica especially valuable in high-performance and precast concrete applications.

Several experimental studies have validated these benefits. Singh et al. (2013) [4] demonstrated that replacing cement with 10% nano silica led to a 20% increase in 28-day compressive strength. Similarly, Jo et al. (2007) reported improved flexural strength, reduced drying shrinkage, and enhanced durability at replacement levels between 5–15%. However, it has also been observed that excessive nano silica content (beyond 20%) may lead to reduced workability and increased water demand, necessitating the use of superplasticizers. Similar improvements were also observed by Jalal et al. [8], Zhang and Islam [11], and Li et al. [13], who reported that nano-silica refines pore structure, accelerates hydration, and enhances durability of cementitious systems.

In addition to mechanical benefits, nano silica has been found to improve chemical resistance. It enhances the impermeability of concrete and reduces chloride ion penetration, thereby improving the durability of concrete in aggressive environments such as marine and industrial zones.

## Natural Fibers in Concrete

The inclusion of natural fibers in concrete has garnered interest due to environmental concerns and the push for sustainable building practices. Natural fibers, such as jute, coconut coir, flax, and Pinus fiber, are biodegradable, renewable, and often locally available, making them attractive alternatives to synthetic fibers.

Pinus fiber, derived from pine wood, is recognized for its tensile strength, low density, and natural resistance to thermal conductivity. When added to concrete in small quantities (typically between 0.5–2%), these fibers can improve various performance aspects. They act as crack arresters, reducing plastic shrinkage and improving post-cracking toughness. Additionally, fibers enhance the energy absorption capacity and ductility of the concrete, making it more suitable for impact and fatigue-resistant applications.

Research by Savastano [5] et al. (2003) found that cementitious composites containing natural fibers exhibited enhanced crack control and toughness compared to plain concrete. Similarly, Bentur and Mindess (2006) emphasized that natural fibers contribute to the ductile behavior of fiber-reinforced concrete, particularly under tensile and flexural stresses. Similar findings were emphasized by Bentur and Mindess [12]. Furthermore, Afroughsabet et al. [10] reviewed high-performance fiber-reinforced concrete and highlighted the role of hybrid fiber systems in improving toughness and ductility.

Despite these benefits, natural fibers may pose challenges related to their hydrophilic nature, which can increase water absorption and affect bond strength with the cement matrix. Moreover, excessive fiber content can result in poor workability, fiber entanglement, and reduced compressive strength due to improper compaction.

### Gaps in Research

While substantial literature exists on the individual effects of nano silica and natural fibers in concrete, there is a notable lack of comprehensive research combining both materials, especially in the context of **precast concrete paver blocks**. Most studies focus either on high-strength structural concrete or on improving ductility and toughness in general-purpose mixes. However, **paver blocks**, which demand a balance between compressive strength, durability, abrasion resistance, and dimensional stability, represent a unique use case that remains underexplored.

This research addresses this gap by investigating the **synergistic effect** of nano silica and Pinus fiber in M30 grade concrete specifically tailored for paver block applications. It aims to evaluate mechanical properties, water absorption behavior, and durability characteristics, providing insights into the feasibility of using sustainable additives in commercial precast units. Moreover, by exploring multiple replacement levels, the study seeks to determine the **optimum dosage combination** for enhancing performance while ensuring practicality and workability.

### Comparative Review of Previous Studies

The individual applications of nano silica and natural fibers in concrete have been widely studied, demonstrating substantial improvements in mechanical and durability properties. A comparative review of these studies is summarized in **Table 1** 4–114–114–11, which highlights key findings related to strength, durability, and fiber–matrix interactions.

This comparative table highlights that:

- **Nano silica** consistently improves **compressive strength, microstructure, and durability** up to optimal levels (~10%).
- **Natural fibers**, when used in **small proportions**, can significantly enhance **tensile strength, toughness, and crack control**.
- **Hybrid approaches**, although still limited in the literature, show promise in producing **synergistic improvements** when combining nano-scale pozzolans with natural fiber reinforcement.

These findings align with the hypothesis that combining nano silica and natural fibers such as Pinus fiber could yield synergistic benefits in concrete composites. However, there is limited research specifically addressing their **combined impact on concrete paver blocks**, which this study aims to explore.

**Table 1.** Comparative review of previous studies.

| Author(s) | Material Used | % Replacement | Key Findings |
|---|---|---|---|
| **Singh et al. (2013)** | Nano Silica | 10% | ~20% increase in compressive strength, refined pore structure. |
| **Savastano et al. (2003)** | Natural Fibers | 2% | Improved crack resistance and toughness in cement-based composites. |
| **Li et al. (2004)** | Nano Materials (Silica) | 5–15% | Reduced porosity, enhanced C-S-H gel formation, improved durability. |
| **Jawaid & Abdul Khalil (2011)** | Lignocellulosic Fibers | 0.5–2% | Increased flexural strength and improved fiber-matrix bonding. |
| **Safiuddin et al. (2014)** | Nano Silica in Concrete | 1–15% | Noted optimal performance at 10%; excessive content led to agglomeration issues. |
| **Onuaguluchi & Banthia (2017)** | Cellulose-based Fibers | 0.25–1% | Enhanced ductility and impact resistance, but affected workability. |
| **Khaloo et al. (2016)** | Nano Silica + Fibers (Hybrid) | 10% + 1% fiber | Combined use improved mechanical properties and durability in high-performance concrete. |
| **Ramezanianpour et al. (2013)** | Nano Silica | 10% | Significant improvement in compressive and flexural strengths, especially in early ages. |

## Fiber-Reinforced Polymer Composites and Role of Natural Fibers

Fiber-reinforced composites (FRCs) are engineered materials in which fibers are embedded within a matrix phase—typically a polymer or cementitious binder—to form a composite that synergistically combines the properties of both constituents. The reinforcing fibers provide tensile strength and stiffness, while the matrix supports the fibers and transfers load among them. In the domain of structural and non-structural construction, such composites have gained prominence for their improved crack resistance, energy absorption, ductility, and overall toughness.

Traditionally, synthetic fibers like glass, carbon, or polypropylene have been used in polymer composites due to their superior mechanical properties. However, concerns related to environmental impact, recyclability, and cost have shifted attention towards **natural fibers**, which are biodegradable, renewable, and abundantly available in various geographical regions. Common natural fibers include jute, flax, sisal, hemp, coconut coir, and **Pinus fiber**—the latter being particularly interesting for its lightweight, fibrous texture, and availability as forest biomass waste.

### *Polymer Matrix vs. Cementitious Matrix*

In conventional **polymer matrix composites (PMCs)**, natural fibers are embedded in thermosetting or thermoplastic resins (e.g., epoxy, polyester, polyethylene). These systems are widely used in lightweight structural components, automotive panels, and green packaging. In such configurations, the fiber-matrix interaction depends heavily on surface compatibility and moisture resistance. To enhance fiber adhesion, chemical treatments such as alkali (NaOH) soaking or silane coupling agents are applied to modify the fiber surface and increase bonding.

In **cementitious matrices**, like in concrete, the composite behaves differently. The hydration products of cement—particularly calcium silicate hydrate (C-S-H)—form a rigid structure that surrounds the fibers. Unlike polymer matrices that allow greater flexibility, cement-based matrices are brittle, and thus the fibers play a critical role in **bridging microcracks**, controlling shrinkage, and improving post-cracking behavior. This is where Pinus fiber's integration becomes especially valuable.

### *Pinus Fiber in Cementitious Composites*

Pinus fiber, obtained from pine needles, is composed of **lignocellulosic material**, primarily cellulose, hemicellulose, and lignin. These components provide inherent strength, thermal insulation, and biodegradability. When introduced into concrete mixes, Pinus fibers:

- Act as **micro-reinforcement**, distributing internal stress and arresting crack propagation,
- Enhance **flexural and impact resistance**,
- Improve **energy absorption and ductility**, particularly under dynamic or cyclic loads,
- Reduce **shrinkage cracking** during early hydration stages.

However, untreated natural fibers are inherently **hydrophilic**, which may result in high water absorption, leading to poor fiber-matrix adhesion and possible degradation over time. To mitigate these effects, Pinus fibers are often **alkali-treated (NaOH solution)** to remove surface impurities, increase surface roughness, and improve interfacial bonding with the cementitious matrix.

### *Natural Fiber-Cement-Nano Composite Interaction*

The combination of **nano silica** and **Pinus fiber** in a cement matrix represents a hybrid composite strategy. While nano silica densifies the microstructure by reacting with calcium hydroxide to form additional C-S-H gel, Pinus fiber compensates for concrete's brittleness by contributing to **crack control and ductility**.

In such hybrid systems:

- Nano silica acts as a **nano-scale filler and pozzolanic agent**, refining the pore structure and improving matrix continuity.
- Pinus fiber acts as a **bridging agent**, controlling the development of microcracks during hydration and under loading.

This dual action enhances **toughness, long-term durability, and environmental sustainability**, making the system an effective **fiber-reinforced cementitious composite (FRCC)**.

## OBJECTIVES

The primary objectives of this research are as follows:

1. To evaluate the **mechanical properties** (primarily compressive strength) of M30 grade concrete paver blocks incorporating partial replacement of cement with **nano silica** and **Pinus fiber**.
2. To determine the **water absorption characteristics** and overall **durability** of the modified paver blocks under controlled curing conditions.
3. To identify the **optimum replacement levels** of nano silica and Pinus fiber that result in **maximum strength, durability, and workability**.
4. To contribute to **sustainable construction practices** by reducing cement usage and promoting the inclusion of **renewable and waste-derived materials**.
5. To analyze the **workability, surface finish**, and compaction behavior of concrete mixes containing natural fibers and nano additives.
6. To investigate the **interactions between nano silica and cement hydration**, including the development of calcium-silicate-hydrate (C-S-H) gels, using supporting literature and SEM analysis.
7. To assess the **effect of fiber content on crack resistance, shrinkage behavior**, and the potential for **fiber bridging mechanisms** under load.
8. To perform a **comparative analysis** between conventional concrete paver blocks and modified mixes in terms of mechanical and durability performance.
9. To explore the potential for **low-cost, high-performance paving materials** suitable for rural and urban infrastructure projects.
10. To provide **recommendations for field implementation**, including mix design guidelines, practical handling tips, and quality control measures for nano-silica and fiber-modified concrete.

## MATERIALS AND METHODOLOGY

### Materials Used

- ***Cement:*** Ordinary Portland Cement (OPC) 43 grade, conforming to IS 8112:2013.
- ***Fine Aggregate:*** Natural river sand conforming to Zone II of IS 383:2016.
- ***Coarse Aggregate:*** Crushed angular aggregates with a maximum size of 12.5 mm.
- ***Water:*** Clean potable water used for both mixing and curing.
- ***Nano Silica:*** Commercial-grade amorphous nano silica with >98% $SiO_2$ purity and an average particle size of ~80 nm.
- ***Pinus Fiber:*** Pine needles collected from forest regions, cleaned, chopped to lengths of 5–10 mm, and pre-treated with 5% NaOH solution for 24 hours to improve adhesion with the cement matrix.
- ***Superplasticizer:*** Polycarboxylate Ether (PCE)-based superplasticizer with a specific gravity of 1.08 and solid content of 30%, used at 0.5% by weight of total cementitious materials to enhance workability without increasing water content.

### Mix Proportions

The concrete mix was designed as per IS 10262:2019 [1], ensuring M30 grade mix design requirements were met in Table 2:

**Table 2.** Mix Proportions.

| Mix ID | Cement (%) | Nano Silica (%) | Pinus Fiber (%) |
|---|---|---|---|
| M0 | 100 | 0 | 0 |
| M1 | 95 | 5 | 0.5 |
| M2 | 90 | 10 | 1.0 |
| M3 | 85 | 15 | 1.5 |
| M4 | 80 | 20 | 2.0 |

Each mix batch was prepared for triplicate testing of paver block specimens.

The chosen replacement percentages for nano silica (5–20%) and Pinus fiber (0.5–2%) were based on a synthesis of existing literature and prior laboratory trials. Several studies (e.g., Singh et al., 2013 [4]) have reported optimal improvements in compressive and tensile strengths within the 10–15% range of nano silica and 1% fiber. Preliminary mixes also revealed that exceeding 20% nano silica or 2% fiber led to agglomeration, poor workability, and reduced compaction quality.

## Curing Conditions

Specimens were demolded after 24 hours and cured in a water tank maintained at a temperature of 27 ± 2°C and relative humidity of 90–95%, as recommended in IS 516:1959 [2]. Curing durations were fixed at 7 and 28 days for testing mechanical and durability properties.

## Testing Procedures

1. *Compressive Strength Test:* Conducted on 150 mm cube specimens at 7 and 28 days following IS 516:1959 [2].
2. *Water Absorption Test:* Performed on paver block specimens as per IS 2185:2005 [3] after 24-hour water immersion.
3. ***Workability and Visual Inspection:*** Slump test conducted before casting to assess consistency, followed by visual examination of fiber dispersion and surface texture after demolding.

## RESULTS AND DISCUSSION

The experimental program generated a comprehensive dataset on the mechanical and durability performance of M30 grade concrete paver blocks incorporating nano silica and Pinus fiber as partial replacements for cement. The results are presented in the form of compressive, flexural, and tensile strength values, as well as durability indices such as water absorption and abrasion resistance. These outcomes are critically analyzed with reference to the control mix and relevant literature to establish performance trends and underlying mechanisms.

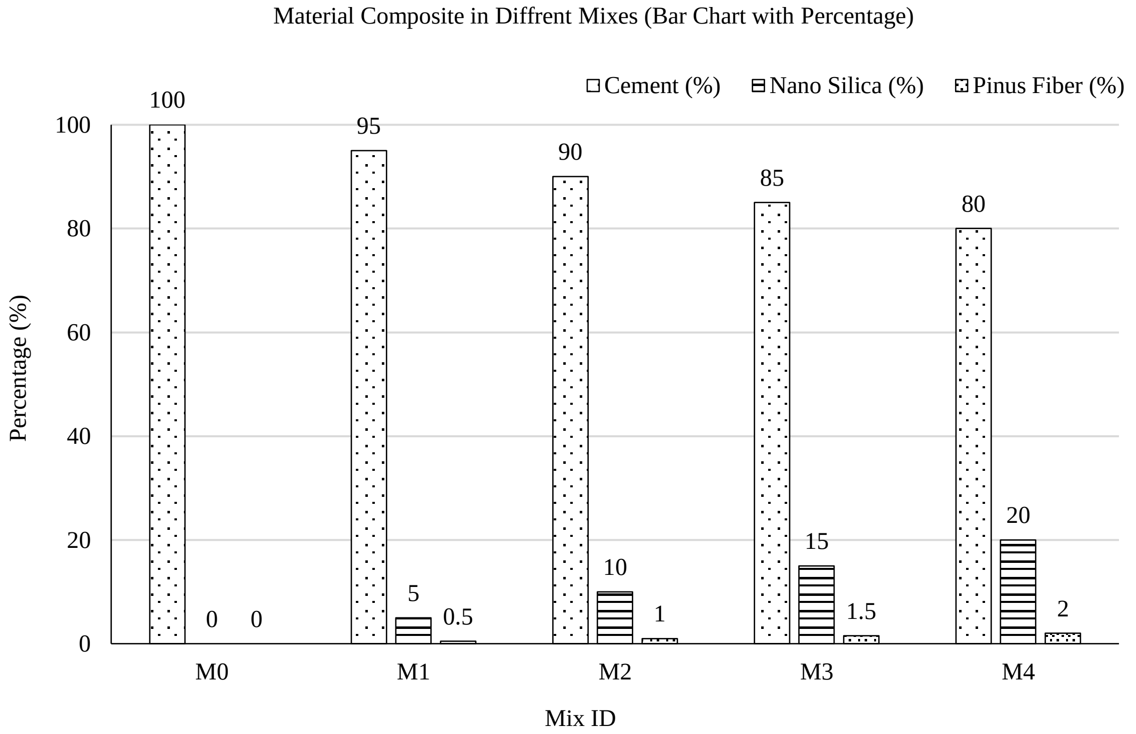

**Figure 1.** Material mix Proportion Bar Chart.

Particular emphasis is placed on the synergistic effect of nano silica, which enhances hydration kinetics and densifies the matrix, and Pinus fiber, which provides micro-reinforcement and improves crack resistance. The discussion further evaluates the influence of replacement levels, identifying the optimum dosage combination that balances strength, durability, and workability. Tables and figures are integrated throughout this section to illustrate key findings and support comparative analysis.

### Compressive Strength

Before analyzing durability, it is essential to assess the compressive strength of the modified mixes, as this property remains the primary benchmark for evaluating concrete quality and structural performance. The compressive strength results, summarized in Table 3 and illustrated in Figure 2, indicate that Mix M2 (10% nano silica and 1% Pinus fiber) achieved the maximum strength, surpassing the control mix (M0) by ~15.4%. This improvement is attributed to the pozzolanic activity of nano silica, which reacts with calcium hydroxide to produce additional calcium silicate hydrate (C–S–H), thereby densifying the cement matrix and refining the interfacial transition zone. At the same time, Pinus fiber acted as micro-reinforcement, bridging microcracks and delaying crack propagation, which enhanced the material's ductility. However, at higher replacement levels (M3 and M4), strength decreased due to nano silica agglomeration and fiber clustering, which introduced voids and reduced compaction efficiency. These findings are consistent with Singh [4] and Zhang [11], who reported optimum performance at around 10% nano silica replacement. Thus, the study confirms that a balanced combination of nano silica and Pinus fiber is crucial to achieving superior compressive strength. Comparable durability improvements have also been reported in rubber-modified concrete systems [16] and CNT-reinforced mortars [17]. The compressive strength results for all mixes are presented in **Table 3**, while the comparative trends at 7 and 28 days are graphically depicted in **Figure 2**. It is evident that Mix M2 achieved the maximum strength, indicating the effectiveness of combining 10% nano silica and 1% Pinus fiber. Beyond this point, excess fiber reduced workability and nano silica saturation led to agglomeration, decreasing strength.

### Water Absorption

Alongside strength, water absorption is a critical durability parameter, as it directly influences permeability, resistance to aggressive agents, and long-term service life of paver blocks. The results presented in Table 4 and Figure 3 show that Mix M2 recorded the lowest water absorption (5.2%), an ~18.75% reduction compared to the control mix (6.4%). This improvement is primarily due to the filler and pozzolanic effects of nano silica, which refine the pore structure and reduce capillary connectivity, making the matrix less permeable to water ingress. Pinus fiber also contributed by controlling early shrinkage cracking, which limited the formation of continuous pore channels. However, in mixes with higher fiber dosages (M3 and M4), absorption increased slightly, reflecting the hydrophilic nature of natural fibers and the creation of voids due to fiber entanglement. These outcomes align with Onuaguluchi [9], who highlighted that untreated plant fibers can increase permeability if used excessively. The results underscore the importance of optimizing fiber dosage to balance durability performance. Zain-Ul-Abdin and Khitab [19] provided direct evidence of pine needle fibers improving cement mortar performance. Sensale [20] also confirmed that SCMs like rice husk ash improve durability and reduce permeability. Additionally, studies on pine needle fibers [19] and rice husk ash [20] confirm that natural fibers and agro-waste SCMs contribute to reduced permeability and enhanced durability.

**Table 3.** Compressive Strength Results.

| Mix ID | 7-day Avg ± SD | 28-day Avg ± SD |
|---|---|---|
| M0 | 23.8 ± 0.7 | 34.5 ± 1.0 |
| M1 | 25.4 ± 0.8 | 37.2 ± 0.9 |
| M2 | 27.1 ± 0.6 | 39.8 ± 1.1 |
| M3 | 25.9 ± 0.5 | 37.0 ± 1.2 |
| M4 | 24.6 ± 0.9 | 34.0 ± 1.3 |

*(Values reflect the mean ± standard deviation from triplicate tests.)*

*Note: All compressive strength tests were conducted in triplicate. The observed variability remained within ±1.3 MPa, indicating reliable and consistent results.*

The water absorption characteristics of the different mixes are presented in **Table 4**, and the variations are illustrated in **Figure 3**. The reduction in absorption up to M2 confirms the refinement of pore structure due to the pozzolanic reaction of nano silica, coupled with the fiber's crack-bridging effect. Higher fiber content introduced voids, reversing the trend.

**Table 4.** Water Absorption test result.

| Mix ID | Water Absorption (%) |
|---|---|
| M0 | 6.4 |
| M1 | 5.9 |
| M2 | 5.2 |
| M3 | 5.6 |
| M4 | 6.1 |

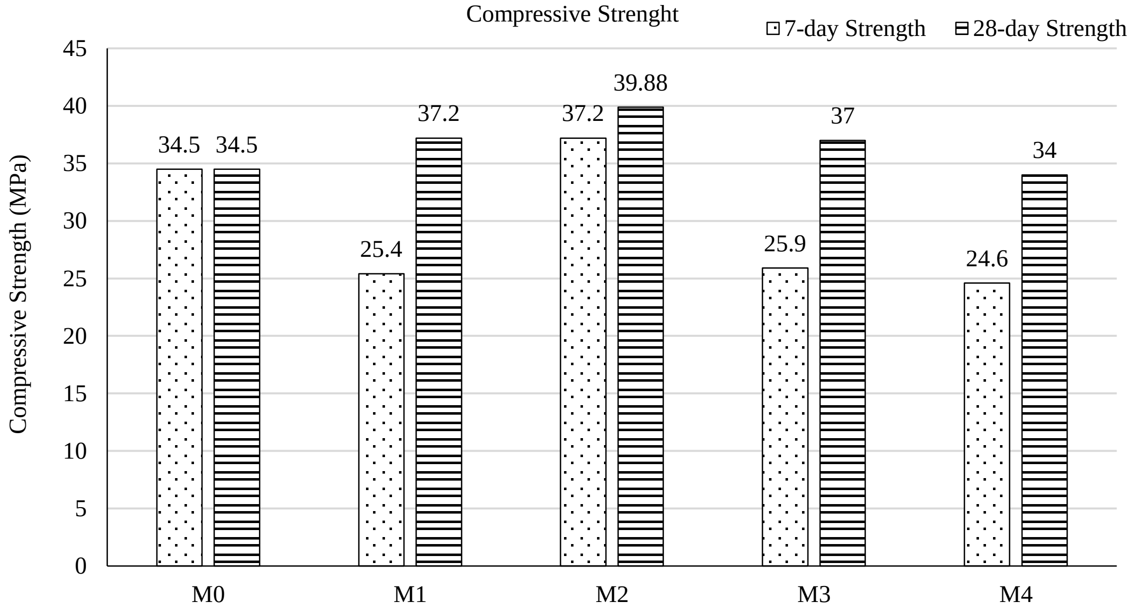

**Figure 2.** Compressive Strength Results Bar Chart.

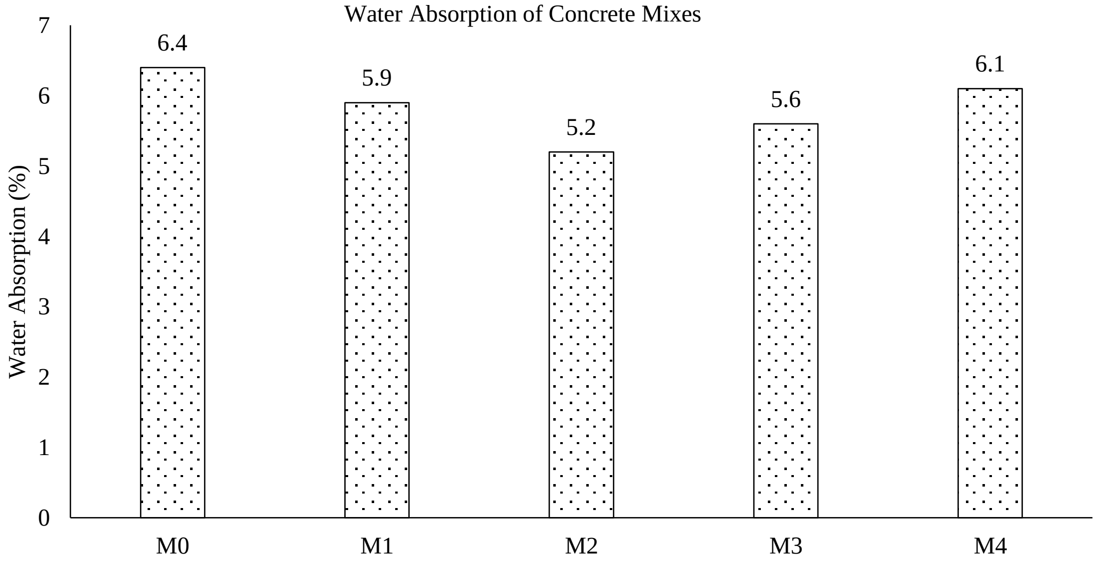

**Figure 3.** Water Absorption test result Bar Chart.

### *Flexural and Tensile Strength Results*

Since paver blocks are subjected to bending and splitting stresses under service conditions, the evaluation of flexural and tensile strength provides insight into the crack resistance and post-cracking toughness of the modified mixes. The results, presented in Table 5, show that Mix M2 again achieved the highest values, with flexural strength increasing from 3.8 MPa in the control to 4.6 MPa, and split tensile strength rising from 2.9 MPa to 3.5 MPa. These improvements are attributed to the ability of Pinus fibers to bridge cracks and absorb energy during loading, while nano silica strengthens the matrix and the ITZ, ensuring effective stress transfer across aggregates. Such improvements are particularly relevant for paving applications, where flexural stresses dominate under wheel loading. Comparable findings were reported by Afroughsabet [10] and Li et al. [13] [6], who observed that hybrid systems of nano silica and fibers enhanced flexural toughness and crack control in cementitious composites. This demonstrates that the combined use of nano silica and Pinus fiber results in concrete that is not only stronger but also more resistant to brittle failure. Comparable improvements were noted in CNT-modified mortars as reported by Siddique and Mehta [17].

Flexural strength was tested using beam specimens (500 × 100 × 100 mm) as per IS 516, and split tensile strength using cylinders (150 mm × 300 mm). The 28-day flexural and split tensile strength results are summarized in **Table 5**. These findings show a clear trend that aligns with compressive strength, with Mix M2 achieving the highest values.

The M2 mix exhibited the highest flexural and tensile strength, correlating with the compressive strength trends. Standard deviation values confirm acceptable consistency across replicates.

### Abrasion Resistance

Given that paver blocks are frequently exposed to surface wear from traffic and environmental conditions, abrasion resistance is an important indicator of their long-term durability and functional performance. The results, summarized in Table 6, reveal that Mix M2 exhibited the lowest weight loss (2.96 g), signifying high abrasion resistance, while the control mix (M0) recorded the highest weight loss (3.85 g). The improvement can be attributed to the dense microstructure created by nano silica, which strengthens the paste–aggregate bond and minimizes weak zones susceptible to grinding. Additionally, Pinus fibers provide reinforcement against surface cracking, thereby reducing the propagation of wear-induced defects.

These results are in agreement with Li [6], who highlighted the role of nano-modified concretes in improving surface durability in pavement applications. Hence, the findings demonstrate the suitability of the modified paver blocks for applications requiring high wear resistance. Li et al. [13] also confirmed the role of nano-particles in refining cement mortar microstructure. Similar enhancements were observed by Nili and Afroughsabet [18] when polypropylene fibers were used.

Abrasion resistance was measured using the Dorry abrasion testing machine in accordance with IS 1237:2012. Results are presented in terms of average weight loss after 2,000 revolutions.

**Table 5.** Flexural and Tensile Strength Results.

| Mix ID | Flexural Strength (MPa) ± SD | Split Tensile Strength (MPa) ± SD |
|---|---|---|
| M0 | 3.8 ± 0.2 | 2.9 ± 0.2 |
| M1 | 4.2 ± 0.2 | 3.2 ± 0.1 |
| M2 | 4.6 ± 0.3 | 3.5 ± 0.1 |
| M3 | 4.1 ± 0.3 | 3.1 ± 0.2 |
| M4 | 3.7 ± 0.2 | 2.8 ± 0.2 |

**Table 6.** Abrasion Resistance.

| Mix ID | Weight Loss (g) ± SD | Abrasion Resistance Class | Performance Remarks |
|---|---|---|---|
| M0 | 3.85 ± 0.15 | Low | Control mix; highest wear, poorest durability |
| M1 | 3.42 ± 0.12 | Moderate | Moderate improvement due to partial nano/fiber |
| M2 | 2.96 ± 0.10 | High | Best performance; dense matrix & fiber bridging |
| M3 | 3.28 ± 0.11 | Moderate | Reduced resistance due to excessive fiber content |
| M4 | 3.60 ± 0.14 | Low | Weaker compaction & fiber entanglement effects |

The abrasion resistance of the different mixes, expressed in terms of average weight loss, is detailed in **Table 6**. The lowest weight loss was recorded for Mix M2, confirming its superior abrasion resistance due to matrix densification and fiber reinforcement. The densified microstructure resulting from nano silica and fiber reinforcement contributed to surface integrity under abrasive conditions.

### Workability and Surface Finish

Workability and surface finish of fresh concrete dictate the ease of placement, compaction, and visual quality of the final product, and are particularly affected by the inclusion of fibers and nano additives. Observations during casting revealed that Mixes M3 and M4 displayed very low slump values (<50 mm), reflecting poor workability due to excessive fiber content and increased internal friction. Fiber entanglement also led to clustering and void formation, which negatively affected surface finish. In contrast, Mix M2 exhibited acceptable workability and a smooth surface finish, supported by the use of a polycarboxylate ether-based superplasticizer. The balanced proportions of nano silica and Pinus fiber in Mix M2 promoted cohesion without excessively increasing viscosity, ensuring uniform distribution of components. This observation is consistent with Jalal M [7-8], who noted that nano silica tends to increase water demand, but this can be managed with suitable admixtures. Thus, the results suggest that the incorporation of nano silica and Pinus fiber must be carefully optimized to achieve a workable mix without compromising performance.

Workability is a crucial property of fresh concrete, especially when fibers and nano additives are introduced, as these can significantly alter the rheology of the mix.

Observations during mixing and casting revealed the following:

- **Mixes M3 and M4** exhibited **reduced slump values**, measured to be **less than 50 mm**, indicating **low workability**. The high content of **Pinus fiber (1.5–2%)** in these mixes led to **fiber entanglement and clustering**, which increased internal friction and hindered proper compaction. This also resulted in **irregular surface finishes** and **visible voids** in some specimens, suggesting poor consolidation.
- In contrast, **Mix M2**—containing **1% Pinus fiber and 10% nano silica**—demonstrated **acceptable slump and workable consistency**, with a **uniform and smooth surface finish** after demolding. The presence of nano silica improved paste cohesion, while the moderate fiber content enhanced the internal bonding without significantly compromising flowability.

The addition of a **polycarboxylate ether-based superplasticizer** at 0.5% by weight of cementitious materials helped maintain acceptable workability, particularly in M1 and M2. However, it was not sufficient to fully offset the workability reduction observed in M3 and M4.

### SEM Image of Nano Silica-Modified Concrete

To support the mechanical and durability observations, microstructural examination using SEM provides direct evidence of the densification of the matrix and the quality of fiber–matrix interactions in the modified mixes. The SEM image in Figure 4 illustrates that the control mix exhibited microcracks and loosely packed hydration products, whereas the nano silica-modified mix demonstrated a denser matrix with fewer voids and improved packing of hydration products.

**Figure 4.** SEM image of nano silica-modified concrete.

This can be attributed to the secondary pozzolanic reaction of nano silica, which consumes calcium hydroxide and forms additional C–S–H gel, thereby improving the interfacial transition zone. Furthermore, the interface between Pinus fibers and the cement paste appeared smoother and more coherent, indicating enhanced bonding due to the alkali treatment of fibers. These findings are consistent with Amin [14-15], who emphasized the role of nano silica in refining microstructure and strengthening ITZ. The microstructural evidence thus validates the experimental outcomes, confirming the synergistic effect of nano silica and Pinus fiber in producing a denser and more durable composite material.

The microstructural characteristics of the nano silica-modified concrete are illustrated in **Figure 4**, which shows a denser, crack-free matrix compared to the control mix. This confirms the role of nano silica in refining pore structure and improving hydration products.

## CONCLUSION

This research validates the potential of using **nano silica** and **Pinus fiber** as sustainable partial replacements for cement in M30 grade concrete paver blocks. Based on the experimental investigation, the following conclusions can be drawn:

1. The **optimum mix (M2)** containing **10% nano silica** and **1% Pinus fiber** achieved the best overall performance.
2. **Compared to the control mix (M0)**, mix M2 showed a **~15.4% increase in 28-day compressive strength** (from 34.5 MPa to 39.8 MPa).
3. **Water absorption was reduced by ~18.75%** (from 6.4% in M0 to 5.2% in M2), indicating a **denser and more durable microstructure** due to nano silica's pozzolanic action.
4. Mixes with higher dosages of fiber and nano silica (M3 and M4) exhibited **workability issues** and slight reductions in strength due to fiber entanglement and nano silica agglomeration.
5. The **combined use of nano silica and Pinus fiber** offers a promising and eco-friendly approach for enhancing concrete paver blocks by improving mechanical properties while reducing cement usage.

In conclusion, the integration of Pinus fiber in a nano-modified cement matrix represents a novel direction in the development of **green composite materials** for construction. These fiber-reinforced composites offer an eco-friendly alternative to synthetic reinforcements, with notable advantages in mechanical behavior, sustainability, and cost-effectiveness. Future work should focus on standardizing treatment methods for natural fibers, optimizing fiber volume fractions, and understanding long-term durability in hybrid composite systems.

## Recommendations

Based on the experimental outcomes of this study on partial replacement of cement with Pinus fiber and nano silica in M30 concrete paver blocks, the following recommendations are made for further research and development:

- *Fiber Length and Distribution Optimization:* The length, aspect ratio, and quantity of Pinus fiber should be optimized to ensure uniform dispersion in the concrete matrix. Proper fiber orientation and distribution are essential for preventing clumping and improving overall mechanical performance.
- *Long-Term Durability Assessment:* Future studies should explore the long-term durability of fiber and nano-silica modified concrete, focusing on:
  - Freeze-thaw resistance in cyclic climate conditions,
  - Abrasion resistance for traffic-wearing surfaces,
  - Chemical durability against sulfate, chloride, and acidic attacks.
- *Pilot-Scale Field Trials:* Pilot studies should be conducted in real-world paving environments to assess performance under actual loading and environmental conditions. Field trials will help validate laboratory findings and refine mix designs for practical use.
- *Optimization of Nano Silica Dosage:* The interaction between nano silica and cement hydration should be studied in greater detail to determine the optimal dosage for maximum pozzolanic activity without compromising workability.
- *Improvement in Workability Techniques:* The use of superplasticizers, viscosity modifying agents (VMAs), or mechanical mixing strategies should be explored to address workability challenges caused by fiber entanglement.
- *Life Cycle Assessment (LCA):* A complete life cycle assessment should be performed to evaluate the environmental impact of incorporating Pinus fiber and nano silica, including energy consumption, $CO_2$ emissions, and recyclability.
- *Economic Feasibility Studies:* A cost-benefit analysis should be carried out to compare the economic implications of using alternative materials versus traditional cement-based concrete in large-scale applications.
- *Microstructural and SEM Analysis:* Advanced microscopic and analytical techniques such as SEM, EDX, and XRD should be employed to understand the interfacial bonding between fibers, nano silica, and the cement matrix.
- *Standardization and Codal Development:* Further research is needed to develop standard mix design guidelines and testing procedures for concrete modified with natural fibers and nanomaterials, especially for use in precast and paving applications.

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