Research Article

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Performance Evaluation of High-strength Concrete Incorporating Alccofine and Nanosilica

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ABSTRACT

Urbanization and infrastructure development necessitate the use of high-performance concrete due to its superior strength and durability. Traditional high-strength concrete often relies on increased cement content, contributing to environmental concerns due to carbon emissions. This study explores the use of supplementary cementitious materials (SCMs), specifically alccofine and nanosilica, to enhance concrete performance while reducing cement consumption. The research investigates M40 and M50 grade concrete with varying water-cement ratios (0.4, and 0.36). Concrete mixes incorporating alccofine and nanosilica were compared with control mixes to determine their optimal proportions. The study evaluates workability, mechanical properties (compressive, split tensile, and flexural strength), and durability aspects such as chemical resistance, water permeability, porosity, and sorptivity. Additionally, microstructural analysis was conducted. Results indicate that the inclusion of alccofine and nanosilica improves hydration, reduces porosity, and enhances mechanical and durability properties. The study underscores the potential of SCMs in developing sustainable high-strength concrete with reduced environmental impact.

Keywords: Alccofine; Nanosilica; Mechanical properties; Durability studies; Microstructural analysis.

1. INTRODUCTION

Concrete is one of the most versatile materials engineered by humans. After water, it is the second most widely used substance globally. Its popularity comes from its ability to form shape when fresh and its exceptional strength and durability once hardened. On average, more than one cubic meter of concrete is produced per person each year, leading to a substantial demand for Portland cement. However, cement production is highly energy-intensive and a significant contributor to CO_2 emissions (Erdem *et al.* 2018; Ghafari *et al.* 2014; Wang *et al.* 2018).

Despite its excellent mechanical properties, conventional cement-based concrete often fails to meet long-term durability requirements. To enhance sustainability, it is essential to replace a considerable portion of cement with industrial by-products and supplementary materials. Over the past few decades, concrete technology has evolved significantly (Ghafari *et al.* 2014). It is no longer a simple combination of cement, aggregates, and water but a sophisticated material incorporating various advanced components. Modern concrete can be tailored to meet specific performance criteria under diverse environmental conditions. Contemporary construction demands additional properties from concrete, including faster construction rates, improved workability, early strength development, enhanced durability, resistance to aggressive environments, and superior structural stability (Ardalan *et al.* 2017).

Given the increasing demands for durable and high-strength construction materials, high-performance concrete (HPC) is emerging as a preferred choice, particularly in rapidly developing nations like India. With its superior mechanical properties, enhanced durability, and ability to withstand harsh environmental conditions, HPC is becoming indispensable for modern infrastructure projects. The rapid urbanization and expansion of transportation networks, including highways, bridges, and high-rise buildings, necessitate the use of advanced concrete materials that offer longer service life and reduced maintenance costs (Ying *et al.* 2017). Additionally, the need for sustainable construction practices has further accelerated the adoption of HPC, as it allows for optimized mix designs incorporating supplementary cementitious materials (SCMs), reducing the environmental impact associated with conventional cement production. Given these advantages, the growing popularity of HPC in India and similar fast-developing regions is a logical progression in the pursuit of resilient and sustainable infrastructure (Ardalan *et al.* 2017).

HPC is designed by incorporating one or more SCMs such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS), along with chemical

admixtures like superplasticizers. While the term "high performance" may seem exaggerated, it primarily refers to the careful selection of materials and mix proportions to achieve specific properties required for a particular structural application, such as enhanced strength and reduced permeability (Panesar 2019; Papadakis and Tsimas, 2002). Essentially, HPC is not a fundamentally different type of concrete but rather an optimized version of conventional concrete with improved performance characteristics.

Supplementary cementitious materials are categorized as either hydraulic or pozzolanic based on their reaction mechanism. Hydraulic materials react directly with water to form cementitious compounds, whereas pozzolanic materials require the presence of calcium hydroxide $Ca(OH)_2$ and water to undergo a chemical reaction that results in cementitious products. Pozzolanic additives, primarily composed of silica and alumina, possess minimal or no inherent cementitious properties. However, certain SCMs, such as high-calcium fly ash, exhibit both pozzolanic and hydraulic characteristics when incorporated into concrete (Teng *et al.* 2013).

Since different SCMs interact uniquely with various cement types, laboratory testing is essential to determine the optimal dosage and assess their impact on concrete properties. The contemporary approach to sustainable concrete production involves blending multiple SCMs with Portland cement to create environmentally friendly and high-performance binders. The effectiveness of SCMs in concrete largely depends on their chemical and physical properties, which vary depending on their origin and composition (Teng *et al.* 2013; Reddy and Ramadoss, 2020; Pawan *et al.* 2019). Among the critical physical properties, fineness plays a crucial role in determining reactivity and strength development in blended binders. Finer particles enhance the dissolution of SCMs, accelerating pozzolanic activity and leading to the formation of additional hydration products that contribute to the long-term strength and durability of concrete (Reddy and Ramadoss, 2020).

The inclusion of specific mineral and chemical admixtures, such as silica fume, fly ash, and superplasticizers, significantly enhances concrete's strength, durability, and workability. Although the initial cost of HPC is higher compared to traditional concrete, its long-term benefits outweigh the upfront expenses. By increasing the service life of the structure and minimizing deterioration, HPC reduces maintenance and repair costs, making it a more economical choice in the long run (Reddy and Ramadoss, 2020; Jindal *et al.* 2020).

In developed nations, HPC is typically characterized by a compressive strength exceeding 70–80 MPa after 28 days of curing, a durability factor above 80%, and a water-to-cement (W/C) ratio lower than 0.35. HPC is produced using carefully selected, high-quality materials and optimized mix designs to achieve superior mechanical and durability properties. The manufacturing process involves precise proportioning, thorough mixing, proper placement, efficient compaction, and controlled curing, all in accordance with industry standards. Generally, the W/C ratio for HPC ranges between 0.20 and 0.45, ensuring enhanced strength and durability while maintaining workability (Jindal *et al.* 2020; Reddy *et al.* 2020; Reddy and Naqash, 2019).

Pawan *et al.* (2019) conducted a comprehensive study on the mechanical properties of M50-grade concrete by incorporating 30% GGBS as a partial replacement for cement, along with varying proportions of alccofine (5%, 10%, 15%, and 20%). Their research aimed to assess the impact of these SCMs on the strength and workability of concrete. The results demonstrated that the optimal combination of 30% GGBS and 10% alccofine significantly enhanced the overall performance of the concrete. Specifically, this mix led to an increase in compressive strength by 2.1%, split tensile strength by 0.65%, and flexural strength by 1.4% compared to the control mix. The improvement in strength properties can be attributed to the pozzolanic reaction of alccofine, which refines the microstructure of the concrete matrix and contributes to the formation of additional calcium silicate hydrate (C-S-H) gel, enhancing its density and durability.

Jindal *et al.* (2020) investigated the performance of geopolymer concrete incorporating rice husk ash as a primary binder, with the addition of 5% and 10% alccofine. The study analyzed mixtures containing Rice Husk Ash (RHA) in varying quantities of 350, 370, and 400 kg/m^3 to assess their impact on concrete properties. The findings indicated that integrating alccofine into rice husk ash-based geopolymer concrete not only improved its strength and durability but also contributed to environmental sustainability. The utilization of RHA, an agricultural by-product, helps in managing waste disposal challenges while simultaneously reducing CO_2 emissions associated with conventional cement production. The pozzolanic nature of both RHA and alccofine enhances the geopolymerization process, leading to a denser microstructure and improved mechanical properties. The study concluded that incorporating alccofine into RHA-based geopolymer concrete is an effective strategy for developing high-performance and eco-friendly construction materials.

2. MATERIALS AND METHODS

2.1 Materials

Cement serves as the primary binding component in concrete, significantly influencing its strength development and long-term durability. It plays a vital role in ensuring cohesion among other constituents,

thereby providing structural integrity to hardened concrete. In this study, ordinary Portland cement (OPC) of grade 53, conforming to IS 12269-2013, was utilized due to its high early strength and superior performance in structural applications. To ensure compliance with the required standards and maintain consistency in mix design, the cement underwent rigorous testing for various properties, including fineness, standard consistency, initial and final setting times, and compressive strength. These tests ensured that the cement met the necessary quality parameters, contributing to the overall performance of the concrete mix.

To improve the durability and mechanical properties of concrete while reducing the environmental impact associated with high cement consumption, SCMs were incorporated into the mix. Among these, Alccofine, a micro-fine mineral additive known for enhancing strength and workability, was employed in varying proportions of 0%, 5%, and 10% across different mixes. Alccofine, due to its ultrafine particle size, fills voids in the concrete matrix, thereby improving particle packing density and increasing overall strength. Additionally, nanosilica, a highly reactive pozzolanic material, was utilized to refine the microstructure of the concrete and promote superior strength development. Due to its nano-scale particle size, nanosilica effectively accelerates hydration reactions, leading to improved early-age strength and reduced porosity. It was incorporated in selected mixes at replacement levels of 0% and 10%, optimizing the balance between workability and strength enhancement.

Fine aggregates used in this study consisted of locally available river sand, conforming to IS 383-2016. Sand plays a crucial role in filling voids between coarse aggregates and ensuring a dense, well-compacted concrete mix. To ascertain its suitability for concrete production, the sand was tested for various physical properties, including gradation, fineness modulus, specific gravity, and water absorption. These tests ensured that the sand provided the required workability and contributed to the uniform distribution of stress within the hardened concrete.

For coarse aggregates, crushed stone aggregates of 20 mm and 10 mm sizes were used in a well-graded proportion to achieve optimum packing density, ensuring better load transfer and enhanced strength characteristics. These aggregates, conforming to IS 383-2016, were carefully selected and subjected to quality tests such as specific gravity, aggregate impact value, and water absorption. These evaluations helped in determining the aggregates' durability and resistance to mechanical wear, both of which are critical for long-term structural stability.

Water is a fundamental ingredient in concrete, facilitating hydration reactions and ensuring proper workability during mixing. In this study, potable water was used for both mixing and curing purposes. To prevent any potential adverse reactions in the concrete matrix, water quality was assessed in accordance with IS 456-2000 guidelines. This ensured that the water was free from impurities that could negatively impact cement hydration and, consequently, the performance of the hardened concrete.

The mix proportions presented in the Table 1 detail the composition of various concrete mixes designed for M40 and M50 grade concrete, incorporating different percentages of Alccofine and nanosilica as SCMs. These variations in cement content, SCM dosage, fine and coarse aggregates, and water-to-binder (W/B) ratio significantly impact the workability, strength, durability, and sustainability of the concrete. The primary objective of these mix designs is to enhance the mechanical and durability properties of concrete while reducing cement consumption and improving sustainability.

For M40 grade concrete, four different mixes (M1–M4) were prepared with varying levels of SCMs. The M1 mix serves as the control mix, containing 380 kg/m³ cement with no Alccofine or nanosilica. This mix provides a baseline for evaluating the effects of SCMs on concrete performance. The M2 mix incorporates 5% Alccofine (19 kg/m³), reducing the cement content to 361 kg/m³, which helps improve early strength gain, workability, and durability. In M3, the Alccofine content is increased to 10% (38 kg/m³), further reducing the cement content to 342 kg/m³, leading to better packing density and improved long-term strength. The M4 mix combines 5% Alccofine (19 kg/m³) and 10% nanosilica (38 kg/m³), reducing cement to 323 kg/m³, with nanosilica enhancing microstructure refinement and reducing porosity. This mixture is expected to provide superior durability, lower permeability, and increased long-term strength. Across all M40 mixes, the W/B ratio remains at 0.40, maintaining sufficient workability while ensuring optimal hydration.

For M50 grade concrete, four different mixes (M5–M8) were developed to achieve higher strength and durability. The M5 mix is the control mix with 400 kg/m³ cement and no SCMs, setting a reference for the high-strength category. The M6 mix introduces 5% Alccofine (20 kg/m³), reducing cement to 380 kg/m³, leading to better early strength gain and durability. In M7, the Alccofine content is further increased to 10% (40 kg/m³), reducing cement to 360 kg/m³, enhancing both compressive and flexural strength. The M8 mix incorporates both 5% Alccofine (20 kg/m³) and 10% nanosilica (40 kg/m³), reducing cement to 340 kg/m³, which results in the densest microstructure among all M50 mixes. The lower W/B ratio of 0.36 across all M50 mixes ensures a denser, more durable concrete with superior mechanical properties and resistance to aggressive environments.

The mix proportion adjustments reflect a strategic approach to optimizing cement content while maintaining high strength and durability. The inclusion of Alccofine enhances early age strength and improves workability, whereas nanosilica significantly refines the microstructure, reducing porosity and increasing long term strength. The control mixes (M1 and M5) serve as benchmarks, while the optimized mixes (M4 and M8) demonstrate the best balance of mechanical properties and sustainability. The reduction in cement content in these optimized mixes contributes to lower carbon emissions, making them an environmentally friendly choice. Additionally, fine and coarse aggregates are slightly adjusted to ensure workability and maintain the structural integrity of the concrete. Table 1 illustrates the mix proportions of concrete in kg/m^3.

Table 1: Mix proportions of concrete prepared with Alccofine and nanosilica (kg/m^3)

Mix ID	Grade	Cement	Alccofine (%)	Nanosilica (%)	Fine Aggregate	Coarse Aggregate	Water	W/B Ratio
M1	M40	380	0	0	720	1150	152	0.4
M2		361	19	0	710	1145	152	0.4
M3		342	38	0	700	1135	152	0.4
M4		323	19	38	695	1130	152	0.4
M5	M50	400	0	0	680	1120	132	0.36
M6		380	20	0	670	1115	130	0.36
M7		360	40	0	660	1105	125	0.36
M8		340	20	40	650	1100	120	0.36

The mixing process of concrete is a crucial step in ensuring uniform distribution of materials, achieving homogeneity, and optimizing the desired mechanical and durability properties. Proper blending of OPC, SCMs such as Alccofine and nanosilica, fine and coarse aggregates, and water plays a significant role in maintaining the quality and performance of the designed M40 and M50 concrete mixes. The process begins with material preparation and batching, where all ingredients are carefully measured according to the specified mix proportions. Cement and SCMs are weighed accurately to maintain consistency, while fine aggregates (river sand) and coarse aggregates (crushed stone of 20 mm and 10 mm sizes) are pre-weighed and stored under controlled conditions to prevent moisture variations. Water is precisely measured to ensure the correct water-to-binder (W/B) ratio, and if chemical admixtures such as superplasticizers are used, they are pre-mixed with a portion of water before being introduced into the mix.

The next step is dry mixing, where cement, Alccofine, and nanosilica are thoroughly blended to ensure even dispersion of the fine particles. Gradually, fine and coarse aggregates are introduced and mixed to achieve proper coating of cementitious materials on their surface. This dry mixing stage typically lasts 30 to 60 seconds in a mechanical mixer, ensuring uniformity before the addition of water. Following this, water is added gradually in controlled proportions to prevent excessive water pockets and ensure even hydration. For mixes containing nanosilica, water is introduced in two stages to improve dispersion and prevent lump formation. The wet mixing process continues for another 2 to 3 minutes, ensuring proper hydration and uniform moisture distribution. If a superplasticizer is included, it is added during the final stage of wet mixing to achieve the desired workability and flow properties.

After the wet mixing process, the homogenization and quality check stage ensure that the fresh concrete has a uniform consistency, adequate workability, and even dispersion of SCMs. A slump test is performed to verify compliance with workability requirements, and if necessary, minor adjustments in water or admixture dosage are made. Once the concrete achieves the desired consistency, it is transported to the casting location, ensuring that it remains protected from evaporation and contamination. For high-SCM content mixes (such as M4 and M8), continuous agitation is maintained during transportation to prevent settling of fine particles. The concrete is placed and compacted using vibrators or manual tamping to remove entrapped air and achieve the desired density and strength. After placement, curing begins immediately to prevent moisture loss and promote strength development. Water curing or curing compounds are applied, with curing lasting 7 to 28 days, depending on exposure conditions and mix specifications. This structured mixing process ensures that the mechanical and durability properties of the concrete are optimized while also enhancing sustainability by incorporating SCMs like Alccofine and nanosilica. The systematic approach results in improved strength, durability, and microstructural refinement, making these concrete mixes ideal for modern high-performance.

2.2 Test Methods

To assess the performance and quality of the concrete mixes, various tests were conducted on fresh and hardened concrete. The key tests included initial and

final setting times, workability, mechanical properties, water absorption, and microstructural analysis using scanning electron microscopy (SEM). The details of the test methods used for each evaluation are as follows:

2.2.1. Initial and Final Setting Times

The setting time of cement paste or concrete determines the period during which it remains workable before hardening. The initial and final setting times were evaluated using the Vicat Apparatus, as per IS 4031 (Part 5): 1988 and IS 1199: 2018.

Initial Setting Time: This is the time elapsed from the addition of water to cement until the paste begins to lose its plasticity. A Vicat needle with a 1 mm² cross-section is used, and the test is conducted under controlled conditions. The time is recorded when the needle penetrates 5 mm from the bottom of the Vicat mold.

Final Setting Time: This represents the time taken for the cement paste to fully set and harden. It is determined when the Vicat needle fails to leave an impression on the paste.

The setting times help in understanding the workability duration and handling time for placing and finishing the concrete mix.

2.2.2. Workability of Concrete

Workability refers to the ease with which fresh concrete can be mixed, placed, compacted, and finished. The following tests were performed to evaluate workability:

Slump Test: Conducted as per IS 1199: 2018, this test determines the consistency and flowability of fresh concrete. A standard metal slump cone (300 mm height, 100 mm top diameter, and 200 mm bottom diameter) is filled with concrete in three layers, each tamped 25 times. The cone is lifted, and the vertical settlement (slump) is measured.

2.2.3. Mechanical Properties of Concrete

The mechanical properties of hardened concrete, including compressive strength, split tensile strength, and flexural strength, were evaluated as per IS codes.

Compressive Strength: Measured as per IS 516: 1959 (Reaffirmed 2021), standard cubes of 150 mm × 150 mm × 150 mm were tested under a compressive testing machine (CTM) at a loading rate of 140 kg/cm² per minute until failure. The compressive strength (MPa) was calculated by using the following equation.

$$f_c = \frac{\text{Maximum Load}}{\text{Cross-sectional Area}} \quad \ldots (1)$$

Split Tensile Strength: Evaluated using cylindrical specimens (150 mm diameter, 300 mm height) following IS 5816: 1999. The concrete cylinder was placed horizontally in a CTM, and the applied force created indirect tensile stress. This formula is typically used to calculate the splitting tensile strength (also called indirect tensile strength) of a cylindrical concrete specimen. The split tensile strength was determined using the formula:

$$f_t = \frac{2P}{\pi DL} \quad \ldots (2)$$

f_t: Tensile strength of the specimen (N/mm²)
P: Maximum load at failure during testing (N)
D: Diameter of the cylindrical specimen (mm)
L: Height of the cylindrical specimen (mm)

Flexural Strength: Conducted as per IS 516: 1959, this test assessed the resistance of concrete beams (100 mm × 100 mm × 500 mm) to bending forces. A two-point loading system was used in a flexural testing machine, and the strength was computed using:

$$f_f = \frac{PL}{bd^2} \quad \ldots (3)$$

f_f: Flexural strength of concrete (N/mm²)
P: Maximum load applied at failure (N)
L: Span length between supports (in mm)
b: Width of the specimen (mm)
d: Depth of the specimen (mm)

These tests provided valuable insights into the structural performance and durability of the concrete mixes. This formula is used to determine the flexural strength of a concrete beam specimen tested under two-point loading (symmetric loading). It measures the ability of concrete to resist bending or flexural tension.

2.2.4. Water Absorption Test

The water absorption test was performed on hardened concrete specimens to evaluate its permeability and porosity, as per ASTM C642. The procedure involved:

1. Drying the concrete samples in an oven at 105 °C for 24 hours until a constant weight (W_d) was achieved.
2. Immersing the specimens in water for 24 hours at room temperature, then weighing them in a saturated condition (W_s).
3. Calculating water absorption percentage using the formula:

$$\text{Water Absorption} = \frac{W_s - W_d}{W_d} \times 100 \quad \ldots (4)$$

Ws: Saturated weight of the sample

Wd: Dry weight of the sample after oven-drying

A lower water absorption percentage indicates higher durability and lower permeability, which is crucial for long-term performance.

2.2.5. Scanning Electron Microscopy (SEM) Analysis

SEM analysis was carried out to examine the microstructural characteristics of hardened concrete, particularly the bond between cementitious materials and aggregates. The analysis helped in understanding the effect of SCMs like Alccofine and Nanosilica on hydration and microstructural refinement. The procedure included:

Sample Preparation: Small fragments of hardened concrete were dried and coated with a thin layer of gold or carbon to enhance conductivity.

Imaging and Analysis: The samples were scanned using a high-resolution SEM, and images were analyzed to observe the formation of hydration products, microcracks, and void structures. The presence of C-S-H (Calcium Silicate Hydrate), ettringite, and unreacted particles was studied to assess the performance of the blended concrete mixes.

The SEM analysis provided detailed insights into pore structure, crack propagation, and the effect of mineral admixtures in improving the concrete's microstructure.

3. RESULTS AND DISCUSSION

3.1 Initial and Final Setting Time

The setting time of concrete is a crucial factor that determines its workability and early strength development. The initial setting time represents the period when concrete starts losing its plasticity, whereas the final setting time marks the point at which the material fully hardens and attains sufficient strength to resist external forces. The setting time is influenced by various factors, including cement type, SCMs, water-to-binder ratio (W/B), and admixtures. In this study, the effect of Alccofine and nanosilica on the setting time of M40 and M50 grade concretes was analyzed.

The results indicate a gradual reduction in both initial and final setting times with the incorporation of Alccofine and nanosilica. In M2, M3, M6, and M7, where Alccofine was added in varying proportions (19% to 40%), a noticeable reduction in setting time was observed. This can be attributed to the ultrafine nature of Alccofine, which accelerates the hydration process by increasing the reaction surface area. Similarly, the introduction of nanosilica in M4 and M8 led to the fastest setting times, with initial setting times of 22 and 23 minutes and final setting times of 561 and 564 minutes, respectively. Nanosilica, due to its high pozzolanic reactivity and ability to act as a nucleation site, enhances the hydration reaction, leading to rapid setting and early strength gain.

Comparing the results for M40 and M50 grade concretes, the control mixes (M1 and M5) without SCMs exhibited the longest setting times, with initial and final setting times of 30 and 600 minutes, respectively. As the SCMs content increased, the initial setting time was reduced by up to 8 minutes, while the final setting time decreased by nearly 40 minutes, demonstrating the accelerating effect of these mineral additives. While faster setting times are beneficial for projects requiring early strength gain and rapid construction, they may pose challenges in terms of workability and placement time. Mixes with high nanosilica content (M4 and M8) are particularly prone to rapid stiffening, which may necessitate the use of superplasticizers or retarders to ensure adequate workability.

Table 2: Initial and final setting time

Mix ID	Grade	Initial Setting Time (minutes)	Final Setting Time (minutes)
M1	M40	30	600
M2		28	584
M3		24	573
M4		22	561
M5	M50	30	600
M6		29	586
M7		27	578
M8		23	564

3.2 Workability

The workability of concrete, an essential property influencing the ease of mixing, placing, and finishing, is significantly impacted by the incorporation of supplementary cementitious materials such as Alccofine and nanosilica. Based on the slump test values presented in the Table 2, a clear trend can be observed in how these additives affect the consistency and fluidity of concrete mixes.

In the control mixes M1 (M40) and M5 (M50), which contain no Alccofine or nanosilica, the slump values were recorded at 90 mm and 80 mm, respectively. These values represent medium workability, indicating that the mixes were sufficiently fluid for ease of handling while maintaining cohesiveness. These mixes serve as a baseline for evaluating the influence of SCMs.

As Alccofine was introduced and its dosage increased in mixes M2, M3, M6, and M7, a progressive reduction in slump was observed. For example, M2 (with 5% Alccofine) recorded a slump of 85 mm, while M3 (10% Alccofine) showed a reduced slump of 75 mm. A

similar pattern was noted in M6 and M7, with slumps dropping from 75 mm to 65 mm. This reduction can be attributed to the finer particle size and high reactivity of Alccofine, which increases the surface area for hydration, thus reducing free water available in the mix and accelerating stiffening. Although Alccofine improves strength and packing density, its usage tends to lower the workability if not compensated with additional water or chemical admixtures (Reddy *et al.* 2020).

The most significant decrease in slump occurred in the mixes that combined both Alccofine and nanosilica, specifically M4 and M8, where the slump dropped to 65 mm and 55 mm, respectively. Nanosilica, being a highly reactive pozzolanic material with ultrafine particles, accelerates early hydration and leads to rapid consumption of mixing water. This causes the mixture to become stiffer much faster, thereby reducing workability. Additionally, the nanosilica improves the microstructure of concrete by filling micro voids, which contributes to strength enhancement but reduces flowability (Reddy and Naqash, 2019).

This inverse relationship between SCM content and workability highlights the importance of optimizing mix proportions when targeting high-performance characteristics. The low slump values in high SCM mixes may require the addition of superplasticizers to restore workability without increasing the water content, thus maintaining the desired low water-to-binder ratio. While the inclusion of Alccofine and nanosilica significantly enhances the mechanical properties and durability of concrete, it adversely affects workability. Therefore, achieving a balance between performance and workability is essential through the strategic use of chemical admixtures and proper mix design adjustments. Table 3 presents the workability of concrete.

Table 3: Workability of concrete

Mix ID	Grade	Slump (mm)	Workability Description
M1	M40	90	Medium
M2		85	Medium
M3		75	Medium-Low
M4		65	Low
M5	M50	80	Medium
M6		75	Medium-Low
M7		65	Low
M8		55	Very Low

3.3 Compressive Strength

The compressive strength of concrete is a critical parameter that determines its load-bearing capacity and structural performance. The results from the experimental study indicate that the incorporation of Alccofine and nanosilica significantly influences the strength characteristics of M40 and M50 grade concretes. The control mixes M1 (M40) and M5 (M50), which contained only OPC without SCMs, exhibited compressive strengths of 42.5 MPa and 53.0 MPa, respectively, at 28 days of curing. These values provide a baseline for comparison against modified mixes incorporating SCMs.

The inclusion of Alccofine in M2, M3, M6, and M7 led to a noticeable increase in compressive strength due to its high fineness and pozzolanic activity, which refined the microstructure and improved the packing density of concrete. For instance, in M40 grade concrete, the strength increased from 42.5 MPa (M1) to 47.0 MPa (M3) with 10% Alccofine replacement, while in M50 concrete, the strength rose from 53.0 MPa (M5) to 58.0 MPa (M7) under similar replacement conditions. This improvement is attributed to the enhanced hydration reaction and formation of additional C-S-H gel, which contributes to greater concrete densification and strength development (Reddy and Meena, 2019).

Further enhancement was observed with the incorporation of nanosilica in M4 and M8, where a combination of 5% Alccofine and 10% nanosilica led to maximum compressive strengths of 49.3 MPa (M40) and 60.5 MPa (M50). The high surface area and reactivity of nanosilica contributed to accelerated hydration, improved microstructural refinement, and enhanced strength gain. The combined presence of Alccofine and nanosilica resulted in denser and more compact concrete, thereby significantly improving both short-term and long-term strength performance (Chithra *et al.* 2016).

The overall strength trends observed in the study suggest that the increased replacement of SCMs directly correlates with higher strength development. Furthermore, the synergistic effect of Alccofine and nanosilica proved more effective than using either SCM individually. The effect was even more pronounced in higher-grade concrete (M50), indicating that SCMs play a more substantial role in high-performance concrete. These results have practical implications, as the use of SCMs reduces cement consumption, thereby lowering CO_2 emissions and promoting sustainable construction. Additionally, the superior strength and durability of these mixes make them ideal for high-rise buildings, bridges, and infrastructure projects, where both strength and longevity are crucial factors. Although SCMs may increase the initial cost of production, their extended service life and lower maintenance requirements make them a cost-effective and sustainable solution for modern construction (Reddy and Meena, 2019; Chithra *et al.* 2016; Du *et al.* 2014). Fig. 1 shows the compressive strength of concrete samples of M40 and M50 grades.

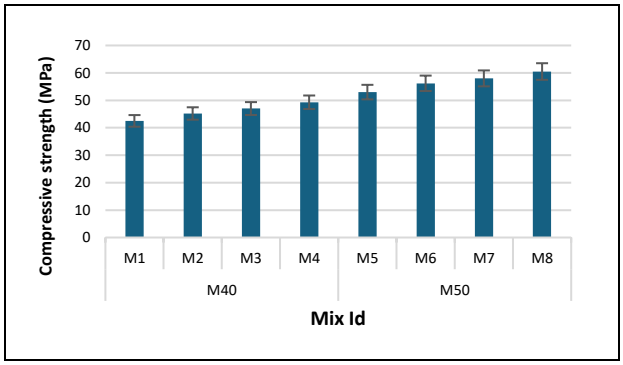


Fig. 1: Compressive strength of concrete

3.4 Split Tensile Strength

The split tensile strength of concrete is a crucial property that reflects its ability to resist tensile forces and cracking. The results obtained from the experimental study indicate that the inclusion of Alccofine and nanosilica significantly influences the tensile strength development of both M40 and M50 grade concretes. The control mixes M1 (M40) and M5 (M50), which contained only OPC without any SCMs, exhibited split tensile strengths of 4.25 MPa and 4.95 MPa at 28 days, respectively. These values provide a benchmark for comparison against the modified mixes incorporating Alccofine and nanosilica (Chithra *et al.* 2016).

The addition of Alccofine in M2, M3, M6, and M7 resulted in an incremental improvement in split tensile strength. The higher fineness and pozzolanic activity of Alccofine contributed to densification of the concrete matrix, enhancing its bonding strength and crack resistance. In M40 concrete, tensile strength improved from 4.25 MPa (M1) to 4.85 MPa (M3) with 10% Alccofine, while in M50 concrete, it increased from 4.95 MPa (M5) to 5.55 MPa (M7) with 10% Alccofine. This increase can be attributed to the formation of additional calcium silicate hydrate (C-S-H) gel, which strengthens the interfacial transition zone (ITZ) and reduces microcracks, thereby enhancing tensile strength.

The highest split tensile strength was recorded in M4 (M40) and M8 (M50), where a combination of 5% Alccofine and 10% nanosilica was used. The values reached 5.10 MPa for M40 and 5.80 MPa for M50 at 28 days of curing. This improvement is attributed to the nano-scale particle size of nanosilica, which further refines the microstructure, enhances the packing density, and contributes to an increased pozzolanic reaction. Nanosilica also acts as a filler material, reducing voids and increasing overall cohesion and tensile stress distribution within the concrete matrix (Du *et al.* 2014).

The early-age strength results (7-day tensile strength) show a similar trend, where mixes containing Alccofine and nanosilica exhibited faster strength development due to their ability to accelerate hydration reactions. The presence of nanosilica in particular played a vital role in early-age strength gain, making it beneficial for applications where rapid strength development is required, such as precast concrete and high-rise construction (Ghafari *et al.* 2014; Kooshafar and Madani, 2020).

Overall, the findings demonstrate that the use of SCMs, particularly Alccofine and nanosilica, leads to a significant enhancement in split tensile strength. The synergistic effect of both materials results in a more compact, refined, and crack-resistant matrix, improving the overall tensile behavior of concrete. These improvements contribute to greater structural durability, reducing the likelihood of cracking and failure under tensile stresses, making these mixes ideal for infrastructure projects requiring high durability and long-term performance. Fig. 2 presents the split tensile strength of concrete samples for 7 and 28 days of curing.

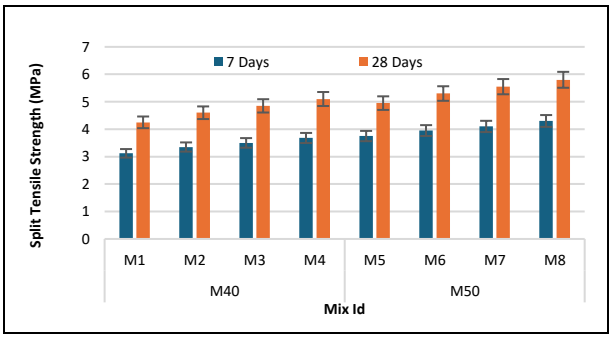


Fig. 2: Split tensile strength of concrete

3.5 Flexural Strength

The flexural strength results of different concrete mixes for M40 and M50 grades at 7 and 28 days are presented in the Fig. 3. The values indicate a progressive increase in flexural strength with the incorporation of Alccofine and nanosilica.

For M40 grade concrete, the control mix (M1) achieved a flexural strength of 4.20 MPa at 7 days and 5.85 MPa at 28 days. With the introduction of Alccofine (M2 and M3), an improvement in strength was observed, with M3 (38% Alccofine) reaching 6.35 MPa at 28 days. When nanosilica (M4) was further added, the flexural strength increased to 6.60 MPa at 28 days, indicating that the pozzolanic reactivity and filler effect of nanosilica enhanced the tensile resistance of the concrete (Hou *et al.* 2013).

For M50 grade concrete, the control mix (M5) exhibited a flexural strength of 4.70 MPa at 7 days and 6.40 MPa at 28 days. The inclusion of Alccofine (M6 and M7) showed significant improvement, with M7 (40% Alccofine) attaining 6.90 MPa at 28 days. The highest flexural strength was recorded for M8, where both 20% Alccofine and 40% nanosilica were incorporated,

resulting in 7.15 MPa at 28 days. This emphasizes the role of nanosilica in densifying the microstructure and enhancing bonding, thereby improving the resistance to bending stresses.

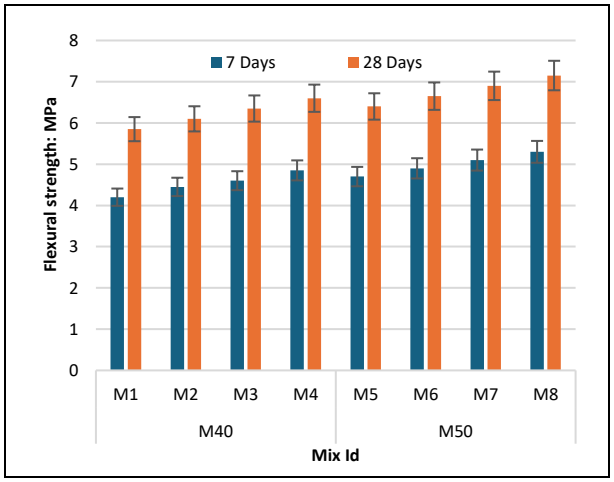


Fig. 3: Flexural strength of concrete

3.6 Water Absorption

Water absorption is a crucial parameter that indicates the permeability and durability of concrete. Lower water absorption values imply a denser microstructure, reducing the ingress of water and harmful chemicals, thereby enhancing the long-term durability of concrete structures.

The results in the water absorption table show a clear decreasing trend with the incorporation of Alccofine and nanosilica in both M40 and M50 grade concretes. The control mixes, M1 (M40) and M5 (M50), exhibited relatively higher water absorption values of 2.45% and 2.40%, respectively. This is due to the higher porosity of conventional cementitious pastes (Hou *et al.* 2013).

With the addition of Alccofine, a significant reduction in water absorption was observed. M3 (M40 with 38% Alccofine) and M7 (M50 with 40% Alccofine) exhibited water absorption of 2.18% and 2.10%, respectively. The improvement is attributed to the ultrafine particle size of Alccofine, which enhances the packing density of the cementitious matrix, thereby reducing the permeability.

A further reduction in water absorption was noted in the mixes containing nanosilica (M4 and M8), with M8 (M50 with 20% Alccofine + 40% nanosilica) achieving the lowest absorption of 1.95%. This highlights the synergistic effect of nanosilica and Alccofine, where nanosilica enhances pozzolanic activity and refines the pore structure, resulting in an even denser concrete matrix (Kooshafar and Madani, 2020).

On the other hand, the results confirm that incorporating Alccofine and nanosilica significantly reduces water absorption, improving the durability, resistance to aggressive environmental conditions, and service life of concrete structures. These findings suggest that optimizing the use of SCMs can produce high-performance concrete with superior impermeability and sustainability. Fig. 4 illustrates the water absorption results of Alccofine based concrete samples.

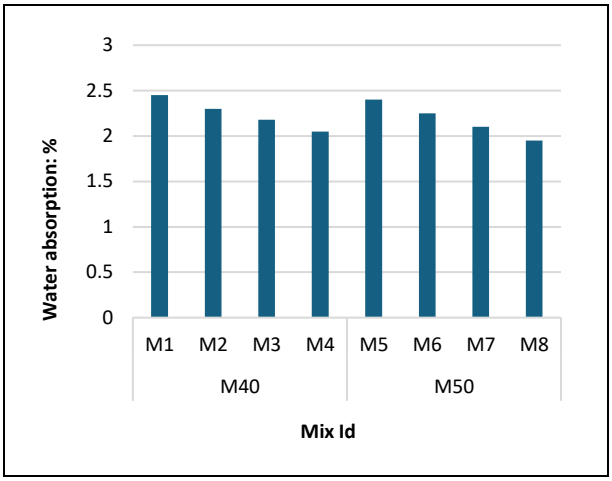


Fig. 4: Water absorption values of concrete

3.7 SEM Analysis

The mechanical properties and durability of concrete, including compressive strength, split tensile strength, flexural strength, and water absorption, are closely linked to its microstructural characteristics. To gain deeper insights into these properties, SEM analysis was conducted on selected concrete mixes. SEM provides a detailed representation of the microstructure, allowing for the correlation of observed improvements in strength and durability with the pozzolanic activity and densification of the cementitious matrix. The results revealed that the incorporation of Alccofine and nanosilica significantly enhanced the microstructural densification, leading to improved mechanical properties. The SEM images of mixes with higher Alccofine and nanosilica content (M4 and M8) exhibited a compact, dense, and well-bonded structure with fewer voids and microcracks, explaining their superior strength performance.

Water absorption, a key indicator of concrete permeability and durability, showed a significant reduction in mixes incorporating Alccofine and nanosilica. The SEM analysis confirmed that these mixes exhibited a less porous structure with a refined cementitious matrix, which effectively minimized water ingress. In contrast, the control mixes (M1 and M5) showed a more porous structure, justifying their higher water absorption values. This suggests that the supplementary cementitious materials (SCMs)

effectively filled the micro-pores, enhancing the overall impermeability and durability of the concrete. Furthermore, the presence of ultrafine nanosilica particles contributed to an accelerated pozzolanic reaction, forming a denser and more uniform C-S-H gel structure. The SEM images displayed a significant reduction in large calcium hydroxide crystals, confirming the enhanced hydration process and the formation of a cohesive, well-packed microstructure.

The initial and final setting time results indicated that the inclusion of Alccofine and nanosilica led to a faster setting process due to their high reactivity. This was further supported by SEM findings, where the presence of ultrafine particles promoted rapid hydration and early strength gain. In terms of workability, the results demonstrated that Alccofine improved the fluidity of concrete, while excessive nanosilica content reduced workability due to its high surface area and increased water demand. The SEM analysis reinforced these observations by showing that nanosilica particles contributed to improved particle packing; however, excessive amounts led to agglomeration, negatively affecting the workability of the mix.

In addition, SEM analysis provided a strong validation of the experimental results obtained for strength, water absorption, setting time, and workability. The incorporation of Alccofine and nanosilica led to significant improvements in the microstructure of concrete, resulting in higher strength, reduced permeability, faster setting, and enhanced durability. These findings highlight the critical role of microstructural refinement in the development of high-performance concrete and confirm that the use of supplementary cementitious materials is essential for improving both mechanical and durability properties. Fig. 5 presents the SEM analysis of mixes M1, M4, M5, and M8.

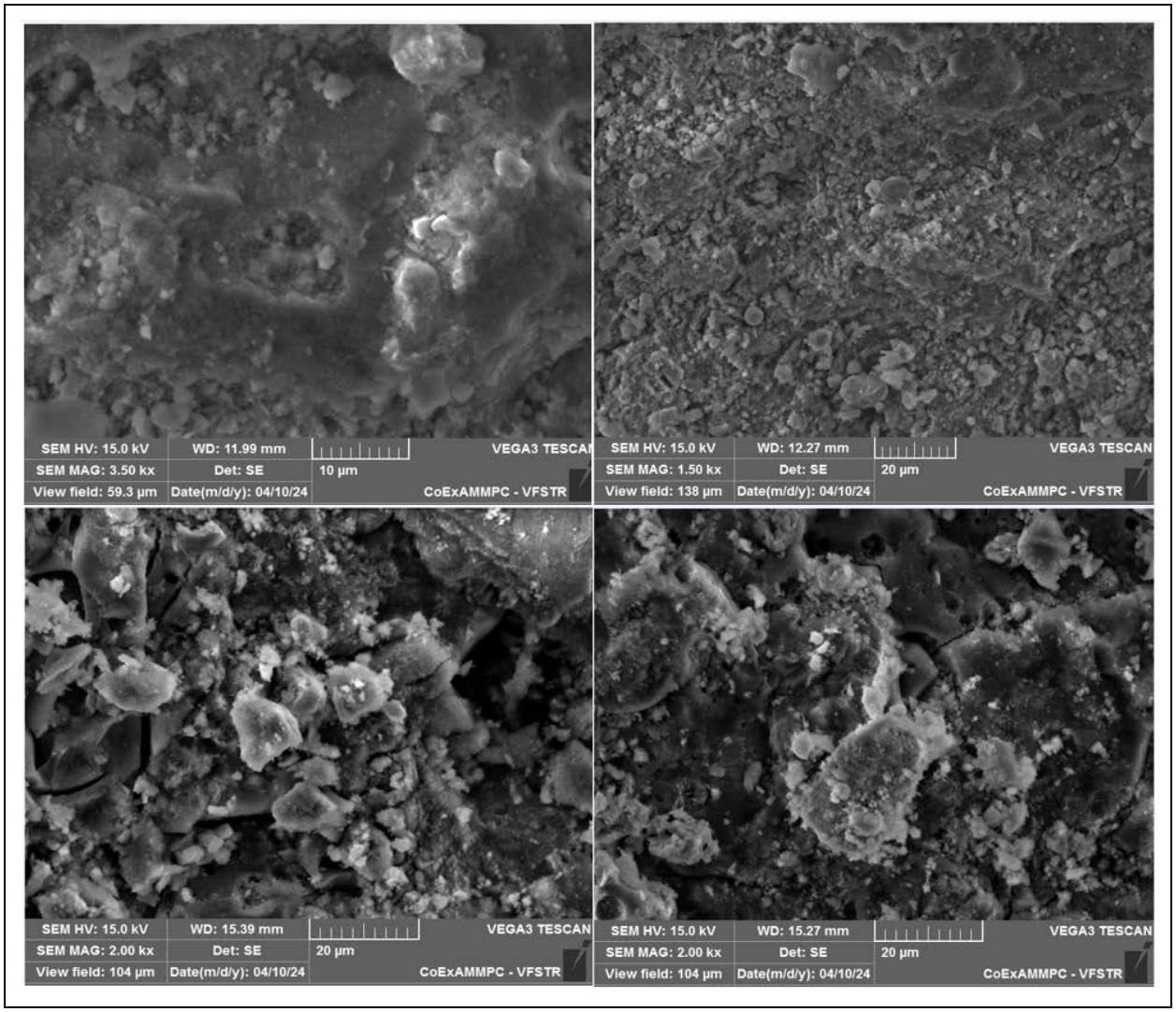


Fig. 5: SEM images of mixes M1, M4, M5 and M8

4. CONCLUSIONS

This study concludes that incorporating Alccofine and nanosilica in concrete significantly enhances its mechanical properties, durability, and setting characteristics. The optimal replacement levels of 10% Alccofine and 10% nanosilica in mixes M4 and M8 yielded the highest compressive, split tensile, and flexural strengths due to their synergistic pozzolanic activity and refined microstructure. Alccofine improved workability through its spherical particles, while nanosilica, despite increasing water demand and reducing workability, accelerated hydration and early strength gain. Water absorption tests and SEM analyses confirmed reduced porosity, improved microstructural densification, and increased formation of calcium silicate hydrate gel, resulting in enhanced durability and lower permeability. These findings establish the potential of Alccofine and nanosilica as effective additives for producing high-performance concrete suitable for demanding construction environments.

Recommendations for Future Research

Further studies can explore the long-term durability performance of Alccofine and nanosilica blended concrete in aggressive environments. Additionally, optimizing mix design parameters with advanced chemical admixtures can further enhance workability while maintaining superior strength and durability properties.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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