Effect of Zeolite and Nano-Alumina on Mechanical and Durability Properties of Fiber Reinforced Concrete

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Abstract — The primary objective of this study is to evaluate the structural and durability performance of fibre-reinforced concrete incorporating zeolite and nano-alumina as partial cement replacement materials. The use of 10% zeolite and 1% nano-alumina aims to enhance mechanical strength, durability, and microstructural properties while reducing cement consumption for sustainable construction. Polypropylene (PP) fibres were added at 0.1%, 0.2%, and 0.3% volume fractions to further improve performance. A comprehensive experimental program included casting cubes for compressive strength, cylinders for split tensile strength, prisms for flexural strength, and disc specimens for sorptivity tests. Six concrete mixes were developed, including control, blended, and fibre-reinforced variants. Results indicate that the combined use of zeolite, nano-alumina, and PP fibres significantly improves strength, crack resistance, and durability. The study confirms that optimized nano-modified fibre-reinforced concrete is a promising solution for sustainable, high-performance construction applications.

Keywords: Compressive Strength, Flexural Strength, Nano-Alumina, Water Sorptivity, Polypropylene Fibres, Split Tensile Strength, Zeolite

I. Introduction

The rapid growth of infrastructure across the globe has become a key indicator of economic development and societal progress. Nations experiencing accelerated urbanization and industrialization consistently exhibit an increased demand for construction materials, particularly concrete. As a result, the construction industry continues to expand, placing significant emphasis on developing materials that can meet evolving structural and environmental requirements. Among all construction materials, concrete remains the most widely used due to its versatility, availability, and adaptability to diverse construction needs. It is extensively utilized in residential, commercial, industrial, and infrastructural projects, making it the backbone of modern civil engineering [1].

Despite its widespread use, conventional concrete faces several challenges, particularly in terms of environmental sustainability and mechanical performance. Cement, the primary binding ingredient in concrete, plays a crucial role in determining its strength and durability. However, the production of cement is highly energy-intensive and contributes significantly to environmental degradation. It is estimated that cement manufacturing alone accounts for nearly 7% of global carbon dioxide (CO_2) emissions, making it one of the major contributors to greenhouse gas emissions worldwide. This alarming environmental impact has driven researchers and engineers to explore alternative materials and innovative technologies aimed at reducing cement consumption while enhancing the performance of concrete [2].

In response to these challenges, recent research has focused on the development of sustainable and high-performance concrete through the incorporation of supplementary cementitious materials and advanced additives. Among these, ultra-fine and nano-scale materials have emerged as promising solutions. These materials improve the particle packing density of concrete, resulting in a denser microstructure and enhanced mechanical and durability properties. The incorporation of materials such as nano-silica, nano-alumina, nano-clay, zeolite, and Alccofine has shown considerable potential in improving the overall performance of concrete under various environmental conditions [3-4].

Zeolite, a naturally occurring or synthetically produced aluminosilicate mineral, has gained attention as an effective supplementary cementitious material. Due to its high silica and alumina content, zeolite exhibits strong pozzolanic activity, reacting with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. This secondary hydration process enhances the microstructural properties of concrete, leading to improved long-term strength and durability. Studies have indicated that replacing cement with approximately 15% zeolite results in optimal mechanical and durability performance without significantly increasing the demand for chemical admixtures. Additionally, the porous structure of zeolite contributes to internal curing, reduces shrinkage, and enhances resistance to aggressive environmental conditions such as chloride attack and sulfate exposure. These properties make zeolite a viable and sustainable alternative for partial cement replacement [5].

Another significant advancement in concrete technology is the use of nano-materials, particularly nano-silica (Nano-SiO_2). Nano-silica is characterized by its extremely fine particle size and high specific surface area, which contribute to its exceptional reactivity in cementitious systems. When incorporated into concrete, nano-silica acts as a nucleation site for the formation of hydration products, accelerating the hydration process and promoting the formation of additional C–S–H gel. This leads to a refined pore structure, reduced porosity, and improved interfacial transition zone (ITZ) between the cement paste and aggregates. Consequently, concrete containing nano-silica exhibits enhanced compressive strength, tensile strength, and durability characteristics, even at early ages. Furthermore, nano-silica significantly reduces permeability and water absorption, thereby improving resistance to chemical attacks and corrosion of reinforcement. Despite these advantages, challenges such as proper dispersion of nanoparticles and cost considerations must be addressed to ensure their effective large-scale application [6-7].

While improvements in the matrix phase of concrete are essential, addressing its inherent brittleness remains equally important. Plain concrete is inherently weak in tension and exhibits low strain capacity, leading to brittle failure under loading conditions. The presence of micro-cracks within the concrete matrix further accelerates crack propagation, reducing the structural integrity and service life of concrete structures. To overcome these limitations, the concept of fibre reinforced concrete (FRC) has been introduced and widely adopted in recent years [8].

Fibre reinforced concrete is a composite material in which discrete fibres are uniformly distributed throughout the concrete matrix. These fibres act as crack arresters, bridging micro-cracks and preventing their propagation under applied stresses. As a result, FRC exhibits improved tensile strength, ductility, toughness, and energy absorption capacity compared to conventional concrete. The inclusion of fibres also enhances post-cracking behavior, allowing the material to sustain loads even after the initiation of cracks. Due to these advantages, FRC has gained widespread acceptance in various applications, including pavements, industrial floors, precast elements, and structures subjected to dynamic and impact loading [9].

The use of polypropylene fibres in concrete dates back to the 1960s, when they were initially introduced for blast-resistant structures. Since then, their application has expanded significantly across various construction sectors. The addition of PP fibres enhances the toughness, flexural strength, tensile strength, and impact resistance of concrete. Moreover, these fibres are highly effective in controlling plastic shrinkage cracking, thereby improving the durability and serviceability of concrete structures. Their non-corrosive nature and resistance to chemical attack further contribute to their suitability for use in aggressive environments [10].

In addition to polypropylene fibres, nano-alumina (Nano Al_2O_3) has also been explored as a potential nano-material for improving concrete properties. Nano-alumina particles fill the voids between cement grains, reducing porosity and enhancing the formation of C–S–H gel. This results in improved interfacial bonding and overall strength of the concrete matrix. The combined use of nano-materials and fibres offers a synergistic effect, leading to significant improvements in both mechanical and durability characteristics of concrete [11-12].

Although considerable research has been conducted on fibre reinforced concrete and the use of supplementary cementitious materials, most studies have focused on individual components or binary blends. Limited research is available on the combined effect of fibres and multiple ultra-fine materials such as nano-silica and zeolite in a single concrete system. Furthermore, there is a lack of comprehensive studies investigating the behavior of such composite materials under different loading conditions, particularly in flexural members subjected to static and cyclic loading [12].

In this context, the present study aims to develop a high-performance, sustainable fibre reinforced concrete by incorporating polypropylene fibres along with nano-silica and zeolite as supplementary materials. The research focuses on evaluating the mechanical performance and durability characteristics of the developed concrete, with particular emphasis on strength enhancement and structural efficiency. By integrating advanced materials and innovative approaches, this study seeks to contribute to the development of next-generation concrete suitable for modern infrastructure demands.

II. MATERIALS AND METHODOLOGY

A. General Description

A comprehensive experimental investigation was carried out to evaluate the performance of fibre-reinforced concrete incorporating supplementary cementitious materials. A preliminary study was conducted to determine the optimum dosage of zeolite and nano-alumina for enhancing concrete properties. Based on the findings, polypropylene (PP) fibres were used as micro-reinforcement in varying volume fractions of 0.1%, 0.2%, and 0.3%. A total of specimens were cast to assess mechanical and durability characteristics, including 36 cubes (150 × 150 × 150 mm), 54 cylinders (150 × 300 mm), 18 cylinders (100 × 200 mm), and 18 prisms (100 × 100 × 500 mm). Control specimens were prepared to establish baseline properties, and comparative analysis was performed with modified mixes. Cubes were used for compressive strength, water absorption, and porosity tests; cylinders for split tensile strength and modulus of elasticity; prisms for flexural strength; and disc specimens (100 × 50 mm) for sorptivity measurements. The mix nomenclature included conventional concrete (CC), zeolite-based concrete (Z), zeolite with nano-alumina (ZA), and fibre-reinforced ternary mixes (ZAP-1, ZAP-2, ZAP-3) with increasing fibre content.

B. Materials Used

Ordinary Portland Cement (OPC) of 53 grade conforming to IS: 12269–2013 was used as the primary binder. The cement exhibited adequate fineness, standard consistency, and strength characteristics suitable for structural applications. Manufactured sand (M-sand) was used as fine aggregate due to its uniform grading, angular shape, and environmental benefits. It had a specific gravity of 2.62 and conformed to Zone II as per IS: 383–2016. Crushed coarse aggregate with a maximum size of 20 mm and specific gravity of 2.72 was used, ensuring good mechanical interlocking and strength development. A high-range water-reducing admixture, Kuna Plast PC-50, was used to improve workability without increasing water content. The admixture enhanced flowability, cohesiveness, and resistance to segregation. Nano-silica, characterized by its ultra-fine particle size and high surface area, was incorporated to enhance hydration and microstructure densification. Zeolite, procured commercially, was used as a partial cement replacement due to its pozzolanic activity and ability to improve durability. Nano-alumina was added as a nano-modifier to enhance the interfacial transition zone and mechanical properties. Polypropylene fibres of 12 mm length, 0.04 mm diameter, and aspect ratio of 300 were used. These fibres possess high tensile strength and low density, making them effective in improving crack resistance, ductility, and toughness of concrete.

C. Mix Design

The concrete mix was designed as per IS: 10262–2019. The control mix achieved a compressive strength of 39.04 MPa with a water-binder ratio of 0.48. The mix proportions included 387 kg/m³ of cement, 654 kg/m³ of fine aggregate, and 1219 kg/m³ of coarse aggregate. For modified mixes, 10% cement was replaced with zeolite, and 1% nano-alumina was added. Polypropylene fibres were incorporated in varying proportions (0.1%, 0.2%, and 0.3%). The water content was maintained constant at 187 kg/m³ for all mixes. Superplasticizer dosage was adjusted to achieve the desired workability.

D. Specimen Preparation

Concrete mixing was carried out using a tilting drum mixer. Dry materials, including cement, aggregates, zeolite, and nano-alumina, were first mixed thoroughly. Approximately 80% of water along with the superplasticizer was then added gradually and mixed to achieve uniform consistency. Polypropylene fibres were introduced slowly and uniformly to prevent clustering. The remaining water and admixture were added, followed by thorough mixing. The fresh concrete was placed into steel moulds and compacted using a vibrating table to eliminate air voids. After casting, specimens were demoulded after 24 hours and cured in water for 28 days under controlled conditions to ensure proper hydration.

E. Testing Procedures

Compressive strength tests were conducted on cube specimens using a compression testing machine (CTM) of 3000 kN capacity, following IS: 516–1959. The load was applied at a controlled rate until failure, and strength was calculated based on maximum load. Split tensile strength was determined using cylindrical specimens as per IS: 5816–1999. The specimens were subjected to diametrical compression, inducing tensile stresses leading to failure. Flexural strength tests were performed on beam specimens using a two-point loading setup. The load was applied at a constant rate until fracture, and the modulus of rupture was calculated. Sorptivity tests were conducted on disc specimens in accordance with ASTM C1585-04. Oven-dried specimens were partially immersed in water, and the rate of capillary absorption was measured over time to evaluate permeability characteristics

III. Results and Discussions

A. Compressive Strength

The experimental results demonstrate that the incorporation of polypropylene fibres (PPF) significantly enhances the compressive strength of ternary blended concrete. All modified mixes exhibited higher strength compared to conventional concrete (CC), confirming the beneficial role of fibres and supplementary cementitious materials. The improvement is primarily attributed to the crack-bridging action of fibres and the enhanced bonding within the cementitious matrix. Among all the mixes, ZAP-2 exhibited the highest compressive strength, showing an increase of 19.33% over CC. Other mixes such as Z, ZA, and ZAP-1 also showed improvements of 4.84%, 7.73%, and 15.21%, respectively. This progressive increase highlights the combined effect of zeolite, nano-alumina, and fibres in enhancing strength. When compared with the zeolite-only mix (Z), additional improvements were observed in ZA (2.76%), ZAP-1 (9.89%), and ZAP-2 (13.82%), indicating the positive influence of nano-alumina and fibres.

Furthermore, relative to ZA, the mixes ZAP-1 and ZAP-2 showed additional increases of 6.22% and 9.66%, respectively, confirming the effectiveness of fibre reinforcement. The fibres act as crack arresters, limiting crack propagation and enabling better stress distribution, which ultimately leads to improved compressive performance.

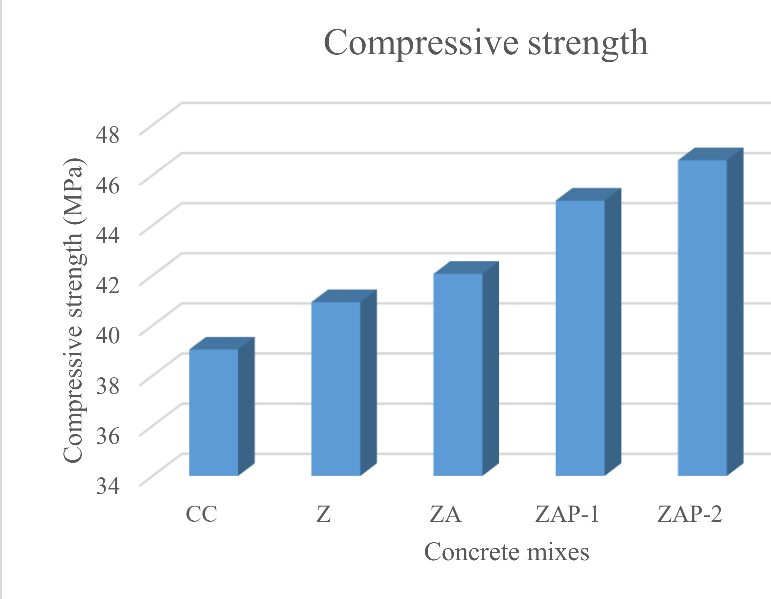

Fig. 1: Effect of PPF on compressive strength

B. Split Tensile Strength

The split tensile strength results reveal a significant improvement due to the incorporation of zeolite, nano-alumina, and polypropylene fibres. The enhancement in tensile strength is more pronounced than in compressive strength, indicating the effectiveness of fibres in resisting tensile stresses. The highest improvement was observed in ZAP-3, with an increase of 66.26% compared to CC. Other mixes such as Z, ZA, ZAP-1, and ZAP-2 showed increases of 13.85%, 28.31%, 47.28%, and 56.02%, respectively. The steady increase demonstrates that higher fibre content contributes to better tensile resistance.

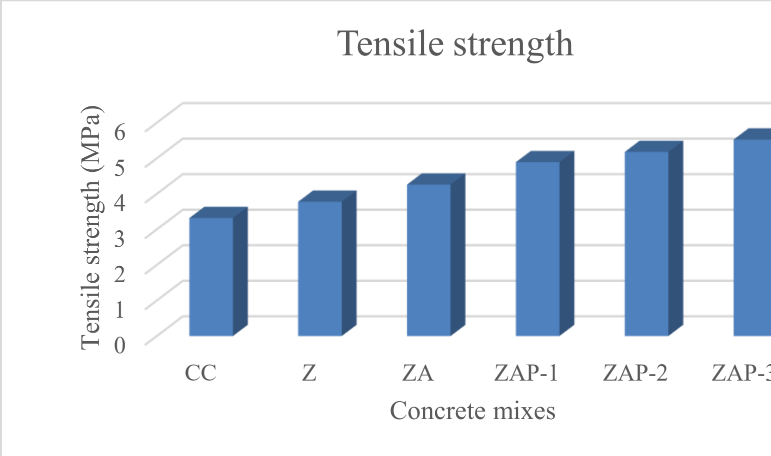

Fig. 2: Effect of PPF on tensile strength

Compared with Z, the mixes ZA, ZAP-1, ZAP-2, and ZAP-3 showed additional increases of 12.39%, 29.36%, 37.03%, and 46.29%, respectively. Similarly, relative to ZA, further improvements of 14.78%, 21.59%, and 29.81% were observed for ZAP-1, ZAP-2, and ZAP-3. These results highlight the role of nano-alumina in improving the interfacial transition zone and the effectiveness of fibres in bridging cracks. The fibres enhance tensile behaviour by preventing sudden crack propagation and improving ductility, resulting in a more gradual failure pattern.

C. *Flexural Strength*

The flexural strength results indicate that the addition of zeolite, nano-alumina, and polypropylene fibres significantly improves the bending performance of concrete. Among all the mixes, ZAP-3 exhibited the highest flexural strength, with an increase of 26.15% over CC. Other mixes also showed notable improvements, with Z, ZA, ZAP-1, and ZAP-2 exhibiting increases of 9.2%, 15.38%, 18.46%, and 21.53%, respectively. Compared to Z, the mixes ZA, ZAP-1, ZAP-2, and ZAP-3 showed further improvements of 5.63%, 8.45%, 11.26%, and 25.35%, respectively. Similarly, relative to ZA, additional increases of 2.66%, 5.33%, and 18.6% were observed for ZAP-1, ZAP-2, and ZAP-3. The improvement in flexural strength is mainly due to the crack-bridging mechanism of polypropylene fibres and the enhanced bonding at the interfacial transition zone. Fibres delay crack propagation and improve load-carrying capacity under bending, leading to higher modulus of rupture.

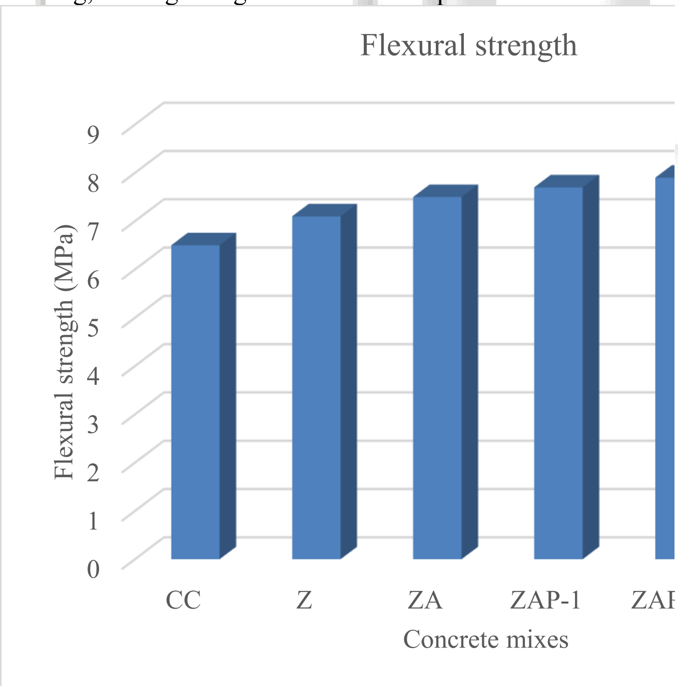

Fig. 3: Effect of PPF on flexural strength

D. *Sorptivity*

Sorptivity results indicate that the inclusion of polypropylene fibres significantly improves the durability of concrete by reducing water absorption. Lower sorptivity values were observed in fibre-reinforced ternary mixes compared to CC, indicating reduced permeability. The mix containing 0.2% PPF exhibited the lowest sorptivity, suggesting an optimum fibre content for durability enhancement. The reduction in water absorption is attributed to the pore-blocking effect of fibres and the refinement of pore structure due to the presence of zeolite and nano-alumina. The combined effect of these materials results in a denser microstructure with reduced interconnected pores, limiting capillary water movement. Additionally, fibres help control micro-crack formation, further restricting water ingress. Overall, the results confirm that the synergistic use of zeolite, nano-alumina, and polypropylene fibres enhances both mechanical properties and durability of concrete, making it suitable for high-performance and sustainable construction applications.

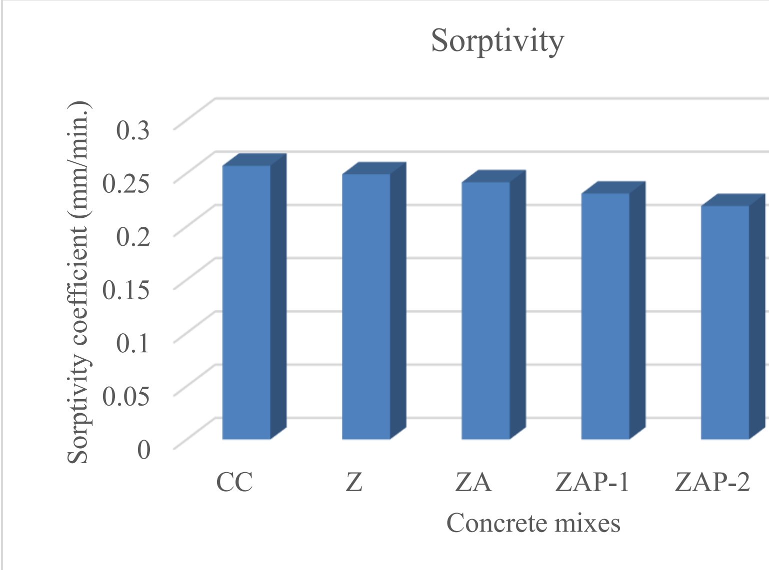

Fig. 4: Effect of PPF on water sorptivity

IV. Conclusion

1) The present study successfully achieved its objectives by evaluating the combined influence of polypropylene (PP) fibres, nano-alumina (NA), and zeolite on the performance of concrete, contributing to sustainable construction practices.
2) The incorporation of zeolite, nano-alumina, and polypropylene fibres significantly enhanced the compressive strength of concrete. The optimum mix (ZAP-2) showed an improvement of 19.33% over conventional concrete, indicating the effectiveness of ternary blending.
3) A progressive increase in compressive strength with increasing fibre content highlights the crack-bridging ability of fibres and improved microstructural densification due to supplementary materials.
4) Split tensile strength showed remarkable improvement, with the ZAP-3 mix exhibiting a 66.26% increase, confirming the crucial role of fibres in enhancing tensile resistance and controlling crack propagation.
5) The improvement in tensile properties is attributed to enhanced bonding within the matrix and strengthening of the interfacial transition zone (ITZ) due to nano-alumina and zeolite.
6) Flexural strength results demonstrated significant enhancement, with a maximum increase of 26.15% for ZAP-3, indicating improved resistance to bending stresses and higher energy absorption capacity.

7) The combined action of fibres and nano-materials effectively restricted crack formation and propagation, resulting in improved ductility and structural performance.
8) Sorptivity results confirmed enhanced durability, with reduced water absorption observed in fibre-reinforced mixes. The optimum performance was achieved at 0.2% fibre content, indicating effective pore blocking and reduced permeability.
9) The reduction in sorptivity is due to microstructure refinement and disruption of capillary pores by fibres and supplementary cementitious materials.
10) Overall, the study confirms that ternary blended fibre-reinforced concrete is a sustainable, high-performance material, suitable for modern construction requiring improved strength, durability, and environmental compatibility.

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