

EXPERIMENTAL STUDY ON HYBRID FIBER-REINFORCED CONCRETE WITH ALCCOFINE AND ZEOLITE AS PARTIAL CEMENT REPLACEMENTS

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Received: June 02, 2025; Revised: October 01, 2025; Accepted: October 10, 2025

Abstract

The study investigates the mechanical, durability, and microstructural performance of hybrid fiber-reinforced concrete (HFRC) incorporating Alccofine and natural zeolite as supplementary cementitious materials (SCMs) replacing a portion of Ordinary Portland cement (OPC). Concrete mixes were formulated with a fixed water-to-binder (w/b) ratio of 0.48 and subjected to standard curing for 28 days. The mechanical behavior was evaluated through compressive strength, splitting tensile strength, flexural strength via four-point bending, and static elastic modulus testing. Durability performance was assessed through water absorption and rapid chloride penetration tests (RCPT). Integrating steel fibers (SF) and polypropylene fibers (PPF) in a hybrid configuration significantly enhanced mechanical strength and resistance to durability-related degradation. Compared to the control, the optimized HFRC mix exhibited substantial performance gains : compressive strength increased by 21.13%, splitting tensile strength by 32.33%, flexural strength by 41.05%, and elastic modulus by 32.14%. Durability indicators also improved, with notable reductions in water absorption and chloride ion permeability, suggesting enhanced long-term performance in aggressive environments. These results demonstrate that combining Alccofine and natural zeolite with hybrid fiber reinforcement yields synergistic improvements in structural and durability aspects, promoting the development of high-performance, sustainable concrete systems.

Keywords: Alccofine; Hybrid Fiber-Reinforced Concrete; Natural Zeolite; Polypropylene Fibers; RCPT; Steel Fibers

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DOI: <https://doi.org/10.55766/sujst10102>

Suranaree J. Sci. Technol. 33(2):010413(1-15)

Introduction

Concrete technology continually evolves, with researchers striving to enhance the performance, durability, and sustainability of concrete structures. One of the recent advancements in this area is the development of ternary blended concretes, which utilize multiple supplementary cementitious materials (SCMs) to optimize mechanical and durability properties. Building on this innovation, the present study explores a novel approach to further improve the performance of ternary blended concrete through fiber reinforcement. Specifically, this research investigates the synergistic effects of incorporating Alccofine and Zeolite as SCMs, combined with hybrid fiber reinforcement using steel fibers (SF) and polypropylene fibers (PPF) at varying volume fractions. This unique combination aims to overcome conventional concrete's limitations while leveraging each additive's benefits. Concrete remains the most widely used construction material worldwide, yet it faces significant engineering challenges related to cracking, brittleness, and durability under varying environmental conditions (Shaikh, 2013; Tassew & Lubell, 2014; Yin *et al.*, 2015; Kizilkanat *et al.*, 2015; Pakravan & Ozbakkaloglu, 2019). Incorporating micro-level reinforcements such as chopped fibers has emerged as a promising approach to enhance crack resistance and mechanical behavior (Ding & Kusterle, 2000). For instance, steel fibers improve flexural strength and fracture resistance by bridging cracks, while Zeolite contributes to better fiber-matrix adhesion (Gülşan *et al.*, 2019).

Although several studies have examined the influence of fibers on concrete performance, often focusing on fixed water-to-binder ratios and determining optimal fiber contents (Reddy & Meena, 2019), the interplay between water-to-binder ratios, fiber type, and SCM combinations remains underexplored. There is a notable gap in the literature regarding the combined effects of Alccofine, Zeolite, and hybrid fibers in ternary blended concrete systems. This study seeks to fill that gap by systematically evaluating how integrating Alccofine, Zeolite, and hybrid fibers (SF and PPF) influences the mechanical properties of ternary blended concrete across different water/binder ratios and fiber contents.

In addition to experimental advancements, it is equally important to link material-level innovations with structural-scale applications. For example, studies such as “Numerical Analysis on Structural Behaviour of Concrete-Filled Steel Tubular Columns” demonstrate how material enhancements

directly influence the performance of large-scale composite members. The present research, by establishing improved mechanical and durability properties of Zeolite–Alccofine–hybrid fiber concrete, provides a robust database that can support future FEM-based or analytical modelling of hybrid structural systems. This connection positions the study not only as a material innovation but also as a potential enabler for improved numerical predictions and design optimizations in structural engineering practice.

Furthermore, while this work primarily focuses on experimental validation, it has important implications for structural-scale applications. For instance, numerical investigations such as “Numerical Analysis on Structural Behaviour of Concrete-Filled Steel Tubular Columns” have demonstrated how improvements at the material level directly influence the load-bearing performance of large-scale structural members (Utkarsh *et al.*, 2023). By providing a robust dataset on Zeolite–Alccofine–hybrid fiber concrete, the present study lays the groundwork for future FEM-based and analytical modelling efforts, thereby bridging material innovation with broader structural engineering applications.

Recent bibliometric evidence further underscores the significance of this research direction. For example, “A comprehensive bibliometric analysis of punching shear failures in flat slabs” highlights that durability-related mechanisms (such as cracking, chloride penetration, and carbonation) are increasingly studied in conjunction with structural behavior, particularly shear performance. This demonstrates that durability in hybrid FRC is not merely a material property but a factor directly influencing the safety, service life, and reliability of structural systems (Utkarsh *et al.*, 2025). The bibliometric trend confirms that durability-focused hybrid FRC research is an emerging frontier, linking material innovation with structural-scale implications.

Finally, while the present study is primarily experimental, its outcomes provide valuable datasets on both mechanical and durability indices. These can serve as input for advanced modelling and structural analyses. Numerical studies, such as “Numerical Analysis on Structural Behaviour of Concrete-Filled Steel Tubular Columns”, have shown that improved material datasets enhance FEM-based predictions of large-scale behavior (Urkude *et al.*, 2025). Thus, this work not only establishes material-level advancements in Zeolite–Alccofine–hybrid fiber concretes but also creates a

foundation for bridging experimental insights with structural-scale modelling and predictive analytics.

Literature Review

The integration of fibers into cementitious composites has been a significant area of research, with various fiber types offering distinct mechanical advantages. Multiple studies have explored synthetic, natural, and hybrid fibers to enhance properties such as tensile strength, durability, fracture resistance, and overall structural integrity.

Shaikh (2013) reviewed using short fibers in geopolymer composites, focusing primarily on mechanical enhancements. The review highlighted that fibers compensate for the brittle nature of geopolymer matrices and contribute to shrinkage control and long-term durability. The study stressed the importance of fiber-matrix interface bonding and fiber orientation in achieving the desired mechanical performance.

Razavi *et al.* (2021) explored the effects of nano-silica incorporation on the mechanical behavior of Engineered Cementitious Composites (ECCs), including a high volume of natural zeolite as a partial cement replacement. This research aligns with sustainable construction goals by utilizing eco-friendly materials while enhancing performance. Their experimental analysis demonstrated that including nano-silica significantly improved compressive and tensile strengths, especially in mixes with higher zeolite content. Nano-silica acted as a pozzolanic agent and filler, refining the microstructure and promoting better fiber-matrix bonding. The study also noted enhanced strain-hardening behavior and ductility, which are critical for ECC applications where controlled cracking and energy absorption are key. These improvements highlight the role of nanomaterials in compensating for potential strength losses due to high replacement levels of ordinary Portland cement with zeolite (Razavi *et al.* 2021) work supports the notion that nanotechnology can effectively boost the mechanical integrity of green concretes, paving the way for high-performance, sustainable structural materials.

Gülşan *et al.* (2019) explored the development of a self-compacting geopolymer concrete reinforced with steel fibers and nano-silica. Their experimental results demonstrated a synergistic effect between the steel fibers and nano additives, improving flowability, compressive strength, and crack control. This research underlined the potential of combining chemical and mechanical enhancements in next-generation construction materials.

Chi *et al.* (2017) employed finite element modeling to simulate the behavior of hybrid fiber concrete incorporating steel and polypropylene

fibers. Utilizing a modified concrete damaged plasticity model, the study captured the complex stress-strain response under loading. The numerical findings were consistent with experimental results, showcasing the hybrid system's superior energy absorption and resistance to damage propagation.

Parallel to SCM research, fiber reinforcement has emerged as a reliable strategy to counteract the brittle nature of concrete. Steel fibers (SF) are known to enhance toughness, crack-bridging capacity, and post-cracking load resistance, while polypropylene fibers (PPF) contribute to shrinkage control and spalling resistance (Kizilkanat *et al.*, 2015; Pakravan & Ozbakkaloglu, 2019). When used in combination, hybrid fibers can provide a synergistic effect by addressing micro- and macro-cracking simultaneously (Tassew & Lubell, 2014). Several investigations have highlighted that hybrid fiber-reinforced concrete (HFRC) demonstrates significant improvements in flexural strength, split tensile strength, and fracture energy, though the magnitude of improvement depends on fiber type, aspect ratio, and dosage (Yin *et al.*, 2015; Ding & Kusterle, 2000).

Despite these advances, existing literature shows two major gaps. First, few studies have systematically examined the interaction between SCMs and hybrid fibers in a ternary blended system, particularly one that integrates both Zeolite and Alccofine. Second, while the structural performance of fiber-reinforced concretes has been widely studied, the durability dimension of HFRC remains less explored. Recent bibliometric studies, such as "A comprehensive bibliometric analysis of punching shear failures in flat slabs", underscore that durability and structural shear performance are interlinked and are under active research. This trend suggests that improving durability at the material level through optimized SCMs and hybrid fibers can directly influence shear-critical structural elements such as slabs and composite columns.

Furthermore, advanced numerical and modelling approaches in structural engineering have shown increasing reliance on accurate experimental datasets. For instance, the study "Numerical Analysis on Structural Behaviour of Concrete-Filled Steel Tubular Columns" highlights how improved material formulations enhance predictive accuracy in FEM models for large-scale elements. Similarly, recent trends emphasize the use of machine learning (ML) and metaheuristic-optimized ANN models to integrate mechanical and durability datasets for predictive analysis in FRP- and fiber-reinforced systems. However, such data-driven frameworks require high-quality experimental benchmarks, which remain scarce for ternary blended, hybrid fiber concretes.

Against this backdrop, the present study contributes to filling these gaps by generating a comprehensive experimental dataset that couples mechanical properties (strength, stiffness, toughness) with durability indices (water absorption, chloride penetration, microstructural behaviour) in Alccofine–Zeolite hybrid FRC. These insights not only advance material-level understanding but also serve as a foundation for structural-scale modelling and predictive analytics in next-generation concrete research.

Research Gap:

Based on the reviewed literature, studies incorporating a dual supplementary cementitious material (SCM) system consisting of Alccofine and Zeolite are currently unavailable. Furthermore, research combining dual SCMs with hybrid fiber reinforcement (steel and polypropylene fibers) remains highly limited. In this study, the individual effects of Alccofine and Zeolite are investigated, along with their combined performance in a triple-blended concrete system (OPC + Alccofine + Zeolite). Additionally, the influence of steel and polypropylene fibers is examined separately at varying dosages, and their synergistic effect is evaluated within the triple-blended concrete matrix.

Materials and Methods

Cement

This research used OPC 53 grade cement (IS 12269:2013). Table 1 details the cement parameters employed in all concrete mixtures for this study.

Table 1. Properties of binding materials

Properties	Values
Final Setting Time	384 min
Specific Gravity	3.15
Initial Setting Time	55 min

Coarse Aggregate

The crushed granites of 20 mm & 12 mm of angular shape were used with a specific gravity of 2.82 when tested as per IS 2386:2016 and IS 383:2016.

Fine Aggregate

Zone III river sand with a specific gravity of 2.71 was used (IS 383:2016).

Superplasticizer

Conplast SP430 is used to obtain a good slump of 0-75 mm slump value (IS:456-2000). The properties of SP are furnished in Table 2

Table 2. Superplasticizer Properties

Properties	Values
Availability Colored	Appears in dark brown
Availability Form	In Liquid
Specific Gravity	1.26

Zeolite and Alccofine

Alccofine 1203 and Zeolite with specific surface area and specific gravity were used in the present investigation, as shown in Table 3. The selection of Alccofine and natural Zeolite as partial cement replacements in this study is guided by their proven abilities to enhance both the mechanical and durability properties of concrete, while simultaneously contributing to sustainability. Alccofine is an ultra-fine ground granulated slag-based material with a specific surface area typically above 120 m²/g, enabling it to act as a micro-filler and highly reactive pozzolan. Its ultra fineness contributes to pore refinement, improved particle packing, and accelerated hydration, particularly in the early stages. Studies by (Patel & Shah, 2015) showed that Alccofine improves early compressive strength, reduces permeability, and enhances resistance to chloride ingress due to the denser microstructure it produces. Compared with conventional mineral admixtures like fly ash or silica fume, Alccofine has been reported to be more effective in enhancing strength gain within the first 28 days due to its higher reactivity and micro-filling capacity (Jamenraja & Ravichandran, 2023).

Table 3. Properties of Zeolite and Alccofine 1203

Materials	specific surface area (m ² /g)	Specific gravity
Zeolite	19.24	2.6
Alccofine 1203	120	2.74

Natural Zeolite, a crystalline aluminosilicate mineral, exhibits significant pozzolanic activity through its ability to react with calcium hydroxide to form secondary C–S–H gel. Its porous framework structure also acts as an internal curing agent by retaining water and gradually releasing it to sustain hydration, which reduces autogenous shrinkage and micro-cracking (Abrahimi & Bhikshma, 2024) have confirmed that zeolite incorporation decreases the permeability and chloride ion penetration of concrete, thereby improving durability in aggressive environments. Moreover, zeolite's ion-exchange capacity contributes to alkali-silica reaction (ASR) mitigation, a critical durability concern in long-term service life of concrete structures.

When combined, Alccofine and Zeolite exhibit complementary effects. Alccofine provides rapid strength development and microstructural

densification, while zeolite improves long-term pozzolanic reactions, durability, and shrinkage resistance. This synergistic action is consistent with reports (Gülşan *et al.*, 2019), who demonstrated that ternary blends incorporating ultra-fine slag and zeolite led to significant improvements in both strength and durability indices compared to binary blends.

From a sustainability perspective, partial replacement of cement with Alccofine and Zeolite directly contributes to reducing clinker consumption and CO₂ emissions associated with cement production (Meenatchi *et al.*, 2023) emphasized that using high-reactivity SCMs can cut embodied carbon without sacrificing performance, aligning with global low-carbon construction goals.

Thus, the combined use of Alccofine and Zeolite in this research is not only technically justified for performance improvement but also strategically aligned with sustainable construction practices. This dual advantage performance enhancement and ecological benefit makes their selection both scientifically and practically significant.

Properties of Polypropylene fiber

Polypropylene is used as micro-reinforcement in the present research study. The addition of polypropylene fiber improved the properties of concrete. Table 4 shows the properties of polypropylene fiber.

Table 4. Properties of Polypropylene Fiber

Properties	Observations
Type of fiber	Polypropylene
Aspect Ratio(l/d)	300
Tensile Strength (MPa)	450

Properties of steel fiber

Steel fiber has been used as a micro-reinforcement in the present research study. Properties of Steel fibers are listed in Table 5.

Table 5. Properties of Steel Fiber

Properties	Values
Shaped	Hooked End
Length	60 mm
Diameter	0.80 mm
Specific gravity	7.85

Mix Proportions

In accordance with IS 10262:2019 guidelines, M30 grade concrete was designed and developed. Twelve distinct mix formulations were prepared, incorporating combinations of Alccofine and natural zeolite as partial replacements for cement. Additionally, discrete fibers were introduced into selected mixes to evaluate their influence on performance parameters. Zeolite and Alccofine were incorporated at replacement levels of 10% and 15% by weight of cement, respectively. All concrete mixtures including control, binary, and ternary blended systems with and without fiber reinforcement were designed with a constant water-to-binder (w/b) ratio of 0.48. The superplasticizer (SP) dosage was adjusted for each mix to achieve the target workability. The detailed mix proportions for all variations are presented in Table 6.

Preparation of control specimens

The concrete constituents were dry mixed, followed by adding a portion of water and high-range water-reducing admixture (HRWRA) as per the mix design. After initial blending, the remaining water and HRWRA were added and thoroughly mixed. Steel fibers were gradually introduced into

Table 6. Mix Proportions of Concrete

Mix Id	Cement Kg/m³	FA Kg/m³	CA Kg/m³	Zeolite Kg/m³	Alccofine Kg/m³	SF%	PPF%	SP	
CC	387	654	731.4	487.6	-	-	-	8.78	
CA	328.95	654	731.4	487.6	-	58.05	-	8.94	
CZ	348.3	654	731.4	487.6	38.7	-	-	8.98	
CAZ	290.25	654	731.4	487.6	38.7	58.05	-	9.02	
AZS1	290.25	654	731.4	487.6	38.7	58.05	0.5	9.15	
AZS2	290.25	654	731.4	487.6	38.7	58.05	1.0	9.21	
AZS3	290.25	654	731.4	487.6	38.7	58.05	1.5	9.54	
AZP1	290.25	654	731.4	487.6	38.7	58.05	-	0.1	9.24
AZP2	290.25	654	731.4	487.6	38.7	58.05	-	0.2	9.25
AZP3	290.25	654	731.4	487.6	38.7	58.05	-	0.3	9.41
AZSP1	290.25	654	731.4	487.6	38.7	58.05	0.5	0.1	9.46
AZSP2	290.25	654	731.4	487.6	38.7	58.05	1.0	0.2	9.85
AZSP3	290.25	654	731.4	487.6	38.7	58.05	1.5	0.3	9.78

Table 7. Details of Test Specimens

Test Conducted	Specimen	Standard Documents	Size(mm)	No. of specimens
Compressive Strength	Cube	IS 516:1959 (Affirmed to 2004)	150×150	39
Flexural Strength	Prism	IS 516:1959 (Affirmed to 2004)	100×100×500	39
Split Tensile Strength	Cylinder	IS 516:1959 (Affirmed to 2004)	150×300	39
Elasticity of Modulus	Cylinder	IS 516:1959 (Affirmed to 2004)	150×300	39
Sem Analysis	Solid samples	ASTM C1723-16(2022)	10mm	6

the wet mix and uniformly dispersed. Control specimens (cubes, cylinders, and prisms) were cast and compacted using a vibrating table. After 24 hours, specimens were demolded and cured in water for 28 days. The details of casting, curing, and testing of the specimens are presented in Table 7.

Test Methods

The investigation involved two distinct stages. In the initial phase, varying proportions of Alccofine and Zeolite were experimented with to determine the ideal combination while partially replacing the binder material. In the subsequent phase, we introduced steel fibers (0.5%, 1.0%, and 1.5%) and polypropylene fibers (0.1%, 0.2%, and 0.3%) at different volume fractions to the concrete, alongside the optimal amounts of Zeolite and Alccofine. Within the context of ternary blended concrete, we conducted assessments of mechanical properties.

Results and Discussion

Compressive Strength Test

Cubes were cast and tested for f_{ck} , and the test results are presented in Table 8. The compressive strength analysis of the specimens reveals a range of Performances, with varying combinations indicating the influence of different materials or mixes.

The control specimen (CC) shows a strength of 39.56 MPa and serves as a baseline. Specimens incorporating waste glass powder, such as CA (4) at 41.91 MPa and CZ at 42.56 MPa, exhibit significant improvements. Notably, the AZ series (AZS1 to AZSP3) demonstrates a consistent upward trend in compressive strength, with AZSP2 reaching a peak of 47.92 MPa. The inclusion of specific additives or the optimization of mix designs can enhance the overall strength (Dabbaghi *et al.*, 2021; Fallah *et al.*, 2017). The results indicate that the careful selection of materials can lead to superior performance in concrete applications, highlighting the potential for

innovative uses of fibers and cementitious materials in construction.

Table 8. Test Results of Compressive Strength

Specimen	Compressive Strength (MPa)
CC	39.56
CA	41.91
CZ	42.56
CAZ	44.14
AZS1	45.79
AZS2	46.12
AZS3	44.98
AZP1	44.35
AZP2	46.02
AZP3	44.65
AZSP1	46.88
AZSP2	47.92
AZSP3	46.03

The effects of steel and polypropylene fibers on cube compression is shown in Figure 1. The improved trend of f_{ck} was observed with the addition of hybrid fibers (Zhang and Li, 2013; Yap *et al.*, 2014). A peak of 5.94% and 7.58% was observed for the binary concrete (CA and CZ) specimens, and the ternary concrete was observed at 11.58% (CAZ) compared to the control (CC) specimen. The enhancement in strength was due to denser packing of particles with the addition of Zeolite and Alccofine. With addition of fibers with different fractions to the ternary blended concrete were observed in increasing strength was 15.75%, 16.58%, 13.70% (AZS1, AZS2, AZS3), 3.74%, 4.49%, 2.01% when compared with control concrete (CC) and ternary blended concrete (CAZ) and 12.11%, 16.33%, 12.87% (AZP1, AZP2, AZP3), 1.2%, 4.26%, 1.16% when compared with CC and CAZ respectively. When CAZ is added with hybrid fibers, it was observed in the enhancement of strength 18.50%, 21.13% and 16.35%, and 6.21%, 8.56%, 4.28% (AZSP1, AZSP2 and AZSP3) compared to control concrete (CC) and ternary blended concrete (CAZ). The maximum

enhancement was observed at the AZSP2 specimen, mainly due to the bridging action of fibres and improved bond between the cement matrices.

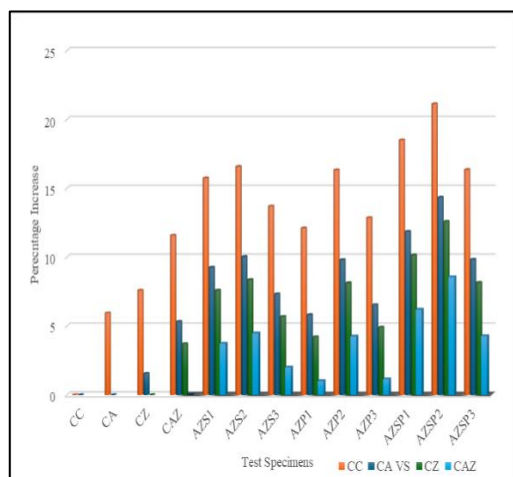


Figure 1. Effects of fibers on compressive strength

Table 9. Test Results of Modulus of Rupture

Specimen	Modulus of Rupture (MPa)
CC	6.97
CA	7.25
CZ	7.85
CAZ	7.98
AZS1	8.24
AZS2	8.56
AZS3	8.98
AZP1	8.12
AZP2	8.42
AZP3	8.67
AZSP1	8.41
AZSP2	8.79
AZSP3	9.21

Modulus of Rupture Test

The size of the specimen was $100 \times 100 \times 500$ mm, and the test results were furnished in Table 9 as per IS 516:1959. The modulus of rupture (MPa) values for the different specimen types indicate their flexural strength or bending resistance. The specimen types with the lowest modulus of rupture are CC at 6.97 MPa and CA at 7.25 MPa. The specimen types with the highest modulus of rupture are AZSP3 at 9.21 MPa, AZS3 at 8.98 MPa, and AZSP2 at 8.79 MPa. The modulus of rupture generally increases from the CC and CA specimens to the CZ, CAZ, AZS, AZP, and AZSP specimens, indicating that the composition and manufacturing process of the latter specimens result in higher values. Higher modulus of rupture values indicates greater flexural strength and load-bearing capacity (Abacian *et al.*, 2018; Xue *et al.*, 2019a). The variations in modulus of rupture observed across the

different specimen types are likely due to differences in their material composition, microstructure, and manufacturing process. The crack width decreased with increasing fiber volume fraction.

The effect of fibers on flexural strength is illustrated in Figure 2. An increase of 4.02% and 12.63% was observed for the binary concrete (CA and CZ) specimens, and the ternary concrete was noted as 14.49% (CAZ) compared to the CC specimen. The strength enhancement was due to the particle packing of cementitious materials added to the concrete. With addition of steel fibers and polypropylene fibers with different volume fractions to the ternary blended concrete were observed in increasing strength in flexural strength was 18.22%, 22.81%, 28.84% (AZS1, AZS2, AZS3), 3.26%, 7.27%, 2.01% when compared with control concrete (CC) and ternary blended concrete (CAZ) and 16.50%, 20.80%, 24.39% (AZP1, AZP2, AZP3), 1.02%, 5.51%, 8.65% when compared with CC and CAZ respectively. When CAZ is added with hybrid fibers, it was observed in the enhancement of strength 20.66%, 26.11% and 32.14% (AZSP1, AZSP2 and AZSP3), 5.39%, 10.15%, and 15.41% compared with control concrete (CC) and ternary blended concrete (CAZ) (Yap *et al.*, 2014). The maximum enhancement was observed at the AZSP2 specimen, mainly due to the stitching action of steel fibers and polypropylene fibers, and the pore refinement of the matrix is caused by Zeolite and Alccofine (Xue *et al.*, 2019b).

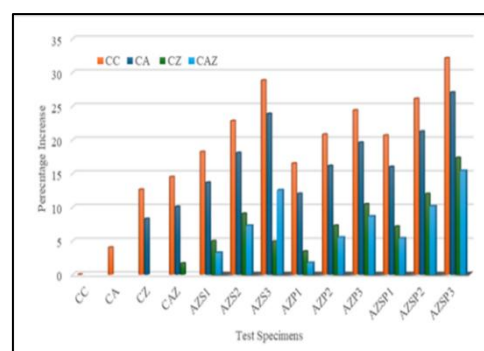


Figure 2. Effects of fibers on the modulus of rupture

Elasticity Modulus Test

The cylinder Specimens, size 150×300 mm, were made as per IS:516:1959. The test outcomes are mentioned in Table 10 and Figure 3. The analysis of the elasticity module test results shows that the specimens have variable stiffness. The specimens CA, CZ, CAZ, AZS1, AZS2, AZS3, AZP1, AZP2, AZP3, AZSP1, AZSP2, and AZSP3 have elasticity modules ranging from 40.25 GPa to 44.98 GPa, indicating a progressive increase in

stiffness. The specimen CC has the lowest elasticity modulus at 36.89 GPa. This variation in stiffness could be related to differences in the composition or microstructure of the materials used to manufacture these specimens (Li *et al.*, 2016).

Table 10. Test Results of Elasticity Modulus

Specimen	Elasticity Modulus (GPa)
CC	37.48
CA	37.97
CZ	38.16
CAZ	38.94
AZS1	39.06
AZS2	39.48
AZS3	40.13
AZP1	39.15
AZP2	40.54
AZP3	41.32
AZSP1	40.74
AZSP2	41.25
AZSP3	41.97

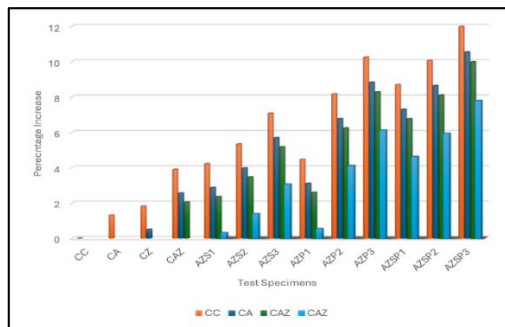


Figure 3. Effects of Fibers on Elasticity Modulus

The effect of steel fibers and polypropylene fibers on the elasticity modulus was shown in Figure 3. An increase of 1.31% and 1.81% was observed for the binary concrete (CA and CZ) specimens, and the ternary concrete was observed as 3.90% (CAZ). The increased elasticity modulus was due to the improved bond between the matrix and cement paste. With addition of steel fibers and polypropylene fibers with different volume fractions to the concrete were observed as 0.54%, 4.11%, 6.11% (AZS1, AZS2, AZS3), 0.31%, 1.39%, 3.06% compared to control concrete (CC) and ternary blended concrete (CAZ) and 8.71%, 10.06%, 11.98% (AZP1, AZP2, AZP3), 4.62%, 5.93%, 7.78% compared to control concrete (CC) and ternary blended concrete (CAZ) respectively. When ternary blended concrete is added with hybrid fibers, it was observed in modulus of elasticity 8.71%, 10.06%, 11.98% (AZSP1, AZSP2 and AZSP3), 4.55%, 6.15% and 7.15% compared to control concrete (CC) and ternary blended concrete (CAZ) respectively.

Split Tensile Strength

Specimens of size 150 × 300 mm were tested for split tensile strength, and the test results are in Table 11.

Table 11. Test Results of Split Tensile Strength

Specimen	Split Tensile Strength (MPa)
CC	4.98
CA	5.21
CZ	5.36
CAZ	5.84
AZS1	5.95
AZS2	6.09
AZS3	6.23
AZP1	5.87
AZP2	5.94
AZP3	6.19
AZSP1	6.26
AZSP2	6.34
AZSP3	6.59

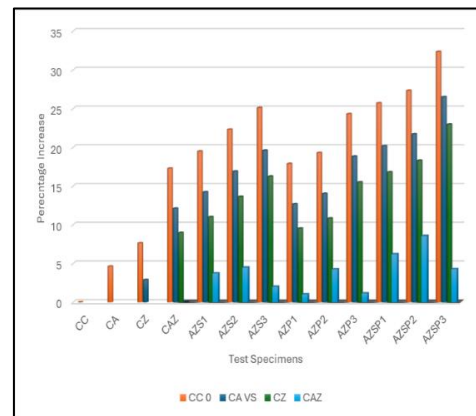


Figure 4. Effects of fibers on split tensile strength

The effect of fibers on split tensile strength is shown in Figure 4. An increase of 4.62% and 7.63% has been observed for the binary concrete (CA and CZ) specimens, and the ternary concrete was observed as 17.27% (CAZ). The increase in split tensile strength was due to matrix densification (Zhang and Li, 2013; Yap *et al.*, 2014). With addition of fibers with different fractions to the ternary blended concrete were observed in increased split tensile strength was 4.62%, 22.29%, 25.10% (AZS1, AZS2, AZS3), 1.88%, 4.28%, 6.68% and 17.87%, 19.28%, 24.30% (AZP1, AZP2, AZP3), 1.01%, 1.71%, 5.99%, compared to control concrete (CC) and ternary blended concrete (CAZ) respectively. When ternary blended concrete is added with hybrid fibers, it was observed in the enhancement of strength 25.70%, 27.31% and 32.33% (AZSP1, AZSP2 and AZSP3), 7.19%, 8.56%, 12.84% compared to control concrete (CC) and ternary blended concrete (CAZ). The maximum

enhancement was observed at the AZSP2 specimen, mainly due to the stitching action of steel and polypropylene fibers and the pore refinement caused by Zeolite and Alccofine (Nasr *et al.*, 2019; Naseroleslami and Chari, 2019).

Water Absorption

The test results (Figure 5 and Table 12) demonstrate that ternary blend cement, Alccofine, and Zeolite, combined with hybrid fiber reinforcement (AZSP2), provide the most effective reduction in water absorption. This suggests a synergistic effect between the supplementary cementitious materials and fibers in refining the concrete microstructure and reducing porosity (Gayathri *et al.*, 2016; Naseroleslami & Chari, 2019; Nasr *et al.*, 2019). The improved water absorption characteristics of AZSP2 indicate enhanced durability properties, which align with the superior mechanical performance observed in previous strength tests. In the control mix (CC) as a baseline, it is noted that conventional concrete has the highest water absorption at 1.29%. The Alccofine modified concrete (CA) shows a 1.18% reduction in water absorption compared to CC. This significant decrease can be attributed to the fine particle size of Alccofine, which helps to fill micro-voids and refine the pore structure of the concrete. Zeolite-modified concrete (CZ) exhibits a 1.12% decrease in water absorption from CC. The pozzolanic reaction of Zeolite contributes to this reduction by producing additional gel. The ternary blend (CAZ) combines Alccofine and Zeolite, reducing water absorption by 0.98% from CC. This synergistic effect demonstrates the complementary nature of these supplementary cementitious materials in refining the concrete microstructure. The increases may be due to the agglomeration of fibres (Naseroleslami & Chari, 2019). Similar effects were observed in previous works. The decrease and then increase in depth of water penetration may be due to increased porosity with an increase in fiber content. The decrease in depth of water is probably due to the pore blocking effect and less capillary porosity (Ramezaniapour *et al.*, 2013). Examining the steel fiber-reinforced specimens, it shows that AZS1 0.94% showed decrease from CC, AZS2 0.91% showed a decrease % from CC) and AZS3 0.93% showed decrease from CC, this trend suggests that increasing the steel fiber content leads to lower water absorption, likely due to the fibre ability to bridge micro-cracks and create a more tortuous path for water ingress. The polypropylene fiber-reinforced specimens show a similar trend as AZP1, AZP2, and AZP3 decrease by 0.92%, 0.89%, and 0.96% from CC. The hydrophobic nature of polypropylene fibers may contribute to this

reduction, with higher fiber contents leading to greater improvements. Eventually, hybrid fiber-reinforced specimens present an interesting pattern, such as AZSP1, AZSP2, and AZSP3, which decrease from CC by 0.84%, 0.73%, and 0.89%. Notably, AZSP2 dramatically reduces water absorption, suggesting an optimal combination of steel and polypropylene fibers at higher dosages.

Table 12. Test Results of Water Absorption

Specimen	Water Absorption in percentage
CC	1.29
CA	1.18
CZ	1.12
CAZ	0.98
AZS1	0.94
AZS2	0.91
AZS3	0.93
AZP1	0.92
AZP2	0.89
AZP3	0.96
AZSP1	0.84
AZSP2	0.73
AZSP3	0.89

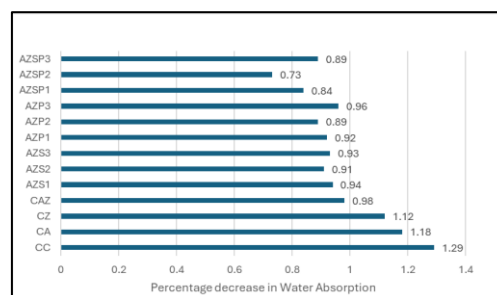


Figure 5. Water Absorption Test

Rapid Chloride Penetration Test (RCPT)

The Experimental setup as shown in Figure 6. Figure 7 & Table 13 show the data for a range of concrete mixtures labelled from CC to AZSP3. In contrast, Figure 7 shows Interpretation of RCPT Test Results, providing the depth of chloride penetration in millimetres after 28 days for the same mixtures when tested as per ASTM C1202-19. RCPT is a standardized method used to assess the resistance of concrete to chloride ion penetration. This test is crucial for evaluating the durability of concrete structures, especially those exposed to marine environments or de-icing salts. Lower penetration depths generally indicate better resistance to chloride ingress and potentially more durable concrete.

Table 13. Test results of RCPT

Specimens	RCPT for 28 days (coulombs)	Depth of penetration (mm) for 28 days
CC	1100	10.5
CA	900	8
CZ	1000	8
CAZ	850	9
AZS1	1100	10
AZS2	950	11
AZS3	800	9
AZP1	1500	12
AZP2	1400	10
AZP3	900	8
AZSP1	1500	12
AZSP2	1200	6
AZSP3	1000	11



Figure 6. Rapid chloride penetration test setup

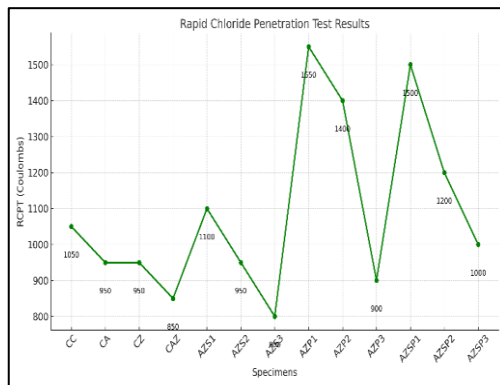


Figure 7. Rapid chloride penetration test

Depth of Penetration

The depth of penetration chart observed significant variations among the different concrete mixtures, CC (Control Concrete) shows relatively high penetration at about 10.5 mm. CA, CZ, and CAZ mixtures show improved performance compared to CC, with penetration depths ranging from 7 to 9 mm. The AZS series (AZS1, AZS2, AZS3) demonstrates further improvement, with penetration depths between 8 and 10 mm. The AZP

series (AZP1, AZP2, AZP3) performs even better, with depths ranging from 7 to 9 mm. The AZSP series (AZSP1, AZSP2, AZSP3) exhibits the best overall performance, with penetration depths as low as 6 mm for AZSP2. The results suggest that the various admixtures and supplementary cementitious materials used in the concrete mixtures have significantly influenced chloride penetration resistance. The trend results as show in Figure 8.

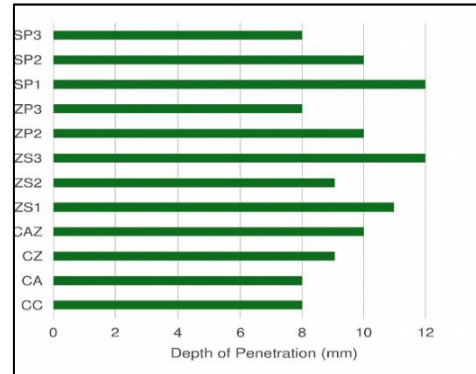


Figure 8. Depth of chloride penetration test results

The baseline mixture shows the highest chloride penetration, indicating it would be most vulnerable to chloride-induced corrosion in aggressive environments. The progressive improvement from CA to CZ to CAZ implies that the admixtures (possibly calcium nitrite, Zeolite, or other pozzolanic materials) effectively reduce chloride penetration. AZS, AZP, and AZSP Series: These series likely represent different combinations and proportions of admixtures. The consistent improvement across these series suggests synergistic effects between the materials used. AZSP2 shows the lowest penetration depth, indicating it has the highest resistance to chloride ingress (Reddy & Meena, 2019; Zhang and Li, 2013). This mixture could be particularly suitable for structures in severe chloride environments.

Lower chloride penetration depths correlate with reduced risk of reinforcement corrosion, potentially extending the service life of concrete structures. Enhanced durability can reduce maintenance needs and longer structure lifespans, contributing to more sustainable construction practices. The results demonstrate the potential for tailoring concrete mixtures to specific environmental exposures, optimizing performance and cost-effectiveness. While RCPT provides valuable insights, it should be considered alongside other durability indicators for a comprehensive assessment.

SEM Analysis

SEM analyses were performed on prepared specimens CC, CA, CAZ, AZS2, AZP2, and AZSP2. The SEM images depict the characteristic micromorphology of non-fiber concrete and Hybrid fiber, with a total of 6 specimens, showcased. When supplementary materials are added to concrete, the unreacted calcium and silica react with water to form additional C-S-H gel, improving the bonding between the cementitious matrix (ASTM C1723-16). Through SEM analysis, the Zeolite reacts with CH to produce CSH due to the acceleration of hydration of tricalcium and dicalcium, which makes the concrete denser & homogeneous, as is evident if we compare Figure 9(a) with Figure 9(b)CC. Figure 9 presents SEM images of six different test specimens labeled (a) CC, (b) CA, (c) CAZ, (d) AZS2, (e) AZP2, and (f) AZSP2. These high-resolution images reveal each specimen's microstructure and surface morphology at a

textures, particle sizes, and structures across the samples. For instance, CC appears to have a more fragmented, flaky structure, while CA shows larger, interconnected formations. CAZ and AZS2 display finer, more homogeneous textures, whereas AZSP2 exhibits more complex, layered structures with visible pores. These SEM images provide valuable insights into the internal composition and arrangement of particles in each specimen, which can be correlated with their macroscopic properties, such as strength (Wu *et al.*, 2017).

Figure 9(a) CC specimen shows a highly fragmented structure with many small, flaky particles. The surface appears rough and irregular, with numerous small voids visible. This fragmented structure might explain why CC has the lowest split tensile strength, as there are many potential weak points and crack propagation paths. Figure 9(b) CA compared to CC. CZ exhibits larger, more

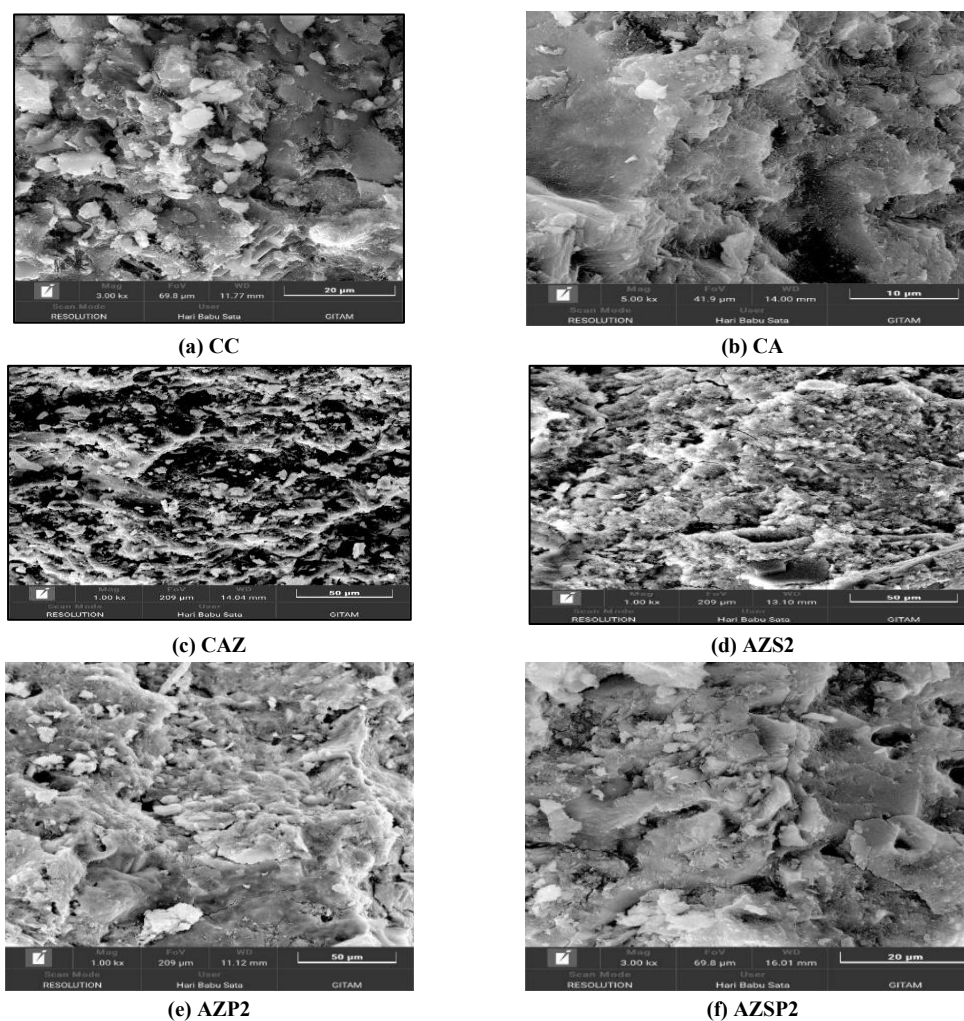


Figure 9. (a-f).SEM images of six different test specimens

microscopic level. The images show varying interconnected formations. The structure appears

more cohesive, with fewer but larger pores. This improved connectivity could contribute to its 7.63% higher strength than CC. Figure 9(c) CAZ sample shows a finer, more homogeneous texture than CC or CA. The particles appear smaller and more tightly packed, which could explain their slight strength improvement over CC (4.62% increase). Figure 9(d) AZS2 (Patel & Shah, 2015) displays a unique combination of fine particles and larger, smoother regions. This hybrid structure, combining aspects of CA and CZ, might be responsible for its significant strength increase (17.27% over CC). Figure 9(e) AZP2 specimen shows a complex, layered structure with visible pores. The surface appears to have a mix of smooth areas and more textured regions, suggesting a more advanced formulation. This complex microstructure likely contributes to its high strength (22.29% increase over CC). Figure 9(f) AZSP2 exhibits a complex structure with more visible pores and a slightly rougher overall texture. The layered arrangement and interconnected particles could explain its high strength (19.28% increase over CC), though its slightly more porous nature might account for its lower strength than ASP2.

The progression from CC to the more complex formulations (AZSP2) shows a clear trend towards more sophisticated microstructures. These particle size, arrangement, and interconnectivity changes directly correlate with the observed increases in split tensile strength. The more advanced formulations achieve a balance between particle cohesion and pore structure, which is crucial for both strength and potentially other properties like durability and permeability.

XRD (X-Ray Diffraction)

Figure 10(a-f) presents X-Ray Diffraction (XRD) patterns for six specimens: CC, CA, CAZ, AZS2, AZP2, and AZSP2. XRD is a powerful technique used to analyse the crystalline structure. The key observations from these XRD patterns show multiple peaks at various 2-theta angles, indicating the presence of multiple crystalline phases in each sample.

The intensity of the peaks varies significantly among the samples, with some showing very high, sharp peaks (e.g., CAZ) and others displaying more moderate peak intensities (e.g., CC, CA). While there are some common peak positions across all samples (suggesting some common crystalline phases), there are also notable differences in peak positions and relative intensities between samples. The background levels differ between samples, indicating varying amounts of amorphous content. CC shows multiple peaks of varying intensities across the 2-theta range. CA displays a

very intense, sharp peak at a low 2-theta angle, suggesting a dominant crystalline phase. CAZ is similar to CC but with some variations in peak intensities. CAZ shows a pattern with reduced peak intensities compared to CA, suggesting possible phase changes. AZS2, AZP2, AZSP2. These show similar overall patterns but with subtle differences in peak intensities and positions, indicating slight variations in their crystalline structures. The variations in XRD patterns likely correlate with the differences in split tensile strength observed earlier. For instance, the sharp, intense peak in CA might be related to its improved strength over CC.

In Conventional Concrete (CC), a strong CH peak, indicating typical hydration products, Moderate C-S-H peaks, and the Presence of unhydrated cement phases are noted. Alccofine-modified Concrete (CA) reduced CH peak intensities compared to CC, enhanced C-S-H peak intensities and broadening, and lower unhydrated cement phase peaks were seen. The Zeolite-modified Concrete (CZ) shows a Significant reduction in CH peak intensities and increased C-S-H peak intensities. Alccofine-Zeolite modified Concrete (CAZ) found the lowest CH peak intensity among all specimens and the highest C-S-H peak intensities and broadening. Also, minimal unhydrated cement phase peaks are captured. Eventually, Fiber-Reinforced Specimens (AZS2, AZP2, AZSP2) show further reduction in CH peak intensities and enhanced C-S-H peak intensities. There is a Potential peak broadening due to increased disorder in the crystal structure.

XRD shows monotonic CH peak reduction plus a more prominent/left-shifted gel hump, which directly evidences the expected $\text{SiO}_2\text{--Al}_2\text{O}_3\text{--CaO}$ interactions : you're moving away from the Ca-rich corner toward Si/Al-rich compositions, lowering the Ca/Si of the binding gel and stabilizing more aluminate-bearing hydrates.

Mineralogical correlation to the $\text{SiO}_2\text{--Al}_2\text{O}_3\text{--CaO}$ system (how the chemistry drives the XRD)

Thermodynamics/phase-assemblage: In ternary $\text{CaO--Al}_2\text{O}_3\text{--SiO}_2\text{--(SO}_3\text{, CO}_2\text{)--H}_2\text{O}$, adding siliceous/aluminous SCMs (Alccofine, zeolite) consumes CH and lowers C-S-H Ca/Si, while increasing Al uptake into the gel (C-A-S-H) and shifting Aft/AFm/carboaluminate equilibria exactly the changes your patterns imply.

XRD signatures of that shift: more amorphous gel (bigger 20-35° hump), weaker CH peaks, possible emergence/intensification of carboaluminates if carbonate is available (sometimes overlapping near 11-12° and 20-21°), and occasional residual zeolite/quartz reflections.

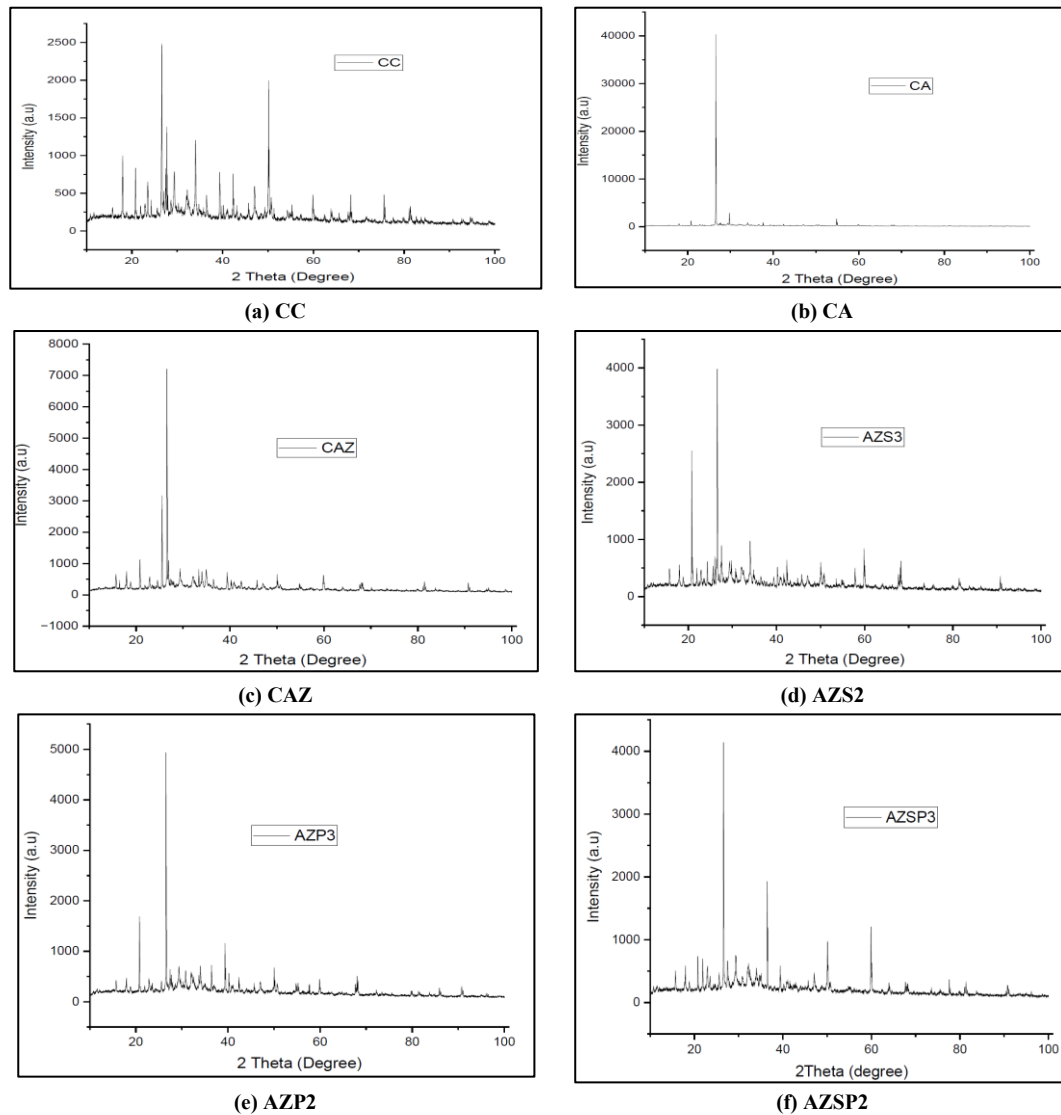


Figure 10. (a-f) XRD for the Test Specimens

XRD patterns show a progressive decrease in portlandite reflections ($\approx 18^\circ$ and 34°) with Alccofine and zeolite additions, consistent with pozzolanic consumption of $\text{Ca}(\text{OH})_2$ and formation of additional C-S-H / C-A-S-H gel.”

“Concomitant broadening and slight left-shift of the $20\text{--}35^\circ$ amorphous hump indicate an increased amorphous gel fraction and Al incorporation into C-S-H, i.e., formation of C-A-S-H.”

“Residual zeolite/quartz peaks confirm partial reaction of the zeolitic component; their persistence suggests that reactivity is limited by kinetics/availability of CH and that some framework remains as filler.”

“The changes in crystalline phase intensities are consistent with thermodynamic expectations for $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3$ systems where increased Si and

Al drive the assemblage toward Al-substituted gels and carboaluminate species.”

Conclusions

1. The incorporation of Zeolite and Alccofine as mineral admixtures enhances concrete densification by filling voids between cement particles. In a binary blend, Alccofine alone improved compressive strength by 5.94%, split tensile strength by 4.62%, flexural strength by 4.02%, and modulus of elasticity by 9.11% compared to control concrete.

2. Binary blending with Zeolite alone improved compressive strength by 7.58%, split tensile strength by 7.63%, flexural strength by 12.63%, and modulus of elasticity by 11.82%

compared to control concrete. The combined use of Zeolite and Alccofine further enhanced performance, with increases of 11.58% in compressive strength, 17.27% in split tensile strength, 14.49% in flexural strength, and 13.80% in elasticity.

3. Fiber reinforcement significantly enhanced mechanical properties. Overall, fiber inclusion increased compressive strength by 16.58%, split tensile strength by 25.10%, flexural strength by 28.84%, and modulus of elasticity by 19.22%. Polypropylene fibers alone improved these properties by 16.33%, 24.30%, 24.39%, and 21.04%, respectively. The hybrid use of steel and polypropylene fibers yielded the highest improvements: 21.13% in compressive strength, 32.33% in split tensile strength, 32.14% in flexural strength, and 21.93% in elasticity. Hybrid fibers also enhanced crack resistance compared to plain concrete.

4. SEM analysis helps to examine the compactness of Alccofine and Zeolite-based concrete specimens with internal structure through a dense matrix, and a few micro-cracks with fewer pores give higher strength.

5. XRD analysis provides a comprehensive and quantitative assessment of the microstructural development in ternary blended fiber-reinforced concrete. It offers insights into the complex interactions between cement, supplementary cementitious materials, and fibers, and their collective impact on concrete properties and performance.

6. The RCPT results presented in the image demonstrate significant potential for improving concrete's resistance to chloride penetration through careful selection and combination of admixtures and supplementary materials. The AZSP series, particularly AZSP2, shows promising performance that could translate to more durable and sustainable concrete structures in challenging environments.

Future Scope

- Data-driven modelling: Application of machine learning (ML) and artificial neural networks (ANN) to predict hydration kinetics, strength development, and durability based on composition ($\text{SiO}_2\text{--Al}_2\text{O}_3\text{--CaO}$ ratios) and microstructural data.
- Structural-scale validation: Large-scale testing on structural elements (e.g., slabs, columns, beams) to assess mechanical performance, crack resistance, and long-term durability under realistic exposure conditions.
- Life-cycle assessment (LCA): Quantification of embodied CO_2 , energy consumption, and service life extension benefits of

clinker replacement with Alccofine and zeolite for sustainability profiling.

- Integration into design frameworks: Linking laboratory mineralogical findings with predictive models and field performance data to develop guidelines for practical adoption in sustainable infrastructure.

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