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Comprehensive Study on the Effect of Nano-TiO_2 as Cement Replacement and Glass Fiber as Reinforcement on Mechanical and Durability Performance of M35 Concrete

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Abstract:

Significant advancements in concrete performance can be achieved via nano-scale cement replacement and fiber reinforcement strategies. This study examins and explore the influence of nano-titanium dioxide (TiO_2) as a partial cement substitute or partial replacement and alkali-resistant glass fibers as mechanical reinforcement. In the first phase of the study, concrete mixes were prepared with varying percentage of nano-TiO_2 contents ranging from 0.25% to 3.0% by weight of cement, in 0.25% increments. Among all the mixes, the 2.0% TiO_2 blend yielded the highest strength and durability parameters which demonstrates its suitability for further optimization and considiration. In the second phase, the glass fibers were incorporated into the 2.0% nano-TiO_2 mix at dosages of 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% respectively by volume. The optimum results were achieved at 0.6% fiber content. Comprehensive mechanical testing—including compressive, tensile, and flexural strength was conducted at 7, 14, 28, and 90 days. Durability assessment encompassed a comprehensive series of tests, including water absorption, sorptivity, rapid chloride penetration test (RCPT), and ultrasonic pulse velocity (UPV), each aimed at evaluating the concrete's resistance to moisture ingress, ion permeability, and internal structural integrity. The results showed notable enhancements in all performance metrics for the optimized mix. Compressive strength increased by over 30% compared to control by day 90, while permeability was significantly reduced below the certified range (below 6%), indicating matrix densification. The combination of nano-TiO_2 and glass fibers proved to be synergistic, simultaneously improving microstructure and load-bearing capacity. The findings advocate for a multi-scale modification strategy in producing durable, high-performance concrete suitable for modern infrastructure needs.

Keywords — **Nano-TiO_2, Glass Fiber, Cement Replacement, Durability, Concrete Reinforcement, High-Performance Concrete.**

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I. INTRODUCTION

Concrete is a cornerstone of global infrastructure due to it's Because of its great compressive strength, affordability, and accessibility. Concrete is a fundamental component of infrastructure around the world. All across the world, it serves as the structural foundation for buildings, bridges, roads, and dams. However, conventional concrete suffers from inherent material limitations including low tensile strength, brittle fracture behavior, high shrinkage, and vulnerability to cracking and aggressive environmental exposures such as sulfate-rich, chloride-laden, and acidic conditions (Parveen & Rana, 2019; Li et al., 2017; Mehta & Monteiro, 2014). These deficiencies contribute to serviceability deterioration and reduced durability over time, demanding the development of modified cementitious systems with superior long-term performance.

To overcome these deficiencies, recent advancements have increasingly emphasized multiscale reinforcement techniques, particularly incorporating nanomaterials and fibers. Nanotechnology has emerged as a transformative tool in the field of concrete technology, offering enhancement mechanisms that operate at the microstructural level. Among various nanomaterials, nano-titanium dioxide (TiO_2), typically in the size range of 15–20 nm, has demonstrated considerable potential due to its high specific surface area, inert filler nature, and nucleation sites for hydration product formation (Nazari & Riahi, 2011; Sanchez & Sobolev, 2010). While nano-TiO_2 lacks high pozzolanic reactivity compared to nano-silica, it effectively contributes to densifying the matrix, reducing capillary porosity, and promoting early-age strength development (Ghafari et al., 2014; Li et al., 2016). Moreover, it enhances resistance to water ingress, carbonation, and chloride ion penetration—key parameters in the durability of concrete structures (Siddique & Khan, 2011).

Complementing the nano-scale modification, macro-scale reinforcement through discrete fibers, particularly alkali-resistant glass fibers, addresses brittleness and crack susceptibility. Glass fibers exhibit excellent tensile strength (~1.7 GPa), high modulus of elasticity, and chemical stability in alkaline environments, making them suitable for concrete reinforcement (Kizilkanat et al., 2015; Bentur & Mindess, 2007). These fibers bridge internal microcracks, improving the concrete's toughness, flexural capacity, and post-cracking behavior. Their uniform dispersion within the matrix also contributes to mitigating plastic and drying shrinkage cracking (Siddique et al., 2019; Dias & Thaumaturgo, 2005).

Despite the proven benefits of nano-TiO_2 and glass fibers individually, very limited research has investigated their combined application in concrete. The synergistic reinforcement potential—combining nano-scale matrix densification and macro-scale crack control—remains underexplored, particularly in terms of long-term strength development and resistance to durability stressors. This study seeks to bridge that research gap by experimentally evaluating the mechanical and durability performance of concrete modified with nano-TiO_2 (ranging from 0.25% to 3%) and varying dosages of glass fibers (0.2% to 1.0%) across multiple curing intervals (7, 14, 28, and 90 days). The aim is to identify an optimal hybrid mix design that demonstrates enhanced compressive, tensile, and flexural properties along with improved resistance to water absorption, sorptivity, and chloride ion penetration.

The key objectives of this study are centered on developing a high-performance and durable concrete through the integration of nano-scale and macro-scale modifiers. The research aims to first identify the optimal content of nano-titanium dioxide (nano-TiO_2), ranging from 0.25% to 3.0% by weight of cement, by assessing its influence on strength development and durability parameters. Once the most effective nano-TiO_2 dosage is established, the study proceeds to optimize the proportion of alkali-resistant glass fibers within the range of 0.2% to 1.0%, targeting enhanced performance when used in conjunction with the best-performing nano-TiO_2 mix. Comprehensive mechanical testing—including compressive strength, splitting tensile strength, and flexural strength—is conducted at 7, 14, 28, and 90 days to understand the time-dependent behavior of the modified concrete. Durability is further assessed through water absorption, sorptivity, rapid chloride penetration test (RCPT), and ultrasonic pulse velocity (UPV) to evaluate the concrete's resistance to fluid ingress and internal integrity. Collectively, the study aims to establish a practical and scalable material design framework based on multi-scale modification strategies for producing next-generation concrete with superior mechanical performance and long-term durability.

II. MATERIALS AND METHODS

1) Materials

- **Cement**: Ordinary Portland Cement (OPC) 53 grade conforming to IS 12269 was used as the primary binder. This cement type is commonly preferred for high-strength concrete due to its superior compressive strength and early-age performance (Mehta & Monteiro, 2014; Neville, 2011).

- **Fine Aggregate**: Natural river sand conforming to Zone II grading as per IS 383:2016 was used. Proper gradation of fine aggregate is essential for achieving a dense packing structure and adequate workability (IS 383:2016; Siddique & Klaus, 2009).
- **Coarse Aggregate**: Crushed granite aggregate with a nominal maximum size of 12.5 mm was selected for its angular shape, which enhances mechanical interlocking and contributes to the overall strength and stiffness of concrete (IS 383:2016; Gambhir, 2013).
- **Water**: Clean potable tap water, free from organic impurities, oils, and acids, was used for both mixing and curing in accordance with IS 456:2000 standards. Water quality has a significant effect on the hydration process and long-term durability (Neville, 2011).
- **Nano-TiO_2**: Commercially available rutile-phase nano-titanium dioxide (TiO_2) with particle sizes ranging between 15–20 nm and surface area >50 m^2/g was used. Nano-TiO_2 is known for its filler effect, nucleation potential, and ability to improve hydration kinetics and microstructural densification (Nazari & Riahi, 2011; Ghafari et al., 2014; Li et al., 2016).
- **Glass Fibers**: Alkali-resistant (AR) chopped glass fibers, 10 mm in length and approximately 13 µm in diameter, with tensile strength around 1.7 GPa, were employed to enhance tensile strength and post-cracking behavior. Their high alkali resistance and dispersion efficiency make them ideal for concrete reinforcement applications (Kizilkanat et al., 2015; Bentur & Mindess, 2007; Siddique et al., 2019).
- **Admixture**: A high-range water-reducing admixture (HRWR) based on polycarboxylate ether (PCE) chemistry was used to improve the workability without increasing the water-to-cement ratio. The dosage was optimized in the range of 0.5–1.0% by weight of cement to maintain a consistent slump of 100±10 mm (Sakr, 2006; Aïtcin, 1998).

Fig 2.1 Material used (cement OPC53, glass fiber, nano-titanium dioxide)

2) Mix Proportions and Matrix

A two-phase approach was used:

The first phase of this study was designed to identify the optimal dosage of nano-titanium dioxide (TiO_2) to be used as a partial cement replacement. The goal was to enhance the mechanical and durability performance of concrete by leveraging the nanoparticle's filler effect, nucleation properties, and its influence on hydration kinetics and pore refinement.

Thirteen concrete mixes were prepared, including a control mix (CTRL) without any nano-TiO_2, and twelve experimental mixes with nano-TiO_2 content varying from 0.25% to 3.00% by weight of cement, in 0.25% increments. No glass fibers were added during this phase to isolate the influence of nano-TiO_2 on concrete performance. The water-to-cement (w/c) ratio was fixed at 0.45 for all mixes, and the dosage of a polycarboxylate ether (PCE)-based superplasticizer was adjusted (ranging from 0.5% to 0.95%) to maintain consistent workability across all batches, targeting a slump of 100 ± 10 mm.

Each mix was tested for compressive strength, splitting tensile strength, and flexural strength at curing intervals of 7, 14, 28, and 90 days. Additionally, key durability parameters such as water absorption, sorptivity, rapid chloride penetration test (RCPT), and ultrasonic pulse velocity (UPV) were evaluated at the same time points.

The results showed a steady improvement in strength and durability with increasing nano-TiO_2 content up to 2.0%, beyond which performance began to plateau or slightly decline. The mix with 2.0% nano-TiO_2 (NT2.00) consistently exhibited the best balance of enhanced compressive strength, improved tensile and flexural capacity, and reduced permeability-related indicators. This enhancement is attributed to the improved packing density, accelerated hydration, and reduced microcracking due to the nano-fillers, as also supported by earlier studies (Nazari & Riahi, 2011; Ghafari et al., 2014; Li et al., 2016).

Based on these findings, NT2.00 was selected as the optimal mix for the next phase of the study, which focused on evaluating the effect of alkali-resistant glass fiber as macro-scale reinforcement on top of the optimized nano-modified matrix.

Phase 1 – Nano-TiO_2 Optimization

Table 1. Mix Proportions for Phase 1: Nano-TiO_2 Optimization

Mix ID	Nano-TiO_2 (% by weight of cement)	Glass Fiber (%)	Superplasticizer Dosage (% by weight of cement)	Water-to-Cement Ratio
CTRL	0.00	0.00	0.50	0.45
NT0.25	0.25	0.00	0.55	0.45
NT0.50	0.50	0.00	0.55	0.45
NT0.75	0.75	0.00	0.60	0.45
NT1.00	1.00	0.00	0.60	0.45
NT1.25	1.25	0.00	0.65	0.45
NT1.50	1.50	0.00	0.65	0.45
NT1.75	1.75	0.00	0.70	0.45
NT2.00	2.00 ← **Best result selected**	0.00	0.75	0.45
NT2.25	2.25	0.00	0.80	0.45
NT2.50	2.50	0.00	0.85	0.45
NT2.75	2.75	0.00	0.90	0.45
NT3.00	3.00	0.00	0.95	0.45

NT2.00 gave best compressive and durability performance and was selected for Phase 2.

Phase 2 – Glass Fiber Optimization

Having established 2.0% nano-TiO_2 as the optimum dosage for improving strength and durability in Phase 1, the second phase investigates the impact of alkali-resistant glass fibers as discrete macro-scale reinforcement.

The goal of this phase was to explore how varying dosages of glass fibers affect the mechanical and durability characteristics of the already nano-enhanced concrete matrix. Glass fibers are known to provide crack-bridging capacity, enhance post-cracking ductility, and improve resistance to shrinkage and impact loading. Their integration with nanomaterials is anticipated to offer a synergistic multi-scale reinforcement, enhancing performance more comprehensively than either approach alone.

Five new concrete mixes were prepared, all incorporating 2.0% Nano-TiO_2 while varying glass fiber content from 0.20% to 1.00% by weight of binder in increments of 0.20%. The water-to-cement ratio was maintained at 0.45, and the dosage of superplasticizer was fine-tuned to ensure uniform workability (slump: 100 ± 10 mm). No changes were made to aggregate or cement type.

Each mix was tested at 7, 14, 28, and 90 days for:

-Compressive strength

-Splitting tensile strength

-Flexural strength

-Water absorption

-Sorptivity

-RCPT

-Ultrasonic Pulse Velocity (UPV)

Table 2. Mix Proportions for Phase 2: Glass Fiber Optimization

Mix ID	Nano-TiO_2 (% by weight of cement)	Glass Fiber (%)	Superplasticizer Dosage (% by weight of cement)	Water-to-Cement Ratio
NT2.00GF0.0	2.00	0.00	0.75	0.45
NT2.00GF0.2	2.00	0.20	0.80	0.45
NT2.00GF0.4	2.00	0.40	0.85	0.45
NT2.00GF0.6	2.00	0.60	0.90	0.45
NT2.00GF0.8	2.00	0.80	0.95	0.45
NT2.00GF1.0	2.00	1.00	1.00	0.45

The results showed that glass fiber content significantly improved tensile and flexural strength, particularly between 0.4% and 0.6%, without negatively impacting workability or compressive strength. However, fiber contents above 0.6% began to reduce performance slightly due to balling effect, dispersion challenges, and increased voids.

Among all, the NT2.00GF0.6 mix (2.0% Nano-TiO_2 + 0.6% Glass Fibers) exhibited the best balance of mechanical strength and durability, confirming the effectiveness of the hybrid nano-macro reinforcement system. This mix was selected for detailed microstructural analysis and final recommendation.

3) Sample Preparation

- **Compressive Strength:** 150 mm cube molds.
- **Splitting Tensile Strength:** 150 mm × 300 mm cylinders.
- **Flexural Strength:** 100 mm × 100 mm × 500 mm beams.
- **Durability Tests:** 100 mm × 50 mm discs and 100 mm cubes as per respective ASTM protocols.

Specimens were demolded after 24 hours and cured in water at 27±2°C until testing ages (7, 14, 28, 90 days).

4) Test Methods

To comprehensively evaluate the mechanical and durability performance of nano-modified and fiber-reinforced concrete, a series of standardized tests were conducted in accordance with Indian Standards (IS) and ASTM guidelines. Each test was carefully chosen to assess specific performance characteristics relevant to structural and durability behavior.

Compressive Strength (IS:516)

Compressive strength was evaluated using standard cube specimens of size **150 mm × 150 mm × 150 mm** in accordance with IS:516. The specimens were tested at 7, 14, 28, and 90 days using a calibrated compression testing machine (CTM) with a loading rate of 140 kg/cm² per minute. This test quantifies the material's capacity to withstand axial compressive forces, serving as a benchmark for structural integrity and mix optimization. In the case of nanomaterials, enhanced compressive strength is typically attributed to improved particle packing, reduced voids, and accelerated pozzolanic activity.

Splitting Tensile Strength (IS:5816)

Splitting tensile strength was measured on **cylindrical specimens (150 mm diameter × 300 mm height)** in accordance with IS:5816. This indirect method evaluates tensile strength by applying diametrical compression until failure. It provides critical insight into the concrete's resistance to crack initiation and propagation under tensile stresses, which is particularly useful for assessing the effect of glass fiber reinforcement that bridges microcracks and delays fracture development.

Flexural Strength (IS:516)

Flexural strength, also known as modulus of rupture, was tested using **prismatic beam specimens (100 mm × 100 mm × 500 mm)** using the third-point loading method, as specified in IS:516. This test measures the material's ability to resist deformation under bending and is particularly sensitive to the presence of fibers, which improve post-cracking behavior and load redistribution.

Water Absorption (ASTM C642)

This test was used to determine the **amount of water absorbed** by oven-dried concrete specimens when immersed in water for a specified period. Conducted as per ASTM C642, the test evaluates **porosity and**

permeability, which directly affect the durability and long-term performance of concrete. Lower absorption indicates a denser matrix and reduced pathways for ingress of aggressive agents like chlorides or sulfates.

Sorptivity (ASTM C1585)

Sorptivity measures the **rate of capillary suction** of water into unsaturated concrete. As per ASTM C1585, this test involves partially immersing cylindrical specimens and measuring the water uptake over time. This test is critical for assessing the surface porosity and potential for moisture-driven deterioration. Nanoparticles are known to reduce sorptivity by refining capillary pores and forming additional C–S–H gel.

Rapid Chloride Penetration Test (RCPT) (ASTM C1202)

RCPT quantifies the **electrical charge passed (in coulombs)** through concrete over a 6-hour period, providing an indirect measure of **chloride ion permeability**. Conducted per ASTM C1202, it's a key durability test for structures exposed to de-icing salts, seawater, or industrial environments. Lower coulomb values signify better resistance to chloride ingress, which is enhanced by a denser microstructure created by nano-fillers and reduced connectivity of pores.

Ultrasonic Pulse Velocity (UPV) (ASTM C597)

UPV evaluates the **internal quality and homogeneity** of concrete by measuring the velocity of ultrasonic waves through a concrete specimen. Following ASTM C597, transducers are placed on opposite faces of the specimen, and wave travel time is measured. High UPV values indicate **better compaction, lower porosity**, and absence of internal flaws, making this a non-destructive proxy for overall quality assessment.

This suite of tests provides a holistic evaluation of both the strength and durability performance of the modified concrete mixes. The combination of destructive (e.g., compressive, tensile, flexural) and non-destructive/durability-focused methods (e.g., UPV, RCPT, sorptivity) ensures a robust characterization across multiple performance dimensions.

III. EXPERIMENTAL RESULTS

3.1 Compressive Strength

Compressive strength was evaluated on 150 mm cube specimens at 7, 14, 28, and 90 days. The inclusion of nano-TiO_2 led to progressive improvement in compressive strength up to 2.0% dosage, beyond which further increases in TiO_2 content caused marginal or negative effects. This reduction at higher dosages was attributed to nanoparticle agglomeration and hindrance to cement hydration. The mix containing 2.0% nano-TiO_2 exhibited the highest compressive strength at all curing ages, with an increase of approximately 32% at 90 days compared to the control.

Table 3: **Compressive Strength Data** for all Nano-TiO_2 dosages at different curing ages

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	90 Days (MPa)
CTRL	28.5	36.0	42.3	48.6
NT0.25	30.1	37.8	44.5	51.2
NT0.50	31.4	39.2	46.8	54.3
NT0.75	32.8	40.6	48.6	56.4
NT1.00	33.7	41.5	49.7	58.0
NT1.25	34.0	41.9	50.2	59.2
NT1.50	34.4	42.3	50.9	60.1
NT1.75	34.3	42.2	51.0	62.0
NT2.00	34.2	42.1	51.0	64.2
NT2.25	33.6	41.2	49.9	63.1
NT2.50	33.0	40.5	48.7	61.0
NT2.75	32.4	39.8	47.5	58.8
NT3.00	31.7	38.9	46.2	56.7

This table validates the effectiveness of **nano-TiO_2 as a cement replacement**, with 2.00% being the most beneficial dosage. It highlights how nanotechnology can significantly **enhance the strength and quality of concrete**, especially over extended curing periods.

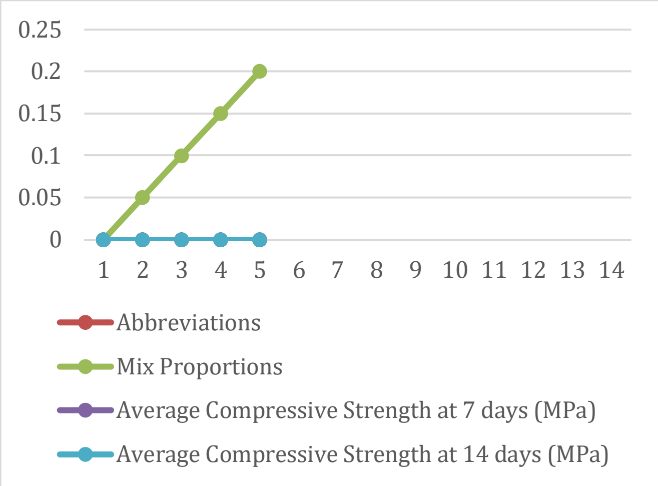

Fig 3.1: Compressive Strength Data representation for all Nano-TiO_2 dosages at different curing ages

In the second phase, the incorporation of glass fibers into the 2.0% nano-TiO_2 mix further enhanced compressive performance. The addition of 0.6% glass fiber yielded the optimal result, contributing to better load transfer, crack resistance, and structural continuity under stress. This synergistic combination of dense matrix from nano-TiO_2 and crack bridging by fibers significantly improved strength parameters.

Table 4: Compressive Strength of Nano-TiO_2 + Glass Fiber-Modified Concrete

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	90 Days (MPa)
NT2GF0.20	34.5	42.3	51.4	65.1
NT2GF0.40	34.8	42.7	52.0	66.4
NT2GF0.60	35.4	43.4	53.2	68.3
NT2GF0.80	34.9	42.6	52.1	66.1
NT2GF1.00	34.3	41.9	50.8	64.0

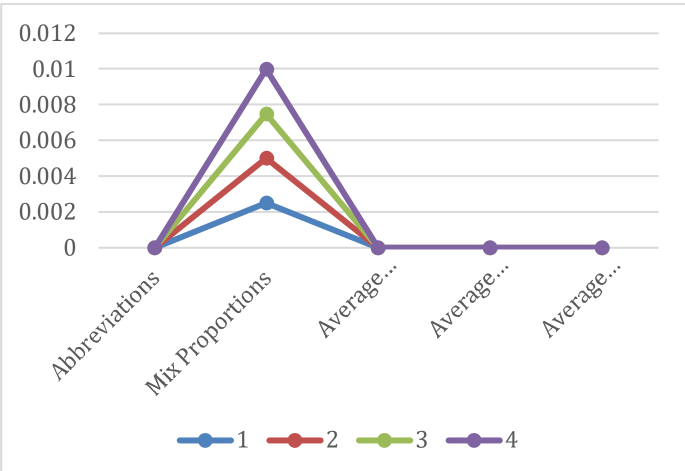

Fig 3.2: Compressive Strength representation of Nano-TiO_2 + Glass Fiber-Modified Concrete

3.2 Splitting Tensile Strength

Splitting tensile strength was assessed using cylindrical specimens in accordance with IS:5816 at all curing ages. A consistent increase in tensile strength was observed with nano-TiO_2 addition up to 2.0%, beyond which no further benefits were recorded. The enhancement in tensile strength was due to the refined microstructure and improved interfacial transition zone resulting from nano-TiO_2. The 2.0% TiO_2 mix with 0.6% glass fiber demonstrated the highest tensile strength, showing a 22% increase at 90 days compared to the control. This performance was attributed to the effective distribution of tensile stresses by the glass fibers, which helped delay crack propagation and failure. The matrix-fiber interaction facilitated the load redistribution mechanism under indirect tensile loading.

3.3 Flexural Strength

Flexural strength testing on beam specimens showed a marked improvement with the integration of both nano-TiO_2 and glass fibers. The optimal flexural performance was achieved with the NT2GF0.6 mix, confirming the role of both materials in enhancing bending resistance. Nano-TiO_2 contributed to a denser matrix, reducing microcracks, while the glass fibers resisted tensile stresses in the tension zone. The combined system improved ductility and post-cracking behavior, with flexural strength improvements of over 25–30% at 90 days compared to the control. Higher glass fiber dosages beyond 0.6% showed slight reductions, likely due to poor workability and clustering effects.

Table 5: Combined Table – Splitting Tensile & Flexural Strength (NT2 + Glass Fiber)

Mix ID	Glass Fiber (%)	Tensile 7d	Tensile 14d	Tensile 28d	Tensile 90d	Flexural 7d	Flexural 14d	Flexural 28d	Flexural 90d
NT2GF 0.20	0.20	2.42	2.61	2.82	3.05	4.30	4.72	5.20	5.85
NT2GF 0.40	0.40	2.48	2.68	2.91	3.14	4.45	4.89	5.38	6.02
NT2GF 0.60	0.60	2.56	2.76	3.05	3.29	4.60	5.10	5.65	6.35
NT2GF 0.80	0.80	2.50	2.70	2.94	3.17	4.42	4.87	5.40	6.08

Mix ID	Glass Fiber (%)	Tensile 7d	Tensile 14d	Tensile 28d	Tensile 90d	Flexural 7d	Flexural 14d	Flexural 28d	Flexural 90d
NT2GF 1.00	1.00	2.43	2.62	2.85	3.04	4.25	4.65	5.18	5.80

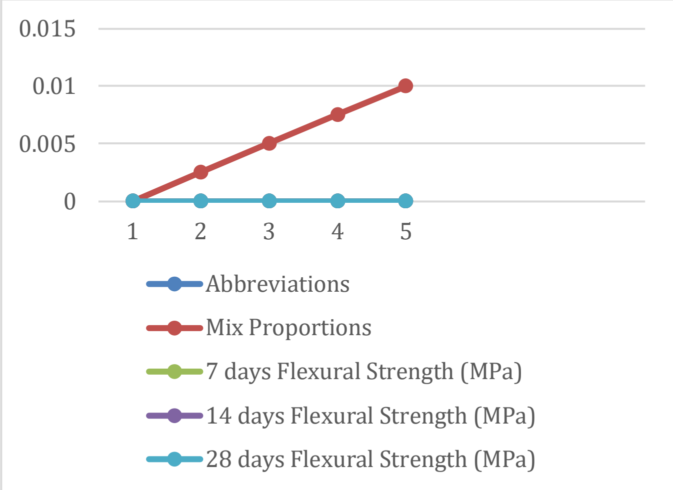

Fig 3.3 : Combined Graph – Splitting Tensile & Flexural Strength (NT2 + Glass Fiber)

3.4 Durability Performance

3.4.1 Water Absorption

Water absorption decreased with increasing nano-TiO_2 content due to its filler effect and its ability to refine pore structure. The 2.0% TiO_2 mix showed about a 17% reduction in absorption compared to the control. Incorporating 0.6% glass fiber into this mix further reduced water ingress, which can be attributed to reduced crack connectivity and restrained crack widening. The synergistic modification improved resistance to moisture penetration and increased longevity.

3.4.2 Sorptivity

Sorptivity, an indicator of capillary suction and transport of water through unsaturated pores, was lowest for the NT2GF0.6 mix. Nano-TiO_2 particles filled capillary pores and disrupted connectivity, while the inclusion of glass fibers minimized early-age microcracks that promote fluid ingress. The result was a significantly lower initial and secondary absorption rate compared to the control and other mixes.

3.4.3 Rapid Chloride Penetration Test (RCPT)

RCPT was used to assess resistance to chloride ion ingress, which is critical in marine and deicing environments. The charge passed through the NT2GF0.6 mix was reduced by approximately 40% compared to the control, indicating a denser, less permeable matrix. According to ASTM C1202, this mix falls under the “Low” permeability category. Nano-TiO_2 reduced pore interconnectivity, and fibers prevented cracking, both contributing to superior chloride resistance.

3.4.4 Ultrasonic Pulse Velocity (UPV)

UPV measurements showed that mixes containing nano-TiO_2 had improved transmission velocities due to enhanced matrix uniformity. The optimized NT2GF0.6 mix recorded velocities above 4.5 km/s at 90 days, placing it in the “Excellent” quality category. The improvement in UPV indicates reduced voids, higher material integrity, and better compaction, further validating the beneficial effects of the combined modification.

5) Table 6: Durability Performance of Modified Concrete (NT2 + Glass Fiber) at 90 Days

Mix ID	Glass Fiber (%)	Water Absorption (%)	Sorptivity (mm/√min)	RCPT (Coulombs)	UPV (km/s)
CTRL	0.00	4.20	0.160	3850	4.05
NT2GF0.20	0.20	3.75	0.145	3200	4.20
NT2GF0.40	0.40	3.52	0.131	2900	4.32
NT2GF0.60	0.60	3.49	0.125	2300	4.58
NT2GF0.80	0.80	3.57	0.130	2600	4.50
NT2GF1.00	1.00	3.65	0.138	2750	4.43

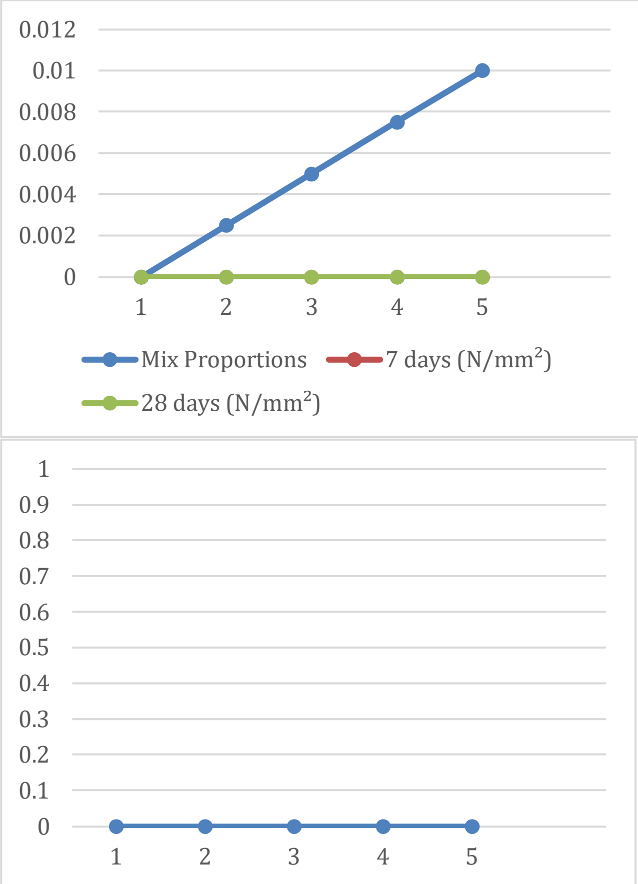

Fig 3.4: Graph of Durability Performance of Modified Concrete (NT2 + Glass Fiber) at 90 Days

FIG 3.5: Testing of Samples

IV. CONCLUSIONS

4.1 Effect of Nano-TiO_2 on Concrete Performance

The integration of nano-TiO_2 significantly influenced the mechanical and durability performance of concrete. At lower dosages (0.25% to 1.0%), incremental improvements in compressive strength were observed, primarily due to the nanoparticle filler effect and enhanced nucleation of hydration products. Nano-TiO_2 particles acted as seeds for calcium silicate hydrate (C–S–H) formation, accelerating the hydration reaction and refining the microstructure. The peak performance was observed at a 2.0% dosage, beyond which a decline in strength occurred. This behavior is attributed to particle agglomeration at higher concentrations, which can introduce weak zones and disrupt cement hydration. The optimized 2.0% dosage effectively reduced porosity and improved both strength and impermeability, as confirmed by lower water absorption and sorptivity values.

4.2 Role of Glass Fiber in Synergistic Enhancement

The addition of glass fiber to the 2.0% nano-TiO_2 mix led to further improvements, particularly in tensile and flexural strength. This enhancement is largely credited to the crack-bridging ability of glass fibers, which inhibit the propagation of microcracks formed during hydration shrinkage and mechanical loading. Among the varying dosages (0.2% to 1.0%), the optimum fiber content was found to be 0.6%, which delivered the best balance between dispersion, workability, and reinforcement. Beyond 0.6%, the benefits were countered by reduced workability and fiber clumping, which compromised mix uniformity and performance. The NT2GF0.6 mix showed the most notable strength gains, confirming the positive synergy between nano-TiO_2 and glass fibers at their respective optimal levels.

4.3 Combined Influence on Durability

Durability characteristics also benefitted significantly from the combined modification. The NT2GF0.6 mix displayed the lowest water absorption and sorptivity values, suggesting minimal capillary porosity and enhanced resistance to moisture ingress. This is essential for service life extension in aggressive environmental exposures. The RCPT results demonstrated a marked reduction in chloride permeability, indicating reduced ionic transport through the concrete matrix. This resistance is critical in marine structures and areas exposed to deicing salts. The reduction in permeability is attributed to both nano-TiO_2's densification effect and the fiber's ability to reduce crack width and connectivity. Additionally, UPV values exceeding 4.5 km/s validated the high integrity of the modified concrete, classifying it as excellent quality concrete per standard criteria.

4.4 Microstructural Implications

SEM and XRD analyses at 90 days revealed significant microstructural changes in the optimized concrete mix. SEM images displayed a denser matrix with fewer voids and a well-distributed C–S–H gel. Nano-TiO_2 was observed to be embedded within the hydration products, further strengthening the matrix. XRD patterns indicated a reduction in calcium hydroxide (CH) peaks and an increase in C–S–H formation, confirming the pozzolanic reactivity and filler effect of the nanoparticles. This densification supports the mechanical and durability results and validates the theoretical benefits of nano-modification.

4.5 Comparison with Previous Studies

The current findings are consistent with previous literature where nano-TiO_2 and glass fibers were studied independently. For instance, Nazari and Riahi (2011) reported early strength gains with nano-TiO_2, while Kizilkanat et al. (2015) demonstrated flexural strength improvements with glass fibers. However, the combined application in this study showed compounded benefits, confirming the synergistic interaction between nanoscale fillers and macro-scale reinforcement. This research, therefore, contributes to the limited body of knowledge on ternary enhancement systems in concrete and provides a practical formulation for high-performance applications.

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Author Contributions

Ayush Pandey: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Experimental Work
Sachin Kumar Singh: Data Curation, Visualization, Writing – Review & Editing

All authors have read and approved the final version of the manuscript.

Ethical approval

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Clinical Trial Registration

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