Experimental Investigation on the Synergistic Effect of Nano TiO_2, ZnO, and Polypropylene Fibers in Sustainable Concrete

Amrit Singh [1], Ushendra Kumar [2]
[1] *MTech Student,Lucknow Institute of Technology (L.I.T.), Lucknow, 226002, India.*
[2] *Assistant Professor,Lucknow Institute of Technology (L.I.T.), Lucknow, 226002, India.*

***Abstract*—This investigation systematically examines the influence of nano titanium dioxide (Nano-TiO_2) on the mechanical and microstructural properties of concrete reinforced with polypropylene fibers. Experimental mixtures were prepared with varying Nano-TiO_2 concentrations (0–5% by weight of cement) and a fixed dosage of 0.5% polypropylene fiber by volume. The mechanical behavior was characterized via split tensile, compressive and flexural strength tests at 28 days. Workability was evaluated using slump tests, and the material's internal structure was analyzed through microstructural examination. The results indicate that an optimal dosage of 2% Nano-TiO_2 yielded the most significant performance enhancements. Compared to the reference mixture, this composition demonstrated 6.45% increases in compressive strength, 12.78% increase in splitting tensile strength and a 16.21% increase in flexural strength. Consequently, this research concludes that the synergistic interaction between Nano-TiO_2 particles and polypropylene fibers presents a viable strategy for developing high-performance concrete.**

***Index Terms*—High-Performance Concrete, Nano-TiO_2, Polypropylene Fiber, Compressive Strength, Flexural Strength, Microstructure, Workability.**

I. INTRODUCTION

Concrete is the widely used construction material globally, essential for infrastructure ranging from residential buildings to large-scale civil projects like dams and transportation networks. However, conventional concrete is inherently brittle, making it susceptible to crack propagation, which limits its service life and durability. Furthermore, rapid global urbanization has intensified the demand for raw materials, leading to the depletion of natural aggregates and significant environmental impacts, including construction waste and greenhouse gas emissions. These challenges conflict with the principles of sustainable and low-carbon development [1, 2, 8]. Consequently, there is a critical need to develop innovative materials that enhance performance while reducing environmental footprint. Nanotechnology offers a transformative approach to concrete engineering. By manipulating materials at the nanoscale, it is possible to create a new generation of cementitious composites with superior physical and mechanical properties. The primary goal is to refine the concrete's microstructure. In conventional concrete, the hydration of cement leaves behind a network of pores ranging from micrometers to millimeters, which act as weak points [2-6]. Nanoparticles, such as nano-TiO_2, nano-SiO_2, and nano-Al_2O_3, can address this issue. Due to their minute size and high surface area, they act as fillers, densifying the cement paste by filling nano- and micro-scale voids. This mechanism leads to a more compact concrete matrix and introduces nucleation points that promote the generation of extra calcium-silicate-hydrate (C-S-H) gel, which serves as the key binding component in concrete. This refined microstructure inhibits crack initiation and propagation, thereby enhancing the bond between the cement paste and aggregates [5-7, 14]. While the addition of nanomaterials effectively increases compressive strength, it can also exacerbate the material's brittleness [8-10]. To counteract this, reinforcing fibers are incorporated to improve tensile strength and ductility. It is well-established that fibers, such as polypropylene (PP), steel, or carbon, enhance the energy absorption capacity of concrete, making it more resistant to impact and fatigue. Fiber’s bridge micro-cracks, controlling their growth and improving the material's toughness, flexural strength, and resistance to shrinkage [11, 12]. Previous research has demonstrated the benefits of combining mineral admixtures and fibers. For instance, Karthikeyan & Dhinakaran [13] reported that a 0.5% addition of PP fibers significantly improved the impact resistance of concrete containing silica fume. Similarly, studies have shown that hybrid fiber systems (e.g., steel and polypropylene) can yield superior performance compared to single-fiber systems [14]. This study aims to build on this knowledge by investigating the combined effect of Nano-TiO_2 particles and PP fibers. We hypothesize that the synergistic action of Nano-TiO_2 (for microstructural densification) and PP fibers (for crack-bridging and toughness) will lead to a high-performance composite. This paper presents a systematic experimental investigation where cement was replaced with Nano-TiO_2 at levels of 0%, 1%, 2%, 3%, 4%, and 5% in concrete containing a constant 0.5% volume of PP fibers. The effects on workability, mechanical strength (compressive, split tensile, and flexural), and microstructure are evaluated and discussed.

II. MATERIALS & METHODOLOGY

2.1. Materials

- Cement: Ordinary Portland Cement (OPC), 43 Grade, conforming to IS 4031:1996 [16], was used. Its physical properties are detailed in Table 1.
- Aggregates: Natural River sand was used as the fine aggregate (Zone II, specific gravity of 2.68) and crushed stone was used as the coarse aggregate (specific gravity of 2.77). Aggregates complied with IS 383:2016 [17, 18].
- Admixtures: A polycarboxylate-based superplasticizer (Fosroc Conplast SP430, specific gravity 1.415) was used to ensure adequate workability. Potable tap water was used for mixing.
- Nano-TiO_2 and Polypropylene Fiber:The Nano-TiO_2 particles and monofilament polypropylene (PP) fibers were sourced from commercial suppliers. Their key properties are listed in Table 2.

Table 1: Key Physical parameters of Cement

Test	Result
Specific Gravity	3.07
Standard Consistency	29.6%
Initial Setting Time	45 min
Final Setting Time	410 min
Fineness (by sieve)	5.7%

Table 2: Properties of Nano-TiO_2 and Polypropylene Fiber (PPF)

Material	Property	Value
Nano-TiO_2	Particle Size	40-400 nm
	Purity	96%
	Structure	Rutile
	pH Value	6.7
Polypropylene Fiber	Length	12 mm
	width	.5-1 mm

For every concrete mix, samples were prepared for mechanical evaluation: 150 mm cubes for compressive strength, 100 mm × 200 mm cylindrical specimens for split tensile strength, and prisms measuring 150 mm × 150 mm × 700 mm for flexural strength assessment. After 24 hours, all specimens were removed from their molds and subjected to water curing until they reached the designated testing periods of 7, 14, and 28 days.

Figure1.NanoTiO2 used in mix design

Figure2.Polypropylene fiber for mix design

2.2. Mix Proportions and Specimen Preparation

The concrete mix was designed for a characteristic compressive strength of 35 N/mm² (M35) according to IS 10262:2019 [19]. A constant water-cement (w/c) ratio of 0.375 was maintained for all mixes. Six mixtures were prepared. The control mix, designated PT0, contained 0% Nano-TiO_2. The other five mixes, PT1, PT2, PT3, PT4, and PT5, contained 1%, 2%, 3%, 4%, and 5% Nano-TiO_2 as a partial replacement for cement by weight, respectively. All mixes included 0.5% PP fiber by volume.Mix proportions are shown in Table 3.

Table 3: Concrete Mix Proportions (per m³)

Material	Quantity (kg/m³)
Cement	420.61
Fine Aggregate	169.51
Coarse Aggregate	646.80
Water	1191.4
Super plasticizer	As needed for workability
Polypropylene Fiber	4.50 (0.5% by volume)
Nano-TiO_2	0% to 5% of cement weight

III. RESULTS AND DISCUSSION

3.1. Workability (Slump Test)

The workability of fresh concrete, assessed via the slump test, was significantly influenced by the Nano-TiO_2 content. As shown in Table 4, the slump value decreased progressively as the percentage of Nano-TiO_2 increased. The control mix (PT0) had a slump of 112 mm, which reduced to 84 mm for the PT5 mix.

The high specific surface area of the nanoparticles is considered responsible for this reduction. The Nano-TiO_2 particles adsorb a portion of the mixing water onto their surface, reducing the amount of free water available to lubricate the mix. This leads to a stiffer, more cohesive mixture. While this effect can be beneficial for controlling segregation, excessive additions can make the concrete difficult to place and compact. To maintain consistent workability, the dosage of superplasticizer was adjusted as needed.

Table 4: Slump Test Results for Different Mixes

Mix Code	Nano-TiO_2 (%)	Slump (mm)
PT0	0	112
PT1	1	108
PT2	2	102
PT3	3	98
PT4	4	92
PT5	5	84

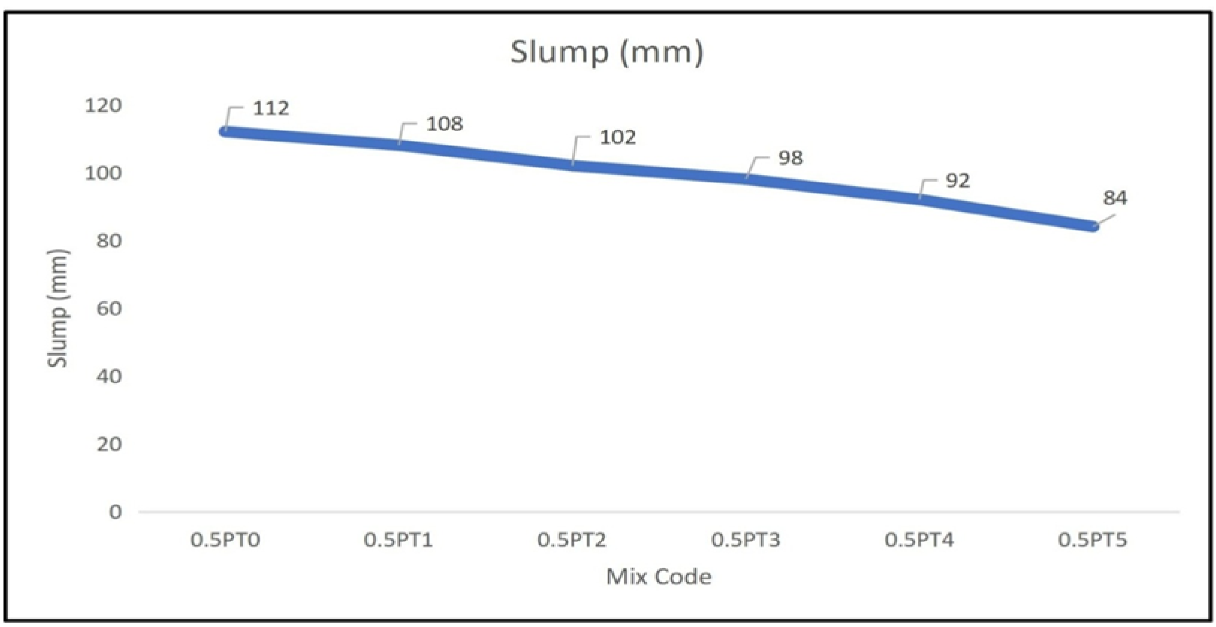

Figure3. Slump data for different concrete mix

3.2. Compressive Strength

The compressive strength results at 7, 14, and 28 days are presented in Figure 4. The strength of all mixes increased with curing age, as expected. An increase in compressive strength was observed with Nano-TiO_2 addition up to 2%, showing superior performance over the control mix (PT0). The 28-day compressive strength of the control mix was 43.18 MPa. The PT2 mix (2% Nano-TiO_2) achieved the highest strength of 45.29 MPa, representing a 4.89% increase. Beyond this optimal point, further additions of Nano-TiO_2 led to a gradual decline in strength. The PT5 mix (5% Nano-TiO_2) exhibited a strength slightly lower than the control. This trend suggests two competing mechanisms:

[1] Enhancement (at low dosages): Nano-TiO_2 particles fill micro-voids (filler effect) and act as nucleation sites, accelerating cement hydration and producing a denser C-S-H gel.

[2] Detriment (at high dosages): Excessive nanoparticles tend to agglomerate due to van der Waals forces. These agglomerates act as weak spots or artificial voids within the matrix, negating the benefits of the filler effect and leading to a reduction in strength.

Table5: Compressive strength value determines through experimental study

Mix Code	Compressive Strength		
	7days	14days	28 days
0.5PT0	27.9	32.9	42.18
0.5PT1	29.2	32.6	44.78
0.5PT2	28.2	35.8	45.29
0.5PT3	27.5	32.8	44.85
0.5PT4	27.1	34.2	43.78
0.5PT5	25.9	31.5	42.9

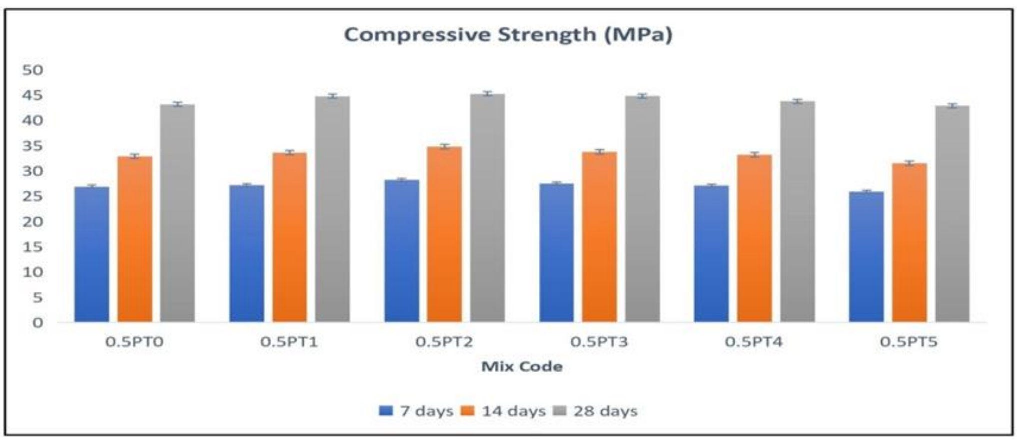

Figure4.Compressive strength results data

3.3. Splitting Tensile and Flexural Strength

This results for splitting tensile and flexural strength, shown in Figures 5 and 6, followed a similar trend to compressive strength.

- Splitting Tensile Strength: The PT2 mix again showed the highest performance, reaching a 28-day strength of 5.12 MPa, a 15.32% improvement over the control mix's 4.44 MPa. This significant increase is due to the combined action of the PP fibers bridging potential cracks and the densified matrix created by the Nano-TiO_2, which improves the bond between the fibers and the paste.
- Flexural Strength: The flexural strength also peaked with the PT2 mix, achieving 5.23 MPa at 28 days a 14.69% increase compared to the control. This highlights the crucial role of PP fibers in resisting bending loads. The fibers distribute stress across the specimen and prevent catastrophic failure, while the enhanced microstructure from Nano-TiO_2 provides a stronger, more resilient matrix for the fibers to anchor into.

Table 5: Split tensile strength value determines through experimental study

Mix Code	Split Tensile Strength		
	7 days	14 days	28 days
0.5PT0	3.08	3.98	4.44
0.5PT1	3.24	4.23	4.78
0.5PT2	3.68	4.35	5.12
0.5PT3	3.28	4.28	4.89
0.5PT4	3.17	4.10	4.66
0.5PT5	2.99	3.88	4.24

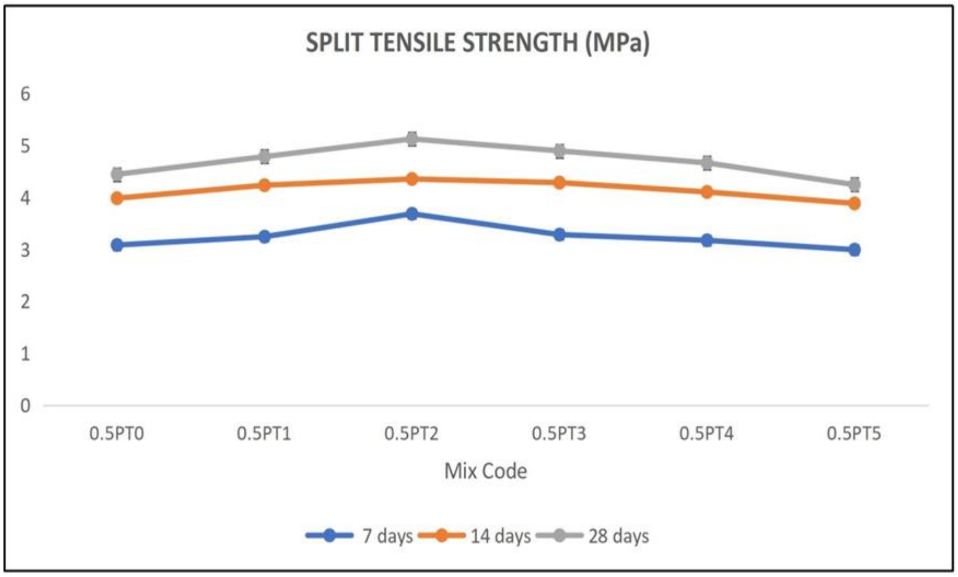

Figure5.Flexural strength data

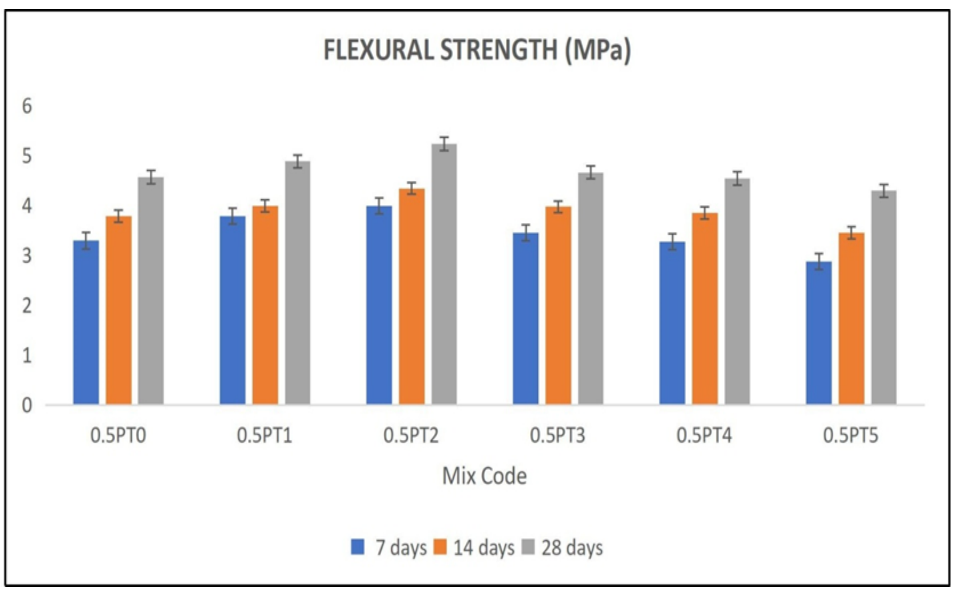

Figure6. Split tensile strength results data

IV. CONCLUSION

This study successfully demonstrated the synergistic benefits of combining Nano-TiO_2 particles and polypropylene fibers to enhance the properties of concrete. Based on the experimental results, the following conclusions are drawn:

1. Optimal Dosage: The most effective performance was achieved with a mixture containing 2% Nano-TiO_2 as a cement replacement and 0.5% PP fiber by volume (PT2). This composition yielded the highest mechanical strength.
2. Mechanical Performance: At 28 days, the optimized PT2 mix showed significant improvements over the control concrete: compressive strength increased by 4.89%, splitting tensile strength by 15.32%, and flexural strength by 14.69%.
3. Workability: The addition of Nano-TiO_2 reduces the workability of fresh concrete due to its high surface area. This effect must be managed, typically through the use of superplasticizers, to ensure proper application.

In summary, the strategic combination of nanoparticles and fibers presents a robust pathway for developing high-performance concrete with superior strength and ductility, suitable for advanced construction applications.

REFRENCES

[1] Behfarnia, K., Azarkeivan, A., & Keivan, A. (2013). Studied the role of titanium dioxide and zinc oxide nanoparticles in enhancing the strength and structural performance of standard concrete mixes.

[2] Martins, T. M. D. R., Pacheco-Torgal, F., Miraldo, S., Aguiar, J. L., & Jesus, C. M. G. (2016). Investigated how combining fly ash and nano-TiO_2 contributes to the production of superior strength concrete.

[3] Reshma, T. V., Manjunatha, M., Bharath, A., Tangadagi, R. B., Vengala, J., & Manjunatha, L. R. (2021). Explored mechanical behavior and endurance properties of concrete infused with TiO_2 and ZnO, alongside fiber inclusion. Materialia, 18, 101138.

[4] Mehdipour, M. (2015). Assessed improvements in fiber-based concrete when nanoparticles are introduced to alter its mechanical and physical traits. In Nanomaterials and Nanotechnology for Composite Structures (p. 59).

[5] Mehdipour, M. Examined fiber-reinforced concrete microstructures with a focus on the effects of nanomaterials and polymer fibers. (Specific publication info required)

[6] Raza, A., Azab, M., Baki, Z. A., El Hachem, C., El Ouni, M. H., & Kahla, N. B. (2023). Experimental work on geopolymer concrete using micro-carbon fibers and nano-TiO_2 to improve its toughness and structural texture. Alexandria Engineering Journal, 64, 451–463.

[7] Martins, T. M. D. R., Pacheco-Torgal, F., Miraldo, S., Aguiar, J. L., & Jesus, C. M. G. (2016). Comprehensive evaluation of high-performance cementitious materials with nano-TiO_2 and supplementary cementitious materials.

[8] Wei, X., Xiaoqing, W., & Chunmei, L. (2024). Evaluated how recycled concrete is strengthened through the joint use of polypropylene fibers and titanium dioxide nanoparticles. International Journal of Concrete Structures and Materials, 18(1), 28.

[9] Alsafy, M., Al-Hinai, N., & Alzebdeh, K. (2024, September). Comparison of natural (date palm) and synthetic (TiO_2) nanoparticle additives in composite mechanical performance. In Materials Science Forum (Vol. 1126, pp. 61–75).

[10] Ying, J. (2023). Proposed techniques for improving structural and durability features in concrete made with reused aggregates. In Multi-Functional Concrete with Recycled Aggregates (pp. 127–143).

[11] Feng, S., Jiang, Y., Lyu, J., Xiao, H., Zhang, Q., Song, R., ... & Ren, Z. (2024). Demonstrated how nanosilica and fiber inputs improve both strength and internal structure in pavement concrete with reused coarse aggregate. Construction and Building Materials, 428, 136404.

[12] Sun, S., Du, Y., Sun, S., Yu, Q., & Li, Y. (2024). Mechanical performance and bonding capacity of polypropylene-fiber-reinforced recycled concrete were examined in this study. Materials Science, 30(3), 396–403.

[13] Karthikeyan, B., & Dhinakaran, G. (2018). Focused on how ultra-fine TiO_2 and silica fume contribute to improved performance in both plain and fiber-infused cement mixes. Construction and Building Materials, 161, 570–576.

[14] Yahaghi, J., Muda, Z. C., & Beddu, S. B. (2016). Investigated the effect of adding polypropylene fibers to oil palm shell concrete to enhance its impact resistance. Construction and Building Materials, 123, 394–403.

[15] BIS (2013). IS 8112: Guidelines for 43-grade Ordinary Portland Cement. Bureau of Indian Standards, New Delhi.

[16] BIS (1996). IS 4031 (Parts 1–6): Standard methods for physical testing of hydraulic cement. Bureau of Indian Standards, New Delhi.

[17] BIS (1963). IS 2386 (Parts 1–4): Procedures for testing aggregates used in concrete. Bureau of Indian Standards, New Delhi.

[18] BIS (2016). IS 383: Specification for fine and coarse aggregate intended for concrete production. Bureau of Indian Standards, New Delhi.

[19] BIS (2019). IS 10262: Standardized guidelines for designing concrete mix proportions. Bureau of Indian Standards, New Delhi.

[20] BIS (2021). IS 516 (Part 1/Sec 1): Procedures for testing hardened concrete strength including compression, flexural, and split tensile strength. Bureau of Indian Standards, New Delhi.

[21] Li, H., Hua, Z., & Ou, J.-P. (2007). Evaluated fatigue life of concrete pavements integrated with nanomaterials under flexural loading. International Journal of Fatigue, 29, 1292–1301.

[22] Girao, A. V., Richardson, I. G., Porteneuve, C. B., & Brydson, R. M. D. (2007). Characterized the nanostructure and composition of C–S–H formed in hydrated white cement at elevated temperatures. Cement and Concrete Research, 37, 1571–1582.