Research Article

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Investigation of Mechanical Properties of M25 Grade Concrete Incorporating Nano-TiO_2 and Coconut Fibers

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ABSTRACT

The research examines the impact of nano-TiO_2 and coconut fibers as reinforcements on the mechanical properties of M25 grade concrete. The experimental tests determined compressive strength, splitting tensile strength and flexural strength of the fiber reinforced concrete. Nano-TiO_2 addition results in improved microstructural density and durability, while coconut fibers helped the material become more resistant to cracks and reduce brittleness, showing resistance to crack formation. Water-to-cement ratio was adjusted to fulfil specific workability and strength performance requirements. The study proves that the blend of nano-TiO_2 with coconut fibers generates effective improvement in the mechanical characteristics of M25 grade concrete to support structural applications.

Keywords: M25 grade concrete; Nano-TiO_2; Coconut fibers; Sustainable construction.

1. INTRODUCTION

Concrete remains a leading construction material due to its superior strength, long-term durability, and adaptability. Improving its mechanical behavior and eco-efficiency is a significant area of research. The incorporation of nanomaterials such as nano-TiO_2 and nano-SiO_2 enhances performance by refining the microstructure, decreasing porosity, and reducing carbon emissions (Jakhar *et al.* 2024; Döndüren and Al-Hagri, 2022; Tanimola and Efe, 2024; Sujitha *et al.* 2024). Incorporating nanoscale additives into concrete can also help reduce air pollution, supporting sustainable building practices. Nano-TiO_2, in particular, has shown effectiveness in recycled aggregate concrete, enhancing tensile strength, freeze-thaw resistance, and microstructural stability (Wei *et al.* 2024). Its surface modification of natural fibers improves fiber-matrix bonding, mechanical strength, and water resistance in eco-friendly composites (Prasad *et al.* 2021). Similarly, combining nano-TiO_2 with natural fibers like coconut fiber improves toughness and provides biodegradable, lightweight alternatives to synthetic materials (Natrayan *et al.* 2022; Lumingkewas *et al.* 2019).

The use of graphene derivatives and carbon nanotubes further boosts mechanical performance at low dosages, enhancing efficiency and reducing environmental impact (Jiang and Wang, 2017; Jing *et al.* 2024). Incorporating agro-industrial waste, such as rice husk ash and coconut fiber, complements these enhancements by reducing waste and reliance on non-renewable resources (Morato *et al.* 2023; Abdalla *et al.* 2023).

In polymer composites, nanotechnology plays a transformative role. Rutile TiO_2 and nanoclay enhance structural, thermal, and moisture-resistant properties in fiber-reinforced systems, while pairings like coir fiber with h-BN facilitate the development of renewable, eco-friendly materials for sustainable applications (Rathnam *et al.* 2020; Srinivasa Perumal *et al.* 2024; Venkatachalam *et al.* 2023).

The present study explored the combined effect of nano-TiO_2 and coconut fibers on the mechanical properties of M25 grade concrete. The research addresses a critical gap in existing literature by evaluating the synergistic influence of a nano-modifier and natural fiber reinforcement in a single concrete mix. Few previous studies have independently assessed these additives, their combined impact on strength and durability remains underexplored. The findings demonstrate notable improvements in compressive, tensile, and flexural strength due to enhanced matrix densification and fiber bridging effects. The novelty of this study lies in

promoting a sustainable and cost-effective method to improve concrete performance using readily available materials. The optimized water-to-cement ratio and uniform fiber dispersion ensured improved workability and crack resistance. This hybrid reinforcement approach offers promising potential for developing high-performance, eco-friendly concrete for structural applications.

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this research were chosen because they could improve certain mechanical qualities and were compatible with the design of M25 grade concrete mixes. The main binder was ordinary Portland cement of grade 53, which complies with IS: 12269-1987 specifications. The cement had a standard consistency of 30% and a specific gravity of 3.15. Locally produced river sand that used as the fine aggregate. It was passed through a 4.75 mm screen and had a specific gravity of 2.63 complying with IS: 383-2016 Zone II requirements.

Crushed angular granite stones with a nominal size of 20 mm, a specific gravity of 2.74, and a water absorption capacity of 0.5% made up the coarse aggregates. To guarantee uniformity in hydration and strength development, potable tap water free of organic and inorganic impurities was used during mixing and curing processes.



Fig. 1: Raw materials used for concrete preparation

Nano-TiO_2 was added as a mineral admixture because of its pozzolanic activity and nano-scale particle size, which is usually less than 100 nm in diameter. The nano-TiO_2 used in this study was white, highly pure (>99%), and sourced from a certified chemical supplier. Its high surface area and reactivity were anticipated to enhance the microstructure of the cementitious matrix.

Because of their high tensile strength coconut fibres were chosen as the natural reinforcing element. The fibres were cut to lengths of 30 to 50 mm after being manually removed from mature coconut husks and cleansed to get rid of any surface contaminants. To minimise water absorption during mixing, the fibres were air-dried after being soaked in water for a full day. To guarantee uniform dispersion and efficient reinforcement, initial testing was used to optimise the aspect ratio and fibre dose.

Fig. 1 displays the primary raw materials used in concrete preparation: cement, water, fine aggregate (sand), and coarse aggregate (gravel).

2.2 Mix Design and Preparation

The concrete mix was proportioned to achieve a compressive strength of 25 MPa at 28 days, in accordance with IS: 10262-2019 guidelines for M25 grade concrete. To create baseline performance characteristics, a control mix without additives was first prepared. Subsequent mixes contained nano-TiO_2 and coconut fibers in varied quantities to assess their impact on mechanical behavior.



Fig. 2: Cast concrete specimens

For all mixes, the water-to-cement ratio was kept at 0.45 and the workability was adjusted to stay within reasonable bounds (slump range: 75–100 mm). To guarantee that the fibres and nano-TiO_2 were distributed evenly throughout the matrix, a pan mixer was used. The

mixing procedure was carried out in phases to avoid fibre clumping. Cement, aggregates, and nano-TiO_2 were first mixed dry, then water was added gradually, and lastly coconut fibres were integrated.

The polycarboxylate ether-based superplasticizer (0.5–0.8% by weight of cement) was used to increase workability without sacrificing strength. In order to assess compressive strength, splitting tensile strength, and flexural strength, all concrete mixtures were formed into standard cubes (150 × 150 × 150 mm), cylinders (150 mm diameter × 300 mm height), and beams (100 × 100 × 500 mm). The specimens were cured in water at 27 ± 2°C for 7, 14, and 28 days after the molds were demolded after 24 hours.

Fig. 2 shows freshly cast concrete specimens in molds, including one rectangular beam mold and three cube molds. These samples are typically used for mechanical testing such as compressive, flexural, and split tensile strength evaluations.

Fig. 3 shows multiple cylindrical concrete specimens freshly cast in molds and placed for initial setting. These samples were prepared for compressive and split tensile strength testing after curing.



Fig. 3: Multiple cylindrical Concrete Specimens freshly cast in molds

2.3 Testing Procedures

A compression testing equipment with a 2000 kN capacity was used to measure compressive strength in accordance with IS: 516-1959. For every test period, the average of three specimens was noted. Flexural strength was determined using the third-point loading technique outlined in IS: 516-1959, and splitting tensile strength was evaluated on cylindrical specimens in accordance with IS: 5816-1999. To assess the development of strength properties, all mechanical testing was carried out at predetermined curing intervals.

Workability of fresh concrete was measured using the slump cone test, and observations regarding fiber distribution and mix cohesion were documented qualitatively during casting. In all experiments, proper handling, curing, and testing protocols were maintained to ensure the reliability and reproducibility of results.



Fig. 4: Concrete cube specimen undergoing compressive strength

Fig. 4 depicts a concrete cube specimen undergoing compressive strength testing using a universal testing machine (UTM). The visible cracks and deformation indicate that the sample has reached or is nearing its failure load.

3. RESULTS AND DISCUSSION

Table 1 presents the results of 18 concrete specimens incorporating varying percentages of nano-TiO_2 (0.5%–3.0%) and coconut fiber (0.5%–1.5%) with different water-to-cement ratios (0.4–0.5).

The mechanical properties measured include compressive strength, splitting tensile strength, and flexural strength. Mix 8 with 1.5% nano-TiO_2 and 1.0% coconut fiber achieved the highest values across all tested strengths. Beyond this concentration, mechanical properties generally declined, indicating a threshold beyond which the additive benefits diminish. Overall, moderate additions of nano-TiO_2 and coconut fiber enhanced the strength and durability characteristics of the concrete composite.

Table 1. Mechanical properties of concrete mixes

Mixes	Nano-TiO_2 (%)	Coconut Fiber (%)	Water/Cement Ratio	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)
1	0.5	0.5	0.4	26.3	3.26	5.76
2	0.5	1.0	0.45	28.4	3.9	6.13
3	0.5	1.5	0.5	26.9	3.3	5.6
4	1.0	0.5	0.45	27.8	3.46	5.81
5	1.0	1.0	0.5	27.96	3.53	5.77
6	1.0	1.5	0.4	29.4	4.53	6.23
7	1.5	0.5	0.5	29.67	5.2	6.5
8	1.5	1.0	0.4	30.5	5.8	7.2
9	1.5	1.5	0.45	30.34	5.67	6.98
10	2.0	0.5	0.4	29.8	5.01	6.82
11	2.0	1.0	0.45	28.67	5.12	6.3
12	2.0	1.5	0.5	28.45	4.39	5.23
13	2.5	0.5	0.5	28.1	4.67	5.83
14	2.5	1.0	0.4	27.8	4.37	5.87
15	2.5	1.5	0.45	27.12	4.23	5.99
16	3.0	0.5	0.45	26.8	3.78	5.94
17	3.0	1.0	0.5	26.46	3.4	5.78
18	3.0	1.5	0.4	26.09	3.25	5.6

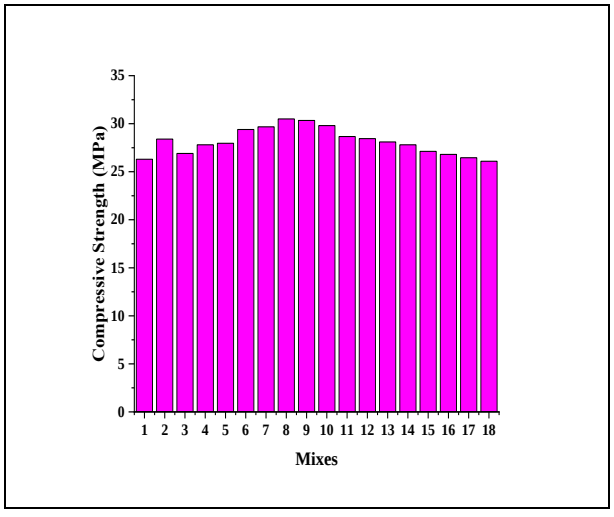


Fig. 5: Compressive strength analysis graph

3.1 Compressive Strength

The bar chart (Fig. 5) represents the compressive strength (in MPa) of 18 different concrete mixes. Each mix is labelled from 1 to 18 along the X-axis, while the Y-axis shows compressive strength values. The strength increases gradually from Mix 1 and reaches its maximum at Mix 8, around 30–31 MPa. Beyond Mix 8, a decreasing trend in strength is observed, continuing until Mix 18. This suggests that Mix 8 yields the highest compressive strength among all the tested mixes. The consistent drop in values after Mix 8 may indicate an over- or under-dosage of certain mix components.

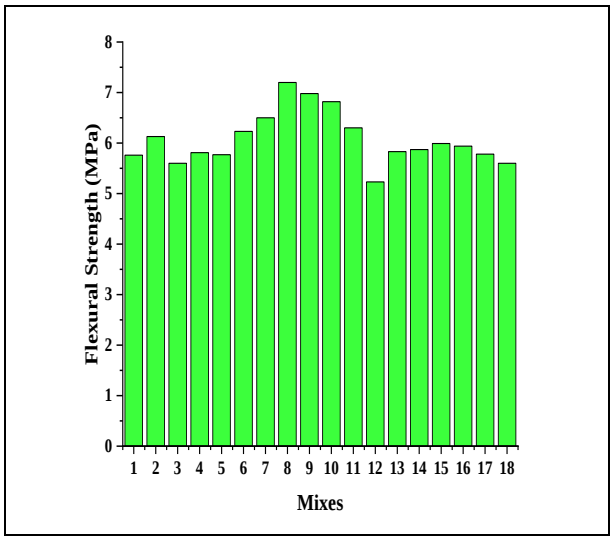


Fig. 6: Flexural strength analysis

3.2 Flexural Strength

The bar chart (Fig. 6) shows the flexural strength (in MPa) for 18 different concrete mixes. Flexural strength values are plotted on the Y-axis, while the X-axis represents each mix from 1 to 18. The strength rises steadily from Mix 1 and peaks at Mix 8, reaching just over 7 MPa. After Mix 8, the values gradually decrease, with a noticeable drop at Mix 12. Mixes 13 to 18 show slight fluctuations but generally maintain moderate flexural strength. The trend suggests that Mix 8 offers optimal performance in terms of flexural resistance.

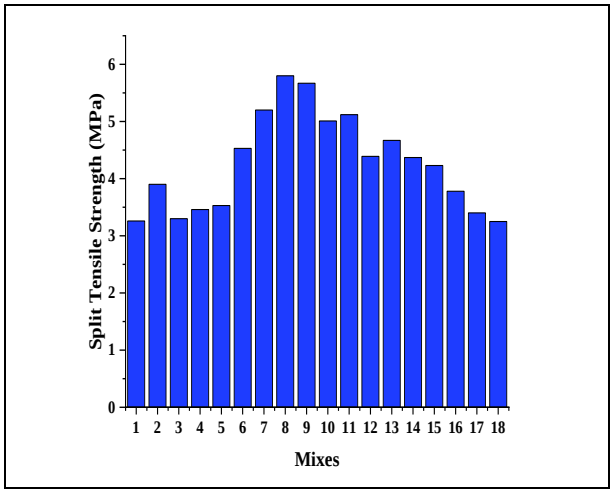


Fig. 7: Split tensile strength analysis

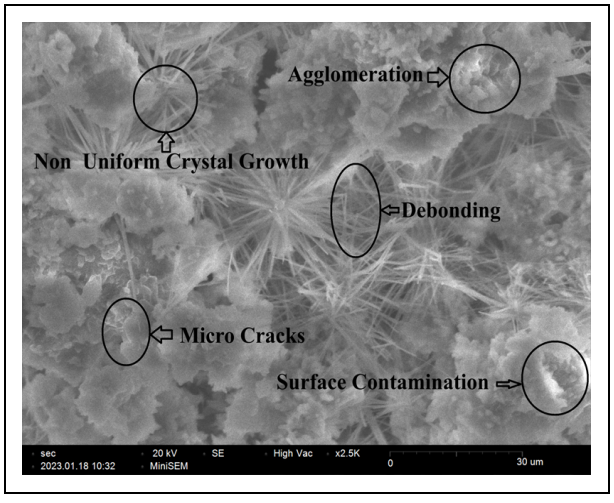


Fig. 8: SEM analysis of the sample (Mix 8)

3.3 Split Tensile Strength

Fig. 7 illustrates the split tensile strength (in MPa) for 18 different concrete mixes. The strength values are plotted on the Y-axis, with each mix numbered from 1 to 18 on the X-axis. Initial mixes show moderate tensile strength, with a significant rise starting from Mix 6. Peak tensile strength is observed at Mix 8, followed closely by Mix 9. After Mix 9, the tensile strength progressively declines, reaching its lowest at Mix 18. This trend highlights Mix 8 as the most effective for maximizing split tensile strength.

Fig. 8 shows the scanning electron microscope micrograph taken at a magnification of 2500x, showing the microstructure of a material with visible needle-like or fibrous crystalline formations. These radiating structures are characteristic of certain hydrated compounds, such as ettringite, which commonly forms in cementitious materials. The fibrous crystals are interspersed within a denser, irregular matrix, suggesting a well-developed microstructure with possible filler or hydration product interactions. The observed morphology indicates effective integration of components, likely contributing to enhanced mechanical performance and durability in the composite material.

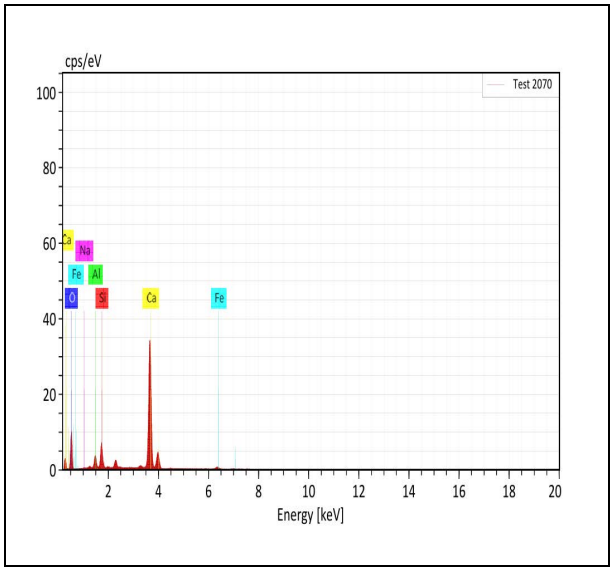


Fig. 9: EDAX analysis of concrete samples (Mix 8)

An Energy Dispersive X-ray Spectroscopy (EDS) spectrum (Fig. 9) reveals the elemental composition of the tested sample. Identifiable peaks in the spectrum show the presence of oxygen (O) together with sodium (Na) and aluminum (Al), Titanium (Ti) and calcium (Ca) and iron (Fe) in the examined material. The relative element abundances correspond to peak intensities which are measured in counts per second per electron volt (cps/eV). The strong peaks of Si and Ca show that the specimen contains silicate and calcium-based phases which are characteristic of cementitious or composite materials. Multiple energy ranges of Fe detection indicate the instrument measures different oxidation states and forms of iron.

Table 2 presents the quantitative results of Energy Dispersive X-ray Spectroscopy (EDS) analysis for a concrete sample with Mix Id 8 is shown in Fig. 9, highlighting the elemental composition by mass and

atomic percentages. Oxygen dominates the composition with a normalized mass percentage of 65.23% and an atomic percentage of 80.56%, followed by calcium at 24.08% mass and 11.87% atom percentage, indicating a highly oxygenated, calcium-rich material, likely of cementitious nature. Smaller proportions of silicon, aluminium, sodium, and iron are also present, suggesting the inclusion of silicates and minor metal oxides. The associated absolute and relative error values offer insight into the precision of the measurements.

Table 2. Quantitative results of an energy dispersive X-ray spectroscopy

Element	At. No.	Netto	Mass %	Mass Norm. %	Atom %	Abs. Error % (1 sigma)	Rel. Error % (1 sigma)
Oxygen	8	17115	74.50	65.23	80.56	9.75	13.09
Sodium	11	1064	1.85	1.62	1.40	0.18	9.44
Aluminium	13	7404	4.12	3.61	2.64	0.23	5.69
Calcium	20	96111	27.50	24.08	11.87	0.83	3.03
Iron	26	1537	1.02	0.89	0.32	0.06	6.34
Titanium	14	14903	5.21	4.56	3.21	0.25	4.90
Sum			114.20	100.00	100.00		

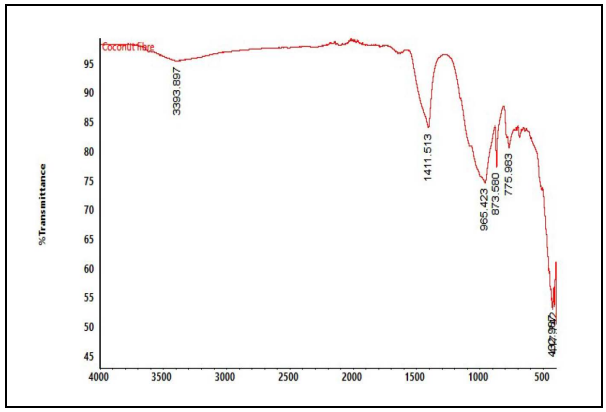


Fig. 10: FTIR analysis of mix 8 concrete sample images

The FTIR spectrum of coconut fibre is shown in Fig. 10. The presence of O–H stretching, which is characteristic of hydroxyl groups, is shown by a large peak close to 3333 cm^{-1} the C–H stretching of aliphatic chains is shown by the band at around 2918 cm^{-1}. C=O stretching and aromatic C=C bonds are indicated by peaks at 1731 cm^{-1} and 1637 cm^{-1}.

4. CONCLUSION

This study demonstrated that the incorporation of nano-TiO_2 and coconut fibers significantly enhances the mechanical performance of M25 grade concrete. Among the various mix designs tested, mix 8, containing 1.5% nano-TiO_2 and 1.0% coconut fiber, exhibited the highest compressive (30.5 MPa), tensile (5.8 MPa), and flexural (7.2 MPa) strengths, marking it as the optimal combination. The improvements are attributed to the synergistic effects of nano-TiO_2-induced matrix densification and the crack-bridging capability of coconut fibers. However, exceeding the 1.5% nano-TiO_2 threshold led to a decline in performance, likely due to particle agglomeration and reduced workability. Additionally, lower water-to-cement ratios, particularly 0.4, contributed to increased matrix compaction and strength.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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