

Effect of TiO_2 and TiO_2/gCN Nanomaterial Incorporation on Mechanical Strength of M30 Concrete

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Abstract - This study investigates the influence of TiO_2 nanoparticles and TiO_2/gCN nanocomposite on the mechanical properties of M30 grade concrete. TiO_2 nanoparticles were synthesized using the sol-gel method, while graphitic carbon nitride (gCN) was prepared via thermal polycondensation. The TiO_2/gCN nanocomposite was fabricated through physical mixing and ultrasonication. Concrete specimens were prepared by replacing 1% of cement with nanomaterials. Mechanical properties including compressive strength, split tensile strength, and flexural strength were evaluated at 7 and 28 days. Results indicate that nanomaterial incorporation significantly enhances the strength characteristics of concrete. The TiO_2/gCN -modified concrete exhibited the highest improvement with compressive strength increases of about 13.22% at 7 days and 13.53% at 28 days. Similarly, split tensile strength improved by approximately 14.37% at 7 days and 6.94% at 28 days, while flexural strength increased by about 13.92% at 7 days and 11.07% at 28 days. The enhancement is attributed to improved particle packing, pore refinement, and accelerated hydration due to the nano-filler effect.

Keywords- Nanoconcrete, TiO_2 , gCN, Mechanical strength, Compressive strength, Split tensile strength, Flexural strength

1. Introduction

Concrete is the most widely used construction material in the world due to its versatility, availability of raw materials, and relatively low cost [1]. However, despite its widespread application, conventional concrete exhibits certain inherent limitations, particularly in terms of tensile strength, brittleness, and durability [2]. The presence of microcracks, pores, and a weak interfacial transition zone (ITZ) between cement paste and aggregates often leads to reduced mechanical performance and premature structural deterioration [3]. Therefore, enhancing the mechanical properties of concrete has remained a key area of research in civil engineering materials.

In recent years, nanotechnology has emerged as a promising approach to overcome these limitations by modifying the microstructure of cementitious materials at the nanoscale [4]. Nanomaterials possess extremely small particle size and high specific surface area, which enables them to act as effective fillers and nucleation sites within the cement matrix [5]. Among various nanomaterials, titanium dioxide (TiO_2) has gained significant attention due to its chemical stability, high reactivity, and ability to enhance hydration processes [6]. When incorporated into concrete, TiO_2 nanoparticles can accelerate the formation of hydration products such as calcium silicate hydrate (C-S-H), resulting in improved density and strength of the matrix [7].

Furthermore, the incorporation of hybrid nanocomposites has shown even greater potential in improving concrete properties. Graphitic carbon nitride (gCN), a two-dimensional layered material, when combined with TiO_2 , forms a TiO_2/gCN nanocomposite that offers synergistic effects. The layered structure of gCN provides a large surface area and facilitates better dispersion of TiO_2 nanoparticles, thereby enhancing the overall interaction within the cement matrix [8]. This hybrid system not only improves particle packing but also strengthens the interfacial bonding between cement paste and aggregates, leading to improved mechanical performance.

The improvement in concrete strength due to nanomaterials can be attributed to multiple mechanisms, including the nano-filler effect, pore refinement, and accelerated hydration kinetics. The nano-filler effect helps in filling microvoids and reducing porosity, while the nucleation effect promotes the formation of additional hydration products. These combined effects lead to

a denser microstructure, improved load transfer, and enhanced resistance to crack initiation and propagation [9]. As a result, both compressive and tensile-related properties such as split tensile and flexural strength are significantly improved.

In this context, the present study aims to investigate the effect of TiO_2 nanoparticles and TiO_2/gCN nanocomposite on the mechanical properties of M30 grade concrete. The study focuses on evaluating compressive strength, split tensile strength, and flexural strength at different curing ages (7 and 28 days). By comparing the performance of plain and nanomodified concrete, the research seeks to establish the effectiveness of nanomaterial incorporation as a viable strategy for enhancing the structural performance of concrete.

2. Materials and Methods

2.1. Nanomaterial Synthesis

The nanomaterials used in this study, namely TiO_2 nanoparticles and TiO_2/gCN nanocomposite, were synthesized using well-established chemical routes to ensure high purity and uniformity. TiO_2 nanoparticles were prepared via the sol-gel method using titanium isopropoxide as the precursor. Initially, a homogeneous solution of deionized water, ethanol, and glacial acetic acid was prepared and stirred to ensure proper mixing. Titanium isopropoxide was then added dropwise under continuous stirring, allowing hydrolysis and polycondensation reactions to occur, leading to the formation of a stable sol. The mixture was further stirred for an extended duration to promote particle growth and stabilization. The resulting precipitate was filtered, washed with deionized water and ethanol to remove impurities, and subsequently dried at moderate temperature to obtain fine TiO_2 nanoparticles. Graphitic carbon nitride (gCN) was synthesized separately by thermal polycondensation of urea in a muffle furnace at elevated temperature (around 550°C) for several hours, resulting in a layered yellow powder structure. The TiO_2/gCN nanocomposite was then prepared by physically mixing equal proportions of TiO_2 and gCN in deionized water followed by probe ultrasonication to ensure uniform dispersion and intimate interfacial contact. The mixture was filtered, dried, and finely ground to obtain a homogeneous nanocomposite powder, which was used for further concrete preparation.

Concrete Preparation and Formation

The concrete specimens were prepared using M30 grade mix designed as per IS 456:2000 and IS 10262:2019 guidelines. Ordinary Portland Cement (OPC 43 grade), fine aggregates (Zone II sand), and coarse aggregates (20 mm nominal size) were used along with a superplasticizer (Conplast 430-G8) to achieve the desired workability. The water-cement ratio was maintained at 0.40. For nanomodified mixes, 1% of cement (by weight) was replaced with TiO_2 nanoparticles and TiO_2/gCN nanocomposite, respectively. The nanomaterials were first dispersed in mixing water using ultrasonication to minimize agglomeration and ensure uniform distribution within the cement matrix. The mixing process involved dry mixing of cement and aggregates followed by gradual addition of the nanomaterial-containing water and admixture to achieve a homogeneous mix. The fresh concrete was then poured into standard moulds of cubes, cylinders, and beams for compressive, split tensile, and flexural strength tests, respectively. Proper compaction was ensured using vibration to eliminate entrapped air. After casting, the specimens were covered to prevent moisture loss and demoulded after 24 hours. The demoulded specimens were cured in water under controlled conditions for 7 and 28 days. This systematic preparation ensured uniform dispersion of nanomaterials and consistent development of mechanical properties in the hardened concrete.

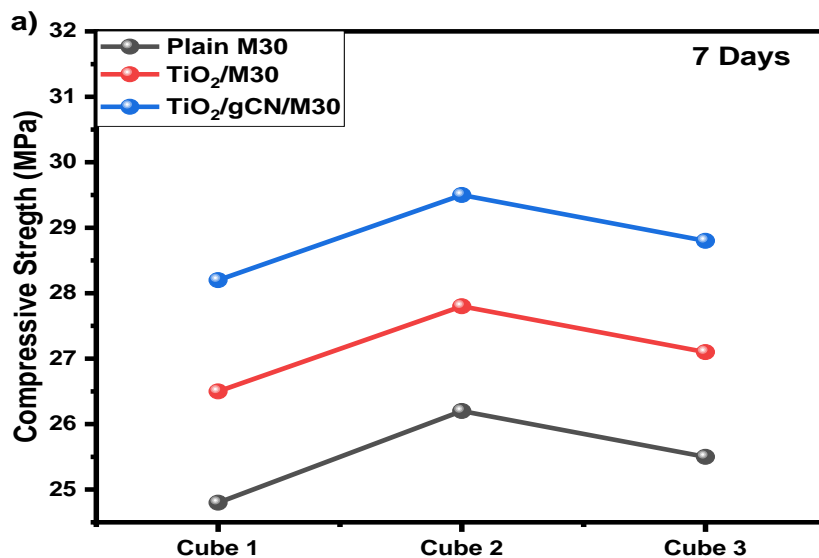
3. Results and Discussion

3.1. Compressive strength Analysis

The values of compressive strength for plain and nanomaterial modified concrete were tested after 7 days and after 28 days (Figure 1 and 2). In the case of plain M30 concrete, the recorded individual 7-day strengths were 24.82 MPa, 26.17 MPa and 25.49 MPa giving an average of 25.49 MPa whereas the 28 days strengths were 37.18 MPa, 38.63 MPa and 39.07 MPa giving an average of 38.29 MPa. The comparatively low difference between the three specimens shows that there were a consistent mix, casting, curing, and testing of the specimens. For 1% $\text{TiO}_2/\text{M30}$ concrete, the 7 days strengths of 26.47 MPa, 27.83 MPa, 27.12 MPa yielded an average of 27.14 MPa, while the 28 days strengths were 40.23 MPa, 41.47 MPa and 40.82 MPa with an average of 40.84 MPa, which is clearly higher than the control mix (plain M30 concrete). Similarly, 1% $\text{TiO}_2/\text{gCN}/\text{M30}$ concrete gave 7-day strengths of 28.23 MPa, 29.48 MPa and 28.86 MPa with the mean of 28.86 MPa and 28-day strengths of 42.83 MPa, 44.12

MPa and 43.47 MPa, respectively (with average value 43.47 MPa). The increase in compressive strength due to nano-modifications to the mixes may be attributed to the micro-filler effect and subsequent densification of the matrix, which help in ensuring improved transfer of loads and internal reduction of the internal voids, which increases the compressive capacity of the concrete [10].

The increase in compressive strength noticed in nanomaterial modified concrete in the current study agrees with the available literature. The study by He et al. [11] has shown that the addition of TiO_2 nanoparticle initially increases the strength of concrete through micro- fill ability which amounts to dense microstructure inside the concrete. They found that when 3% percent TiO_2 were added, their data showed an approximate 5% in strength and this was mainly due to the fact that the nanoparticles had been found to fill the micro-voids and enhance the packing of particles. Further improvement in strength due to the incorporation of nanomaterials have been attributed to the effect of nucleation in the hydration of cement. Visali et al. [12] found that addition of ZnO nanoparticles raised the density of concrete to a peak of 31.2 per cent of compressive strength of M25 cement after 28 days of curing. They credited this enhancement to the fact that ZnO nanoparticles acted as nucleation sites of hydration products, hence, enhancing speed in the formation of calcium silicate hydrate (C-S-H). Similarly, Heikal et al. [13] demonstrated that 1% nano- Fe_2O_3 reacts with calcium hydroxide (C-H) to produce nano-reinforced hydration products which increase the density of the microstructure and significantly enhance compressive strength. In addition, unreacted nanoparticles serve as extra nuclei of C-S-H in the formation of hydration in the pore structure. Mechanistic findings made by Sarkar et al. [14] also support the contribution of nanomaterials to the modification of microstructure of cementitious systems. In their effort, they found that the V_2O_5 addition was favorable in facilitating the formation of needle-shaped nano- scale mullite structures, which enhanced the concrete by increasing the level of micro-structural bonding and phase transformation. The nanomaterial used in the current research is different however, the nature of the concept of densifying the micro-structure and enhancing bonding within the matrix is also similar.



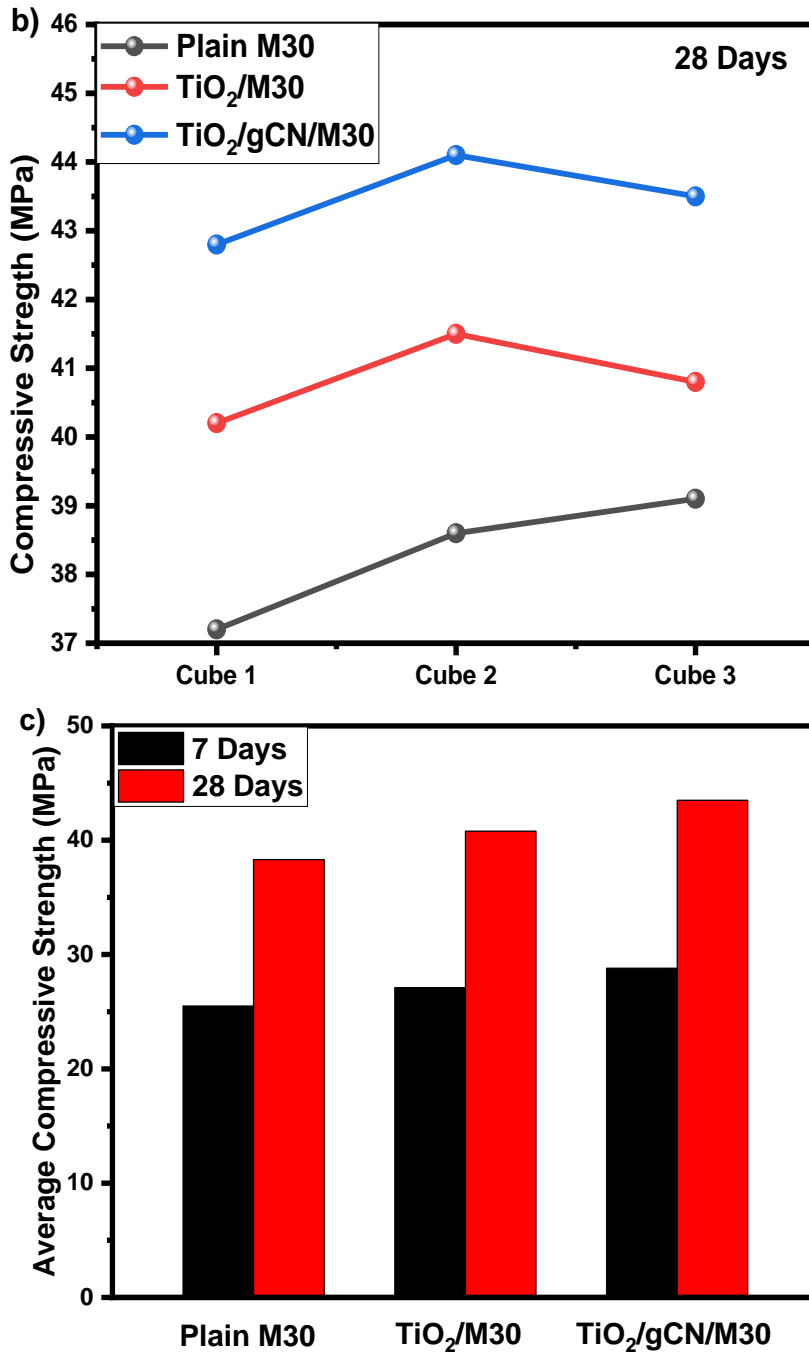


Figure 1: Comparative compressive strength results of plain M30, TiO₂/M30, and TiO₂/gCN/M30 concrete cube showing (a) 7-day curing strength, (b) 28-day curing strength, and (c) corresponding average compressive strength values.

Table 1: Comparative 7 days and 28 days compressive strength results of plain M30, TiO₂/M30, and TiO₂/gCN/M30 concrete cube.

Sr. No.	Concrete Type	7-Days Average Compressive Strength (MPa)	28-Days Average Compressive Strength (MPa)
1.	Plain M30	25.49	38.29
2.	TiO ₂ /M30	27.14	40.84
3.	TiO ₂ /gCN/M30	28.86	43.47

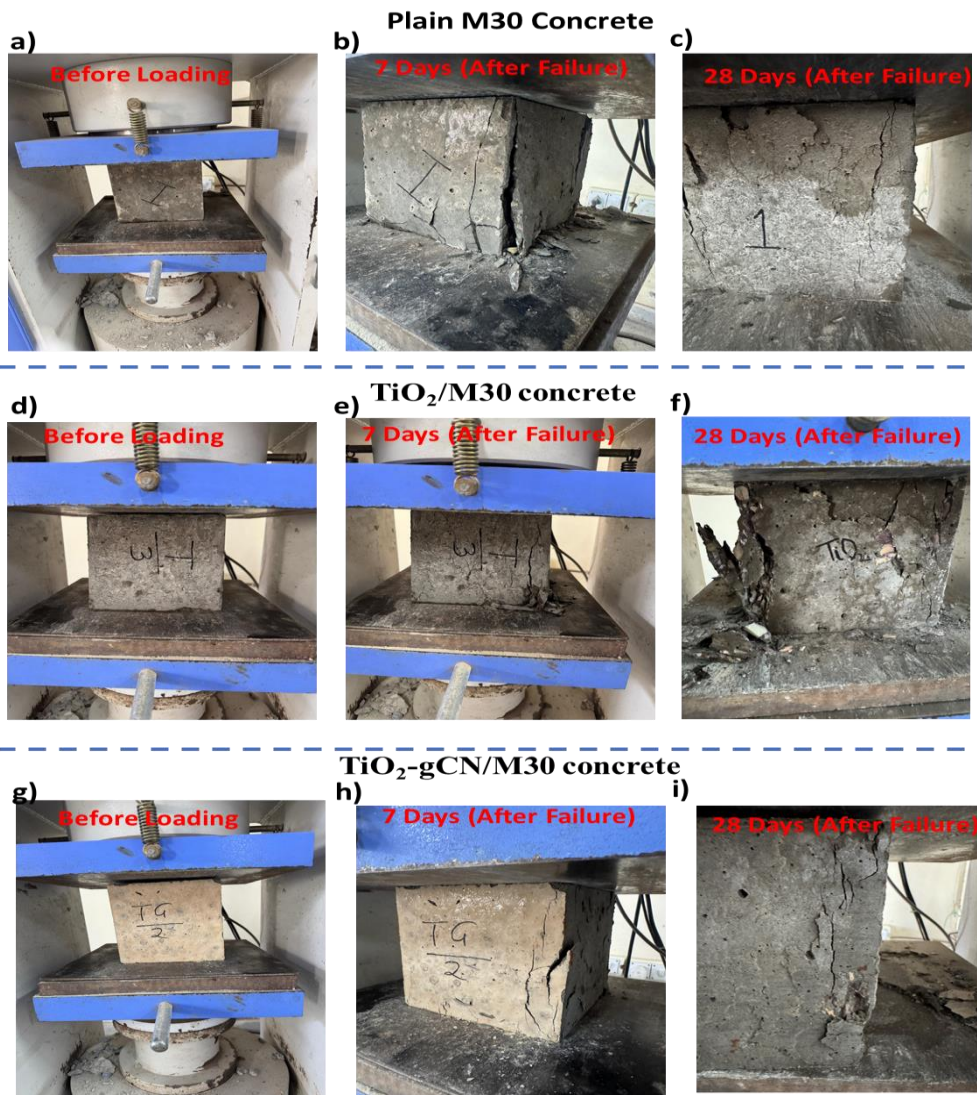


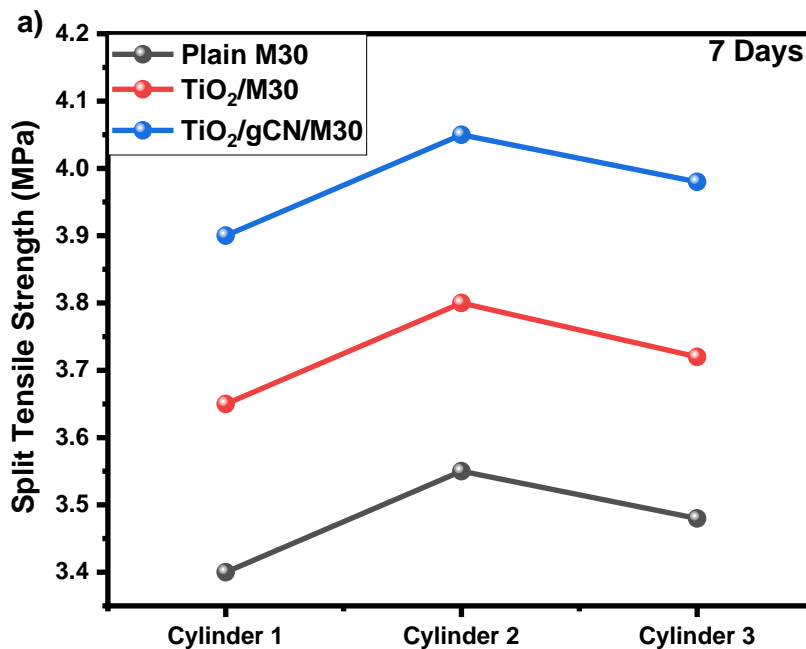
Figure 2: Photographs of concrete cube specimens (plain M30, 1 TiO₂/M30, and TiO₂/gCN/M30) before loading and after compressive strength testing for 7-day and 28-day cured specimens showing failure patterns after loading.

3.2. Split tensile Strength

The observed results of the split tensile strength show a systematic enhancement when nano-modified cement systems were incorporated, with the trend being fairly similar to that of compressive strength described above (Figure 3 and 4). The average split tensile strength of the control M30 concrete was 3.48 MPa after seven days and 4.32 MPa after 28 days. These values are consistent with the typical behavior of M30 grade concrete, where tensile strength generally lies in the range of 8 to 12 percent of the compressive strength. In the present study, the compressive strength of plain M30 concrete after 28 days was 38.29 MPa, and the corresponding split tensile strength of 4.32 MPa is approximately 11.28 percent of the compressive strength, confirming the internal consistency and reliability of the experimental results.

With the incorporation of 1% TiO₂ nanoparticles in M30 concrete, the average split tensile strength increased to 3.72 MPa at seven days and 4.47 MPa at 28 days, showing an improvement of approximately 6.90% and 3.47%, respectively, compared to the control mix. This enhancement is in agreement with the corresponding increase in compressive strength (from 38.29 MPa to 40.84 MPa at 28 days), indicating that TiO₂ nanoparticles not only improve the load-bearing capacity but also enhance resistance to crack initiation and propagation under tensile stress. This behavior can be attributed to the nucleation effect of nanoparticles, which accelerates hydration, refines the microstructure, and improves stress transfer within the cement matrix.

For TiO₂/gCN/M30 concrete, the split tensile strength was found to be 3.98 MPa at seven days and 4.62 MPa at 28 days, representing an increase of approximately 14.37% and 6.94%, respectively, compared to plain concrete. The proportional improvement in both compressive and tensile strengths suggests a synergistic effect of the hybrid nanocomposite, which enhances matrix continuity and resistance to microcrack formation. Since tensile failure in concrete is primarily governed by crack initiation and propagation, the observed improvement indicates that the TiO₂/gCN nanocomposite significantly enhances crack-bridging capability and interfacial bonding within the matrix, resulting in superior mechanical performance compared to conventional concrete.



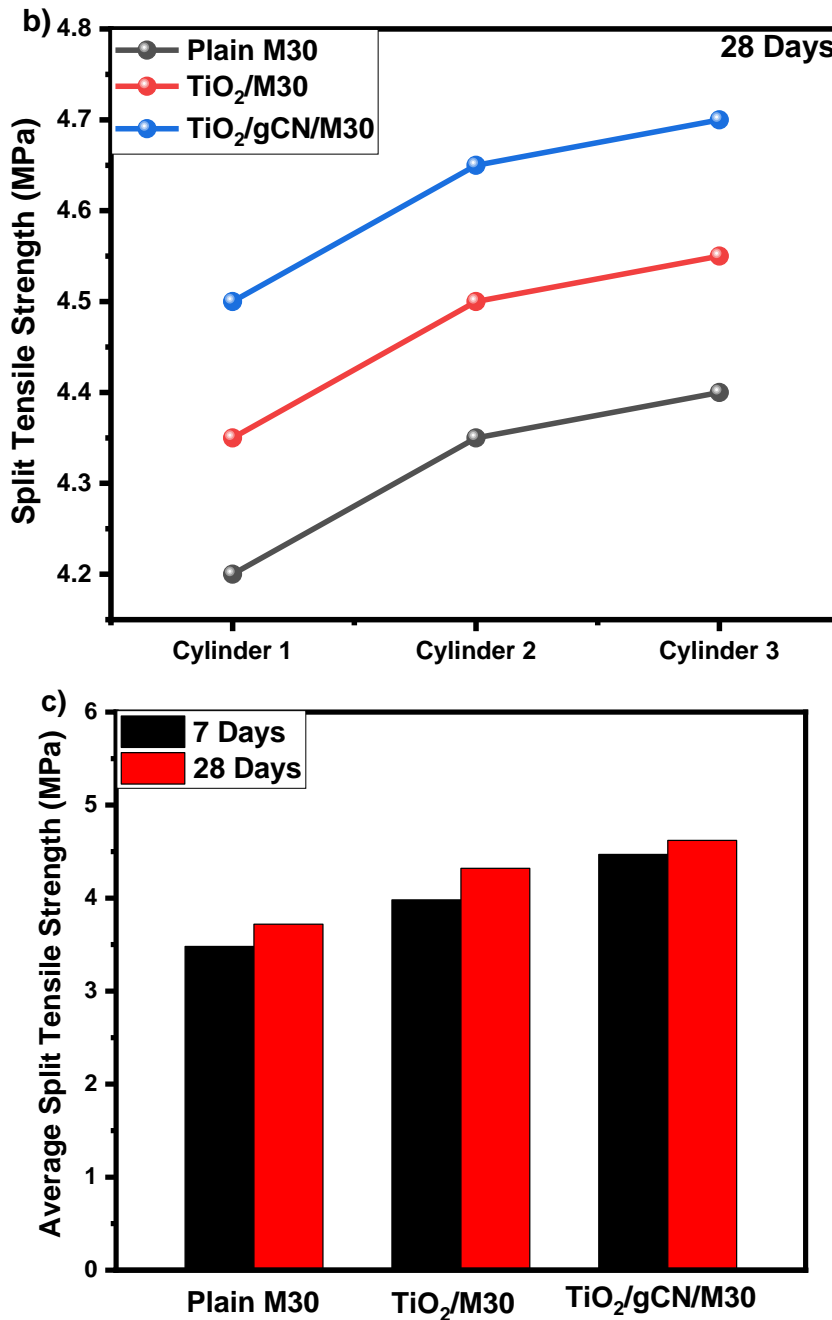


Figure 3: Comparative split tensile strength results of plain M30, TiO₂/M30, and TiO₂/gCN/M30 concrete cylinder showing (a) 7-day curing strength, (b) 28-day curing strength, and (c) corresponding average split tensile strength values.

Table 2: Comparative 7 days and 28 days split tensile strength results of plain M30, TiO₂/M30, and TiO₂/gCN/M30 concrete cube.

Sr. No.	Concrete Type	7-Days Average Split Tensile Strength (MPa)	28-Days Average Split Tensile Strength (MPa)
1.	Plain M30	3.48	4.32
2.	TiO ₂ /M30	3.72	4.47
3.	TiO ₂ /gCN/M30	3.98	4.62

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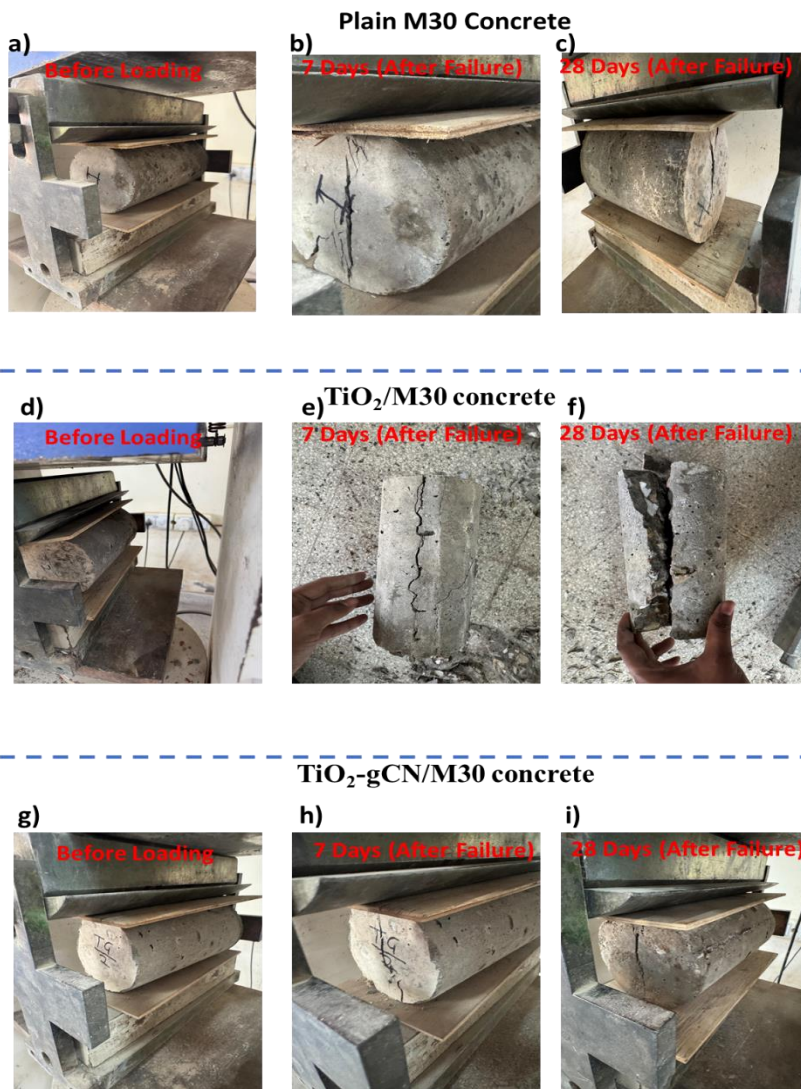


Figure 4: Photographs of concrete cylinder specimens (plain M30, TiO₂/M30, and TiO₂/gCN/M30) before loading and after split tensile strength testing for 7-day and 28-day cured specimens showing failure patterns after loading.

3.3. Flexural Strength

The flexural strength results for plain M30 concrete, TiO₂/M30 concrete, and TiO₂/gCN/M30 concrete are represented in Figure 5.

For plain M30 concrete, the 7-day flexural strengths of the three specimens were 3.80 MPa, 3.95 MPa, and 3.90 MPa, giving an average of 3.88 MPa. At 28 days, the corresponding values increased to 4.80 MPa, 5.00 MPa, and 5.10 MPa, with an average of 4.97 MPa. The 28-day flexural strength shows an improvement of approximately 28% compared to the 7-day strength, indicating normal strength gain with hydration.

For the 1% TiO₂/M30 concrete, the 7-day flexural strengths were 4.05 MPa, 4.20 MPa, and 4.12 MPa, resulting in an average of 4.12 MPa. At 28 days, the flexural strengths were 5.10 MPa, 5.30 MPa, and 5.25 MPa with an average of 5.22 MPa. Compared to plain M30, this represents an improvement of approximately 6.19% at 7 days and 5.03% at 28 days. The enhancement in flexural strength suggests improved matrix densification and better resistance to tensile stresses developed at the extreme fibre during bending.

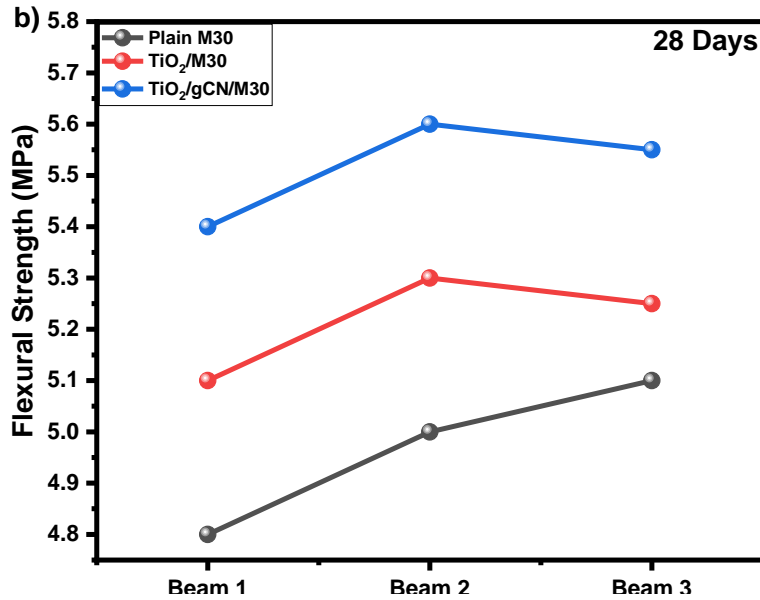
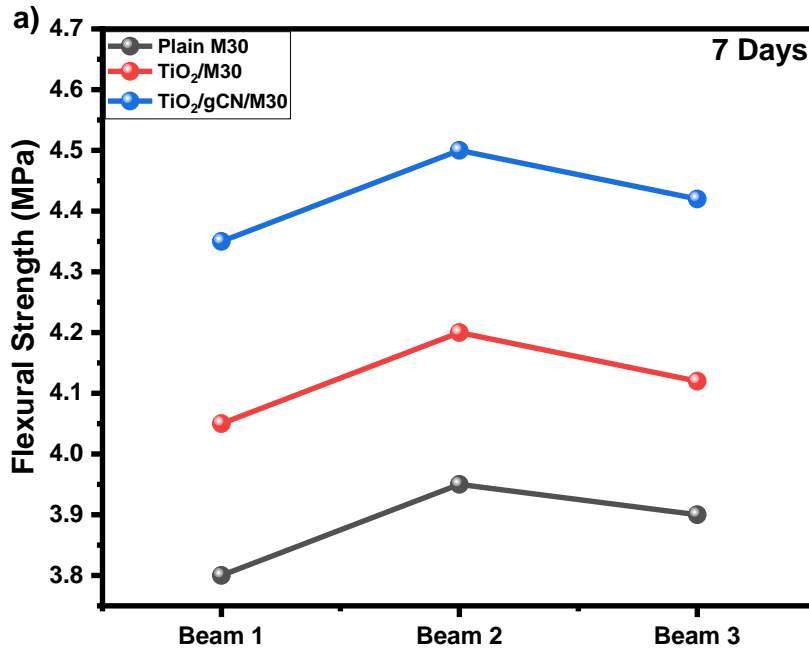
The TiO₂/gCN/M30 concrete exhibited the highest flexural performance. At 7 days, the three specimens showed flexural strengths of 4.35 MPa, 4.50 MPa, and 4.42 MPa, yielding an average of 4.42 MPa. At 28 days, the values further increased to 5.40 MPa, 5.60 MPa, and 5.55 MPa, with an average of 5.52 MPa. The improvement over plain M30 at 7 days is approximately 13.92% and at 28 days is approximately 11.07%. Since flexural strength is governed primarily by tensile crack initiation and propagation, the higher values indicate enhanced crack resistance and improved stress transfer within the cement matrix due to the hybrid nano-modification.

These results are in agreement with other studies that had been conducted about nano-modified cementitious materials. Janus et al. [15] have demonstrated that the incorporation of 1 % nano-TiO₂ produces the highest flexural strength of the compositions considered (1%, 3%, and 5%), thus justifying the assumption that low concentrations of nanoparticles present beneficial refinements to cement composites microstructure. However, a further increase in TiO₂ dose after this level gives rise to nanoparticle agglomeration, which causes an unevenly distributed microstructure and subsequent reduction in flexural strength. In another study, Francoso et al. [16] investigated the effect curing temperature on flexural strength of 1% TiO₂ incorporated concrete, it was found that, at higher curing temperatures of 45°C, flexural strength exhibited a significantly decline by 12%, whereas, at lower curing temperatures of 5°C the flexural strength increases crease. The positive effect of TiO₂ on flexural strength was further enhanced at the ambient curing temperature of 20°C. Further in a research conducted by Visali et al. [12] they reported that the addition of ZnO nanoparticles increased flexural strength of the concrete by 2.8 MPa to about 5.0 MPa after 28 days cure depending on the increment in the ZnO content (3 0.5) to 7 0.5). All these observations support the positive contribution of nano-scale additives to cementitious matrices in strengthening the crack resistance and the overall strength of cementitious matrices.

For a span length of 400 mm under third-point loading, the middle third region extends from 133 mm to 267 mm from the support. After 7 days curing the TiO₂-M30 concrete shows type A failure with crack distance of 170 mm from nearest point. Whereas, both plain M30 concrete as well as TiO₂/gCN M30 concrete shows type B failure with the crack distance of 130-140 mm from the nearest point. After 28 days curing, all the specimen i.e. pure M30 concrete, TiO₂/M30 concrete, and TiO₂/gCN M30 concrete shows failure within this middle third at a distance of approx.170 mm, indicating Type A failure as per IS 516: 2021 (Figure 6). This shift toward a more central fracture location suggests improved stress distribution, enhanced tensile resistance, and better crack-bridging behavior due to the synergistic effect of TiO₂ and graphitic carbon nitride. The nanocomposite likely contributed to matrix densification and stronger interfacial bonding, resulting in a more homogeneous structure and a more ideal flexural crack pattern under bending [17].

The results of flexural strength, directly correlates with compressive and split tensile strength results discussed above. In all the samples, plain M30 concrete exhibited the poor mechanical performance, TiO₂/M30 concrete showed an average increase, and TiO₂/gCN/M30 concrete showed the highest strength. Thus the overall results suggests that the addition of nanomaterials not only increases tensile-based traits and crack resilience, but also compressive load-bearing capacity. The similar

improvement of the three mechanical parameters indicates that there is a total improvement of matrix integrity and internal bonding in the nano-modified concretes.



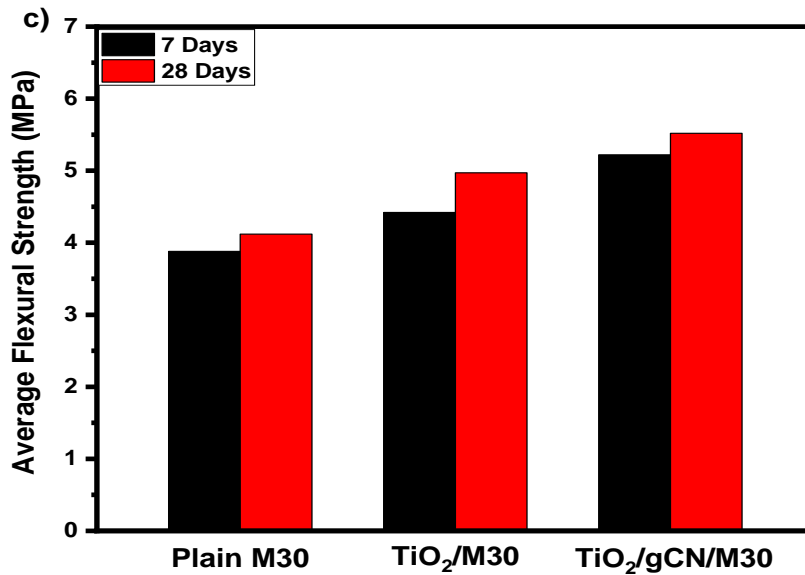


Figure 5: Comparative flexural strength results of plain M30, TiO₂/M30, and TiO₂/gCN/M30 concrete beams showing (a) 7-day curing strength, (b) 28-day curing strength, and (c) corresponding average flexural strength values.

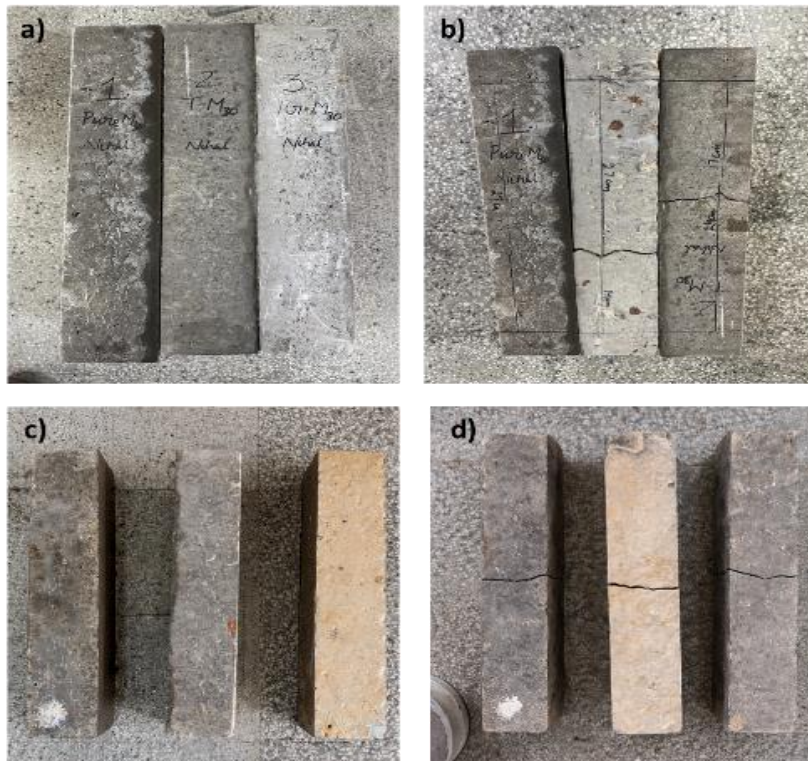


Figure 6: Photographs of concrete beam specimens (plain M30, TiO₂/M30, and TiO₂/gCN/M30) before loading and after flexural strength testing for 7-day and 28-day cured specimens showing failure patterns after loading.

Table 3: Comparative 7 days and 28 days flexural strength results of plain M30, TiO₂/M30, and TiO₂/gCN/M30 concrete cube.

Sr. No.	Concrete Type	7-Days Average Flexural Strength (MPa)	Type of Failure	28-Days Average Flexural Strength (MPa)	Type of Failure
1.	Plain M30	3.88	Type B	4.97	Type A
2.	TiO ₂ /M30	4.12	Type A	5.22	Type A
3.	TiO ₂ /gCN/M30	4.42	Type B	5.52	Type A

4. Conclusion

This study involved evaluating mechanical properties, including compressive strength, split tensile strength, and flexural strength. The results demonstrated consistent improvement with the incorporation of nanomaterials. The TiO₂/gCN/M30 concrete showed an increase of approximately 13.22% at 7 days and 13.53% at 28 days in compressive strength compared to plain M30 concrete. Similarly, split tensile strength improved by about 14.37% at 7 days and 6.94% at 28 days, while flexural strength increased by approximately 13.92% at 7 days and 11.07% at 28 days. These enhancements are attributed to improved particle packing, pore refinement, accelerated hydration, and strengthening of the interfacial transition zone. Additionally, improved flexural failure behavior indicated enhanced crack resistance and better stress distribution in nanomodified concrete. Overall, the results highlight that The incorporation of TiO₂ and TiO₂/gCN nanomaterials significantly enhances mechanical properties of M30 concrete. TiO₂/gCN showed maximum improvement in compressive, tensile, and flexural strength, making it suitable for advanced construction applications.

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