

IMPACT OF NANOPARTICLES AND STEEL FIBERS ON THE MECHANICAL PROPERTIES OF CONCRETE BEAMS: AN EXPERIMENTAL STUDY

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Highlights:

- the proposed work establishes the impact of incorporating nanoparticles and fibers into concrete beams on density, compressive strength, tensile strength, modulus of elasticity, flexural strength, and shear strength;
- this work assesses the effect of nanoparticles on density, finding that it remains unaffected; note that compressive strength increases only with SiO₂ in the 350 series;
- this work evaluates the influence of nanoparticles on tensile strength, observing an increase in the 550 series and a decrease in the 350 series;
- this work investigates changes in the modulus of elasticity, noting improvements in mixtures without steel fibers but no strong correlation with compressive strength;
- this work analyzes the effect of Al₂O₃ on flexural strength, showing minor improvements but decreased residual strengths;
- this work examines shear strength changes, with slight improvements from nanoparticles in the 550 series; note strength losses with the combination of steel fibers and Al₂O₃;
- this work conducts flexural tests to determine the impact of nanoparticles, revealing minimal strength gains and no significant changes in failure modes or cracking patterns.

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Abstract. This study examines the combined effects of nanoparticles (SiO₂ and Al₂O₃) and steel fibers on the mechanical and flexural performance of concrete beams with binder contents of 350 and 550 kg/m³. Eight mixtures were tested following IS and RILEM standards. Nanoparticles showed minimal influence on density but affected strength and deformation. SiO₂ increased compressive strength by 16% in the 350 series, while Al₂O₃ improved flexural strength by about 4%. In the 550 series, only slight gains in strength and stiffness were observed, with maximum loads between 233–240 kN and moments of 78.7–81.0 kN·m. Steel fibers (0.5%) enhanced ductility, raising maximum deflection to 31.5 mm compared to 9–14 mm in non-fibered beams. Stiffness ratios (E_{III}, theo/E_{III}, exp) ranged from 0.78–1.70, confirming model reliability. Overall, Al₂O₃ improved stiffness, SiO₂ enhanced ductility, and fibers increased post-cracking resistance, demonstrating the potential of combined nanomaterial-fiber reinforcement for improving concrete performance.

Keywords: nanoparticles, fibers, concrete beams, density, compressive strength, tensile strength, modulus of elasticity.

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1. Introduction

Among various construction materials, concrete is the most preferred construction material owing to its high compressive strength, durability, availability, and ease in formation to any shape. Yet ordinary concrete is still subject to cracking in tension, brittle behaviour after cracking, environmental damage, and loss of stiffness over time. As a result, recent studies have concentrated on the enhancement of cementitious matrices via fibres, mineral admixtures, recycled components and nanomaterials to enhance

their mechanical behavior, crack resistance, durability and functional performance (Jha et al., 2024; Kumar et al., 2024; Sharma et al., 2022).

Since discrete fibres are able to bridge cracks, they play an important role in fibre reinforcement, they also assist in re-distributing tensile stresses, slowing down crack expansion, and enhancement of post cracking energy absorption. Sharma et al. (2022) have reviewed the synergistic effect of mineral admixtures and fibres on ultra-high-performance concrete and reported that the engineering properties are greatly influenced by fibre

characteristics, matrix composition and interfacial properties. Singh et al. (2023) carried out studies on Nylon 6 fibre reinforced pavement cements concretes, establishing the significance of synthetic fibres for cementitious material strength. Along the same lines, Kumar et al. (2024) studied rice-husk ash – recycled aggregates based fibre reinforced concrete, the study brings out the synergistic impact of fibre reinforcement and eco-friendly materials in mitigating strength and deformability.

On the structural level, the enhanced flexural behavior of RC beams is achieved through efficient control of cracking and stress sharing in the cracked state. Al-Saidy et al. (2023) have studied reasonable strengthening techniques for reinforced concrete beams with textile-reinforced mortars and confirmed the significance of external reinforcement methods to raise the beam-level flexural performance. While textile-reinforced mortar is not the same as dispersed steel-fibre reinforcement, the paper verifies that increased tensile reinforcement and better interfacial stress transfer among materials can largely affect cracking, load carrying capacity, and deformation. These processes can be applied directly to the formation of concrete beams with internal fibre reinforcement.

Durability is also a concern because degradation in structural performance may be due to cracking and environmental exposure. Chen et al. (2024) Have investigated the macro-polypropylene-fibre-reinforced self-compacting concrete (MPSCC) in a series of deteriorative tests and highlighted the significance of fibre-modified matrices in application to durability-related practices. Li et al. (2024) studied the microstructural damage and macroscopic mechanical degradation of cement paste in freeze-thaw cycling and how internal cracking can degrade tensile strength and elastic modulus. These results indicate that concrete modification should be assessed not only with respect to peak strength but also with respect to damage evolution, crack growth, stiffness degradation, and resistance to environmental actions.

Supplementary cement-based materials and alternative binders play also a role in matrix densification and mechanical properties. Jha et al. (2024) studied the performance of fly ash and ground-granulated blast-furnace-slag-engine green concrete and analysed their influences on compressive, flexural, splitting tensile strengths. Zhang et al. (2025) studied the preparation and cementitious property of magnesium silicate hydrate and calcium silicate hydrate using coal gangue as raw material, focusing on the relation between hydrate formation, the microstructure, and the mechanical performance. The results suggest that alterations in the binder chemistry and hydration products can lead to changes in pore structure, interfacial quality and stress transfer capacity.

In parallel, advances in nanotechnology have further broadened the approaches to tailor cementitious materials. Nanomodification has effect on nucleation, hydration, pore refinement, interfacial bonding, cracking/bonding behaviour, crack initiation and transport. Jin et al. (2023)

fabricated a nanomodified self-healing mortar and integrated it with semantic-segmentation-based crack detection, substantiating the significance of nanoscale modification for crack detection and repair-centric cementitious materials. They also highlight the increasing importance of quantitatively tracking crack formation and recovery, rather than solely depend on conventional strength measurements.

Graphene quantum dots and carbon quantum dots are becoming novel nanoscopic modifiers for cement based materials. Win et al. (2024a), among others, studied the chemophysical mechanisms of high-strength cement composites with a graphene quantum-dot suprastructure and related their performances in nucleation, nanoscale reinforcement, microstructural refinement, and stress transfer. In a similar study, Win et al. (2024b) studied the impact of graphene quantum dots on the thermal and mechanical properties of semiconductors cement composites, focusing on dispersion and interfacial interaction. Prasittisopin et al. (2025) later reviewed the forefront research on carbon quantum dots for building materials and their prospective impacts in mechanical performance, durability, sensing, and multifunctionality.

Advanced fiber-reinforced systems have also been developed to perform other functions rather than general strengthening. Liu et al. (2024) studied an economical self-sensing ultra-high-performance fibre-reinforced concrete with steel slags. Their work demonstrates that fibre networks and conductive or reactive phases may be integrated to produce mechanically enhanced, damage-sensitive materials. Meanwhile, the simulation results of high-performance concrete by using optimized neural-network methods were presented by Wang and Cong (2024), indicating the significance of considering the complex interactions among constituents of the mixture to predict the strength and workability. Yadav et al. (2023) also proved that biological alteration and supplementary cementitious materials affect the compressive and split tensile strengths of concrete, which further elaborates on current strategies available to enhance concrete content.

In general, the studies reviewed prove that fibres, SCMs, nanoscale additives, recycled materials, and high-performance systems can influence the mechanical, durability and cracking response of concrete. Nonetheless, the quoted references concerned textile reinforcement, synthetic-fibre concrete, green binders, self-healing mortar, quantum-dot-based composites, environmental degradation and predictive modelling, each as an individual research theme. However, a similarly detailed comparison of SiO_2 - and Al_2O_3 -based concretes, with and without steel fibres at the beam level is still missing in the literature. Consequently, in this work, an experimental investigation is carried out to study the effect of these nanoparticles and steel fibres on density, compressive strength, tensile strength, modulus of elasticity, flexure strength, stiffness, ductility, and cracking patterns of concrete beams with two different binder contents.

2. Materials and methods

2.1. Materials

2.1.1. Cement

Ordinary Portland Cement (OPC) grade 53 complying with IS 269:2015 (Bureau of Indian Standards, 2015) and IS 4031:1999 (Bureau of Indian Standards, 1999a) was used in all the mixtures. Before use, its specific gravity, softness, setting time, and compressive strength were tested to ensure it met standards. The cement was supplied by UltraTech Cement LLC.

2.1.2. Aggregates

River sand classified as zone II according to IS 383:2016 (Bureau of Indian Standards, 2016) was used as fine aggregate. Its modulus of softness and water absorption capacity were studied before mixing. According to IS 2386 (Bureau of Indian Standards, 1963), crushed granite with a size of 6–14 mm was used as the coarse aggregate. Fine aggregates and coarse aggregates were characterized for specific gravity, impact load and compressive strength to verify their suitability for structural applications.

2.1.3. Nanoparticles

Al₂O₃ with medium particle size less than 100 nm and large surface area was used as nanomaterials. Both types of nanoparticles were prepared by AdNano Technologies Pvt. Ltd., Bangalore. Their purity, particle size distribution, and dispersion quality were characterized to ensure uniform performance in concrete mixtures.

2.1.4. Fibers

Fibers (Sika Fiber Force-60), Sika India, Mumbai, complying with ASTM A820 were incorporated into the selected blends. Fibers were added at a rate of 39.3 kg/m³ (equivalent to 0.5%) to improve the post-cracking behavior in ac-

cordance with RILEM TS 162-TDF recommendations. Their physical properties, including their length, diameter, lateral ratio, and tensile strength, were checked before use.

2.1.5. Mixtures

A High-Reducing Water-Reducing Admixture (HRWRA), Glenium SKY 526, BASF India Ltd., was used in various proportions ranging from 0.9–2.7 kg/m³ depending on the admixtures in each admixture. This was to improve performance and at the same time reduce the water requirement in high-quality concrete mixes.

2.1.6. Water

Drinking water was used for mixing and coating according to IS 456:2000 (Bureau of Indian Standards, 2000). To determine whether the water is suitable for concrete preparation, the water was tested for pH, chloride content, and Total Dissolved Solids (TDS).

2.2. Concrete mix design

Eight concrete mixtures were prepared with varying binder contents, nanoparticle additions, and steel fibers, as summarized in Table 1. Detailed mixing ratios for binder contents of 350 kg/m³ and 550 kg/m³ are presented in Table 2.

Eight concrete mixes were prepared as shown in Tables 1–2. All the mixtures were compacted evenly to achieve a total volume of about 1 m³, varying the amount of fine sand and medium sand slightly to ensure consistency. The moisture content of the cement paste was controlled to 20 L/m³, and the ratio of water to binder was calculated, including the contribution of nanoparticles to the binder.

2.3. Specimen preparation

Concrete specimens were cast in different shapes and sizes to evaluate various mechanical properties. For compres-

Table 1. Composition of concretes

Constituent	Name	I Mass (kg) / Vol. (L)	II Mass (kg) / Vol. (L)	III Mass (kg) / Vol. (L)	IV Mass (kg) / Vol. (L)	V Mass (kg) / Vol. (L)	VI Mass (kg) / Vol. (L)	VII Mass (kg) / Vol. (L)	VIII Mass (kg) / Vol. (L)
Cement	OPC 53 Grade	230 / 74	223 / 71	223 / 71	350 / 112	343 / 110	343 / 110	350 / 112	343 / 110
Admixtures	Limestone filler	120 / 44	120 / 44	120 / 44	—	—	—	—	—
	SiO ₂	—	7 / 3	—	—	7 / 3	—	—	—
	Al ₂ O ₃	—	—	7 / 2	—	—	7 / 2	—	7 / 1.8
Aggregates (Fines)	Fine Sand 0/1	227 / 86	228 / 87	229 / 87	239 / 91	238 / 91	240 / 91	239 / 91	240 / 91
	Medium Sand 0/4	681 / 259	684 / 260	688 / 261	718 / 273	715 / 272	719 / 273	718 / 273	719 / 273
Coarse Aggregates	Sand 4/8	187 / 71	188 / 71	188 / 71	190 / 72	190 / 72	190 / 72	190 / 72	190 / 72
	Gravel 6/14	755 / 284	760 / 286	759 / 285	770 / 289	769 / 289	770 / 289	770 / 289	770 / 289
Adjuvant	Glenium SKY 526	0.9 / 0.9	0.9 / 0.8	0.9 / 0.8	2.1 / 2.0	2.7 / 2.6	2.4 / 2.3	2.1 / 2.0	2.1 / 1.9
Water	Effective	161 / 161	156 / 156	156 / 156	140 / 140	140 / 140	140 / 140	140 / 140	140 / 140
	Absorption	—	—	—	—	—	—	—	—
Air content of paste/ Entrapped air	Air	— / 20	— / 20	— / 20	— / 20	— / 20	— / 20	— / 20	— / 20
Fibers	Sika Fiber	—	—	—	—	—	—	39.3 / —	39.3 / —

Table 2. Water/binder ratio for all concrete mixtures

Beam	Cement (kg)	Silica (SiO ₂) (kg)	Alumina (Al ₂ O ₃) (kg)	Total Binder (kg)	Water (kg)	Water/binder ratio (w/b)
I	230.0	0	0	230.0	161.0	0.70
II	223.0	7.0	0	230.0	156.0	0.68
III	223.0	0	7.0	230.0	156.0	0.68
IV	350.0	0	0	350.0	140.0	0.40
V	343.0	7.0	0	350.0	140.0	0.40
VI	343.0	0	7.0	350.0	140.0	0.40
VII	350.0	0	0	350.0	140.0	0.40
VIII	343.0	0	7.0	350.0	140.0	0.40

sive strength testing, 150 × 150 × 150 mm cubes were prepared, while for split tensile strength testing, 150 × 300 mm cylinders were cast. For flexural strength, small-scale beams of 100 × 100 × 500 mm were used, and structural-scale reinforced concrete beams of 150 × 300 × 1200 mm were prepared with 12 mm tensile bars, 10 mm compression bars, and 8 mm stirrups placed at 100 mm center-to-center spacing and Fe500 reinforcement with 25 mm casing. All specimens were subjected to proper casting, vibration, and curing in water for 28 days before testing.

2.4. Testing methods

2.4.1. Fresh properties

The properties of concrete mixtures were evaluated using slump test as per IS 1199:2018 (Bureau of Indian Standards, 2018) to measure workability, while air content was determined by compression method.

2.4.2. Mechanical properties

The hardened properties were evaluated through a series of standardized tests. Compressive strength was determined at 7 and 28 days following IS 516:2021 (Bureau of Indian Standards, 2021) while split tensile strength was measured as per IS 5816:1999 (Bureau of Indian Standards, 1999b). The modulus of elasticity was obtained from the stress-strain curve under compression as per IS 516:2021 (Bureau of Indian Standards, 2021). The flexural strength was evaluated using the third-point loading method as specified in IS 516:2021 (Bureau of Indian Standards, 2021), and the fracture energy was calculated from the load-CMOD curves following the recommendations of RILEM TC 50-FMC.

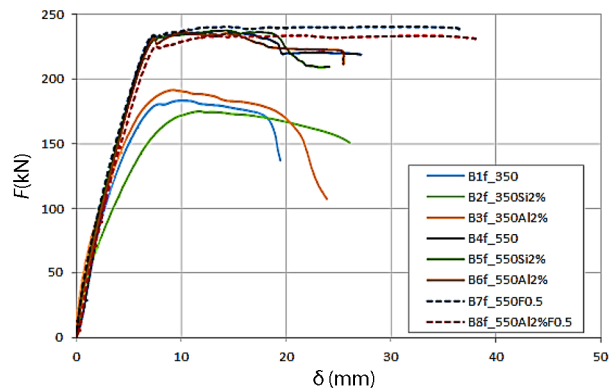
2.4.3. Beam flexural tests

The structural-scale beams were tested under displacement-controlled loading at a rate of 0.1 mm/min, with a support spacing of 400 mm and a load applied at the third points. Linear Variable Differential Transducers (LVDTs) were used to measure the deflection, while CMOD measurements were used to monitor the crack opening displacement. The resulting load-deflection curves were analyzed to determine the modulus of rupture, stiffness, and residual strength of the beams.

3. Analysis of flexural behavior

3.1. Load-displacement relationship

The first part of the flexural behavior analysis focuses on the relationship between load (F) and displacement (δ). Experimental F - δ diagrams were generated for each of the eight beams tested in bending. These curves were obtained similarly to the shear tests, with F measured by a load cell in the actuator and δ recorded by an LVDT positioned at the beam's mid-span, directly under the load application point. The results are presented in Figure 1, which aims to facilitate the analysis of how the deflections of the beams evolved as a function of the imposed load.

**Figure 1.** Load-displacement diagrams of the beams in the bending test

The bending tests use a monotonic, displacement-controlled loading scheme. The load is applied in steps using a servohydraulic device until failure. At each step, the corresponding load and average deflection are recorded by a load cell and a linear displacement transducer (LVDT). The load is gradually increased to allow for more detailed observation of the beam response, especially in terms of fracture and stiffness reduction.

Typically, the initial load is applied in small increments (e.g., 5 kN or less) to delay the onset of fracture (transition from state I to state II). As the test progresses and stiffness decreases, the load increments need to be adjusted to control the deflection measurement and avoid sudden failure. Small increments or continuous monitoring

of displacement near the ultimate load ($F_{\max}$) ensure accurate measurement of shear stress and post-load ductility, especially for high-value fiber-reinforced beams.

Deformation measurements at different levels (e.g., 25%, 50%, 75%, and 100% $F_{\max}$) are used to generate stiffness and crack evolution plots (Figures 2–4), and time-curvature curves are obtained by applying torcost displacement and duogonist.

Table 3 presents the values for the maximum load ($F_{\max}$) and maximum displacement ($\delta_{\max}$) for the eight beams in the bending test. In this work, $F_{\max}$ was considered as the maximum supported force value.

Table 3. Load and deflection values of the bending test

Beam	$f_{cm,cyl}$ (MPa)	$F_{\max}$ (kN)	$\delta_{\max}$ (mm)
B1f_350	32.1	182.78	10.00
B2f_II%	34.6	174.44	11.70
B3f_III%	32.1	190.97	9.25
B4f_550	59.3	235.48	11.56
B5f_V%	59.3	236.95	14.27
B6f_VI%	58.2	236.34	10.29
B7f_VII	63.2	239.94	31.50
B8f_VIII	62.8	233.10	21.58

To evaluate the compressive strength of each concrete mix, three standard cylindrical specimens (150 mm diameter $\times$ 300 mm height) were tested for each mix

as per IS 516:2021 (Bureau of Indian Standards, 2021) guidelines. The reported compressive strength values ($f_{cm,cyl}$) represent the average of the results of three tests performed after 28 days under standard conditions.

The standard deviation of each of the three samples was calculated to evaluate the variability of the results. The standard deviation for all mixtures ranged from 1.2 to 2.4 MPa, indicating good consistency and quality control during mixing, casting, and curing. These compressive strength values can be used for visual analysis and to calculate theoretical flexural parameters such as moments of resistance.

The analysis of the F - δ diagrams reveals three phases: State I, with a steep, straight ascent indicating no cracking; State II, a less steep rise showing concrete cracking; and State III, nearly horizontal with significant crack development and minimal load variation. Findings include higher maximum bending forces ($F_{\max}$) in the 550 series, with the B8f_VIII beam showing the lowest force. In the 350 series, 2% Al_2O_3 nanoparticles improve $F_{\max}$ significantly. Nanoparticles have minimal effect on the 550 series, with some benefits from Al_2O_3 in the 350 series. Deformation plots at various load levels are shown in Figures 2–3, with slight deviations possible.

The Figure 3 show that the beams with fibers present the greatest maximum deformation, while the B3f_III% beam presents the smallest. It is also noticeable that the most significant variation in deformation occurs after the application of at least 75% of the load, which may be

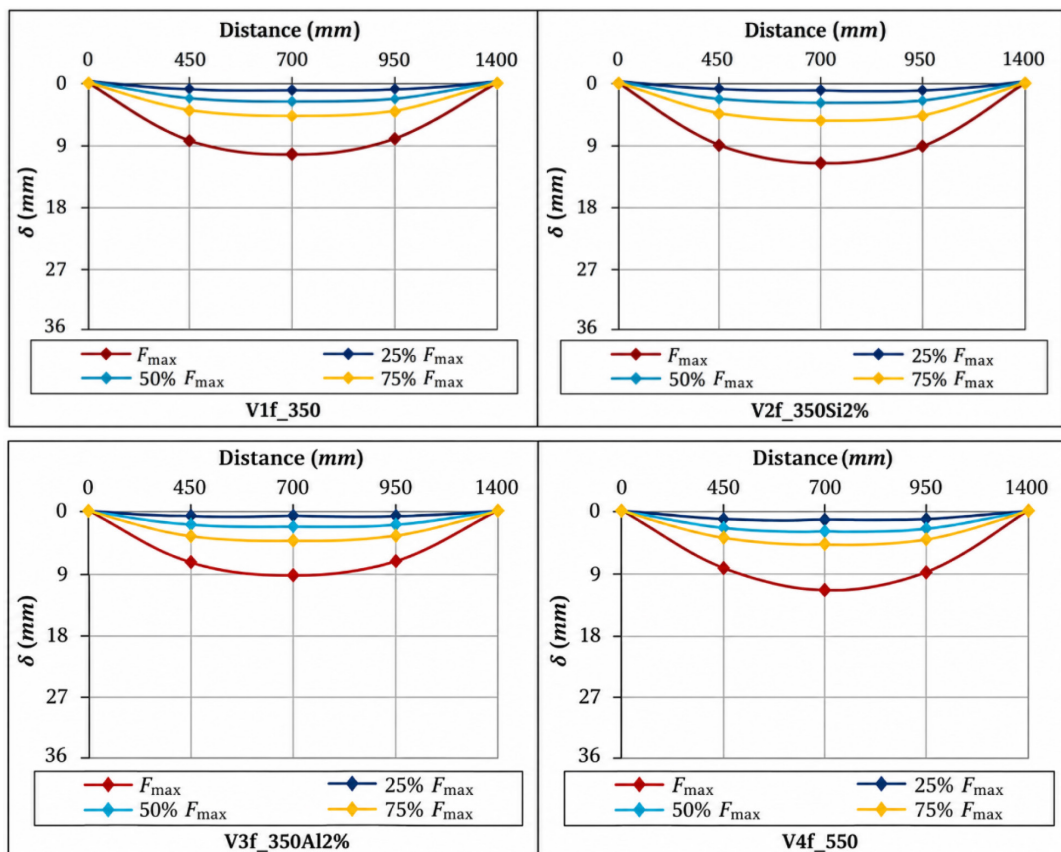


Figure 2. Evolution of the deformation of the beams tested for bending

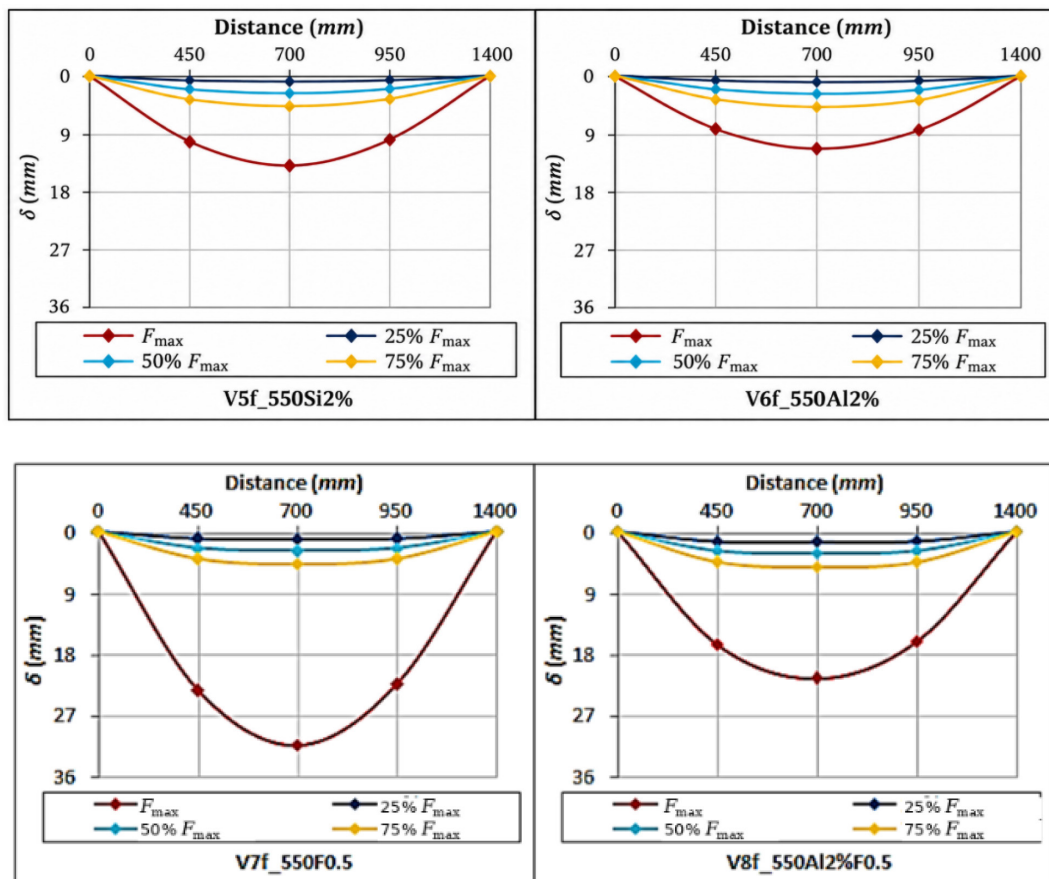


Figure 3. Evolution of the deformation of the beams tested for bending

related to losses in stiffness caused by the existence of a more pronounced cracking.

Since the deformations take into account the maximum force detected in the beams, and since this varies from beam to beam, it was also decided to make a comparison between the series, for a common load value. As such, the value of 150 kN was chosen to compare the deflection in the different beams (Figure 4).

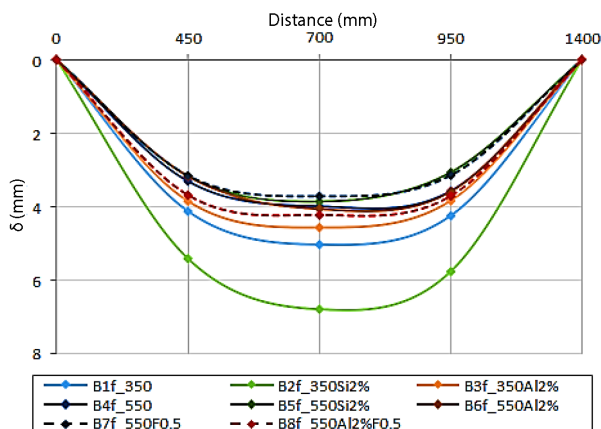


Figure 4. Deformation of the bending test beams – $F = 150$ kN

For the same force stage, the beams B3f_III%, B5f_V% and B7f_VII are those that present the lowest deformation

for the 350, 550 without fibres and 550 with fibres series, respectively. In addition, there does not appear to be a clearly beneficial trend with the incorporation of nanoparticles (considering both series). This analysis provides indications about the stiffness of the beams, which will be analysed below, with which a comparison should be made.

3.2. Analysis of moment values

Among the most essential parameters to be analysed are the moments associated with the structural behaviour of the beams: the maximum (experimental) moment and the theoretical (or design) moment. It is also relevant to study the relationship between the moment values and other parameters (e.g., curvature values).

In an initial phase, the theoretical values of the resistant moments (M_{theo}) in the bending test beams were assessed to predict experimental values and compare them later. The design value of the resistant moment (M_{theo}) for beams without fibers was determined using an equivalent rectangular distribution of compression stresses, as recommended in IS 456: 2000 (Bureau of Indian Standards, 2000). For beams with fibers, M_{theo} included the additional contribution of tensile force from the fibers, following the RILEM TC 162-TDF recommendation. Table 4 shows the theoretical moments for all beams, highlighting that a 11–18% increase in moment was expected when

transitioning from the 350 to 550 series. Nanoparticles had varying effects, reducing flexural strength in the 350 series but not affecting the 550 series significantly.

The experimental maximum moment (M_{max}) was determined based on F_{max} values from the tests (Table 5). In the 350 series, the addition of Al_2O_3 nanoparticles increased strength by 4%, while SiO_2 nanoparticles reduced it by 5%, with no nanoparticle benefit observed in the 550 series. The ratio of theoretical to experimental moments (M_{theo}/M_{max}) showed better approximation in flexural strength predictions than in shear force, with most theoretical values being lower than experimental ones (Table 6). Finally, the moment-curvature relationship, calculated through horizontal displacement transducers, showed that beams from the 550 series displayed greater curvature than those from the 350 series, aligning with expectations based on the behavior observed in $F-\delta$ curves.

Table 4. Theoretical moment values

Beam	$f_{cm,cyl}$ (MPa)	x (m)	M_{theo} (kN.m)	$M_{theo} / M_{theo,ref}$	
				Series 350	Series 550
B1f_350	32.1	0.1214	61.64	1.00	–
B2f_II%	34.6	0.1123	60.76	0.99	–
B3f_III%	32.1	0.1203	58.45	0.95	–
B4f_550	59.3	0.0737	69.18	–	1.00
B5f_V%	59.3	0.0714	67.20	–	0.97
B6f_VI%	58.2	0.0737	69.12	–	1.00
B7f_VII	63.2	0.0744	70.32	–	1.02
B8f_VIII	62.8	0.0745	70.34	–	1.02

Where x represents the depth of the neutral axis to the top of the section, which is the equilibrium strain obtained from the material strength and reinforcement strain measurements.

Table 5. Experimental moment values

Beam	$f_{cm,cyl}$ (MPa)	M_{max} (kN.m)	$M_{max} / M_{max,ref}$	
			Series 350	Series 550
B1f_350	32.1	61.69	1.00	–
B2f_II%	34.6	58.87	0.95	–
B3f_III%	32.1	64.45	1.04	–
B4f_550	59.3	79.48	–	1.00
B5f_V%	59.3	79.97	–	1.01
B6f_VI%	58.2	79.77	–	1.00
B7f_VII	63.2	80.98	–	1.02
B8f_VIII	62.8	78.67	–	0.99

Although beams B1f and B3f have similar compressive strength ($f_{cm,cyl} = 32.1$ MPa), they exhibit different behaviors during bending. Beam B1f breaks at a lower load of 182.78 kN, while B3f remains stable at a higher load of 190.97 kN, indicating that factors other than compressive strength affect the bending behavior. The improved

performance of B3f is attributed to the addition of 2% Al_2O_3 nanoparticles, which refines the microstructure, improves the ITZ, and enhances the tensile properties of the concrete matrix. These improvements contribute to increased crack resistance and improved stress redistribution after cracking, explaining the higher bending capacity of B3f.

Table 6. Relationship between theoretical and experimental values of the moment

Beam	M_{theo} / M_{max}
B1f_350	1.00
B2f_II%	1.03
B3f_III%	0.91
B4f_550	0.87
B5f_V%	0.84
B6f_VI%	0.87
B7f_VII	0.87
B8f_VIII	0.89

Despite the comparable strength of B3f, the maximum deflection of the B2f beam is greater (11.70 mm for B2f vs. 9.25 mm for B3f). This phenomenon can be explained by the presence of 2% SiO_2 nanoparticles in B2f, which increase the viscosity of the paste and may contribute to the improved ductility during bending. Although SiO_2 does not improve the bending strength as much as Al_2O_3 , it improves the ductility after fracture and allows a larger deformation before failure. These results show that the type of nanoparticles affects not only the strength but also the deformation properties: Al_2O_3 improves strength and stiffness, while SiO_2 affects ductility.

In addition to the observed mechanical responses, the underlying mechanisms of nanoparticle interactions with the cement matrix provide a clear explanation for these differences. Al_2O_3 contributes primarily through a nano-reinforcing effect. Due to its high stiffness and hardness, Al_2O_3 particles act as reinforcing additives that improve stress transfer across the matrix, refine the ITZ and control microcrack growth. This increases flexural strength and stiffness, as seen in beam B3f.

On the other hand, SiO_2 contributes mainly through a nano-bridging effect. The very fine SiO_2 particles react pozzolanically with calcium hydroxide to form an additional C–S–H gel, which fills the pores and improves the paste cohesion. This enhanced matrix continuity provides effective crack-bridging at the nanoscale, delaying crack propagation and allowing for more deformation before failure. As seen in beam B2f, this mechanism improves ductility, although the peak flexural strength is not significantly increased compared to Al_2O_3 .

Therefore, the experimental results are consistent with these mechanisms: Al_2O_3 increases strength and stiffness through nano-reinforcement, while SiO_2 improves ductility through nano-bridging.

3.3. Stiffness analysis

The flexural stiffness (EI) of a reinforced concrete beam, which depends on the modulus of elasticity, section inertia, and reinforcement percentage, typically decreases with increased deflection and cracking. Analyses were conducted separately for "State I" (non-cracked) and "State II" (cracked). Theoretical stiffness estimates were made first, followed by experimental measurements from the eight beams. Comparisons reveal that experimental stiffness values ($E_{II, \text{exp}}$) are consistently lower than theoretical predictions ($E_{II, \text{theo}}$). This discrepancy may arise from the experimental method used or other factors such as the type of nanoparticles, with Al_2O_3 generally enhancing stiffness while SiO_2 has a negative effect. Table 7 highlights that experimental stiffness values ($E_{II, \text{exp}}$) are consistently lower than theoretical predictions ($E_{II, \text{theo}}$).

Table 7. Relationship between theoretical and experimental stiffness values

Beam	$E_{II, \text{theo}} / E_{II, \text{exp}}$
B1f_350	1.63
B2f_II%	1.70
B3f_III%	1.70
B4f_550	1.16
B5f_V%	1.57
B6f_VI%	0.78
B7f_VII	1.09
B8f_VIII	1.36

Figures 5–6 illustrate the flexural stiffness (EI) of each beam in relation to moments (M) up to the maximum moment. The figures include measured stiffness from

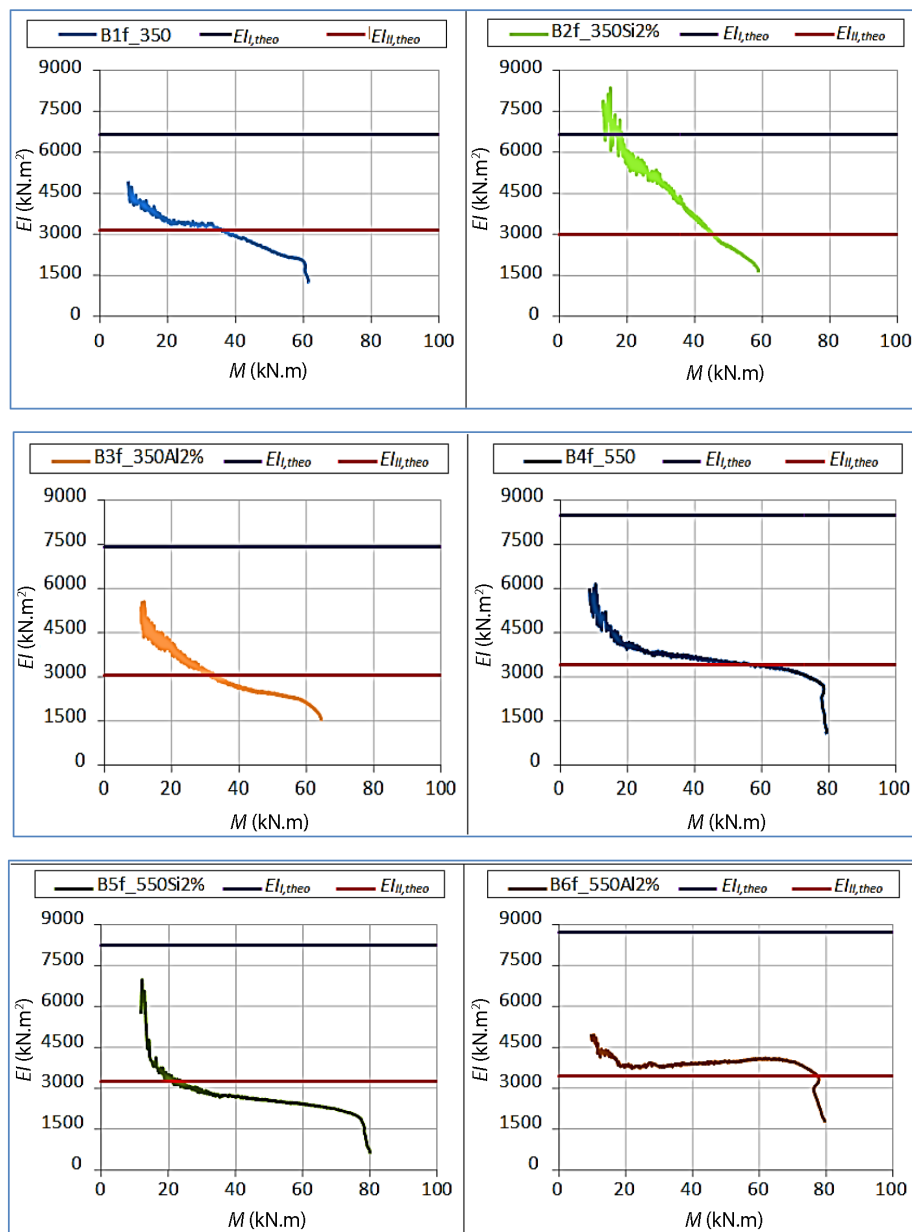


Figure 5. Comparison between theoretical and experimental stiffness values

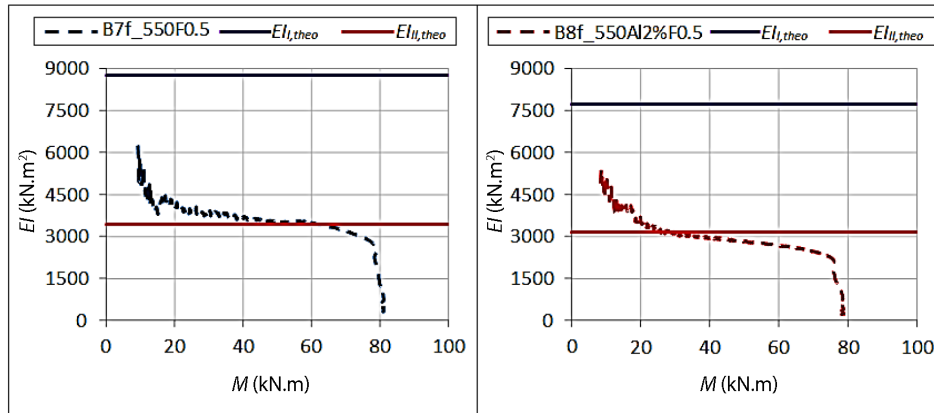


Figure 6. Comparison between theoretical and experimental stiffness values

horizontal displacement transducers (E_{exp}), theoretical stiffness for an uncracked cross-section (State I – $E_{I,theo}$), and theoretical stiffness for a fully cracked cross-section (State II – $E_{II,theo}$). Ideally, beam stiffness should range between these theoretical values from the beginning of loading until reinforcement yields.

In fact, the E_{exp} values do not remain entirely within the area limited by the theoretical values $E_{I,theo}$ and $E_{II,theo}$, shown in the diagrams in the previous figures. This phenomenon is not easy to justify – there may be small differences between the design value and the real value of the neutral axis position (x), which can greatly differentiate the stiffness values (theoretical and experimental).

Figure 7 illustrates the evolution of experimental stiffness with moment values, divided into three regions:

- First region: A steep decline in stiffness, corresponding to the appearance and opening of cracks.
- Second region: A more gradual and stable loss of stiffness, related to the growth and widening of cracks.
- Third region: A sudden drop in stiffness, indicating the approach to failure.

Initial high and variable stiffness values result from beam adjustment and limited accuracy of horizontal LVDTs for small displacements. The initial stiffness zone is similar across beams, except for beam B2f_II%. The final zone shows higher stiffness values for the 550 series beams, with similar progression within each series. Notable variations exist between initial and final stiffness for beams in both series.

3.4. Error in measuring applied load

Once again, to understand the deviations between the values of the load exerted by the actuator and the load recorded by the load cells, the error value calculated by Eq. (1) is presented.

$$Error(\%) = \left(\frac{F_{act} - F_{cell}}{F_{act}} \right) \times 100, \quad (1)$$

where F_{act} is the load applied by the actuator, F_{cell} is the load measured by the load cell.

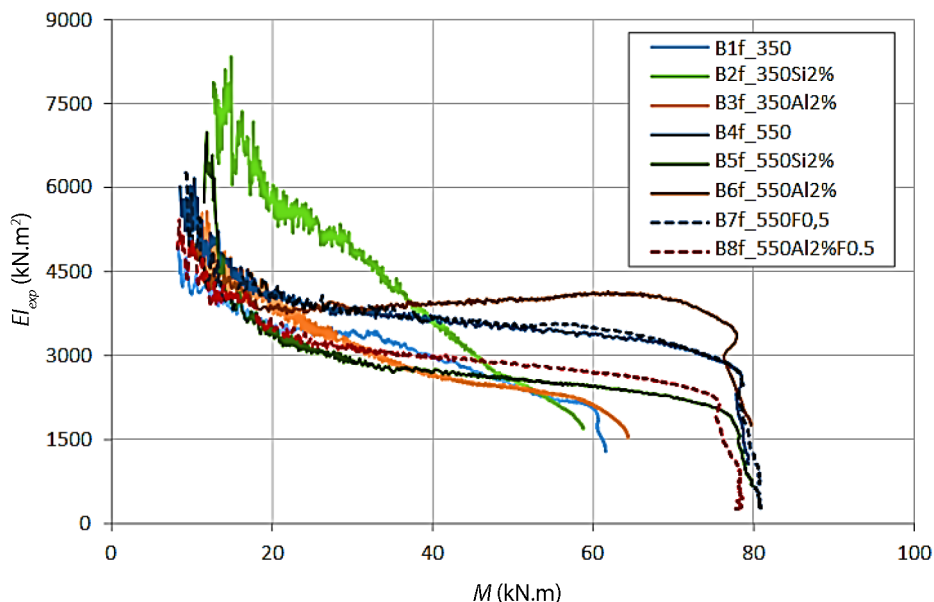


Figure 7. Stiffness evolution with the moment

The average error between all tested samples was 0.92%, indicating good calibration and consistency between the measured values and the measured loads.

3.5. Cracking and type of failure

The evolution of cracking in beams during flexion tests is described, comparing beams with and without fibers. Figures 8–9 illustrate load-displacement diagrams and cracking images at key points.

- Beams without fibers behave more brittle, while those with fibers exhibit more ductile behavior.

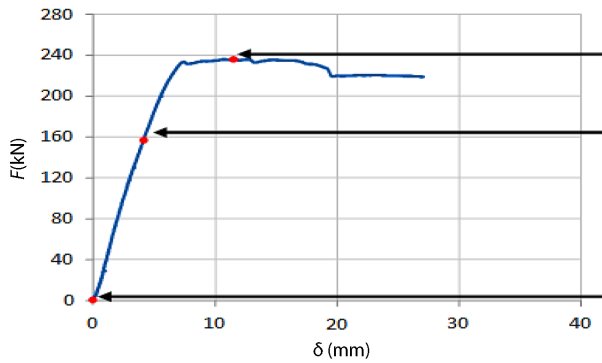


Figure 8. Correspondence between cracking and the load-displacement diagram – B4f_IV

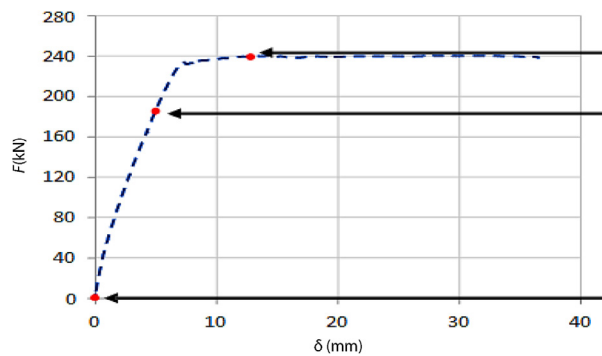


Figure 9. Correspondence between cracking and the load-displacement diagram – B7f_VII

- Three points are highlighted in the diagrams:
 - ◆ At the start, no deformation or cracking.
 - ◆ During “State II,” slight deformation and minimal cracking.
 - ◆ At the yielding point, significant cracking and deformation, with larger cracks and more deformation in beams with fibers.

As a note, it is clear that it was considered to present the cracking of all the flexural test beams at moments prior to the maximum load value (to understand its evolution), but it was evident that this cracking was small and, therefore, difficult to visualize.

The final configuration (Figure 10) reveals the crack patterns on each beam, with vertical and horizontal LVDTs used for observation. Cracks were observed to converge towards the central area where failure occurred. Beams in the 350 series showed more significant damage and concrete detachment, especially at the upper edge, compared to the 550 series, where cracks were less developed. Beams with fibers displayed more concentrated cracks in the central area and larger openings. All beams exhibited similar failure modes, without sudden concrete crushing, though those with fibers demonstrated increased ductility. The incorporation of nanoparticles had minimal impact on the cracking pattern. Additionally, details of the detachment (Figure 11) show how the matrix, reinforcement adhesion, and fiber dispersion were arranged within the beams.

Although only eight concrete beams were tested in this study, the experimental protocol was designed to account for various influencing parameters, including binder composition, steel content, and the incorporation of different nanoparticles (SiO_2 and AlO_2). The different mixes were then subjected to a series of material property tests and their compressive strength, tensile strength, and elastic modulus were tested with different numbers of repetitions.

Although a larger sample size could further enhance the generalizability of the findings, the current framework provides robust comparative insights and provides

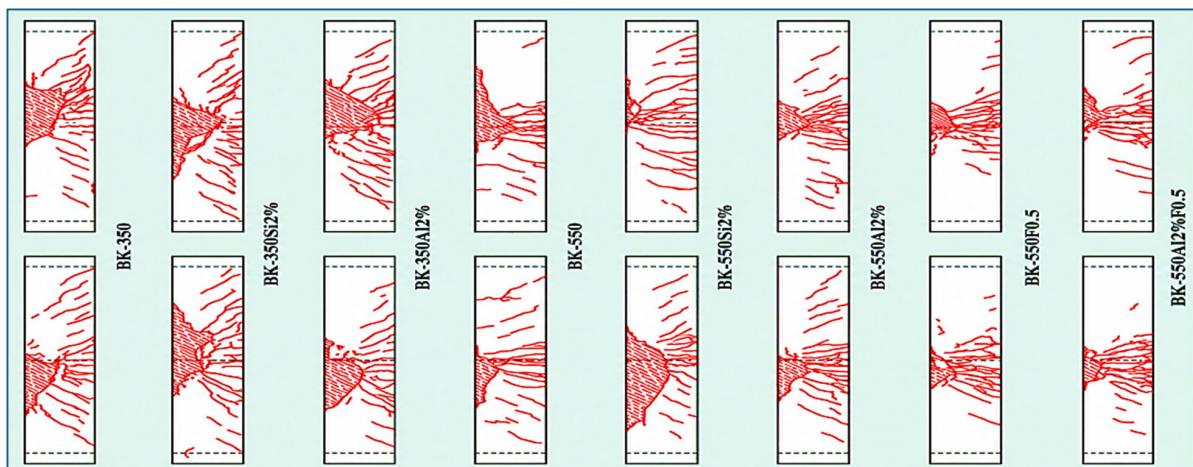


Figure 10. Crack pattern of beams – flexural test

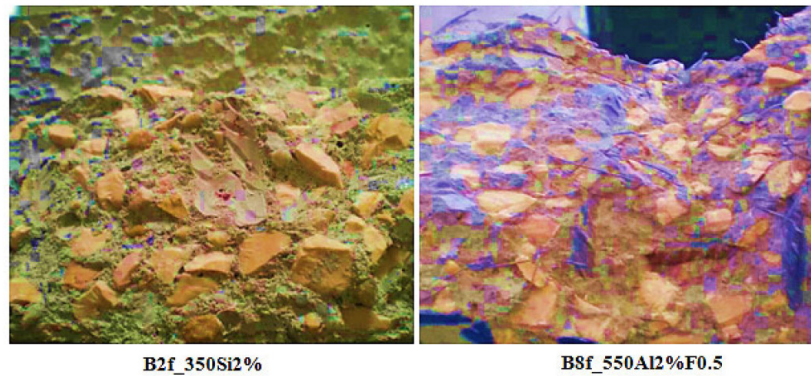


Figure 11. Detail of the detachment of the bending test beams

a reliable experimental basis. Future studies should build on this and incorporate more structural scale elements to further validate and extend the conclusions.

3.6. Statistical evaluation of test results

Three mechanical tests (compressive strength, tensile strength, flexural strength, and elastic modulus) were performed to increase the reliability and repeatability of the experimental results. Results are presented together with mean, Standard Deviation (SD), and Coefficient Of Variation (COV). The COV is calculated as the ratio of the mean of the standard deviation (expressed as a percentage) and provides an understanding of the consistency of the results. Overall, the blends showed low variability, with COV values ranging from 3% to 7% for compressive strength and slightly higher COV values (up to 10%) for tensile and tensile tests, which are more pronounced for microstructural differences and crack growth. The addition of nanoparticles and fibers increased the variability slightly, which is attributed to the small dispersion differences, but the overall statistical reliability was within the acceptable range recommended by ASTM C39 and IS 516:2021 (Bureau of Indian Standards, 2021). Table 8 presents the statistical summary of the compressive strength results at 28 days for all eight concrete mixes.

Table 8. Statistical summary of compressive strength results at 28 days

Beam	Mean Strength (MPa)	Standard Deviation (MPa)	COV (%)
I	24.3	1.1	4.5
II	28.1	1.4	5.0
III	27.7	1.2	4.3
IV	42.9	1.9	4.4
V	45.3	2.0	4.4
VI	44.6	2.3	5.2
VII	42.7	1.8	4.2
VIII	43.2	2.1	4.9

4. Discussion

4.1. Effect of nanoparticles on compressive strength

The compressive strength test results show that the compressive strength continues to increase with the addition of SiO_2 and Al_2O_3 , especially at lower water-binder ratios (w/b). The compressive strength of mixes II and III (containing 7 kg NS or NA) is 7–10% higher than that of the control mix (mix I), which is due to the filling effect and pozzolanic activity of nanoparticles. The compressive strength improvement is more significant for mixes V and VI, which have the highest content of nanoparticle cementitious materials (350 kg), indicating the potential application of nanoparticles in high water-binder ratio cementitious systems.

The densification of the microstructure helps to reduce brittleness and improve strength, which is due to accelerated melting and additional C-S-H formation. These findings are similar to those of Jin et al. (2022) and Wang et al. (2023).

4.2. Effect of cracking tensile strength

The cracking tensile strength shows the same trend as the compressive strength. Mixes containing nanoparticles (NS) and nano-nanoparticles (NA) showed higher tensile strength, especially in Mix VI, which showed an improvement (about 15%) over the control. This improvement was attributed to the interaction between the nanoparticles, resulting in tighter bonding at the matrix-aggregate interface and thicker ITZ.

The synergistic effect of nanoparticles with different binders is particularly beneficial for extraction, which was also confirmed by Liu et al. (2023) in their study of Al_2O_3 -modified concrete. These results indicate an improvement in cracking potential, which is critical for long-term durability.

4.3. Rotational technique

Beam tests showed that the flexural strength (modulus of rupture) of the mixes containing nanoparticles was sig-

nificantly improved. Among all the samples, Mix VI (Al_2O_3 , 350 kg) showed the highest flexural strength, which was 20–22% higher than the conventional control (Mix IV). The load-displacement curves of the nanoparticle-modified samples showed an extended ductile phase and a larger area under the curve, indicating better energy absorption and post-fracture performance.

This enhancement may be ascribed to nanoscale pores refinement, interface bonding, crack bridging and crack propagation retardation. Jin et al. (2023) showed the effect of nanomodification on crack control and self-healing in cementitious materials, whereas Win et al. (2024a, 2024b) linked graphene quantum dots to rapid nucleation, nano-bridging, efficient transfer of stress and mechanical performance.

In addition, the use of nanoparticles is more effective than using nanoparticles alone. However, no significant effect was observed for blends V and VIII (NS vs. NA) at higher loads, suggesting that both nanoparticles have similar macroscopic expansion benefits when used in blends.

4.4. Statistical reliability of mechanical results

Table 8 summarizes the standard deviation and coefficient of variation (COV) for all 28-day mechanical tests. All COVs were below 10%, indicating good repeatability and uniformity between samples. Notably, the nanoparticle blends had slightly lower standard deviations, indicating better microstructural compatibility. This supports the hypothesis that nanoparticles can not only improve interfacial strength but also serve as a key indicator for quality control of flexible materials.

4.5. Literature comparison

Compared to previous studies, this study confirms the effectiveness of these nanoparticles in improving mechanical properties, especially bending properties. Previous studies (e.g., Chen et al., 2022; Kumar et al., 2021) mainly focused on strength or compression behavior, while this study extends this understanding by systematically evaluating beam-level performance and incorporating statistical analysis of variability.

The results of this study are also consistent with the findings of Sharma et al. (2022) and Jha et al. (2023) who found that composite additives can improve material ductility and crack resistance. However, unlike previous studies using mice or synthetic cells (e.g., Singh et al., 2022; Yadav et al., 2024), the results of this study not only demonstrate structural optimization of nanoparticles, but also functionalization of progenitor cells.

5. Conclusions and future developments

The mechanical properties of concrete beams reinforced with steel fibers containing SiO_2 and Al_2O_3 were evaluated in this study. The experimental results show that the addition of nanoparticles affects the strength of the con-

crete mix, but its mechanical response varies depending on the type of nanoparticles, the amount used, and the interaction with other components. The improvement in compressive strength is most pronounced with the addition of SiO_2 in the mixtures, especially in the high binder formulation (350 kg/ m^3), while the effect of Al_2O_3 is less pronounced. The addition of Al_2O_3 only slightly improves the tensile strength and sometimes the residual strength after fracture decreases. The addition of nanoparticles to the 550-series connector slightly improves its sealing properties; however, the addition of Al_2O_3 steels unexpectedly leads to a decrease in overall strength, suggesting that negative interactions or dispersion issues may exist. In addition, the failure mode and fracture mode remain unchanged, indicating that the nanoparticles do not significantly alter the macrostructural response under bending loads. Overall, the study showed that nanoparticles can enhance the mechanical properties of concrete beams, especially under shear and compressive strength conditions, but their performance is not satisfactory, especially when combined with steel fibers. These findings provide new knowledge by revealing the importance of material contacts and interactions in multicomponent cementitious systems. Future studies should investigate nanoparticles, fiber types, mixture compositions, larger sample sizes, and long-term durability tests to fully understand and understand the potential of nano-modified concrete for structural applications.

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