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Research Article

Experimental investigation on the performance of concrete incorporating nano-silica and nano-titanium dioxide

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Abstract

The incorporation of nano-sized mineral additives has emerged as an effective approach to enhance the microstructure and mechanical performance of cementitious materials; however, comparative information on the individual effects of nano-silica (NS) and nano-titanium dioxide (NT) across different concrete grades remains limited. Therefore, this study investigates the influence of NS and NT as partial cement replacements on the mechanical properties of M20, M30, and M40 concrete. Concrete mixes incorporating 2%, 4%, and 6% NS and NT were evaluated for workability and mechanical properties after 7, 28, and 90 days of curing. The results indicated that both nano-additives enhanced concrete performance, with an optimum replacement level of 4%. Compared with the control concrete, the optimum NT and NS mixes improved the 90-day compressive strength by approximately 15.6% and 11.8%, respectively. The improved performance was attributed to enhanced particle packing, pore refinement, and accelerated hydration, resulting in a denser cement matrix. However, increasing the nano-additive content to 6% reduced workability and mechanical performance due to particle agglomeration, which hindered uniform dispersion and hydration. Overall, both NS and NT enhanced concrete performance, with NT exhibiting slightly greater improvements than NS at the optimum replacement level.

1. Introduction

Concrete is one of the most widely used construction materials worldwide because of its ease of production, versatility in shaping, and desirable mechanical and durability properties [1]. However, conventional concrete still suffers from several inherent limitations, such as brittleness, higher porosity, and vulnerability to environmental degradation, which may adversely affect the long-term performance. To address these limitations, nanomaterials have been increasingly investigated for improving the microstructure and mechanical performance of cement-based composites; however, their comparative performance across different concrete grades remains insufficiently understood [2–4]. Nanotechnology involves manipulating materials at dimensions typically below 100 nm, where they exhibit unique physical, chemical, and mechanical characteristics compared with their bulk counterparts [5–7]. When applied to concrete technology, nanomaterials can significantly refine the pore structure, improve particle packing density, accelerate cement hydration, and strengthen the interfacial transition zone (ITZ) between cement paste and aggregates. These improvements collectively enhance the mechanical performance and durability of concrete. Among the different nanomaterials investigated in cementitious systems, nano-silica (NS) and nano-titanium dioxide (NT) have attracted considerable attention due to their distinct functional mechanisms and ability to improve concrete properties.

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Nano-silica is highly pozzolanic due to its ultrafine amorphous SiO_2 particles and large specific surface area. It reacts rapidly with calcium hydroxide generated during cement hydration to form additional calcium silicate hydrate (C–S–H) gel, thereby densifying the cement matrix and refining the pore structure. The incorporation of NS enhances compressive strength, improves bonding characteristics, and increases resistance against chemical and environmental deterioration. Moreover, NS acts as an efficient nucleation site, accelerating hydration and promoting a more homogeneous distribution of hydration products throughout the concrete matrix [8–11].

Nano-titanium dioxide (NT) primarily improves concrete through filler and nucleation effects, enhancing particle packing and microstructural compactness. In addition, its photocatalytic properties provide self-cleaning functionality, making NT attractive for sustainable concrete applications [12,13]. These characteristics make NT-modified concrete particularly suitable for sustainable urban infrastructure and architectural applications. Binary concrete systems, in which cement is partially replaced with either NS or NT, provide an effective approach for evaluating the individual influence of each nanomaterial without the interference of combined modification effects [14,15]. In the present study, binary concrete refers to concrete mixes in which a portion of cement is independently replaced with either NS or NT. Such an approach enables a clearer understanding of the individual influence of each nanomaterial, without interference from synergistic effects associated with combined nanomodification. Although numerous studies have reported improvements in concrete performance through the incorporation of nanomaterials, most previous investigations have primarily focused either on the combined use of nanomaterials or on the behavior of a single concrete grade. Consequently, the independent and comparative influence of nano-silica and nano-titanium dioxide across multiple concrete grades remains insufficiently understood. Furthermore, although several studies have reported optimal replacement levels of around 4%, limited research has systematically examined how different concrete grades respond to varying dosages of NS and NT under identical experimental conditions. Therefore, the novelty of the present research lies not merely in identifying an optimum replacement level, but in establishing a comprehensive comparative framework to evaluate the grade-dependent behavior of NS- and NT-modified concrete.

Concrete grade plays a crucial role in determining the response of concrete to nano-modification because the initial matrix density, water-cement ratio, and pore structure vary significantly with grade. Lower-grade concrete, such as M20, generally possesses a comparatively porous microstructure and may therefore exhibit greater relative improvement through pore refinement and densification. In contrast, higher-grade concrete such as M30 and M40 may respond differently because of their already compact matrix and lower water-cement ratio, where nanomaterials may predominantly influence hydration efficiency and packing characteristics. Despite the practical importance of this aspect, comparative studies evaluating the independent effects of NS and NT across different concrete grades under uniform conditions remain scarce in existing literature.

To address this research gap, the present study systematically investigates the separate incorporation of NS and NT at replacement levels of 0%, 2%, 4%, and 6% by weight of cement in M20, M30, and M40 grade concrete. The study focuses on evaluating compressive, split tensile, and flexural strengths, while also examining practical limitations, such as reduced workability and nanoparticle agglomeration at higher dosages. Unlike previous studies that largely reported isolated performance improvements, the present work provides a direct comparative evaluation of the independent behavior of NS and NT across multiple concrete grades under identical experimental conditions, thereby offering new insight into grade-specific nano-modification behavior that has not been comprehensively reported earlier.

The inclusion of nano-silica is expected to enhance strength development through pozzolanic reactivity and nucleation effects, leading to improved formation of C–S–H gel and stronger bonding within the cement matrix. Nano-titanium dioxide, while less chemically reactive, is anticipated to improve concrete performance through filler action, particle packing, and microstructural densification. However, at higher replacement levels, both nanomaterials may adversely affect workability and lead to particle agglomeration, thereby reducing performance efficiency. Understanding these threshold limits is essential for the practical implementation of nano-modified concrete in structural applications. Nano-silica and nano-titanium dioxide are generally compatible with conventional Portland cement-based systems and can be incorporated using standard concrete production practices. Their performance under normal, humid, and moderately aggressive service conditions highlights their practical applicability for a wide range of structural and infrastructure applications.

Overall, this research contributes to existing knowledge by developing a clearer and grade-specific understanding of the independent effects of NS and NT on concrete performance. By comparing three concrete grades and multiple replacement levels under consistent experimental conditions, the study provides valuable insight into optimal dosage selection, performance sensitivity, and the suitability of nano-modifiers for different structural applications. The findings are expected to support the development of durable, sustainable, and high-performance concrete systems while also contributing toward the optimization of cement utilization and the reduction of environmental impacts associated with concrete production.

1.2 Research Gap

The present study addresses the limited understanding of the independent and grade-dependent effects of nano-silica (NS) and nano-titanium dioxide (NT) in concrete. Previous studies have mainly focused on combined nanomaterial use or single concrete grades, making it difficult to compare the individual performance of NS and NT across different matrix conditions. Consequently, the independent influence of these nanomaterials across different concrete grades remains insufficiently understood**.** Although NS enhances strength through pozzolanic activity and NT improves pore refinement and filler action, the optimal dosage behavior across multiple grades remains insufficiently explained. Existing research also lacks systematic comparisons of nano-modified concrete with varying matrix densities and water-cement ratios, while practical issues such as reduced workability, higher water demand, and nanoparticle agglomeration have received limited attention. These unresolved issues limit the scientific understanding required to establish grade-specific guidelines for the effective use of NS and NT in concrete. Therefore, to address these research gaps, this study conducts a comparative investigation of NS- and NT-modified concrete for M20, M30, and M40 grades at replacement levels of 0%, 2%, 4%, and 6%, evaluating compressive, split tensile, and flexural strength under identical experimental conditions to establish grade-specific nano-modification behavior, identify optimum dosage levels, and provide the scientific basis for selecting appropriate nanomaterial replacement levels in different concrete grades**.**

1.3 Literature Review

Several researchers have investigated the influence of nanomaterials on the hydration and microstructural behavior of cementitious composites, particularly focusing on nano-silica (NS) and nano-titanium dioxide (NT). Yang et al. [16] reported that the incorporation of nano-silica significantly accelerates cement hydration due to its high pozzolanic reactivity and nucleation effect, leading to the rapid formation of secondary calcium silicate hydrate (C–S–H) gel and a denser cement matrix. The study further observed that NS effectively refines the pore structure and reduces capillary porosity, thereby improving the compressive strength and durability of concrete. However, the authors also noted that excessive NS incorporation may lead to nanoparticle agglomeration and increased water demand, thereby adversely affecting workability and uniform dispersion within the cement matrix. Similarly, Althoey et al. [17] concluded that nano-silica contents in the range of 2–4% generally provide optimum enhancement in hydration characteristics, mechanical strength, and pore refinement, whereas higher replacement levels may lead to microstructural discontinuities due to poor particle distribution.

Nano-titanium dioxide has also been extensively studied for its contribution to microstructural densification and durability enhancement of cementitious composites. Donduren and Al-Hagri [18] reported that NT improves the mechanical properties of concrete primarily through filler action and hydration acceleration rather than through strong pozzolanic reactivity. The ultrafine particles of NT act as nucleation sites for hydration products and contribute to pore refinement by filling nanoscale voids within the cement matrix. In addition, NT was found to improve the interfacial transition zone (ITZ) by reducing micro-voids and enhancing the compactness of hydration products surrounding aggregates. Nevertheless, the study highlighted that higher NT dosages may negatively affect workability and result in particle agglomeration, ultimately reducing the efficiency of microstructural refinement. Similar observations were reported by Jenifer et al. [19], who emphasized that NT significantly improves early-age hydration and compressive strength through its nucleation and filler effects, while simultaneously imparting photocatalytic and self-cleaning properties to concrete surfaces.

Recent investigations have further emphasized the importance of refining pore structure and modifying ITZs to improve the performance of nano-modified concrete. Tanimola and Efe [20] observed that both NS and NT contribute to reducing porosity and enhancing matrix densification, although through different mechanisms. Nano-silica predominantly improves concrete through pozzolanic reactions and accelerated C–S–H gel formation, whereas nano-titanium dioxide contributes mainly through physical filler action and particle packing enhancement. The study further reported that improved ITZ characteristics result in better stress transfer between aggregates and cement paste, thereby increasing compressive, split tensile, and flexural strength. Although several studies have demonstrated the beneficial effects of NS and NT on concrete performance, most previous investigations were limited either to a single concrete grade or to combined nano-modification systems. Comparative evaluation of the independent behavior of NS and NT across multiple concrete grades remains relatively unexplored. The existing literature also yields inconsistent conclusions on optimal replacement levels because the effectiveness of nanomaterials is strongly influenced by matrix density, water-cement ratio, and dispersion characteristics. Therefore, the present study addresses this research gap by systematically evaluating the independent effects of nano-silica and nano-titanium dioxide at different replacement levels in M20, M30, and M40 grade concrete under uniform experimental conditions. This approach provides a clearer understanding of grade-dependent hydration behavior, pore structure refinement, and interfacial transition zone development in nano-modified concrete systems.

Maheswaran et al. [21] studied the influence of rice husk ash and nano-silica in geopolymer concrete. Nano-silica is found to enhance the hardened properties of concrete at all curing ages, with 3% nano-silica achieving the optimum performance. S. Abd El-Aleem et al. [22] examined the thermal expansion, microstructure, and hydration characteristics of cement incorporating NS as a partial replacement of OPC up to 6%. NS increased water demand and delayed setting when used with a polycarboxylate superplasticizer, due to its high SSA and fine particle size. Increasing NS content reduced pH and free portlandite, while increasing chemically combined water due to enhanced pozzolanic activity. Microstructural refinement and mechanical properties improved significantly up to 3% NS, with marginal gains up to 5%. The substitution of NS lowered the coefficient of thermal expansion, whereas cement pastes with 3% nano-silica showed increased thermal expansion with curing age due to continued hydration and pozzolanic reactions. Overall, NS additions up to 5% enhanced the chemical, physio-mechanical, and thermal properties of OPC, leading to increased compressive strength through nano-filler effects and microstructural densification.

Nazari et al. [23] reported that incorporating nano-titanium dioxide into self-compacting concrete effectively filled micro-pores, resulting in a denser, stronger microstructure. The experimental outcomes showed improved split tensile and flexural strength up to 4% of nano-titanium dioxide. However, beyond this optimal dosage, the benefits declined, indicating a point of diminishing returns when NT > 4%. Garima Rawat et al. [24] examined the strength and rheological aspects of concrete containing nano-titanium dioxide. NT was used as a partial substitute for cement at concentrations ranging from 0% to 3%, with increments of 0.50%. The slump of concrete decreases with increasing substitution level due to the high SSA, leading to reduced workability and increased water demand. M. Suneel and G. V. Rama Rao [25] studied the influence of nano-titanium dioxide on M40 and M60 concrete. The Fresh behavior of concrete, as assessed by slump and compaction factor, is reduced with increased NT substitution due to its high specific surface area (SSA), which increases water demand. The presence of NT is found to improve concrete's mechanical behaviour.

2. Materials and Their Characterization

2.1 Cement

Ordinary Portland Cement (OPC) of 53 grade, conforming to IS 12269:2013, was used as the binding material in this study. The cement was procured from a local commercial supplier and is readily available in the local market. Its physical properties are presented in Table 1, while its chemical composition is presented in Table 4.

Table 1. Physical parameters of cement

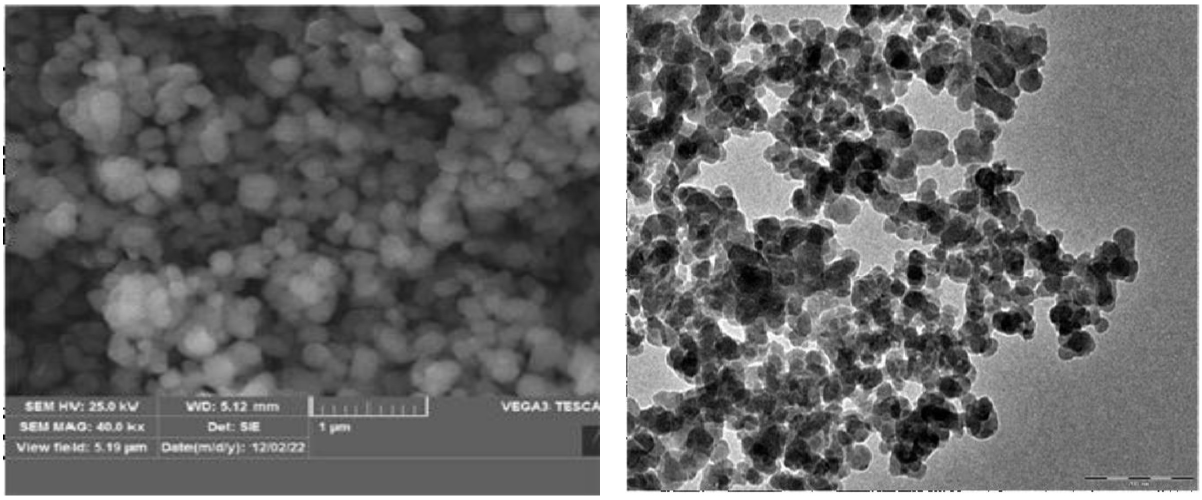
Parameter	Outcomes
Normal consistency	32%
Specific gravity	3.14
Initial setting time (minutes)	165
Final setting time (minutes)	280

2.2 Nano-Titanium Dioxide

Nano-titanium dioxide (Nano-TiO_2) was used as a partial replacement for cement at replacement levels of 0%, 2%, 4%, and 6% by weight of cement. The Nano-TiO_2 was procured from Herenba Instruments & Engineers, Chennai. Its chemical composition and physical properties are presented in Table 2, while its morphology is shown in Figure1.

Table 2. Physical properties of nano-titanium dioxide

Parameter	Outcomes
Particle size	15nm
Bulk Density	0.9 g/cm^3
pH	6.3
Purity	> 99.9%
Reactivity	Non-reactive
BET Surface area	185 m^2/g



(a) (b)

Fig. 1. Morphology of (a) Nano-titanium dioxide (b) Nano silica

2.3 Nano Silica

In the present study, nano-silica (NS) was used as a partial replacement for cement at replacement levels of 0%, 2%, 4%, and 6% by weight of cement. The physical properties of NS are presented in Table 3, while its chemical composition is provided in Table 4.

Table 3. Physical properties of nano-silica

Property	Outcomes
Particle size	10-20 nm
Specific Surface Area	200 – 600 m^2/g
Color	white powder
Purity	> 99.9%
Bulk Density	0.18-0.23g/cm^3
Melting Point	1600^0C

Table 4. Chemical composition of cement and nano-silica (%)

Chemical Composition (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LOI
Cement	21.5	6.85	1.5	62.5	1.6	0
Nano Silica	94.5	5.24	0.008	0.05	0.21	0

The nanoscale particle size and high specific surface area of Nano-TiO_2 promote the filler effect by filling micro voids and the nucleation effect by providing additional sites for C–S–H gel formation. These mechanisms contribute to a denser microstructure and improved pore refinement.

2.4 Aggregate

River sand was used as the fine aggregate and was found to conform to Zone II as per IS 383:2016. The specific gravity and water absorption of the fine aggregate were 2.62 and 1.20%, respectively. Crushed granite of 20 mm and 10 mm sizes, procured from a local source, was used as the coarse aggregate. The specific gravity and water absorption of the coarse aggregate were 2.78 and 0.80%, respectively. The particle size distribution (gradation) curves of both the fine and coarse aggregates are presented in Figure 2.

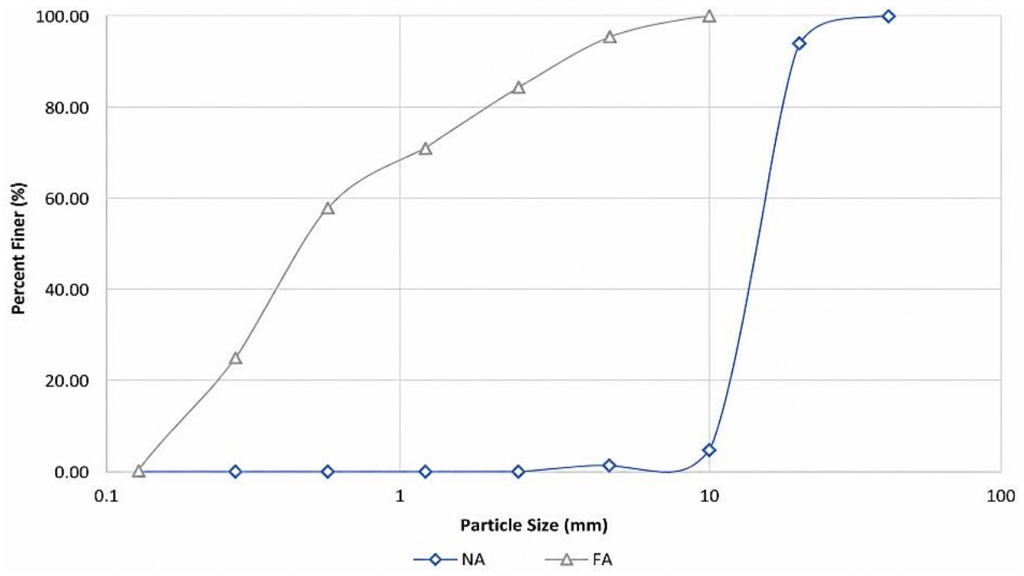


Fig. 2. Particle Size Distribution Curve of Natural Aggregate (NA) and Fine Aggregate (FA)

3. Methodology

The experimental investigation was carried out in accordance with the relevant Indian Standard specifications. The concrete mix proportions were designed in accordance with IS 10262:2019 [26]. Nano-silica (NS) and nano-titanium dioxide (NT) were incorporated as partial cement replacement materials. During concrete mixing, the required quantities of coarse aggregates, fine aggregates, cement, nano-silica, and nano-titanium dioxide were introduced into the concrete mixer and dry-mixed to achieve a uniform distribution of all dry constituents. Subsequently, the total mixing water and a polycarboxylate ether-based superplasticizer at a dosage of 0.2% by weight of cement were added, and mixing was continued for approximately 3–5 minutes until a homogeneous concrete mix was obtained before casting. The workability of fresh concrete was evaluated using the slump cone test in accordance with IS 1199:2018 [27]. The slump test was performed immediately after mixing using the standard slump cone (300 mm height, 200 mm bottom diameter, and 100 mm top diameter), and the concrete was filled in three equal layers, each compacted with 25 strokes of a standard tamping rod as specified in the code**.**

The hardened properties of concrete were assessed through compressive, split tensile, and flexural strength tests. Compressive strength testing was conducted in accordance with IS 516 (Part 1/Sec 1):2021 [28], which evaluates the capacity of concrete to resist axial compressive loads and serves as a primary indicator of structural performance. Compressive strength tests were conducted on 150 × 150 × 150 mm cube specimens using a compression testing machine at curing ages of 7, 28, and 90 days. Split tensile strength testing was carried out in accordance with IS 516 (Part 1/Sec 1):2021[29] to assess the tensile resistance and cracking behavior of concrete. The test was performed on 150 mm diameter × 300 mm height cylindrical specimens under diametrical loading at curing ages of 7, 28, and 90 days. Flexural strength was determined in accordance with IS 516 (Part 1/Sec 1):2021[29] to evaluate the bending resistance of the developed concrete mixes. Flexural strength tests were performed on prism specimens of size 100 × 100 × 500 mm under two-point loading at curing ages of 7, 28, and 90 days.

Fig. 3. Fabrication of concrete specimens

Fig. 4. Specimens under water curing

Fig. 5. Experimental setup for compressive strength test

For each mix proportion and testing parameter, three specimens were cast and tested at curing ages of 7, 28, and 90 days to examine both early-age and long-term performance characteristics. The average value of the three specimens was reported as the representative result for each test. In addition, the standard deviation and coefficient of variation were calculated from the three test results to evaluate the experimental variability and data reliability, and the corresponding error bars have been included in the relevant figures. All specimens were compacted using a table for approximately 30–60 seconds, or until no visible air bubbles were observed, to ensure adequate compaction and eliminate entrapped air. After casting, the specimens were demolded after 24 hours and cured under standard water-curing conditions until the respective testing ages. The experimental setup is illustrated in Figures 3–7.

Fig. 6. Test setup for Split tensile strength

Fig. 7. Test setup for Flexural strength

3.1 Mix Proportions

The mix proportions corresponding to various grades of concrete incorporating nano-titanium dioxide and nano-silica are presented below. Tables 5, 6, and 7 provide the mix notations for concrete mixes using nano-titanium dioxide and nano-silica as a replacement for cement by weight (%).

Table 5. Mix notations for concrete using nano-titanium dioxide

Mix ID	Explanation
M20CC	M20 grade conventional concrete
M20T2	M20 grade concrete with 2% nano-titanium dioxide
M20T4	M20 grade concrete with 4% nano-titanium dioxide
M20T6	M20 grade concrete with 6% nano-titanium dioxide
M30CC	M30 grade conventional concrete
M30T2	M30 grade concrete with 2% nano-titanium dioxide
M30T4	M30 grade concrete with 4% nano-titanium dioxide
M30T6	M30 grade concrete with 6% nano-titanium dioxide
M40CC	M40 grade conventional concrete
M40T2	M40 grade concrete with 2% nano-titanium dioxide
M40T4	M40 grade concrete with 4% nano-titanium dioxide
M40T6	M40 grade concrete with 6% nano-titanium dioxide

Table 6. Mix notations for concrete using nano-silica

Mix ID	Explanation
M20CC	M20 grade conventional concrete
M20S2	M20 grade concrete with 2% nano-silica
M20S4	M20 grade concrete with 4% nano-silica
M20S6	M20 grade concrete with 6% nano-silica
M30CC	M30 grade conventional concrete
Mix ID	Explanation

M30S2	M30 grade concrete with 2% nano-silica
M30S4	M30 grade concrete with 4% nano-silica
M30S6	M30 grade concrete with 6% nano-silica
M40CC	M40 grade conventional concrete
M40S2	M40 grade concrete with 2% nano-silica
M40S4	M40 grade concrete with 4% nano-silica
M40S6	M40 grade concrete with 6% nano-silica

Table 7. Mix proportions of control and nano-TiO_2/Nano-SiO_2 modified concrete mixes

MIX	Cement Kg/m³	F.A Kg/m³	C.A Kg/m³	NANO TIO2 Kg/m³	Water liter/m³
M20CC	330	714.8	1277.8	0	159
M30CC	400	654.67	1223.89	0	176
M40CC	435	638.33	1243.9	0	166
M20T2	323.4	714.8	1277.8	6.6	159
M20T4	316.8	714.8	1277.8	13.2	159
M20T6	310	714.8	1277.8	19.8	159
M30T2	392	654.67	1223.89	8	176
M30T4	384	654.67	1223.89	16	176
M30T6	376	654.67	1223.89	24	176
M40T2	426.3	638.33	1243.9	8.7	166
M40T4	417.6	638.33	1243.9	17.4	166
M40T6	408.9	638.33	1243.9	26.1	166
M20S2	323.4	714.8	1277.8	6.6	159
M20S4	316.8	714.8	1277.8	13.2	159
M20S6	310	714.8	1277.8	19.8	159
M30S2	392	654.67	1223.89	8	176
M30S4	384	654.67	1223.89	16	176
M30S6	376	654.67	1223.89	24	176
M40S2	426.3	638.33	1243.9	8.7	166
M40S4	417.6	638.33	1243.9	17.4	166
M40S6	408.9	638.33	1243.9	26.1	166

4. Results and Discussion

4.1 Slump Cone Test

Figure 8 illustrates the variation in workability of the concrete mixes as measured using the slump cone apparatus. The slump values for conventional concrete were 75 mm, 70 mm, and 64 mm for M20, M30, and M40 grades, respectively. A gradual reduction in workability was observed with increasing concrete grade, primarily due to a decrease in the water–cement ratio from M20 to M40 mixes, resulting in denser concrete matrices. The incorporation of nano-titanium dioxide (NT) and nano-silica (NS) further reduced the slump values with increasing nano-material dosage. This reduction in workability is mainly due to the extremely fine particle size and the nanoparticles' high specific surface area (SSA). Due to their ultra-fine nature, NS and NT particles absorbed a considerable amount of free water from the concrete mixture and increased internal friction between particles, thereby reducing the mobility of the fresh concrete. In addition, the nanoparticles occupied the micro-voids between cement grains, resulting in a more cohesive, compact matrix that reduced flowability.

A quantitative comparison showed that the slump reduction was more pronounced in nano-silica-modified concrete than in nano-titanium dioxide-modified concrete. In NT-incorporated concrete, the slump decreased from 75 mm to 55 mm in M20, from 70 mm to 46 mm in M30, and from 64 mm to 38 mm in M40 mixes, corresponding to reductions of approximately 26.7%, 34.3%, and 40.6%, respectively. In contrast, NS-incorporated concrete exhibited a greater reduction in slump, decreasing from 75 mm to 51 mm in M20, from 70 mm to 43 mm in M30, and from 64 mm to 34 mm in M40 mixes, representing reductions of approximately 32.0%, 38.6%, and 46.9%, respectively. The comparatively higher slump loss observed in NS-modified concrete can be associated with the finer particle size and larger specific surface area of nano-silica relative to nano-titanium dioxide. The higher SSA of NS increased water absorption and promoted particle agglomeration at higher dosages, thereby reducing dispersion efficiency and significantly affecting the behavior of fresh concrete.

The observed reduction in workability also indicates that nano-material incorporation alters the rheological characteristics of concrete by increasing cohesiveness and reducing the amount of free water available for lubrication. Although this behavior contributed to matrix densification and improved particle packing, excessive reduction in workability may adversely affect mixing, placing, and compaction operations in practical applications. Therefore, in the present study, the water content and superplasticizer dosage were kept constant for all experimental mixes, with a superplasticizer dosage of 0.2% by weight of cement. Similar observations have been reported in earlier studies, where the incorporation of nano-silica increased cohesiveness, reduced slump values, and enhanced the compactness of the concrete matrix due to its high pozzolanic activity and surface area characteristics [30,31]. The observed workability characteristics indicate that both nano-silica and nano-titanium dioxide are compatible with conventional cementitious systems and can be incorporated using standard concrete production practices. This compatibility supports their potential application under normal construction and service conditions, provided adequate workability is maintained.

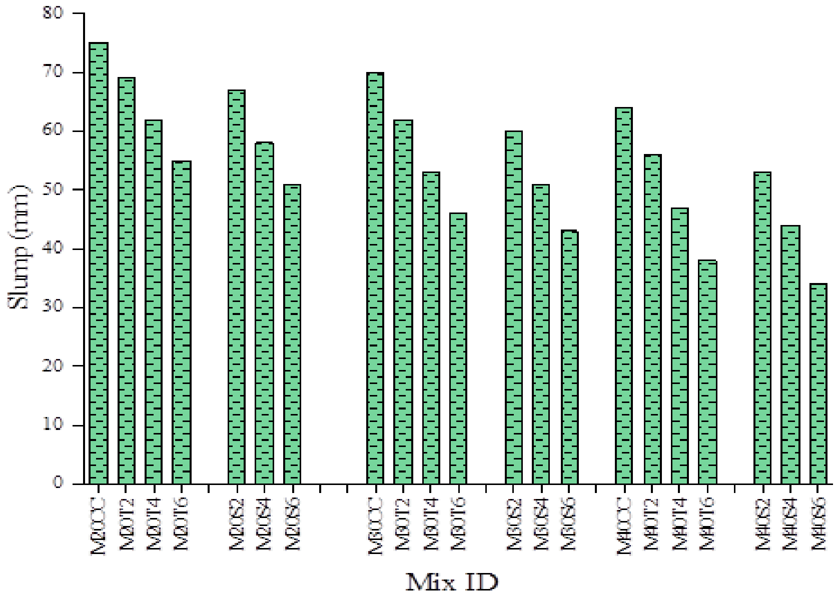


Fig. 8. Slump values of all concrete mixes, illustrating the variation in workability with different nano-silica and nano-TiO_2 replacement levels

4.2 Compressive Strength

The compressive strength of the conventional concrete at 28 days was 27.08 MPa, 39.86 MPa, and 50.44 MPa for the mixes M20CC, M30CC, and M40CC, respectively. The results of the hardened concrete tests are presented in Tables 8 and 9. At the same time, the corresponding variations in compressive strength for mixes incorporating nano-titanium dioxide (NT) and nano-silica (NS) are illustrated in Figures 9 and 10. The results indicate that compressive strength increased with both curing age and concrete grade, demonstrating continuous hydration and progressive densification of the cementitious matrix. Among all replacement levels investigated, the 4% nano-material replacement produced the highest mean compressive strength under the present testing conditions. For nano-titanium dioxide, the mixes M20T4, M30T4, and M40T4 attained compressive strengths of 29.70 MPa, 44.26 MPa, and 57.04 MPa, respectively, corresponding to strength improvements of 9.68%, 11.04%, and 13.08% compared to their respective control mixes. Similarly, the mixes containing 4% nano-silica (M20S4, M30S4, and M40S4) achieved compressive strengths of 29.18 MPa, 43.44 MPa, and 55.83 MPa, representing increases of 7.75%, 8.98%, and 10.69%, respectively. A comparative evaluation indicates that nano-titanium dioxide exhibited slightly greater compressive strength enhancement than nano-silica across all concrete grades. 7 days compressive strength increased with 2% and 4% nano additions, peaked at 4%, then slightly decreased at 6% replacement.

Based on the observed compressive strength trends and previous studies, the improvement in compressive strength may be attributed to mechanisms such as accelerated hydration, nucleation action, pore refinement, and microstructural densification. These mechanisms are presented as plausible explanations consistent with the literature rather than as direct evidence from the present investigation. The incorporation of Nano-Silica (NS) and Nano-Titanium Dioxide (NT) significantly influenced the hydration behavior and mechanical performance of concrete through distinct but complementary mechanisms. Nano-silica primarily contributed through its high pozzolanic reactivity and strong nucleation effect, whereas nano-titanium dioxide mainly acted as a nano-filler, improving particle packing and refining the pore structure. Due to its extremely fine particle size and high specific surface area, NS accelerated cement hydration by providing additional nucleation sites for the precipitation of hydration products, thereby enhancing hydration kinetics during the early stages of curing. Furthermore, the amorphous silica present in NS reacted with calcium hydroxide released during cement hydration to form additional secondary Calcium Silicate Hydrate (C–S–H) gel, resulting in matrix densification and reduction in capillary porosity. The increased formation of C–S–H gel improved bonding within the cement matrix and enhanced load transfer under compressive loading conditions.

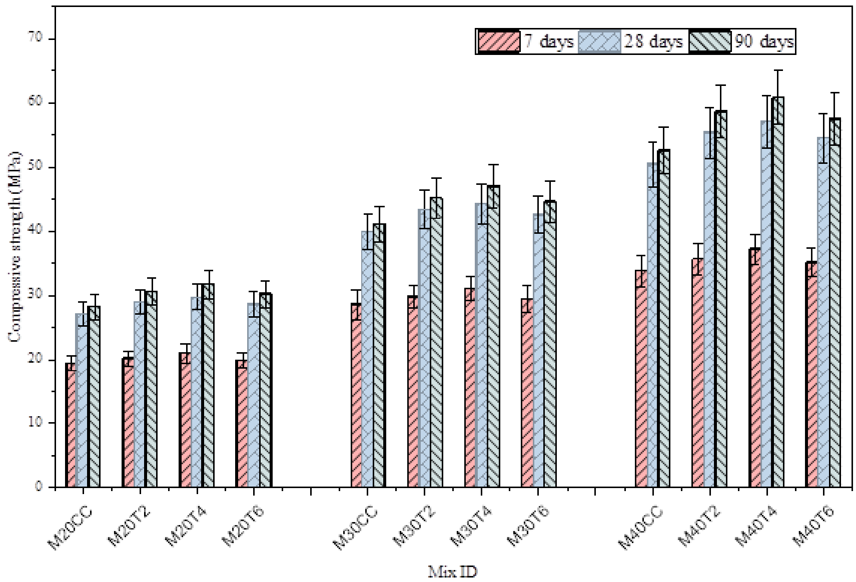


Fig. 9. Compressive strength of concrete at different curing ages with varying nano-titanium dioxide contents

In contrast, NT contributed predominantly through filler action, occupying nanoscale voids within the cement matrix and improving packing density, thereby producing a denser, more homogeneous microstructure. Although NT exhibited comparatively lower pozzolanic activity than NS, its incorporation significantly improved pore refinement and reduced microstructural defects within the concrete matrix. The enhanced compactness produced by NT reduced internal voids and restricted crack propagation, thereby contributing to greater compressive strength development, particularly in higher-grade concrete mixes with lower water–cement ratios.

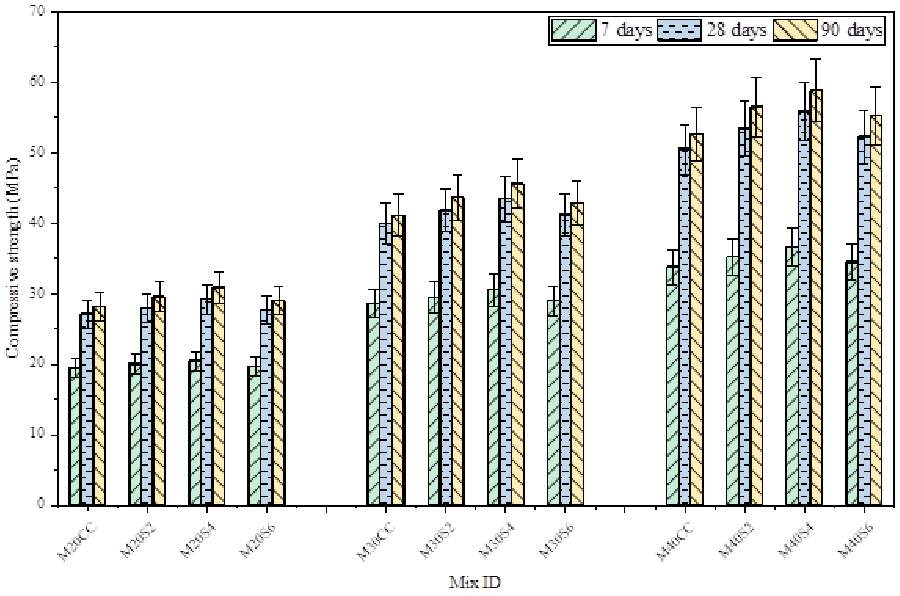


Fig. 10. Compressive strength of concrete at different curing ages with varying nano-silica contents

Table 8. Mechanical properties of hardened concrete using nano-titanium dioxide

Mix ID	Compressive strength (MPa)			Split tensile strength (MPa)			Flexural strength (MPa)		
	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
M20CC	19.44	27.08	28.16	1.95	2.71	2.86	2.24	3.12	3.28
M20T2	20.19	29.02	30.59	2.02	2.86	3.07	2.31	3.29	3.48
M20T4	20.95	29.70	31.65	2.07	2.94	3.16	2.36	3.38	3.59
M20T6	19.85	28.60	30.20	1.99	2.81	3.03	2.28	3.23	3.42
M30CC	28.56	39.86	41.06	2.20	3.04	3.22	2.51	3.64	3.82
M30T2	29.76	43.42	45.16	2.29	3.24	3.49	2.60	3.83	4.09
M30T4	31.02	44.26	46.98	2.38	3.35	3.63	2.70	3.97	4.25
M30T6	29.45	42.56	44.60	2.25	3.18	3.44	2.56	3.78	4.02
M40CC	33.76	50.44	52.56	3.10	4.18	4.42	3.11	4.51	4.80
M40T2	35.63	55.34	58.60	3.24	4.51	4.87	3.24	4.79	5.20
M40T4	37.14	57.04	60.75	3.38	4.68	5.04	3.37	4.97	5.42
M40T6	35.10	54.48	57.40	3.19	4.42	4.77	3.19	4.72	5.09

Table 9. Mechanical properties of hardened concrete using nano-silica

Mix ID	Compressive strength (MPa)			Split tensile strength (MPa)			Flexural strength (MPa)		
	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
M20CC	19.44	27.08	28.16	1.95	2.71	2.86	2.24	3.12	3.28
M20S2	20.02	27.96	29.54	1.98	2.80	3.00	2.28	3.20	3.43
M20S4	20.41	29.18	30.89	2.01	2.88	3.10	2.31	3.30	3.52
M20S6	19.64	27.63	29.04	1.97	2.77	2.95	2.26	3.17	3.36
M30CC	28.56	39.86	41.06	2.20	3.04	3.22	2.51	3.64	3.82
M30S2	29.48	41.78	43.64	2.24	3.16	3.40	2.57	3.77	4.03
M30S4	30.51	43.44	45.55	2.30	3.28	3.53	2.63	3.90	4.17
M30S6	29.00	41.11	42.80	2.23	3.13	3.35	2.54	3.73	3.94
M40CC	33.76	50.44	52.56	3.10	4.18	4.42	3.11	4.51	4.80
M40S2	35.17	53.37	56.47	3.18	4.39	4.72	3.20	4.70	5.10
M40S4	36.58	55.83	58.78	3.30	4.55	4.90	3.30	4.88	5.32
M40S6	34.48	52.22	55.18	3.16	4.33	4.66	3.16	4.65	5.00

At early curing ages, strength enhancement was mainly associated with accelerated hydration kinetics and nucleation effects, while at later curing ages, the continued formation of secondary hydration products and pore refinement became dominant mechanisms governing strength development. However, beyond the optimal replacement level of 4%, a marginal reduction in compressive strength was observed, which may be attributed to nanoparticle agglomeration due to the extremely high specific surface area of nanomaterials. Agglomeration reduced dispersion efficiency and created localized weak zones within the concrete matrix, thereby limiting further improvement in mechanical performance. Overall, the results demonstrate that both NS and NT effectively enhance compressive strength through hydration, pore refinement, and matrix densification, with nano-titanium dioxide exhibiting comparatively superior performance under the investigated conditions.

4.3 Split Tensile Strength

The split tensile strengths at 28 days for the control mixes M20CC, M30CC, and M40CC were 2.71 MPa, 3.04 MPa, and 4.18 MPa, respectively. Incorporation of nano-materials resulted in a noticeable enhancement in tensile performance, as illustrated in Figures 11 and 12. The results of the hardened concrete tests are presented in Tables 8 and 9. At the optimum 4% replacement level, nano-titanium dioxide mixes M20T4, M30T4, and M40T4 achieved split tensile strengths of 2.94 MPa, 3.35 MPa, and 4.68 MPa, corresponding to percentage increases of 8.49%, 10.20%, and 11.96%, respectively, over the control mixes. Similarly, nano-silica mixes M20S4, M30S4, and M40S4 attained strengths of 2.88 MPa, 3.28 MPa, and 4.55 MPa, indicating improvements of 6.27%, 7.89%, and 8.85%, respectively. The results reveal that nano-titanium dioxide provided greater enhancement in split tensile strength than nano-silica, which may be associated with its superior ability to improve particle packing, reduce pore connectivity, and restrict microcrack propagation within the cementitious matrix. 7 days split tensile strength improved progressively up to 4% nano replacement, indicating enhanced early crack resistance before marginal reduction at 6%.

The improvement in split tensile strength can be attributed to the enhanced microstructural densification and strengthening of the Interfacial Transition Zone (ITZ) between the cement paste and aggregate particles. The ultra-fine particle size and high surface activity of both NS and NT contributed to void filling, accelerated hydration, and the refinement of the pore structure, resulting in a denser, more compact matrix [35]. Nano-silica primarily enhanced tensile performance through pozzolanic reactivity and secondary C–S–H gel formation, thereby improving bonding characteristics within the cement matrix. The additional C–S–H gel generated by the reaction between nano-silica and calcium hydroxide reduced micro-voids and strengthened the aggregate–paste interface, thereby improving resistance against tensile cracking. In contrast, nano-titanium dioxide mainly contributed through its filler action and pore refinement, producing a more homogeneous microstructure with reduced stress-concentration zones. The improved particle packing achieved through NT incorporation enhanced stress transfer within the concrete matrix and contributed to greater crack resistance under tensile loading.

The observed enhancement in tensile strength may also be associated with improved characteristics of the ITZ, which is generally considered the weakest region in conventional concrete. The refinement of the ITZ reduced microcrack formation around aggregate surfaces and enhanced aggregate–paste bonding, thereby increasing the load-carrying capacity of the concrete under indirect tensile stresses. Furthermore, the denser microstructure and reduced pore connectivity delayed crack initiation and propagation, thereby improving tensile resistance. However, beyond the optimum replacement level of 4%, the tensile strength exhibited a marginal reduction, which may be attributed to nanoparticle agglomeration and non-uniform dispersion within the concrete matrix. Due to the extremely high specific surface area of nanomaterials, excessive incorporation increased the tendency for particles to cluster, thereby creating localized weak zones and reducing the effectiveness of hydration-enhancement and pore-refinement mechanisms. Overall, the results demonstrate that both NS and NT significantly improved split tensile strength through ITZ densification, enhanced hydration, pore refinement, and improved aggregate–paste bonding, with nano-titanium dioxide showing comparatively superior performance under the investigated conditions [33,34].

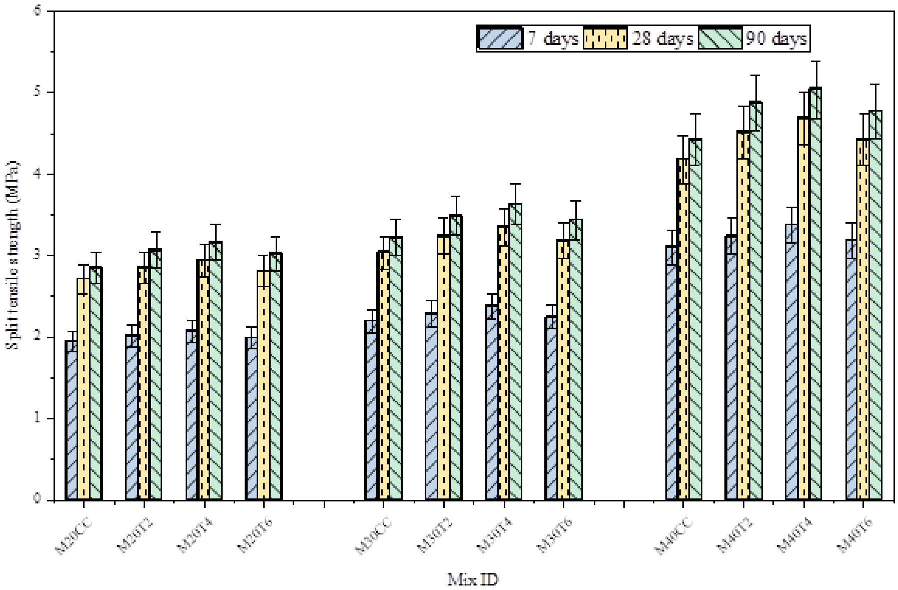


Fig. 11. Split tensile strength of concrete at different curing ages with varying nano-titanium dioxide contents

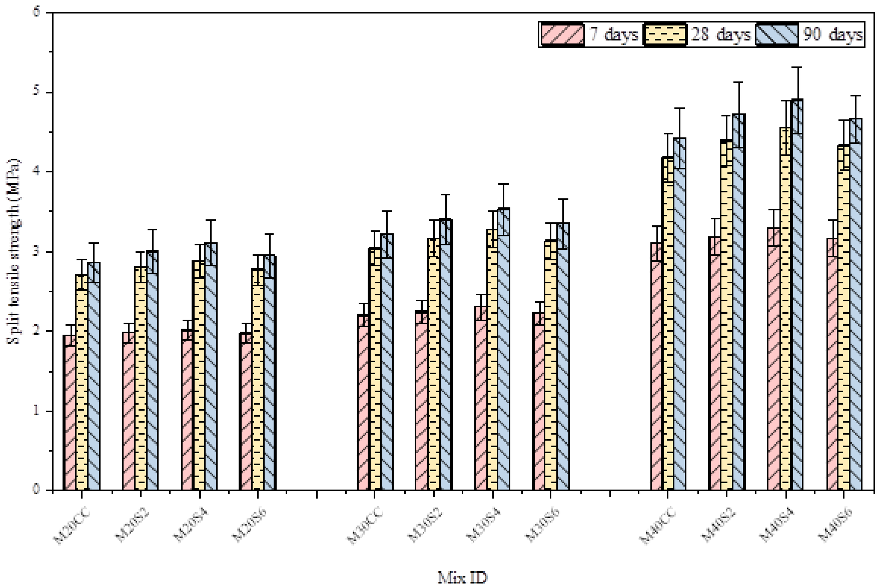


Fig. 12. Split tensile strength of concrete at different curing ages with varying nano-silica contents

4.4 Flexural Strength

The flexural strengths of the conventional concrete mixes were recorded as 3.12 MPa, 3.64 MPa, and 4.51 MPa for M20CC, M30CC, and M40CC, respectively. Figures 13 and 14 demonstrate that incorporating nano-materials improved the flexural strength of concrete across all grades. The results of the hardened concrete tests are presented in Tables 8 and 9. At the optimum 4% replacement level, nano-titanium dioxide mixes M20T4, M30T4, and M40T4 achieved flexural strengths of 3.38 MPa, 3.97 MPa, and 4.97 MPa, corresponding to increases of 8.33%, 9.07%, and 10.20%, respectively, compared to the control mixes. Similarly, nano-silica mixes M20S4, M30S4, and M40S4 recorded strengths of 3.30 MPa, 3.90 MPa, and 4.88 MPa, representing improvements of 5.77%, 7.14%, and 8.20%, respectively. A comparative evaluation of the flexural performance indicates nano-titanium dioxide exhibited higher mean flexural strength values than nano-silica at identical replacement levels under the present testing conditions. This behavior suggests that nano-titanium dioxide contributed more effectively toward improving crack resistance, stress distribution, and load-transfer capability within the concrete matrix. 7days flexural strength increased consistently with 2% and 4% nano additions, reaching maximum at 4%, followed by slight decline at 6%.

The enhancement in flexural strength can be attributed to the combined effects of micro-filling action, accelerated hydration, pore refinement, and strengthening of the Interfacial Transition Zone (ITZ) between the cement paste and aggregate particles. The incorporation of NS and NT refined the pore structure and reduced micro-voids in the cementitious matrix, thereby producing a denser, more homogeneous microstructure that resists crack initiation and propagation under flexural loading conditions. Nano-silica primarily enhanced flexural behavior through pozzolanic activity and secondary Calcium Silicate Hydrate (C–S–H) gel formation, thereby improving matrix compactness and strengthening bonding within the cement paste. The additional C–S–H gel formed by the reaction between nano-silica and calcium hydroxide contributed to reduced porosity and improved cohesion within the concrete matrix.

In contrast, nano-titanium dioxide mainly acted through filler and pore-refinement mechanisms by occupying nano-scale voids and enhancing particle packing density. The improved compactness achieved by NT incorporation reduced stress concentration zones and enhanced the concrete matrix's ability to transfer stresses efficiently under bending conditions. The denser microstructure also enhanced crack-bridging resistance and delayed microcrack propagation, thereby contributing to superior flexural performance. Furthermore, the refinement of the ITZ reduced weak interfacial regions around aggregate particles and improved aggregate–paste bonding, thereby increasing flexural resistance. The enhanced stress-transfer efficiency and reduced pore connectivity observed in nano-modified concrete indicate a strong relationship between microstructural densification and the development of flexural strength.

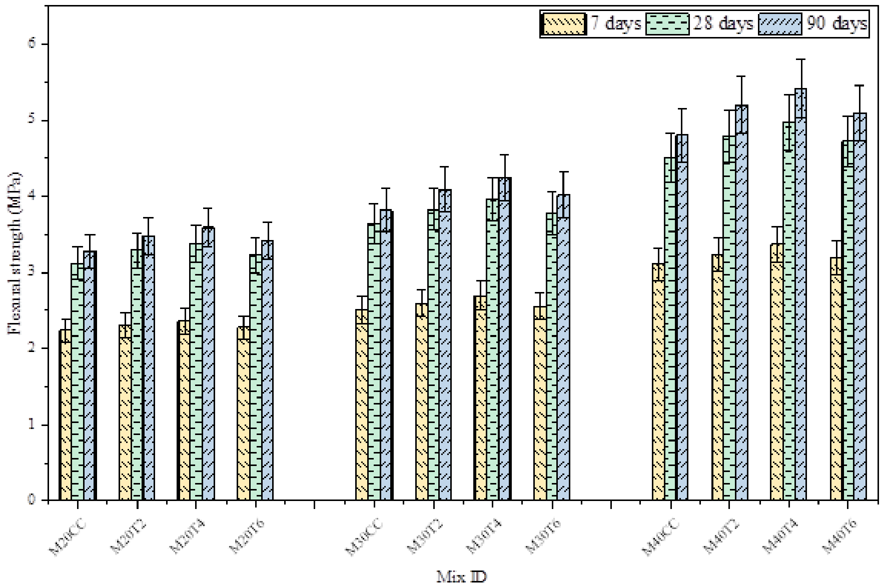


Fig. 13. Flexural strength of concrete at different curing ages with varying nano-titanium dioxide contents

However, beyond the optimum replacement level of 4%, a marginal reduction in flexural strength was observed in both NS- and NT-modified concrete mixes. This reduction may be attributed to nanoparticle agglomeration caused by the extremely high specific surface area of nano-materials, which reduced dispersion efficiency and created localized weak zones within the concrete matrix. Excessive nano-material incorporation also increased water demand and affected the uniformity of hydration product distribution, thereby limiting further enhancement in flexural performance. Overall, the comparative analysis confirms that both nano-titanium dioxide and nano-silica significantly improved the mechanical properties of concrete, with optimum performance consistently observed at 4% replacement. Among the two nano-materials, nano-titanium dioxide demonstrated comparatively superior performance in compressive, split tensile, and flexural strength, indicating its greater effectiveness in enhancing the overall mechanical behavior, crack resistance, and structural integrity of concrete [36]. The percentage-based evaluation further underscores the practical significance of these improvements and demonstrates the potential of nano-modified concrete for developing high-performance construction materials with improved mechanical properties under the present testing conditions.

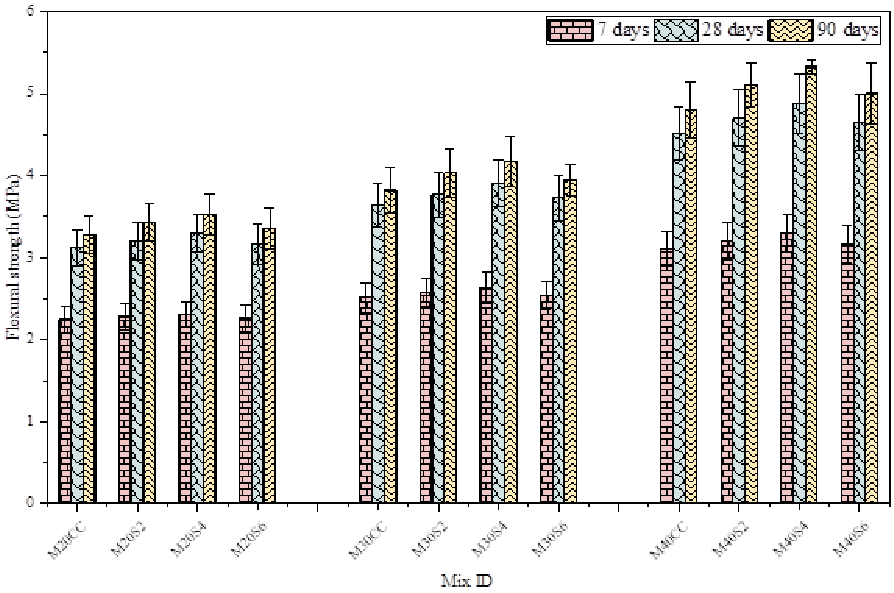
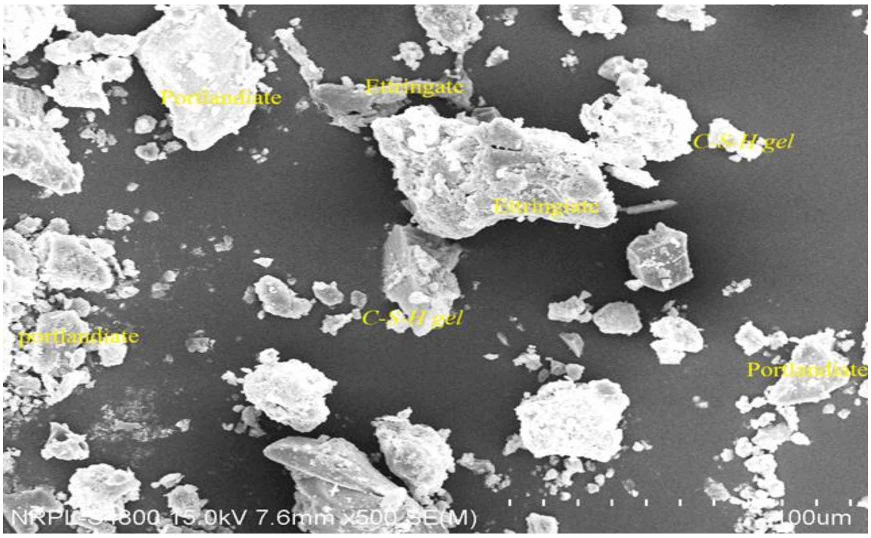


Fig. 14. Flexural strength of concrete at different curing ages, illustrating the influence of varying nano-silica replacement levels on strength development

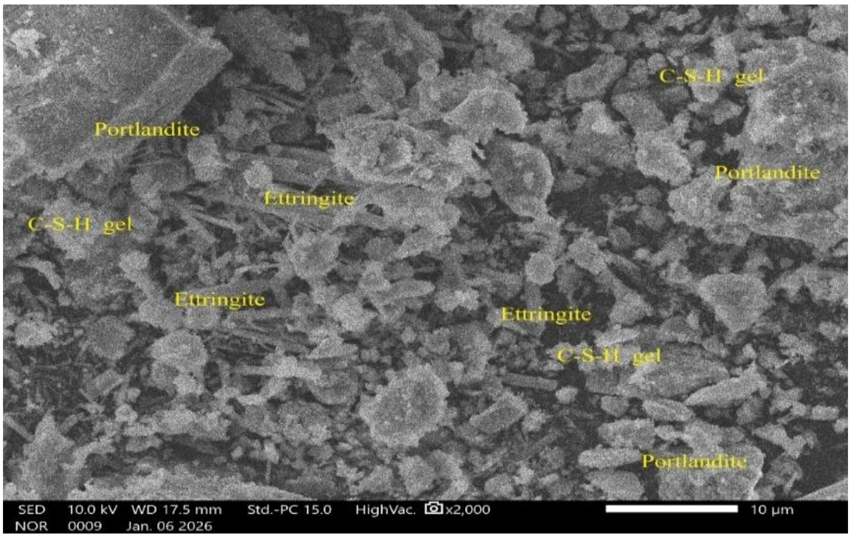
The results indicate that both nano-silica and nano-titanium dioxide are compatible with conventional Portland cement-based concrete and can be incorporated using standard concrete production practices, demonstrating their potential for structural applications under normal service conditions. A comparison of early-age and 28-day strength development indicates that nano-modified concretes exhibited accelerated hydration during the initial curing period, resulting in higher early-age strength than the corresponding control mixes. Continued curing further enhanced strength development across all concrete grades through ongoing cement hydration, secondary C–S–H formation (for nano-silica), and progressive pore refinement and matrix densification. Although similar hydration trends were observed for M20, M30, and M40 concretes, the higher-grade mixes exhibited relatively greater strength enhancement due to their denser cementitious matrix, which enabled the nano-materials to contribute more effectively to hydration product development and microstructural refinement.

6. Microstructural Investigations Using Scanning Electron Microscopy

The SEM micrograph of mix M20S4, as shown in Figure 15, shows a dense and homogeneous matrix dominated by C–S–H gel with reduced portlandite ($Ca(OH)_2$) crystals and fewer micro-voids. The incorporation of 4% nano-silica enhances the microstructure due to its high surface area and strong pozzolanic reactivity. Nano-silica reacts with $Ca(OH)_2$ released during cement hydration to form additional secondary C–S–H gel, leading to matrix densification and pore refinement. Moreover, nano-silica acts as a nucleation site, accelerating early hydration and improving ITZ bonding. The reduced presence of large CH crystals and improved packing of hydration products confirm enhanced microstructural compactness. Therefore, the SEM results indicate that Figure 15 (a) shows improved strength and durability performance of the 4% nano-silica M20 concrete mix. The enhanced microstructural densification can be attributed to the high surface area and pozzolanic reactivity of nano-silica, which promotes the formation of additional C–S–H gel and contributes to matrix densification and pore refinement. Nano-silica promotes a pozzolanic reaction by consuming $Ca(OH)_2$ and generating additional C–S–H gel. At the same time, nano-titanium dioxide acts predominantly as a nucleation site, accelerating hydration and facilitating uniform precipitation of hydration products. These mechanisms contribute to pore refinement and improved ITZ quality, resulting in a denser and more compact cementitious matrix.



(a)



(b)

Fig. 15. (a)FESEM Control Mix of M40 and (b) FESEM of mix M20S4

The SEM image of the control mix shows the formation of the primary hydration products, including C–S–H gel, ettringite, and portlandite (CH). The well-developed C–S–H gel indicates effective cement hydration and contributes to strength development, while the presence of ettringite confirms normal hydration. Portlandite crystals are also observed, indicating adequate hydration of the cement paste. Overall, the control mix exhibits a well-hydrated and stable microstructure with a continuous cementitious matrix.

The SEM image of M30S4 with nano-silica, shown in Figure 16, reveals a relatively dense and compact microstructure with abundant C–S–H gel and fewer $Ca(OH)_2$ crystals compared with the control mix. These observations suggest that the incorporation of nano-silica may have promoted pozzolanic activity, leading to the formation of additional C–S–H gel and a reduction in $Ca(OH)_2$. The fine particle size and high surface area of nano-silica may also provide nucleation sites that are consistent with enhanced hydration. The reduced micro-voids and improved interfacial transition zone (ITZ) observed in the SEM images indicate a more compact cement matrix. Overall, the SEM observations suggest that nano-silica contributes to improved microstructural compactness, which may be associated with enhanced mechanical performance and potential durability improvement;

however, this aspect requires verification through dedicated durability tests. Compared with the control mix, M30S4 exhibits a denser and more homogeneous cement matrix with increased C–S–H gel, fewer portlandite crystals, reduced porosity, and a more compact ITZ. These qualitative observations are consistent with improved microstructural development associated with nano-silica incorporation.

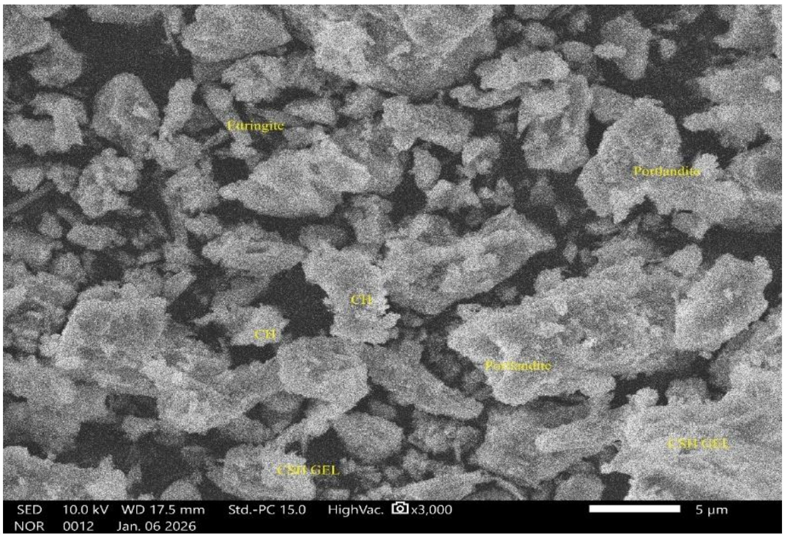


Fig. 16. FESEM of mix M30S4

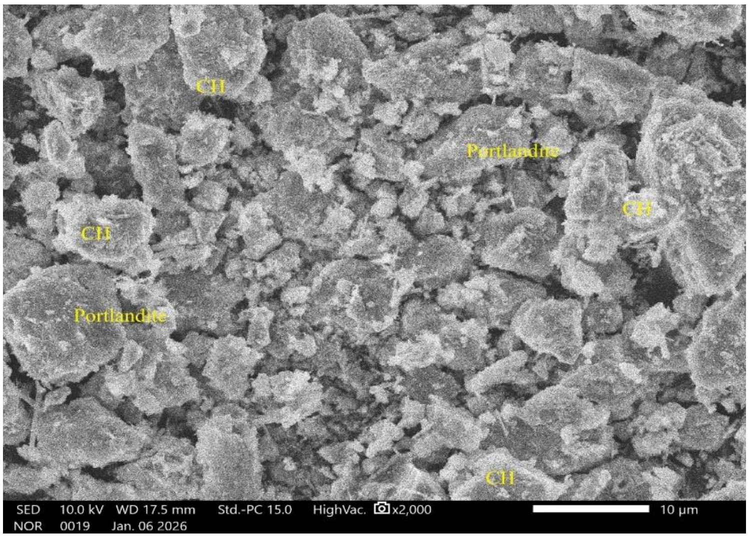


Fig. 17. FESEM of M40S4

The SEM image of M40S4 concrete mix with nano-silica, shown in Figure 17, reveals a very dense, compact microstructure with continuous C–S–H gel and minimal $Ca(OH)_2$ crystals. The reduction in portlandite confirms the pozzolanic reaction of nano-silica, which forms additional secondary C–S–H gel. The nano-silica particles also act as nucleation sites, accelerating hydration and refining the pore structure. Reduced micro-voids and improved ITZ bonding indicate enhanced matrix densification. Overall, the microstructure confirms improved strength and durability performance of M40 nano-silica concrete. The dense microstructure further indicates enhanced hydration kinetics, increased secondary C–S–H formation, pore refinement, and improved mechanical performance. Compared with the control mix, M40S4 exhibits a more compact and homogeneous microstructure with a higher amount of C–S–H gel, fewer portlandite crystals, reduced pore spaces, and a denser ITZ, demonstrating superior matrix densification and enhanced mechanical and durability characteristics.

The SEM image of the M20T4 mix shown in Figure 18 reveals a dense, compact microstructure with reduced pore size and improved matrix continuity. A well-developed C–S–H gel phase is observed, indicating enhanced hydration. The ITZ appears refined, with fewer microcracks and voids. This improvement is attributed to the nucleation and filler effects of nano-materials. Nano-particles provide additional nucleation sites, accelerating C–S–H formation and refining pores. Limited pozzolanic interaction may further contribute to matrix densification. The observed microstructural densification is primarily attributed to the nucleation and filler effects of nano-TiO_2, which accelerate cement hydration and promote C–S–H gel development. Consequently, pore refinement and improved ITZ bonding enhance compressive, tensile, and flexural performance while contributing to long-term durability. Compared with the control mix, M20T4 exhibits a denser microstructure with increased C–S–H gel, reduced pores, a refined ITZ, and improved matrix continuity, indicating enhanced mechanical and durability performance.

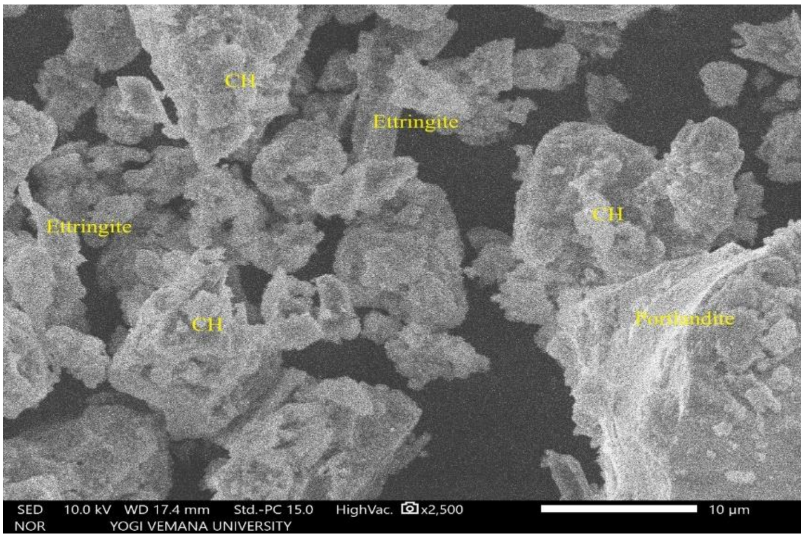


Fig. 18. FESEM of M20T4

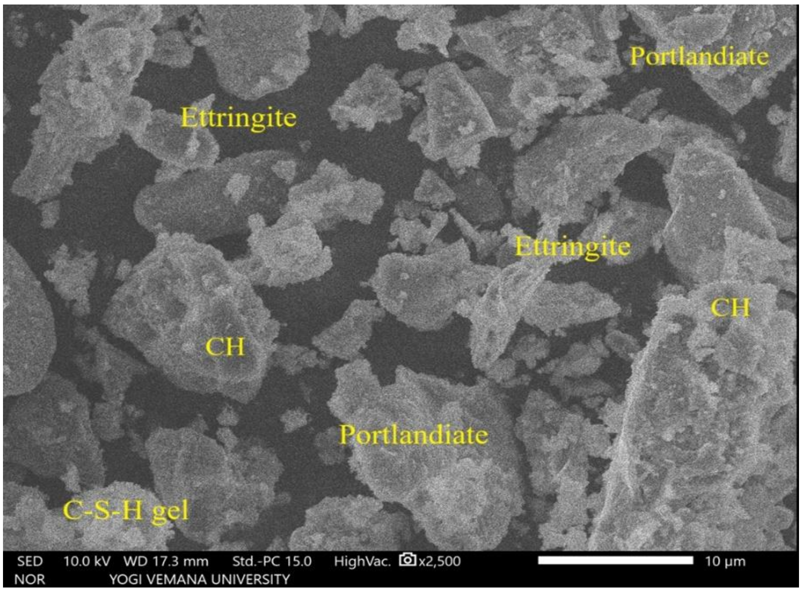


Fig. 19. FESEM of M30T4

The SEM micrograph of M30T4 shown in Figure 19 reveals a hydrated matrix dominated by C–S–H gel with identifiable ettringite and portlandite/CH crystals. The matrix appears comparatively compact with fewer discontinuities at the observed scale (~10 μm). The 4% nano TiO_2 primarily contributes through nucleation and micro-filler effects, promoting uniform hydration product distribution and improved matrix continuity. The visible CH indicates that TiO_2 largely behaves as an inert nano-addition rather than a strongly pozzolanic material. The enhanced hydration kinetics induced by nano-TiO_2 nucleation sites facilitate increased C–S–H gel development and pore structure refinement. This improved microstructural continuity strengthens the ITZ and aggregate–paste bonding, thereby contributing to the observed improvements in compressive, split tensile, and flexural strength, and durability performance. Compared with the control mix, M30T4 exhibits a denser matrix, higher C–S–H content, refined ITZ, reduced porosity, and improved overall performance.

The M40T4 mix shown in Figure 20 exhibits a dense and relatively homogeneous microstructure with reduced pore connectivity. Well-developed C–S–H gel is evident along with ettringite and CH crystals. Compared to lower replacement levels, M40T4 shows improved matrix compactness and a refined ITZ, indicating enhanced aggregate–paste bonding. The nano TiO_2 enhances hydration kinetics and particle packing through nucleation and filler effects. The enhanced microstructural compactness observed in M40T4 is attributed to the nucleation and micro-filler effects of nano-TiO_2, which accelerate cement hydration and promote the formation of a dense C–S–H gel network. Consequently, pore refinement and improved ITZ characteristics strengthen aggregate–paste bonding, contributing to the observed enhancement in compressive, split tensile, and flexural strengths, as well as improved durability performance. Compared with the control mix, M40T4 exhibits a denser microstructure, increased C–S–H gel, refined ITZ, reduced pore connectivity, and improved overall performance.

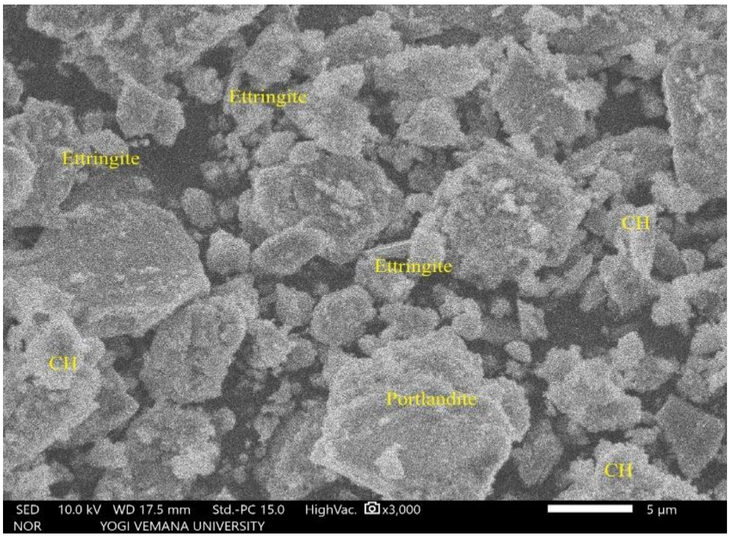


Fig. 20. FESEM of M40T4

The SEM observations suggest that the incorporation of nano-silica and nano-TiO_2 is associated with improved microstructural densification. The SEM images show increased C–S–H gel, reduced visible pore connectivity, and a more compact interfacial transition zone (ITZ), which are consistent with a denser cement matrix and improved aggregate–paste bonding. These qualitative observations may help explain the higher compressive, split tensile, and flexural strengths observed up to the 4% replacement level. At higher replacement levels, the SEM images indicate less uniform particle distribution, which may be associated with nanoparticle agglomeration and could have limited further microstructural refinement and strength development. The proposed mechanisms, including nucleation, filler, and pozzolanic effects, are presented as possible interpretations based on the SEM morphology and have not been independently verified by complementary microstructural analyses.

The nucleation effect of nano-TiO_2 promotes a more uniform precipitation and distribution of hydration products throughout the cementitious matrix. This improved continuity of the C–S–H gel network is consistent with the denser microstructure observed in the SEM images and the corresponding enhancement in compressive, split tensile, and flexural strengths. The SEM observations indicate that nano-silica and nano-TiO_2 are compatible with conventional Portland cement systems, producing a compact and homogeneous microstructure, supporting their potential use in concrete under normal service conditions.

7. Conclusions

- Fresh concrete behavior, as evaluated by the slump test, showed a progressive reduction in workability with increasing concrete grade (M20–M40), mainly due to the reduction in the water–cement ratio, which resulted in stiffer and less flowable mixes.
- The incorporation of nano-titanium dioxide and nano-silica further reduced the slump values because of their high specific surface area and ultra-fine particle size. Among the two nanomaterials, nano-silica exhibited a greater reduction in workability due to its higher reactivity and greater water demand.
- The compressive strength increased with both higher concrete grades and longer curing periods, indicating enhanced hydration and progressive densification of the cementitious matrix with time.
- The incorporation of nano-titanium dioxide and nano-silica significantly enhanced compressive strength, with the 4% replacement level producing the highest mean compressive strength values under the present experimental conditions across all grades of concrete. Nano-titanium dioxide exhibited comparatively higher strength enhancement than nano-silica, demonstrating its superior efficiency in improving matrix densification and hydration kinetics.
- The improvement in compressive strength is attributed to the micro-filling and nucleation effects of nano-titanium dioxide, along with the pozzolanic reactivity of nano-silica, which promotes the formation of additional C–S–H gel. These mechanisms refine the pore structure, reduce micro-voids, and improve the compactness and durability of the concrete matrix.
- The incorporation of nano-materials resulted in noticeable enhancement in split tensile strength for all concrete grades and curing ages compared to conventional concrete, confirming their effectiveness in improving tensile resistance and crack control characteristics.
- The optimum split tensile strength was obtained at a 4% replacement level, where a denser microstructure and stronger paste–aggregate interfacial bonding were achieved. Beyond this dosage, the tensile and compressive strengths showed marginal reduction due to nanoparticle agglomeration and loss of matrix homogeneity.
- Flexural strength also improved with the addition of nano-titanium dioxide and nano-silica, particularly at later curing ages. The enhancement is mainly associated with improved matrix cohesion, pore refinement, and stronger interfacial transition zone (ITZ) bonding, which collectively enhanced crack resistance and load transfer capacity.
- From a practical perspective, the findings of this study demonstrate that controlled incorporation of nano-materials, particularly at a 4% replacement level, can be effectively utilized for the development of high-performance concrete with improved compressive strength. The enhanced mechanical performance and microstructural observations indicate the potential of nano-modified concrete for structural applications requiring higher load-carrying capacity and improved crack resistance. However, the reduction in workability highlights the necessity for appropriate mix design adjustments and the use of superplasticizers to ensure adequate fresh concrete performance during field implementation.
- The study also highlights that, under the present testing conditions, concrete incorporating nano-titanium dioxide exhibited higher mean compressive, tensile, and flexural strength values than concrete containing nano-silica. These findings indicate the potential of nano-titanium dioxide for enhancing the mechanical performance of cement-based composites.
- Across all concrete grades (M20, M30, and M40), both nano-silica and nano-titanium dioxide improved mechanical performance, with nano-titanium dioxide consistently exhibiting greater enhancement at the optimum 4% replacement level under the present experimental conditions.

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