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Original Article

Optimizing the Performance of Barite Concrete with Nano-Additives: A Sustainability Approach

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Abstract - *Growing emphasis on sustainable construction practices has led to increased interest in incorporating alternative mineral-based materials into concrete formulations. Although barite powder is commonly known for its application in radiation shielding, its potential as a partial cement substitute remains largely unexplored due to uncertainties regarding its impact on hydration kinetics, ettringite stability, and long-term performance. This research investigates the combined effect of barite powder with Nano-Silica (NS) and Nano-Titania (NT) on enhancing both the mechanical behavior and internal structure of concrete. Barite was introduced as a partial cement replacement at dosage levels of 0%, 5%, 10%, 15%, and 20%, while NS and NT were consistently incorporated at 1% by weight of cement. Workability was evaluated using standard slump and compaction factor tests. Compressive and split tensile strengths were determined at curing ages of 7, 14, and 28 days. Microstructural evolution and hydration products were also characterized through Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). The findings demonstrate that the incorporation of barite powder resulted in improved workability, with a 5% substitution leading to enhanced strength by promoting densification of the matrix and a reduction in porosity. Nevertheless, an increase in replacements resulted in a reduction of strength attributed to the formation of secondary ettringite. The optimal performance was observed at 5-15% barite with NS and NT, where improved microstructure and enhanced C-S-H gel formation were evident. Statistical validation using one-way ANOVA confirmed the significance of barite content combined with NS particles and curing age on mechanical performance. The combined use of nanomaterials and barite yielded superior strength and durability compared to their individual application.*

Keywords - *Barite powder, Nano-silicon dioxide, Nano-titanium dioxide, fresh properties, Mechanical properties, Microstructure, Synergistic effect, ANOVA.*

1. Introduction

The construction sector is increasingly challenged to reduce its environmental footprint while maintaining material performance and economic viability [1]. Cement production, in particular, accounts for a significant proportion of global CO_2 emissions due to its energy-intensive manufacturing process [2]. As a response, researchers have investigated various Supplementary Cementitious Materials (SCMs) to partially replace cement partially, thereby enhancing the sustainability of concrete [3].

One such promising material is barite powder, a naturally occurring barium sulfate mineral found abundantly in the Kadapa region of Andhra Pradesh, India. Traditionally used for radiation shielding in the medical and nuclear sectors due to its high density, barite has recently gained attention for its role in modifying concrete properties [4-5].

Barite's utilization in concrete offers a sustainable alternative to conventional materials by increasing mix density and potentially improving long-term durability. However, its low pozzolanic activity and tendency to form expansive hydration products such as ettringite, particularly under sulfate-rich conditions, pose challenges related to strength development and microcracking [6-8]. These limitations necessitate modification strategies to enhance the performance of barite-blended cementitious systems.

To overcome these limitations and improve barite-blended concrete's microstructural and mechanical behavior, nano-engineering strategies are increasingly being employed. Nano Silica (NS) and Nano Titanium dioxide (NT) are two well-researched nano-additives that can alter the hydration kinetics and microstructure of cement composites [9, 10].

The development of C–S–H contributes significantly to the structural integrity as well as the long-term performance of the cement matrix. Conversely, NT enhances photocatalytic activity and facilitates early-age strength development by acting as a nucleation site during hydration [11]. When combined with barite, these nanomaterials potentially mitigate microstructural weaknesses and refine pore structure, thereby improving mechanical behavior and service life [12].

Numerous studies have shown that incorporating NS and NT enhances concrete's mechanical strength, durability, and functional properties [13-19]. NS improves compressive strength and reduces permeability by promoting C–S–H formation [16, 19-21], while NT adds mechanical benefits and self-cleaning properties due to its photocatalytic action [20-21].

However, their effectiveness is dosage-dependent; excessive amounts can impair workability and lead to particle agglomeration. Hence, optimizing the dosage, typically within 0.5–2% by cement weight, is critical to achieving balanced performance [19-21].

The synergistic use of barite with nanomaterials like NS and NT has been explored to a limited extent. Preliminary findings suggest this combination can improve workability, suppress ettringite formation, and reduce microcracking due to better packing density and hydration control [6-22].

Furthermore, nano-additives can influence sulphate reaction kinetics, thereby reducing the risk of expansion-related damage associated with barite incorporation at higher dosages [23]. The increased surface area contributes to reduced mixing water demand relative to cement content, which in turn promotes a more compact internal structure and improved mechanical strength [24].

Nevertheless, identifying the optimal dosage and understanding the combined effects of barite with nanomaterials remains a key research gap. Moreover, only a few investigations have thoroughly assessed these material blends through robust statistical evaluation. To ascertain the impact of different mix design factors on mechanical properties, analytical techniques such as Analysis of Variance (ANOVA) need to be used.

This method provides a methodical framework for performance optimization by making it easier to analyze the quantitative variations produced by curing times and material compositions [25, 26].

This research explores the influence of Nano-Silica (NS) and Nano-Titania (NT) on the fresh, mechanical, and microstructural characteristics of concrete formulated with barite as a partial cement replacement. At different curing ages, compressive and tensile strength were assessed. Energy Dispersive X-ray Analysis (EDAX) and Scanning Electron Microscopy. An analysis of variance (ANOVA) was used to statistically validate the effects of curing time and nano-additives on the observed properties.

The objective is to establish an optimized mix design that combines barite's environmental and performance advantages with nanoscale additives to produce durable, high-quality concrete suited for sustainable construction.

2. Methodological Approach

2.1. Materials Incorporated

OPC was used as the main binder in the concrete mix. The cement had a specific gravity of 3.15 and fineness of 8.3. Barite powder was used as a partial cement substitute and was sourced from the Kadapa region of Andhra Pradesh. The barite that was utilized had a particle fineness of 6% and a measured specific gravity of 4.2. Nano-Silica (NS) with a mean particle size of 17 nm and a surface area of 202 m^2/g was obtained from Astrra Chemicals in Chennai, India.

Nano-Titanium dioxide (NT), primarily in anatase form with an average particle size of 25 nm, was obtained from Vedayukt India Pvt. Ltd., Jharkhand, India and with a specific surface area of 100 m^2/g was employed to enhance the performance characteristics of the concrete matrix. Potable water was used to mix and cure the concrete samples. The fine aggregate incorporated into the mix exhibited a specific gravity of 2.55, a fineness modulus of 2.6, and a water absorption capacity of 0.74%. Crushed granite, utilized as the coarse aggregate, had a maximum particle size of 20 mm, a specific gravity of 2.7, a fineness modulus of 5.6, and a water absorption rate of 0.35%. Conplast SP430 superplasticizer was incorporated at 1% of the cement weight to improve the mix's workability.

2.2. Mix Proportioning

A total of 15 concrete mixtures were designed to achieve M40 grade strength, all prepared with a fixed water-to-binder ratio of 0.32. This ratio was arrived at based on the guidelines provided in IS 10262:2019 and IS 456:2000, which recommend lower water-cement ratios (≤0.35) for higher-grade concretes to ensure adequate strength and durability.

A value of 0.32 was selected to balance workability with the targeted compressive strength of 40 MPa. Barite powder was incorporated at substitution rates of 0%, 5%, 10%, 15%, and 20% based on the cement mass, while NT and NS particles were employed as an additive at a fixed dosage of 1% NS and NT was selected based on studies that identifies 1% as the optimum level for improving the microstructure and mechanical properties of concrete without causing particle agglomeration [10, 12, 27, 28].

A control mix without barite powder and nano additives was also prepared for comparison. The detailed mix proportions and their designations for all the mixes were presented in Table 1.

2.3. Mixing, casting and curing

Concrete mixes were shaped in 150 mm cubes for compressive testing and in 150 mm × 300 mm cylinders to determine split tensile strength. After a 24-hour initial setting period, the specimens were demoulded and placed in a curing tank with water regulated at 27 ± 2 °C, where they remained for 7, 14, and 28 days.

Table 1. Mix proportions and designations of concrete

S.NO	Mix designation	Cement Kg/m^3	Barites Powder Kg/m^3	NS Kg/m^3	NT Kg/m^3	FA Kg/m^3	CA Kg/m^3	Water Kg/m^3	SP Kg/m^3
1	CM	400	0	0	0	731	1239	128	4
2	BC1	380	20	0	0	731	1239	128	4
3	BC2	360	40	0	0	731	1239	128	4
4	BC3	340	60	0	0	731	1239	128	4
5	BC4	320	80	0	0	731	1239	128	4
6	NS	400	0	4	0	731	1239	128	4
7	BNS1	380	20	4	0	731	1239	128	4
8	BNS2	360	40	4	0	731	1239	128	4
9	BNS3	340	60	4	0	731	1239	128	4
10	BNS4	320	80	4	0	731	1239	128	4
11	NT	400	0	0	4	731	1239	128	4
12	BNT1	380	20	0	4	731	1239	128	4
13	BNT2	360	40	0	4	731	1239	128	4
14	BNT3	340	60	0	4	731	1239	128	4
15	BNT4	320	80	0	4	731	1239	128	4

Fig. 1 Preparation and testing of the samples

2.4. Tests Conducted

The Fresh concrete behaviour was assessed through the slump and compaction factor, and was performed (as per IS 1199:1959) immediately after mixing the concrete. A total of 135 cube and cylindrical specimens were cast and tested for compressive and split tensile strength after 7, 14, and 28 days of curing, as illustrated in Figure. 1.

Following 28 days of curing, the fractured surfaces of samples CM, BC1, BC4, BNT1, BNT4, BNS1, and BNS4 SEM analysis was conducted to investigate surface characteristics and internal matrix evolution, towards the development of C–S–H gel throughout cement hydration. Energy Dispersive X-ray Spectroscopy (EDAX) was employed to examine the elemental composition, specifically calcium and silicon, to identify hydration products. This combined SEM and EDAX approach has been validated in previous studies as a reliable technique for investigating hydration behaviour in cementitious systems incorporating nanomaterials [12, 27].

2.5. ANOVA Analysis

One-way ANOVA was performed using Python in Google Colab to assess the effect of curing age on compressive and split tensile strength. Each mix CM, Barites (BC), NT, NS, Barites+NT, and Barites+NS was analyzed independently to determine statistical significance ($p < 0.05$).

3. Results and Discussions

3.1. Fresh Properties

The assessment of workability variations, based on slump and compaction factor tests across different concrete mixes, was carried out using MATLAB, and the corresponding results are displayed in Figures 2, 3, and 4. According to IS 1199:1959, a slump value between 50–100 mm is considered to indicate medium workability. The Control Mix (CM) recorded a slump of 98 mm, which falls within this range, thereby indicating moderate workability. With the inclusion of 5% barite as a partial cement replacement (BC1), the slump increased to 112 mm, indicating the high slump concrete and suggesting an improvement in flowability due to the fine particle nature of barite powder. Further, it was increased with the addition of barite powder. The highest slump value of 172 mm was observed at 20% barite (BC4), indicating excessive fluidity.

This could lead to segregation and bleeding, affecting the structural integrity of the concrete. The Control Mix (CM) compaction factor is 0.88, indicating a relatively cohesive mix. Mix BC1 shows an improvement with the inclusion of barite powder. The compaction factor of all the mixes improved with the addition of barite powder. The maximum value was obtained at BC4 of 0.94 mm, indicating the highly workable concrete. As observed in Figure 3, the NT mix exhibited a slump value of 80 mm and a compaction factor of 0.87, which corresponds to a moderate level of workability. The workability showed a gradual increase from BNT1(95mm and 0.89) to BNT4(120mm and 0.91) due to the presence of barite powder, which enhanced flowability. In contrast, NT alone did not significantly improve workability, as its high surface area increased water demand [27, 29], leading to a lower slump and compaction factor. Figure 4 illustrates that the NS mix achieved a slump measurement of 82 mm and a compaction factor of 0.86, which corresponds to intermediate workability characteristics. However, NS inclusion shows a reduction in workability compared to the

NT mix and CM. This is because the smaller particle size of NS particles with high surface area increases water demand and reduces the workability. The workability showed a gradual. Increase from BNS1(90mm and 0.86) to BNS4(115mm and 0.91) due to the presence of barite powder, which can be attributed to the presence of barite powder that enhances flowability through its filler effect and to the inclusion of a 1% superplasticizer, which significantly improves particle dispersion and reduces internal friction among cementitious constituents.

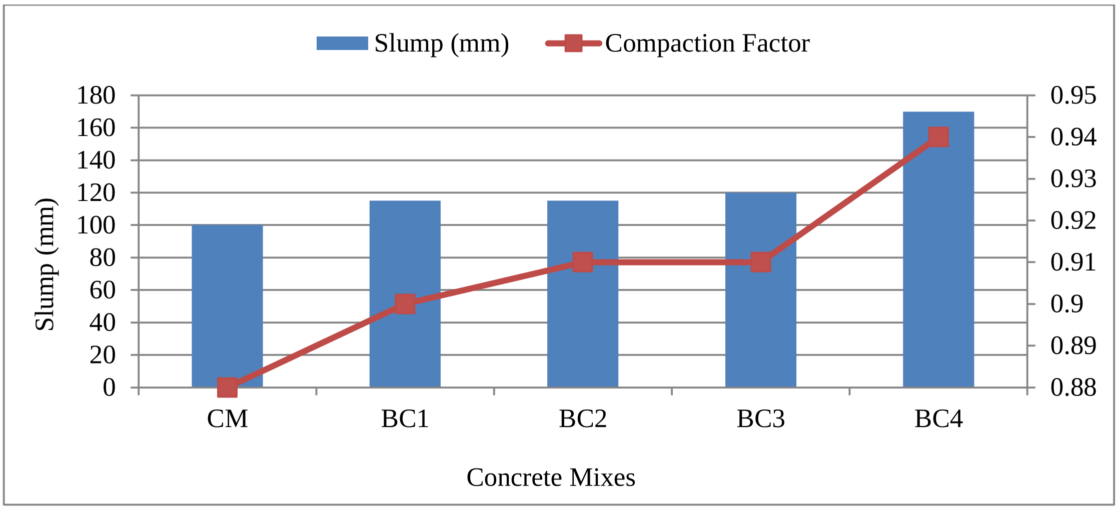


Fig. 2 Variation of workability for BC mixes

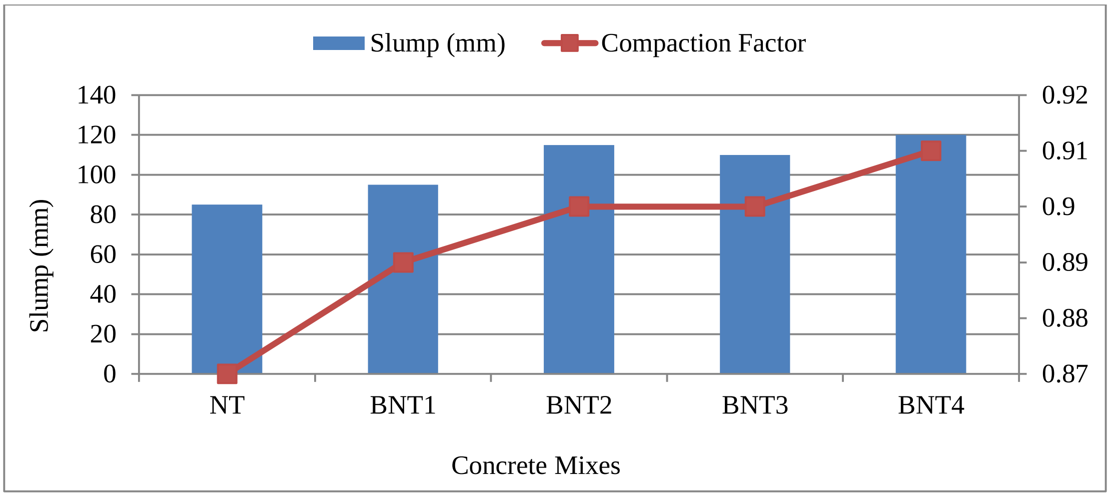


Fig. 3 Variation of workability for BNT mixes

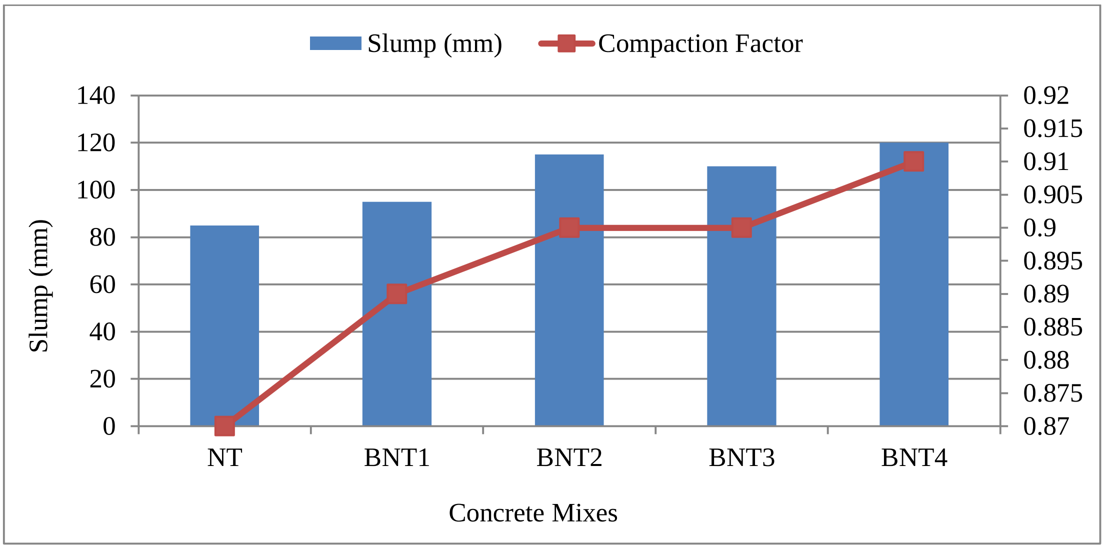


Fig. 4 Workability variation for BNS mixes

3.2. Compressive Strength

The development of compressive strength in concrete containing barite, observed at 7, 14, and 28 days of curing, is shown in Figure 5. The 28-day compressive strength values for all mixes CM, BC1, BC2, BC3 and BC4 are recorded as 48.37 MPa, 52.84 MPa, 50.89 MPa, 49.11 MPa and 48.46 MPa, respectively. The CM, BC1, BC2, BC4, and BC3 values surpass the target compressive strength of 48.26 MPa. Compared to the target compressive strength, the BC4 mix declined. The maximum compressive strength was observed with the BC1 mix of 52.84 MPa. To strengthen the microstructure and utilization of barite powder in concrete, NT and NS particles were integrated into the barite concrete.

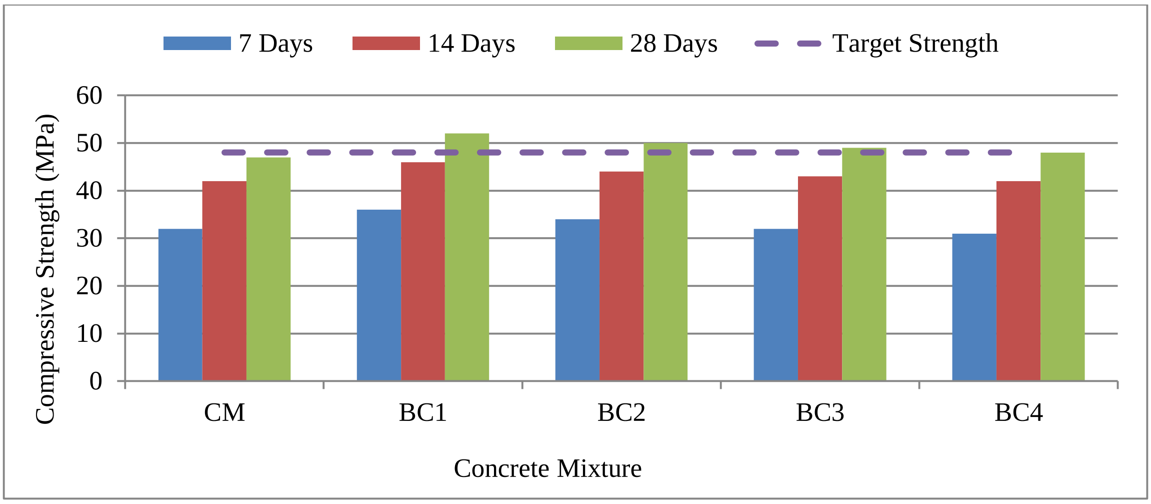


Fig. 5 Comparative compressive strength performance of BC mixes

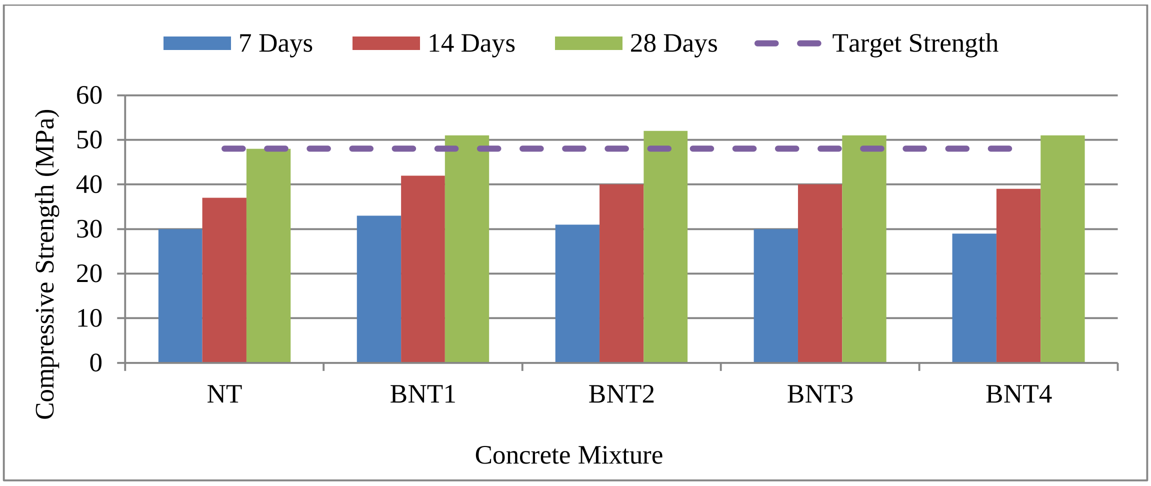


Fig. 6 Comparative compressive strength performance of BNT mixes

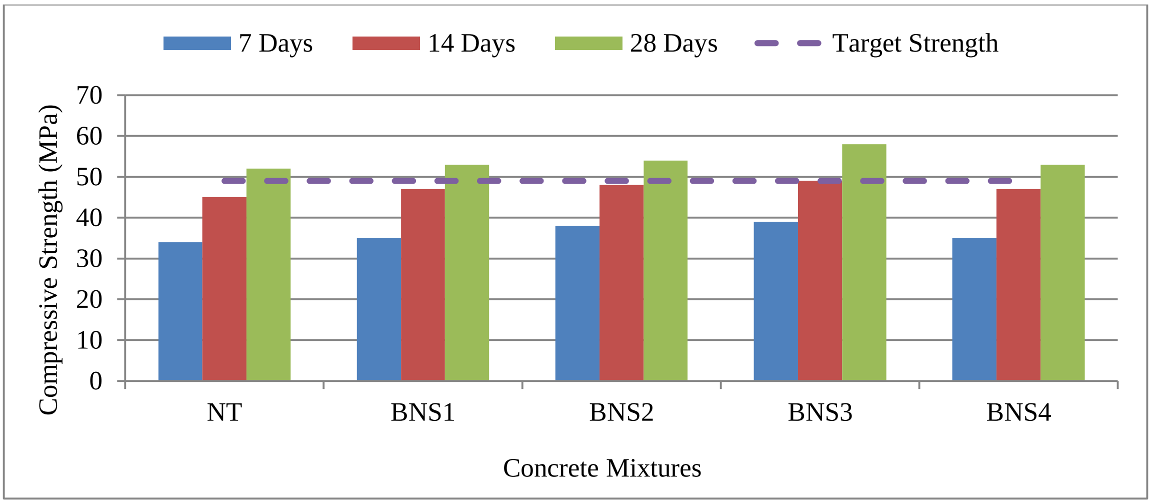


Fig. 7 Comparative compressive strength performance of BNTS mixes

Figures 6 and 7 depict the effect of incorporating NT and NS on the compressive performance of barite-based concrete across different curing durations. The compressive strength measured at 28 days for NT, BNT1, BNT2, BNT3, and BNT4 was found to be 49.78 MPa, 53.59 MPa, 51.2 MPa, 50.4 MPa, and 49.72 MPa, respectively. All concrete mixtures achieved compressive strengths above the specified target of 48.26 MPa. The maximum compressive strength was obtained at the BNT1 mix as 53.59 MPa. Because (NT) functions as an inert fine filler that contributes to porosity reduction in cementitious composites. Due to its non-pozzolanic nature, NT does not partake in chemical hydration reactions; however, it significantly enhances the homogeneity of the cement matrix, leading to improved microstructural integrity [30].

The enhancement in the microstructural integrity of concrete is primarily attributed to the nanoscale dimensions and elevated surface area of NT, which enhance the packing density and promote a more homogeneous and compact cementitious matrix [12]. This densification contributes to better mechanical performance. Figure 4 illustrates the 28-day compressive strength values for the NS, BNS1, BNS2, BNS3 and BNS4 mixtures, which are 51.98 MPa, 52.71 MPa, 54.62 MPa, 57.78 MPa, and 52.93 MPa, respectively, demonstrating that the incorporation of these materials positively influenced the strength development of the concrete. From Figure 4, the 28-day compressive strength results of mixes NS, BNS1, BNS2, BNS3 and BNS4 are obtained as 51.98MPa, 52.71MPa, 54.62 MPa, 57.78 MPa, and 52.93MPa, respectively. Each mix demonstrated a compressive strength greater than the specified target of 48.26 MPa.

BNS3 recorded the highest compressive strength of 57.78 MPa among all the mixes. This improvement is attributed to the pronounced pozzolanic activity of NS, which actively reacts with Calcium Hydroxide (CH) formed as a byproduct of cement hydration. The reaction facilitates the formation of supplementary C–S–H gel, resulting in a compact and refined matrix microstructure. The enhanced efficiency of nano-silica can be linked to its large specific surface area and non-crystalline form, both of which accelerate initial hydration reactions and support early strength gain [28, 31].

3.3. Split Tensile Strength

Figures 8, 9, and 10 depict the split tensile strength progression of concrete blends containing barite along with NT and NS, evaluated at curing periods of 7, 14, and 28 days. All mixes show progressive strength gain with the curing age. From Figure 8, the split tensile strength of mixes CM, BC1, BC2, BC3 and BC4 after 28 days is 4.72MPa, 5.16MPa, 4.97MPa, 4.78MPa, and 4.68MPa. Mix BC1 exhibits the maximum split tensile strength of 5.16 MPa, and further, it was decreased with the addition of barite powder.

However, mixing BC2 and BC3 yields better performance than the control mix. Mixes NT, BNT1, BNT2, BNT3 and BNT4 are shown in Figure 9. produces the split tensile strength of 4.87MPa, 5.29MPa, 4.98MPa, 4.86MPa and 4.76MPa respectively. Mix NT produces a better improvement of 4.87 MPa, in comparison to the control mix. This may indicate enhanced performance due to the presence of nano titanium particles. The maximum split tensile strength was obtained with the BNT1 mix of 5.29 MPa, and it decreased slowly; however, all the mixes yielded good performance in comparison to the control mix.

From Figure 10, after 28 days of curing, the mixes NS, BNS1, BNS2, BNS3 and BNS4 exhibit a split tensile strength of 5.20MPa, 5.38 MPa, 5.46 MPa, 5.78 MPa, and 5.29 MPa, respectively. The reference mix NS produces the better performance with NS particle integration to the concrete; in comparison to the reference mix, this integration also yields good performance for all the mixes containing barite powder. BNS3 yields the highest split tensile strength of 5.78 MPa.

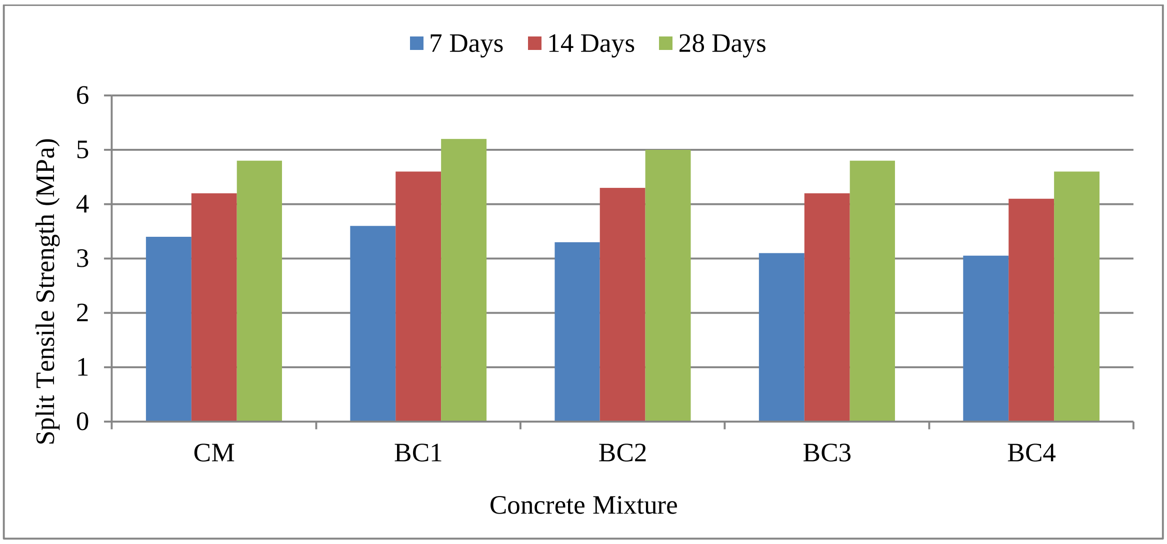


Fig. 8 Comparative split tensile strength performance of BC mixes

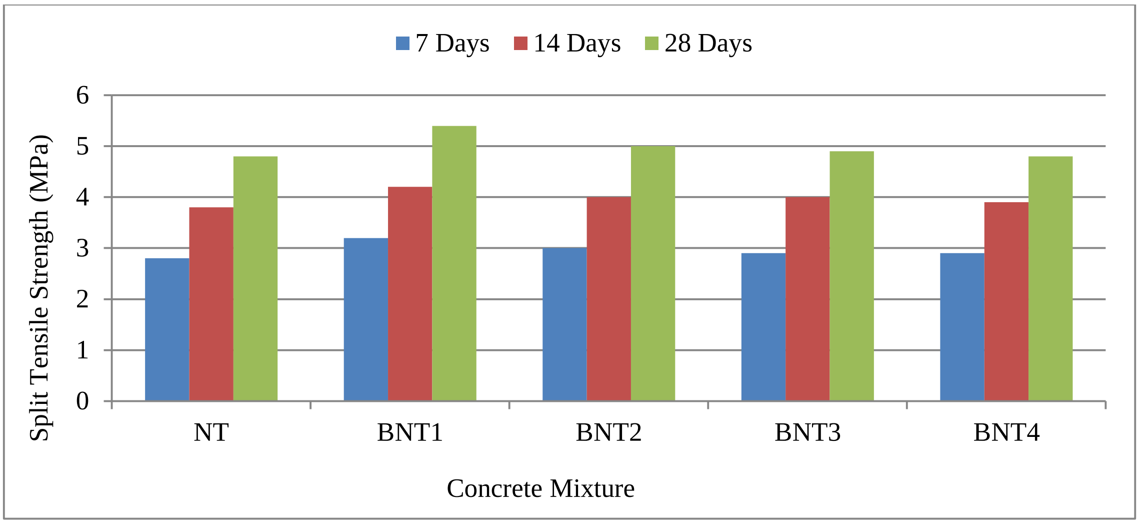


Fig. 9 Comparative split tensile performance of BNT mixes

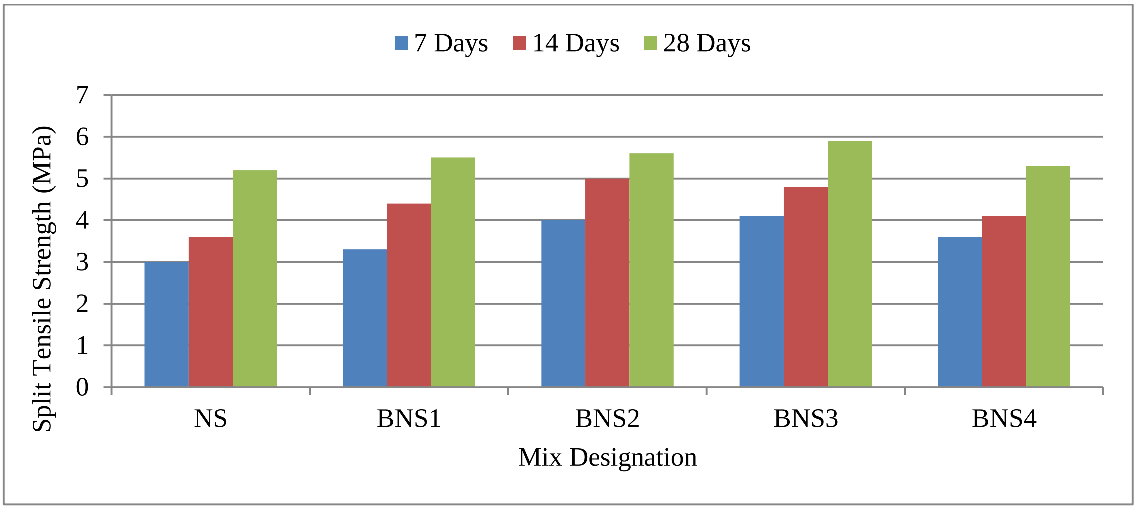


Fig. 10 Comparative split tensile strength performance of BNS mixes

3.4. Weight Density

Figures 11, 12 and 13 represent the variation of fresh and dry density of BC, BNT and BNS concrete mixtures, respectively. From the Figure 11 CM's fresh and dry concrete densities are 2557 kg/m³ and 2447 kg/m³, respectively. The fresh concrete density was increased from CM (2557 kg/m³) to BC4 (2703 kg/m³). This is due to the addition of barite powder, a high-density material that enhances the bulk density of concrete in its fresh state. The dry density also follows a similar trend from CM (2447 kg/m³) to BC1 (2539 kg/m³), further declining from BC2 (2527 kg/m³) to BC4 (2527 kg/m³). From the results, it is observed that the loss in weight density of the BC4 mix is high compared to that of the other mixes. The increasing density loss suggests that the barite initially enhances fresh and dry densities at 5% dosage (BC1), but higher contents (BC3 and BC4) reduce dry density, likely due to increased porosity [16, 17].

The Fresh concrete density increases from NS (3112 kg/m³) to BNS4 (3553 kg/m³), as illustrated in Figure 13, indicating a denser mix due to barite and nano-silica additions [16, 32]. The highest dry density was obtained at BNS3 (2975 kg/m³), which corresponds to a lower density loss of 14.8%. This indicates enhanced particle packing efficiency and hydration. The enhancement in density is likely due to the uniform distribution of NS within the matrix, which contributes to reduced pore volume and minimizes internal voids [11]. Higher dry density typically results in better compaction and fewer capillary pores, thereby contributing to increased mechanical strength [33, 34].

3.4. Statistical Evaluation Using ANOVA

ANOVA analysis confirmed that curing age statistically impacted all concrete mixes ($p < 0.05$). Notably, the Barites+NS and NS mixes displayed both strong significance and balanced F-values, indicating consistent and reliable strength development over time. While NT and Barites+NT also showed significant effects, their extremely low *p*-values coupled with high F-values may suggest sensitivity rather than stability. Overall, Barites+NS and NS emerged as the most effective and dependable formulations under varying curing durations.

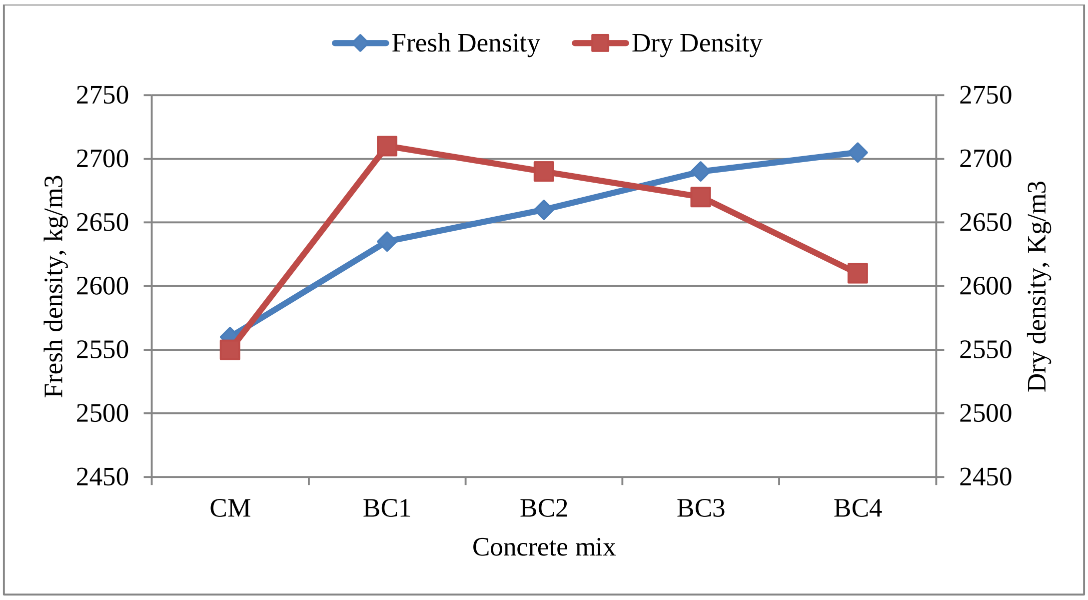


Fig. 11 Comparison of weight density values across BC mixes

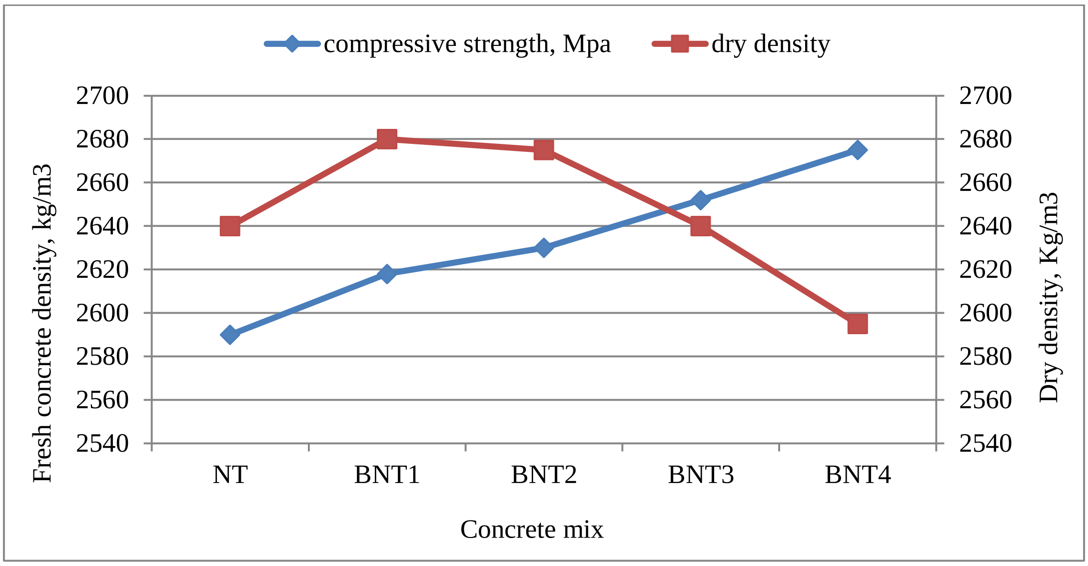


Fig. 12 Comparison of weight density values across BNT mixes

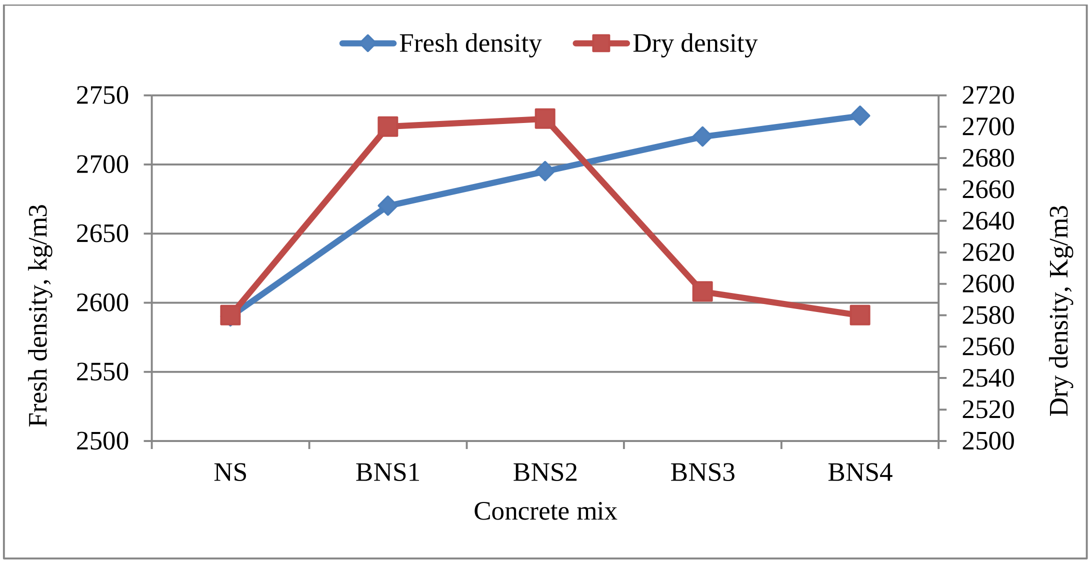


Fig. 13 Comparison of weight density values across BNS mixes

Table 2. Statistical findings of compressive strength

Mix	CF	DF	SS	Var.	F	P-value
CM	CA	2	515.975	257.987	118.574	2×10^{-5}
BC	CA	2	974.992	487.496	9.812	4.50×10^{-4}
NT	CA	2	629.419	314.709	183.361	1.00×10^{-5}
BNT	CA	2	1748.985	874.493	36.193	1.00×10^{-5}
NS	CA	2	632.817	316.408	30.903	6.90×10^{-4}
BNS	CA	2	1476.360	738.180	26.119	1.00×10^{-5}

3.5. Microstructure Analysis

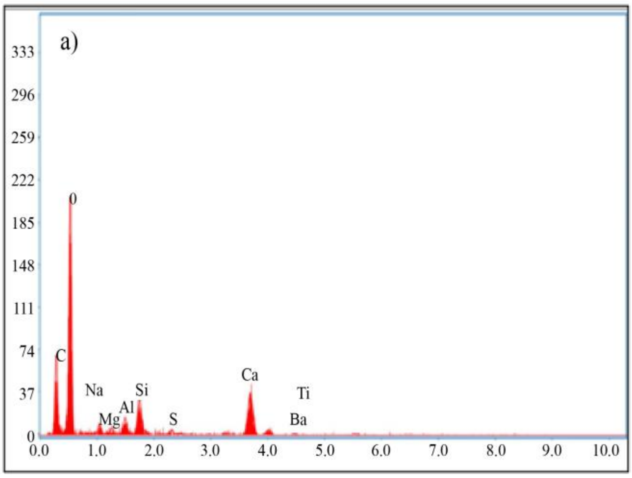
The SEM analysis shows a dense and compact microstructure resulting from the Nano-Silica (NS) pozzolanic reaction on barite concrete. A dense matrix with tiny pore spaces was observed in the control mix [27], suggesting the formation of hydration products based on SEM morphology. Barites integrated concrete mix BC1 exhibits a clear image of sponge-like CSH gel and CH crystals and a massive ettringite structure after 28 days of curing [35].

Barites contain barium sulphate ($BaSO_4$), which contributes sulphate ions to the mix. Barite powder contains sulphate (SO_4^{2-}) ions, which react with tricalcium aluminate (C_3A) in cement to form ettringite ($Ca_6 Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$) [27, 34]. Controlled sulphate availability improves ettringite formation in the early hydration phase, which helps in initial setting, volume stability, and early strength gain.

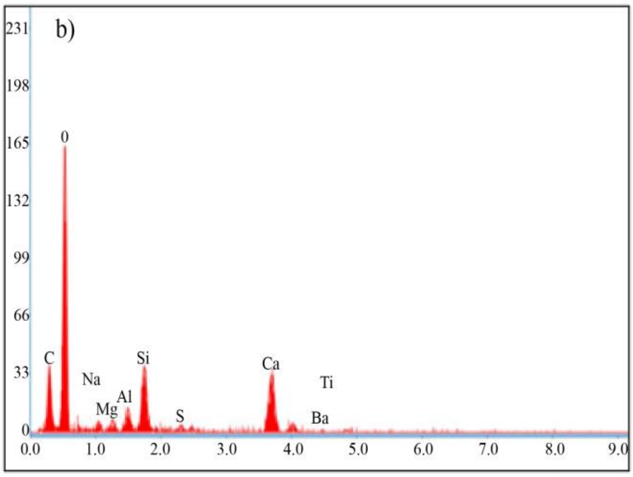
The addition of barite content contributes to more sulphate content in the concrete and Ettringite Formation. Mix BC4 exhibits the cauliflowered structure due to excessive sulphate levels, leading to expansion and cracking. Well-hydrated CSH and CH were found at the BNT1 mix. This is attributed to nano-TiO_2 (NT) acting as a non-reactive fine filler, reducing porosity, lacking pozzolanic activity, and contributing to a more homogeneous cement matrix [7, 12, 36, 37-39].

Furthermore, the Si/Ca atomic ratio derived from EDAX spectra is a critical parameter reflecting the extent and quality of the pozzolanic reaction. An increase in the Si/Ca ratio, particularly in NS3 mix shown in Figure 14(d), indicates enhanced secondary C-S-H formation, which is associated with improved mechanical strength of concrete. The SEM image of NS3 demonstrates a tightly packed microstructure with refined porosity, indicating efficient hydration and pozzolanic activity driven by nano-silica [8, 10].

The dominant phase observed appears to be solid and compact in morphology, consistent with the characteristics of C–S–H, a key hydration product that significantly contributes to mechanical strength. Hydration products' fine-textured, amorphous nature suggests that nano-silica enhanced secondary hydration, leading to a denser cementitious matrix [11].



(a)



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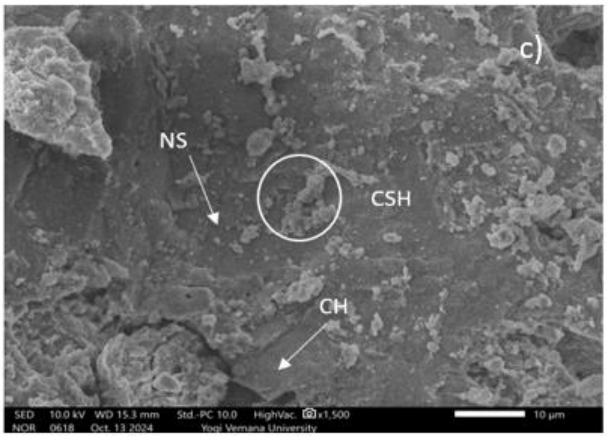

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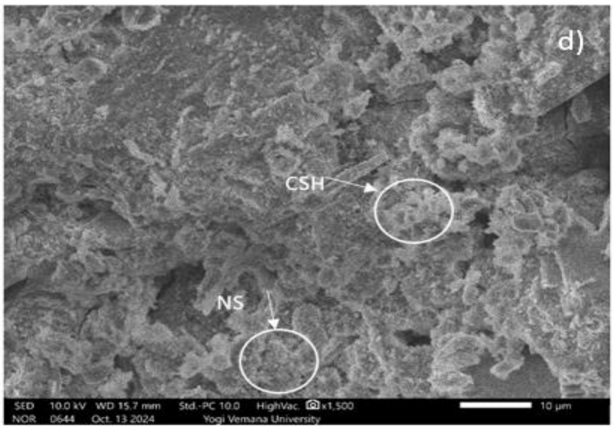

(d)

Fig. 14. EDX and SEM image of NS3 concrete, (a) EDX pattern of NS1 mix, (b) SEM image of NS1 mix, (c) EDX pattern of NS3 mix, and (d) SEM image of NS3 mix.

4. Comparative Analysis

A comprehensive comparative Analysis was conducted to assess the influence of NS and NT incorporation, along with barite powder (0–20%) as partial cement replacement, on concrete's fresh, mechanical and microstructural performance. The performance of these modified mixes was compared against a Control Mix (CM) to identify the optimal nanomaterial and replacement level.

From the fresh property results, a reduction in slump was observed with the inclusion of both NS and NT, more significantly in NS mixes due to their higher surface area and finer particle size, which increases water demand [40]. However, the slump values remained within acceptable workability limits as per IS:1199–1959.

Regarding mechanical properties, all modified mixes surpassed the 28-day target compressive strength of M40 concrete (48.25 MPa). Among them, the mix with 15% barite and 1% NS (BNS3) exhibited the highest compressive strength (57.78 MPa), indicating accelerated hydration and enhanced gel formation due to the pozzolanic activity of NS [9]. The mix BNT1 showed moderate strength gains primarily due to filler packing, as nano-titanium (NT) functioned mainly as an inert filler rather than a reactive pozzolan [41]

SEM analysis of BNS3 revealed a dense and compact matrix with a refined pore structure, indicative of efficient hydration and secondary gel formation. The micrographs showed a predominant presence of fibrous and clustered C-S-H gel, consistent with improved pozzolanic activity. In contrast, NT mixes showed less uniform and porous microstructures [42].

Energy-dispersive X-ray spectroscopy (EDX) demonstrated elevated Si/Ca ratios in mixtures containing nano-silica, indicating enhanced pozzolanic reactions. This implies increased consumption of calcium hydroxide and enhanced formation of Calcium Silicate Hydrate (C-S-H), which contributes to a more compact and robust microstructure [13]. Regarding hardened density, concrete blends containing barite and nano-silica (BNS series) exhibited higher unit weights than the control and nano-titania (NT) mixtures. This improvement is most likely due to the reduced internal voids and improved packing efficiency caused by nano-silica particles' extremely fine and amorphous nature [44].

The findings clearly demonstrate that nano-silica (NS) yields better mechanical performance than nano-titania (NT). The composition containing 15% barite and 1% NS (BNS3) produced the highest strength, owing to the complementary effects of the weight density of barite powder and the strong pozzolanic reactivity of NS. Compared to existing systems using single additives, this dual incorporation significantly enhanced C–S–H formation and matrix densification, as validated by SEM–EDX. These improvements mark a distinct advancement over previously reported methods in terms of mechanical strength and microstructural refinement.

ANOVA results showed that curing duration significantly affected strength outcomes ($p < 0.05$). The barite–nano-silica mix exhibited the highest strength gains, with F-values of 26.12 (compressive) and 41.95 (split tensile), indicating a strong link between curing time and performance. Nano-silica blends showed greater strength variation with age than nano-titania. In contrast, control and barite-only mixes showed minimal change, confirming the effectiveness of nano-silica, particularly at 15% barite replacement.

5. Conclusion

Based on the experimental analysis, the following conclusions were drawn regarding the influence of barite powder in combination with (NS) and (NT) on concrete performance:

- The incorporation of barite powder improved workability due to its fine particle size and filler effect, particularly at lower replacement levels. Conversely, including NS and NT marginally reduced workability due to their high specific surface area and associated water demand. However, the use of a superplasticizer facilitated acceptable workability across all mixes, indicating the feasibility of achieving optimal rheological performance through appropriate material proportions.
- The integration of nano-silica and barite powder in concrete led to significant mechanical and microstructural improvements. The optimal mix (BNS3) exhibited superior strength due to enhanced C–S–H formation and matrix densification. SEM analysis displayed a densely packed matrix with minimal porosity, indicating effective microstructural refinement. EDX results showed increased concentrations of key hydration elements, supporting the formation of additional binding phases. These outcomes underscore the combined efficiency of nano-silica and barite in producing high-strength concrete aligned with sustainability goals.

- Curing age is a statistically significant factor influencing both compressive and tensile strengths across all mix types. Mixes containing nano-additives exhibited stronger curing-age dependency, especially when combined with barite, indicating complex interactions that enhance hydration and strength gain.

Future Research Scope

Based on the present outcomes, Future studies will examine long-term durability, resistance to adverse conditions, and structural performance in radiation-shielding and precast applications, aligning with sustainable construction goals.

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