Facilitating Eco-Friendly Construction Practices with the Sustainable Application of Nanomaterials in Concrete Composites

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ABSTRACT

This research concentrates on the development of Nano Modified Concrete (NMC) and evaluates its performance through an extensive analysis of various strength and durability properties. The study encompasses assessments such as slump cone test, compressive strength, split tensile strength, flexural strength, permeability and acid resistance. The objective is to appraise the structural robustness of NMC, employing Nanosilica (NS) and Nanoclay (NC) as supplementary cementitious materials. Sixteen distinct concrete mixtures underwent casting and testing, featuring diverse cement replacement rates (0%, 1%, 2%, and 3%) of NS and NC at varying addition levels (0%, 5%, 10%, and 15% of nano additives by weight of fine aggregate) for each trial. Comparative analysis with conventional concrete underscores the notable enhancement in mechanical strength achieved by NMC without compromising its fresh and hardened state properties. Additionally, the incorporation of NS and NC contributes to increased slump values, facilitating improved workability due to smoother concrete surfaces. The findings suggest that the introduction of NMC leads to an overall improvement in the long-term performance of concrete structures. Adding NS and NC not only improves the properties of concrete but also plays a role in alleviating soil pollution.

Keywords: Nanosilica; Nanoclay; Concrete composites; Durability; Flexural behavior.

1. INTRODUCTION

Mineral additives like Silica Fume (SF) or Nanosilica (NS) enrich concrete strength and durability due to their fine particles, extensive surface area, and high SiO_2 content. Nanosilica is preferred for its smaller size and greater surface area compared to SF. It consists of porous and nearly spherical SiO_2 nanoparticles, offering significant benefits in the glass and concrete industries (Arasu A *et al.* 2023). Nanosilica particles are exceptionally small, approximately 1/100th the size of cement particles, and can be categorized into P-type and S-type, with P-type having significantly a larger surface area due to nano-porous structures. Nano-concrete employs Portland cement particles with diameters below 500 nm as the cementing agent. Currently, cement particle diameters range from a few nanometers to about 100 micrometers (Krishnaswami *et al.* 2022). Micro-cement, with an average particle size reduced to 5 micrometers, is an improvement. However, nano-concrete demands a further order of magnitude decrease in particle size for enhanced properties (Kartikeyan *et al.* 2014).

Because NS is pozzolanic, adding it to conventional mortar enriches axial strength and accelerates cement hydration (Boobala Krishnan *et al.* 2023). When excess $Ca(OH)_2$ and NS interact during cement hydration, the $Ca(OH)_2$ level is reduced, minimizing sulfate attack and chemical leaching while postponing the development of microcracks. Nanosilica functions in two ways: it fills in holes in the cement paste to create a denser, more impermeable mortar texture physically, and it operates chemically through a pozzolanic reaction to make more C-S-H gel (Ganapathy *et al.* 2023). The ideal material amounts in mixtures are sometimes complex and time-consuming, depending on the number of parameters and performance limitations. Designing and analyzing statistical experiments can help to simplify this complexity. Component proportions, not absolute numbers, determine the qualities of final products (Hakamy *et al.* 2014). Mixture experiments that are well-designed, especially those that employ the factorial design approach in Design of Experiments (DOE), are useful in determining which combination of factors yields the optimum mixture properties (S. Maheswaran *et al.* 2013).

Introducing NS at 5% replacement of cement enriched axial strength, which significantly increased up to 28 days, but at 10%, no additional improvement was observed. The best result was noted with 10% NS + 5% SF. Silica fume contributed to a notable reduction in chloride penetration rate by diminishing pore connectivity in the mixture, enhancing durability (Varuthaiya *et al.* 2012). The effects of nano SiO_2 diameter (100 nm and 250 nm) and amount (1%, 3%, 5% by weight of cement) on the mechanical characteristics and consistency of polymer-cement mortars (PCM) were examined. Moreover, XRD was used to track the hydration of cement mixtures. The pozzolanic reaction can be accelerated by adding NS, which will enrich the amount of CH that reacts and the conversion of C-S-H (Arasu *et al.* 2023).

Incorporating Poly Propylene (PP) fiber and replacing nano SiO_2 up to 7% enhanced cement mortar axial strength by 6.49%. However, exceeding 0.3% PP fiber diminished axial strength while enriching flexural strength. The synergy of nano SiO_2 particles was evident. Additionally, up to 0.5% PP fiber decreased water absorption in mortar, signaling pore refinement and improved durability (Arasu *et al.* 2023). Examining the impact of nano materials on concrete axial strength, NS, NC, or their combination were added in various proportions. Nanosilica proved more effective than NC, and wet mix exhibited greater efficiency than dry mix. Combining NS and NC significantly enhanced axial strength compared to using a single type. The optimum blend comprised of 3% nanoparticles, with 25% NS and 75% NC, showcasing remarkable enrichment in concrete compressive strength (Arasu A *et al.* 2023).

It has been demonstrated that adding nanomaterials – NS and NC, in particular – improves the permeability and strength of concrete. Amazingly, the compressive strength and permeability of the concrete mixture have improved significantly even with very little amounts of these nanoparticles. This finding emphasizes how nanotechnology might improve the overall functionality and longevity of concrete buildings by making small but significant compositional changes (Kumar *et al.* 2022; Sureshbabu *et al.* 2023). Examining concrete microstructure and strength properties with nano SiO_2, silica underwent planetary ball mill grinding until achieving nano size. It was then incorporated into concrete at 5%, 10%, and 15% by weight of cement. Experimental results revealed increased axial strength, with the highest strength observed at a 10% replacement rate, indicating the effectiveness of nano SiO_2 in enhancing concrete performance (Thirukumaran *et al.* 2023).

The ideal concentration of NC was found to be 1% by researchers studying Hemp Fabric (HF) Reinforced NC–Cement Nano composites. The HF-reinforced nano composites with 1wt% NC showed improvements in flexural strength and fracture toughness of 26.2% and 24.9%, respectively, and decreased porosity by 15.5%, improved density by 5.3%, and so on. On the other hand, flexural strength and fracture toughness of HF-reinforced cement composites suffered when the NC content exceeded 1%. Employing NC to create blended cement mortar, researchers aimed for a marginal boost in mechanical strength. Results indicated a significant enhancement in axial strength, with a 300% enrichment at 7 days for 1% NC and a 290% increase for 2% NC. By the 28th day, the enrichment reached 310% for 1% NC and 200% for 2% NC, demonstrating the positive impact of NC on long-term strength development in cement mortar (Vivek *et al.* 2020). Mineral additives, characterized by low reactivity and diminutive sizes, have garnered increased attention due to a rising demand for new alternatives amidst scarcity in traditional mineral admixtures like fly ash (FA) and blast furnace slag in certain regions (Vivek *et al.* 2018). The heightened pozzolanic activity of sugarcane bagasse ash, even with high quartz contamination levels, attributed to the reduction in particle size during grinding. This underscores the potential of non-conventional mineral additions as viable alternatives in regions facing limitations with traditional sources (Vivek *et al.* 2020).

2. MATERIALS

2.1 Cement

The concrete had a specific gravity of 3.15 (IS:1727-1967) and standard consistency of 31% (IS:4031-1968 part-4). Soundness was assessed at 0.94 mm using the Le Chatelier apparatus (IS:4031-1968) and met the required criteria. The initial and final setup times were reported as 35 and 344 minutes, respectively (IS:4031-1968 part-5). The compressive strength tested at 28 days was 55.8 N/mm², above the standard code. These findings confirm the concrete's compliance with established criteria and emphasize its outstanding compressive strength at the required age.

2.2 Fine Aggregate

Fine aggregate collected from Cauvery River basin near Karur has been used for experimental study satisfies the requirement as per IS 383:1970. The aggregate was air dried and screened to remove all foreign matters. The aggregates showed a fineness modulus of 2.62, specific gravity of 2.62 and bulk density of 1.62 g/cm^3. Sand confirming Zone-III and stored in a room was used for casting specimens.

2.3 Coarse Aggregate

The coarse aggregates utilized in the study were sourced from a nearby quarry, consisting of crushed granite with maximum sizes of 20 mm and 12 mm, adhering to IS 383-1970 standards. The coarse aggregate

exhibited a fineness modulus of 6.75, bulk density measuring 1.66 g/cm³, and a specific gravity of 2.78. These characteristics ensure compliance with the specified requirements and contribute to the overall suitability of the coarse aggregates for the intended experimental investigation.

2.4 Nanosilica

The test findings for the tested material closely match the requirements, confirming its quality and adherence to strict criteria. The vital metric, specific surface area, is measured at 202 m²/g, slightly higher than the range 200 ± 20 m²/g. The specific gravity at 20 °C is 2.28, which falls within the permitted range 2.00 to 2.40. The material has a pH of 4.15, which falls within the usual range 3.7 to 4.5. Furthermore, vital properties such as loss on drying at 105 °C (0.47%), loss on ignition at 1000 °C (0.66%), and sieve residue (0.02%) comfortably meet the specified parameters. Significantly, the SiO_2 concentration (99.88%) is higher than anticipated, while the carbon, chloride, and impurity contents (Al_2O_3, TiO_2, and Fe_2O_3) are much lower than the designated limits. Together, these findings confirm the superiority of the substance, fulfilling or surpassing criteria in a number of areas.

2.5 Nanoclay

The study shows that the nanoclay sample is closely aligned with the set requirements on a variety of factors. Silica (SiO_2) concentration is detected at 45.00%, somewhat lower than the norm of 47.00%. Alumina (Al_2O_3) fulfills the criterion at 36.00%, whereas, ferric oxide (Fe_2O_3) falls slightly short at 0.70% vs the standard of 1.00%. Calcium oxide, MgO, and TiO_2 are all within safe ranges. Loss on ignition is 14.00%, which meets the norm of 15.00%. Oxides of potassium (K_2O) and sodium (Na_2O) are within the required limits. Specific gravity at 20 °C is 2.6, slightly below the range 2.3 to 3.0. The material has a desirable brightness and whiteness at 78.00% and 80.00%, respectively. Additional features including pH value, bulk density, acid solubility, water and oil absorption, moisture, and retention on 500 mesh either satisfy or slightly differ from the required specifications.

3. METHODOLOGY

In adherence to the M40 specifications, the concrete mix design was carried out following the guidelines and directives outlined by the Indian Standards (IS) rules, specifically IS 10262:2009. The constituents employed in the mix (Table 1) included cement 53 grade, fine sand, coarse aggregate, nanosilica, and nanoclay.

Table 1. The concrete mix representation

Mix No	Mix Representation
T1	0% NS + 100% Cement & 0% NC + 100% FA + 100% CA
T2	0% NS + 100% Cement & 5% NC + 95% FA + 100% CA
T3	0% NS + 100% Cement & 10% NC + 90% FA + 100% CA
T4	0% NS + 100% Cement & 15% NC + 85% FA + 100% CA
T5	1% NS + 99% Cement & 0% NC + 100% FA + 100% CA
T6	1% NS + 99% Cement & 5% NC + 95% FA + 100% CA
T7	1% NS + 99% Cement & 10% NC + 90% FA + 100% CA
T8	1% NS + 99% Cement & 15% NC + 85% FA + 100% CA
T9	2% NS + 98% Cement & 0% NC + 100% FA + 100% CA
T10	2% NS + 98% Cement & 5% NC + 95% FA + 100% CA
T11	2% NS + 98% Cement & 10% NC + 90% FA + 100% CA
T12	2% NS + 98% Cement & 15% NC + 85% FA + 100% CA
T13	3% NS + 97% Cement & 0% NC + 100% FA + 100% CA
T14	3% NS + 97% Cement & 5% NC + 95% FA + 100% CA
T15	3% NS + 97% Cement & 10% NC + 90% FA + 100% CA
T16	3% NS + 97% Cement & 15% NC + 85% FA + 100% CA

4. RESULTS AND DISCUSSION

4.1 Fresh Concrete Test

The slump test results (Fig. 1) indicate a clear trend in the workability of concrete mixes with varying proportions of NS, natural coarse aggregate (NC), FA, and cementitious materials (CA). As the percentage of NS increases in the mix, the slump values tend to decrease. For instance, in mix T1 with 0% NS, the slump is 113 mm, whereas in mix T5 with 1% NS, the slump is slightly higher at 116 mm. This suggests that the addition of NS has a slight stiffening effect on the concrete. Additionally, variations in the proportions of NC and FA also show an impact on slump values. Mix T4, with 15% NC and 85% FA, exhibits the lowest slump of 103 mm, indicating a reduced workability compared to other mixes. Overall, the results highlight the intricate relationship between mix composition and workability, providing valuable insights for optimizing concrete formulations in construction applications.

4.2 Compressive Strength Test

The compressive strength results (Fig. 2) reveal a consistent pattern in the performance of concrete mixes at different curing periods. As the percentage of NS increases, the compressive strength generally shows an upward trend. For instance, in mix T1 with 0% NS, the compressive strength at 28 days is 45.26 MPa, while in mix T5 with 1% NS, the value rises to 47.36 MPa. Furthermore, the influence of variations in the

proportions of NC and FA is evident. Mix T11, with 2% NS, 10% NC, and 90% FA, exhibits the highest compressive strength of 51.45 MPa at 28 days. This suggests that careful adjustment of NS and other constituents can enhance the compressive strength of concrete, providing valuable insights for optimizing concrete formulations in structural applications. The increasing strength values with curing time also highlight the importance of longer curing durations for achieving optimal performance.
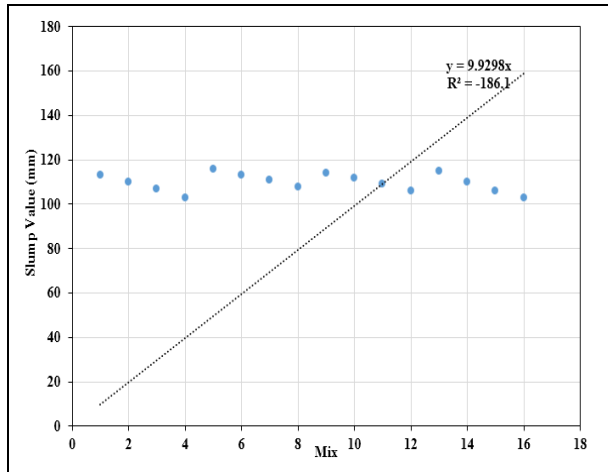

Fig. 1: Slump test values in mm
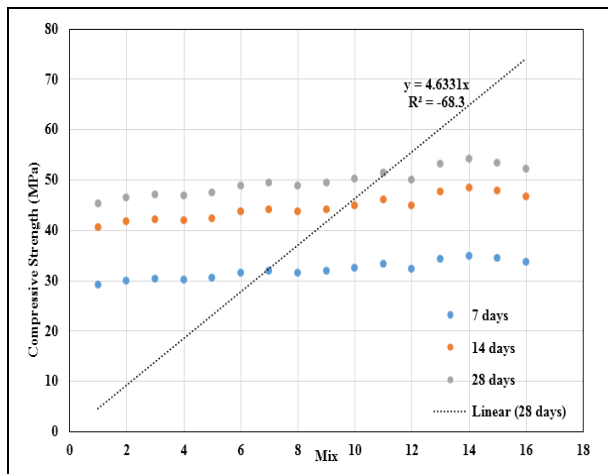
Fig. 2: Compressive strength in MPa

4.3 Split Tensile Strength

The split tensile strength data (Fig. 3) show a consistent pattern in the mechanical behavior of concrete mixtures across various curing times. Incorporating NS into the mix often improves split tensile strength. For example, in mix T1 with 0% NS, the split tensile strength at 28 days is 4.89 MPa, but in mix T5 with 1% NS, it rises to 5.11 MPa. Furthermore, the proportions of NC and FA affect the split tensile strength. Mix T11, which contains 2% NS, 10% NC, and 90% FA, has the maximum split tensile strength of 5.55 MPa at 28 days. These findings

indicate that the addition of NS, along with changes in other constituents, can improve the split tensile force of concrete, providing insights for boosting mixes in applications where tensile strength is vital, such as pavements and structural elements subjected to bending forces.
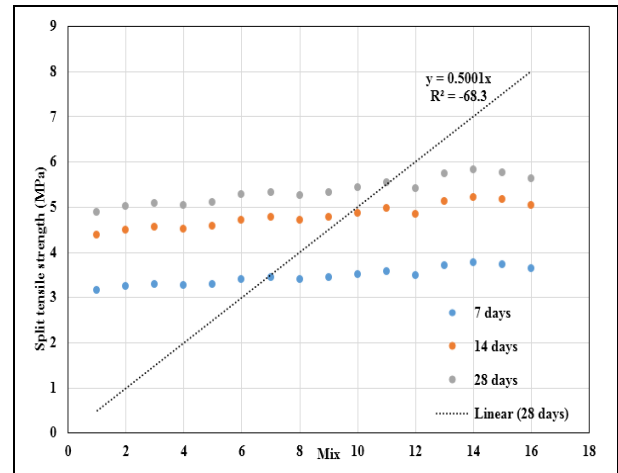

Fig. 3: Split tensile strength in MPa

4.4 Flexural Strength test

The flexural strength data (Fig. 4) show a continuous trend in the mechanical performance of concrete mixes throughout various curing times. The addition of NS to the mixtures typically increases flexural strength. For example, in mix T1 with 0% NS, the flexural strength at 28 days is 5.48 MPa, but in mix T5 with 1% NS, it rises to 5.73 MPa. Furthermore, the proportions of NC and FA affect flexural strength. Mix T11, which contains 2% NS, 10% NC, and 90% FA, has the maximum flexural strength of 6.23 MPa at 28 days.
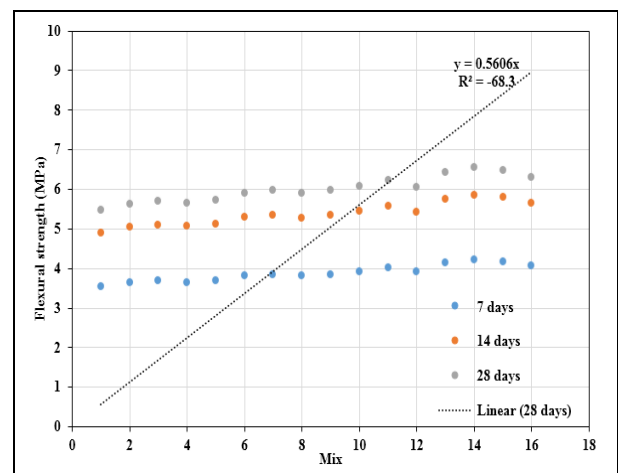

Fig. 4: Flexural strength in MPa

These data imply that the addition of NS, together with changes in other elements, can significantly improve the flexural strength of concrete. This

knowledge is crucial for applications requiring resistance to bending forces, such as beams and slabs in construction.

4.5 Permeability Test

The permeability data (Fig. 5) show the effect of NS and different quantities of NC and FA on the permeability of concrete mixes after 28 days. In general, the addition of NS reduces permeability. The permeability of mix T1 with 0% NS is 0.041 x 10^{-6} mm/sec, but mix T9 with 2% NS reduces to 0.039 x 10^{-6} mm/sec. Furthermore, minor differences in NC and FA proportions affect permeability. Mix T13, with 3% NS, 0% NC, and 100% FA, has the lowest permeability (0.038 x 10^{-6} mm/sec). These data suggest that the addition of NS, together with changes in other mix ingredients, has the potential to improve the impermeability of concrete. This knowledge is useful in situations where resistance to water infiltration is a major requirement, such as in constructions exposed to harsh weather conditions.
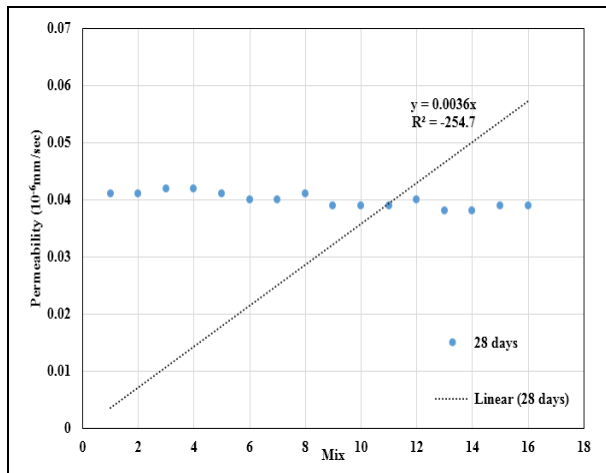

Fig. 5: Permeability test in 10^{-6} mm/sec

4.6 Acid Resistance Test

The percentage of weight loss observed after 28 days of curing offers information on the durability and potential for material breakdown in concrete mixtures. The findings show a link between the proportion of NS and weight reduction, with higher NS content often resulting in lower weight loss. Mix T13, with 3% NS, has the smallest weight loss of 5.18%, whereas mix T5, with 1% NS, has outstanding durability with a weight loss of 7.05%. Furthermore, differences in NC and FA proportions are visible, as demonstrated in mix T11 with 2% NS, 10% NC, and 90% FA, which has a weight loss of 5.94%, showing improved deterioration resistance. These findings highlight the potential of NS and careful mix design modifications to increase concrete durability, providing insights for applications in harsh climatic situations.

The percentage of strength loss after 28 days is useful for determining the durability and performance of concrete mixes under different situations. The statistics show a continuous trend in which the use of NS reduces the percentage of strength loss. Mix T13, with 3% NS, has the lowest strength loss at 7.55%, whereas mix T5, with 1% NS, has good durability with a strength loss of 10.28%. Variations in NC and FA proportions also effect strength loss, as seen by mix T11 with 2% NS, 10% NC, and 90% FA, which has an 8.66% strength loss. These findings highlight the potential of NS and careful mix design modifications to improve the resistance of concrete to strength deterioration, giving useful insights for applications in settings that may challenge the long-term performance of concrete buildings. Fig. 6 and Fig. 7 show the percentage of loss in weight and strength in acid resistance test.
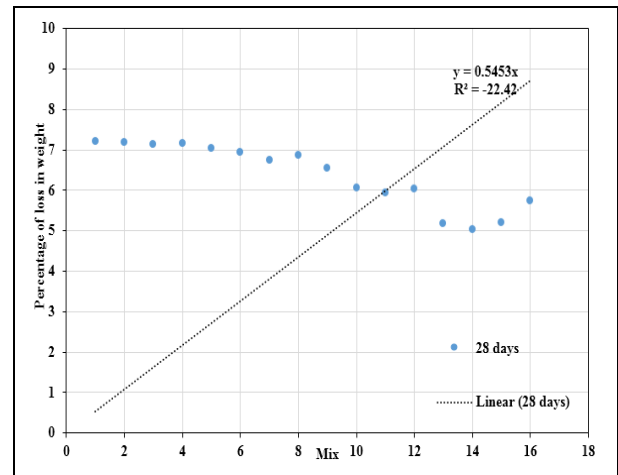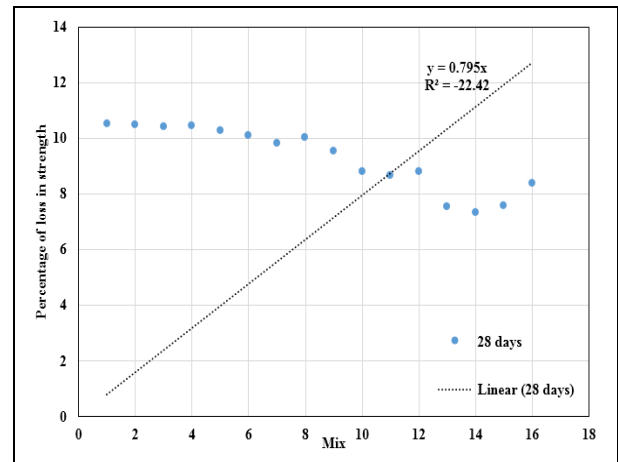

Fig. 6: Percentage of loss in weight

Fig. 7: Percentage of loss in strength

5. CONCLUSION

The thorough examination of the mechanical and long-term characteristics of concrete mixtures containing different ratios of FA, NC, and NS has shed

light on the complex interaction between mix composition and concrete performance. The findings of the slump test showed a small stiffening impact as the NS content increased, emphasizing the necessity for careful mix design to provide the best workability. Simultaneously, the findings for compressive strength showed a steady increase with NS addition, indicating that NS may be able to improve the mechanical strength of concrete. The results of the split tensile and flexural strength tests supported the beneficial effects of NS on the tensile and flexural characteristics of concrete, demonstrating how well it works to increase the resistance to bending forces and tensile stresses. According to the permeability data, adding NS tends to decrease permeability, which is important for applications where water permeation resistance is required. Promising results were found in the durability examinations, especially with regard to strength and weight loss. Increased NS percentages were frequently associated with decreased weight loss and strength loss, highlighting the potential of NS to improve the long-term durability of concrete. These characteristics were also impacted by changes in the ratios of NC and FA, underscoring the need of a well-balanced mix design. The findings highlight the important influence of NS on a number of concrete performance metrics. The results offer insightful advice for improving concrete formulations, particularly for uses where increased strength, longevity, and resistance to environmental variables are vital. Adding NS and NC not only improve the properties of concrete, but also plays a role in alleviating soil pollution. The research advances the field of high-performance and sustainable concrete and opens the door for creative approaches to building materials and design.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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