Research Article

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Enhancing Concrete Sustainability and Strength: Utilization of Industrial By-products in Tetranary Blended Nano Concrete

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ABSTRACT

The manufacturing process of ordinary portland cement depletes natural resources like limestone quickly and emits significant amounts of CO2 into the environment due to the high energy consumption during calcination. Current research aims to identify alternative cementitious materials to replace Ordinary Portland Cement (OPC). Building on earlier investigations, this study emphasizes the use of industrial by-products rich in alumina and silica as partial substitutes for OPC. Specifically, it examines the effects of integrating materials such as fly ash and colloidal nano silica (CNS) into concrete as partial cement replacements and utilizing manufactured sand (M-sand) as a full substitute for fine aggregate. The research introduces a Tetranary Blended Nano Concrete mix that combines 30% fly ash and varying nano silica levels (1%, 2%, and 3%) with 100% M-sand. The compressive strength of an M30-grade concrete mix was tested over a curing period of up to 90 days. Findings indicate that incorporating nano silica significantly improves the compressive strength of Tetranary Blended Nano Concrete. Furthermore, the complete substitution of fine aggregate with M-sand not only enhanced the concrete's mechanical properties but also contributed to its sustainability. The addition of nano silica to fly ash significantly enhances early strength and provides moderate improvement in overall compressive strength. To validate the compressive strength values obtained, the Response Surface Method was employed for mathematical modelling and statistical analysis, allowing for the prediction of compressive strength values from the regression equation and comparison with experimental data.

Keywords: Fly ash; Nano-silica; M-sand; Response Surface Method.

1. INTRODUCTION

The use of concrete in construction is growing every year along with the expansion of infrastructure. Concrete produced with Ordinary Portland Cement (OPC) is extensively utilized globally due to its widespread availability and convenient operational flexibility. The production of ordinary Portland cement (OPC) is an energy-intensive process that generates significant greenhouse gas emissions, particularly carbon dioxide (CO_2), contributing substantially to environmental issues like global warming (Kathirvel *et al.* 2012). Studies indicate that OPC manufacturing accounts for approximately 3% of global energy consumption and 9% of man-made CO_2 emissions. These environmental challenges underscore the urgent need to identify and adopt alternative materials that can reduce OPC usage while promoting sustainable construction practices. A promising solution lies in utilizing industrial by-products with pozzolanic properties as supplementary cementitious materials (SCMs) in concrete, thereby advancing the development of eco-friendly building materials (Singh *et al.* 2013; Jalal *et al.* 2012). Industrial solid waste poses significant environmental challenges, including air pollution, soil compaction, and groundwater contamination through leachate (Reddy *et al.* 2018). Pozzolanic by-products such as fly ash (FA), rice husk ash (RHA), ground granulated blast furnace slag (GGBS), red mud (RM), silica fume (SF), and metakaolin (MK) have shown great potential as supplementary cementitious materials (SCMs) (Kathirvel *et al.* 2012). Incorporating these pozzolans into cement not only enhances the mechanical and durability properties of concrete but also improves its microstructure (Lincy *et al.* 2018). This improvement occurs through the modification of the interfacial transition zone (ITZ) and the refinement of the pore structure via pozzolanic reactions (Berra *et al.* 2012). In this study, industrial by-products like fly ash, which exhibits pozzolanic behavior, were utilized as partial substitutes for cement in concrete. This approach can significantly mitigate the environmental impact associated with greenhouse gas emissions from cement production. Additionally, nanoparticles are gaining traction in the construction sector due to their high specific surface area, which enables better reactivity and contributes to the advancement of high-performance concrete materials (Chithra *et al.* 2016).

Nanomaterials such as colloidal nano silica (CNS) possess exceptional pozzolanic properties, significantly improving the physical and mechanical characteristics of concrete (Aly *et al.* 2012; Zhang and Li, 2011). The inclusion of CNS in concrete accelerates pozzolanic reactions, leading to the formation of additional calcium-silicate-hydrate (C-S-H) gel, which is essential for enhancing strength and durability (Singh *et al.* 2013). Furthermore, CNS densifies the interfacial transition zone (ITZ) by filling and sealing pores within the concrete matrix, thereby improving its overall compactness and structural integrity (Berra *et al.* 2012). In addition to these mechanical benefits, the inclusion of CNS contributes significantly to the sustainability of concrete production. By enhancing the pozzolanic reaction, CNS reduces cement consumption, which lowers carbon emissions and energy demand during manufacturing. Moreover, CNS improves concrete durability by densifying its microstructure, reducing permeability, and extending the lifespan of structures. These benefits align with sustainable construction practices, promoting resource efficiency and supporting the circular economy through the effective integration of industrial by-products.

In addition to the cementitious components, aggregates play a crucial role in the performance of concrete. The excessive extraction of natural river sand, which is conventionally used as fine aggregate, has led to severe ecological and environmental challenges (Reddy and Meena, 2018), including the depletion of natural sand reserves, destruction of aquatic ecosystems, and increased erosion. To mitigate these effects, M-Sand, a by-product of the crushing process of hard granite stones has emerged as a sustainable alternative to natural river sand in concrete production. M-Sand not only addresses the scarcity of natural sand but also provides improved particle size distribution and shape characteristics, leading to enhanced concrete performance in terms of strength and durability. Moreover, using M-Sand in concrete reduces the environmental impact associated with sand mining, promotes the efficient utilization of industrial waste materials, and contributes to the circular economy by reducing the dependence on natural resources (Raj *et al.* 2016).

The combination of FA, CNS, and M-sand in the study is based on their complementary and synergistic contributions to enhancing the performance and sustainability of concrete. Fly ash, a pozzolanic material, reacts with calcium hydroxide in the cement matrix to form additional calcium silicate hydrate (C-S-H), which improves strength and reduces permeability (Kathirvel *et al.* 2012). This also helps in reducing the greenhouse gas emissions associated with cement production. Colloidal nano silica, with its high surface area and reactivity, accelerates pozzolanic reactions, enhancing early-age strength and densifying the interfacial transition zone (ITZ), thereby reducing porosity and improving durability (Lincy *et al.* 2018). M-sand, a manufactured sand alternative to natural river sand, offers superior particle gradation and angularity, resulting in better packing density and improved interlocking within the concrete matrix. This combination ensures that the mechanical performance of the concrete is optimized while addressing environmental concerns. The synergistic effect arises as the reactivity of CNS enhances the pozzolanic activity of FA, and M-sand's properties contribute to reducing voids and creating a dense microstructure. Together, these materials provide a balanced approach to achieving superior strength, durability, and sustainability in concrete production (Chithra *et al.* 2016).

The current study investigates the effects of incorporating 30% FA with varying amounts of CNS (i.e., 0%, 1%, 2%, and 3%), (Chithra *et al.* 2016; Reddy and Meena, 2018; 2021) as well as 100% replacement of fine aggregate with M-Sand, on the compressive strength of TBNC for M30 grade concrete up to 90 days of curing. The Response Surface Method (RSM) was used to generate regression equations for compressive strength of M30 concrete. The study considers the potential reduction in CO_2 emissions achieved by replacing natural fine aggregates with M-sand and incorporating fly ash as a partial cement replacement. M-sand, produced as a by-product of granite crushing, eliminates the ecological damage and carbon emissions associated with river sand extraction and transportation. Its local availability further minimizes the carbon footprint of concrete production. Similarly, the inclusion of 30% fly ash, an industrial by-product, significantly reduces the reliance on OPC, which is a major source of greenhouse gas emissions. Cement production involves energy-intensive processes like calcination, contributing substantially to CO_2 emissions. By substituting fly ash for a portion of OPC, the study not only mitigates these emissions but also promotes the utilization of industrial waste, aligning with sustainable construction practices.

2. RESEARCH SIGNIFICANCE

This research focuses on addressing the environmental issues of traditional concrete production by using sustainable materials like Fly Ash, Nano Silica, and Manufactured Sand (M-Sand). Replacing 30% of cement with Fly Ash and adding Nano Silica helps lower carbon emissions and improve the strength of concrete. Using M-Sand instead of natural sand reduces the harmful effects of sand mining and helps conserve natural resources. The study highlights how industrial by-products can make concrete more environmentally friendly. Colloidal Nano Silica (CNS) not only strengthens concrete but also makes it more durable by filling pores and improving its resistance to environmental damage. This reduces the need for repairs and extends the life of structures, supporting sustainable and efficient construction practices.

3. MATERIALS

Various concrete mixtures were prepared using 53-grade OPC, adhering to the guidelines specified in BIS:12269–2013. The OPC used exhibited a fineness modulus of 3.24%, a specific gravity of 3.14, a standard consistency of 30%, an initial setting time of 30 minutes, and a final setting time of 600 minutes. Fine aggregate was locally sourced river sand that passed through a 4.75 mm sieve. Classified under grading zone II as per BIS:383–2016, the sand had a fineness modulus of 2.79%, a water absorption rate of 1.25%, and a specific gravity of 2.47.

The coarse aggregate used was crushed rock, locally sourced, with particle sizes below 20 mm, meeting the requirements of BIS:383–2016. Manufactured sand (M-Sand), a by-product of granite crushing, was also used. Characterized by its angular, coarse texture, M-Sand exhibited a fineness modulus of 2.79, with most particles ranging between 0.6 mm and 1.18 mm in size, and it complied with Zone II specifications outlined in BIS:383–2016. The coarse aggregate had a specific gravity of 2.6 and a fineness modulus of 12.5%, indicating its particle size distribution. The water used for mixing was neutral, with a pH value of 7–8.

Additionally, mineral admixtures such as fly ash (FA) and colloidal nano silica (CNS) were incorporated. The FA, obtained from Dr. NTR Vijayawada Thermal Power Station in Andhra Pradesh, was identified as low-calcium Class F fly ash per BIS:3812–2013, with a fineness modulus of 1.3% and a specific gravity of 1.62. CNS, comprising silica nanoparticles suspended in water, was procured from Bee-Chems Chemicals in Kanpur. Furthermore, the study employed CONPLAST-SP430, a chloride-free, sulfonated naphthalene-based superplasticizer conforming to ASTM C494-2017 standards.

4. MIX DESIGN AND RESEARCH METHODOLOGY

In this study, M30 grade concrete was designed according to BIS:10262 – 2019, with the detailed mix specifications outlined in Table 1. Cement was partially replaced with a blend of FA and CNS, maintaining FA at 30% of the binder content and varying CNS from 0% to 3% by weight of the cement. M-sand was used as a full substitute for fine aggregate in all mixtures. The process involved mixing water and CNS prior to combining with the dry ingredients. The water-to-binder ratio was consistently set at 0.43 across all mix designs. The mix compositions for both the experimental and standard concrete (CM) are provided in Table 1. Concrete mixes were prepared under controlled conditions at an ambient temperature of 27°C ± 2°C. The preparation process involved dry mixing of OPC, FA, M-sand, and coarse aggregate for approximately 3 minutes. This was followed by blending water, CNS, and superplasticizer for 2 to 3 minutes before combining with the dry mix. Cube samples, each measuring 150mm × 150mm × 150mm, were cast and after 24 hours, demoulded and placed in water for curing at room temperature. To assess the compressive strength, the tests were conducted in accordance with BIS:516 – 1959 (reaffirmed in 2013). Concrete typically achieves around 90% of its target strength after 28 days, with slower strength development thereafter. The study evaluated compressive strength at 7, 28, and 90 days of curing. The cubes were tested between steel plates with no additional compaction, and a continuous load was applied at a rate of 1.4 N/mm² per minute until failure. The maximum load recorded during the test was noted.

Table 1. Mix ratios for M30 grade concrete

Materials	OPC	Fine Aggregate	Coarse Aggregate	Water
Quantity (kg/m3)	375.542	670.16	1150.968	157.72

Mix Proportion = 1: 1.78: 3.06: 0.42

5. MIX DESIGNATIONS

- **CM**: Standard Concrete Mix
- **F30M100:** Concrete Mix incorporating 30% FA and 100% M-Sand
- **F30N1M100:** Concrete Mix with 30% FA, 1% CNS, and 100% M-Sand
- **F30N2M100:** Concrete Mix comprising 30% FA, 2% CNS, and 100% M-Sand
- **F0N3M100:** Concrete Mix consisting of 30% FA, 3% CNS, and 100% M-Sand

6. RESULT AND DISCUSSION

6.1 Compressive Strength Result

Figure 1 illustrates the compressive strength results for M30 grade concrete, which was blended with 30% FA and different levels of CNS (1%, 2%, and 3%) as partial replacements for OPC. M-sand was used as a full replacement for fine aggregate. The concrete was cured for periods of 7, 28, and 90 days.

The results from the graph indicates significant insights into the performance of TBNC mixes that incorporate CNS, FA, and M-sand, compared to standard concrete mixes. The data indicate a notable enhancement in the compressive strength of TBNC specimens, particularly when up to 2% of the OPC content was replaced with CNS. This increase is attributed not only to the active role of CNS but also to the beneficial properties of M-sand. M-sand, with its superior gradation and angularity compared to natural sand, provides a better packing density, thereby reducing voids and contributing to the overall strength of the concret. Moreover, the angular particles of M-sand improve the bond between the cement paste and aggregate, further enhancing strength.

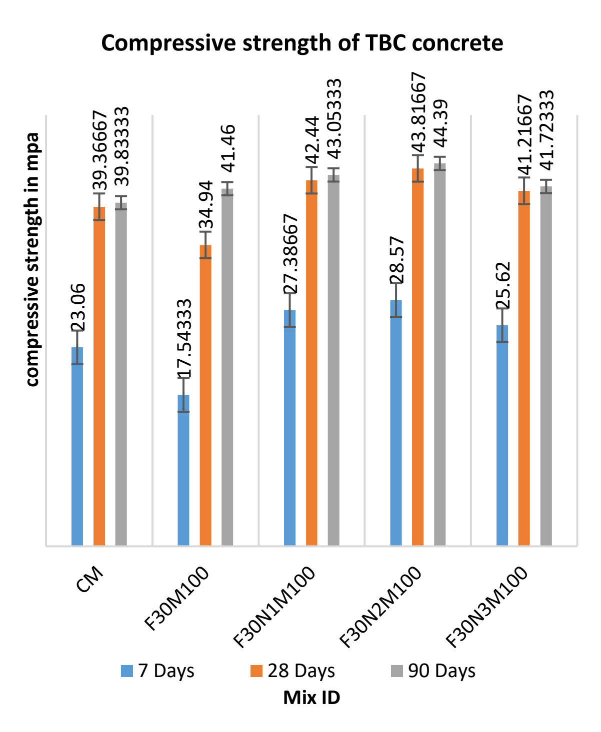

Fig. 1: The compressive strength results for M30 grade concrete

However, it is important to note that when CNS content exceeded 2%, a slight decrease in compressive strength was observed. This suggests that while CNS addition up to a certain threshold improves strength, exceeding this limit can lead to diminishing returns. The reduction in strength at higher CNS levels may be due to the excessive leaching of CNS particles, which surpasses the amount of liberated lime available for the hydration process, weakening the pore structure.

The improvement in early-age compressive strength is largely attributed to the accelerated hydration process facilitated by CNS and the optimal particle size distribution provided by M-sand. These effects are consistent at both 28 and 90 days of curing. The combination of CNS, FA, and M-sand not only enhances compressive strength compared to conventional concrete but also ensures a denser and more durable concrete matrix.

The inclusion of M-sand plays a crucial role in these improvements, as its angular particles provide better interlocking and bonding within the matrix, complementing the effects of FA and CNS. This results in a more compact microstructure, contributing to the early development of strength. However, it is essential to control the proportion of CNS to avoid negative impacts on strength and maintain the integrity of the concrete.

The integration of CNS and M-sand, alongside FA, yields promising results in enhancing the compressive strength of TBC, particularly in the early stages of curing. These findings underscore the importance of careful material selection and proportioning in the design of high-performance concrete mixes. Further research is necessary to fully understand the mechanisms at play and to optimize the use of these supplementary materials for various construction applications.

This study includes a comparative analysis of the compressive strength of TBNC and conventional M30 concrete. The results demonstrate that TBNC, incorporating FA, CNS, and M-sand, achieves significantly higher compressive strength, particularly at early and intermediate curing stages. This enhancement is attributed to the improved pozzolanic activity of CNS and the densified microstructure facilitated by M-sand. Additionally, the full replacement of natural sand with M-sand promotes sustainability and cost efficiency. However, it is acknowledged that precise material proportions are critical to maximizing these benefits and avoiding diminishing returns. Further studies are planned to include flexural strength and durability assessments to comprehensively compare the overall performance of TBNC with conventional concrete.

6.2 Design of Experiments (DOE) by Response Surface Method (RSM)

In this study, the Design of Experiments (DOE) utilizing Response Surface Methodology (RSM) was employed for the mathematical modeling and statistical analysis to predict the accuracy of the experimentally obtained compressive strength values of TBNC mixtures. RSM is a robust statistical approach commonly used in both industrial and research settings for process development, optimization, and enhancement. This methodology evaluates the influence of one or more independent variables and their interactions on a response variable. The relationship between the response and the input variables can be expressed by the following equation:

$$Y=F(\xi 1,\xi 2,\xi 3,\ldots,\xi k)+\varepsilon \qquad \ldots (1)$$

In this equation, $\xi 1,\xi 2,\xi 3,\ldots,\xi k$ represent the input variables, F denotes the approximate response function, and ε denotes the statistical residual error. To evaluate the response of the input variables in the current analytical study, a second-order polynomial equation was utilized instead of a linear one, as shown below:

$$Y=\beta o+\sum_{i=1}^{k} \beta i\xi i+\sum_{i=k}^{k} \beta ii\xi^2 ii+\sum_{i=1}^{k}\sum_{j=1,j\neq 1}^{k} \beta ij\ \xi i\xi j + \varepsilon \quad \dots (2)$$

Here, Y represents the response variable, β denotes the coefficients, ξ represents the factors, and ε signifies the error term. The terms βo, βi , βii and βij correspond to the regression coefficients for the intercept, linear, quadratic, and interaction terms, respectively, while ξi and ξj represent the input variables.

Table 2. Comparison of experimental and predicted values for M30 grade TBNC using RSM regression analysis

%M sand	% CNS	Days	CST (actual)	CST (predicted)	Residual Error
0	0	7	23.06	23.356	-0.2965
100	0	7	17.543	18.709	-1.1658
100	1	7	27.386	25.603	1.7830
100	2	7	28.570	28.153	0.4169
100	3	7	25.620	26.357	-0.7375
0	0	28	39.366	38.969	0.3970
100	0	28	34.940	35.498	-0.5587
100	1	28	42.440	41.878	0.5614
100	2	28	43.816	43.913	-0.0966
100	3	28	41.300	41.603	-0.3031
0	0	90	39.833	39.933	-0.1004
100	0	90	41.460	39.935	1.5240
100	1	90	43.053	44.796	-1.7430
100	2	90	44.390	45.311	-0.9217
100	3	90	42.723	41.482	1.2411

In the current experimental design, one response variable and three independent variables were selected for analysis. The compressive strength (CST) of TBNC was designated as the response variable, while the %M-sand, %CNS, and days were considered as the three independent variables. To generate response surface and residual plot graphs, RSM was applied, utilizing regression analysis to explore the relationships between these variables. For conducting the statistical analysis and determining the regression coefficients, MINITAB software was employed. A quadratic prediction model, as expressed in equation (3) below, was used to derive the results, which were then evaluated using Design of Experiments (DOE) to assess the model's goodness of fit.

$$Z = A + BX1 + CY1 + DX12 + EY12 + F\ X1Y1 \quad \dots (3)$$

By analysing the data in RSM the following equation was obtained for M30 grade concrete

CST=16.43- 0.0504 %Msand + 9.24 %CNS + 1.0504 Days- 2.173 %CNS*%CNS- 0.008770 Days* Days+0.000560 %Msand*Days-0.0245 %CNS*Days

The actual and predicted CST for M30 grade concrete, along with their respective residual errors, are detailed in Table 2. The regression analysis via RSM reveals that the coefficient of determination (R^2) for the actual CST stands at 98.72%, while the predicted CST shows an R^2 of 89.62% for M30 grade TBNC concrete.

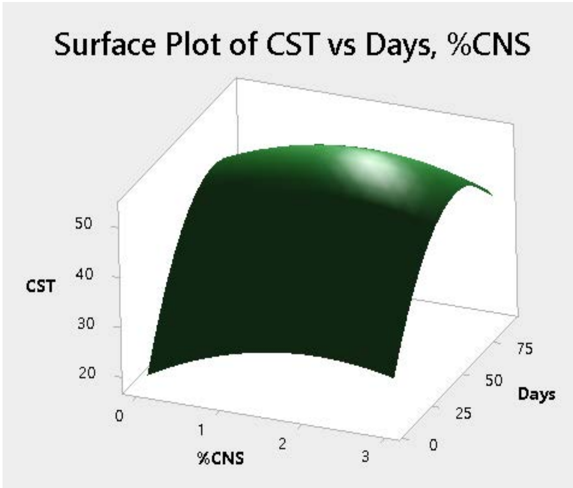

Fig. 2: Response surface plot for "CST" versus "%CNS", "Days"

The information presented in Table 2 compares the predicted and experimental values of compressive strength, along with the associated residual errors. The regression model, derived from response surface analysis, correlates CST (Z) with the Days (Y) and %CNS (X), as illustrated in Figure 2. The model demonstrates a high level of accuracy, with the predicted response surface plot exhibiting an error margin of less than 5%, corresponding to a 95% confidence level.

6.3 Residual Plots from RSM Analysis

Figure 3 represents four residual plots associated with the compressive strength test (CST) data: the Normal Probability Plot, the Versus Fits Plot, the Histogram Plot, and the Versus Order Plot. Each plot provides distinct insights into the behavior of residuals, which are crucial for validating the assumptions underlying the regression model and assessing the model's overall accuracy.

The evaluation of these residual plots suggests that the regression model used to predict the compressive strength of TBNC mixtures is statistically reliable. The residuals demonstrate approximate normality, constant variance, and independence, with no systematic patterns detected. This high level of model fit, reflected by low residual errors and high confidence, confirms the robustness of the regression model. These findings are consistent with earlier results, underscoring the model's accuracy and validity in predicting compressive strength based on varying proportions of CNS, M-sand, and curing durations. These results highlight the model's effectiveness in optimizing TBNC mix designs and ensuring precise predictions of concrete performance.

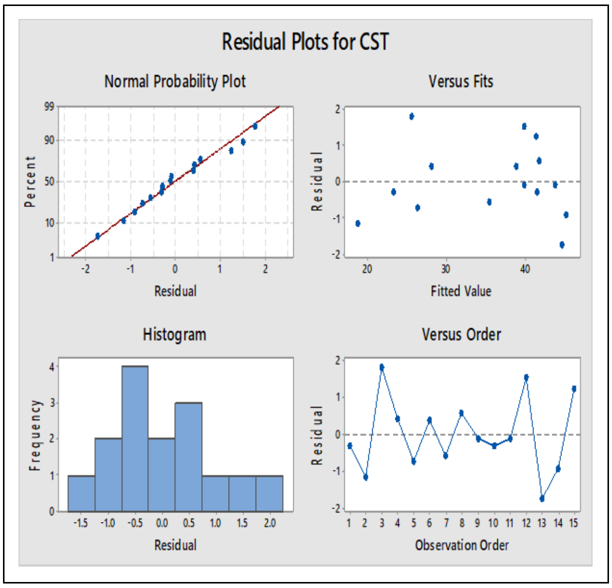

Fig. 3: Residual plot for compressive strength

6.4 Cost and Energy Efficiency

The cost analysis of the TBNC mix revealed that the inclusion of fly ash and M-sand reduces overall material costs. Although CNS incurs higher initial costs, its benefits in reducing cement usage and enhancing durability justify its inclusion. Additionally, energy consumption is minimized due to the replacement of energy-intensive OPC with fly ash and the use of M-sand as an eco-friendly aggregate. The low dosage of CNS ensures that its energy impact remains minimal, resulting in a net reduction in energy consumption for TBNC production.

7. CONCLUSION

The present study has successfully demonstrated that the utilization of industrial by-products like FA, CNS, and M-Sand in concrete production not only improves its mechanical performance but also offers a sustainable alternative to conventional materials. By integrating 30% FA as a partial cement replacement and varying CNS content from 0% to 3%, in combination with a 100% substitution of natural sand with M-Sand. The application of these materials yielded concrete mixes that exhibited significant improvements in compressive strength, especially when CNS was introduced up to a 2% replacement level. However, as the study reveals, the proportion of CNS must be carefully controlled. Beyond the 2% threshold, the inclusion of CNS led to a marginal decrease in compressive strength, indicating that excessive amounts of CNS may disrupt the hydration process by oversaturating the system with pozzolanic particles. This reinforces the need for a balanced approach when incorporating nano-materials into concrete, ensuring that their beneficial effects are maximized without compromising the integrity of the mix. The comprehensive analysis using the Response Surface Methodology (RSM) further validated the experimental findings by providing robust regression models that predict the compressive strength of the TBNC mixes. These models, derived from statistical analysis, offer valuable insights into the interaction between variables such as %M-Sand, %CNS, and curing time, and can serve as useful tools for optimizing mix designs in future research and practical applications.

The RSM model demonstrates a high level of accuracy, with the predicted response surface plot exhibiting an error margin of less than 5%, corresponding to a 95% confidence level. This study has also demonstrated the potential of incorporating FA, CNS, and M-Sand into concrete as a sustainable alternative to conventional materials. This research proves that using the right combination of materials can make concrete both stronger and more environmentally friendly. Colloidal Nano Silica (CNS) plays a key role in improving the properties of concrete. By enhancing the strength and durability of concrete, CNS ensures that structures can last longer and require fewer repairs, saving resources over time. Additionally, CNS reduces the need for large amounts of cement, which is a major source of carbon emissions. This helps lower pollution and makes the production process more sustainable. The extended lifespan of buildings and efficient use of materials also mean less waste and better preservation of natural resources. Overall, CNS is an innovative and essential addition to modern concrete, helping construction become more eco-friendly and future-ready. The TBNC mix not only improves mechanical properties and sustainability but also offers cost and energy efficiency by incorporating industrial by-products and minimizing cement dependency.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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