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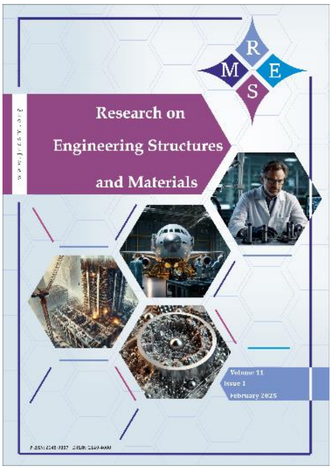

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Online Publication Date: 30 May 2024
URL: http://www.jresm.org/archive/resm2024.172ma0202rs.html
DOI: http://dx.doi.org/10.17515/resm2024.172ma0202rs

To cite this article
Reddy AN, G. Reddy GK, P. Reddy N, Reddy KS, Kavyateja BV. Analyzing the impact of nano-sized silica on composite concrete: A static approach utilizing response surface method. *Res. Eng. Struct. Mater.*, 2025; 11(1): 165-178.

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Research Article

Analyzing the impact of nano-sized silica on composite concrete: A static approach utilizing response surface method

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Article Info

Article history:

Received 02 Feb 2024
Accepted 28 May 2024

Keywords:

Fly Ash;
Alccofine;
Nano silica;
Tetranary blended nano concrete;
Statistical analysis;
Response surface method

Abstract

The utilization of composite materials as alternatives to Ordinary Portland Cement (OPC) is essential in mitigating the environmental impact of cement production. This study investigates the potential of industrial by-products rich in silica and alumina, such as fly ash (FA), alccofine (ALC), and nano silica (CNS), to partially replace OPC in concrete. Tetranary blended nano concrete (TBNC) compositions, incorporating 25% FA, 10% ALC, and varying proportions of CNS (0%, 0.5%, 1%, 2%, and 3%), were examined for their compressive strength in M30 and M60 grade concrete following a 90-day curing period. Results demonstrate the significant influence of CNS on compressive strength of TBNC. To validate these findings, Response Surface Methodology (RSM) was employed for mathematical modeling and statistical analysis, predicting compressive strength values and comparing them with experimental data. This research underscores the viability of utilizing industrial by-products in concrete production, thereby promoting sustainable construction practices.

1. Introduction

Utilization of concrete is increasing every year with increase in the infrastructure. Concrete manufactured by using Ordinary Portland Cement (OPC) is widely used throughout the world because of availability and flexibility in easy operation [1]. The production of OPC requires a substantial amount of thermal energy and emits a large quantity of greenhouse gases, such as carbon dioxide (CO_2), which have severe environmental consequences and contribute to global warming [2,3]. OPC production has been reported to be liable for about 3% and 9% of worldwide energy consumption and anthropogenic emission of CO_2, respectively [4,5]. So, there is a need to search for the alternate materials, which can help to reduce the usage of OPC and produce sustainable construction materials in construction industry. The solution to this problem is to utilizing the industrial by-product which process pozzolanic nature as supplementary cementations materials (SCMs) in concrete [6]. The solid waste generated from industries creates disturbance in environment due to air pollution, land filings and pollutes the ground water by leachate. The by- products such as Fly Ash (FA), Rice Husk Ash (RHA), Ground Granulated Blast Furnace Slag (GGBS), Red mud (RM), Alccofine (ALC), Silica Fume (SF), Metakaolin (MK) etc., which are pozzolanic in nature can be used as SCMs [7,8]. Blending different types of pozzolans with cement improves the properties (durability and mechanical) of concrete [9,10]. The most

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DOI: http://dx.doi.org/10.17515/resm2024.172ma0202rs

important effects of Pozzolan admixture enhances the microstructure of concrete or cement paste by altering the interfacial transition zone (ITZ) and reducing pore structure via pozzolanic reaction [11,12]. In the present study, industrial by-products of pozzolanic nature, such as FA and ALC, are substituted for cement in concrete. By substituting these materials for cement in concrete, pollution-causing gas emissions from the cement production process will be reduced.

Moreover, the introduction of nanoparticles like colloidal nano silica (CNS) presents an opportunity to enhance concrete properties further [3]. CNS, with its high pozzolanic nature, can accelerate pozzolanic reactions within concrete, resulting in improved mechanical and physical properties. By incorporating CNS into concrete mixes, we can achieve greater strength and durability while reducing environmental impact [5]. Several studies have investigated the impact of nano-sized silica on the compressive strength, tensile strength, and flexural strength of concrete [9-12]. Research indicates that the addition of nano-sized silica particles improves the packing density of concrete mixtures, resulting in higher compressive strength [10]. Furthermore, nano-sized silica enhances the ITZ between cement paste and aggregates, leading to increased bond strength and improved mechanical properties [11]. Moreover, nano-sized silica has been found to enhance the durability of concrete by reducing permeability and increasing resistance to chloride ion penetration, sulfate attack, and alkali-silica reaction [13,14]. The fine particles of nano-sized silica fill in the pores and capillary voids within the concrete matrix, effectively reducing water ingress and preventing the ingress of deleterious substances [15]. Pervious research studies suggest that nano-sized silica can act as a viscosity-modifying admixture, improving the workability and flowability of concrete mixtures. This property is particularly advantageous in high-performance concrete and self-compacting concrete applications. Furthermore, investigations into the hydration kinetics of nano-sized silica in cementitious systems have revealed its role in accelerating cement hydration and promoting the formation of additional calcium silicate hydrate (C-S-H) gel. This accelerated pozzolanic reaction contributes to early strength development and improved long-term mechanical properties of concrete [9-15].

In this study, we focus on investigating the combined effects of 25% FA, 10% ALC, and varying amounts of CNS on the compressive strength of Ternary Blended Nano Concrete (TBNC) for M30 and M60 grade concrete over a 90-day curing period. By examining the influence of these materials on concrete strength, we aim to contribute to the development of sustainable construction practices and the utilization of industrial waste. Additionally, we have employed Response Surface Methodology (RSM) to develop regression equations for the compressive strength of M30 and M60 grade concretes separately. RSM helps to model and optimize complex processes, such as concrete strength development, by analyzing the interactions between multiple variables [16]. In RSM utilizing the design of experiments (DOE) method, several mathematical models have been developed and employed. One common model is the quadratic model, which assumes a second-order relationship between the independent variables and the response [17]. By utilizing RSM, we can gain insights into the optimal combination of materials to achieve desired concrete properties, thereby enhancing the efficiency and effectiveness of this research. The relevance of the static approach lies in its ability to provide precise and reliable data on the performance of concrete mixtures over time [16,17]. By subjecting the TBNC specimens to a consistent curing environment, we can accurately evaluate the long-term effects of incorporating FA, ALC, and CNS on concrete strength. This method allows us to capture the gradual development of concrete strength and assess the durability of the composite material. Moreover, the static approach enables us to systematically investigate the individual and combined contributions of FA, ALC, and CNS to the mechanical properties of TBNC. By maintaining a stable testing environment throughout the curing period, we can isolate the effects of each material and analyze their synergistic interactions on concrete strength. The static approach facilitates the comparison of different concrete mix designs and helps identify optimal combinations of supplementary materials for achieving desired performance characteristics [16]. This structured methodology enhances the reliability and reproducibility of findings, ensuring robust conclusions regarding the efficacy of TBNC in sustainable construction practices. The static approach serves as a fundamental tool in this research, allowing for a detailed and structured analysis of the influence of supplementary materials on the compressive strength of TBNC. Through this approach, we aim to provide valuable insights into the development of sustainable concrete mixtures and contribute to the utilization of industrial waste in construction applications [16,17].

2. Research Significance

The primary challenge in modern construction lies in attaining the requisite strength of standard concrete, predominantly reliant on OPC. However, the surge in industrialization has led to the accumulation of non-engineered industrial waste, posing detrimental effects on the environment and ecosystems. The main aim of the present research is to explore the alternative building materials with industrial solid waste, potentially beneficial for the construction sector. This study investigates the potential of utilizing pozzolanic industrial solid waste as a cementitious supplement, offering a sustainable alternative to OPC. By advocating for the incorporation of industrial waste as admixtures or partial cement replacements, efforts are directed towards reducing cement consumption and addressing environmental contamination attributed to industrial byproducts. In particular, our research explores the effects of a composite mixture comprising FA, ALC, and CNS on the compressive strength of M30 and M60 grade concrete. By examining the influence of these materials on concrete strength, we aim to contribute to sustainable construction practices and mitigate the environmental impact of industrial waste. The adoption of RSM in our study serves to enhance the efficiency and effectiveness of our research. RSM allows for the modeling and optimization of complex processes, such as concrete strength development, by analyzing the interactions between multiple variables. In the context of our research, the RSM model enables us to systematically investigate the combined effects of fly ash, alccofine, and colloidal nano silica on the compressive strength of M30 and M60 grade concrete. By utilizing RSM, we can develop regression equations that provide insights into the optimal combination of materials to achieve desired concrete properties. Overall, the use of RSM facilitates a comprehensive understanding of the relationship between input variables and concrete strength, enabling us to optimize concrete mixtures for enhanced mechanical performance while minimizing environmental impact.

3. Materials

This research utilizes OPC of 53-grade as the binder in the experimental setup. Coarse and fine aggregates serve as filler materials, supplemented with super-plasticizers, specifically poly-carboxylic ether. The OPC utilized adheres to the standards set by the Bureau of Indian Standards (IS) with reference to IS: 12269-2013 [18]. The OPC exhibits a specific gravity of 3.12, fines of 6.50%, and initial and final setting times of 50 minutes and 420 minutes, respectively. The fine and coarse aggregates undergo testing according to IS: 383-1970 [19]. The angular shaped locally available crushed stone was used coarse aggregates, 20 mm downgraded, feature a specific gravity of 2.78, fineness modulus of 7.2%, and water absorption of 0.86%. Meanwhile, the fine aggregates, 4.75 mm downgraded and falling within the II grading zone as per IS 383-1970 [19], exhibit a specific gravity of 2.68, fineness modulus of 2.7%, and water absorption of 1.02%. Low calcium FA (Class F type) is sourced from the Vijayawada Thermal Plant in Andhra Pradesh, aligning with the specifications outlined in IS 3812-2013 [20]. This FA boasts a specific gravity of 2.3 and a fines modulus of 1.19%. ALC-1203, obtained from Ambuja Cement Ltd in Goa, conforms to

American Society for Testing and Materials (ASTM) C989-1999 [21] and possesses a specific gravity of 2.9. ALC is characterized as an ultrafine slag material and glass-based SCM sourced from steel or iron industries. Notably, ALC comprises fine solid glass spheres of non-crystalline polymorph or amorphous silicon dioxide. The high specific surface area of ALC particles exerts a significant influence on both the fresh and hardened state properties of concrete, as documented in various studies. In the study, scanning electron microscope (SEM) analysis was conducted to examine the morphology and microstructure of fly ash and alccofine particles used in our composite concrete. The SEM images revealed essential insights into the characteristics of these materials. The chemical properties of FA obtained from SEM and Energy Dispersive X-ray Analysis (EDAX) are given below and in figure1, the figure 1 revealed that the elemental characteristics in terms of weight percentage and atomic percentage. The analysis discerns four major elements, with distinctive compositions as follows:

1. C K (Carbon):
    - Weight Percentage: 59.2%
    - Atomic Percentage: 68.02%
2. O K (Oxygen):
    - Weight Percentage: 31.9%
    - Atomic Percentage: 27.6%
3. Al K (Aluminium):
    - Weight Percentage: 2.7%
    - Atomic Percentage: 1.4%
4. Si K (Silicon):
    - Weight Percentage: 6.07%
    - Atomic Percentage: 2.9%

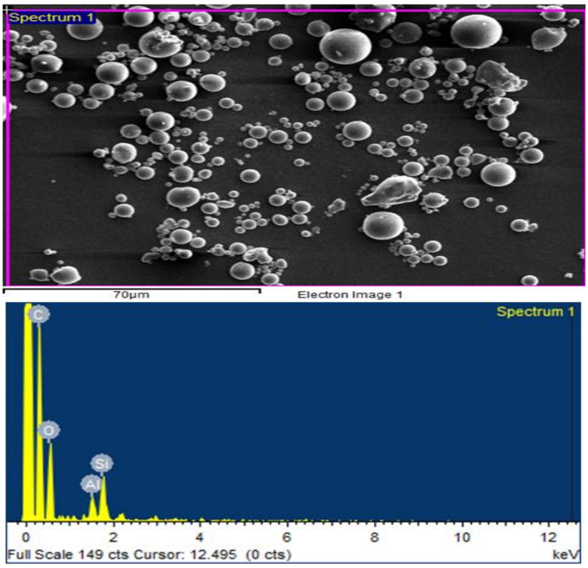

Fig. 1. SEM and EDAX image of FA

From figure 1, the SEM images revealed essential insights into the characteristics of these materials. For fly ash, the SEM observations indicated an amorphous structure, with spherical particles ranging in size from 0.5 µm to 70 µm. This spherical morphology is consistent with previous research findings [30,31] and is known to contribute to improved packing density and reduced water demand in concrete mixtures. The predominant presence of Carbon and Oxygen, comprising 59.2% and 68.02% in weight and 31.9% and 27.6% in atomic percentages, respectively, highlights their significant role in the elemental composition of the FA. Aluminum and Silicon are found in lower concentrations, with 2.7% and 1.4% in weight and 6.07% and 2.9% in atomic percentages, respectively as shown in figure 1. These chemical properties elucidate the elemental composition of FA, offering valuable insights into its potential impact on concrete properties and its suitability for use as a supplementary cementitious material. The data provided by EDAX contributes to a comprehensive understanding of the composition of FA, essential for informed decisions in concrete mix design and sustainable construction practices [22,23].

The chemical properties of ALC derived from EDAX are given figure 2, delineating the elemental characteristics in terms of weight percentage and atomic percentage. From the figure 2, the SEM analysis revealed an amorphous structure with angular particles, with sizes ranging from 0.5 µm to 30 µm. This angular morphology is advantageous for enhancing the pozzolanic activity of ALC, promoting better interfacial bonding with cementitious materials and resulting in enhanced mechanical properties of concrete [22,23] and the EDAX analysis reveals the composition of five major elements as follows. The predominant presence of Carbon and Oxygen, comprising 45.6% and 57.6% in weight and 35.2% and 33.3% in atomic percentages, respectively, underscores their substantial role in the elemental composition of ALC. Aluminium, Silicon, and Calcium are found in comparatively lower concentrations, emphasizing the multifaceted composition of ALC. These chemical properties offer insights into the elemental composition of ALC, crucial for understanding its potential impact on concrete properties. The presence of Calcium suggests its pozzolanic nature, contributing to enhanced durability and strength characteristics in concrete. The data provided by EDAX facilitates informed decision-making in concrete mix design, particularly when incorporating ALC as a supplementary cementitious material in construction practices. These SEM observations provide valuable insights into the microstructural characteristics of FA and ALC, which are essential for understanding their influence on the properties of composite concrete [22,23].

1. C K (Carbon):
    - Weight Percentage: 45.6%
    - Atomic Percentage: 57.6%
2. O K (Oxygen):
    - Weight Percentage: 35.2%
    - Atomic Percentage: 33.3%
3. Al K (Aluminium):
    - Weight Percentage: 4.01%
    - Atomic Percentage: 2.2%
4. Si K (Silicon):
    - Weight Percentage: 6.3%
    - Atomic Percentage: 3.4%
5. Ca K (Calcium):
    - Weight Percentage: 8.6%
    - Atomic Percentage: 3.2%

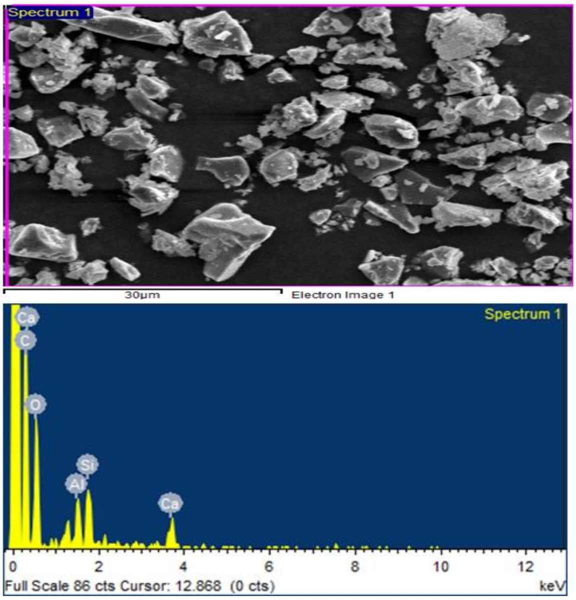

Fig. 2. SEM and EDAX image of ALC

CNS, procured from Bee-Chems Chemicals in Kanpur, boasts a specific gravity of 1.21, particle size ranging from 10-20 nm, and a surface area of 150-180 m^2/g. A high-range water-reducing admixture primarily composed of poly-carboxylic ether, in accordance with ASTM-C494 [24] standards, is employed throughout the study. In the study, nano-sized silica, particularly in colloidal form, plays a critical role in enhancing the performance of composite concrete. The fine particles of CNS help densify the concrete microstructure, filling voids and pores, thereby improving packing density, reducing permeability, and enhancing mechanical properties [11]. Additionally, CNS promotes better adhesion between the cement paste and aggregates, leading to improved bond strength and overall mechanical performance of the concrete [12]. Through our research, we aim to elucidate the significant role of colloidal nano silica in composite concrete and its incorporation method, contributing to the advancement of sustainable and durable construction materials. The concrete preparation utilizes portable tap water available on the university premises, featuring a pH value of 7-8, adhering to the recommendations outlined in IS 456-2000 [25].

4. Mix Design

M30 and M60 grade of mix designs were prepared as per the guidelines given in IS: 10262-2009 [26] and American Concrete Institute (ACI) 211.4R-2008 [27] respectively. The design mix of 1:2.06:3.63 with w/c ratio 0.43 was adopted for casting of M30 grade of concrete and for M60 grade the design mix of 1:1.6:2.19 with w/c ratio 0.30 was adopted. The details of mix design and proportions are given in Table 1. The OPC was partial replaced by combination of 25% FA, 10% ALC and with varying amounts of CNS (i.e. 0%, 0.5%, 1%, 2% and 3%). The quantity of all ingredients of concrete was determined according to the design ratio of the mixes. The CNS is incorporated by first mixing it with water to form a stable suspension, ensuring uniform dispersion throughout the concrete mix. Once dispersed, nano silica contributes to improving various aspects of concrete properties. Its high surface area facilitates enhanced pozzolanic activity, reacting with calcium hydroxide in the cement paste to form additional C-S-H gel, thus enhancing strength and durability. The ingredients were mixed thoroughly until the mix obtained uniform colour. The cubes of 100x100x100 mm were filled with concrete and vibrated with the help of table vibrator. The specimens were allowed for air curing for 24 hrs and de-moulded. They are allowed for 7-, 28-, 56- and 90-days curing periods and tested for compressive strength.

Table 1. Details of mix design and proportions

GC	MN	OPC (kg/m^3)	FA (kg/m^3)	ALC (kg/m^3)	CNS (kg/m^3)	CNS content	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)
M30	C1	350.2	-	-	-	-	721.5	1273.8	150.59
	T0	236.4	87.5	26.3	-	0%	721.5	1273.8	150.59
	T0.5	235.2	87.5	26.3	1.18	0.5%	721.5	1273.8	150.59
	T1	234.06	87.5	26.3	2.37	1%	721.5	1273.8	150.59
	T2	231.7	87.5	26.3	4.73	2%	721.5	1273.8	150.59
	T3	229.33	87.5	26.3	7.10	3%	721.5	1273.8	150.59
M60	C2	540.1	-	-	-	-	625.5	1180.8	162.03
	S0	364.5	135.02	40.5	-	0%	625.5	1180.8	162.03
	S0.5	362.7	135.02	40.5	1.8	0.5%	625.5	1180.8	162.03
	S1	360.9	135.02	40.5	3.6	1%	625.5	1180.8	162.03
	S2	357.3	135.02	40.5	7.3	2%	625.5	1180.8	162.03
	S3	353.7	135.02	40.5	10.9	3%	625.5	1180.8	162.03

GC- Grade of Concrete, MN- Mix Notation, C1- M30 Grade Conventional Concrete
T0 - M30 grade blended concrete mix containing 25% FA, 10% ALC and 0% CNS
T0.5 - M30 grade blended concrete mix containing 25% FA, 10% ALC and 0.5% CNS
T1 - M30 grade blended concrete mix containing 25% FA, 10% ALC and 1% CNS
T2- M30 grade blended concrete mix containing 25% FA, 10% ALC and 2% CNS
T3- M30 grade blended concrete mix containing 25% FA, 10% ALC and 3% CNS,
C2 – M60 grade Conventional Concrete mix,
S0 - M30 grade blended concrete mix containing 25% FA, 10% ALC and 0% CNS
S0.5 - M30 grade blended concrete mix containing 25% FA, 10% ALC and 0.5% CNS
S1 - M30 grade blended concrete mix containing 25% FA, 10% ALC and 1% CNS
S2- M30 grade blended concrete mix containing 25% FA, 10% ALC and 2% CNS
S3- M30 grade blended concrete mix containing 25% FA, 10% ALC and 3% CNS
CNS content - Percentage by weight of cement

5. Experimental Setup

The prepared specimen is mounted on the lower platen of a compression testing machine, ensuring proper alignment to prevent eccentric loading as per the guidelines provided in IS 516:2018 [28]. A compressive load is at 1.4N/mm^2/minute applied gradually to the specimen at a specified rate until failure occurs, which is typically characterized by visible cracking or crushing. Throughout the test, data on applied load and deformation are continuously recorded. After testing, the data are analyzed to determine the compressive strength of the concrete specimen, providing valuable insights into its structural performance and integrity.

6. Results

6.1 Compressive Strength (CS)

The compressive strength results of M30 grade and M60 grade blended concrete with combination of 25% FA, 10% ALC and varying percentages of CNS (0%, 0.5%, 1%, 2% and 3%) at a curing period of 7, 28, 56 and 90 days are shown in Figure 3 and Figure 4.

Form the Figure 3 and Figure 4 it is noticed that a minor improvement in compressive strength is achieved with combination of 25% FA, 10% ALC and 0% CNS (T0 and S0 mixes), the strength increased by 9.8%, 7.08%, 7.07%, 7.04% and 12.8%, 9.03%, 8.9%, 8.5% for the ages of 7, 28, 56 and 90 days respectively, in comparison to the M30 grade and M60 grade conventional concrete mixes C1 and C2, which is attributed to the reason that the concrete matrix gets densified due to the plugging of pores by ALC particles [12]. The compressive strength is further enhanced significantly with CNS, The compressive strength of T0 – T3 mixes containing 0.5%, 1%, 2% and 3% CNS is increased by 20.6%, 26.8%, 23.9%,14.1% and 9.8%, 14.09%, 12.17%, 8.78%, for the ages of 7 and 28 days respectively, in comparison to the M30 Grade conventional concrete mix C1.

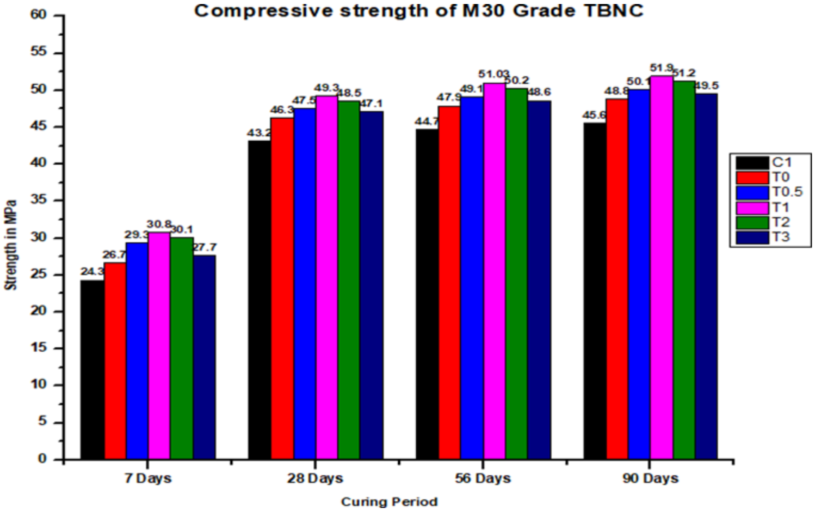

Fig. 3. Compressive Strength of M30 Grade of concrete

Whereas for M60 grade of concrete, the compressive strength of S0 – S3 mixes containing 0.5%, 1%, 2% and 3% CNS is increased by 21.5%, 25.1%, 23.5%, 20.9% and 13.7%, 17.5%, 16.3%, 12.8%, for the ages of 7 and 28 days respectively, in comparison to the conventional concrete mix C2. The enhancement in the initial age (7 day) compressive strength of blended concrete is due to accelerated hydration reaction in concrete on the addition of CNS [29,30]. In hydration process CNS helps in accelerating the pozzolanic reaction by formation of more Calcium Hydroxide (CH) resulting in quick hydration of tricalcium silicate (C_3S) and Dicalcium silicate (C_2S) resulting in formation of more C-S-H which helps in formation of denser matrix in concrete structure resulting in high improvement in early age strength [31]. In the hydration reaction, the nucleation effect by nano silica accelerates the consumption of C_3S, which results in release of more CH [32]. The better dispersion of CNS particles with cement showed enhancement in compressive strength for all the blended mixes. The enhancement of compressive strength continued till the CNS concentration increased up to 1% and reduces slightly for 2% and 3%. The reason for the decrease in compressive strength may be due to the separation of particles because of excess number of nano particles or due to the higher potential of agglomeration, due to poor dispersion of nano particle in mixture leads to effect of pore structure of concrete resulting in strength decrement [33]. The later age (i.e. 56 and 90 days) compressive strength showed a negligible change for 28 days compressive strength which is because of accelerated heat of hydration process, moreover, the addition of micro and nano sized SCM's are responsible for the development of denser microstructure. It is also noticed that most of the hydration process gets completed at 28 days curing period which becomes very slow and will continue over time, thus showing minimum variations in compressive strength at a curing period of 56 and 90 days [34].

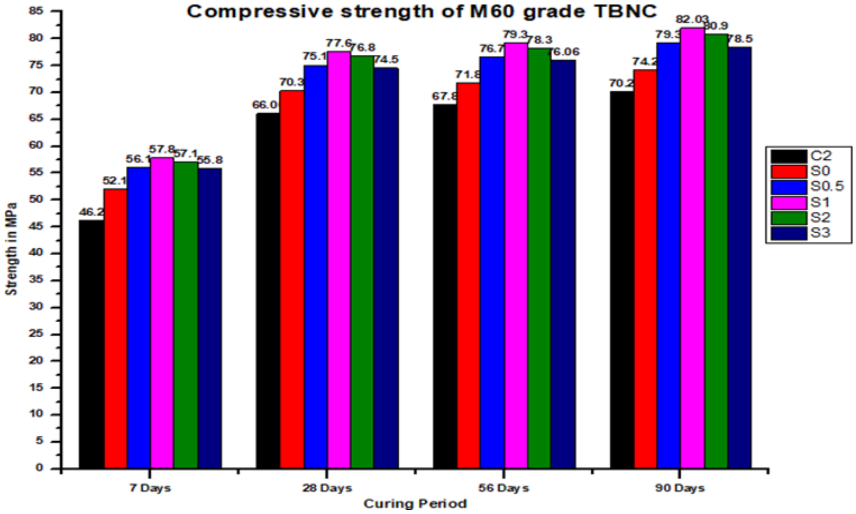

Fig. 4. Compressive Strength of M60 Grade of concrete

6.2 Design of experiments (DOE) by Response Surface Method (RSM):

In our study, RSM was utilized to assess the compressive strength (CS) of TBNC through a structured DOE. RSM, a statistical tool widely employed in industry and research, facilitated mathematical modeling and statistical analysis to predict the validity of experimental CS values. We adopted a second-order polynomial equation, as opposed to a linear model, to comprehensively evaluate the input variables responses. The response can be represented by the equation mentioned below equation 1.

$$y = F\,(£1, £2, £3\ldots\ldots£k) + \varepsilon \qquad (1)$$

Where the input variables are represented by £1, £2, £3…£k, approximate response function is denoted by F and static residual error is denoted by ε, in the present analytical study for evaluating the input variables response, the second order polynomial equation was used instead of the linear polynomial. In this study experimental design, was mainly focused on one response variable, CS, and two independent variables: Curing Period (CP) and Colloidal Nano Silica Percentage (%CNS). Through regression analysis conducted using MINITAB software, we obtained coefficient values to construct a quadratic prediction model equation, as per equation 2. This equation allowed us to predict CS based on varying CP and %CNS combinations. Subsequently, DOE was employed to evaluate the goodness of fit of our model, assessing its effectiveness in representing the observed data accurately. Additionally, RSM facilitated the development of response surface graphs and residual plot graphs, aiding in visualizing the relationships between CP, %CNS, and CS. This systematic approach enabled us to optimize TBNC formulations and enhance our understanding of the factors influencing its compressive strength.

$$Z = A + BX1 + CY1 + DX12 + EY12 + F\,X1\,Y1 \qquad (2)$$

In the equation X1 represents the %CNS, Y1 represents the CP and Z represents the CS. By RSM analysis the following polynomial regression equation 3 is obtained for M30 grade of concrete

$$CS = 23.39 + 3.99\ \%CNS + 0.851\ CP - 1.266\ \%CNS \times \%CNS - 0.006436\ CP \times CP + 0.0001\%CNS \times CP \qquad (3)$$

By RSM analysis the following polynomial regression equation 4 is obtained for M60 grade of concrete:

$$CS = 48.36 + 7.94\ \%CNS + 0.830\ CP - 2.325\ \%CNS \times \%CNS - 0.00603\ CP \times CP + 0.0011\ \%CNS \times CP \qquad (4)$$

Table 2. Experimental and predicted values by using RSM regression expression for m30 grade of TBNC

%CNS	CP	CS (Actual)	CS (Predicted)	Residual Error	R^2 (Actual)	R^2(Predicted)
0	7	26.7	29.03326	-2.33326	90.62%	82.28%
0.5	7	29.3	30.71313	-1.41313		
1	7	30.8	31.76004	-0.96004		
2	7	30.1	31.95497	-1.85497		
3	7	27.7	29.61806	-1.91806		
0	28	46.3	42.18122	4.11878		
0.5	28	47.5	43.86229	3.637712		
1	28	49.3	44.91039	4.389606		
2	28	48.5	45.10772	3.392276		
3	28	47.1	42.77321	4.326791		
0	56	47.9	50.88107	-2.98107		
0.5	56	49.1	52.56374	-3.46374		
1	56	51.03	53.61344	-2.58344		
2	56	50.2	53.81397	-3.61397		
3	56	48.6	51.48265	-2.88265		
0	90	48.8	47.87722	0.922781		
0.5	90	50.1	49.56183	0.538174		
1	90	51.9	50.61347	1.286529		
2	90	51.2	50.81788	0.382121		
3	90	49.5	48.49044	1.009558		

The actual CS and predicted CS by RSM for M30, M60 grades and their residual errors are represented in Table 2 and Table 3 respectively. From the RSM analysis the regression coefficient (R^2) of CS (Actual) is 90.62%, CS (Predicted) is 82.28% and for M30 grade of TBNC concrete and the R^2 of CS (Actual) is 90.19% and R^2 of CS (Predicted) is 82.45% for M60 grade of TBNC concrete.

Table 3. Experimental and Predicted values by using RSM regression expression for M60 Gradeof TBNC

%CNS	CP	CS (Actual)	CS (Predicted)	Residual Error	R^2(Actual)	R^2(Predicted)
0	7	52.1	53.88003	-1.78003	90.19%	82.45%
0.5	7	56.1	57.27344	-1.17344		
1	7	57.8	59.50422	-1.70422		
2	7	57.1	60.47791	-3.37791		
3	7	55.8	56.8011	-1.0011		
0	28	70.3	66.88768	3.412317		
0.5	28	75.1	70.29297	4.807034		
1	28	77.6	72.53562	5.064377		
2	28	76.8	73.53306	3.266938		
3	28	74.5	69.88	4.620001		
0	56	71.8	75.96168	-4.16168		
0.5	56	76.7	79.38279	-2.68279		
1	56	79.3	81.64128	-2.34128		
2	56	78.3	82.67039	-4.37039		
3	56	76.06	79.049	-2.989		
0	90	74.2	74.27442	-0.07442		
0.5	90	79.3	77.71477	1.585234		
1	90	82.03	79.99248	2.037516		
2	90	80.9	81.06004	-0.16004		
3	90	78.5	77.4771	1.022897		

6.2.1 Residual Plots form RSM Analysis

From the RSM analysis, Normal probability plot and 3D response surface plots were obtained. The figure 5 represents the normal probability plot and figure 6 represents the 3D response surface plots for M30 and M60 grade of TBNC.

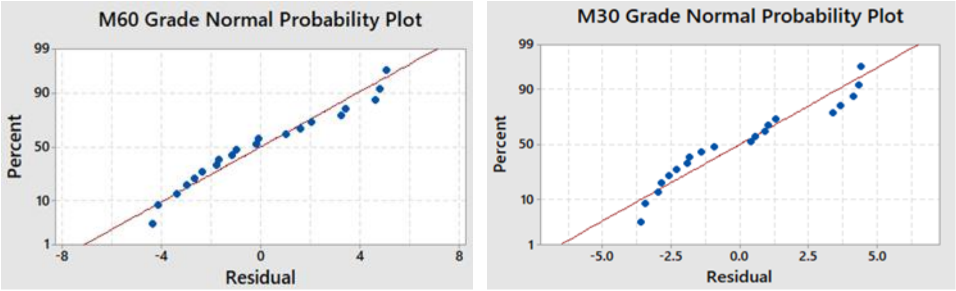

Fig. 5. Normal probability plot for M30 grade and M60 grade of TBNC from RSM analysis

The points which are present nearer to the reference line indicates low error and the points far from the reference line indicate more error. From the figure 5 it is is clearly seen that the CS plot was approximated well in a line and the points are closer to the reference line. It can be concluded that the percentage of residual error is less and the probability between percentage and residual values is satisfied. From this analysis it can be concluded that the obtained CS results are in acceptable range for both M30 and M60 grade of TBNC.

Figure 6 depicts a 3D response surface plot with CS vs %CNS and CP from the developed model. The surface plot's curvature suggests that the CS of TBNC mix is highly dependent on its CNS concentration. Development in CS with the progression of curing age is usual, however in TBNC, high early age strength is achieved, and the graphical depiction does not indicate a sharp rise in terms of curing age.

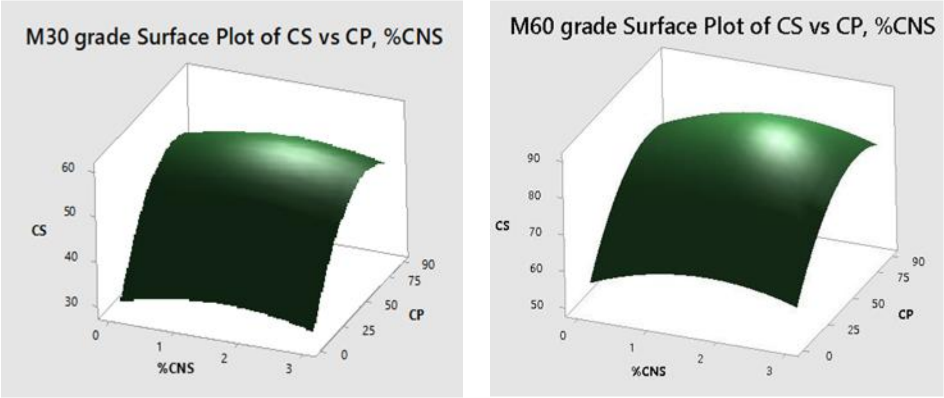

Fig. 6. Normal probability plot for M30 grade and M60 grade of TBNC from RSM analysis

From the RSM analysis it is clearly seen that the percentage of residual error is less than 5%, So that it can be concluded that the obtained results confidence level is about 95% for both M30 and M60 grade of TBNC [16]. In the study, it was aimed to investigate the synergistic effects of incorporating nano-sized silica alongside industrial pozzolanic materials, namely FA and ALC, in concrete mixes to enhance mechanical properties while reducing environmental impact. Through rigorous experimentation and analysis, we evaluated the compressive strength of composite concrete mixes containing varying concentrations of nano-sized silica over a 90-day curing period. The findings demonstrated that the addition of CNS in combination with FA and ALC led to significant improvements in compressive strength compared to traditional concrete mixes [17]. This result aligns with previous literature suggesting that nano-sized silica enhances the mechanical properties of concrete by improving packing density, enhancing bond strength, and reducing permeability [16,17]. Furthermore, the study contributes to the advancement of sustainable construction practices by highlighting the efficacy of utilizing industrial by-products as supplementary cementitious materials. By linking the results to the research objectives and relevant literature, we emphasize the potential of incorporating nano-sized silica in concrete formulations to achieve high-performance and environmentally friendly construction materials [16,17].

7. Conclusions

The combination of constant percentages of FA and ALC quantity showed moderate enhancement in compressive strength of concrete at all ages. With 25% FA, 10% ALC and 1% CNS showed better enhancement in compressive strength at all ages form both M30 and M60 grade of TBNC concrete. CNS helped to accelerate the hydration reaction which helped the TBNC to improve early strength gaining capacity. At early age the strength had improved about 26.8% for M30 grade and 25.1% for M60 grade when compared with conventional concrete mixes for 7 days curing period, not only the early age enhancement the CNS helped to improve the long-term strength property also the strength enhancement was about 14.09%, 14.08%, 13.72% for M30 grade and 17.5%, 16.94%, 16.8% for M60 grade when compared with conventional concrete mixes for 28-, 56- and 90-days curing period. Incorporation of CNS in blended concrete can be considered as an effective way for enhancing the overall performance of the concrete. The better dispersion of CNS particles with cement showed enhancement in compressive strength for all the blended mixes. The enhancement of compressive strength continued till the CNS concentration increased up to 1% and reduces slightly for 2% and 3%. The decrease in CS may be attributable to the separation of particles as a result of an excess of nanoparticles or to a higher potential for agglomeration as a result of poor dispersion of nanoparticles in the mixture, which has an effect on the pore structure of concrete, resulting in a decrease in strength. The experimental CS was predicted using the RSM approach in order to forecast the CS values, and the residual error was found to be within an acceptable range, indicating a valid prediction. The replacement of cement in TBNC with a combination of FA, ALC, and CNS led to the development of high-strength TBNC concrete. This subsequently leads to the development of TBNC by combining several SCMs that may contribute to cost savings and sustainability

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