



RSM OPTIMIZATION OF MECHANICAL AND DURABILITY PROPERTIES OF SELF-COMPACTING CONCRETE INCORPORATING ZINC ASH AND BLASTING GRIT NANOPARTICLES

Rabeea W. Bazuhair^{1*}, Ehab A. Mlybari¹, and Wasayo Sanam Sahito¹

Department of Civil Engineering, College of Engineering and Architecture, Umm Al-Qura University, Makkah, Saudi Arabia

*Corresponding Author, Received: 29 May 2025, Revised: 13 May 2026, Accepted: 15 May 2026

ABSTRACT: In concrete mixtures, Portland cement is a common building material. Replacing part of the cement with supplementary cementitious materials (SCMs) can make concrete more environmentally friendly, improve its properties, and reduce its cost. This study investigates the mechanical performance of self-compacting concrete (SCC) incorporating two SCMs, zinc ash (ZA) and blasting grit (BG), which are industrial waste by-products used as partial cement replacements. The average particle size for BG and ZA are 300 nm and 60 nm, respectively, and both materials have high specific gravity and a spherical particle shape. The experimental program was designed using Response Surface Methodology (RSM), and the mix proportions were optimized to achieve the best performance. Using a Box-Behnken design under RSM, experiments were conducted to model and optimize the compressive strength (CS) and flexural strength (FS) of SCC, leading to the development of mathematical models. The independent variables were the mass percentages of ZA (0–0.75%), BG (0–1.5%), and curing time (7, 14, 21, and 28 days). Analysis of Variance (ANOVA) confirmed the statistical significance of the models, with R^2 values exceeding 95% for both strength properties. The optimal mix was found to contain 0.5% ZA and 1% BG, which resulted in a 21.2% increase in 28-day compressive strength and a 17.8% improvement in flexural strength compared to the control mix. The combined use of ZA and BG not only enhances mechanical properties but also promotes waste valorization in concrete production. The RSM approach provided a reliable predictive model for identifying strength-efficient mix proportions, offering a practical tool for sustainable SCC mix design.

Keywords: Sustainable Construction; Self-Compacting Concrete (SCC); RSM Optimization; Mechanical Performance; Zinc-Based Nanoparticles.

1. INTRODUCTION

Self-compacting concrete (SCC) is considered as a new construction material with the adaptability to pass through small areas, around rebar, and under formwork, is the key development in structural concrete in the last few years. It coagulates due to gravity alone; no further vibration, separation, or aeration are needed. To make the paste more viscous, a viscosity modifier can be added [1]. These frequently contain polymers consisting of long-chain molecules that may absorb and immobilize free water molecules. It is crucial to verify all the fundamental hypotheses and test findings of the design model of the SCC structure [2] since this mixed design modification might alter the material's mechanical characteristics. Concrete was initially employed in building construction perhaps less than a century later. With the increased usage of concrete, however, substantial research has recently been

effective in enhancing its qualities by adding different extra cementitious ingredients, such as pozzolans and nanoparticles [3].

Recent advances in nanotechnology have drawn significant scientific interest to new uses of particles with a size of 10–9 nanometers or less. This could be because materials with the same chemical make-up lack the qualities that nanoscale particles do [4], which are significantly superior in terms of particle size. Six different iterations of the ideal SCC were created, using different design methodologies like statistics, factorial design, etc. Particle packing and mixed design, often known as Eco-SCC, were used to build high-performance SCCs and their SCC-Design [5].

Investigated the likelihood of mistakes and uncertainties. To considerably replace up to 63% of the cement in fly ash slag, research is being done to create SCC [6]. Lightweight SCCs (LWSCCs) that are simple to deploy and made of lightweight concrete (LWC) have been investigated for mixed ratios,

densities, and mechanical qualities [7-8]. In the coarse aggregate and mortar stages of the SCC, five suggested design approaches—statistical factor models, compressive strength (CS) techniques, dense filling methods, paste model rheology, and empirical design methods were investigated [9]. The design of SCC compounds and the link between their properties and fresh and tempered attributes were studied empirically [10]. The compressive strength, split tensile strength, and durability of SCC with silica, metakaolin, rice husk incineration residue, and fly slag (10% and 20% of cement load) samples after 7 and 28 days revealed better attributes of freshly installed and cured concrete [11].

The mechanical characteristics of palm oil fuel powder (POFA), an agricultural waste that is risky to dispose of unless it is recycled, were originally deteriorated with the goal of forming a sturdy SCC as a partial cement substitute [12]. In addition to SCC with SiO_2 , TiO_2 , and Al_2O_3 nanoparticles, fresh concrete's rheological qualities as well as the physical and mechanical characteristics of hardened concrete were improved, demonstrating the effectiveness of this technique [13]. When tested under standard corrosion and sulphate attack circumstances, SCC combined with POFA at varied concentrations (10%, 15%, and 20%) demonstrated good mechanical and durability qualities of SCC with corrosion and sulphate destruction. Additionally, drying shrinkage and surface moisture absorption are decreased without negatively compromising compressive strength [14]. By mixing red mud with nanoparticles of SiO_2 , Al_2O_3 , and CaO , fresh concrete and hardened SCC were produced, both of which had increased compressive strength as determined by XRF and XRD [15].

Additionally, incorporating red mud into SCC increased its shear strength and modulus, which decreased drying shrinkage. In SCC, fly ash (FA) and ground blast furnace slag (GGBFS) were combined in varied ratios (20, 30, and 40%). Mechanical qualities are negatively impacted by decreased wet density, increased cement setting time, and early water porosity [16]. Effect of waste volume on the final mortar's rheological and strength properties Sandblasting chemicals have substituted natural sand partially or entirely, which has decreased the expense of disposal and storage [17]. This experimental work using cement mortar revealed that compressive strength reduces with increasing nano concentration, particularly with nano SiO_2 and 0.5% ZnO_2 [18]. The effects of solid waste-derived zinc on the delay of hydration and loss of mechanical characteristics of zinc-containing

Portland cement diminish both the maximum temperature and heat flux [19]. When ZnO_2 powder and water were mixed at a certain constant (W/Z), phase composition, crystal structure, and microstructure of cement composites were examined. It was discovered that the zinc hydroxide ($\text{Zn}(\text{OH})_2$) phase had an impact on hydration delay (>48 h) [20].

Concrete's ability to hydrate is slowed down by the usage of electric arc furnace dust (EAFD), which emphasizes the necessity for alternate recycling. Cement pastes were studied using a ZnO_2 cement hydration model. By lowering cement mortar shrinkage and interacting favorably with calcium hydroxide, Zinc oxide nanoparticles have been discovered to significantly affect the microstructure and mechanical characteristics of cementitious materials [21]. By boosting their mechanical strength and longevity, Zinc oxide nanoparticles enable concrete's compressive strength, strength, and the hydration of cement particles.

Rich in zinc oxide, zinc ash, a by-product of the galvanizing industry, can improve cementitious systems' pozzolanic activity and filler effect. Because of its angular shape and mineral content, blasting grit—an abrasive leftover from surface treatment processes—helps to promote particle packing and mechanical interlocking. When used together, they encourage recycling of garbage and may improve SCC's strength performance.

There hasn't been much investigation into the use of nanoparticles to SCC to enhance its mechanical and physical qualities [5]. The nanoparticles' strong reactivity makes them operate as a heterogeneous core for the cement paste, which further encourages cement hydration [22-23]. They also serve as nano-fillers and nano-reinforcers, increasing the microstructure's density and lowering porosity [24]. For all nanoparticles, effective dispersion is a significant issue [5-7]. The "smart" (temperature and strain measurement) and hyper mechanical potential of cement mortar combined with nanoparticles.

2. RESEARCH SIGNIFICANCE

To date, research has, however, mostly concentrated on employing microscale cement replacement materials to attain superior strength performance without applying Response Surface Methodology (RSM) for multi response optimization. How ultra-fine and nanoscale particles impact the properties of concrete in optimum way is still a mystery with various mix proportions and curing period [25]. While silica fume, fly ash, and metakaolin nanoparticles have been studied in SCC,

comprehensive study on the combined usage of ZA and BG nanoparticles is lacking, especially when it comes to mechanical performance modeling utilizing statistical techniques like RSM. The current work employed ZA and BG nanoparticles to find impact of them on compressive, flexural, and pore structure measurements on the concrete including obtaining mathematical models, optimum input values using RSM, while encouraging the utilization of environmentally friendly industrial waste.

3. MATERIALS AND TEST METHODS

3.1 Raw Materials

Ordinary Pozzolana Portland Cement (PPC) that complies with ASTM C150 standard was utilized in this study. Table 1 provides information on the cement's chemical and physical characteristics.

When producing self-compacting concrete or regular concrete, aggregates with a 60mm average size are employed. Molten zinc metal produces zinc oxide (ZnO), commonly referred to as zinc ash (ZA), which is oxidized zinc. Hot dip galvanizing and other zinc coating procedures are the typical sources of zinc ash (Figure 1 a). To create zinc oxide suitable for agricultural use, another person combines the zinc ash. Various procedures, like galvanizing, make use of the metallics once again. Other people recovered the zinc in metallic form by smelting both treated and raw ashes. The formation of SCC, high-performance concrete, depends heavily on chemical additives like water reducers, retarders, viscosity modifiers, flow agents, and superplasticizers.

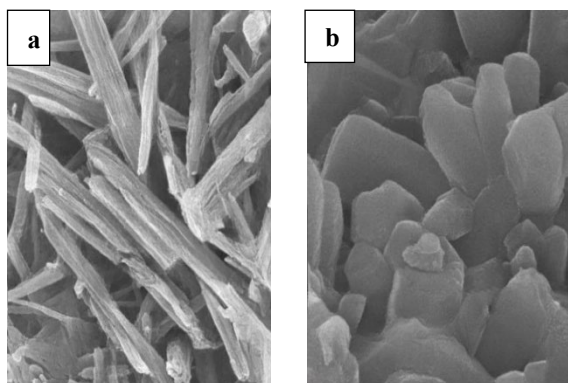


Fig. 1 SEM images of (a) ZA (b) BG

Without impacting the strength of the concrete, an effective superplasticizer may minimize slump and water by 20–30%. Depending on the kind of concrete that is needed, the dose ranges from 0.5 to 2% by weight of cement. The mixed water came

from the tap. Since steel grit/steel shot is softer than aluminum oxide and doesn't shatter as easily, it is frequently used in airless applications. Additionally, it is used in direct weight applications where a large profile is necessary. When shot peening ferrous materials, steel shot is used. Metallic abrasives are ideal for shot peening and airless impacting because of their extended lives. Table 2 shows the compositions of ZA and BG.

Table 1 Portland cement's characteristics (chemical and physical)

Chemical characteristics			Physical characteristics	
Cement	Notation	Mass (%)	Specific gravity:	3.15
Calcium oxide	CaO	0.65	Fineness (%):	0.89
Silicon dioxide	SiO ₂	0.21	Consistency (%):	32
Aluminum oxide	Al ₂ O ₃	0.05	Initial setting Time (IST) Min:	143
Ferric oxide	Fe ₂ O ₃	0.02	Final setting time (FST) Min:	205
Sulfur trioxide	SO ₃	2	Soundness (mm):	0.6

Table 2 Compositions of ZA and BG.

Zn	Fe	Pb	Al	Cu	Cd	Mg	Cl
61.2	0.65	0.23	1.64	0.069	0.0001	0.019	24.85

3.2 Mix Proportion Design of SCC

Using the absolute mass method, the SCC mixture fraction was constructed in this study. The SCC required a compressive strength of 69 MPa. This is standard for concrete of strength class C60 with a guaranteed rate of 95%. The objective workability characteristics of fresh SCC are slump greater than 260 mm, slump greater than 700 mm, flow time T500 less than 5 seconds, and a density of at least 2450 kg/m³ is preferred for fresh SCC. A total of four sets of mixtures were prepared for SCC using the relevant factors shown in Table 3.

Table 3. Self-Compacting Concrete mix proportions

Materials	C	ZA	FA	BG	AC	CA	W	W/C	SP
SCC1	466	0	1016	0	0.02	747	186	0.4	6
SCC2		1.165		2.4	0.015				
SCC3		2.33		4.8	0.01				
SCC4		3.495		7.3	0.005				

3.3 Preparation for Test Specimens

Cement, ZA and BG nanoparticles of average 200 nm, coarse aggregate, and fine aggregate were mixed in a laboratory concrete drum mixer to create the SCC. Cement, ZA, and BG were all included in the powder. Various mass percentages of ZA (0,0.25, 0.5, and 0.75), and BG (0, 0.5, 1, 1.5) were utilized. Water was then added, and the mixture was dry combined for 2 minutes before being mixed again for 3 minutes. Following mixing, samples of ready-mixed concrete were tested for flexural strength (FS). Three specimens were tested and the average value was utilized. The supplied concrete CS is assessed in terms of the specific 150 mm cubes evaluated after 28 days. The stated code of practice determines the strength of these specimens, which are cured for 28 days, guaranteeing that 95% of tested cubes fulfil this criterion [14]. The ASTM C293 Standard like the tensile tests, flexural tests were carried out. After being saturated for 24 hours, the molds were wrapped with polyethylene sheets. Prior to the experiment, the specimens were demolded and given a water cure at 20 °C. The concrete specimens underwent FS testing on 7 and 14 days. The averaging of three replicates produced the results that were presented.

3.4 Compressive Strength Test

The strength of the cement that not more than 5% of test results are anticipated to fall below is known as the typical strength. The concrete cube test's compressive strength gives information about all of concrete's properties. One may determine whether concrete work has been done properly by using this test. Concrete's compressive strength is calculated using a typical 150 mm cube whose compressive strength was tested after 28 days. Concrete specimens that have been cast, tested, and cured for 28 days are considered to have characteristic strength; 95% of the tested cubes should not have that is less than this value [24]. Figure 2 shows the Compressive Strength Test kit.

3.5 Flexural Strength Test

The load at which the material fails under bending is referred to as this bending strength. Analyze the non-reinforced concrete beams' or slabs' resistance to lateral failure. An unreinforced concrete slab, beam, or other structure's flexural strength is the amount of force and pressure it can bear before ceasing to bend. Flexural strength is sometimes referred to as breaking strength, rupture

modulus, or flexural strength. For bend testing, beam specimens in the sizes 150mm length, 150mm width, and 700mm height and 100mm length, 100mm width, 500mm height were tested. These samples are put through bending tests in accordance with ASTM C-293 and the Structural Design Qualification Standard as a universal guide of concrete strength. The average flexural strength of SCC samples was assessed utilizing three samples and a simple central loaded beam. Figure 3 shows the Flexural Test Set up



Fig. 2 Compression test set up

3.6 RSM for Mathematical Modeling

Statistical analysis provides meaning, breathing life into the data and useful statistical tests can produce precise conclusions from the results. It provides a brief definition of the variables, an understanding of quantitative yet distinguishing variables, and measures of central tendency. To ascertain the link between a collection of independently quantifiable parameters and one or more answers, the Response Surface Methodology (RSM) combines mathematical and analytical methodologies [26, 27]. Finding functional parameters that may or may not have a major impact on the underlying reaction is possible using RSM [28]. RSM may also be thought of as a collection of analytical and mathematical problem-solving methods. The outcomes are influenced by several elements (input variables) [26]. RSM is especially beneficial for multidimensional models because it sets desirable objectives in terms of responses or variables [29]. There are several

design models accessible, including Central Composites (CCD), Box-Behnken, and historical data. Both independent variables and correlated arithmetic results can be produced with them. The arithmetical correlation response and independent variables may be produced using these. The number of variables and each variable's variance are important factors in determining the sort of design model [26]. Equation (1) illustrates the use of a second-order function with a higher degree polynomial model [11].



Fig. 3 Flexural test set up

$$y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i < j} \beta_{ij} X_i X_j + \xi \quad (1)$$

The CCD contains a factor planning component of 2^k , where k is the quantity of connected variables or factors that are handled at two levels of a low and high value [24] using positive and negative values are used to code where the average of these limits serves as the focal point of it. The Zero-Point region that satisfies ideal requirements is called focal point. RSM from Minitab version 23 software was employed in this work to design the experiment and conduct a statistical analysis in constructing the mathematical relationships between the variables and the responses. To model a variable using RSM, a series of procedures must be followed to realize the research goal, which necessitates identifying the research problem based on the established objectives for research optimization. The four levels of nanoparticle (ZA and BG) substitution for fine aggregate and curing period were the independent factors considered. The type of experimental design—CCD under RSM

using total of 20 mix combinations were tested, each with triplicate specimens for compressive and flexural strength tests to ensure data reliability.

4. RESULTS AND DISCUSSION

The experimental strategy comprises examining the effects of six factors on the establishment of strengths under various degrees of control. From the experimental designs, 20 trial runs were chosen to determine the best conditions. The technical information sheet and some preliminary tests were used to determine the lowest and highest levels for variables. Table 4 displays the design matrix for the 20 trial runs. The results of investigations on solid states (different weight percentages of nanoparticles, such as ZA and BG, and curing times between 7, 14, 21, 28 and 56 days compressive and flexural strengths) were statistically assessed using design of experiments. The effort aimed to enhance compressive and flexural strengths depending on selected factor values with the least 20 number of tests possible.

4.1 Flexural Strength

Nano composite particles are used to test the flexural strength of SCC. Out of SCC1, the reference mix, 4 other types of mixes were created, with 0% fine aggregate and ZnO and BG additions to the cement. Mass percentages of ZnO (0 to 0.75% @ 0.25%) and of BG (0 to 1.5% @ 0.5%) in the remaining types of combinations. Figure 4 shows the curing period over a 28-day, mix SCC3's flexural strength is 10% higher than mix SCC1's. The quick consumption of $\text{Ca}(\text{OH})_2$ framed by Portland Pozzolana during cement hydration at young ages, along with the strong reactivity of nano-sized zinc oxide in cement particles, is what causes the significant increase of flexural quality in nano composites concrete. As a result, cement hydration is accelerated, and more response elements are framed. Additionally, nanocomposite particles restore the concrete's molecular density, which reduces the amount of large holes in the material. The best results were obtained at 0.5% ZA and 1% BG addition, although later addition of the nano composites to self-compacting concrete causes a decrease in the concrete's flexural strength while bringing the test results for SCC4 closer to the control mix. It might be because there are more BG and nano-zinc oxide particles in the blends than is necessary for them to consolidate with the unmanaged lime throughout the hydration process, which causes excess silica to drain out and lowers quality because it takes the place of some of the

Table 4 Experimental design plan for strengths

N0.	SSC type	A ₁ (C+ZA)	A ₂ (FA+BG)	A ₃ (FA+BG+CA)/(C+ZA)	A ₄ (Curing time)	CS (MPa)	FS (MPa)
1	SCC1	466.0	1016.0	3.783	7	28.11	2.87
2	SCC2	467.1	1018.4	3.779	7	29.51	3.02
3	SCC3	468.3	1020.8	3.774	7	30.27	3.12
4	SCC4	469.5	1023.3	3.770	7	29.08	2.98
5	SCC1	466.0	1016.0	3.783	14	42.81	3.98
6	SCC2	467.2	1018.4	3.779	14	44.94	4.18
7	SCC3	468.3	1020.8	3.774	14	46.10	4.32
8	SCC4	469.5	1023.3	3.770	14	44.29	4.12
9	SCC1	466.0	1016.0	3.783	21	43.25	4.42
10	SCC2	467.2	1018.4	3.779	21	44.25	4.65
11	SCC3	468.3	1020.8	3.774	21	45.40	4.80
12	SCC4	469.5	1023.3	3.770	21	46.40	4.58
13	SCC1	466.0	1016.0	3.783	28	48.30	4.55
14	SCC2	467.2	1018.4	3.779	28	50.67	5.34
15	SCC3	468.3	1020.8	3.774	28	51.96	5.53
16	SCC4	469.5	1023.3	3.770	28	49.95	5.06
17	SCC1	466.0	1016.0	3.783	56	46.57	4.51
18	SCC2	467.2	1018.4	3.779	56	47.57	4.74
19	SCC3	468.3	1020.8	3.774	56	44.74	4.90
20	SCC4	469.5	1023.3	3.770	56	45.74	4.67

cementitious material without improving performance. Furthermore, powerless zones may be caused by the deformities that result from the dispersion of nanoparticles. As can be observed, the insertion of nanoparticles reduces the pore area of self-compacting concrete while simultaneously increasing its density using nanocomposites. So, the self-compacting concrete's pore structure is enhanced.

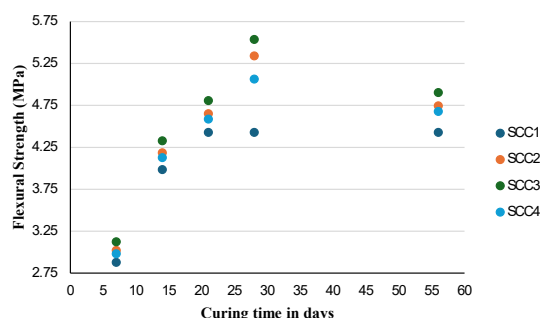


Fig.4 Flexural strength vs curing time

Table 4 displays the effects of all parameters, including those of type A₁ to A₄, on the flexural strength of SCC. Table 5 provides a summary of the ANOVA findings holding p-values for each flexural strength parameter. The major implications (A₁, A₂, A₃, and A₄), the quadratic impact of A₄*A₄, and the interactions (A₁*A₄, A₂*A₄, and A₃*A₄) were all statistically meaningful at the 95% level of confidence (p

0.05), according to the p-values.

Table 5 ANOVA results of flexural strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	11.016	1.377	38.46	0.000
Linear	4	4.192	1.048	29.27	0.000
A ₁	1	0.187	0.187	5.24	0.043
A ₂	1	0.388	0.388	10.84	0.007
A ₃	1	0.065	0.065	1.82	0.205
A ₄	1	2.916	2.916	81.43	0.0005
Square	1	6.249	6.249	174.50	0.000
A ₄ *A ₄	1	6.249	6.249	174.50	0.0002
2-Way Interaction	3	0.007	0.002	0.07	0.973
A ₁ *A ₄	1	0.003	0.003	0.10	0.754
A ₂ *A ₄	1	0.006	0.006	0.17	0.687
A ₃ *A ₄	1	0.001	0.001	0.04	0.002
Error	11	0.393	0.035		
Total	19	11.411			
Model Summary	S	R ²	R ² -(adj)	R ² -(pred)	
	0.189241	96.55%	94.04%	73.67%	

Only the Curing period A₄ was noteworthy as the primary influence for the flexural strength. The quadratic relationships of the A₄*A₄ and the interactions of A₃*A₄ were also statistically significant (p<0.05), suggesting that the impact on the flexural strength was not straight or that the response surface had curvature. The regression

coefficients for the models are displayed in the coefficient columns (Table 5).

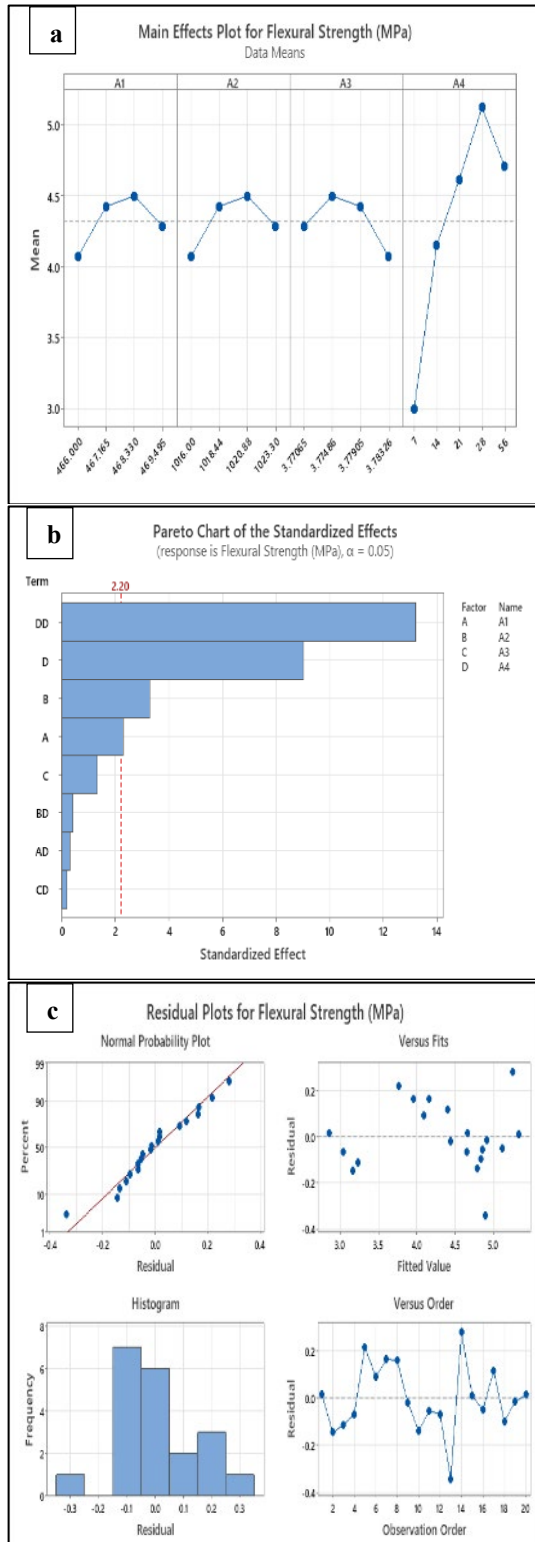


Fig. 5 (a) main effect plots and (b) Pareto diagram of the standardized effects for flexure strength

It represent the average changes in solution when one factor's level is changed while keeping the levels of the other components of the model remain the same. For illustration, it is clear from ANOVA that when ZA is 0.5% and BG is 1%, the flexural strength will improve significantly when the level of the curing period is increased by one.

Equation (2) shows the polynomial functions that match the data and explains the bulk of the deviations in the flexure strength. These polynomial functions contain linear terms and 2nd order terms, which include both nonlinear and two-variable interaction terms.

$$\text{Flexural Strength (MPa)} = 58100 - 87.5 * A1 + 23.2 * A2 - 10829 * A3 + 700 * A4 - 0.002336 * A4 * A4 - 0.90 * A1 * A4 + 0.207 * A2 * A4 - 130 * A3 * A4 \quad (2)$$

Figure 5a and 5b, which depict the main effect plots and Pareto diagrams of the standardized impacts for flexural strength, show that factor A4 (curing period), which had the most positive or biggest influence, was followed by factors A2 and A1 (BG% and ZA%). Another noteworthy element was the quadratic component $A4^2$, which affects the response in conformity with a second order polynomial. The entire collection of standardized residuals in Figure 5c also illustrates the statistical relevance of the data distribution being close to the baseline line graph. The equivalent models of flexural strength are found to account for 96.4% and 83.2% of the total variation by the adjusted coefficients of regression ($R^2(\text{adj})$) in Table 4. The predicted coefficients of results ($R^2(\text{pred})$), which were predicted to be 94.04% and 73.67%, respectively, demonstrated how well the models predicted the data.

The surface plot of flexure strength (Figure 6a to 6e) on the 3D contour plot shows that it may reach a maximum of 4.9 MPa when varying two distinct factors while holding the other two constant. Similar values for other factors for the percentage of nanoparticles were also observed to have an impact on the FS. To verify the statistical models' estimated values for the FS of the SCC, they were tested experimentally in a lab under identical circumstances.

4.2 Compressive Strength

Table 4 displays the results of the four factors' effects on CS, including the curing times of 7, 14, 21, 28- and 56-days. An ANOVA's findings for CS are shown in Table 6, where the p-values reveal that the four main effects (A1 to A4), the quadratic

components of A4, and the interactions A1*A2, A2*A4, and A3*A4 were statistically meaningful at the 95% confidence level for the examined levels. According to the P-values, only the curing duration has a significant positive impact on individual and quadratic terms, and the ratio of nanoparticles (ZA+BG) was significant when there was interaction ($p < 0.005$). Introduction of nanoparticles and a 28-day curing period resulted in an increase in compressive strength.

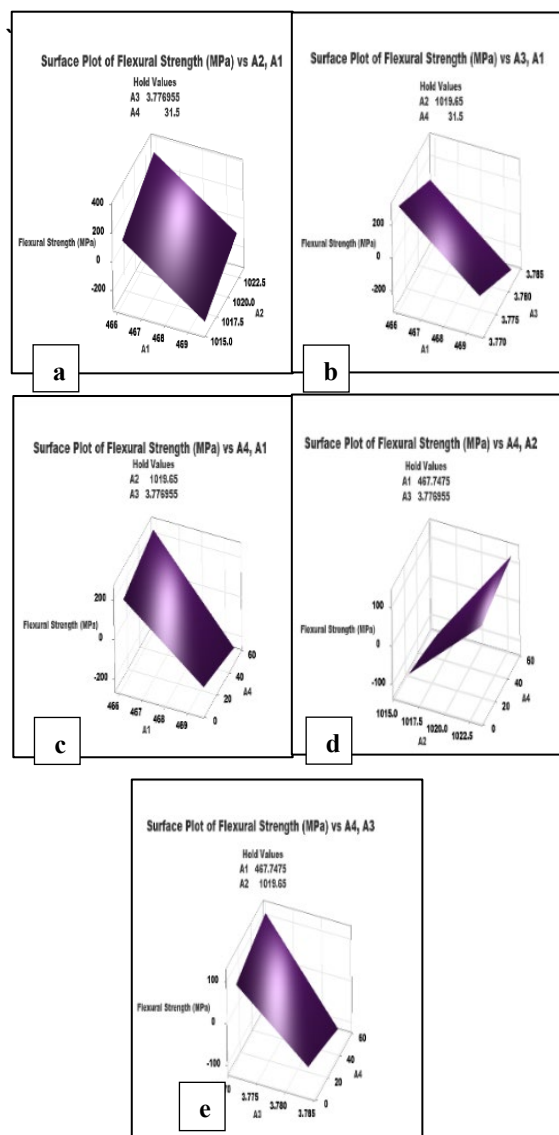


Fig. 6 3D Response surface plot for Flexural Strength with (a) A1x A2 (b) A1x A3 (c) A1x A4 (d) A2x A4 and (e) A3x A4

Equations depict the polynomial functions used to describe the connection in both the observed strengths and the variable levels (3).

$$\text{Compressive Strength (MPa)} = -136030 - 287 \cdot A1 + 178 \cdot A2 + 23494 \cdot A3 + 19015 \cdot A4 - 0.02266 \cdot A4 \cdot A4$$

$$- 6.7 \cdot A1 \cdot A4 - 2.76 \cdot A2 \cdot A4 - 3457 \cdot A3 \cdot A4 \quad (3)$$

According to the high $R^2(\text{adj})$ values for the CS, the model explains 95.69% of the total variance. As shown by the anticipated coefficient of determination value of 85.46%, the model is reasonably predictable. Figure 7b displays the Pareto diagrams of the standardized effects for CS, and all terms that cross the reference line are marked as statistically significant at the 5% level. These plots demonstrate that the curing length (A4), with Figure 6a displaying the sole level 4 (28-day) curing period rise in strength, is the factor at both the single and nonlinear terms having the biggest influence on the CS. Every increase or decrease over this threshold of the component denotes a reduction in the strength results. The distribution of the data matched with the trend line in Figure 7c's residual plots, which displays the normal distribution, indicates that the data are statistically meaningful. The biggest negative coefficient in the equation, A1, causes the compressive strength to decline. However, even though it is a quadratic term with curved lines, A1 was statistically significant.

A1's varying effects on compressive and flexural strength are probably caused by ZA's microfiller behavior, which densifies the matrix to increase compressive strength but might not have as much of an impact on tensile stress distribution, which controls flexural performance. Imperfect dispersion or interfacial gaps between the grit and cement paste may provide uneven results in A3, where a larger percentage of BG is present. This locally reduces flexural performance while still enhancing compressive strength through particle packing. Uneven, angular particles in BG are seen in the SEM images (Fig. 1); these particles enhance interlock but might create micro-voids if overused. The tiny, porous shape of ZA aids in matrix densification and the filler effect.

The addition of nanoparticles shows the enhancement in the results of the strength of concrete with nanoparticles as compared to concrete without nanoparticles. It is obtained in normal concrete about compressive strength that is same as the compressive strength results of SCC shown in Figure 8. SCC3 shows a 10% increase in compressive strength of SCC than SCC1. There is continuous improvement in compressive quality in the nano composites SCC are because of the drastic consumption of $\text{Ca}(\text{OH})_2$ framed by Portland Pozzolana during hydration cement at early stages identified with the increased reactivity of nanosized zinc oxide in cement elements.

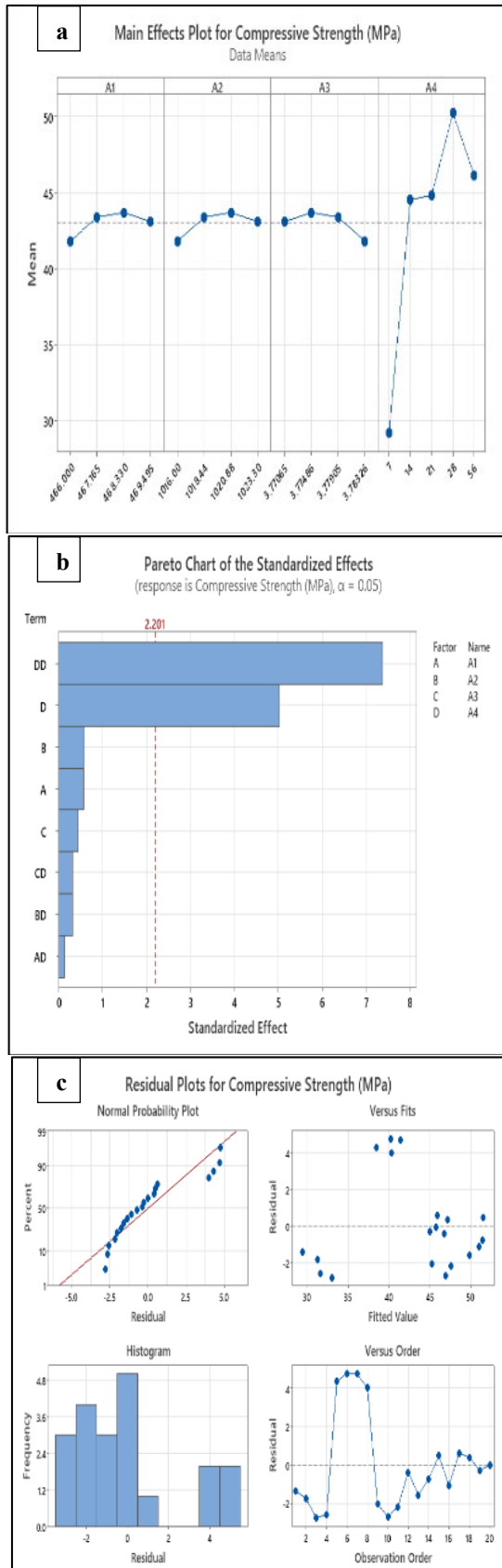


Fig. 7 (a) Main effect plots, (b) Pareto chart of the standardized effects for compressive strength, and (c) residual plots.

Table 6 Analysis of variance for compressive strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Coefficients
Model	8	934.16	116.770	10.78	0.000	5.1431
Linear	4	314.33	78.582	7.25	0.004	
A1	1	3.48	3.481	0.32	0.582	-202.5
A2	1	3.68	3.680	0.34	0.572	108.5
A3	1	2.13	2.134	0.20	0.666	-94.1
A4	1	274.19	274.191	25.31	0.000	0.7886
Square	1	587.75	587.749	54.25	0.000	
A4*A4	1	587.75	587.749	54.25	0.000	-1.402
2-Way Interaction	3	7.33	2.444	0.23	0.877	
A1*A4	1	0.21	0.206	0.02	0.893	-39
A2*A4	1	1.09	1.087	0.10	0.007	18.5
A3*A4	1	1.14	1.140	0.11	0.752	-20.1
Error	11	119.18	10.835			
Total	19	1053.34				
Model Summary	S	R ²	R ² -(adj)	R ² -(pred)		
	3.2916	95.69%	85.46%	70.31%		

Therefore, cement hydration is quickened, and greater quantities of response items are framed. In addition, nanocomposite particles regain the concrete's molecular density, leading to fewer big pores in the concrete. The optimum results were obtained at 0.5% addition but later further addition of the nano composites in SCC gives the decreasing results of the CS but results of test of SCC4 observed nearer to the control mix. The similar effect of incremental CS of SCC with different types of nano particles in concrete [6]. It was experienced such an increase in CS of SCC in occurrence of Jarosite [25]. It may be due to the rise in nano-zinc oxide particles present in the blends greater than the amount necessary during the hydration process to consolidate with the uncontrolled lime, causing excess silica to drain out and causing lack of quality as it substitutes some portion of the cementitious substance, and it doesn't add to the performance. Additionally, it might be because of the deformities created in scattering nanoparticles that cause powerless zones. It is evident that with the addition of nanoparticles, gives decrease in the pore area of SCC and at the same time nanocomposites increases the density of the SCC. As a result, the SCC's porous structure has been enhanced.

Uneven, angular particles in BG are seen in the SEM images (Fig. 1); these particles enhance interlock but might create micro-voids if overused. The tiny, porous shape of ZA aids in matrix

densification and the filler effect. The observed patterns in strength responses can be explained by the considerable effects of dose and dispersion on the efficiency of these particles.

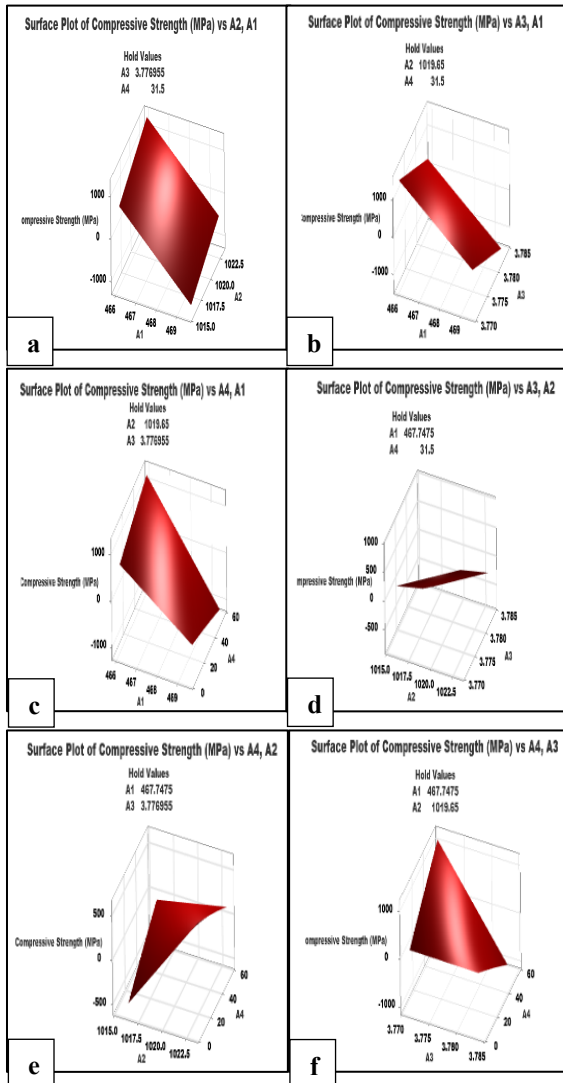


Fig. 8 3D Response surface plot for CS with (a) $A_1 \times A_2$ (b) $A_1 \times A_3$ (c) $A_1 \times A_4$ (d) $A_2 \times A_3$ (e) $A_2 \times A_4$ and (f) $A_3 \times A_4$.

Wide prediction intervals and the existence of negative values, especially in forecasts for flexural strength, indicate model uncertainty and potential extrapolation outside of the range of valid data. Increasing the number of experimental runs, particularly at critical ZA and BG concentrations, may assist narrow confidence limits and increase model resilience.

4.3 Multi-Objective Optimization Response Analysis

To maximize the strength performance of the specimens incorporating nanoparticles, a multi-

objective optimization was conducted using RSM. The optimization process aimed to determine the optimal combination of nanoparticle content, cement and fine aggregate replacement ratios, and curing duration to achieve the best performance of self-compacting concrete (SCC). Within the specified water/cement ratio and coarse aggregate content of the SCC mixtures, the nanoparticles (ZA and BG) were utilized as partial replacements for cement and fine aggregates. The optimization targeted both compressive strength and flexural strength during the curing period. Table 7 presents the multi-objective optimization results obtained from the RSM analysis using Minitab software, together with a summary of the optimization criteria. The results indicated that the optimum SCC performance was achieved with a mixture containing 0.5% ZA and 1% BG as partial replacements at a water-to-cement ratio of 0.4 and a curing period of 28 days. The optimized mixture exhibited the highest desirability value of 100%.

Table 7 Optimization criteria and results.

Variable	Setting
A1	468.33
A2	1023.3
A3	3.77
A4	28

Response	Fit	SE Fit	95% CI	95% PI
Flexural Strength (MPa)	487	344	(-271, 1245)	(-271, 1245)
Compressive Strength (MPa)	2366	5990	(-10817, 15549)	(-10817, 15549)

Response	Goal	Lower	Target	Upper	Weight
Flexural Strength (MPa)	Maximum	2.87	5.53		1
Compressive Strength (MPa)	Maximum	28.11	51.96		1



Fig. 9 Optimized strengths at optimal input settings

4.4 Confirmation Experiments

Table 8. Validation of results for CS and TR

NO.	SCC type	A1	A2	A3	A4	Compressive Strength (MPa)			Flexural Strength (MPa)		
						Experimental	Predicted	%Deviation	Experimental	Predicted	% Deviation
1	SCC1	466.0	1016	3.783	7	28.11	28.17	0.20	2.87	2.76	4.041
2	SCC2	467.2	1018	3.779	7	29.51	29.32	0.62	3.02	3.24	7.39
3	SCC3	468.3	1020	3.774	7	30.27	30.46	0.64	3.12	3.49	11.78
4	SCC4	469.5	1023	3.770	7	29.08	28.44	2.19	2.98	3.47	16.77
5	SCC1	466.0	1016	3.783	14	42.81	47.21	10.26	3.98	4.33	8.81
6	SCC2	467.2	1018	3.779	14	44.94	48.46	7.82	4.18	4.34	3.85
7	SCC3	468.3	1020	3.774	14	46.10	49.21	6.75	4.32	4.60	6.35
8	SCC4	469.5	1023	3.770	14	44.29	47.68	7.64	4.12	4.38	6.34
9	SCC1	466.0	1016	3.783	21	43.25	46.03	6.43	4.42	4.37	1.06
10	SCC2	467.2	1018	3.779	21	44.25	47.38	7.07	4.65	4.91	5.73
11	SCC3	468.3	1020	3.774	21	45.40	47.75	5.17	4.80	5.18	7.82
12	SCC4	469.5	1023	3.770	21	46.40	46.70	0.64	4.58	5.16	12.66
13	SCC1	466.0	1016	3.783	28	48.30	50.63	4.80	4.55	4.89	7.51
14	SCC2	467.2	1018	3.779	28	50.67	52.07	2.77	5.34	5.73	7.39
15	SCC3	468.3	1020	3.774	28	51.96	52.06	0.19	5.53	5.46	1.38
16	SCC4	469.5	1023	3.770	28	49.95	51.49	3.08	5.06	5.71	12.93
17	SCC1	466.0	1016	3.783	56	46.57	48.81	4.82	4.51	4.87	7.84
18	SCC2	467.2	1018	3.779	56	47.57	50.66	6.49	4.74	4.54	4.20
19	SCC3	468.3	1020	3.774	56	44.74	47.10	5.22	4.90	4.85	0.98
20	SCC4	469.5	1023	3.770	56	45.74	48.47	5.96	4.67	4.83	3.29

If the deviation is within the limits imposed by the statistical models of RSM are confirmed using trial results utilizing combinations of attributes for CS and FS. When the expected trial outcomes are compared, the percentage deviation is calculated and reported in Table 8 by calculating the ratio of trial and predicted to trial value. Deviation demonstrates that the selected approach has a strong acceptance limit. Table 8 shows strong consistency and model dependability, with an average forecast error of 5.4% for CS and 6.1% for FS throughout all curing times. Notwithstanding considerable variation in the forecasts, this overview serves to support the model's utility. The possibility that batch-to-batch variations in the ZA and BG, inconsistent hand mixing, or localized nanoparticle agglomeration may be the cause of certain discrepancies above 10%. These elements may introduce outliers that the model is unable to detect and affect the mechanical response.

5. CONCLUSIONS

The study investigates mechanical properties of SCC utilizing ZA and BG nanoparticles. Overall, the strength and structure of concrete are both enhanced by the inclusion of nanoparticles. One way that nanoparticles can improve concrete is by acting as a filler to increase its density, which greatly reduces the porosity of the concrete.

Nanoparticles, on the other hand, can also serve as a matrix in cement paste because of their enhanced activity, which limits the dimensions of the Ca (OH)₂ particle and increases the possibility of tropism. They can also function as an activator to quicken the hydration of cement.

The experimental program was designed using the RSM, and predictive models were developed to evaluate the strength performance of SCC mixes incorporating ZA and BG nanoparticles. The models considered curing time and nanoparticle weight percentages as the main variables affecting the performance of the SCC mixes.

The findings and their interpretation led to the following conclusions: the replacement of up to 0.5% ZA and 1% BG, with fixed proportions of fine aggregate, water, and CR, improved both the flexural and compressive strengths of SCC. In contrast, higher nanoparticle content and extended curing periods resulted in a reduction in SCC strength. However, curing periods shorter or longer than 28 days, when combined with nanoparticle inclusion, showed only slight improvements in the strength of SCC mixes. The RSM-based models developed to predict the strength performance of SCC were found to be highly significant, well-correlated.

Reliable for prediction. The multi-objective optimization results indicated that the optimal mix design, achieving maximum strength, was obtained at a 28-day curing period. Any deviations from this

condition resulted in only minor adjustments, such as partial replacement of cement with ZA% and fine aggregate with BG%.

This study focused on the compressive and flexural strengths of SCC mixes. Specific nanoparticle replacement levels were considered, with a maximum of 0.75% cement replacement by weight for nano ZA and 1.5% by volume for BG. Using curing time, nanoparticle content, and their interactions as input variables, the developed models accurately predict SCC strength performance. This approach reduces the need for extensive experimental work, saving both time and cost.

Future research is recommended to investigate the effects of higher concentrations of acidic and saline solutions over extended exposure periods on SCC mixtures. Extended durability studies are also suggested to evaluate the performance of the developed SCC mixtures for different environmental conditions.

6. REFERENCES

- [1] Abdi H., Chin W. W., Vinzi V. E., Russolillo G., and Trinchera L. eds., *New perspectives in partial least squares and related methods*, New York, NY: Springer, Vol.56, 2013.
- [2] Borucka-Lipska, J., Acid resistance, water permeability and chloride penetrability of concrete containing crushed basalt as aggregates. *Neural Comput Appl*, 2016, 31, pp.137-150.
- [3] Asteris P. G., Ashrafi A., Rezaie-Balf M., Prediction of the compressive strength of self-compacting concrete using surrogate models. *Computation Concrete*, 2019, 24, pp.137-150. DOI:10.12989/cac.2019.24.2.137.
- [4] Safiuddin M., Raman S. N., Abdus Salam M., Jumaat M. Z., Modeling of compressive strength for self-consolidating high-strength concrete incorporating palm oil fuel ash. *Materials*. 2016, 20, 9(5), pp.396.
- [5] Ashish D. K., and Verma S. K., An overview on mixture design of self-compacting concrete. *Structural Concrete*, 2019, 20(1), pp.371-395. <https://doi.org/10.1002/suco.201700279>.
- [6] Nazari A., and Riahi S., The effects of zinc dioxide nanoparticles on flexural strength of self-compacting concrete. *Compos. Part B* 2011, 42, pp.167-175.
- [7] Vakhshouri B., and Nejadi S., Mix design of lightweight self-compacting concrete. *Case Studies in Construction Materials*, 2016, 4, pp.1-14. DOI: 10.1016/j.cscm.2015.10.002.
- [8] Vakhshouri B., and Nejadi S., Compressive strength and mixture proportions of self-compacting lightweight concrete. *Comput. Concr*, 2017, 19, pp.555-566. DOI:10.12989/cac.2017.19.5.000
- [9] Shi C., Yang X., Yu Z., and Khayat H., Design and application of self-compacting lightweight concretes. In *SCC'2005-China: 1st international symposium on design, performance and use of self-consolidating concrete*. RILEM Publications SARL, 2005, pp. 55-64. DOI:10.1617/2912143624.005.
- [10] Nepomuceno M. C., Pereira-de-Oliveira L. A., and Lopes S. M. R., Methodology for the mix design of self-compacting concrete using different mineral additions in binary blends of powders. *Construction and Building Materials*, 2014, 64, pp.82-94. DOI: 10.1016/j.conbuildmat.2014.04.021.
- [11] Siamardi K., Optimization of fresh and hardened properties of structural light weight self-compacting concrete mix design using response surface methodology. *Construction and Building Materials*, 2022, 317, pp.125928. DOI:10.1016/j.conbuildmat.2021.125928.
- [12] Alsubari B., Shafigh P., Ibrahim Z., Alnahhal M. F., and Jumaat M.Z., Properties of eco-friendly self-compacting concrete containing modified treated palm oil fuel ash. *Construction and Building Materials*, 2018, 158, pp.742-754. DOI: 10.1016/j.conbuildmat.2017.09.174.
- [13] Niewiadomski P., Hoła J., and Ćwirzeń A., Study on properties of self-compacting concrete modified with nanoparticles. *Archives of Civil and Mechanical Engineering*, 2018, 18(3), pp.877-886. DOI: 10.1016/j.acme.2018.01.006.
- [14] Navid Ranjbar N. R., Arash Behnia A. B., Belal Alsubari B. A., Payam Moradi Birgani P. M. B., and Mohd Zamin Jumaat M. Z. J., Durability and mechanical properties of self-compacting concrete incorporating palm oil fuel ash. *Journal of Cleaner Production*, 2016, 112(1), pp.723-730. DOI:10.1016/j.jclepro.2015.07.033.
- [15] Liu R. X., and Poon C. S., Utilization of red mud derived from bauxite in self-compacting concrete. *Journal of cleaner production*, 2016, 112, pp.384-391. DOI:10.1016/j.jclepro.2015.09.049.
- [16] Singh N., Kumar P., and Goyal P., Reviewing the behaviour of high volume fly ash based self-compacting concrete. *Journal of Building Engineering*, 2019, 26, pp.100882. DOI: 10.1016/j.jobbe.2019.100882.

- [17] Ji T., Preliminary study on the water permeability and microstructure of concrete incorporating nano-SiO₂. *Cement and concrete Research*, 2005, 35(10), pp.1943-1947.
- [18] Jo B. W., Kim C. H., Tae G. H., and Park J. B., Characteristics of cement mortar with nano-SiO₂ particles. *Construction and building materials*, 2007, 21(6), pp.1351-1355.
- [19] Li H., Xiao H. G., and Ou J. P., A study on mechanical and pressure-sensitive properties of cement mortar with nanophase materials. *Cement and Concrete research*, 2004, 34(3), pp.435-438.
- [20] Qing Y., Zenan Z., Deyu K., and Rongshen C., Influence of nano-SiO₂ addition on properties of hardened cement paste as compared with silica fume. *Construction and building materials*, 2007, 21(3), pp.539-545.
- [21] Lin K. L., Chang W. C., Lin D. F., Luo H. L., and Tsai M. C., Effects of nano-SiO₂ and different ash particle sizes on sludge ash-cement mortar. *Journal of environmental management*, 2008, 88(4), pp.708-714.
- [22] Suji D., Adesina A., and Mirdula R., Optimization of self-compacting composite composition using Taguchi-Grey relational analysis. *Materialia*, 2021, 15, p.101027. DOI: 10.1016/j.mtla.2021.101027.
- [23] Arefi M. R., and Rezaei-Zarchi S., Synthesis of zinc oxide nanoparticles and their effect on the compressive strength and setting time of self-compacted concrete paste as cementitious composites. *International journal of molecular sciences*, 2012, 13(4), pp.4340-4350. <https://doi.org/10.3390/ijms13044340>.
- [24] Patil H., and Dwivedi A., Impact of nano ZnO particles on the characteristics of the cement mortar. *Innovative Infrastructure Solutions*, 2021, 6(4), pp.222. DOI:10.1007/s41062-021-00588-9.
- [25] Ding X., Zhao M., Qiu X., Wang Y., and Ru Y., The optimization of mix proportion design for SCC: Experimental study and grey relational analysis. *Materials*, 2022, 15(4), pp.1305. DOI: 10.3390/ma15041305.
- [26] Anderson M. J., and Whitcomb P. J., RSM simplified: optimizing processes using response surface methods for design of experiments. Productivity press. New York, 2016. DOI: <https://doi.org/10.1201/9781315382326>
- [27] Raissi S., and Farsani R. E., Statistical process optimization through multi-response surface methodology. *World academy of science, Engineering and Technology*, 2019, 51(46), pp.267-271.
- [28] Bezerra M. A., Santelli R. E., Oliveira E. P., Villar L. S., and Escaleira L.A., Response surface methodology (RSM) as a tool for optimization in analytical chemistry. *Talanta*, 2008, 76(5), pp.965-977.
- [29] Reji M., and Kumar R., Response surface methodology (RSM): An overview to analyze multivariate data. *Indian J. Microbiol. Res*, 2022, 9(4), pp.241-248.