CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 6, ISSUE 2, 2026, In-Press
DOI: https://doi.org/10.15282/construction.v6i2.14171

RESEARCH ARTICLE

Modelling and optimisation of the synergistic influence of maize husk ash and nano sugarcane fiber ash cement mortar compressive strength employing response surface methodology

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Abstract: The increased worldwide interest in sustainable construction materials, linked to the rising amount of generated agricultural waste, has led researchers to the use of agro-waste in cementitious applications. To this end, this study investigates the interactive effects of maize husk ash and nano sugarcane fibre ash on the compressive strength development of cement mortar. A response surface methodology experimental design was employed to describe the interactions between maize husk ash (MHA) and nano sugarcane fibre ash (NSFA) and to identify an optimal mixture proportion for increased compressive strength. Thirteen experimental runs were generated in this study, and the compressive strength was determined at 7 and 28 days. The results of the study showed that the combination of MHA and NSFA increased the compressive strength compared to the control mix. The interaction between MHA and NSFA was found to be significant. This shows that MHA and NSFA work hand-in-hand to enhance microstructural densification, hasten hydration kinetics, and refine particle packing, although excessive MHA negatively impacted the early strength due to content dilution effects and delayed pozzolanic activity. The use of RSM optimisation was used to establish that the best combination was 8.25% MHA and 2.2% NSFA, with the predicted strength at 7 days being 9.58 MPa and at 28 days being 13.75 MPa. The accuracy and reliability of the RSM model to predict results are the outcome of high conformity between the experimental values and the predicted values. In addition, the model had a very low percentage error of less than 5%. The study shows that agro-waste can be used to improve strength, thereby positively impacting sustainability.

Article History
Received :
Revised :
Accepted :
Published :

Keywords
Maize husk ash
Nano sugarcane fibre ash
Compressive strength
Response surface methodology

1. Introduction

Over the years, one major paradigm shift towards the use of sustainable and environmentally friendly materials has taken place in the construction industry, which has focused mainly on the use of supplementary cementitious materials (SCMs) for the development of structures [1-3]. For this reason, the need to improve the properties of building materials, conserve their components, and increase worldwide environmental awareness has become the driving force for this paradigm shift [4-6]. For this reason, the use of supplementary cementitious materials has become popular due to the new inventions of using these materials for the development of structures, which are based on the ability to improve the properties of these materials with lower cement contents [4, 7, 8]. The demands of sustainability and strength in the structure of buildings have made the development of high-performance and environmentally friendly materials one of the major driving forces of the paradigm shift during the last few years [2, 4, 9]. As a way to reduce ecological effects and enhance the long-term performance of infrastructure systems, the use of environmentally friendly alternatives in the manufacturing of concrete has drawn significant attention from academics and industry [1, 7, 10]. In this context, adding agricultural waste to cementitious systems has shown promise as a strategy to lower the carbon footprint of cement production while also enhancing the durability and mechanical properties of mortar [5, 8, 11]. Sugarcane residues and maize husk derivatives are two of the many agro-industrial by-products that have special physicochemical properties that make them attractive options for sophisticated cement-based composites [12-14].

Sugarcane fibres have a high surface area by nature, a high cellulose content, and remarkable tensile characteristics, especially at the nanoscale [15, 16]. Strong interfacial interactions with cement hydrates are made possible by the high aspect ratio and functional groups of nano sugarcane fibre ash (NSFA), which may improve matrix densification and crack-bridging ability at both early and later ages [15, 17]. In addition, as a silica-rich pozzolan, maize husk ash (MHA) can partially replace cement while taking part in secondary hydration events that improve compressive behaviour and refine the pore structure [14, 18]. Compared with other agricultural ashes, MHA usually contains trace alkalis, alumina, and reactive amorphous silica that can work in concert to increase the pozzolanic activity of blended cement mortar [14, 19]. The combined use of highly reactive pozzolanic ash and nano-scale fibre as SCM has not been thoroughly investigated, although both NSFA and MHA have separately shown quantifiable advantages in cementitious systems. MHA can enhance the microstructure by consuming portlandite and creating more calcium silicate hydrate (C–S–H), whereas nano materials can enhance the properties of concrete and improve its durability [18, 19]. In particular, in regard to improving compressive strength, a crucial factor influencing structural performance, their combination may produce a composite effect larger than the sum of their separate benefits [20].

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The optimisation of the optimal levels of two or more variables is inherently challenging and consumes considerable energy and time [3, 21]. The other aspect is related to the dosages of NSFA and MHA, which are equally important, and the response of the mechanical reaction of the cement mortar is subject to possible interactive effects, which may sometimes present non-linear results. Therefore, to achieve the optimisation of the mix combinations and statistically establish the significance of each of the input variables, interactive effects, and possible non-linear responses, a statistical and systematic approach is needed [21, 22]. Thus, response surface methodology (RSM) is a highly accurate and efficient approach that helps achieve the objectives of this research. Response surface methodology is a highly accurate statistical approach that significantly reduces the number of experiments, time, and materials required while considering the optimisation of several variables [20, 21]. RSM is useful in developing accurate predictive models of the response behaviour of a system and is highly useful in optimisation studies [20, 22].

Hence, the present work uses the RSM approach and intends to explore the synergistic effect of MHA and NSFA on compressive strength. The objectives of the proposed work are (a) to define the impact of the NSFA and MHA individually and collectively on the compressive strength performance; (b) to efficiently construct statistical models to predict the compressive strength considering various compositions; and (c) to identify the optimal level of addition for the maximum improvement in the compressive strength performance. The results of this work advance sustainable material design techniques that are in line with the principles of the circular economy and advance the scientific knowledge of bio-enhanced cement composites.

2. Materials and Methods

2.1 Materials

2.1.1 Maize Husk Ash

The maize husks used for producing MHA were collected from local maize farms located in Samaru Zaria, Kaduna State, Nigeria. The MHA was properly cleaned, allowed to air dry, and then oven-dried at 100 °C to eliminate moisture. To produce highly reactive ash, initial carbonisation at 200–250 °C for an hour was performed to remove volatile components, after which another calcination in a muffle furnace at 650–750 °C for three hours was performed to produce an amorphous, silica-rich MHA. The MHA was then air-cooled and sieved through a 75 µm (BS No. 200) standard sieve to guarantee a uniform particle size for further processing. With a moisture content of 2.29%, a specific gravity of 2.69, and a loss on ignition (LOI) of 2.91%, the as-received MHA demonstrated sufficient thermal decomposition of the husk and minimal residual carbon. The suitability of MHA as a reactive pozzolanic supplemental cementitious material is confirmed by its precise oxide composition.

2.1.2 Nano Sugarcane Fibre Ash

Raw sugarcane bagasse fibres were obtained from a local farm located at Ahmadu Bello University, Zaria, Kaduna State, Nigeria, and were subjected to controlled combustion and high-energy milling to create NSFAs. To eliminate moisture, the fibres were cleaned, allowed to air dry, and then oven-dried at 100 °C. To produce high-reactivity ash, a two-stage burning procedure was used: (a) initial carbonisation at 350 °C for an hour to eliminate volatiles and (b) final calcification in a muffle furnace at 600 °C for four hours, guaranteeing the creation of amorphous silica-rich NSFAs. To provide a homogeneous precursor for nano-processing, the calcined ash was manually crushed and sieved through a 75 µm screen. The physical properties of the NSFAs are shown in Table 1. A powerful planetary ball mill was used to create nano-sized ash utilising 20 standard steel balls and grinding jars. To achieve nanoscale refinement, approximately 40 g of the NSFA was ground for three hours at 200 rpm via the large-to-small particle reduction process.

Table 1. NSFA physical properties

Properties	Values	
	NSFA	MHA
Average particle size (nm)	33	124
Viscosity (cps)	17	20
Specific surface area ($m^{2/}g$)	78	47
Bulk density (g/cm^3)	1.37	0.84
pH	8.9	9.7

2.1.3 Fine Aggregate

The fine aggregate used in this investigation was obtained from A.A. Kwari Quarry, which is located opposite the Aviation Collage, Samaru, Zaria, Nigeria. The material's bulk density of 1696 kg/m³, specific gravity of 2.66, and silt concentration of 1.97% were all within permissible ranges for the construction of high-quality concrete. The fine aggregate particle size distribution is shown in Figure 1. The aggregate is in Zone 1 according to BS 882:1992 [23] grading limits. Approximately 99.5% of the material, as indicated in Table 2, passes through a 4.75 mm sieve, satisfying the BS 812-2:1995 [24] criterion that construction-use fine aggregates have particle sizes less than 5 mm. These findings support its viability for application in cementitious mixtures as fine aggregates.

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Table 2. Fine aggregate gradation analysis

Sieve Size (mm)	4.75	2.36	1.18	0.6	0.3	0.075	Pan	Total
Weight Retained (g)	2	70	235	157	29	2.5	1.5	497
Percentage Retained (%)	0.4	14.1	47.3	31.6	5.8	0.5	0.3	100
Percentage Passing (%)	99.6	85.5	38.2	6.6	0.8	0.3	0	-

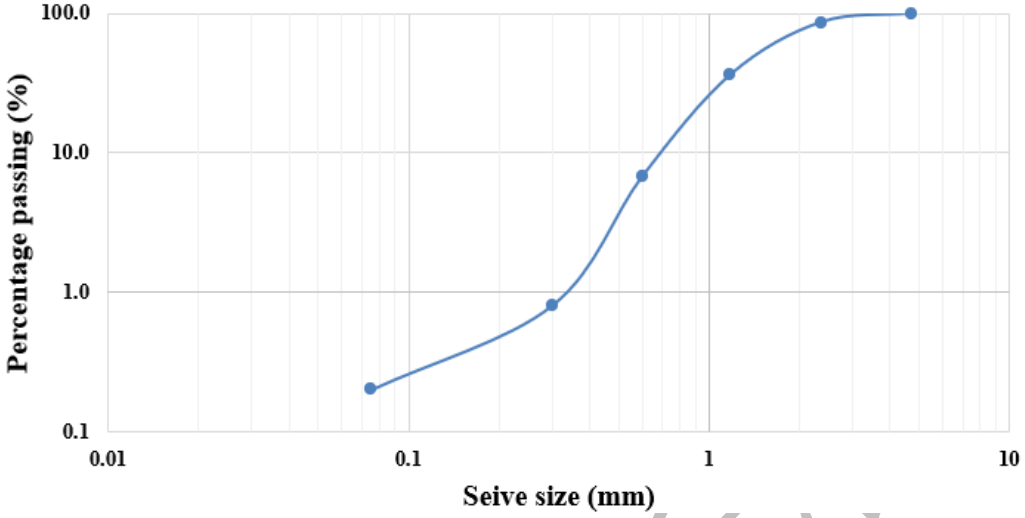


Figure 1. Gradation of fine aggregates

2.1.4 Cement

Ordinary Portland cement (OPC) with a 42.5R classification, which complies with applicable EN and BS requirements, was used in this investigation. The material had a specific gravity of 3.14 and a determined moisture content of 1.78%, which are normal values for cement.

2.1.5 Water

This study employed drinkable, pure water that was delivered via a dependable pipe-borne distribution system. This ensured that there were no contaminants, which could interfere with the process of hydration or the eventual mechanical properties of the concrete cubes, by following the standard specifications for mixtures of cement materials.

2.2 Methods

2.2.1 Sieve Analysis

As stipulated by BS 812-103.1:1985 [25], a sieve examination of the fine aggregate was conducted to determine its particle size distribution. A pan was placed at the bottom of a stack of already weighed standard sieves that were placed in descending order of aperture size after a 1 kg sample of sharp sand was weighed. For a predetermined amount of time, the assembly was mechanically shaken to guarantee efficient particle separation. Following the sieving process, the material that remained on each sieve was collected and weighed. This allowed the granulometric properties of the fine aggregate to be determined, as well as the percentage of material that passed and was retained.

2.2.2 Oxide Content of the Study Materials

X-ray fluorescence (XRF) spectroscopy was used to assess the oxide compositions of the cement, NSFA, and MHA. The analysis was carried out in compliance with the protocols outlined in BS EN 196-2:1995 [26] at the Multi-User Laboratory at the university.

2.2.3 Cement Preliminary Test

The cement specific gravity and preliminary tests were conducted as per BS EN 196-3:2016 [27] at the University Concrete Laboratory. Additionally, the consistency of the cement paste was assessed via the same standards used for the initial and final setting times. The soundness of the cement was evaluated via the Le Chatelier method on the basis of samples with a water-to-cement ratio established via the consistency test.

2.2.4 Cement Mix Design of the Experiment

To design and optimise the cement mortar mix proportions, the RSM was used. MHA and NSFA were 0 to 20% and 0 to 4%, respectively. Thirteen (13) test mixes were created via the RSM program, which defines lower and upper boundaries inside the DOE matrix, as shown in Table 3. The design's focal point was reproduced five times to increase the analysis's dependability and enable enhanced error estimation [21, 28]. This increased the statistical confidence and reproducibility

of the experimental study. Mortar mixes using the cements were prepared in line with BS EN 196-1:2005 [29]. The dry materials, which consisted of cement, MHA, and NSFA, were mixed first for approximately two minutes to ensure the even distribution of the components. Then, water was introduced, and the mixture was mixed for three more minutes to achieve homogenous mortar. The fresh mortar was poured into cube molds in two separate layers, and each layer was compacted on a vibrating table. After the mortar had formed, it was covered with moisture protection and demolded after 24 hours. The samples were subsequently stored in tap water at 23 ± 2 °C for 7 and 28 days [30-32].

Table 3: Design of the experiments for blending proportions

Mix	Input variable		Output variables	
	Additives		Compressive strength	
	MHA (%)	NSFA (%)	7 days	28 days
1	20	4	4.01	8.31
2	10	2	9.14	13.28
3	10	2	9.29	13.49
4	0	4	9.62	13.86
5	0	0	9.84	14.56
6	0	2	10.89	14.98
7	10	0	8.84	12.99
8	20	0	6.11	10.19
9	10	2	9.32	13.51
10	10	2	9.24	13.47
11	20	2	6.44	10.62
12	10	4	7.39	11.71
13	10	2	9.27	13.41

2.2.5 Compressive Strength

The compressive strength of the cement mortar was evaluated via a universal testing machine in accordance with BS 1881-116:1983 [33]. Triplicate samples were made for every experimental mixture, and mortar cubes were meticulously cast and cured for 7 and 28 days. To ensure precision and reproducibility, the average strength values from the triplicate samples were recorded after the compressive load was applied to failure. Figure 2 shows the preparation mixing, curing, and crushing of the modified concrete samples.



Figure 2. Preparation, curing, casting and crushing of the modified concrete samples

3. Results and Discussion

3.1 Chemical Composition

The chemical compositions of the OPC, MHA, and NSFA samples determined via X-ray fluorescence (XRF) analysis are provided in Table 4. The total SiO_2, Al_2O_3, and Fe_2O_3 contents in the MHA and NSFA are 81.51% and 90.73%, respectively, which exceeds the minimum value of 70% according to ASTM C618-99 requirements for natural pozzolans. High concentrations of silica can stimulate secondary hydration due to the reaction with calcium hydroxide and the

subsequent formation of extra calcium silicate hydrate (C-S-H). This leads to densification and increased performance. Moreover, agricultural ashes rich in amorphous silica presented notable pozzolanic properties and improved the compressive strength of cement-based materials [34, 35].

Table 4: Chemical composition (wt%) of the study material

Material	Fe_2O_3	SiO_2	Al_2O_3	P_2O_5	CaO	Cl	MgO	ZnO	TiO_2	K_2O	Na_2O
OPC	2.79	23.41	2.83	-	70.05	-	0.87	0.39	0.21	0.69	0.19
MHA	0.97	79.41	1.13	5.67	1.38	0.64	1.74	0.04	0.09	2.71	1.04
NSFA	1.83	87.23	1.65	1.34	1.06	0.81	1.36	0.01	0.02	1.95	1.15

3.2 Preliminary Cement Tests

The cement's appropriateness for mortar manufacturing is confirmed by the findings reported in Table 5. Important characteristics, such as specific gravity, soundness, uniformity, and setting times, are all within the bounds specified by industry standards. During mixing, the cement's consistency of 29% guaranteed appropriate workability. The measured beginning and final setting periods were 91 and 201 minutes, respectively, which allowed for sufficient handling time. The risk of cracking in hardened mortar is decreased because soundness testing via the 3 mm Le Chatelier approach revealed little potential for volumetric expansion. Its specific gravity of 3.15 provides additional evidence that its density is suitable for use in buildings. The properties of the cement listed in Table 5 comply with the requirements of BS EN 196-3, thus confirming the suitability of the cement for mortar manufacturing. The values of consistency, setting time, and soundness lie in the range of those values that are normally found in OPC. The value of specific gravity also coincides with that found in Portland cement [32, 36].

Table 5. Basic cement tests

Test	Specific gravity	Soundness	Consistency	Initial setting time	Final setting time
Units	-	mm	%	mm	mm
Standards			BS-EN196-3 (2016)		
Limits	3.1 to 3.16	< 10	26 to 33	≥ 45	≤ 600
Results	3.15	3	31	91	201
Remark			Pass		

3.3 RSM Regression Evaluation

Using RSM software, a quadratic polynomial model was used in the regression analysis to predict the compressive strength of the cement mortar. Because it reflects the highest-order polynomial that contains all the significant terms without being impacted by aliasing in the design matrix, this model was chosen. The interaction effects of MHA and NSFA on mortar strength were therefore considered to be most effectively captured by the quadratic model. The model's statistical significance and predictive value within the response surface framework are demonstrated by the ANOVA findings for compressive strength at 7 and 28 days, which are shown in Table 6. The P values for the compressive strength responses in this investigation were significantly less than 0.0001, indicating statistical significance [20]. For the 7- and 28-day compressive strengths, the corresponding F values were 796.13 and 393.76, respectively, which were noticeably high. The robustness of the model is confirmed by the consistently low p values (<0.05) across the entire model, which shows that the probability of achieving such high F values by chance is quite low (<0.01%) [20]. The generated model adequately represents the link between the input variables and compressive strength, as evidenced by the lack of fit test being insignificant when model adequacy was further assessed at a 95% confidence level [28]. The RSM software established that the generated models were designed to minimise the addition of redundant factors while preventing aliasing effects.

Table 6. Cement mortar ANOVA analysis

Parameter	Sum of squares	DoF	Mean square	F value	p value	Comment
Compressive strength at 7 days						
Selected model	Quadratic					
Model	42.90	5	8.58	796.13	< 0.0001	Significant
A-Maize husk ash	31.69	1	31.69	2940.62	< 0.0001	
B-Nano sugarcane fibre ash	2.37	1	2.37	219.78	< 0.0001	
AB	0.8836	1	0.8836	81.98	< 0.0001	
A^2	1.17	1	1.17	108.67	< 0.0001	
B^2	3.99	1	3.99	369.75	< 0.0001	
Residual	0.0754	7	0.0108			
Lack of Fit	0.0564	3	0.0188	3.94	0.1093	Insignificant
Pure Error	0.0191	4	0.0048			
Cor Total	42.98	12				

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Compressive strength at 28 days						
Selected model	Quadratic					
Model	43.49	5	8.70	393.76	< 0.0001	Significant
A-Maize husk ash	33.99	1	33.99	1538.72	< 0.0001	
B-Nano sugarcane fibre ash	2.48	1	2.48	112.43	< 0.0001	
AB	0.3481	1	0.3481	15.76	0.0054	
A^2	1.08	1	1.08	49.03	0.0002	
B^2	3.20	1	3.20	144.83	< 0.0001	
Residual	0.1546	7	0.0221			
Lack of Fit	0.1201	3	0.0400	4.65	0.0860	Insignificant
Pure Error	0.0345	4	0.0086			
Cor Total	43.64	12				

The above analysis revealed that for both the 7-day and 28-day compressive strengths, all the Prob > F values of the various terms of the model remained less than 0.05, thus revealing the significance of these parameters for the mortar mixture [21, 28]. Additionally, for the prediction of the compressive strength of cement mortar, NSFA has been found to outperform MHA among the parameters, thus emphasising its importance for the maximum properties of the composite material [28].

3.4 Model Validation Matrices

Table 7 shows the model fit for the 7- and 28-day compressive strengths, and with high coefficients of determination (R^2) of 0.998 and 0.996, respectively, the model nearly matched the predicted R^2 values, indicating little chance of overfitting or underfitting. The model's resilience and efficacy in navigating the design space were confirmed by the Adequate Precision (AP), which represents the signal-to-noise ratio, which was 97.78 at 7 days and 76.96 at 28 days. The model has good precision, stability, and predictive dependability, as evidenced by the consistently higher mean values compared with their standard deviations (SDs) and the low coefficients of variation (CVs) [21, 37]. All these parameters confirm that the developed model is accurate, dependable, and appropriate for modelling, optimising, and predicting the compressive strength of cement mortar with MHA and NSFA incorporation [20, 21].

Table 7. Model validation parameters

Parameter	R^2	Adj.R^2	Pred.R^2	CV	SD	Mean	AP
7-day compressive strength	0.998	0.997	0.987	1.23	0.104	8.42	97.78
28-day compressive strength at	0.996	0.995	0.980	0.99	0.126	12.65	76.96

The predictive model for compressive strength at 7 and 28 days is represented by Eqs. (1-2), where the signs of the coefficients show how each element affects the reaction. Negative coefficients indicate variables that have a negative or inhibitory effect on the reaction, whereas positive coefficients are associated with elements that increase the compressive strength [21, 28].

$$7\ days \text{ compressive strength} = 9.27 - 2.298A - 0.63B - 0.47AB - 0.65A^2 - 1.20B^2 \quad (1)$$

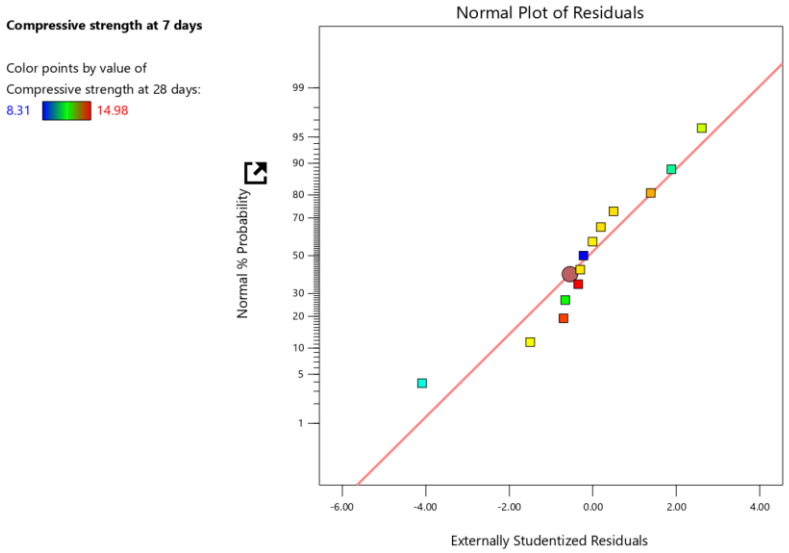
$$28\ days \text{ compressive strength} = 13.43 - 2.38A - 0.64B - 0.23AB - 0.61A^2 - 1.06B^2 \quad (2)$$

The MHA and NSFA contents are indicated by A and B, respectively.

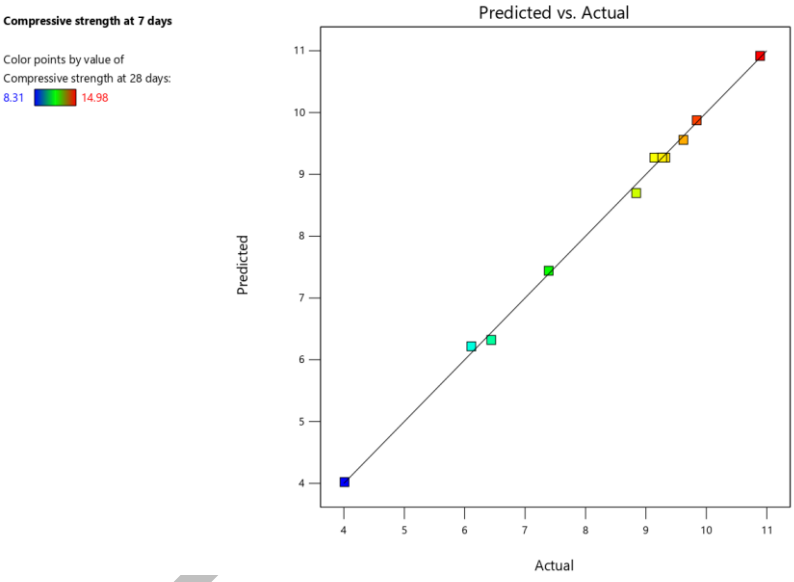
3.5 Model Fit and Diagnostic Plots

The residuals' normal probability charts for the compressive strength models at 7 and 28 days are shown in Figure 3. The regression models are dependable and statistically sound since the residuals are symmetrically distributed along a straight line. The model's prediction accuracy is further confirmed by the points' close conformance to the equality line [21, 37]. Furthermore, the data points are consistently aligned along the 45-degree line in the predicted versus observed plots for both the 7- and 28-day strengths, demonstrating that the models successfully reproduce the experimental results. This recurring pattern demonstrates how well the proposed models capture the behaviour of cement mortar's laboratory compressive strength [20, 28].

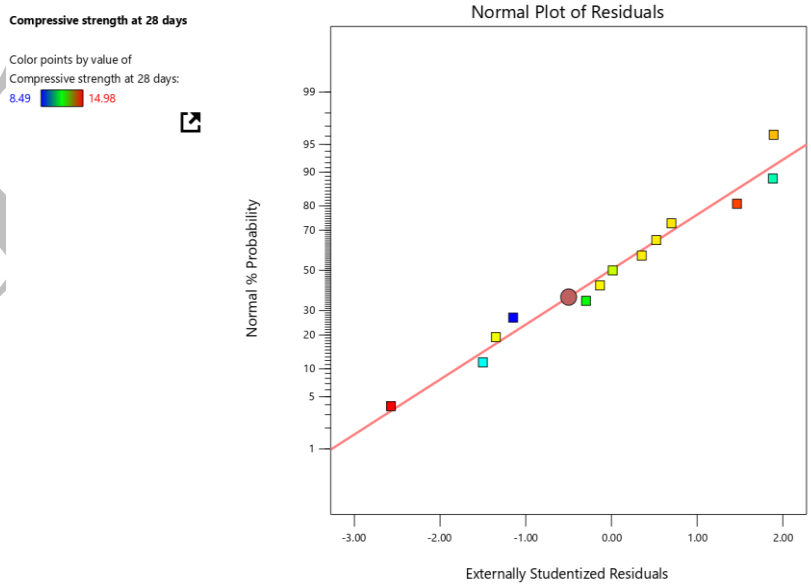
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Compressive strength at 7 days
Color points by value of
Compressive strength at 28 days:
8.31
14.98
Normal Plot of Residuals
Normal % Probability
Externally Studentized Residuals

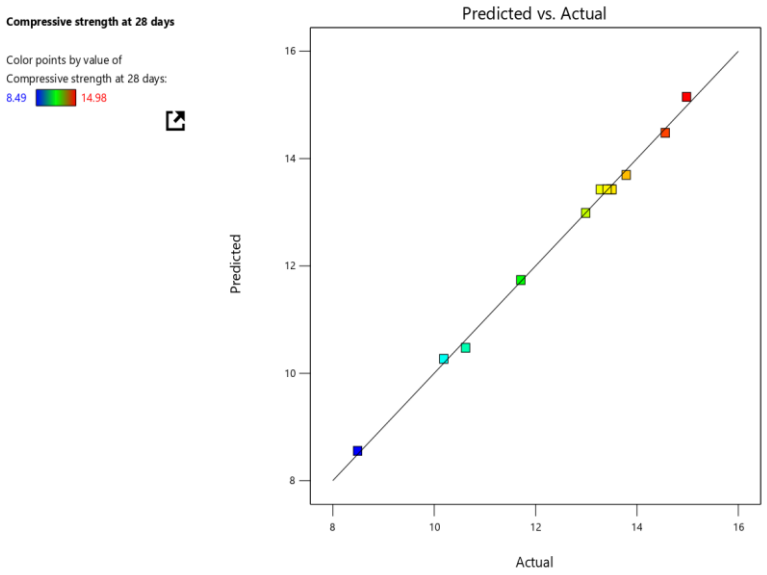
(a)


Compressive strength at 7 days
Color points by value of
Compressive strength at 28 days:
8.31
14.98
Predicted vs. Actual
Predicted
Actual

(b)


Compressive strength at 28 days
Color points by value of
Compressive strength at 28 days:
8.49
14.98
Normal Plot of Residuals
Normal % Probability
Externally Studentized Residuals

(c)

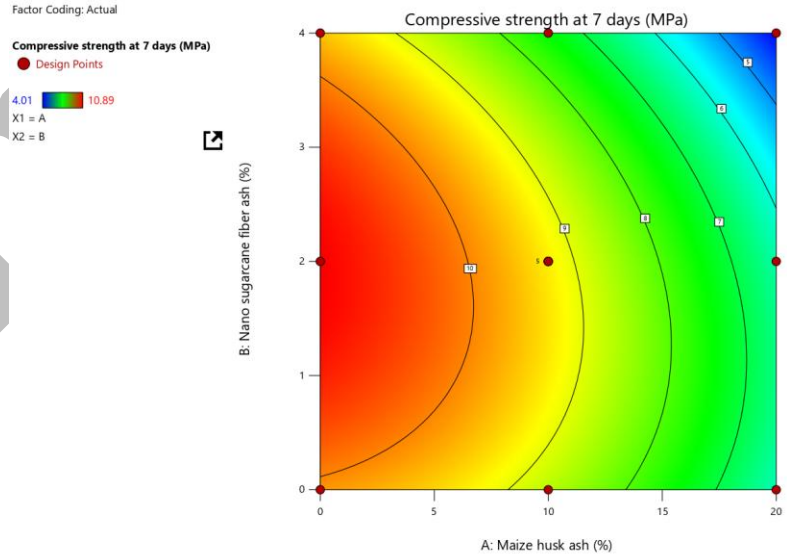


(d)

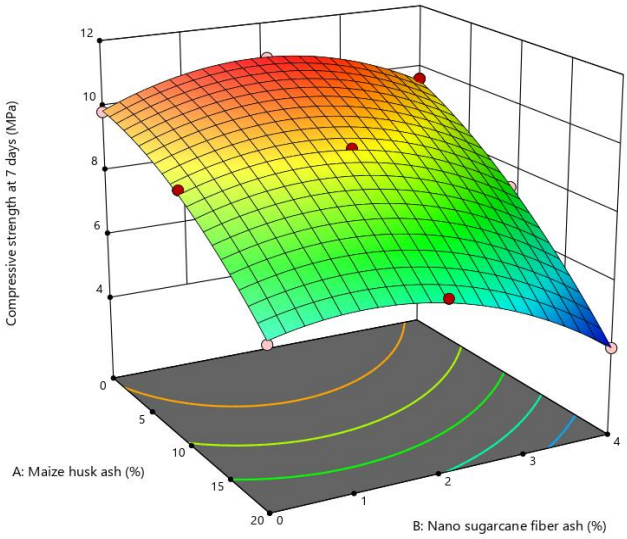
Figure 3. Diagnostic plots of the developed compressive strength model at (a) and (b) 7 days and (c) and (d) 28 days

3.6 2D and 3D Surface Plots for the Developed Model

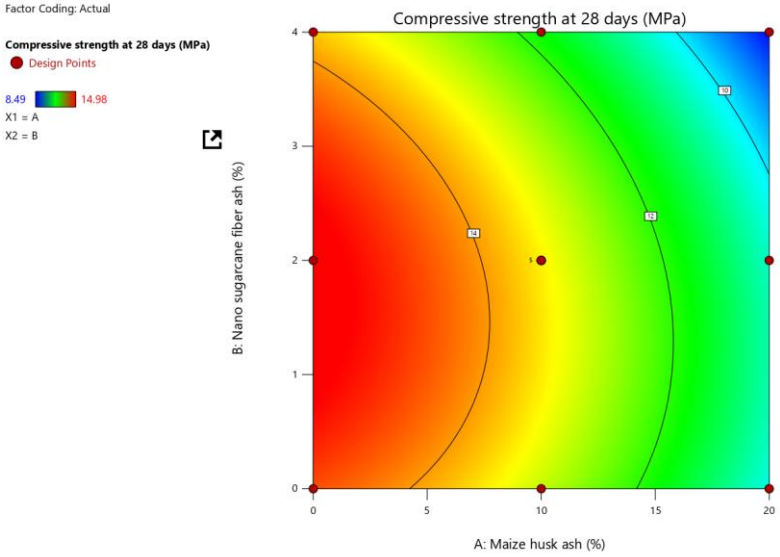
Figure 4 shows the RSM 2D and 3D response surface plots, which indicate that MHA has a stronger effect on the compressive strength than does NSFA. The distinct roles of the two additives are that the compressive strength increases with increasing NSFA content and decreases with increasing MHA content. The response surface shows a reddish-yellow area that corresponds to the optimal zone with the maximum compressive strength; the green areas show moderate effects; and the bright blue areas show places that have little effect on strength [20]. The strength decreases were most noticeable as the MHA concentration rose from 13 to 30%, whereas NSFA addition from 0 to 18% significantly increased the strength; however, the impact peaked at higher NSFA concentrations. This behaviour can be explained by variations in pozzolanic activity, chemical composition, and particle size [19, 20]. While NSFA improves compressive strength through enhanced particle packing, micro-filler effects, and quicker pozzolanic reactions, resulting in a denser and stronger mortar matrix, excessive MHA can dilute the cement matrix and decrease strength due to poorer reactivity and a larger particle size [20]. Therefore, a certain combination range where the compressive strength is maximised is defined by the synergistic interaction between MHA and NSFA.



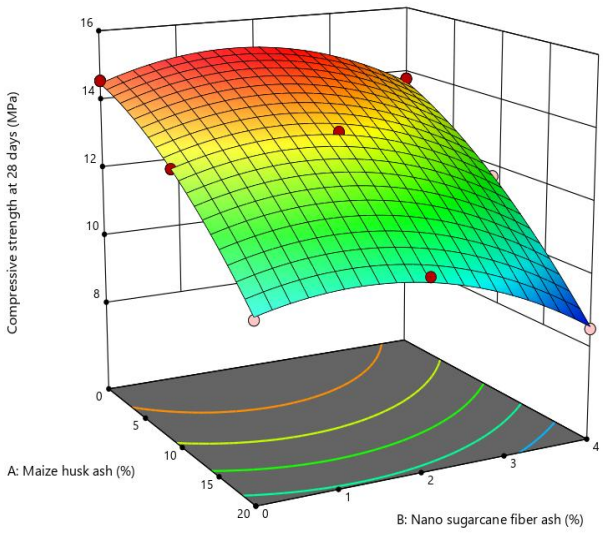
(a)



(b)



(c)



(d)

Figure 4. 2D and 3D response surfaces showing the synergistic effects of MHA and NSFA on the cement mortar compressive strength at (a) and (b) 7 days and (c) and (d) 28 days.

3.7 Numerical Optimisation and Validation

To assess the prediction accuracy of the generated model and determine the mixing conditions that maximise the compressive strength while respecting the designated MHA and NSFA content limits, a numerical optimisation approach was utilised. Figure 5 depicts the optimisation ramp, which indicates both the input variables during optimisation and the related response. The optimal combination for improving the compressive strength of cement mortar at 7 and 28 days was 8.25% MHA and 2.2% NSFA, resulting in compressive strengths of 9.58 MPa at 7 days and 13.75 MPa at 28 days.

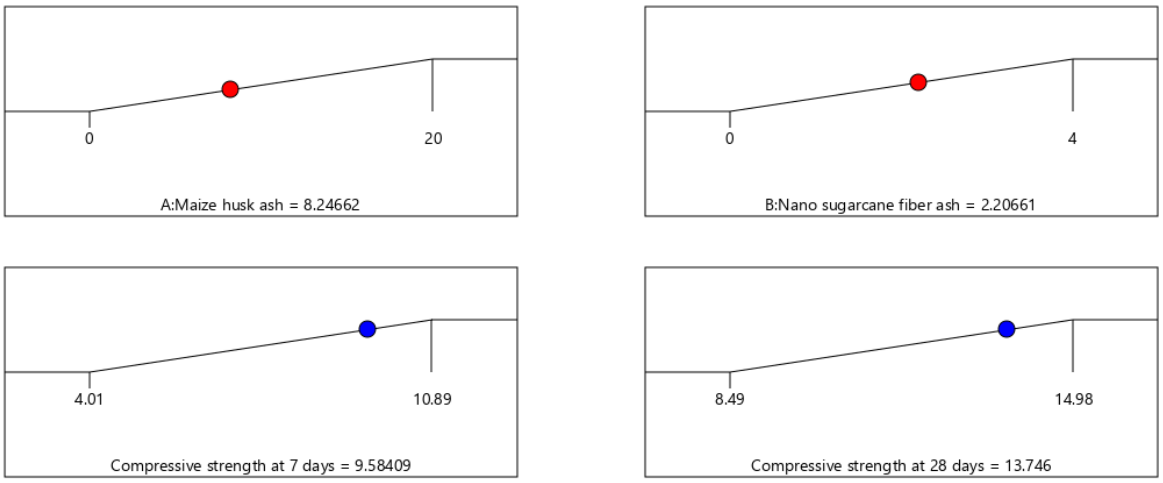


Figure 5. Study optimisation response ramps

Furthermore, more tests were performed to assess the performance of the developed model accurately. Eq. 3 was used to calculate the percentage error (%) between the experimental data and the RSM model predictions, allowing for an assessment of the model's accuracy and dependability [20, 21]. The ability of the developed model to optimise the MHA and NSFA contents to increase the compressive strength of cement mortar was validated via analysis.

$$Error\ (\%) = \left|1 - \frac{RSM\ Model\ value}{Experimental\ value}\right| \times 100 \quad (3)$$

Table 8 presents the solutions optimised by the RSM and the associated percentage errors. The model predictions and experimental data showed very good agreement, with all the errors being less than 5% [21]. This close agreement validates the precision, resilience, and efficacy of the RSM-based optimisation model in predicting and optimising the compressive strength of cement mortar, incorporating MHA and NSFA.

Table 8. Developed model validation

Input variable		Compressive strength (MPa)	Response value		Error (%)
			RSM model	Experimental	
MHA (%)	8.25	7 days	9.58	9.37	2.19
NSFA (%)	2.2	28 days	13.75	13.24	3.71

4. Conclusion

This study employed RSM to reveal the fundamental interaction between MHA and NSFA, which could improve the compressive strength of cement-based mortars. The RSM models developed, which had strong coefficients of determination, negligible lack-of-fit, and low prediction errors (<5%), were found to be statistically robust, indicating their reliability for prediction purposes. NSFA contributed more to the improved compressive strength because of better particle packing and enhanced pozzolanic activity. However, MHA contributed more to the reduction in compressive strength at higher doses. The models developed indicated the optimum combination of 8.25% MHA and 2.2% NSFA, which corresponded to maximum compressive strengths of 9.58 MPa at 7 days and 13.75 MPa at 28 days, revealing the vast possibility for the integration of these binders into green, high-performance materials for civil engineering applications. Further investigations of these material types at later ages (56, 90 days of curing) are highly recommended to demonstrate how long pozzolanic activity can continue and how it contributes to the long-term microstructural property development of MHA and NSFA.

Acknowledgments

The authors acknowledge support provided by the Harnessing Talent (HANT) Postdoctoral Fellowship (PDF) and the Sustainable Environment and Transportation Research Group (SET-RG), Department of Civil Engineering, Midlands, Durban University of Technology, Durban 3021, South Africa.

Funding
The authors declare that no funds, grants, or other support was received during the preparation of this manuscript.

Conflict of Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Availability of Data and Materials
The data supporting this study's findings are available upon request from the corresponding author.

Ethics Statement
Not applicable.

Generative Artificial Intelligence Disclosure
Not applicable.

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