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Optimization of Sandcrete Block Compressive Strength using Response Surface Methodology

Victor Onyia
Civil, Construction, and Environmental Engineering Dept.
The University of Alabama
Tuscaloosa, AL, USA

Japhet Ezema
Civil Engineering Dept.
University of Nigeria, Nsukka
Enugu State, Nigeria

***Abstract*—This study optimizes the compressive strength of sandcrete blocks (SB) by investigating the effects of key mixture and geometric parameters. A Response Surface Methodology (RSM) approach was employed, using a Central Composite Design (CCD) to model the complex interactions between the process variables. The parameters investigated included coconut shell ash (CSA) as a partial cement replacement, center-web to end-web (CW/EW) ratio, and the curing age. Results from compressive strength tests of sandcrete blocks were used for this model. The developed quadratic model was statistically significant and demonstrated that these factors and their interactions have a substantial impact on strength. Numerical optimization via the desirability function identified an optimal compressive strength at a CSA content of 0%, a CW/EW ratio of 2:1, and a curing age of 28 days. This study confirms that RSM is an effective tool for optimizing sandcrete block properties, providing a predictive model that captures the non-linear effects of both mixture and process parameters.**

***Keywords*—Cement, coconut shell ash, compressive strength, curing age, sandcrete block, end-web to centre-web ratio, response surface methodology, central composite design, pozzolans**

I. INTRODUCTION

Sandcrete blocks are fundamental and a widely used building material across many developing nations, particularly in West Africa. Their popularity is driven by factors such as relative affordability, ease of production, and versatility in masonry construction. The quality and structural integrity of buildings made with these blocks are inherently tied to their compressive strength, a critical mechanical property specified in various national and international building codes, including the Nigerian Industrial Standard NIS 87:2000 [1].

The pursuit of enhanced compressive strength, coupled with the global push for more sustainable construction practices, has motivated research into partial replacement of cement with supplementary cementitious materials. A promising avenue is the utilization of agricultural waste ashes, such as rice husk ash and palm oil fuel ash, which have demonstrated pozzolanic properties capable of improving the long-term performance of cementitious composites [2, 3]. Coconut Shell Ash (CSA), a by-product of agricultural waste, represents one such material with the potential to enhance the performance of sandcrete blocks while addressing environmental waste management concerns [4]. The utilization of agricultural waste ashes as supplementary cementitious materials presents a viable pathway towards sustainable construction. These pozzolanic materials are rich in amorphous silica and have demonstrated significant potential for the partial replacement of cement [5, 6]. Pozzolans are siliceous or aluminous materials that, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties [6]. The incorporation of these pozzolanic materials has been shown to enhance the long-term compressive and flexural strength of cementitious composites, including sandcrete blocks (SBs).

Beyond material composition, the geometric configuration of hollow sandcrete blocks, particularly the center-web to end-web ratio (CW/EW), is a critical factor influencing structural performance. Web geometry governs load distribution and the failure mechanism under compressive loading [4]. Simultaneously, the curing age remains a fundamental parameter controlling and dictating the strength development of cement-based materials [7]. The interaction between these material variables (CSA and cement) and process variables (CW/EW ratio and curing age) creates a complex, multi-factorial system that is poorly optimized through a traditional one-factor-at-a-time experimental approach, such as the Taguchi mix design.

While previous studies have often examined these parameters in isolation, the complex, non-linear interactions between them are not fully elucidated. Conventional methods like the Taguchi approach, while useful for parameter screening, are limited in their ability to model these intricate interactions and build comprehensive predictive models for optimization [8]. In contrast, Response Surface Methodology (RSM) is a powerful collection of statistical and mathematical techniques specifically designed for such multi-variable problems. RSM is adept at modeling, analyzing, and optimizing responses where several influential variables are involved, and it can efficiently quantify individual and interactive effects to find optimal factor settings [9].

Therefore, this study leverages Response Surface Methodology to systematically model and optimize the compressive strength of sandcrete blocks. The specific objectives are, firstly, to develop a predictive quadratic model correlating the compressive strength of sandcrete blocks with key input variables: CSA proportion, CW/EW, and curing age. Secondly, to statistically analyze the individual and interactive effects of these parameters on compressive strength. Thirdly, to numerically identify the optimum combination of CSA proportion, CW/EW, and curing age that maximizes the compressive strength.

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II. METHODS

A. Optimisation with Response Surface Methodology

RSM employs two fundamental components for the optimization of process parameters: carefully designed experiments and empirical model fitting using polynomial functions. The methodology typically utilizes structured experimental designs, such as the Central Composite Design (CCD), which allows for the efficient estimation of linear, interaction, and quadratic effects of the model parameters with a minimal number of experimental runs. A key advantage of RSM is that it generates a predictive mathematical model, which enables the visualization of the response surface through contour plots. This visualization makes it possible to precisely identify optimal factor settings and understand the complex interactions between variables.

B. Central Composite Design

For this study, a Response Surface Methodology (RSM) framework was employed to model and optimize the process parameters. CCD, a standard and efficient design for fitting second-order (quadratic) models, was selected. The design was chosen to investigate the three critical controllable factors influencing the compressive strength of the sandcrete blocks: the Coconut Shell Ash (CSA) replacement percentage, the CW/EW, and the curing age.

The experimental region for each factor was defined by appropriate lows and highs, as detailed in Table 1. The CCD structure incorporates factorial points to estimate linear and interaction effects, axial points to estimate curvature, and center points to estimate pure error. This arrangement allows for the comprehensive exploration of the factor space and the development of a robust predictive model with a minimal number of experimental runs.

TABLE 1. MIXTURE-PROCESS PARAMETER

S/N	Mixtures	Percentages						
1.	CSA	0	5	10	15	20	25	30
2.	Cement	100	95	90	85	80	75	70
	Processes	High			Low			
3.	CW/EW	2			1			
4.	Curing (days)	28			3			

C. Production of Coconut Shell Ash and Sandcrete Blocks

Sandcrete blocks measuring 150 mm × 225 mm × 450 mm were made using a sand-to-binder ratio of 1:12. The materials were manually mixed until a uniform consistency was achieved. The homogeneous mixture was then poured into molds on flat wooden pallets and compacted using a hand-ramming method. After compaction, the freshly formed SBs were immediately demolded and cured for 28 days to gain sufficient strength. Curing involved daily watering and covering the blocks with plastic sheets to prevent moisture loss. Collected coconut shells were sun-dried for a week. Once dried, they were broken into smaller pieces with a hammer and spread on a large tray, ensuring the removal of any remaining moisture. During the carbonization stage, the sun-dried shells were placed in a furnace and incinerated at 400°C. Immediately after burning, the shells were quickly removed and allowed to cool within an hour. The cooled, charred shells were then crushed with a mechanical crusher to produce a fine powder. This powder, known as coconut shell ash, was sieved through a BS No. 200 test sieve and stored in airtight containers until use.

D. Compressive Strength Modeling using Minitab

a) Defining factor ranges: setting low and high levels for each factor in the experimental design.
b) Creating a response surface design: generating the set of experiments needed to fit a quadratic model.
c) Incorporating existing experimental results: this will enhance the designed CCD.
d) Defining a custom response surface design, considering the existing data points.
e) Analyzing the response surface.
f) Optimizing: using the response optimizer and contour plots to identify the peak compressive strength.

III. RESULTS AND DISCUSSION

A. Analysis of Compressive Strength and Model Fitting

The results of the compressive strength tests for the experimental runs generated by the CCD are shown in Tables 3 and 4. An initial review of the data indicated that the CW/EW ratio significantly affected the structural performance of the blocks, with the 2:1 ratio generally producing higher compressive strengths compared to the 1:1 ratio. This is likely due to improved load distribution and more effective stress paths provided by the optimized web geometry.

An RSM analysis was performed to model the relationship between the parameters and compressive strength using Minitab 22 [10]. An analysis of variance (ANOVA) for the fitted quadratic model is shown in Table 2. The model was found to be highly significant, with a low p-value (< 0.0001) and a high coefficient of determination ($R^2 = 0.9278$), indicating that the model explains 93% of the variability in compressive strength. The values of R-sq(adj) and R-sq(pred) from Table 3 confirm the model's adequacy. The normal probability plot in Figure 1 closely follows a straight line, demonstrating a good fit. The residuals versus fit in Figure 2 are randomly scattered around zero with no apparent pattern, indicating that the model includes all important terms and provides reliable predictions.

TABLE 2. ANALYSIS OF VARIANCE (ANOVA)[10]

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	2.19196	0.54799	84.55	0.000
Linear	3	2.18641	0.72880	112.45	0.000
CSA	1	0.11657	0.11657	17.99	0.001
Curing	1	1.75232	1.75232	270.37	0.000
CW/EW	1	0.31752	0.31752	48.99	0.000
Square	1	0.00846	0.00846	1.30	0.271
CSA*CSA	1	0.00846	0.00846	1.30	0.271
Error	15	0.09722	0.00648		
Total	19	2.28918			

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TABLE 3: MODEL SUMMARY

S	R-sq	R-sq(adj)	R-sq(pred)
0.0805064	95.75%	94.62%	92.78%

Regression Equation:

$$Y = 0.1241 - 0.0013X_1 + 0.0237X_2 + 0.2520X_3 - 0.0003X_3^2 \quad (1)$$

X_1 = CSA percentage, X_2 = Curing age (days), X_3 = CW/EW, Y = Compressive strength (N/mm^2).

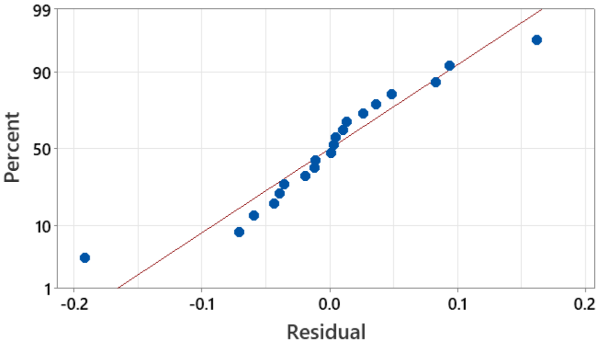

Fig. 1. Normal Probability Plot

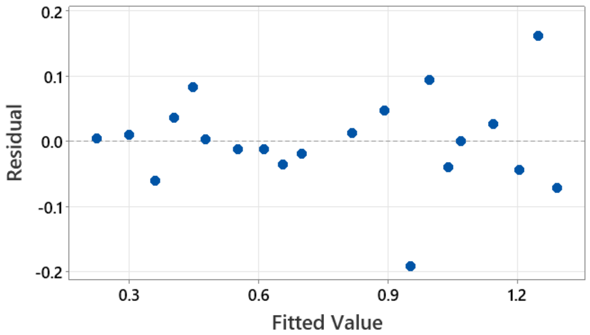

Fig. 2. Versus Fit

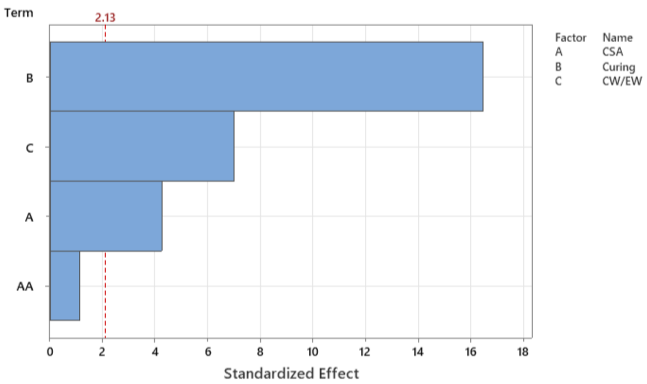

Fig. 3. Pareto Chart of Standardized Effects

B. Effect of Process Parameters and Optimization

The effects chart from Figure 3 reveals that curing age was the most influential factor, followed by CW/EW and CSA content. Furthermore, insignificant interaction effects were observed, particularly the quadratic effect of CSA content. Tables 4 and 5 represent these relationships, showing that the compressive strength increases with longer curing ages and an increase in the center web thickness, as identified by [11].

Numerical optimization using the desirability function was conducted to maximize compressive strength. The optimal combination of process parameters was identified as 0% CSA, a CW/EW ratio of 1:2, and a curing age of 28 days, resulting in a predicted compressive strength of 1.2911 N/mm². This strength value indicates the peak performance projected by the model after 28 days.

C. Interpretation of Strength Development

The observed strength gain can be attributed to the dual processes of cement hydration and the pozzolanic reaction between the Portland cement and Coconut Shell Ash (CSA). The pozzolanic reaction is instigated by the hydration of cement, which releases calcium hydroxide. The CSA, rich in amorphous silica, subsequently reacts with this compound in the presence of moisture to form additional calcium silicate hydrate gels, which are the primary strength-bearing phases in cementitious systems.

The critical importance of curing age is directly related to the time-dependent nature of these reactions. While cement hydration happens quickly in the initial stages, the pozzolanic reaction involving CSA is usually slower [12, 13]. The 28-day curing period allows sufficient time for this secondary reaction to progress significantly, resulting in a denser microstructure and increased strength. This explains why the model identified curing age as a key factor for achieving gains in compressive strength. The CW/EW ratio, as a geometric factor, greatly influences strength by optimizing the load-bearing cross-section and reducing stress concentrations within the block, thereby enabling the developed material strength to be more fully expressed under load.

TABLE 4. COMPRESSIVE STRENGTH AT 3-DAY CURING AGE

S/N	CSA percent	CW/EW	CS (N/mm^2)
1.	0	1	0.4471
2.	5	1	0.4331
3.	10	1	0.4038
4.	15	1	0.3594
5.	20	1	0.2998
6.	25	1	0.2250
7.	30	1	0.1350
8.	0	2	0.6991
9.	5	2	0.6851
10.	10	2	0.6558
11.	15	2	0.6114
12.	20	2	0.5517
13.	25	2	0.4770
14.	30	2	0.3870

TABLE 5. COMPRESSIVE STRENGTH AT 28-DAY CURING AGE

S/N	CSA percent	CW/EW	CS (N/mm^2)
1.	0	1	1.0391
2.	5	1	1.0251
3.	10	1	0.9958
4.	15	1	0.9514
5.	20	1	0.8918
6.	25	1	0.8170
7.	30	1	0.7270
8.	0	2	1.2911
9.	5	2	1.2771
10.	10	2	1.2478
11.	15	2	1.2034
12.	20	2	1.1438
13.	25	2	1.0690
14.	30	2	0.9790

IV. RESULTS AND DISCUSSION

The addition of CSA in cement and concrete has gained considerable importance because of the requirements of environmental safety and more durable construction in the future [14]. The use of CSA as a partial replacement of cement in masonry blocks and concrete has received attention in recent years. The literature review clearly demonstrates that CSA is an effective pozzolan that can contribute to the mechanical properties of sandcrete blocks. The reactivity of CSA varies depending on its manufacturing process. CSA addition tends to retard the initial setting time [12, 13]. Additionally, CSA blended sandcrete units can decrease the total porosity and modify the pore structure of the cement mortar and concrete [15], and significantly reduce the permeability, which allows the influence of harmful ions, leading to the deterioration of the concrete matrix. CSA in sandcrete can improve compressive strength if added at the correct percentage [16]. CSA helps in enhancing the long-term mechanical properties of sandcrete.

Tables 4 and 5 present the results of compressive strength tests for the experimental runs generated by the RSM analysis. The compressive strength was slightly higher in the CW/EW configuration of 2. Although laboratory experiments used for the model showed a peak in compressive strength at 10 percent CSA replacement, the model predicted an overall decrease as the percentage of CSA increased, consistent with the findings of. [15] But contrary to [4, 17] . This observed contrast may result from the model's correction of outlier data points identified in the laboratory tests. The same trend appeared for both the 3-day and 28-day tests. The 0% CSA replacement and CW/EW of 2:1 produced the highest compressive strength of 1.2911 N/mm² after 28 days. This is because cement gains more strength with increased curing age, regardless of CSA addition.

Although the model showed a decrease in compressive strength, the use of CSA as a pozzolanic additive remains important in sandcrete blocks because of other benefits like lower density and permeability, increased workability, which are not captured in this RSM. [16]. Additionally, CSA's lower density[18] and pozzolanic reactivity support sustainable, lightweight construction and repair works. Therefore, more research is necessary on how CSA affects other mechanical properties of sandcrete blocks.

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