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## STRENGTH PREDICTION AND OPTIMIZATION OF ANIMAL BONE ASH- METAKAOLIN CEMENT BLENDS VIA RESPONSE SURFACE METHODOLOGY

Jarumi Luka<sup>1</sup>, Olubajo Olumide Olu <sup>1\*</sup>, Ibrahim Ikara Abdulkarim<sup>2</sup> and Abubakar Aliyu<sup>2</sup>

<sup>1</sup>Department of Chemical Engineering, Abubakar Tafawa Balewa University, Bauchi

<sup>2</sup>Department of Civil Engineering, Abubakar Tafawa Balewa University, Bauchi

### ABSTRACT

*This paper tries to investigate the effect of blending animal bone ash (ABA) and metakaolin (MK) on the mortar compressive strength of ternary cement blends. The mortar strengths of the ternary cement blends are influenced by several parameters such as blending ratio, replacement level and curing age. The mortar strength of the ternary cement blend was optimized via response surface methodology using central composite design and Box and Behnken design. Both models were compared to obtain the best strength prediction. Results showed that both models experimental data for the prediction of the mortar strength satisfied second order polynomial regression. The mortar strength of ABA-MK-PLC experienced an increase as the blending ratio between 0.2 -0.5 and curing age between 3 -60 days whereas a slight reduction in the mortar strength was observed as the replacement level was increased between 7.5 – 12.5 wt.%. This slight diminution observed despite the high replacement level further proves that pozzolanic activities occurred. The analysis of variance (ANOVA) indicated that the curing age significantly affected the response for both CCD and BBD models respectively with the best mortar strength prediction via CCD. The ANOVA revealed that predicted  $R^2$  ( $R^2_{pred}$ ) and  $R^2$  for CCD was very close in comparison with BBD and thus most suitable to describe the mortar compressive strength of the cement blends with  $R^2_{pred}$  of 0.9107. The interactive effect of the blending ratio, replacement level and curing age were also investigated and optimized. The optimum condition for the prediction of the mortar strength of the ternary cement blend were blending ratio 0.423, replacement level 7.565 wt.%, and curing age 60 days.*

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### INTRODUCTION

The effective utilization of materials and reduction of cost in construction industry, require the use of cementitious materials such as metakaolin and animal bone ash as a better option of producing an economically good cement blend. An obvious advantage is that ABA similar to limestone which may contribute to the early strength while silicon oxide present in MK may increase the long-term strength, which may result in an adequate development of strength, soundness and setting

time of the new improved cement blend (Jarumi *et al.*, 2022, Olubajo *et al.*, 2020). Metakaolin is the anhydrous calcined form of clay employed as a pozzolan and its choice as a supplementary cementitious material result in increased compressive and flexural strength, reduced permeability, reduced potential for efflorescence, increase resistance to chemical attack, increased durability, etc. (Kakali *et al.*, 2016). Whereas animal bone ash is believed to be composed of about 55.82% of CaO, which is one of the main ingredients in the production of cement,

and about 42.39% phosphorus pent-oxide and 1.79% water. The content of CaO makes it useful as an ingredient in the production of cement (Mussi, 2014). Agricultural waste is the waste produced from agricultural materials which include any material that is rendered useless during the processing of agricultural produce such as meat processing. The disposal of these waste call for concern, because they can cause health problem, contamination of water resources and polluting the environment, especially land (Narajam, 2015). Animal bones are agricultural waste materials generated from slaughter house and abattoirs. Other sources of bones are obtained from meals (i.e., bones that cannot be consume during meals). These bones are found littering the environment and consequently constituting environmental problems and pollution which can be readily be collected in abundance (Winton *et al.*, 2013). According to Xiaolu and Huisheng (2015), the effect of metakaolin, fly ash resulting in calcium hydroxide enhancing the strength of the cement blend much faster. This however, was in agreement with Dinakar *et al.* (2013) who also observed that cement replacement with metakaolin at 5-15 wt.% at an interval of 5% on high strength properties of concrete improved the compressive strength of the binary cement. Research work carried out by Olubajo *et al.* (2020) on the study of OPC blended with RHA and MK revealed that water consistency initial and final setting time, volume expansion as well as significantly improved mortar compressive strength at replacement between 5- 20 wt.% at an interval of 5 wt.%. Sanjay *et al.* (2014) noted that at 15% MK replacement improved its compressive strength which agreed with Narmatha and Felix (2014) in which cement was replaced by 15% metakaolin, thus enhancing its compressive strength. In consideration of compressive strength using MK as a partial replacement for cement, Nikhila and Kumar

(2015) agreed with the view of El-Diadamony *et al.*, (2018) at 15% MK replacement, that at 5% replacement the highest compressive strength was obtained at a curing age of 60 days. In a related development the effect of metakaolin on the concrete compressive strength were determined at the curing ages of 7 and 28 days with Sunny *et al.* (2017) work indicating that the strength properties improved significantly. Hamdy *et al.* (2019) investigated the hydration and characteristics of metakaolin pozzolanic cement paste and revealed that cement substitution of up to 20 wt.% by MK as pozzolanic material resulted in a higher compressive strength value at earlier curing ages (7-28 days) and improvement of the mechanical and durability properties. In a related development, Tsai-Lung *et al.* (2013) also carried out research on the effect of metakaolin on strength and efflorescence quality of cement-based composite and noticed that the compressive strength of cement-based composite was at its peak at a replacement of 15% considering 5-25 wt.% replacement.

Varma *et al.* (2016) conducted a research work on the effect of utilizing bone powder ash as partial replacement of constriction materials and noticed that the compressive strength improved significantly. Abraham *et al.* (2018) studied the effects on the varying dosage replacement of cement content by animal bone powder in normal concrete mix production, resulting in a decrease in the concrete compressive strength as the animal bone powder dosage was increased from 5% - 25% replacement at interval of 5%. Akinyele *et al.* (2016) studied the effect of partial replacement of cement with bone ash and wood ash concrete at a replacement of 5-25 wt. % at interval of 5 wt.% and revealed that bone ash was a better pozzolanic material than the wood ash based on the chemical analysis carried out on both materials. The compressive strength was

maximum at 10% replacement of bone ash which can partially replace cement in concrete at 28 days curing age. According to Olutaiwo *et al.* (2018), utilizing cow bone ash as partial replacement for cement in highway rigid pavement construction influenced both the physico-mechanical and chemical properties of the pavement construction by a gradual increment in the compressive strength up to 10% after which the strength decreases. Harkamal *et al.* (2019) worked on the partial replacement of cement with animal bone powder along with the addition of polypropylene fiber in concrete. The study revealed that at replacement levels of 5-15 wt.% at interval of 5% and at curing ages of 7, 14 and 28 days, the compressive strength increases at 10% suggesting that poly propylene fiber and animal bone powder can be used to replace cement.

The strength of a material is one of the hallmark properties that determine the quality of cement produced. The strength of cement could be influenced by several factors such as cement replacement, extent of hydration rate dependent on the curing age, chemical composition of the raw materials employed etc. cement replacement could either be high or low depending on the requirement for various purposes. Replacement of cement with several biomasses such as animal bone ash (Jarumi *et al.*, 2022) rice husk ash (Olubajo *et al.*, 2020), coal bottom ash, fly ash, saw dust ash, orange peel ash, locust bean pod ash, sugarcane bagasse and date palm seed pod ash etc. has been adopted with various successes Olubajo and Osha (2013), Olubajo (2017), Olubajo et al (2020a), Olubajo et al. (2019), Olubajo et al. (2020b) Olubajo (2020), Ilya et al. (2023). Blending in cement is an act of mixing cement with supplementary cementitious materials or fillers to enhance the properties and in turn the quality of cement. the benefits of blending cannot be overemphasised as their

benefits can be categorized into mainly technical, economical and environmental benefits. There are several works on strength prediction as well as optimization of sawdust ash – eggshell powder cement blends, coal bottom ash and limestone cement blends with the application of response surface methodology yielding positive strength prediction Olubajo (2017), Olubajo et al. (2019) and Abubakar *et al.* (2020). The blending could either be by cement or aggregate replacement and addition to cement or aggregate. Furthermore, this study monitors the strength gain and tries to adequately predict the strength of cement blended with animal bone ash and metakaolin as partial cement replacement as well as determination of the optimum condition for maximum strength of ABA-MK cement blends. The issue of time wasting by waiting for curing days to determine the strength gain coupled with the use of significant amount of materials adding to cost of research outlines the importance of this research.

The experiment for the research work were designed to predict the strength of cement blended with ABA-MK as well as optimize and determine the maximum strength at optimum conditions. The parameters to be optimized include the blending ratio, replacement level and curing age. Most researches conducted indicated that the most significant parameter that influence the strength gain in comparison with others was the extent of hydration rate expressed as curing age evident by higher F value from analysis of variance (ANOVA).

## 2. Experimental Study

### 2.1 Materials and Methods

The design summary for the dependent variables are the mortar strengths via CCD and BBD models with blending ratio, replacement level and curing age as independent variables. The independent variables were chosen as blending ratio lower,

middle and upper limit are denoted as 0.20, 0.50, 0.8; replacement level lower, middle and upper limits denoted by 7.5 wt.%, 10 wt.%, 12.5wt.%; curing age lower, middle and upper limits are denoted as 3 days, 28 days, 60 days respectively. Face central composite factorial design comprising of 3 levels and 3 factors with Design Expert 13 where -1 denotes low value of the independent variable (0.2, 7.5 wt.%, 3 days), 0 used for the medium value (0.5, 10 wt.%, 28 days) and for the high value (0.8, 12.5 wt.%, 60 days) were employed to investigate the effect of the above factors on the responses. A model was fitted to the response surface generated by the experiment.

$$S_i = \beta_0 + \sum_{i=1}^k (\beta_i x_i) + \sum_{i=1}^k (\beta_{ii} A_i^2) + \sum_{i \neq j}^k (\beta_{ij} A_i A_j) \quad (2)$$

Where  $S_i$  denotes the mortar strength of ABA-MK cement blends,  $\beta_0$  is the coefficient constant,  $\beta_i$  is the linear coefficient,  $\beta_{ii}$  quadratic coefficient effect,  $\beta_{ij}$  is the interaction coefficient effect and  $A_i A_j$  is the coded values of variable  $i j$  respectively.  $S_1$  and  $S_2$  denotes mortar strength from CCD and BBD respectively while  $A_1$  as ABA/ABA-MK ratio as blending ratio which is dimensionless,  $A_2$  as replacement level in wt.% and  $A_3$  is curing age in days.

### 3. Result and Discussion

Table 1 present the experimental results obtained from the determination of the mortar compressive strength of cement blended with ABA and MK based on design of experiment via RSM for CC and BB designs to investigate its effect of blending ratio, replacement level and curing age on the mortar strength of ABA-MK cement blends respectively. The ANOVA technique was employed to undertake the statistical analysis of the results in order to evaluate the model and its parameters were

$$S_k = f(\text{Blending ratio, Replacement level, Curing age}) \quad (1)$$

Design Expert 13 software was employed to obtain the best fit data and estimate the optimal conditions for mortar strength. RSM was employed in the determining the optimal factors to obtain maximum strength via CCD, BBD as well as the interaction of variables were estimated. 20 and 17 runs were carried out to fit the general model of equations (1) for CCD and BBD respectively and to obtain optimum condition for blending ratio, curing age, replacement level for the optimum mortar strength of the cement blend.

presented in Table 2. The predictive model for the determination of the mortar strength of ABA-MK- cement blends, some of the model terms were modified by selecting some model terms with probability values with 95% confidence level as well as F test of the experimental results employed to determine how statistically significant model terms are. The graphs for 3D response surface and contour were obtained to describe on the individual and interactive effect on the factors.

The two models employed include Central composite design (CCD) and Box & Behnken design (BBD) in the prediction of the mortar strength of ternary cement blends comprising of PLC, ABA and MK. The independent variables include Blending ratio (ABA/ABA-MK ratio) denoted as  $A_1$ , Replacement level denoted by  $B_2$  and curing age denoted by  $C_3$  while the dependent variables were strength prediction via CCD denoted  $S_1$  and strength prediction via BBD denoted by  $S_2$  respectively. The investigation of

the effect of the various factors on the responses were determined using Design Expert 13. The resultant equations were obtained from the

ANOVA for strength prediction for ABA-MK-cement blend using CCD and BBD models respectively:

Table 1: Experimental Design and Results for CCD ( $S_1$ ) and BBD ( $S_2$ )

Blending ratio A	Replacement level wt.% B	Curing age days C	Mortar strength N/mm <sup>2</sup> $S_1$	Blending ratio, A	Replacement level wt.% B	Curing age days C	Mortar strength N/mm <sup>2</sup> $S_2$
0.5	12.5	28	32.14	0.5	10.0	28	32.06
0.8	12.5	60	33.27	0.8	10.0	3	22.70
0.2	7.5	3	25.61	0.5	12.5	60	34.68
0.5	7.5	28	35.50	0.8	7.5	28	29.80
0.2	10	28	29.45	0.5	12.5	3	24.73
0.8	7.5	60	36.79	0.5	10.0	28	32.06
0.5	10	28	32.06	0.2	10.0	3	25.26
0.2	7.5	60	38.89	0.5	10.0	28	32.06
0.2	12.5	3	24.00	0.8	12.5	28	30.27
0.5	10	60	35.43	0.8	10.0	60	30.80
0.5	10	28	32.06	0.5	10.0	28	32.06
0.8	12.5	3	22.95	0.2	12.5	28	32.24
0.5	10	28	32.06	0.2	10.0	60	32.58
0.5	10	28	32.06	0.2	7.5	28	35.98
0.2	12.5	60	34.12	0.5	7.5	3	21.37
0.5	10	28	32.06	0.5	10.0	28	32.06
0.5	10	3	26.61	0.5	7.5	60	40.70
0.8	7.5	3	24.82	-	-	-	-
0.8	10	28	29.39	-	-	-	-
0.5	10	28	32.06	-	-	-	-

$$S_1 = 49.68 + 26.95A - 5.97B + 0.42C + 0.17AB - 0.018AC - 0.0083BC - 29.67A^2 + 0.28B^2 - 0.0022C^2 \quad (3)$$

$$S_2 = 42.32 - 6.10A - 4.11B + 0.79C + 1.40AB + 0.029AC - 0.033BC - 14.014A^2 + 0.204B^2 - 0.0046C^2 \quad (4)$$

Equations (3) and (4) signify the quantitative effect of the independent variables such as Blending ratio, replacement level and curing age (A, B, C) as well as their interactions with the response; mortar strength from CCD and BBD ( $S_1$ ,  $S_2$ ). The independent variables: A, B and C were inserted into the equations to determine the theoretical dependent variables;  $S_1$  and  $S_2$  respectively. The strength prediction employing both models significantly satisfied quadratic models based on the experimental design and

factor interaction.

The analysis of variance ANOVA for strength prediction of ABA-MK-PLC from CCD and BBD are tabulated in Table 2 with both producing F values for lack of fit of 2 and 2.33 respectively. It was also observed from Table 4 that the F values for the above models  $S_1$  and  $S_2$  for CCD and BBD designs were significant, thus there is 0.01% chance that the model has large F value of 110.86 and 10.43 respectively could occur due to noise.

Table 2: ANOVA for Response Surface Quadratic Model Analysis of Variance for Mortar Strength Prediction of ABA-MK cement blend via CC and BB designs

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
<b>Model S<sub>1</sub></b>	360.19	9	40.02	110.86	< 0.0001	Significant
<b>A</b>	2.39	1	2.39	6.61	0.0278	Significant
<b>B</b>	23.32	1	23.32	64.59	< 0.0001	Significant
<b>C</b>	297.13	1	297.13	823.04	< 0.0001	Significant
<b>A<sup>2</sup></b>	0.1225	1	0.1225	0.3393	0.5731	
<b>B<sup>2</sup></b>	0.1860	1	0.1860	0.5153	0.4893	
<b>C<sup>2</sup></b>	2.83	1	2.83	7.85	0.0187	Significant
<b>AB</b>	19.61	1	19.61	54.32	< 0.0001	Significant
<b>AC</b>	8.23	1	8.23	22.79	0.0008	Significant
<b>BC</b>	8.29	1	8.29	22.96	0.0007	Significant
<b>Residual</b>	3.61	10	0.3610			
<b>Lack of Fit</b>	3.61	5	0.7220	2.00		
<b>Model S<sub>2</sub></b>	350.04	9	38.89	10.43	0.0027	Significant
<b>A</b>	18.97	1	18.97	5.09	0.0587	Significant
<b>B</b>	6.20	1	6.20	1.66	0.2383	
<b>C</b>	249.76	1	249.76	66.96	< 0.0001	Significant
<b>A<sup>2</sup></b>	4.43	1	4.43	1.19	0.3118	
<b>B<sup>2</sup></b>	0.2551	1	0.2551	0.0684	0.8012	
<b>C<sup>2</sup></b>	21.66	1	21.66	5.81	0.0468	Significant
<b>AB</b>	6.70	1	6.70	1.80	0.2221	
<b>AC</b>	6.83	1	6.83	1.83	0.2180	
<b>BC</b>	55.65	1	55.65	14.92	0.0062	Significant
<b>Residual</b>	26.11	7	3.73			
<b>Lack of Fit</b>	26.11	3	8.70	2.33		

Table 3 illustrates the model fit statistics for both models employed in the strength prediction of ABA-MK cement blends. The Predicted  $R^2$  value (0.9901) and Adjusted  $R^2$  value (0.9811) for CCD model was very close compared with BBD with Predicted  $R^2$  value (-0.1486) and Adjusted  $R^2$  value (0.8413). the former model was found to be the most suitable model to describe the mortar strength of the cement blends between 7.5 wt. – 12 wt. % replacement level. The both models produced adequate precision ratios indicating a desirable signal which was greater than 4

(Olubajo et al. 2017, Olubajo et al. 2022; Koocheki et al. 2009). The fit of the model was checked with the coefficient of determination  $R^2$  which indicated 99.01 % of the response variability could be explained by the model. The result indicated that the model can be considered to be statistically significant according to the F test with 95% confidence as the F value of 110.86.

Table 3: Model Fit Statistics for CCD and BBD for strength prediction of ABA-MK cement blends

<i>Source</i>	<i>CCD</i>	<i>BBD</i>
Sum of Squares	<u>360.19</u>	350.04
DF	<u>9</u>	9
Mean square	<u>40.02</u>	38.89
F value	<u>110.86</u>	10.43
Prob> F	<u>&lt;0.0001</u>	0.0027
Std. Dev.	<u>0.6009</u>	1.93
R <sup>2</sup>	<u>0.9901</u>	0.9306
Adj. R <sup>2</sup>	<u>0.9811</u>	0.8413
Pred. R <sup>2</sup>	<u>0.9107</u>	-0.1486
PRESS	<u>32.47</u>	432.05

It could also be seen from Table 3 that strength prediction via CCD and BBD produced R<sup>2</sup> values greater than 80% as several researchers suggested that a fitted model with R<sup>2</sup> more than 80% was considered acceptable but not lower than 75% while the predicted values for the developed models should have a good correlation with the experimental data (Olubajo *et al.*, 2019, Olubajo *et al.*, 2022, Chauhan and Gupta, 2004; Ikara *et al.*, 2019). Result indicated that CCD is the most suitable to predict the strength for Portland limestone cement blended with ABA and MK. The regression values and adjusted regression values for CCD and BBD were 0.9901 and 0.9811; 0.9306 and 0.8413 respectively demonstrating the developed model's appropriateness to predict the mortar compressive strength for ABA- MK cement blends by their R<sup>2</sup> and R<sup>2</sup><sub>adj</sub> value near 1. Zaibunnisa *et al.* (2009) and Arsenovic *et al.* (2012) suggested that in order to find the most reliable empirical equation which fit the experimental data, and considered adequate when the regression value is close to unity which may not necessarily suggest that the model is adequate if the regression value is relatively high. They suggested that adjusted regression value beyond 0.90 which is close to unity can be considered appropriate in determining how adequate the models of the

two independent variable via CCD and BBD.

The ANOVA on the experimental results for the prediction of the mortar strength of ABA-MK-cement blends indicated that the quadratic equation satisfies both responses and the regression was statistically significant evident by high F value for the model especially via CCD (110.86) in comparison with BBD (10.43). The ANOVA results for the prediction of the mortar strength of ABA-MK cement blends for CCD (S<sub>1</sub>) presented in table 4 indicated that the model terms considered to be significant include A<sub>1</sub>, B<sub>1</sub>, C<sub>1</sub>, C<sub>1</sub><sup>2</sup>, A<sub>1</sub>B<sub>1</sub>, B<sub>1</sub>C<sub>1</sub> and A<sub>1</sub>C<sub>1</sub> with the other model terms having p values greater than 0.10 were considered insignificant. Whereas the model terms considered significant for the prediction of the mortar strength of ABA-MK cement blends via BBD (S<sub>2</sub>) include A<sub>2</sub>, C<sub>2</sub>, C<sub>1</sub><sup>2</sup> and B<sub>1</sub>C<sub>1</sub>. The curing age (C) had a large F value of 823.04 and 66.96; blending ratio (A) had a F value of 6.61 and 5.09; replacement level (B) produced a F value of 64.59 and 1.66 for mortar strength via CCD and BBD models respectively. The quadratic term for blending ratio and replacement level independently effects on the model for the prediction of mortar strength of ABA-MK- PLC was found to be insignificant evident by the low F values of 0.3393, 0.5153, and 1.19, 0.0684 which did not fall within p< 0.05 or p < 0.10 respectively.



The F values for the quadratic term of the curing age and the interaction between blending ratio and replacement level, interaction between blending ratio and curing age and interaction between replacement level and curing age all fell within  $p < 0.05$  or  $p < 0.10$  for CCD respectively and considered to be significant. The quadratic term of the curing age and the interaction between replacement level and curing age were the only significant in the prediction of the mortar strength of ABA-MK cement blends while the other interactions and quadratic terms were found to be insignificant for BBD. This significant high F value of curing age from the ANOVA result

is a strong indication that the curing age has a significant influence on the mortar strength of ABA-MK-cement blends in comparison with other factors such as blending ratio and replacement level. The model via CCD, lack of fit was found to be statistically insignificant.

### 3.1 Graphs for Predicted vs Actual and Normal Probability

There exists a strong correlation between the predicted and the experimental or actual value for the mortar strength of ABA-MK- cement blend for CCD and BBD as shown in Figures 1 (a), 2 (a) and 3 (a) respectively.

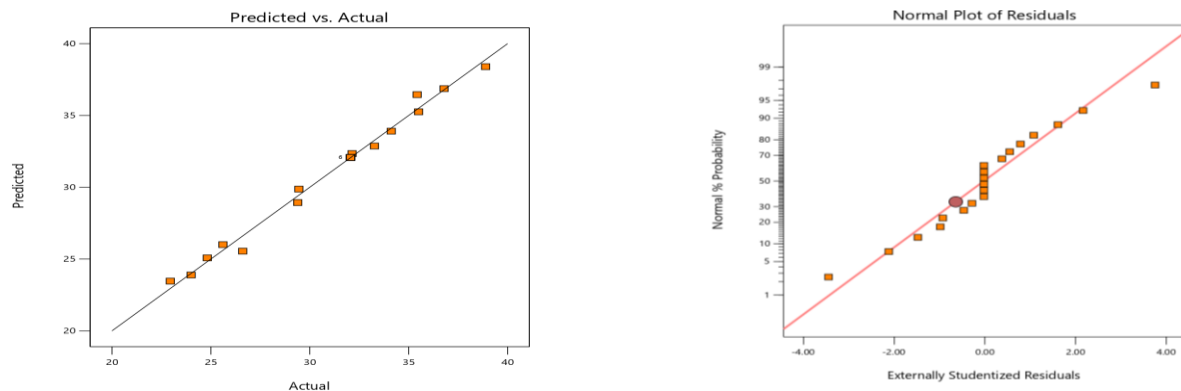


Figure 1: (a) Predicted against actual plot of the model developed for mortar strength via CCD (b) Normal probability plot of residuals indicating significance of the model developed for mortar strength via CCD

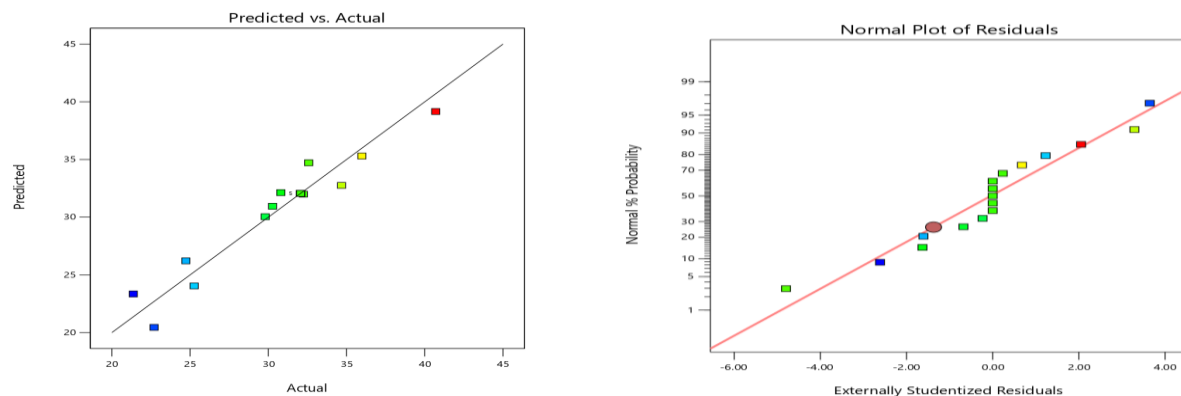


Figure 2: (a) Predicted against actual plot of the model developed for mortar strength via BBD (b) Normal probability plot of residuals indicating significance of the model developed for mortar strength via BBD



The model equation obtained from Design expert 13 in the prediction of the mortar strength for ABA-MK-cement blend was significant adequate for CCD in comparison with BBD. The diagnostics statistics indicating the variance between the

predicted and the actual values in the prediction of the mortar strength for ABA-MK- cement blends via CCD and BBD were presented in Table 4 below.

Table 4: Diagnostic Case Statistics for mortar strength of ABA-MK-cement blends for CCD and BBD

Blending ratio A	Replacement level wt.% B	Curing age days C	Actual Value N/mm <sup>2</sup> CCD	Predicted Value N/mm <sup>2</sup> CCD	Blending ratio, A	Replacement level wt.% B	Curing age days C	Actual Value N/mm <sup>2</sup> BBD	Predicted Value N/mm <sup>2</sup> BBD
0.5	12.5	28	32.14	32.35	0.5	10.0	28	32.06	32.06
0.8	12.5	60	33.27	32.87	0.8	10.0	3	22.70	20.45
0.2	7.5	3	25.61	26.00	0.5	12.5	60	34.68	32.76
0.5	7.5	28	35.50	35.26	0.8	7.5	28	29.80	30.04
0.2	10	28	29.45	29.87	0.5	12.5	3	24.73	26.22
0.8	7.5	60	36.79	36.87	0.5	10.0	28	32.06	32.06
0.5	10	28	32.06	32.07	0.2	10.0	3	25.26	24.04
0.2	7.5	60	38.89	38.40	0.5	10.0	28	32.06	32.06
0.2	12.5	3	24.00	23.89	0.8	12.5	28	30.27	30.95
0.5	10	60	35.43	36.45	0.8	10.0	60	30.80	32.13
0.5	10	28	32.06	32.07	0.5	10.0	28	32.06	32.06
0.8	12.5	3	22.95	23.46	0.2	12.5	28	32.24	32.00
0.5	10	28	32.06	32.07	0.2	10.0	60	32.58	34.72
0.5	10	28	32.06	32.07	0.2	7.5	28	35.98	35.30
0.2	12.5	60	34.12	33.91	0.5	7.5	3	21.37	23.35
0.5	10	28	32.06	32.07	0.5	10.0	28	32.06	32.06
0.5	10	3	26.61	25.55	0.5	7.5	60	40.70	39.16
0.8	7.5	3	24.82	25.08	-	-	-	-	-
0.8	10	28	29.39	28.93	-	-	-	-	-
0.5	10	28	32.06	32.07	-	-	-	-	-

### 3.2 Three-dimensional Surface and Contour Graphs

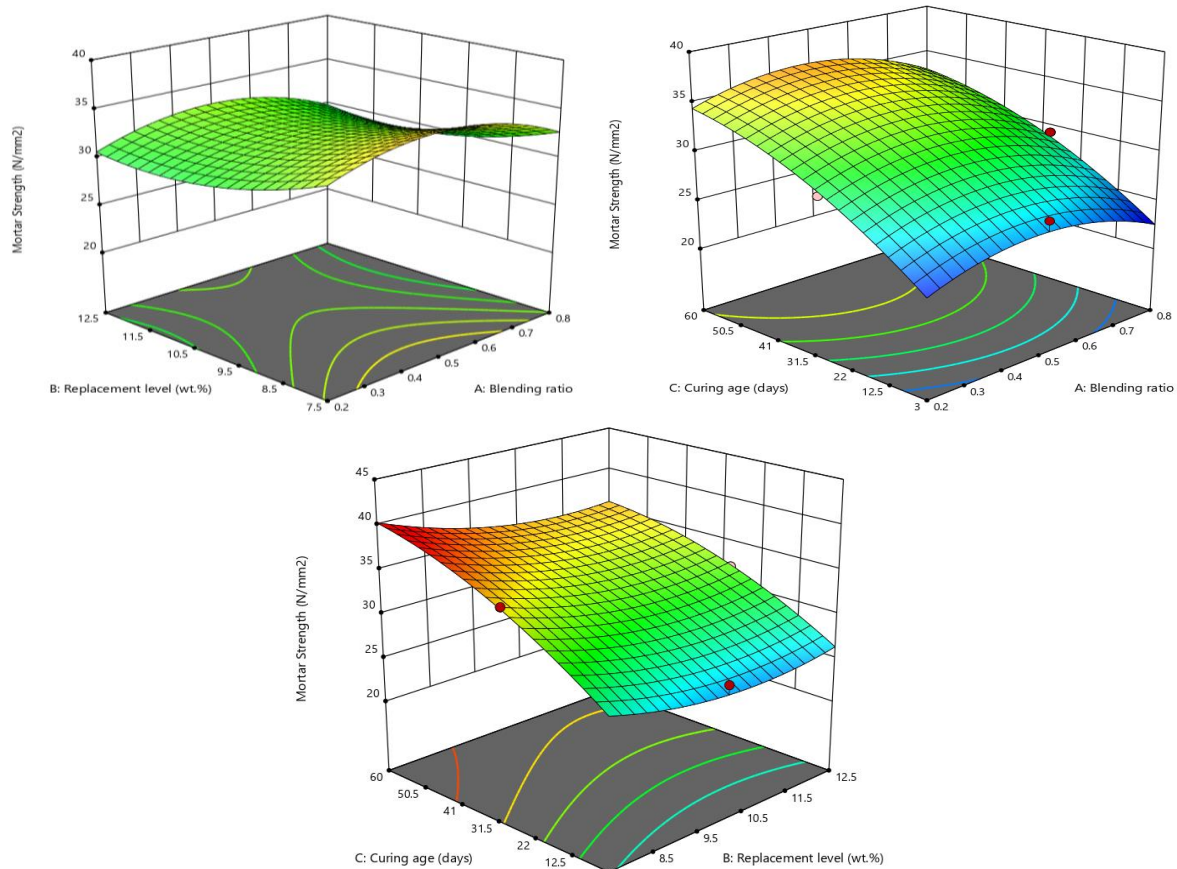
The relationship between the response i.e., mortar strength of ABA-MK cement blend and the factors such as blending ratio, replacement

level and curing age is represented by the 3 D surface and contour graphs. Figures 2 – 5 depicts the diagnostic graphs which determines the regression model adequacy indicating the response surface and contour graphs for the

influence of factors; A (blending ratio), B (replacement level) C (curing age) on the first response  $S_1$  (mortar strength of cement blend via CCD), second response  $S_2$  (mortar strength of cement blend via BBD) respectively. These response surface curves demonstrate the interactions between the various factors and determination of the optimum for the various factors in order to obtain maximum response. According to Dockery (2017), Silva *et al.* (2011), Olubajo *et al.* (2022) that the parabolic nature of contours implies that the interaction between both factors is significant as indicated in Figures 4-6.

From the regression equation, the most significant parameter influencing the prediction of the mortar strength of ABA-MK-cement blends

in the order are curing age C, replacement level B and blending ratio A respectively. Experiments were conducted by varying the parameters using experimental design to investigate the interaction between the factors. The experimental results of the full factorial Central composite design and Box and Behnken design were fitted into the equations 3 and 4 respectively. According to ANOVA, the curing age and replacement level are the most significant variable with effect of curing age (823.04) and the effect of replacement level (64.59) followed by the interaction between blending ratio and replacement level (effect of 54.31) as well as the blending ratio and curing age (22.79) and replacement level and curing age (22.96) which had a lower effect compared with the curing age.



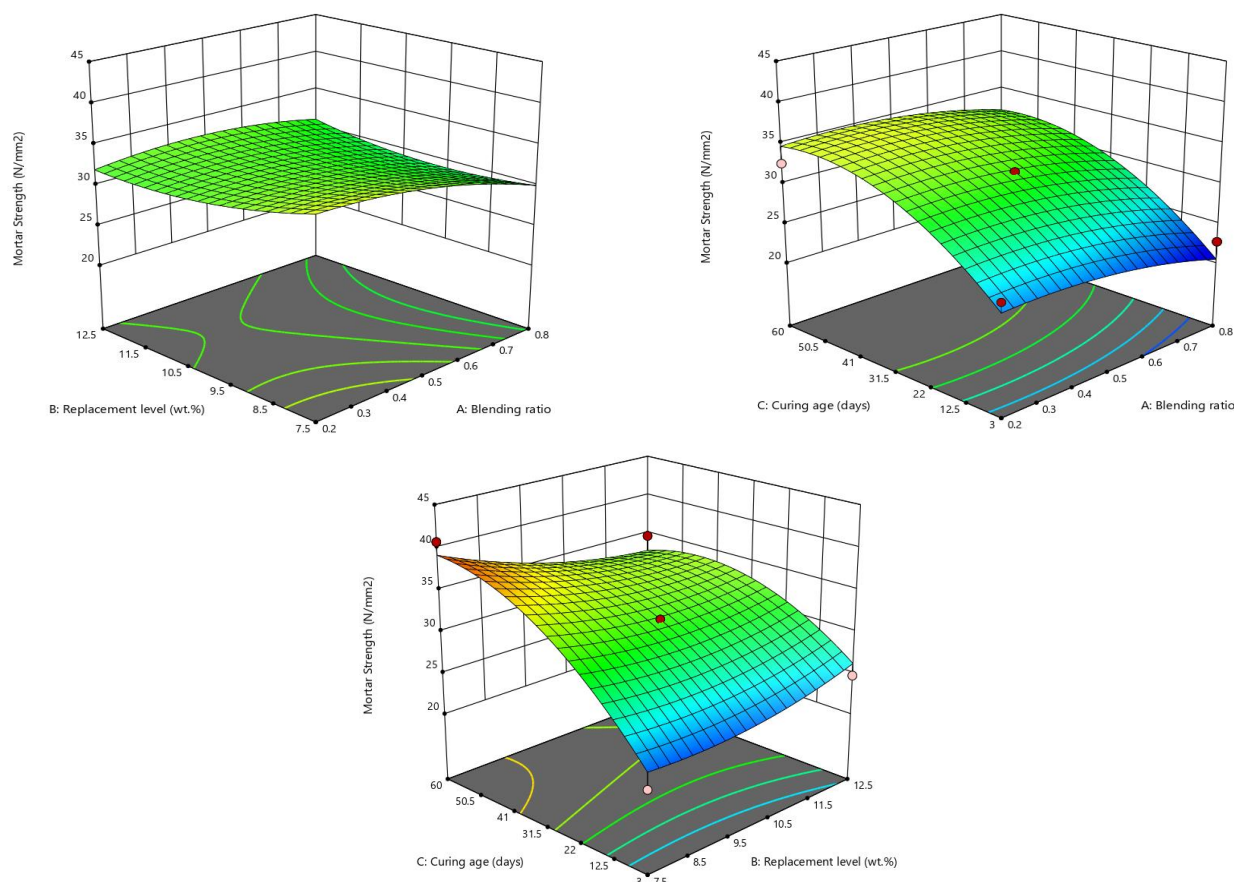


Figure 4 (a) Response surface for interaction on mortar strength of ABA-MK-cement blends between blending ratio and replacement (b): Response surface for interaction on mortar strength of ABA-MK-cement blends between blending ratio and curing age. (c) Response surface for interaction on mortar strength of ABA-MK-cement blends between replacement level and curing age via BBD.

Figures 4 and 5 depicts the response surface curves illustrating the interactive effects of the variables for CCD and BBD respectively. Figure 4 (a) indicates the response for the interactive factors: replacement level and binding ratio which shows that mortar strength increases when blending ratio increases between 0.2 – 0.5 at constant replacement level and curing age. However, it was observed that at higher blending ratio above 0.5 led to a reduction in the mortar strength of ternary cement blends. The maximum mortar strength was obtained at blending ratio of 0.5 for various replacement levels and all curing ages. Figure 4 (b) shows that the mortar strength decreases when the replacement level increase from between 7.5 – 12.5 wt.% at various blending

ratio especially for 60 days. However, at 3 days and 28 days results, the mortar strength diminished when the replacement level increase from 7.5 – 10 wt.% but between 10 – 12.5 wt.% experienced a slight increase in the strength but was lower than 7.5 wt.% strength. Figure 4 b and c show that an increase in mortar strength of cement blends as the curing age was increased at various replacement levels and binding ratios. This trend agrees with the fact that the time of hydration determine the rate of hydration of cement (Jarumi *et al.*, 2022; Olubajo *et al.*, 2020; Olubajo and Osha (2013), Olubajo (2017), Olubajo *et al.* (2020a); Olubajo *et al.* (2019); Olubajo *et al.* (2020b); Olubajo, 2020). The most significant factor being the curing age of the

cement blends and has a positive effect which could be related to the hydration reactions coupled with pozzolanic reactions stemming from silica present in MK and excess lime present. Thus, production of more CSH as the curing days progressed.

Figure 5 (a) indicates that the mortar strength of ABA-MK-PLC decreases as the blending ratio increases especially for 7.5 and 10 wt.% replacement level at various curing ages whereas at 12.5 wt.%, only 3 days mortar strength decreased as the blending ratio was increased while 28- and 60-days mortar strength experienced an increase at lower blending ratio and decrease at higher blending ratio. The 3 days mortar strength increases as the replacement level was increased between 7.5 and 12.5 wt.% for all blending ratios except 0.2. the exception experienced a decrease in the mortar strength followed by an increase. A similar trend was observed at 28 days mortar strength with

increase as replacement level was increased except for blending ratios of 0.2 and 0.4 while at 60 days mortar strength also experienced an increase except for blending ratios of 0.2, 0.4 and 0.5 respectively.

### 3.3 Optimal conditions for mortar strength predictions of ABA-MK cement blends

Optimization of the mortar strength of ABA-MK-cement blends were conducted and the optimal conditions were blending ratio of **0.423**, replacement level of **7.585** wt.% and curing age of approximately **60** days with a mortar compressive strength of **40.131** N/mm<sup>2</sup> with a desirability of **1.000** for CCD whereas BBD optimal conditions with blending ratio of **0.221** replacement level of **7.5** wt.%, curing age of **60** days and mortar compressive strength of **40.251** N/mm<sup>2</sup> and desirability of **0.977**. Figures 6 (a) – (c) depicts graphs of the effect of the interactions of the various factors as a function of mortar strength.

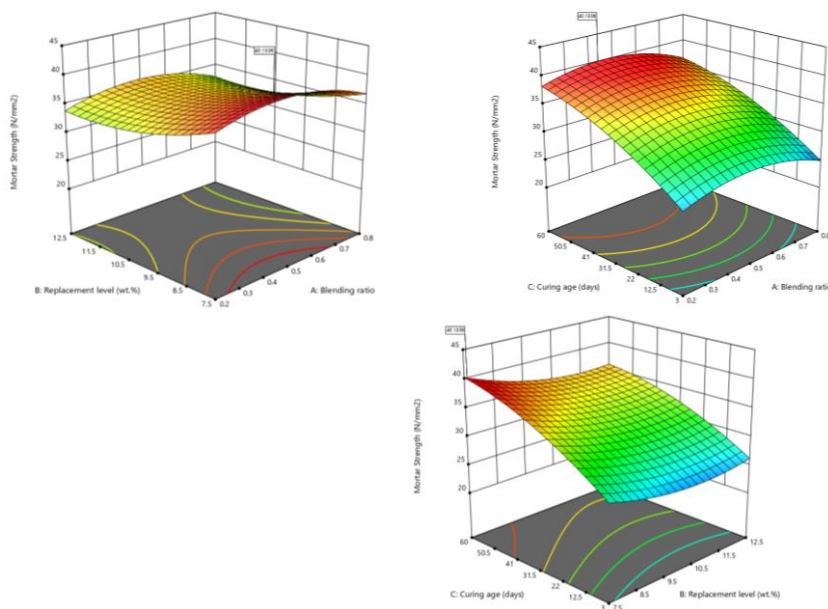


Figure 6 (a): Response surface indicating the optimal conditions for interaction on mortar strength of ABA-MK-cement blends between blending ratio and replacement level (b) Response surface indicating the optimal conditions for interaction on mortar strength of ABA-MK-cement blends between Blending ratio and curing age (c): Response surface indicating the optimal conditions for interaction on mortar strength of ABA-MK-cement blends between replacement level and curing age via. CCD.

#### 4. Conclusion

This work investigated the factors influencing the mortar strength of ABA-MK-PLC conducted at laboratory conditions. The use of response surface methodology via CCD was found to be most effective in the determination or prediction of the mortar strength of ternary cement blends within blending ratio 0 -1.0, replacement level 7.5 – 12.5 wt.% and curing age between 3 and 60 days. The process optimization was carried out using response surface methodology and the model equations for the strength prediction were obtained from 21 and 17 runs using full central composite design and box and Bekhen designs respectively with CCD being the most reliable. The optimum blending ratio, replacement level and curing age were 0.423, 7.565 wt.% and 60 days respectively producing the best strength of 40.131 N/mm<sup>2</sup>. Amongst the factors, the curing age significantly influenced the strength gain due to increase in the hydration reaction time during curing from 3 – 60 days. The model equation developed via CCD can adequately predict the mortar strength of ternary cement blended with ABA and MK between replacement level of 7.5 - 12.5 wt.%.

#### Competing interests

The authors declare that there are no competing interests.

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