

# Strength Prediction and Optimisation of Velvet Tamarind Pod Ash Cement Blends via Response Surface Methodology

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**Abstract.** This paper tries to provide a predictive model for determining the mortar compressive strength of Portland limestone cement blended with Velvet Tamarind Pod ash (VTPA) and eggshell powder (ESP). The mortar compressive strength of VTPA-ESP cement blends was determined according to experimental runs from Design Expert 13 using response surface methodology via Central Composite and Box-Benken designs, respectively. The factors considered include a blending ratio of 0.25–0.75, cement replacement of 2–6 wt.%, and curing age of 3 and 60 days, respectively. Model equations obtained using response surface methodology via CCD adequately predicted the mortar compressive strength for VTPA-ESP cement blends. The design comparison indicated that CCD produced a better prediction of the mortar strength of the ternary cement blends, which satisfied second-order polynomial regression. When researchers held the curing age and blending ratio constant and increased the cement replacement from 2 to 6 wt.%, they observed a slight increase in the mortar strength followed by a decrease. A similar trend was observed at various blending ratios as the curing age progressed from 3-60 days while the cement replacement and blending ratio was held constant, increasing the mortar strengths. When researchers held the curing age and cement replacement constant, they observed increased blending ratios. Results revealed that despite the diminution of the cement with either VTPA or ESP, the strength experienced either similar or better values than control, proving that pozzolanic activity was experienced. The mortar strength prediction was significantly influenced by the curing age for both CCD and BBD, with high F values for the curing age of 246.23 and 49.62, respectively. Researchers obtained the optimal conditions for predicting the mortar strength of VTPA-ESP-cement blends: blending ratio of 0.258, cement replacement of 3.20 wt.% and curing age of 59.23 days with a mortar strength of 44.93 N/mm<sup>2</sup> and desirability of 1.000 for CCD while the blending ratio of 0.283, cement replacement of 2.083 wt.%, curing age of 59.513 days and mortar compressive strength of 45.330 N/mm<sup>2</sup> and desirability of 1.000 BBD respectively.

**Keywords:** Strength Prediction; Optimisation; Velvet Tamarind Pod ash; Eggshell powder; blending ratio; Cement replacement; curing age.

## INTRODUCTION

Concrete or mortar primarily consists of binding materials: cementitious material, aggregates (fine or coarse), or water. Mortar is considered a three-phase composite material comprising a mixture of cement, aggregate, and water, which possesses various applications in the construc-

tion sector for infrastructural development, according to the authors [1, 2]. The study of sustainable construction materials has become necessary to mitigate the various environmental impacts caused by the construction and building industry. The enormous release of this agricultural waste presents a significant environmental challenge, with improper disposal methods lead-

ing to severe health and ecological issues. Velvet tamarind pod ashes and eggshells, often discarded as waste, contribute to this growing concern. These materials, if not managed correctly, can lead to the contamination of water bodies and create unsanitary conditions that pose health risks to communities. In addition to the environmental burden of waste, the high cost of cement production and its associated carbon dioxide emissions exacerbate the problem of global warming, according to authors [3]. Cement production accounts for approximately 7% of artificial greenhouse gas emissions globally, and the industry is actively researching and developing low-carbon technologies to reduce CO<sub>2</sub> emissions. This quest for sustainable construction materials has led to the intuition of various materials, such as agricultural and animal waste products that are environmentally eco-friendly, such as cement blends.

Velvet Tamarind (*Dialium guineense*), a leguminous tree found native to tropical regions of Africa, produces pod shells by authors [4], whose pods are typically discarded as agricultural waste. These pods are rich in fibrous materials that, when processed, may enhance the physical properties of cement composites, according to authors [5]. However, these shells are rich in silica and other fibrous minerals that could enhance the properties of cement. These minerals can improve mortar's mechanical strength and durability, serving as a sustainable waste management and resource utilisation solution. At the same time, eggshell powder ESP is considered a bio-waste material obtained from bakers and fast-food restaurants. These waste materials are generally disposed of in landfills, causing health hazards and polluting the environment. ESP is a common byproduct of the food industry, which has high amounts of calcium similar to the chemical composition of limestone and can be combined with pozzolanic materials, especially ashes, which contain high silica content. Researchers can process eggshell waste into a fine powder as a supplementary cementitious material (SCM). Including eggshell powder (ESP) in cement blends can enhance the hydration process and improve the material's microstructure, increasing compressive strength [6].

Various research scholars have discovered calcium and silica-containing materials (ESP and VTPA), and efforts are being made to experimentally investigate concrete's behaviour with partial cement replacement by those materials authors

[7, 8]. Surprisingly, the strength characteristics of mortar increased with the partial replacement of cement in mortar compared to conventional mortar, according to authors [8, 9]. There are many advantages to the use of cement replacement materials in mortars; the major one is a reduction in cement quantity for concrete production by the author [10], minimising environmental pollution by authors [11, 12], prediction of strengths utilising response surface methodology RSM to evaluate the effect of materials blended with cement which has shown various success outcome ranging from multiple studies such as; fly ash-limestone cement blend [9], coal bottom ash-limestone [13] saw dust ash- eggshell powder [14] and metakaolin and animal bone ash [15] etc. Strength prediction is essential in determining the load structures can withstand, which is a unique property in assessing the quality of material employed [14]. RSM technique has been successful in optimisation techniques and is an essential tool for evaluating the significance of response as a function of various factors. The strength prediction is considered a response, while the factors considered include curing age, cement replacement, and blending ratio.

This study investigated the effect of agricultural waste (velvet tamarind pod ash) and poultry waste materials (eggshell powder) on the mortar strength employing Response Surface Methodology via Box-Behnken Design and Central Composite Designs, respectively, stands as an innovative approach to sustainable material quest which enhances construction materials.

## METHOD

The design summary for the dependent variables is the mortar strengths via CCD and BBD models with curing age, blending ratio and cement replacement as independent variables. The independent variables were chosen as curing age lower, middle and upper limits are denoted as three days, 28 days, 60 days blending ratio lower, middle and upper limits are denoted as 0.25, 0.50, 0.75; cement replacement lower, middle and upper limits denoted by two wt.%, four wt.%, six wt.% respectively. Face central composite factorial design comprising of 3 levels and three factors with Design Expert 13 where -1 denotes the low value of the independent variable (3 days, 0.25, 2 wt.%), 0 used for the medium value (28 days, 0.5, 4 wt.%) and the high value (60 days, 0.75, 6 wt.%) were employed to inves-

tigate the effect of the above factors on the responses. Researchers fitted a model to the response surface generated by the experiment.

$$S_k = f(\text{Curing age, Blending ratio, Cement replacement}) \tag{1}$$

Researchers used Design Expert 13 software to obtain the best-fit data and estimate the optimal conditions for mortar strength. RSM was used to determine the optimal factors to obtain maximum strength via CCD BBD, and the interaction of variables was estimated. 14 and 12 runs were carried out to fit the general model of Equations 1 for CCD and BBD, respectively, and to obtain optimum conditions for curing age, blending ratio and cement replacement for the optimum mortar strength of the cement blend.

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

where  $S_i$  denotes the mortar strength of VTPA-ESP 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  $S_2$  denote mortar strength from CCD and BBD, respectively, while  $A_1$  is curing age in days,  $A_2$  is VTPA/VTPA-ESP ratio as blending ratio which is dimensionless, and  $A_3$  is cement replacement in wt.% and Table 1 presents the experimental results obtained from the determination of the mortar compressive strength of cement blended with VTPA and ESP based on the design of experiment via RSM for CC and BB designs to investigate its effect of curing age, mixing ratio and cement replacement on the mortar strength of VTPA-ESP cement blends respectively. The researchers used the ANOVA method to statistically analyse the results, estimating the model and presenting its parameters in Table 2. In the predictive model for the determination of the mortar strength of VTPA-ESP-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 the 3D surface were obtained to describe the individual and interactive effect of the factors.

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

Curing age days $A_1$	Blending ratio $B_1$	Cement replacement wt.% $C_1$	Mortar strength $N/mm^2$ $S_1$	Curing age days $A_2$	Blending ratio $B_2$	Cement replacement wt.% $C_2$	Mortar strength $N/mm^2$ $S_2$
60	0.25	6	38.39	60	0.25	4	44.16
3	0.75	6	14.7	60	0.5	2	40.52
3	0.5	4	18.96	28	0.75	6	28.16
60	0.5	4	42.9	28	0.75	2	39.38
28	0.25	4	38.76	3	0.5	6	17.00
28	0.75	4	33.31	60	0.5	6	37.54
3	0.75	2	17.74	28	0.25	2	35.36
28	0.5	2	30.94	3	0.75	4	16.41
60	0.75	6	37.5	28	0.25	6	30.40
28	0.5	6	30.69	60	0.75	4	39.12
3	0.25	6	14.8	3	0.25	4	19.02
3	0.25	2	22.53	3	0.5	2	18.06
60	0.75	2	44.44				
28	0.5	4	36.3				

The models employed include Central composite design (CCD) and Box & Behnken design (BBD) to predict the mortar strength of ternary cement blends comprising PLC, VTPA, and ESP. The in-

dependent variables include Curing age, denoted by C; blending ratio (VTPA/VTPA-ESP ratio), denoted by B; cement replacement, denoted by C and 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 was determined using Design Expert 13. The resultant equations were obtained from the ANOVA for strength prediction for the VTPA-ESP-cement blend using CCD and BBD models, respectively:

$$S_1 = 16.858 + 0.764A - 32.715B + 6.195C + 0.109AB - 0.002AC + 0.5BC - 0.0063A^2 + 23.58B^2 - 0.937C^2 \quad (3)$$

$$S_2 = 25.701 + 0.388A - 2.935B - 1.264C \quad (4)$$

Equations 3 and 4 signify the quantitative effect of the independent variables such as Curing age, blending ratio and Cement replacement (A, B, C)

as well as their interactions with the response; mortar strength from CCD while BBD had no interactions ( $S_1, S_2$ ). 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 CCD and BBD models significantly satisfied quadratic and linear models based on the experimental design and factor interaction.

Table 2 tabulates the analysis of variance ANOVA for strength prediction of VTPA-ESP-PLC from CCD and BBD. It observes that the F values for the above models  $S_1$  and  $S_2$  for CCD and BBD designs were significant. Thus, there is a 0.01% chance that the model has a significant F value of 30.70 and 17.47, respectively, which could occur due to noise.

Table 2 – ANOVA for Response Surface Quadratic Model Analysis of Variance for Mortar Strength Prediction of VTPA-ESP cement blend via CC and BB designs

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1541.10	9	171.23	30.70	0.0008	Significant
A	1372.18	1	1372.18	246.05	< 0.0001	Significant
B	8.53	1	8.53	1.53	0.2711	
C	49.42	1	49.42	8.86	0.0309	Significant
AB	4.85	1	4.85	0.8695	0.3939	
AC	0.1089	1	0.1089	0.0195	0.8943	
BC	0.5000	1	0.5000	0.0897	0.7767	
A <sup>2</sup>	65.83	1	65.83	11.80	0.0185	Significant
B <sup>2</sup>	5.59	1	5.59	1.00	0.3629	
C <sup>2</sup>	36.09	1	36.09	6.47	0.0517	Significant
Residual	27.88	5	5.58			
Cor Total	1568.99	14				
Model	1039.45	3	346.48	17.47	0.0004	Significant
A	984.04	1	984.04	49.62	< 0.0001	Significant
B	4.31	1	4.31	0.2172	0.6522	
C	51.11	1	51.11	2.58	0.1429	
Residual	178.47	9	19.83			
Cor Total	1217.91	12				

Table 3 illustrates the model fit statistics for both models employed in the strength prediction of VTPA-ESP-cement blends. The Predicted  $R^2$  value (0.7846) and Adjusted  $R^2$  value (0.9502) for the CCD model were close to unity compared with BBD with Predicted  $R^2$  value (0.7098) and Adjusted  $R^2$  value (0.8047). The first model was the most suitable for describing the mortar strength for cement blends between 2–6 wt. % cement replacement. Both models produced adequate precision ratios, indicating a desirable signal more significant than 4 [13, 14, 16]. The model's

fit was checked with the coefficient of determination  $R^2$ , which indicated that the model could explain 98.22 % of the response variability. The result suggested that the model can be considered statistically significant according to the F test with 95% confidence as the F-value of 30.70.

It could also be seen from Table 3 that strength prediction via CCD and BBD produced  $R^2$  values greater than 80% except for predicted  $R^2$  values, as several researchers suggested that a fitted model with  $R^2$  more than 80% was considered acceptable but not lower than 75% while the ex-

pected values for the developed models should have a reasonable correlation with the experimental data [14, 17, 18].

Table 3 – Model Fit Statistics for CCD and BBD for strength prediction of VTPA-ESP cement blends

Source	CCD	BBD
Sum of Squares	1541.10	1039.45
DF	<b>9</b>	3
Mean square	<b>171.23</b>	346.48
F-value	<b>30.70</b>	17.47
Prob> F	<b>0.0008</b>	0.0004
Std. Dev.	<b>2.36</b>	4.45
R <sup>2</sup>	<b>0.9822</b>	0.8535
Adj. R <sup>2</sup>	<b>0.9502</b>	0.8046
Pred. R <sup>2</sup>	<b>0.7846</b>	0.7098
PRESS	<b>337.82</b>	353.42

Results indicated that CCD is the most suitable for predicting the strength of Portland limestone cement blended with VTPA and ESP. The regression values and adjusted regression values for CCD and BBD were 0.9822 and 0.9502, 0.8535 and 0.8046, respectively, demonstrating the developed model's appropriateness to predict the mortar compressive strength for VTPA-ESP-cement blends by their R<sup>2</sup> and R<sup>2</sup><sub>adj</sub> value near one by authors [19, 20] suggested that to find the most reliable empirical equation which fits the experimental data and is considered adequate when the regression value is close to unity, which may not necessarily suggest that the model is sufficient if the regression value is relatively high. They indicated that an 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 variables via CCD compared to BBD.

The ANOVA on the experimental results for the prediction of the mortar strength of VTPA-ESP-cement blends indicated that the quadratic equation satisfies the first response, and the regression was statistically significant, evident by high F value for the model, primarily via CCD (30.70) in comparison with BBD (17.47). The ANOVA results for the prediction of the mortar strength of VTPA-ESP-cement blends for CCD (S<sub>1</sub>) presented in Table 4 indicated that the model terms considered to be significant include A1, C1, A12, and C12, while the other model terms having values greater than 0.10 were considered insignificant.

Meanwhile, the model terms are deemed significant for predicting the mortar strength of VTPA-ESP cement blends via BBD (S<sub>2</sub>), including only A<sub>2</sub>. The curing age (C) had a substantial F-value of 246.05 and 49.62; blending ratio (A) had an F-value of 1.53 and 0.2172; cement replacement (B) produced an F value of 8.86 and 2.58 for mortar strength via CCD and BBD models respectively. The quadratic term for interaction of the factors and the quadratic term for blending ratio independently affect the model for the prediction of mortar strength of VTPA-ESP- PLC was found to be insignificant, evident by the low F values, 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 cement replacement independently fell within  $p < 0.05$  or  $p < 0.10$  for CCD and were considered significant, respectively. In predicting the mortar strength of VTPA-ESP cement blends, researchers found that the curing age was the only considerable term, while all other terms were insignificant for BBD. This significantly high F-value of curing age from the ANOVA result strongly indicates that the curing age substantially influences the mortar strength of VTPA-ESP-cement blends compared with other factors, such as blending ratio and cement replacement. The CCD model showed that the lack of fit was statistically insignificant.

*Relationship between Experimental and Predicted Strength values.* Figures 1a and b indicate a strong correlation between experimental (actual) and predicted mortar strength values for VTPA-ESP-cement blends for CCD and BBD, respectively.

The model equation obtained from Design Expert 13 for predicting the mortar strength for the VTPA-ESP cement blend was significantly adequate for CCD compared with BBD. The diagnostic statistics indicating the variance between the predicted and the actual values in predicting the mortar strength for VTPA-ESP cement blends via CCD and BBD are presented in Table 4 below.

*Three-dimensional Surface Graphs.* The relationship between the response, i.e., mortar strength of VTPA-ESP-cement blend and the factors such as curing age, blending ratio and cement replacement, were represented by three-dimensional surface graphs.

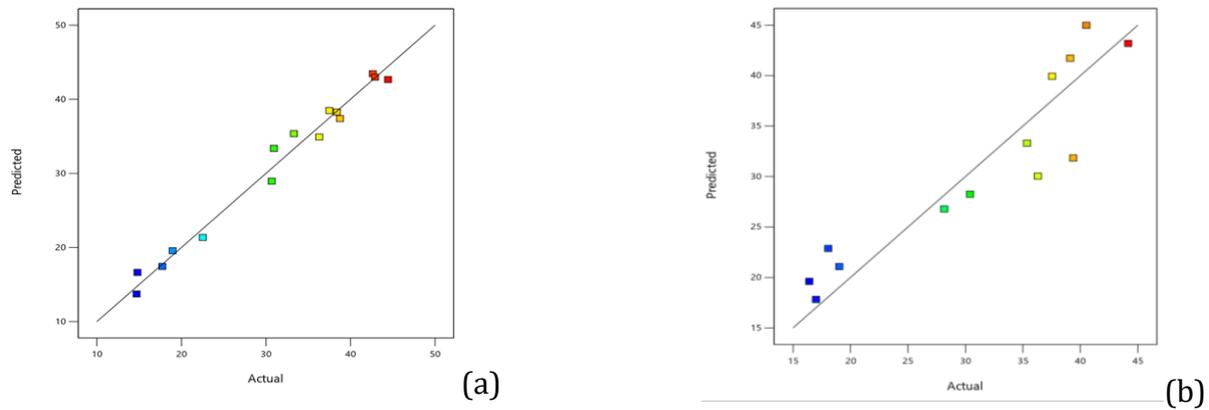


Figure 1 – (a) Predicted against the actual plot of the model developed for mortar strength via CCD  
 (b) Predicted against the actual plot of the model developed for mortar strength via BBD

Table 4 – Diagnostic Case Statistics for mortar strength of VTPA-ESP -cement blends for CCD and BBD.

Curing age, days, A	Blending ratio, B	Cement replacement, wt.%, C	Actual value, N/mm <sup>2</sup> C.C.D.	Predicted Value, N/mm <sup>2</sup> C.C.D.	Blending ratio, A	Cement replacement wt.%, B	Curing age days C	Actual value, N/mm <sup>2</sup> B.B.D.	Predicted Value, N/mm <sup>2</sup> B.B.D.
60	0.25	6	38.39	38.28	60	0.25	4	44.16	43.19
3	0.75	6	14.70	13.73	60	0.5	2	40.52	44.99
3	0.5	4	18.96	19.56	28	0.75	6	28.16	26.78
60	0.5	4	42.90	42.99	28	0.75	2	39.38	31.84
28	0.25	4	38.76	37.40	3	0.5	6	17.00	17.82
28	0.75	4	33.31	35.36	60	0.5	6	37.54	39.93
3	0.75	2	17.74	17.45	28	0.25	2	35.36	33.30
28	0.5	2	30.94	33.37	3	0.75	4	16.41	19.61
60	0.75	6	37.50	38.48	28	0.25	6	30.40	28.25
28	0.5	6	30.69	28.95	60	0.75	4	39.12	41.73
3	0.25	6	14.80	16.64	3	0.25	4	19.02	21.08
3	0.25	2	22.53	21.35					
60	0.75	2	44.44	42.66					
28	0.5	4	36.30	34.91					

Figures 2–5 depict the diagnostic graphs which determine the regression model adequacy, indicating the response surface graphs for the influence of factors A (Curing age), B (blending ratio), and C (cement replacement) on the first response S<sub>1</sub> (mortar strength of cement blend via CCD), second response S<sub>2</sub> (mortar strength of cement blend via BBD) respectively. These response surface curves demonstrate the interactions between the various factors and the determination of the optimum for the multiple factors to obtain maximum response. According to authors [14, 21, 22], the parabolic nature of 3D is seen for CCD, implying that the interaction between both factors is significant, as indicated in Figure 4. From the regression equation, the most critical parameters influencing the prediction of the

mortar strength of VTPA-ESP-cement blends in the order are curing age C, cement replacement 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 complete factorial Central composite design and Box and Behken design were fitted into equations 3 and 4, respectively. According to ANOVA, the curing age and cement replacement are the most significant variables, with the effect of curing age (246.05) and the impact of cement replacement (8.86) followed by the quadratic term of curing age (11.80) and cement replacement (6.94) respectively.

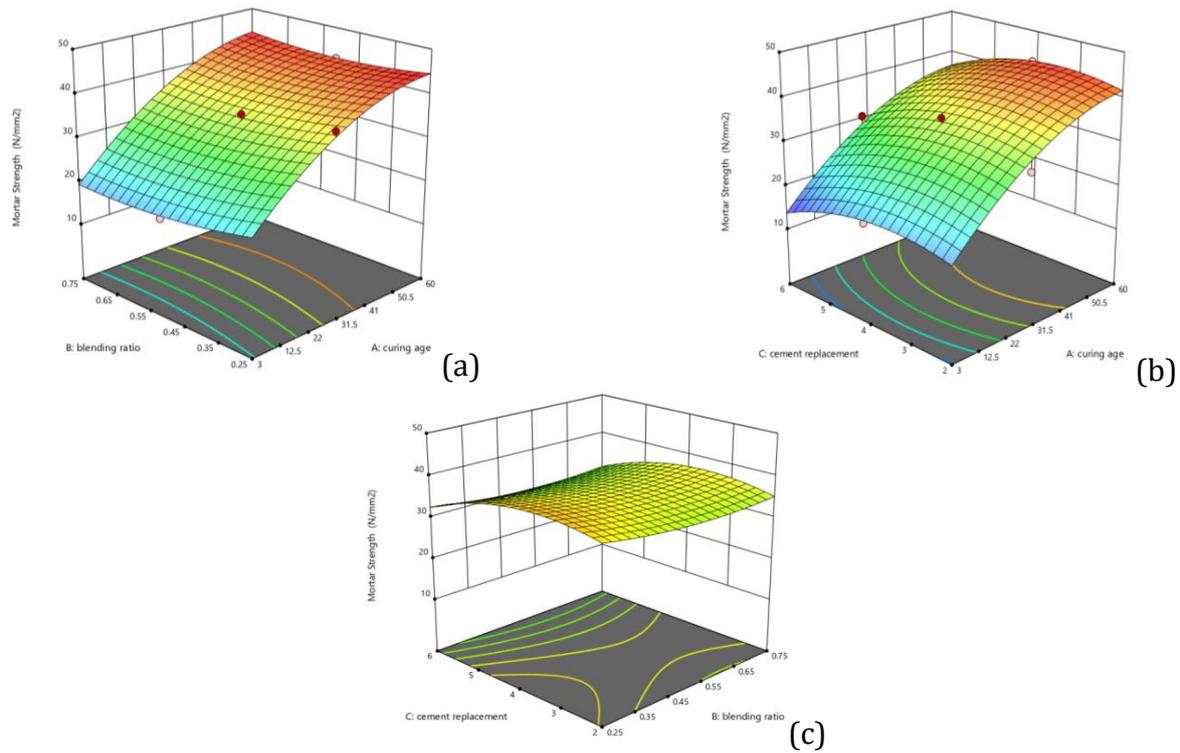


Figure 3 – (a) Response surface graph for interaction on mortar strength of VTPA-ESP-cement blends between blending ratio and curing age; (b) Response surface graph for interaction on mortar strength of VTPA-ESP-cement blends between cement replacement and curing age; (c) Response surface graph for interaction on mortar strength of VTPA-ESP-cement blends between blending ratio and cement replacement via CCD

Figures 3 and 4 depict the response surface curves illustrating the interactive effects of the variables for CCD and BBD, respectively. Figure 3a indicates the response for the interactive factors: increased blending ratio and curing age increased mortar strength when the cement replacement was constant at 2, 4 and 6 wt.%, respectively. Figure 3b shows that the mortar strength increased when the cement replacement was increased between 2–6 wt.% with increased curing age at constant blending ratios. This trend agrees that the hydration time determines the cement hydration rate by authors [6, 8, 13, 15, 17, 23]. The most significant factor is the curing age of the cement blends. It has a positive effect, which could be related to the hydration reactions coupled with pozzolanic reactions stemming from silica present in VTPA and excess lime present. Thus, the production of more CSH as the curing days progressed. Figure 3c shows a decrease in the mortar strength of cement blends, experienced as the blending ratio and cement replacement increased while the curing age was constant. It was also observed that the three factors were increased simultaneously, increasing the mortar compressive strength of the various cement blends. As the curing age pro-

gressed, the blending ratio and cement replacement were constant, which increased mortar strength. Similarly, when the curing age and cement replacement were held constant while the blending ratio was increased, it led to a reduction in the mortar strength. However, as the blending ratio and curing age were held constant while the cement replacement was increased, the mortar strength experienced an increase between 2–4 wt.% followed by a reduction between 4–6 wt.%, respectively.

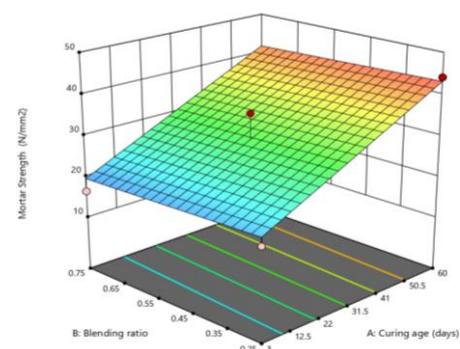


Figure 4 –Response surface for interaction on mortar strength of VTPA-ESP-cement blends between blending ratio and curing age via BBD

Figure 4a suggests that as the curing age progressed while the blending ratio and cement replacement were held constant for BBD, the mortar compressive strength of VTPA-ESP-PLC increased. This increase in mortar strength could be due to the progress of the hydration of the VTPA-ESP cement blends as the curing age was increased. It was also observed that an increase in the blending ratio while curing age and cement replacement decreased mortar strength. A similar trend of reducing strength was observed as the cement replacement was increased while the curing age and blending ratio were held constant. An increase in the blending ratio implies an increase in the VTPA content compared to the ESP at a given cement replacement. This decrease could be attributed to the presence of unburnt

carbon in the ash, resulting in a high water requirement and a reduction in strength.

*Optimal conditions for mortar strength predictions of VTPA-ESP cement blends.* Optimisation of the mortar strength of VTPA-ESP-cement blends was conducted. The optimal conditions were a blending ratio of 0.258, cement replacement of 3.20 wt.% and curing age of 59.23 days with a mortar compressive strength of 44.93 N/mm<sup>2</sup> with desirability of 1.000 for CCD, whereas BBD optimal conditions with a blending ratio of 0.283 cement replacement of 2.083 wt.%, curing age of 59.513 days and mortar compressive strength of 45.330 N/mm<sup>2</sup> and desirability of 1.000. Figures 5 (a)–(c) depict graphs of the effect of the interactions of the various factors as a function of mortar strength.

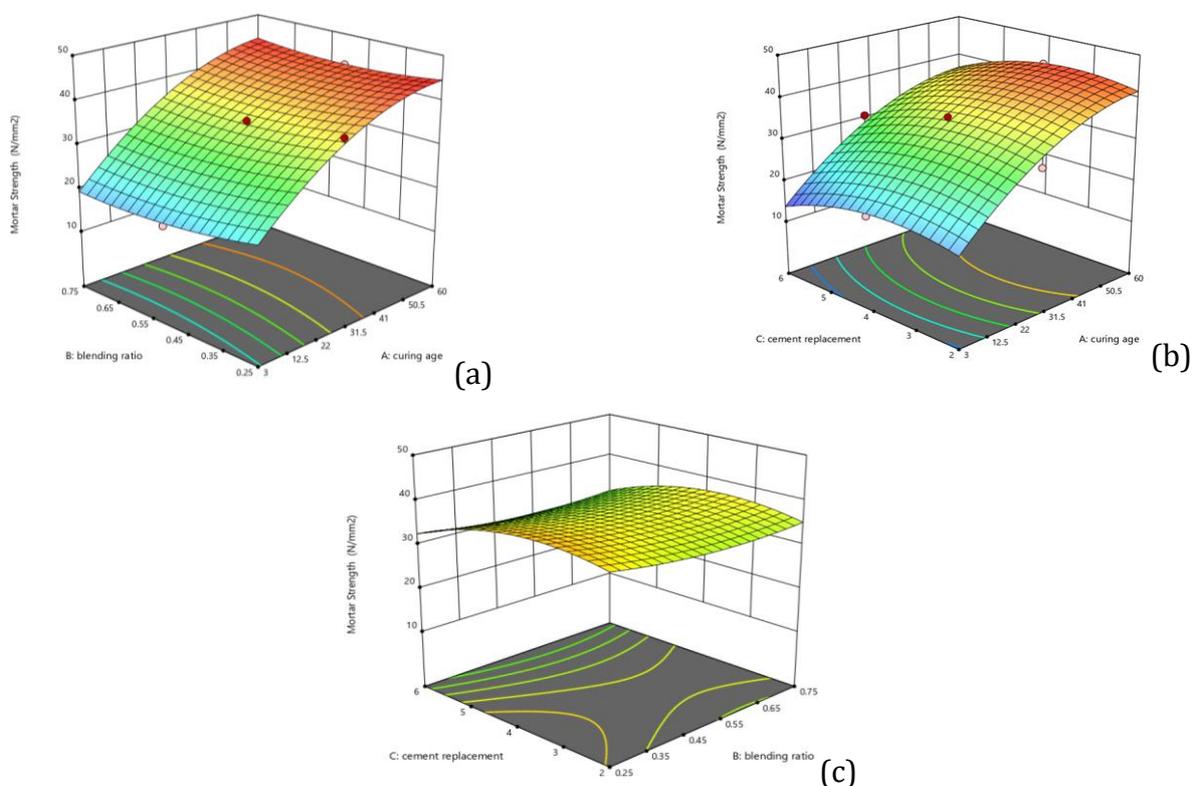


Figure 5 – (a) Response surface indicating the optimal conditions for interaction on mortar strength of VTPA-ESP-cement blends between blending ratio and curing age; (b) Response surface indicating the optimal conditions for interaction on mortar strength of VTPA-ESP-cement blends between cement replacement and curing age (c) The response surface indicates the optimal conditions for interaction on mortar strength of VTPA-ESP-cement blends between cement replacement and blending ratio via CCD

## CONCLUSIONS

This work investigated the factors influencing the mortar strength of VTPA-ESP-PLC conducted under laboratory conditions. The use of response surface methodology via CCD was found to be most effective in determining or predicting the

mortar strength of ternary cement blends within blending ratio 0.25–0.75, cement replacement 2–6 wt.% and curing age between 3 and 60 days. The process optimisation was carried out using response surface methodology, and the model equations for the strength prediction were obtained from 14 and 12 runs using complete cen-

tral composite design and box and Behnken designs, respectively, with CCD being the most reliable. The optimum blending ratio, cement replacement and curing age were 0.259, 3.795 wt.% and 56.72 days, respectively, producing the best strength of 44.58 N/mm<sup>2</sup>. Amongst these factors, curing age significantly influences strength gain due to an increase in the hydration reaction time during curing, which is from 3 to 60 days. The model equation developed via CCD can adequately predict the mortar strength of ternary cement blended with VTPA and ESP between cement replacement of 2-6 wt.%.

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## Conflict of interest

The authors declared that they have no conflict of interest.

## REFERENCES

1. Sahu, A., Kotecha, K. D., Mire, A., & Singh, L. (2020). The Effect Of Ground Granulated Blast Furnace SLAG As On Alternative Cement Replacement Material In Concrete After 28 Days Strength. *International Journal of Innovations in Engineering and Science*, 5(9), 28. doi: [10.46335/ijies.2020.5.9.5](https://doi.org/10.46335/ijies.2020.5.9.5)
2. Ouyang, H., & Chen, X. (2020). 3D Meso-Scale Modeling Of Concrete With A Local Background Grid Method. *Construction and Building Materials*, 257, 119382. doi: [10.1016/j.conbuildmat.2020.119382](https://doi.org/10.1016/j.conbuildmat.2020.119382)
3. Izumi, Y., Iizuka, A., & Ho, H. (2021). Calculation Of Greenhouse Gas Emissions For A Carbon Recycling System Using Mineral Carbon Capture And Utilization Technology In The Cement Industry. *Journal of Cleaner Production*, 312, 127618. doi: [10.1016/j.jclepro.2021.127618](https://doi.org/10.1016/j.jclepro.2021.127618)
4. Chimsah, F. A., Nyarko, G., & Abubakari, A. (2020). A Review Of Explored Uses And Study Of Nutritional Potential Of Tamarind (*Tamarindus Indica L.*) In Northern Ghana. *African Journal of Food Science*, 14(9), 285–294. doi: [10.5897/ajfs2018.174](https://doi.org/10.5897/ajfs2018.174)
5. Auta, I. B., Abdulkarim, I. I., & Olu, O. O. (2023). Effect of Date Palm Seed Pod Ash and Eggshell Powder on the Physico-Mechanical Properties of Cement Blends. *American Journal of Science, Engineering and Technology*. doi: [10.11648/j.ajset.20230801.11](https://doi.org/10.11648/j.ajset.20230801.11)
6. Olubajo, O. O., Makarfi, I. Y., Ibrahim, M. S., Ayeni, S., & Uche, N. W. (2020b). A Study on Ordinary Portland Cement Blended with Rice Husk Ash and Metakaolin. *Path of Science*, 6(1), 3001–3019. doi: [10.22178/pos.54-4](https://doi.org/10.22178/pos.54-4)
7. Raheem, A. A., Olasunkanmi, B. S., & Folorunso, C. S. (2012). Saw Dust Ash As Partial Replacement For Cement In Concrete. *Organization Technology and Management in Construction an International Journal*, 4(2). doi: [10.5592/otmcj.2012.2.3](https://doi.org/10.5592/otmcj.2012.2.3)
8. Olu, O. O. (2020). Effect Of Saw Dust Ash And Eggshell Powder On The Properties Of Cement Blends. *American Journal of Construction and Building Materials*, 4(2), 88. doi: [10.11648/j.ajcbm.20200402.16](https://doi.org/10.11648/j.ajcbm.20200402.16)
9. De Weerd, K., Haha, M. B., Saout, G. L., Kjellsen, K., Justnes, H., & Lothenbach, B. (2011). Hydration Mechanisms Of Ternary Portland Cements Containing Limestone Powder And Fly Ash. *Cement and Concrete Research*, 41(3), 279–291. doi: [10.1016/j.cemconres.2010.11.014](https://doi.org/10.1016/j.cemconres.2010.11.014)
10. Scherer, C., Felippi de Lima, L., & Eunice Zorzi, J. (2023). Effect of partial replacement of cement by fine powders on the corrosion resistance of concrete. *Construction and Building Materials*, 401, 132982. doi: [10.1016/j.conbuildmat.2023.132982](https://doi.org/10.1016/j.conbuildmat.2023.132982)

11. Hamada, H. M., Tayeh, B. A., Al-Attar, A., Yahaya, F. M., Muthusamy, K., & Humada, A. M. (2020). The Present State Of The Use Of Eggshell Powder In Concrete: A Review. *Journal of Building Engineering*, 32, 101583. doi: [10.1016/j.jobe.2020.101583](https://doi.org/10.1016/j.jobe.2020.101583)
12. Kumar, P., Sreelekshmi, K., Anjana, S., Harikrishnan, S., Santhanu, G., & Leena, V. (2020). Role Of Agricultural Wastes In Construction Industry. *International Journal of Engineering Research And*, V9(03). doi: [10.17577/ijertv9is030127](https://doi.org/10.17577/ijertv9is030127)
13. Olubajo, O. O., Osha, O. A., El-Natafy, U., & Adamu, H. (2017). *A Study On Coal Bottom Ash And Limestone Effects On The Hydration And Physico-Mechanical Properties Of Ternary Cement Blends* (Thesis; Abubakar Tafawa Balewa University).
14. Gubio, K. B., Ismail, M. M., & Olu, O. O. (2022). Effect Of Quartz Particle Size and Cement Replacement on Portland Limestone Cement properties. *Journal of Building Material Science*, 4(2), 16–25. doi: [10.30564/jbms.v4i2.5091](https://doi.org/10.30564/jbms.v4i2.5091)
15. Luka, J., Olubajo O. O., & Abuthakir, I. (2022). *A Study on Portland Limestone Cement Blended with Animal Bone Ash and Metakaolin*. *American Journal of Chemical Engineering*, 10(3), 103-115.
16. Koocheki, A., Taherian, A. R., Razavi, S. M. A., & Bostan, A. (2009). Response Surface Methodology For Optimisation Of Extraction Yield, Viscosity, Hue And Emulsion Stability Of Mucilage Extracted From Lepidium Perfoliatum Seeds. *Food Hydrocolloids*, 23(8), 2369–2379. doi: [10.1016/j.foodhyd.2009.06.014](https://doi.org/10.1016/j.foodhyd.2009.06.014)
17. Olubajo, O. O., Makarfi, I. Y., & Odey, O. A. (2019). Prediction Of Loss On Ignition Of Ternary Cement Containing Coal Bottom Ash And Limestone Using Central Composite Design. *Path of Science*, 5(8), 2010–2019. doi: [10.22178/pos.49-3](https://doi.org/10.22178/pos.49-3)
18. Chauhan, B., & Gupta, R. (2004). Application Of Statistical Experimental Design For Optimisation Of Alkaline Protease Production From Bacillus Sp. RGR-14. *Process Biochemistry*, 39(12), 2115–2122. doi: [10.1016/j.procbio.2003.11.002](https://doi.org/10.1016/j.procbio.2003.11.002)
19. Zaibunnisa, A., Norashikin, S., Mamot, S., & Osman, H. (2009). An Experimental Design Approach For The Extraction Of Volatile Compounds From Turmeric Leaves (*Curcuma Domestica*) Using Pressurised Liquid Extraction (PLE). *LWT*, 42(1), 233–238. doi: [10.1016/j.lwt.2008.03.015](https://doi.org/10.1016/j.lwt.2008.03.015)
20. Arsenovic, M., Pezo, L., & Radojevic, Z. (2012). Response surface method as a tool for heavy clay firing process optimisation: Roofing tiles. *Processing and Application of Ceramics*, 6(4), 209–214. doi: [10.2298/pac1204209a](https://doi.org/10.2298/pac1204209a)
21. Dockery, G. (2017). *The Effect Of Temperature On Activation Energy*. Retrieved from <https://sciencing.com/effect-temperature-activation-energy-5041227.html>
22. Silva, G. F., Camargo, F. L., & Ferreira, A. L. (2011). Application Of Response Surface Methodology For Optimisation Of Biodiesel Production By Transesterification Of Soybean Oil With Ethanol. *Fuel Processing Technology*, 92(3), 407–413. doi: [10.1016/j.fuproc.2010.10.002](https://doi.org/10.1016/j.fuproc.2010.10.002)
23. Olubajo O. O., M. Eng, M., & Osha, O.A. (2013). *Influence of Bottom Ash and Limestone Powder on the Properties of Ternary Cement and Mortar*. *International Journal of Engineering Research & Technology (IJERT)*, 2(7).