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Mixture Experiment Models for Predicting the Compressive Strength and Water Absorption of Sand-Quarry Dust Blocks

C. U. Anya[1], N. N. Osadebe[2]
[1] *Federal University of Technology, Owerri, Nigeria*
[2] *University of Nigeria, Nsukka*

ABSTRACT

Partial replacement of sand with quarry dust in sandcrete block production is gaining grounds in Nigeria. Much effort and resources are spent in conducting trial tests to determine the mix proportions to achieve desired properties of the blocks. In this work, mixture experiment models for predicting the compressive strength and water absorption of sand-quarry dust blocks to meet the Nigerian Industrial standard minimum requirements for machine vibrated load bearing sandcrete blocks were formulated using augmented Scheffe's {4, 2} simplex lattice design. The models were tested for lack of fit and were found adequate. The compressive strength model can predict strength ranging from 2.74 to 5.22Nmm^{-2} *while the water absorption model can predict water absorption ranging from 3.21 to 7.84%. The use of the models can help in determining mixes that meet the minimum compressive strength requirement as well the maximum water absorption of the blocks.*

Keywords: *Compressive strength, Water absorption, Mixture experiment models, Sand-Quarry dust blocks, Augmented Scheffe's simplex lattice design.*

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I. INTRODUCTION

Sand-quarry dust blocks are produced by partially replacing river sand with quarry dust in the production of sandcrete blocks. Sandcrete blocks which are obtained by mixing river sand, Ordinary Portland cement and water in appropriate proportions are the major units for wall construction in modern day Nigeria. Sandcrete differs from concrete by the non-inclusion of coarse aggregate in the mix and from cement-sand mortar by its zero slump. Sandcrete is often referred to as a zero slump concrete. The need for the partial replacement of sand with quarry dust has arisen from two major considerations namely: (i) to reduce the need for the use of river sand, thus preventing environmental degradation arising from excessive sand mining and (ii) to provide additional use for quarry dust, a waste product of rock quarrying process which, if left to accumulate in large volumes, is hazardous to the environment.

Works by Oyekan and Kamiyo, (2008) and Anya (2015) show that the inclusion of quarry dust in the production of sandcrete blocks improved the compressive strength and water absorption properties of the blocks. It is now common practice by some block producers in Nigeria to partially replace sand with quarry dust in sandcrete block production. Such producers are confronted with the problem of proportioning the constituents to meet the desired properties of the blocks, notably the compressive strength and water absorption, as there are no existing models for predicting the structural properties of sand-quarry dust blocks. Much effort and resources are spent in conducting trial tests to determine the mix proportions to achieve a desired value of compressive strength and water absorption. There is therefore the need to develop models that can predict the structural characteristics of sand-quarry dust mixes, especially the compressive strength of sand-quarry dust blocks. Such models can also be used to study the component interactions through the use of Cox or Piepel response trace plots. In this work, mixture experiment models for predicting the compressive strength and water absorption of sand-quarry dust blocks were developed using Scheffe's augmented simplex lattice design.

II. MIXTURE EXPERIMENTS AND SCHEFFE'S CANONICAL EQUATION

A mixture experiment is one in which the response is assumed to be dependent on the relative proportions of the constituent materials and not on their total amount (Cornell, 2001). For such experiments, there are two basic requirements that must be satisfied namely; the sum of the proportions of the constituents must add up to one and none of the constituents will have a negative value.

Many mixture experiment model forms exist of which one of the most popular is Scheffe's simplex lattice design. Scheffe (1958) obtained the so called canonical form of the polynomial equation for such designs, which for a second degree polynomial is given as:

$$Y = \sum_{1 \le i \le q} \beta_i X_i + \sum_{1 \le i \le j \le q} \beta_{ij} X_i X_j \quad (1)$$

Y is the response function and X_i ($i = 1$ to q) is the proportion of component i in the mixture. The second degree polynomial is the most commonly used polynomial to fitting mixture experiment data. For a four component mixture, equation (1) can be written as:

$$Y = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{34} X_3 X_4 \quad (2)$$

The estimated coefficients in equation (1) are determined after a mixture regression analysis of the experimental data. The canonical polynomial has fewer terms than the standard polynomial and is often referred to as the $\{q, m\}$ polynomial; m being the degree of the polynomial.

Mixture experiments have been applied by many researchers (Simon, 2003, Osadebe et al, 2007, Ezeh et al. 2010, Onwuka et al, 2011) in solving concrete mix optimization problems.

III. MATERIALS

The materials used for this work are Water, Cement, Sand and Quarry dust. Potable water obtained from a borehole was used in all the processes of manufacture and curing of blocks. Ibeto brand of Ordinary Portland cement which conforms to NIS: 444 (2003) was used. The river sand has a specific gravity of 2.65, bulk density of 1564kg/m^3 and fineness modulus of 2.76. The corresponding values for the quarry dust are 2.74, 1296kg/m^3 and 2.97.

IV. EXPERIMENTAL DESIGN

The experiment was designed and analyzed with Minitab 16 (2010). An augmented {4, 2} Scheffe’s simplex lattice design with 15 points was used. The design simplex is a tetrahedron as shown in Fig. 1. The ten mixes at the vertices and edges of the tetrahedron were augmented with additional five mixes at five points within the simplex. These additional points will serve as check points to validate the models developed. The experiment was replicated at the four vertices and the centroid of the tetrahedron, thus making a total of twenty runs. The experimental runs were also randomized. Pseudo components were used in the design.

Components transformation

The relationship between and the pseudo ratios and the real component ratios used for moulding the blocks at a particular point in the simplex is given as:

$$\boldsymbol{R} = \boldsymbol{AP} \quad (3)$$

Where **R**and **P** are respectively the vectors containing the real and pseudo ratios of the components and **A** is a transformation matrix, its elements define the vertices of the simplex and is obtained after trial mixes.
The transformation matrix, **A** obtained after trial mixes is:

$$\boldsymbol{A} = \begin{pmatrix} 0.52 & 0.61 & 0.75 & 1 \\ 1 & 1 & 1 & 1 \\ 5.4 & 3.6 & 9 & 6 \\ 0.6 & 2.4 & 1 & 4 \end{pmatrix} \quad (4)$$

The elements of each column of **A** represent the components’ proportions at a vertex in the following order: Water (X_1), Cement (X_2), Sand (X_3) and Quarry dust (X_4)

Compressive strength and water absorption tests of Sand-Quarry dust blocks

A total of one hundred and twenty (120) hollow blocks, 450 x 225 x 225mm overall dimensions, were moulded using a Rosa Commetta block moulding machine. The surface area of the solid portion of the blocks is 56880mm^2, representing approximately 56% of the overall surface area of the block. The aggregates were used in their dry condition and batching was by weight. Manual mixing was employed. The blocks were cured under shade for 28 days by sprinkling them with water, twice daily. Sixty blocks (three for each run) were crushed using a universal testing machine and their compressive strength (Yc), determined from the relationship:

$$Yc = \text{Crushing load (N)/ Cross-sectional area (mm}^2) \quad (5)$$

The water absorption test was done in accordance to BS 1881-122 (1983). Water absorption (Yw) was calculated as the difference between the mass of block after soaking in water for 24 hours and the dry mass of the block expressed as a percentage of the dry mass.

V. RESULTS

Table 1 shows the pseudo components and the results of the compressive strength and water absorption tests.

Model equation for compressive strength

The second degree model of Eq. (2) was fitted to the data set of the 20 compressive test results at 95% confidence limit (α= 0.05) using Minitab 16 (2010). The parameter estimates of the coefficients and the analysis of variance tables are respectively shown in Tables 2 and 3 while the normal probability plot of the residuals is shown in Fig. 2.The model equation for compressive strength is therefore:

$$Yc = 4.5540X_1 + 5.2167X_2 + 2.7694X_3 + 2.9256X_4 - 0.1162X_1X_2 - 2.3200X_1X_3 - 2.1427X_1X_4 - 2.4238X_2X_3 - 2.2465X_2X_4 + 1.1097X_3X_4 \quad (6)$$

The *p-value* for lack of fit of 0.259 is greater than the value of α (0.05). The normal probability plot of Fig.2also shows that the residuals fall reasonably close to the reference line. The conclusion, therefore, is that Eq. (6) is adequate for predicting the 28th day compressive strength of sand-quarry dust blocks. The other statistics (which have their usual meanings) in Table 3 lend credence to the adequacy of the model.

Model equation for Water absorption

A similar analysis gave the model equation for Water absorption as:

$$Yw = 4.1596X_1 + 3.2061X_2 + 7.8445X_3 + 7.2282X_4 - 0.3602X_1X_2 + 3.701X_1X_3 + 3.1090X_1X_4 + 2.1090X_2X_3 + 1.1317X_2X_4 - 2.7580X_3X_4 \quad (7)$$

The *p-value* for lack of fit is 0.898 which is greater than 0.05, indicating the adequacy of the model for predicting the water absorption of the blocks,

Response trace plot.

The Piepel response trace plot for both the compressive strength and water absorption models are shown in Fig.3.

VI. DISCUSSION OF RESULTS

(a) Model coefficients

It is seen from Eq. (6) that $\beta_2 > \beta_1 > \beta_4 > \beta_3$ indicating that cement contributes most to the strength followed by water, quarry dust and sand in that order. There is a binary synergistic effect in the interaction between sand and quarry dust as given by the positive value of $\beta_{34.}$ This means that the contribution of the fine aggregates is greater when they are combined than when each is used alone. This goes further to buttress the earlier observation that the inclusion of quarry dust improved the compressive strength of the blocks. For the water absorption model, $\beta_3 > \beta_4 > \beta_1 > \beta_2$ indicating that sand is the greatest contributor with quarry dust, water and cement following in that other. There is antagonistic synergy between sand and quarry dust, indicating that water absorption is reduced when the two aggregates are combined than when each is used alone.

(b) Maximum and minimum predictable model values.

The values of compressive strength predictable with the compressive strength model was found to range from 2.74 to 5.22 Nmm$^{-2.}$ The corresponding values for the water absorption model is 3.21 to 7.84%.

(c) Piepel Response Trace Plots (Components interactions)

As the proportion of cement in the mixture increases (and the other mixture components decrease), the compressive strength increases rapidly. As the cement proportion decreases (and the other components increase), the compressive strength decreases. As the proportion of water increases, and the other components decrease, the compressive strength increases and as the water proportion decreases while the others decrease the strength decreases. The water content is almost optimum. As the proportion of sand decreases, and the other components increase, the compressive strength increases moderately. As the sand proportion increases, and the other components decrease, the compressive strength decreases. The quarry dust behaved in a similar manner as sand.

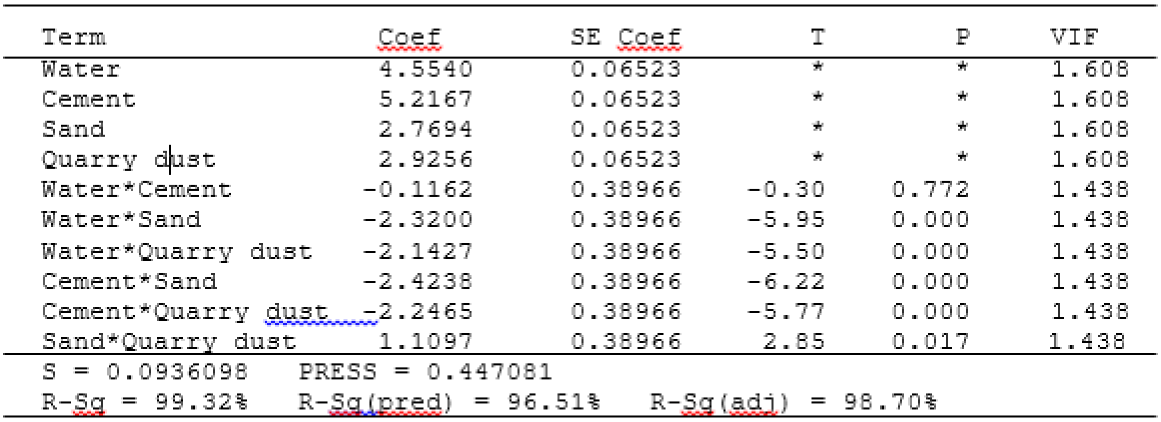
VII. CONCLUSION AND RECOMMENDATION

Models for predicting the compressive strength and water absorption of sand-quarry dust blocks were developed in this work. The models can be used to predict the compressive strength of blocks ranging from 2.74 to 5.22Nmm^{-2} and water absorption of 3. 21 to 7.84%. The use of these models will greatly help Nigerian block producers to meet the Nigerian Industrial Standard, (NIS) : 87 (2004) recommended values of 3.45Nmm^{-2} and 6% for compressive strength and water absorption of machine vibrated load bearing sandcrete blocks respectively.

Table 1 Compressive strength and Water absorption tests results

Run Order	Std Order	Pseudo ratios				Response	
		Water (X_1)	Cement (X_2)	Sand (X_3)	Quarry dust (X_4)	*Yc* (Nmm^{-2})	*Yw (%)*
1	1	1	0	0	0	4.49	4.06
2	7	0	0.5	0	0.5	3.50	5.48
3	12	0.625	0.125	0.125	0.125	3.67	5.41
4	11	0.25	0.25	0.25	0.25	3.34	6.14
5	20	0.25	0.25	0.25	0.25	3.40	6.00
6	15	0.125	0.125	0.125	0.625	3.19	6.53
7	8	0	0	1	0	2.80	7.71
8	9	0	0	0.5	0.5	3.07	6.86
9	18	0	0	1	0	2.72	8.00
10	14	0.125	0.125	0.625	0.125	3.04	6.95
11	6	0	0.5	0.5	0	3.39	6.02
12	16	1	0	0	0	4.65	4.26
13	19	0	0	0	1	2.98	7.13
14	17	0	1	0	0	5.19	3.24
15	4	0.5	0	0	0.5	3.20	6.50
16	10	0	0	0	1	2.84	7.36
17	3	0.5	0	0.5	0	3.09	6.80
18	5	0	1	0	0	5.27	3.16
19	2	0.5	0.5	0	0	4.91	3.54
20	13	0.125	0.625	0.125	0.125	4.01	4.78

Table 2 Estimated Regression Coefficients for Compressive strength (Pseudo components)



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  Term                    Coef      SE Coef       T        P      VIF
  Water                 4.5540      0.06523       *        *    1.608
  Cement                5.2167      0.06523       *        *    1.608
  Sand                  2.7694      0.06523       *        *    1.608
  Quarry dust           2.9256      0.06523       *        *    1.608
  Water*Cement         -0.1162      0.38966   -0.30    0.772    1.438
  Water*Sand           -2.3200      0.38966   -5.95    0.000    1.438
  Water*Quarry dust    -2.1427      0.38966   -5.50    0.000    1.438
  Cement*Sand          -2.4238      0.38966   -6.22    0.000    1.438
  Cement*Quarry dust   -2.2465      0.38966   -5.77    0.000    1.438
  Sand*Quarry dust      1.1097      0.38966    2.85    0.017    1.438
  S = 0.0936098    PRESS = 0.447081
  R-Sq = 99.32%    R-Sq(pred) = 96.51%    R-Sq(adj) = 98.70%
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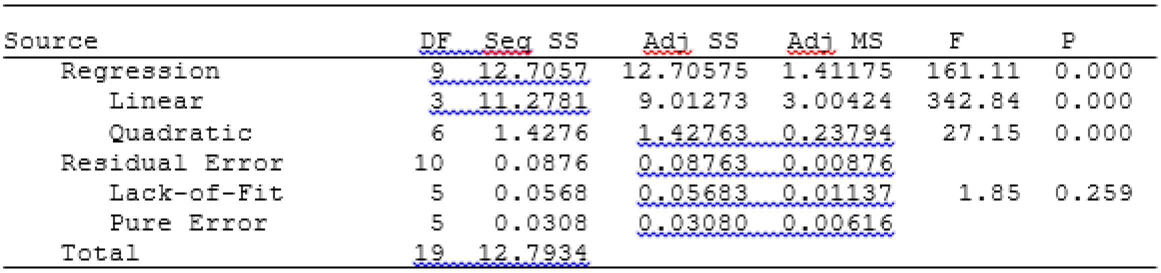
Table 3: Analysis of Variance for Compressive strength (Pseudo components)



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Source                       DF   Seq SS     Adj SS    Adj MS       F      P
   Regression                 9  12.7057   12.70575   1.41175  161.11  0.000
      Linear                  3  11.2781    9.01273   3.00424  342.84  0.000
      Quadratic               6   1.4276    1.42763   0.23794   27.15  0.000
   Residual Error            10   0.0876    0.08763   0.00876
      Lack-of-Fit             5   0.0568    0.05683   0.01137    1.85  0.259
      Pure Error              5   0.0308    0.03080   0.00616
   Total                     19  12.7934
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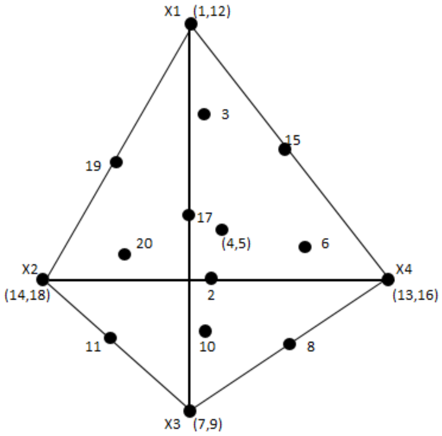


Fig. 1: Augmented {4, 2} Scheffe's simplex lattice showing the points and run order

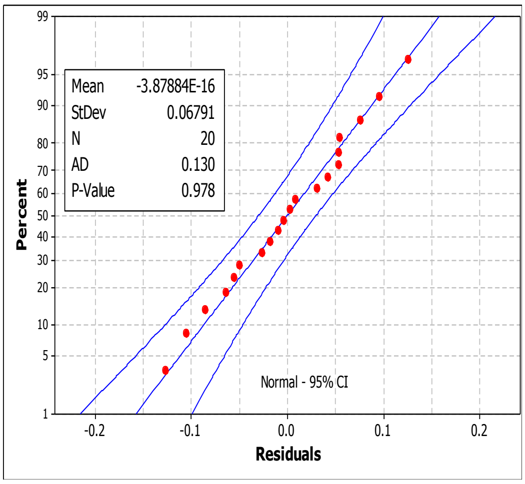
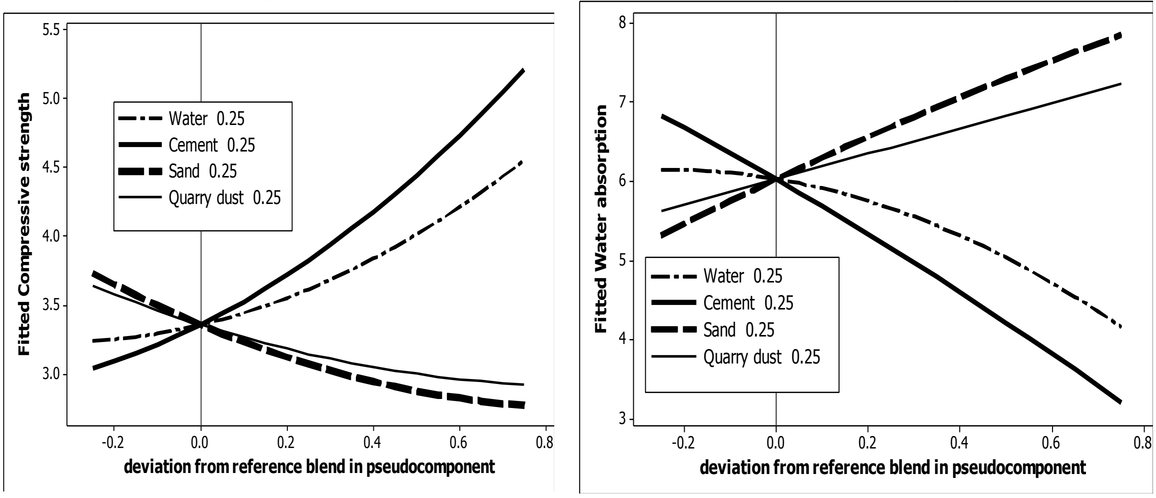


Fig.2 Normal probability plot for compressive strength



(a) Compressive strength (b) Water absorption

Fig.3 Piepel response trace plots (Pseudo components)

VIII. ACKNOWLEGEMENT

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