OPTIMIZATION OF SANDCRETE BLOCK BASED ON SCHEFFE'S MODEL USING QUARRY DUST AS PARTIAL REPLACEMENT OF RIVER SAND

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ABSTRACT

This research work focuses on the optimization of sandcrete hollow block based on Scheffe's model using quarry dust as partial replacement of river sand. The investigation shows that the specific gravity, uncompacted bulk density, moisture content and compacted bulk density of river sand and quarry dust are 2.71 and 2.74; 1523.8 kg/m^3; 1767.86 kg/m^3 and 7.89%; 1.46%; 1819.44 kg/m^3 and 2005.95 kg/m^3 respectively. The maximum average water absorption for hollow sandcrete blocks is 10.56% with 0.6:1:6.5 mix ratio for cement, quarry dust and river sand, which fell below 12% of the dry weight as stipulated by Nigerian Industrial Standards. The maximum average density of hollow sandcrete blocks is 1797.53 kg/m^3 with 0.6375: 1: 6.1625 mix ratio which is within the threshold. Six optimization models were developed from a reduced second-degree polynomial: $\hat{Y} = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3$. The Optimum Experimental Strength and Model Predicted Strength correlate well with R^2 of 0.93.

Keywords: *Compressive strength, Optimization, Quarry dust, River sand, Sandcrete Block, Scheffe's model.*

1 INTRODUCTION

Blocks are those frame units in building used in the construction of walls and partitions. Sandcrete block is a composite material made up of cement, sand, water, molded into different size (NIS 087:2000). BS 6073-1:1981 also defines "Block" as a masonry unit of large size in all dimensions than specified for bricks but no dimension exceeds 650 mm nor should the height exceed either its length or six times its thickness. The three main forms of sandcrete blocks according to Yusuf and Hamza (2011) are solid, cellular and hollow. Hollow sandcrete blocks are more economical in terms of weight, density and compressive strength; they are commonly used in construction works (Olutoge, 2017). They are of sizes and weight that can easily be handled by the bricklayer with the facing surface layer than that of a brick but conveniently dimensioned. The most commonly available sizes are 450mm x 225mm x 225mm (9" block) and 450mm x 150mm x 225mm (6'' block) (Olutoge, 2017). Sandcrete blocks are available for the construction of load bearing and non-load bearing structures (Odeyemi *et al.*, 2015).

Sandcrete blocks constitute a unique class amongst man-made structural component for building in civil engineering work. The importance of the blocks as part of the local building materials cannot be over emphasized in building and construction industry. Sandcrete blocks have been widely used for building construction in Nigeria (Abdulwahab and Tunde, 2016). Cement is a major binding component of hollow sandcrete blocks which are widely used for building and other structures in Nigeria. Quarry dust is a by-product from crushing process during quarrying activities and it is one of those materials that have recently gained attention for use as fine aggregates in the production of concrete and sandcrete block (Sivakumar and Prakash, 2011).

Optimization of sandcrete design mixture is defined as the procedure of finding a mixture for which the total cost of the constituents is lowest, yet satisfying the normal performance of hollow sandcrete block such as strength, durability and workability. Predictive modelling is the name given to a collection of mathematical techniques used to derive mathematical relationships that are brought about using experimental data between a dependent variable and a number of independent variables with the sole aim of measuring and inputting the values of the predictors into the model to forecast or determine the value of the target variable within the shortest possible time (Rajsekaran, 2005). Thus, the time, energy and resources were conserved by the use of predictive models (Rajsekaran, 2005). Mathematical modelling has found various applications in concrete technology, the commonest being the application of predictive models like those derived from Henry Scheffe's mixture models to predict concrete properties such as strength (Mbadike and Osadebe, 2013; Osadebe and Ibearugbulem, 2009; Ezeh and Ibearugbulem, 2009; Onwuka *et al.*, 2009; Adinna *et al.*, 2014). Simple lattice design proposed by Scheffe (1958) used to formulate a mathematical model will be adopted for optimizing the mix proportion and compressive strength of hollow sandcrete block in this project.

2 MATERIALS AND METHODS

Quarry dust was obtained from a site at Maikunkele, Minna Niger State. River Sand from Chanchaga River, sieved to remove impurities and other deleterious materials. Ordinary Portland Cement, which is commercially available in market according to the specification of BS 12 (1996) and Drinkable water free of impurities were all used for this work. The quarry dust and river sand were sieved to separate all undesirable content. Thereafter, the following physical tests were carried out: sieve analysis, moisture content and specific gravity tests. Sandcrete block materials were then batched, mixed, placed and compacted in three layers. 150mm x 225mm x 450mm (6") sandcrete blocks were cast for all measurements. 12 mixes (6 designed mixes and 6 control point mixes) was used based on Scheffe's approach. In respect to the three replicates for each of the twelve mixtures. A total number of 36 sandcrete blocks were cast and their compressive strength determined. An average of three samples from the same mixture under the same conditions was obtained. Three mixes were optimized using quarry dust as partial replacement for sand.

2.1 Method of Optimization of Concrete

Scheffe's simplex lattice design proposed in 1958 was used for optimizing the compressive strength and component ratio of cement, quarry dust plus sand and water cement ratio.

2.1.1 Simplex Lattice Design

The relationship that holds for the component of the mixture is given as in equation (1):

$$\sum_{i=1}^{q} X_i = 1 \qquad (1)$$

Where:

$X_i \geq 0$ = the component concentration

q = the number of components

Therefore, for a 4-component mixture the sum of all the proportions of the components must be unity. That means

$$X_1 + X_2 + X_3 = 1 \qquad (2)$$

Where in this case:

X_1 = proportion of cement water ratio

X_2 = proportion of cement

X_3 = proportion of fine aggregates

For trinary system, q = 4, the regular simplex is a tri-hedron. Each point in the tri-hedron represents a certain composition of the trinary system.

Scheffe (1958) showed that the response function (property) in multi-component system can be approximated by a polynomial. To describe such function adequately, high degree polynomials are required and hence a great many experimental trials. According to Scheffe (1958), a polynomial of degree n in q variable has $C_q^n + n - 1$ coefficients and is in the form:

$$\hat{y} = b_0 + \sum b_i X_i + \sum b_{ij} X_i X_j + \sum b_{ijk} X_i X_j X_k + \cdots + \sum b i_1 i_2 \ldots i_n x i_1 x i_2 x i_n \qquad (3)$$

$1 \leq i \leq q \qquad 1 \leq i \leq j \leq q \qquad 1 \leq i \leq j \leq k \leq q$

The relationship in equation (1) permit the equation component to be eliminated and the number of coefficients reduced to $C_q^n + n - 1$. It is therefore necessary that all the q components be introduced into the model.

Scheffe (1958) suggested that mixture properties can be described by reduced polynomials from Equation (3) subject to the normalization condition of Equation (1) for a sum of independent variables. The reduced second-degree polynomial for a quaternary system is derived as follows:

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{11}{X_1}^2 + b_{22}{X_2}^2 + b_{33}{X_3}^2 \qquad (4)$$

From equation (3.2) $X_1 + X_2 + X_3 = 1$

Then $b_0X_1 + b_0X_2 + b_0X_3 = b_0 \qquad (5)$

Multiplying equation (4) by X_1, X_2, and X_3 in the succession gives:

$$\left.\begin{aligned} X_1^2 &= X_1 - X_1X_2 - X_1X_3 \\ X_2^2 &= X_2 - X_1X_2 - X_2X_3 \\ X_3^2 &= X_3 - X_1X_3 - X_2X_3 \end{aligned}\right\} \quad (6)$$

Substituting equation (5) and equation (6) in equation (4) and transforming, it gives

$$\hat{Y} = (b_0 + b_1 + b_{11})X_1 + (b_0 + b_2 + b_{22})X_2 + (b_0 + b_3 + b_{33})X_3 + (b_{12} + b_{11} + b_{22})X_1X_2 + (b_{13} + b_{11} + b_{33})X_1X_3 + (b_{23} + b_{22} + b_{33})X_2X_3 \quad (7)$$

Denoting:

$$\beta_i = b_0 + b_i + b_{ii} \ ; \ \beta_{ij} = b_{ij} - b_{ii} - b_{jj} \quad (8)$$

The reduced second – degree polynomial in four variables is:

$$\hat{Y} = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad (9)$$

The answer to equation (8) according to Scheffe (1958) for the coefficients of the polynomial is:

$$\beta_i = Y_i \text{ and } \beta_{ij} = 4Y_i - 2Y_i - 2Y_j \quad (10)$$

Where,

$$\beta_i = \beta_1, \beta_2, \ldots\ldots\ldots, \beta_3$$

$$\beta_{ij} = \beta_{12}, \beta_{13}, \ldots\ldots\ldots, \beta_{23}$$

Y_i and Y_{ij} = response (property)

Equation (9) is the governing equation. Scheffe's simplex lattice design provides a uniform scatter of points over the (q – 1) – simplex. The points form a (q -1) – lattice on the simplex where q is the number of mixture components, 'n' is the degree of polynomial. Scheffe (1958) showed that for each component, there exist (n + 1) similar levels, $X_i = 0, \frac{1}{n}, \frac{2}{n}, \ldots, 1$, and all possible mixtures are derived with such values of component concentration. So for (3, 2) – lattice the proportion of every component that must be used are 0, ½ and 1. He also showed that the number of points in (q, n) lattice is given as:

$$\text{Number of point} = \frac{q(q+1)}{n!} \quad (11)$$

$$= \frac{3(3+1)}{2!} = 6 \text{ points}$$

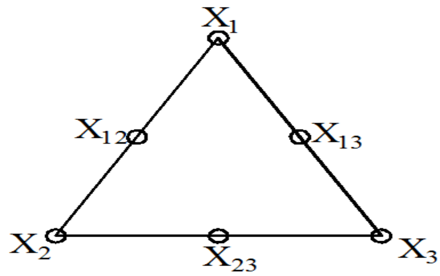

Figure 1: The (3, 2) – Lattice

2.1.2 Experimental Mix Design Formulation

Equation (11) is the relationship that holds for the components of the mixture and is transformed to establish the actual component concentration. The transformed proportion X_i (i = 1 – 3) for each experimental points are called 'pseudo components'. For actual component Z_i the pseudo components X is given by

$$X = BZ \quad (11)$$

where B is the inverse of Z matrix.

Likewise, the inverse transformation from pseudo components to Z_i (actual components) is expressed as

$$Z = AX \quad (12)$$

Where A is the inverse transformation matrix

The actual components for the first four points are chosen arbitrarily for the tri-hedron vertices in component transformation in

Figure 2.

2.1.3 Component Transformation

The arbitrary vertices chosen for the triangle are Z_1 (0.5:1:5.5), Z_2 (0.6:1:6.5) and Z_3 (0.65:1:8) for actual components.

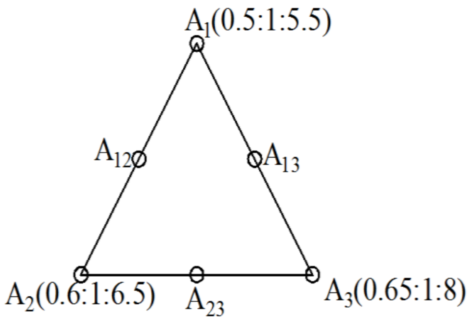

Figure 2: Triangular vertices for (3, 2) Lattice (actual components)

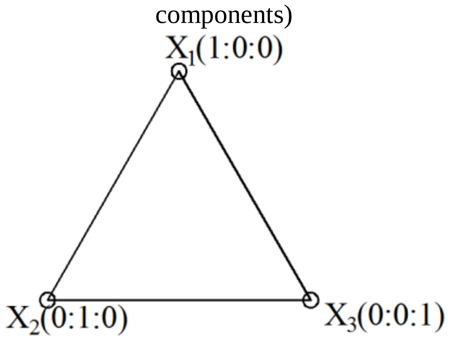

Figure 3: Triangular vertices for (3, 2) lattice (Psuedo components)

Relation between the actual components and pseudo components is according to Scheffe (1958).

From equation (12): Z = AX

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \quad X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$Z = A = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$$

$$\text{i.e. } Z = \begin{pmatrix} 0.5 & 0.6 & 0.65 \\ 1 & 1 & 1 \\ 6 & 6.5 & 8 \end{pmatrix}$$

To obtained other three mix ratio

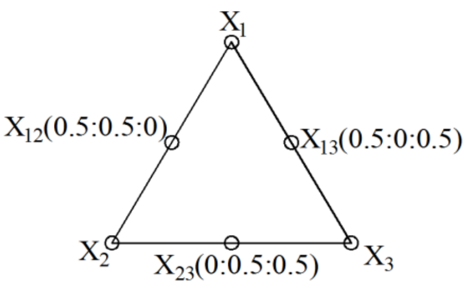

Figure 4: Pseudo components for control points

Table 1: Experimental point of (3, 2) lattice

Mix	Pseudo Components X_i				Actual Components Z_i		
	X_1	X_2	X_3		Z_1	Z_2	Z_3
1	1	0	0	A1	0.5	1	5.5
2	0	1	0	A2	0.6	1	6.5
3	0	0	1	A3	0.65	1	8.0
4	0.5	0.5	0	A12	0.55	1	6.0
5	0.5	0	0.5	A13	0.575	1	6.75
6	0	0.5	0.5	A23	0.625	1	7.25
				Control Point			
7	0.5	0.25	0.25	C1	0.5625	1	6.375
8	0.25	0.75	0	C2	0.575	1	6.25
9	0.75	0.25	0	C3	0.525	1	5.75
10	0.25	0.5	0.25	C4	0.5875	1	6.625
11	0	0.25	0.75	C5	0.6375	1	6.1625
12	0.25	0.25	0.50	C6	0.60	1	7.0

3 RESULTS AND DISCUSSION

The results of physical properties and sieve analysis of Quarry dust and River sand are shown in Tables 2 and Figures 5 – 7.

Tables 2: Physical properties of aggregates

Physical Test	Quarry Dust	River Sand
Specific gravity	2.74	2.71
Moisture content (%)	1.46	7.89
Uncompact Bulk density (kg/m³)	1767.86	1523.81
Compacted Bulk density (kg/m³)	2005.95	1819.44

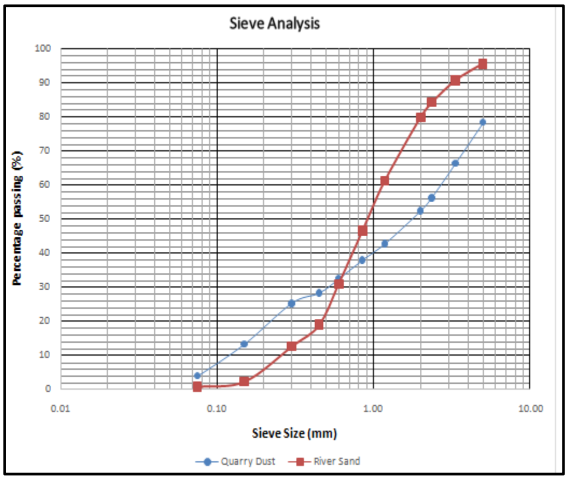

Figure 5: Sieve analysis of Quarry dust and River sand

From 1 above, the specific gravity of river sand and quarry dust are 2.71 and 2.74 respectively which in accordance to BS 812:2 (1995). Uncompacted bulk density of the samples, the bulk density of River sand and quarry dust are 1523.81kg/m^3 and 1767.86kg/m^3 respectively. Compacted bulk density of the samples, the bulk density of River sand and quarry dust are 1819.44 kg/m^3 and 2005.95 kg/m^3 respectively which is in accordance to BS 812:2 (1995).

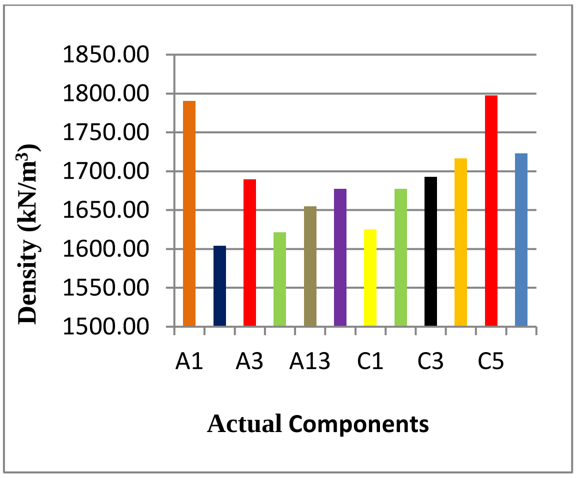

Figure 6: Density of sandcrete hollow blocks

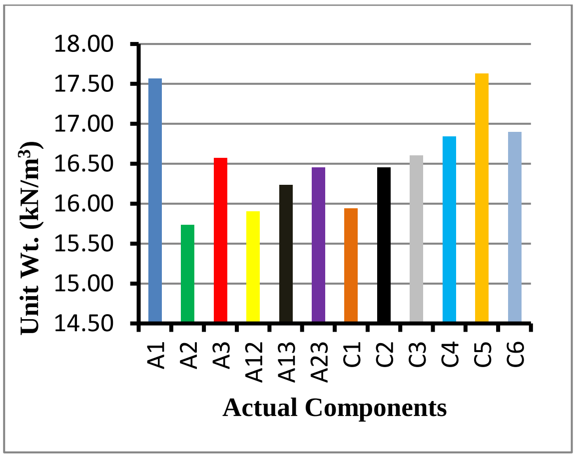

Figure 7: Unit Weight of sandcrete hollow blocks

Estimation of Control Points Pseudo Components

From equation (9):

Control model $\hat{Y} = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3$

From equation (3.10): $\beta_i = Y_i$ and $\beta_{ij} = 4Y_i - 2Y_i - 2Y_j$

Where,

$$\beta_i = \beta_1, \beta_2, \dots \dots \dots, \beta_3$$
$$\beta_{ij} = \beta_{12}, \beta_{13}, \dots \dots \dots, \beta_{23}$$

$$Y_i \text{ and } Y_{ij} = \text{response (property)}$$

Therefore,

$$\beta_1 = Y_1 = 3.06$$

$$\beta_2 = Y_2 = 2.27$$

$$\beta_3 = Y_3 = 2.06$$

$$\begin{aligned}\beta_{12} &= 4Y_{12} - 2Y_1 - 2Y_2 \\ &= 4(2.50) - 2(3.06) - 2(2.27) \\ &= -0.66\end{aligned}$$

$$\begin{aligned}\beta_{13} &= 4Y_{13} - 2Y_1 - 2Y_3 \\ &= 4(2.42) - 2(3.06) - 2(2.06) \\ &= -0.56\end{aligned}$$

$$\begin{aligned}\beta_{23} &= 4Y_{23} - 2Y_2 - 2Y_3 \\ &= 4(2.27) - 2(2.27) - 2(2.06) \\ &= 0.42\end{aligned}$$

Model

$$\begin{aligned}\text{Ymodel 1} &= (3.06 \times 0.5) + (2.27 \times 0.25) \\ &+ (2.06 \times 0.25) \\ &+ (-0.66 \times 0.5 \times 0.25) \\ &+ (-0.56 \times 0.5 \times 0.25) \\ &+ (0.42 \times 0.25 \times 0.25) = 2.49\end{aligned}$$

$$\begin{aligned}\text{Ymodel 2} &= (3.06 \times 0.25) + (2.27 \times 0.75) \\ &+ (2.06 \times 0) \\ &+ (-0.66 \times 0.25 \times 0.75) \\ &+ (-0.56 \times 0.25 \times 0) \\ &+ (0.42 \times 0.75 \times 0) = 2.34\end{aligned}$$

$$\begin{aligned}\text{Ymodel 3} &= (3.06 \times 0.75) + (2.27 \times 0.25) \\ &+ (2.06 \times 0) \\ &+ (-0.66 \times 0.75 \times 0.25) \\ &+ (-0.56 \times 0.75 \times 0) \\ &+ (0.42 \times 0.25 \times 0) = 2.74\end{aligned}$$

$$\begin{aligned}\text{Ymodel 4} &= (3.06 \times 0.25) + (2.27 \times 0.5) \\ &+ (2.06 \times 0.25) \\ &+ (-0.66 \times 0.25 \times 0.5) \\ &+ (-0.56 \times 0.25 \times 0.25) \\ &+ (0.42 \times 0.5 \times 0.25) = 2.35\end{aligned}$$

$$\begin{aligned} \text{Ymodel 5} = & (3.06 \times 0) + (2.27 \times 0.25) \\ & + (2.06 \times 0.75) \\ & + (-0.66 \times 0 \times 0.25) \\ & + (-0.56 \times 0 \times 0.75) \\ & + (0.42 \times 0.25 \times 0.75) = 2.19 \end{aligned}$$

$$\begin{aligned} \text{Ymodel 6} = & (3.06 \times 0.25) + (2.27 \times 0.25) \\ & + (2.06 \times 0.5) \\ & + (-0.66 \times 0.25 \times 0.25) \\ & + (-0.56 \times 0.25 \times 0.5) \\ & + (0.42 \times 0.25 \times 0.5) = 2.28 \end{aligned}$$

Table 3: **S**tatistical Analysis of Experimental and Model strengths

Control points	Experimental strength	Model predicted strength for control
C1	2.11	2.49
C2	2.23	2.34
C3	2.52	2.74
C4	2.40	2.35
C5	2.55	2.19
C6	2.16	2.28

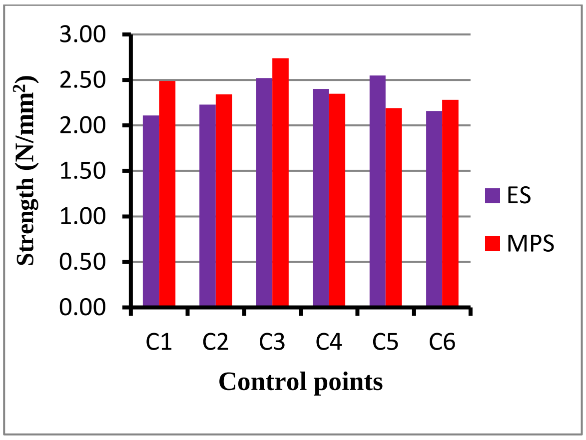

Figure 8: Statistical Analysis of Experimental and Modelled strength for Control points

3.2 ANOVA Statistical Analysis for the Models

The SPSS (Statistical Package for the Social Science) software was used to calculate the ANOVS for the statistical analysis as shown in Table 5

Table 4: ANOVA Statistical Analysis for the Model

Parameters	Experimental strength (ES)	Model predicted strength (MPS)
1	$2.06^{c} \pm 0.07$	$2.44^{a} \pm 0.07$
2	$2.18^{bc} \pm 0.07$	$2.29^{bc} \pm 0.07$
3	$2.47^{a} \pm 0.07$	$2.69^{a} \pm 0.07$
4	$2.35^{ab} \pm 0.07$	$2.30^{bc} \pm 0.07$
5	$2.50^{a} \pm 0.07$	$2.14^{c} \pm 0.07$
6	$2.11^{c} \pm 0.07$	$2.23^{c} \pm 0.07$

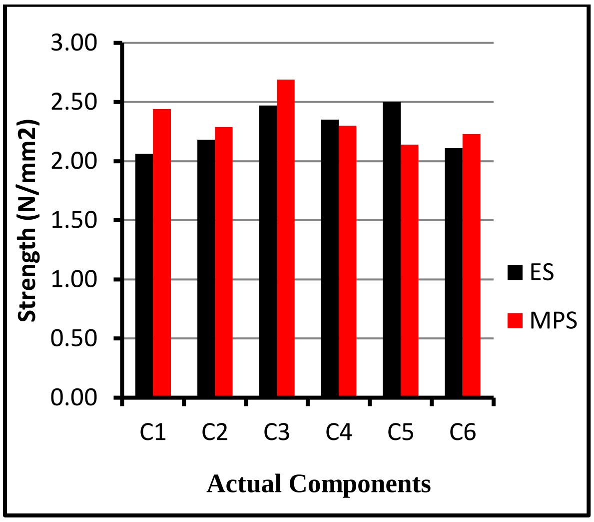

Figure 9: Statistical Analysis of Experimental and Modelled strength for Actual points

Table 4 and Figures 8-9 show the statistical analysis for the models. Experimental strength (ES) five (2.50 N/mm^2) records the best but also similar to experimental strength three (2.47 N/mm^2) whereas experimental strength one (2.06N/mm^2) and six (2.11 N/mm^2) are the least.

On modelled predicted strength for control (MPSC) one (2.44 N/mm^2) and three (2.69 N/mm^2) are statistically similar, two (2.29 N/mm^2) and four (2.30N/mm^2) are also similar. A similar trend was also observed in model predicted strength for control five (2.14 N/mm^2) and six (2.23 N/mm^2). Therefore, the optimum mix of 0.6:1:6.5 and 0.6375:1:6.1625 produced the best correlation of 0.93 between the experimental strength and modelled predicted strength.

This correlation strengthens the optimization study. From the ANOVA Statistical analysis for the models, the Optimum Experimental Strength and Model Predicted Strength are 2.50 N/mm^2 and 2.69 N/mm^2 respectively with a correlation of 0.93. In addition, this correlation value validates the optimization with a reduction in material utilization of 12 – 19%.

4 CONCLUSION

From the Investigation of Optimization of Sandcrete Hollow Blocks with Quarry dust as Partial replacement of River sand, using Scheffe's Model, the following conclusion were drawn;

The properties of the aggregates (river sand and quarry dust) are given as; the specific gravity river sand and quarry dust are 2.71 and 2.74 respectively; the moisture content of river sand (7.89%) is far higher than quarry dust (1.46%); the bulk density of river sand is less than that of quarry dust; for sieve analysis test, river sand is well graded sand while quarry dust is poorly graded soil.

From the result of experiments carried out on the blocks in accordance to NIS 978 (2017), the density of the block ranges from 1603.82 kg/m^3 – 1797.53 kg/m^3 which is less than 1800 kg/m^3 (the maximum allowable density of sandcrete block). The water absorption of the block ranges from 3.77% – 1 0.56% which is less than 12% (the maximum allowable water absorption for sandcrete block).

From the six models developed from 12 mix ratios for the pseudo and control points, using Scheffes' model and statistical analysis (SPSS) the ***optimum*** Experimental strength and Modelled Predicted Strength are 2.50 N/mm^2 and 2.69 N/mm^2 respectively with a correlation of 0.93 from design mix of 0.6:1:6.5 and 0.6375:1:6.1625 for cement, quarry dust and river sand respectively. This correlation validates the optimization with reduction in material utilization of 12 – 19%.

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