OPEN ACCESS

Saudi Journal of Civil Engineering
Abbreviated Key Title: Saudi J Civ Eng
ISSN 2523-2657 (Print) | ISSN 2523-2231 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com/journal/sjce/home

Original Research Article

Mathematical Model for Estimating the Cost of Laterite-Quarry Dust Cement Block

Enang Egbe[1*], Desmond Ewa[1], Godwin Akeke[1]

[1]University of Technology of Cross River State, Nigeria

DOI: https://doi.org/10.36348/sjce.2024.v08i09.004 | **Received:** 27.09.2024 | **Accepted:** 01.11.2024 | **Published:** 20.11.2024

***Corresponding author:** Enang Egbe
University of Technology of Cross River State, Nigeria

Abstract

The cost of Block production which largely depends on the cost of the constituent materials, affects the overall cost of construction. In this paper, a model based on mixture experiment was formulated to optimize cost of block (in Naira). Using the model, one can predict the cost per cubic meter of block if the mix ratios are given. The model can also give possible mix ratios for a specified cost. The model is tested for lack of fit using statically tool and found adequate.

Keywords: Blocks, laterite, quarry dust, Mixture Experiment, Scheffe's augmented lattice equation.

1.0 INTRODUCTION

Estimating the cost of sandcrete blocks is a crucial aspect in construction projects, especially in regions where sandcrete is a prevalent building material due to its affordability and durability. Sandcrete blocks, composed of sand, cement, and water, are widely used in residential, commercial, and infrastructure development across various countries. Proper estimation of the cost involved in procuring and utilizing sandcrete blocks is essential for budget planning and project feasibility assessment. Sandcrete blocks are a fundamental component in many construction projects due to their cost-effectiveness and adaptability (Ede, 2017). The cost estimation process involves considering factors such as raw material prices, labor costs, transportation expenses, and overheads (Oluwafemi, 2019). Additionally, the quality of sandcrete blocks, determined by factors like block density and compressive strength, influences their cost (Olusola *et al*., 2020). Various methodologies have been proposed for estimating the cost of sandcrete blocks. These include traditional methods based on material quantities and unit prices (Ogunbayo & Jimoh, 2018), as well as more advanced techniques utilizing mathematical models and statistical analysis (Fadare & Ojuri, 2016). Furthermore, factors such as market fluctuations and regulatory requirements impact the cost estimation process (Olanrewaju *et al*., 2021). Accurate cost estimation is essential for project planning and management to avoid budget overruns and delays (Oyedele *et al*., 2018). Therefore, researchers and practitioners continually seek to refine methodologies for estimating the cost of sandcrete blocks to enhance project efficiency and sustainability (Kolo & Adeoye, 2020). One such methodology is the development of mathematical models. A mathematical model according to Edwards and Hamson, 1989) cited in (Agunwamba, 2007) is "a simplified representative of certain aspects of real system created using mathematical concept such as functions, graph, diagrams and equations to solve problems in the real world. Models often allow foe quick and cheap evaluation of alternatives, leading to optimal solutions which are not otherwise obvious and also improvement in design, operation and efficiency of engineering system A mathematical models are formulated either through intuitive reasoning about the phenomenon or from physical laws based on evidence from experiment; it is usually constructed in the language of mathematics, logic, and computer following the algebraic rules of syntax (Agunwamba, 2007). Researches have formulated mathematical models for the prediction of strength properties of sandcrerte blocks and also that that blocks made from laterite and quarry dust (Okafor & Egbe, 2017; Okere & Osadebe, 2014; Anya & Osadebe, 2015).

This study is aimed at investigating the properties of masonry unit produced with full replacement of conventional sand, with lateritic soil and quarry dust with the purpose of developing a

Citation: Enang Egbe, Desmond Ewa, Godwin Akeke (2024). Mathematical Model for Estimating the Cost of Laterite-Quarry Dust Cement Block. *Saudi J Civ Eng, 8*(9): 225-232.

mathematical model for estimating the cost of laterite-quarry dust cement block.

Mixture Experiment and Regression Equations

Mixture experiments are designed experiments used to study the effects of various components mixed together in different proportions. This method finds wide application across disciplines like chemistry, engineering, and product development, aiding in the enhancement of formulations and processes (Cornell & Exler, 2015). A mixture experiment according to (Montgomery, 2005) are experiment that involves varying the proportions of two or more ingredients, also known as components of the mixture, and studying the changes that occur in the measured properties (responses) of the resulting end products or outcome they are special class of response surface experiments in which the product under investigation is made up of several components or ingredients. Designs for these experiments are valuable because many product design and development activities in industrial situations has to do formulations or mixtures. Under this circumstance, the response is a function of the proportions of the different ingredients in the mixture. For example, to optimize the tensile strength of stainless steel, requires the mixture of iron, copper, nickel, and chromium in their right quantities. The design and analysis of mixture experiments involve constructing experimental designs that allow for the systematic exploration of the entire mixture space and fitting mathematical models to describe the relationship between the components and the response variables of interest (Myers *et al*., 2016). Optimization in mixture experiments aims to identify the optimal combination of ingredients or components to achieve desired properties or outcomes. This involves using statistical techniques such as response surface methodology (RSM) or desirability functions to find the optimal operating conditions (Montgomery, 2017). Mixture experiments find extensive applications in product formulation, where they are used to develop new products or improve existing ones by optimizing the proportions of ingredients to meet specific performance criteria or consumer preferences (Piepel *et al*., 2012).

Cornel (2002) describe a mixture experiment as "that which the response is presumed to be dependent on relative proportions of the constituent materials and not on their total amount." The two basic requirements that must be satisfied for such experiments are: the sum of the proportions of the constituents must add up to 1 and that none of the constituents will have a negative value. These requirements are represented mathematically as therefore:

$$X_1 + X_2 + \cdots + X_q = \sum_{I=1}^{q} X_i = 1 \text{ .... } (1)$$

$$0 \leq X_i \leq 1$$

Where

q is the number of mixture components.

X_i *(i = 1 to q)* is the volume or mass proportion of component *i* in the mixture.

It should be noted that since the total quantities of the constituents is constrained to 1, only *q-1* of the variables or constituents can be independently chosen.

A number of mixture experiment model have been developed by researchers. One of such which is very popular is the Scheffe's lattice design. The canonical form of the scheffes's polynomial equation for second degree for q component is replicated in the form below

$$y = \sum_{1\leq i\leq q} \beta_i X_i \sum_{1\leq i\leq j\leq q} \beta_{ij} X_i X_j \text{ .... } (2)$$

The number of terms in the Scheffe's polynomial, *N* is the minimum number of experimental runs necessary to determine the polynomial coefficients and is given as:

$$N = C_n^{(q+n-1)} = \frac{(q+n-1)!}{(q-1)!(n)!} \text{ .... } (3)$$

In equation (2) y is the response function and xi(i=1 to q) is the proportion of the component in the mixture. The second degree is the most commonly used polynomial to fitting mixture experiment data. The canonical form of the equation is shown below:

$$\hat{y} = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{34} X_3 X_4 \text{ .... } (4)$$

The estimated coefficients in canonical equation are obtained from the regression analysis of the mixture experiment data. The canonical polynomial has less terms than the standard polynomial and is often referred to as the {q, n} polynomial; n being the degree of polynomial.

A lot of other researchers [20-26] have also employed mixture experiment in solving mix optimization problems.

2.0 MATERIALS AND METHOD

The materials and primary data used for this work are taken from a previous study on predictive models for compressive strength and water absorption of laterite-quarry dust cement Okafor and Egbe (2017), who formulated a regression model for predicting the compressive strength and water absorption of Laterite-quarry dust cement blocks.

Cement

Portland limestone cement (specifically Larfage brand), grade 32.5, sourced from a primary supplier in Calabar, Cross River State, Nigeria, in accordance with BS 12, was utilized for all laboratory experiments.

Water

Clean drinking water, guaranteed free of contaminants, provided by the Cross River State Water Board (CRSWB) Limited, was utilized for both preparing specimens and the curing process.

Laterite

The reddish-brown laterite samples utilized were sourced from an existing borrow pit situated at Akim-Akim in the Odukpani Local Government Area of Cross River State (with coordinates Latitude 050 07.48' and Longitude 080 20.5'). This borrow pit is a primary source for most commercial block producers. The samples were collected using the disturbed sampling technique and subjected to testing at the Soil Mechanics Laboratory of the Civil Engineering Department of Cross River University of Technology, following the standards outlined in BS 1377(BSI, 1990). The specific gravity of the laterite was determined to be 2.56.

Quarry Dust

Quarry dust used for the work was obtained from the abundant deposits at Akamkpa quarry site in Akamkpa, Cross River State; located at a few minutes' drive from Calabar Metropolis. The quarry dust had a specific gravity of 2.52.

The Design of the Experiment

A software [29] was used in designing the experiment using an augmented {4,2} schefee's simplex lattice design. The design simplex is shown in Figure 1 while the design is presented in Table 1. The design contained ten mixes at the vertices and edge of tetrahedron, augmented with five more mixes within the simplex. These five points were used as check point to validate the model developed. There were also replicate points at the vertices and centroid of the tetrahedron, making it a total of twenty point. The design was based on pseudo component and applying randomization.

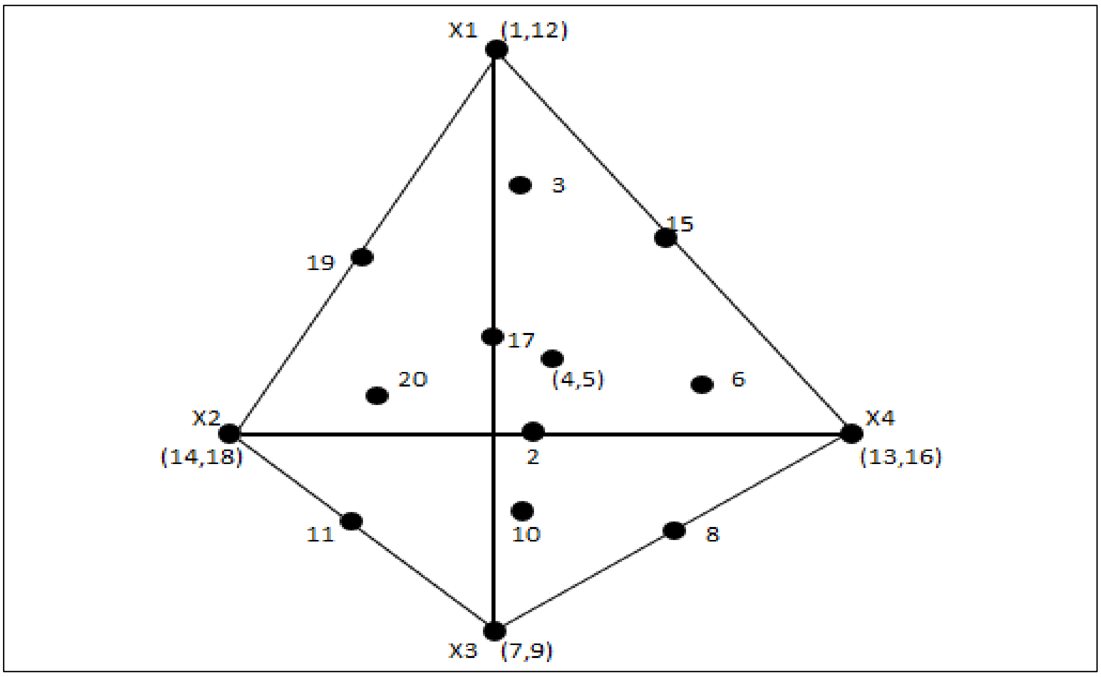


Fig 1: Augmented {4, 2} Scheffe's simplex lattice showing the points and run order

Table 1: Design matrix for {4, 2} Augmented simplex lattice (Psuedo component)

Run Order	Std Order	Pt Type	Blocks	Water (X1)	Cement (X2)	Quarry dust (X3)	Laterite (X4)
1	5	1	1	0	1	0	0
2	11	0	1	0.25	0.25	0.25	0.25
3	16	1	1	1	0	0	0
4	3	2	1	0.5	0	0.5	0
5	7	2	1	0	0.5	0	0.5
6	4	2	1	0.5	0	0	0.5
7	8	1	1	0	0	1	0
8	15	-1	1	0.125	0.125	0.125	0.625
9	2	2	1	0.5	0.5	0	0
10	9	2	1	0	0	0.5	0.5
11	17	1	1	0	1	0	0
12	10	1	1	0	0	0	1
13	1	1	1	1	0	0	0
14	6	2	1	0	0.5	0.5	0
15	19	1	1	0	0	0	1

Run Order	Std Order	Pt Type	Blocks	Water (X1)	Cement (X2)	Quarry dust (X3)	Laterite (X4)
16	12	-1	1	0.625	0.125	0.125	0.125
17	18	1	1	0	0	1	0
18	20	0	1	0.25	0.25	0.25	0.25
19	13	-1	1	0.125	0.625	0.125	0.125
20	14	-1	1	0.125	0.125	0.625	0.125

Legend:
Pt Type 1 = Vertex; Pt Type 2 = Midpoint of an edge; Pt Type 0 = Centroid of the simplex; Pt Type -1 = Axial point (Midway between the centroid and the vertex)

Components Transformation and Production of Laterite-quarry dust cement Blocks

The pseudo ratio was converted to real component ratio used for the production of the blocks.

The relationship between the real component ratios and the pseudo components is indicated by the relation:

$$\boldsymbol{R} = \boldsymbol{AP} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Where; $\boldsymbol{R}$ is a vector containing the real ratios of the components, $\boldsymbol{P}$ is a vector containing the pseudo ratios, $\boldsymbol{A}$ is a transformation matrix which can be obtained from trial mixes given as thus:

$$\boldsymbol{A} = \begin{pmatrix} 0.53 & 0.63 & 0.80 & 0.9 \\ 1 & 1 & 1 & 1 \\ 5.4 & 3 & 9 & 5 \\ 0.6 & 3 & 1 & 5 \end{pmatrix}$$

The element of each column of [A] represents the components proportions at the vertex in the following order Water(X1), Cement (X2), Quarry dust(X3) and Laterite (X4). A total of one hundred and twenty (120) hollow blocks of size 450mm x 225mm x 225mm overall dimensions, were produced using a Vibrating block moulding machine. The surface area of the solid portion of the blocks is 56250mm^2, representing approximately 55% of the total surface area of the block. The aggregates were used in their dry state and batching was by weight. Manual mixing was employed. The blocks were cured in open air for 28 days by sprinkling them with water, twice daily. Sixty blocks each (three for each run) were used to determine the different strength properties. The remaining 20 were for exigencies.

Cost of Production of 1m^3 of laterite-Quarry Dust Mixes

To determine the production cost of the blocks, two primary expenses were taken into consideration: material costs and labour/overhead costs (Anya, 2015). Calculating the material cost for producing 1m^3 of each mix involved multiplying the quantities of each constituent in a cubic meter of the mix by their respective current market prices. The total material cost was then increased by 60% to accommodate for labour and overhead expenses. The quantities of materials per cubic meter of the mixes were derived from the average densities obtained for each mix. Table 2 presents the quantities of constituents necessary to produce 1m^3 of each mix, based on their respective densities. It's important to note that material costs may vary depending on the location.

The volume of a block is 56250 x 225 = 12656250mm^3 = 0.01266m^3.

The number of blocks per m^3, N_b, is therefore given as: 1/ volume of a sample block

$$N_b = \frac{1}{0.0127} = 78.125 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The cost of a block C_b is obtained from the relation:

$$C_b = \frac{C_m}{78.740} = 0.0127C_m \quad \ldots\ldots\ldots\ldots\ldots.. (7)$$

Where

C_m is the cost per cubic meter of a mix.

Table 2: Quantities of materials required for the production of 1m^3 of actual mix ratios

Run Order	Std Order	Average density (kg/m^3)	Actual mix ratios				Quantity of material (Kg/m^3)			
			Water	Cement	Quarry dust	laterite	Water	Cement	Quarry dust	Laterite
1	5	1823	0.63	1.0	3.0	3.0	150.53	238.93	716.80	716.78
2	11	1890	0.72	1.0	5.6	2.4	140.00	194.44	1088.86	450.12
3	16	1962	0.54	1.0	5.4	0.6	140.50	260.19	1405.02	145.07
4	3	1899	0.67	1.0	7.2	0.8	131.55	196.34	1413.67	150.82
5	7	1909	0.77	1.0	4.0	4.0	150.45	195.38	781.53	746.37
6	4	1884	0.72	1.0	5.2	2.8	139.59	193.87	1008.12	525.14
7	8	1962	0.8	1.0	9.0	1.0	133.02	166.28	1496.51	154.49
8	15	1945	0.81	1.0	5.3	3.7	145.74	179.92	953.59	623.97
9	2	1894	0.585	1.0	4.2	1.8	146.11	249.76	1048.99	432.62
10	9	1943	0.85	1.0	7.0	3.0	139.36	163.95	1147.68	461.52

Run Order	Std Order	Average density (kg/m^3)	Actual mix ratios				Quantity of material (Kg/m^3)			
			Water	Cement	Quarry dust	laterite	Water	Cement	Quarry dust	Laterite
11	17	1836	0.63	1.0	3.0	3.0	151.64	240.69	722.08	716.78
12	10	1860	0.9	1.0	5.0	5.0	140.69	156.32	781.59	765.97
13	1	1926	0.54	1.0	5.4	0.6	137.94	255.44	1379.37	145.07
14	6	1958	0.72	1.0	6.0	2.0	145.07	201.48	1208.89	375.10
15	19	1930	0.9	1.0	5.0	5.0	146.00	162.23	811.13	765.97
16	12	1961	0.63	1.0	5.5	1.5	143.14	227.20	1249.62	316.86
17	18	1959	0.8	1.0	9.0	1.0	132.84	166.06	1494.50	154.49
18	20	1883	0.72	1.0	5.6	2.4	139.45	193.68	1084.61	450.12
19	13	1972	0.674	1.0	4.3	2.7	153.24	227.36	977.63	567.45
20	14	1945	0.76	1.0	7.3	1.7	137.36	180.73	1319.37	288.02

3.0 RESULT AND DISCUSSION

The pseudo components, actual mix ratio and response from cost of a cubic meter are contained in Table 3.

Table 3: The pseudo components, actual mix ratio and response from cubic meter

Run Order	Std Order	Pseudo components				actual mix				Response
		Water	Cement	Quarry dust	Laterite X_4	Water	Cement	Quarry dust	Laterite	Cost per m^3
		(X_1)	(X_2)	(X_3)						(N)
1	5	0	1	0	0	0.63	1	3	3	9827.35
2	11	0.25	0.25	0.25	0.25	0.72	1	5.6	2.4	9784.14
3	16	1	0	0	0	0.54	1	5.4	0.6	12863.72
4	3	0.5	0	0.5	0	0.67	1	7.2	0.8	10969.65
5	7	0	0.5	0	0.5	0.77	1	4	4	8747.33
6	4	0.5	0	0	0.5	0.72	1	5.2	2.8	9484.10
7	8	0	0	1	0	0.8	1	9	1	10359.14
8	15	0.125	0.125	0.125	0.625	0.81	1	5.3	3.7	8881.01
9	2	0.5	0.5	0	0	0.585	1	4.2	1.8	11310.31
10	9	0	0	0.5	0.5	0.85	1	7	3	9074.90
11	17	0	1	0	0	0.63	1	3	3	9899.73
12	10	0	0	0	1	0.9	1	5	5	7565.81
13	1	1	0	0	0	0.54	1	5.4	0.6	12628.93
14	6	0	0.5	0.5	0	0.72	1	6	2	10420.62
15	19	0	0	0	1	0.9	1	5	5	7851.74
16	12	0.625	0.125	0.125	0.125	0.63	1	5.5	1.5	11332.93
17	18	0	0	1	0	0.8	1	9	1	10345.24
18	20	0.25	0.25	0.25	0.25	0.72	1	5.6	2.4	9745.98
19	13	0.125	0.625	0.125	0.125	0.674	1	4.3	2.7	10395.65
20	14	0.125	0.125	0.625	0.125	0.76	1	7.3	1.7	10177.18

Development of Cost Model for Laterite –Quarry Dust Cement Block

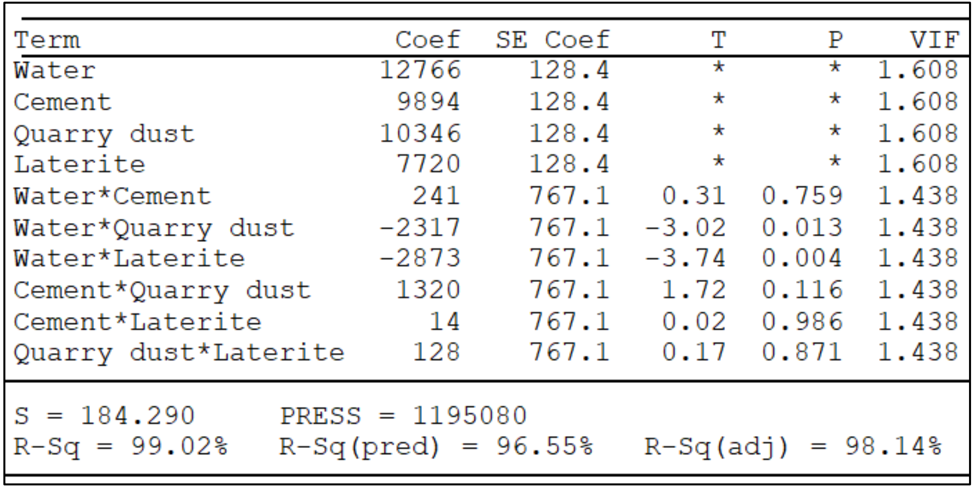
A second degree model (equation (4), was fitted to the data set of the 20 cost test responses at 95% confidence limit (α) using Minitab. The parameter estimate of the coefficients and analysis of variance tables are shown in tables 4 and 5 respectively, while the normal probability plot of the residual is shown in Fig 2.

The model equation for cost is therefore given as thus

$$\hat{y} = 12765.50X_1 + 9894.10X_2 + 10346.20X_3 + 7719.50X_4 + 241.40X_1X_2 - 2317.40X_1X_3 - 2872.60X_1X_4 + 1320.1X_2X_3 + 13.90X_2X_4 + 128.10X_3X_4 \quad \ldots\ldots (8)$$

The p-value for lack-of-fit being 0.088 which is greater than α (0.05). The normal probability plot of the residual in Figure 2, reveals that the residuals fall reasonably close to the reference line, with a p- value of 0.411 (> 0.05), indicating that the data follow a normal distribution, hence justifying the assumption required for use of analysis of variance. The inference drawn from here is that, equation (8) is adequate for predicting the cost per cubic meter of laterite-quarry dust blocks.

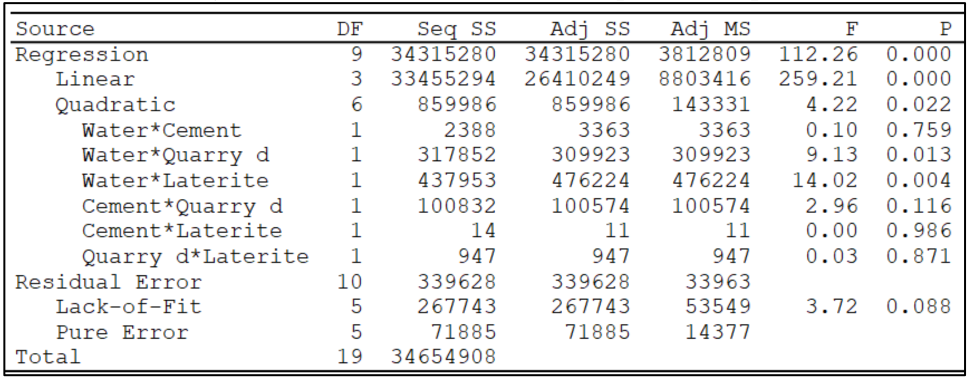
Table 4: Estimated Regression Coefficients for Cost(N/cum) (Scheffe's Pseudo components)



```
Term                         Coef  SE Coef      T      P    VIF
Water                       12766    128.4      *      *  1.608
Cement                       9894    128.4      *      *  1.608
Quarry dust                 10346    128.4      *      *  1.608
Laterite                     7720    128.4      *      *  1.608
Water*Cement                  241    767.1   0.31  0.759  1.438
Water*Quarry dust           -2317    767.1  -3.02  0.013  1.438
Water*Laterite              -2873    767.1  -3.74  0.004  1.438
Cement*Quarry dust           1320    767.1   1.72  0.116  1.438
Cement*Laterite                14    767.1   0.02  0.986  1.438
Quarry dust*Laterite          128    767.1   0.17  0.871  1.438

S = 184.290     PRESS = 1195080
R-Sq = 99.02%   R-Sq(pred) = 96.55%    R-Sq(adj) = 98.14%
```

Table 5: Analysis of Variance for Cost (Scheffe's pseudo component model)



```
Source                   DF    Seq SS    Adj SS    Adj MS       F      P
Regression                9  34315280  34315280   3812809  112.26  0.000
   Linear                 3  33455294  26410249   8803416  259.21  0.000
   Quadratic              6    859986    859986    143331    4.22  0.022
     Water*Cement         1      2388      3363      3363    0.10  0.759
     Water*Quarry d       1    317852    309923    309923    9.13  0.013
     Water*Laterite       1    437953    476224    476224   14.02  0.004
     Cement*Quarry d      1    100832    100574    100574    2.96  0.116
     Cement*Laterite      1        14        11        11    0.00  0.986
     Quarry d*Laterite    1       947       947       947    0.03  0.871
Residual Error           10    339628    339628     33963
   Lack-of-Fit            5    267743    267743     53549    3.72  0.088
   Pure Error             5     71885     71885     14377
Total                    19  34654908
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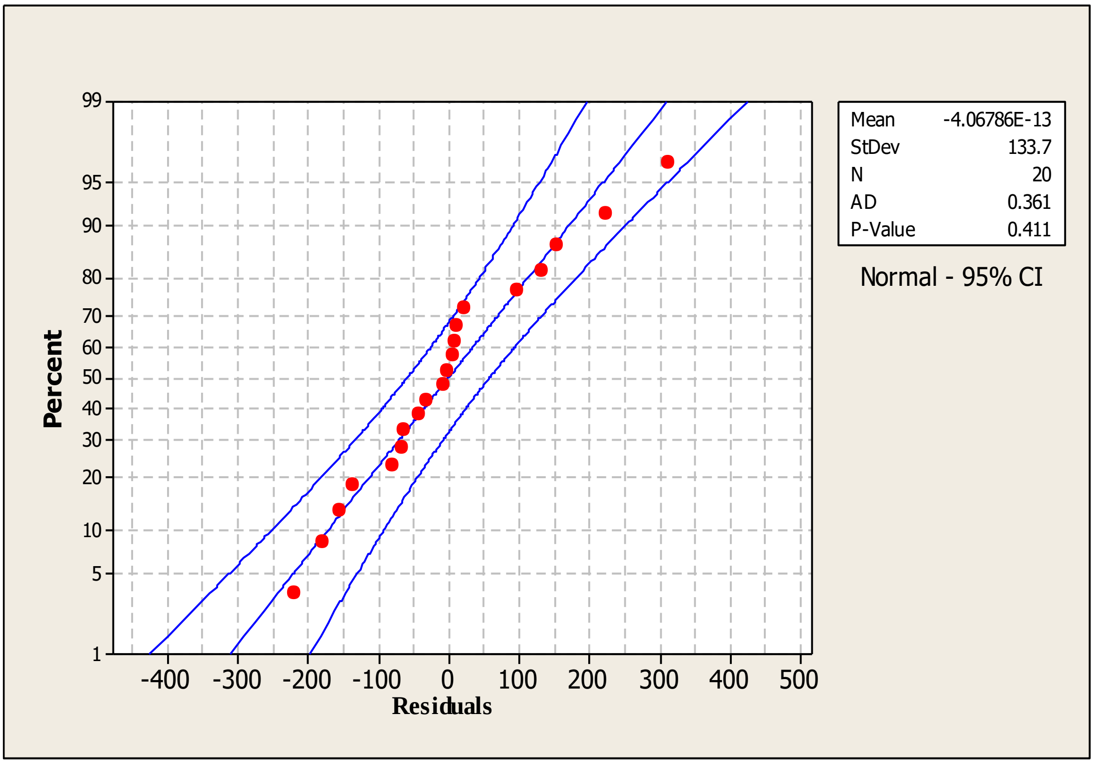

Figure 2: Normal probability plot for Cost residuals (Scheffe's pseudo component)

Table 4.4: Cost estimates for 1m^3 of the different Actual mix ratios

Run Order	**Std Order**	**Quantity of materials (Kg/m^3)**				**Cost of materials (Naira) for 1m^3 of mix**				**Total cost of materials**	**Cost per block**
		Water	**Cement**	**Quarry dust**	**Laterite**	**Water**	**Cement**	**quarry dust**	**Laterite**	**(Naira)**	**(Naira)**
1	5	150.53	238.93	716.80	716.78	150.53	7168.01	1433.60	1075.20	9827.35	125.79
2	11	140.00	194.44	1088.86	450.12	140.00	5833.15	2177.71	1633.28	9784.14	125.24
3	16	140.50	260.19	1405.02	145.07	140.50	7805.66	2810.04	2107.53	12863.72	164.66
4	3	131.55	196.34	1413.67	150.82	131.55	5890.27	2827.33	2120.50	10969.65	140.41
5	7	150.45	195.38	781.53	746.37	150.45	5861.51	1563.07	1172.30	8747.33	111.97
6	4	139.59	193.87	1008.12	525.14	139.59	5816.09	2016.24	1512.18	9484.10	121.40
7	8	133.02	166.28	1496.51	154.49	133.02	4988.35	2993.01	2244.76	10359.14	132.60
8	15	145.74	179.92	953.59	623.97	145.74	5397.70	1907.19	1430.39	8881.01	113.68
9	2	146.11	249.76	1048.99	432.62	146.11	7492.75	2097.97	1573.48	11310.31	144.77
10	9	139.36	163.95	1147.68	461.52	139.36	4918.65	2295.37	1721.53	9074.90	116.16
11	17	151.64	240.69	722.08	716.78	151.64	7220.81	1444.16	1083.12	9899.73	126.72
12	10	140.69	156.32	781.59	765.97	140.69	4689.55	1563.18	1172.39	7565.81	96.84
13	1	137.94	255.44	1379.37	145.07	137.94	7663.19	2758.75	2069.06	12628.93	161.65
14	6	145.07	201.48	1208.89	375.10	145.07	6044.44	2417.78	1813.33	10420.62	133.38
15	19	146.00	162.23	811.13	765.97	146.00	4866.78	1622.26	1216.70	7851.74	100.50
16	12	143.14	227.20	1249.62	316.86	143.14	6816.11	2499.24	1874.43	11332.93	145.06
17	18	132.84	166.06	1494.50	154.49	132.84	4981.66	2988.99	2241.75	10345.24	132.42
18	20	139.45	193.68	1084.61	450.12	139.45	5810.40	2169.22	1626.91	9745.98	124.75
19	13	153.24	227.36	977.63	567.45	153.24	6820.70	1955.27	1466.45	10395.65	133.06
20	14	137.36	180.73	1319.37	288.02	137.36	5422.05	2638.73	1979.05	10177.18	130.27

4.0 CONCLUSION AND RECOMMENDATION

A mathematical model for the prediction of *cost per cubic meter* of elasticity of laterite-quarry dust cement blocks was developed in this work. The model can be used to predict the cost per cubic *meter* of laterite-quarry dust cement blocks. The use of laterite-quarry dust cement will help greatly in reducing the cost associated with providing affordable housing for most sub-Sahara African especially where there is abundant deposit of these materials.

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