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MODELS FOR PREDICTING COMPRESSIVE STRENGTH AND WATER ABSORPTION OF LATERITE-QUARRY DUST CEMENT BLOCK USING MIXTURE EXPERIMENT

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ABSTRACT
The use of laterite, quarry dust and recycle aggregates etc as replacement for sand in sandcrete block production is common trend in developing countries like Nigeria. Most resources and research efforts are committed towards conducting trial test with a view to coming up with mix production that will yield the desired property. This work presents a mathematical model for predicting the compressive strength and water absorption of laterite-quarry dust cement block using augmented Scheffe's simplex lattice design. The statistical models developed can predict the mix proportion that will yield the desired property. The models were tested for lack of fit and found to be adequate.

Keywords: *compressive strength, laterite, mixture experiment, quarry dust, water absorption*

1. INTRODUCTION

Sandcrete blocks are extensively used in construction of buildings and other structures for the service of man. Being a very important construction material, it is expedient that its quality and durability be of paramount concern to designers, builders, and other users of structures made with them. As the demand for natural sand continue to increase on daily basis, arising from the building and construction of new infrastructure and expansion of existing ones, the construction industries of most developing countries are compelled to identify alternative materials in order to lessen or eliminate the demand for natural sand. Laterite and quarry dust are some of the materials that have been identified as suitable alternatives and are now being used either partially or wholly in block production. Their consideration as alternatives to natural sand is informed by the fact that natural sand mining on either side of the rivers, upstream or in-stream is one of the causes of environmental degradation and also a threat to biodiversity. The alarming rate of unrestricted sand mining which damages the ecosystem of natural habitants of organisms living on the riverbeds, affects fish breeding and migration, spells disaster for the conservation of many birds species and increases saline water in the rivers [1]. Further, the demand for sand for construction according to Asiedu et al [2], has led to continuous increase in the cost of construction. Hence utilizing laterite and quarry dust either partially or wholly as substitutes for natural sand in the production of sandcrete blocks can significantly bring down the cost of construction.

Recently, in most major cities across Nigeria, manufacturers of sandcrete blocks have resorted to utilizing a combination of quarry dust and laterite to replace natural sand, and at other occasions, a combination of natural sand, laterite and quarry dust for the production of sandcrete blocks used in the construction of buildings and structures. Producers of sandcrete blocks that utilize these materials use arbitrary mixes and the strength of blocks produced using this combination of quarry dust and lateritic sand as replacement for natural sand cannot be guaranteed. The appropriate mix of laterite and quarry dust or the three is not known. Drawing from the forgoing therefore, the study addresses these gaps and concerns raised.

While the effect of separate inclusion of laterite and quarry dust in sandcrete blocks has been addressed and documented by several researchers, [3, 4], works that combine laterite and quarry dust in sandcrete blocks or concrete are few. One of such work was that by [5] and [6] that utilizes a blend of quarry dust and laterite as full replacement in concrete. The study gave the proportion of 25% laterite and 75% quarry dust as optimum in concrete. There is also lack of appreciation for the role of water in the mix. Most often, as also found in some documented researches, water is added based on

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discretion. This has made replication of such works difficult.

Moreover, there exist no models that predict the strength and other properties of sandcrete blocks made with laterite and quarry dust blend as full replacement for natural sand. The importance of such models cannot be over-emphasized, as they will help in mix proportioning and cater for cost always associated with laborious laboratory trial mixes. The uniqueness of this study is that, while other studies have focused on separate inclusion of quarry dust and laterite in block as partial or full replacement for natural sand, this study investigated the use of laterite and quarry dust blend as full replacement to natural sand in the production building blocks.

2. MIXTURE EXPERIMENT AND SCHEFFE'S EQUATIONS

Mixture experiments are a special class of response surface experiments where the product under investigation is made up of several components or ingredients. In this instance, the response is a function of the proportions of the different ingredients in the mixture.

Cornel [7] describes a mixture experiment as ''that which the response is assumed to be dependent on relative proportions of the constituent materials and not on their total amount.'' The two basic requirements that must be fulfilled 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 thus:

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

$$0 \le X_i \le 1 \qquad (2)$$

In (1) and (2), q is the number of mixture components. and 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 proportions of the constituents is constrained to 1, only *q-1* of the variables or constituents can be independently chosen.

A lot of mixture experiment model have been formulated by researchers. One of such model which is most popular is the Scheffe's simplex lattice design. The canonical form of the Scheffe's [8] polynomial equations for second degree is reproduced in the form below:

$$\hat{y} = \sum_{1 \le i \le q} \beta_i X_i + \sum_{1 \le i \le j \le q} \beta_{ij} X_i X_j \qquad (3)$$

In (3), $\hat{y}$ is the response function and $\mathcal{X}$i(i= 1 to q) is the proportion of component in the mixture. The second degree polynomial is the most commonly used polynomial to fitting mixture experiment data. For a four component mixture, canonical equation can be given as:

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

The estimated coefficients in canonical equation are obtained from a regression analysis of the mixture 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 models have been formulated and applied in many real life situations to solve problems in fields such as Medicine, Pharmacy, Food industry, agriculture and engineering. Osadebe et al [9] formulated a mathematical model for optimization of compressive strength of sand-laterite blocks using Osadebe regression method. Other forms of mixture models that have been formulated as regards sandcrete blocks and concrete are [10 – 22].

2.1 Materials and Methods

The materials used for this work are:

Cement: Ordinary Portland cement, grade 32.5N obtained from a major dealer in Calabar conforming to BS 12 was used for all the tests.

Water: Potable pipe born water supplied by the Cross River State Water Board (CRSWB) limited was used for both specimen preparations and curing.

Laterite: Laterite was obtained from a borrow pit site at Akim- Akim in Odukpani Local Government area of Cross River State. The specific gravity of the laterite was 2.56.

Quarry dust: Quarry dust was obtained from the abundant deposits at Akamkpa quarry site in Akamkpa Local Government area of Cross River State, a few minutes drive from Calabar metropolis. The quarry dust had a specific gravity of 2.52.

2.2 Exprimental design

Minitab 16 [23], a statistical software was used in designing the experiment using an augmented {4, 2} schefee's simplex lattice design. The design simplex is shown in Figure 1 whereas the design matrix of the augmented {4, 2} simplex is shown in Table 1. The design contains ten mixes at the vertices and edge of the tetrahedron, augmented with five more mixes within the simplex. These five points were used as check points to validate the models developed. There were also replicate points at the vertices and centriod of the tetrahedron, making it a total of twenty points. The design was based on pseudo component and randomization was applied.

2.2.1 Components Transformation and Moulding of the Blocks

The pseudo ratio was transformed to real component ratios used for the moulding of the blocks. The relationship between the real component ratios and the pseudo components is as indicated below:

$$R = AP \qquad (6)$$

In (6), R is a vector containing the real ratios of the components, P is a vector containing the pseudo ratios and A is a transformation matrix which can be obtained from trial mixes given as:

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

The element of each column of [A] represents the components proportions at the vertex in the following order Water(X_1), cement (X_2), quarry dust(X_3) and Laterite (X_4).

A total of one hundred and twenty (120) hollow blocks, 450mm x 225mm x 225mm overall dimensions, were moulded using a Vibrating block moulding machine. The surface area of the solid portion of the blocks is 56250mm^2, representing approximately 55% 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 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 compressive strength and water absorption. The remaining 20 were for contingencies.

2.2.2Compressive Strength and Water absorption

The compressive strength of a block is possibly one of the most important strength properties used to judge the overall quality of the block. The compressive strength is also helpful in determining other properties of block with few exceptions. It was determined by BS [24] where the hardened block, after appropriate curing (28 days), is subjected to increasing compressive load until it failed by crushing, and determining the crushing force. Mathematically, it is given as:

$$fc = F/A \qquad (7)$$

In (7), fc is the Compressive Strength, F is the Crushing load and A is the Cross sectional area of the test specimen.

Water absorption was carried out in accordance with the requirement of [25]. It is expressed as the difference between the weight before and after immersion, expressed as a percentage of the dry weight. Mathematically, the water absorption is given as:

$$W_a = \frac{W_d - W_s}{W_d} \times 100\% \qquad (8)$$

Here, W_a is the Water absorption, W_d is the Dry weight of block, and W_s is the Weight of block after soaking in water for 24 hours

3. RESULTS AND DISCUSSIONS

The pseudo components, actual mix ratios and the response from compressive strength and water absorption tests are shown in Table 1.

3.1 Model Development for Compressive Strength

The second degree model (equation (1)), was fitted to the data set of the 20 compressive test responses at 95% confidence limit (α=0.05) using[23]. The parameter estimate of the coefficients and analysis of variance tables are shown in table 2 and 3 respectively, while the normal probability plot of the residual is shown in Fig 2. The model for compressive strength is therefore:

$$\begin{aligned} \hat{y} = 2.4489X_1 + 1.8797X_2 + 1.8500X_3 + 2.1997X_4 \\ + 1.1162X_1X_2 + 0.4207X_1X_3 \\ + 0.2791X_1X_4 + 2.7656X_2X_3 \\ + 1.4236X_2X_4 + 0.3256X_3X_4 \qquad (9) \end{aligned}$$

The *p-value* for lack-of-fit being 0.729 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 0.151 ($>$ 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 (9) is adequate for predicting the 28th day strength of laterite-quarry dust blocks.

Model for Water Absorption

Again using the data in Table 1 a model equation for water absorption is given as:

$$\begin{aligned} \hat{y} = 8.55X_1 + 5.41X_2 + 7.58X_3 + 7.50X_4 - 0.64X_1X_2 \\ - 12.96X_1X_3 - 5.70X_1X_4 + 4.45X_2X_3 \\ + 7.16X_2X_4 - 0.33X_3X_4 \qquad (10) \end{aligned}$$

The model shows that there is insignificant lack-of-fit, the *p-value* for lack-of-fit being 0.855 which is greater than 0.05 and therefore adequate for predicting the 28th day Water absorption of laterite-quarry dust blocks. The normal probability plot of the residuals is shown in Figure 3. It shows that the points fall reasonably close to the reference line and follows a normal distribution with a *p-value* of 0.054 ($>$ 0.05).

4. CONCLUSION AND RECOMMENDATION

Mathematical models for predicting the compressive strength and water absorption of laterite-quarry dust cement blocks were developed in this work. The models can be used to predict the compressive strength of blocks ranging from 1.81 to 2.56N/mm^2. The use of these models will greatly help Nigerian block producers to meet the minimum Nigerian Industrial Standard, [26] recommended values for compressive strength and water absorption. The models also help in reducing the time and energy usually wasted in trial mix.

Table 1: The pseudo components, actual mix ratios and the responses from compressive strength and water absorptions

Run Order	Std Order	Pseudo Component				Actual mix ratio				Responses	
		Water (X1)	Cement (X2)	Quarry dust (X3)	Laterite (X4)	Water (X1)	Cement (X2)	Quarry dust (X3)	Laterite (X4)	Y_c(Nmm-2	Y(w%)
1	5	0	1	0	0	0.63	1	3	3	1.87	5.52
2	11	0.25	0.25	0.25	0.25	0.72	1	5.6	2.4	2.56	5.87
3	16	1	0	0	0	0.54	1	5.4	0.6	2.5	8.09
4	3	0.5	0	0.5	0	0.67	1	7.2	0.8	2.24	5.06
5	7	0	0.5	0	0.5	0.77	1	4	4	2.37	8.4
6	4	0.5	0	0	0.5	0.72	1	5.2	2.8	2.37	6.9
7	8	0	0	1	0	0.8	1	9	1	1.81	6.35
8	15	0.125	0.125	0.125	0.625	0.81	1	5.3	3.7	2.42	7.2
9	2	0.5	0.5	0	0	0.585	1	4.2	1.8	2.56	7.02
10	9	0	0	0.5	0.5	0.85	1	7	3	2.09	7.65
11	17	0	1	0	0	0.63	1	3	3	1.89	5.13
12	10	0	0	0	1	0.9	1	5	5	2.2	7.74
13	1	1	0	0	0	0.54	1	5.4	0.6	2.45	8.99
14	6	0	0.5	0.5	0	0.72	1	6	2	2.54	7.7
15	19	0	0	0	1	0.9	1	5	5	2.2	7.2
16	12	0.625	0.125	0.125	0.125	0.63	1	5.5	1.5	2.56	6.26
17	18	0	0	1	0	0.8	1	9	1	1.9	8.18
18	20	0.25	0.25	0.25	0.25	0.72	1	5.6	2.4	2.49	6.91
19	13	0.125	0.625	0.125	0.125	0.674	1	4.3	2.7	2.5	7.15
20	14	0.125	0.125	0.625	0.125	0.76	1	7.3	1.7	2.3	6.86

Table 2: Estimated Regression Coefficients for Compressive strength (pseudo components)

Term	Coef	SE Coef	T	P	VIF
Water	2.4489	0.02978	*	*	1.608
Cement	1.8797	0.02978	*	*	1.608
Quarry dust	1.8500	0.02978	*	*	1.608
Laterite	2.1997	0.02978	*	*	1.608
Water*Cement	1.6791	0.17793	9.44	0.000	1.438
Water*Quarry dust	0.4207	0.17793	2.36	0.040	1.438
Water*Laterite	0.2791	0.17793	1.57	0.148	1.438
Cement*Quarry dust	2.7656	0.17793	15.54	0.000	1.438
Cement*Laterite	1.4239	0.17793	8.00	0.000	1.438
Quarry dust*Laterite	0.3256	0.17793	1.83	0.097	1.438

S = 0.0427451 PRESS = 0.152307

R-Sq = 98.51% R-Sq(pred) = 87.61% R-Sq(adj) = 97.17%

Table 3: Analysis of Variance for Compressive Strength (pseudo components)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	1.21058	1.210584	0.134509	73.62	0.000
Linear	3	0.41479	0.498662	0.166221	90.97	0.000
Quadratic	6	0.79579	0.795793	0.132632	72.59	0.000
Water*Cement	1	0.18407	0.162708	0.162708	89.05	0.000
Water*Quarry d	1	0.02135	0.010215	0.010215	5.59	0.040
Water*Laterite	1	0.01906	0.004495	0.004495	2.46	0.148
Cement*Quarry d	1	0.44759	0.441402	0.441402	241.58	0.000
Cement*Laterite	1	0.11761	0.117018	0.117018	64.04	0.000
Quarry d*Laterite	1	0.00612	0.006117	0.006117	3.35	0.097
Residual Error	10	0.01827	0.018271	0.001827		
Lack-of-Fit	5	0.00657	0.006571	0.001314	0.56	0.729
Pure Error	5	0.01170	0.011700	0.002340		
Total	19	1.22885				

Table 4: Estimated Regression Coefficients for water absorption (Scheffe's pseudo components)

Term	Coef	SE Coef	T	P	VIF
Water	8.55	0.3685	*	*	1.608
Cement	5.41	0.3685	*	*	1.608
Quarry dust	7.58	0.3685	*	*	1.608
Laterite	7.50	0.3685	*	*	1.608
Water*Cement	-0.64	2.2012	-0.29	0.777	1.438
Water*Quarry dust	-12.96	2.2012	-5.89	0.000	1.438
Water*Laterite	-5.70	2.2012	-2.59	0.027	1.438
Cement*Quarry dust	4.45	2.2012	2.02	0.071	1.438
Cement*Laterite	7.16	2.2012	3.25	0.009	1.438
Quarry dust*Laterite	-0.33	2.2012	-0.15	0.885	1.438

S = 0.528812 PRESS = 17.9427

R-Sq = 86.92% R-Sq(pred) = 16.06% R-Sq(adj) = 75.14%

Table 5:Analysis of Variance for water absorption (Schefee's pseudo components)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	18.5797	18.5797	2.06441	7.38	0.002
Linear	3	4.0461	10.8153	3.60510	12.89	0.001
Quadratic	6	14.5335	14.5335	2.42225	8.66	0.002
Water*Cement	1	0.0344	0.0237	0.02372	0.08	0.777
Water*Quarry d	1	8.7917	9.7007	9.70067	34.69	0.000
Water*Laterite	1	1.5638	1.8744	1.87435	6.70	0.027
Cement*Quarry d	1	1.1828	1.1441	1.14408	4.09	0.071
Cement*Laterite	1	2.9547	2.9573	2.95728	10.58	0.009
Quarry d*Laterite	1	0.0061	0.0061	0.00611	0.02	0.885
Residual Error	10	2.7964	2.7964	0.27964		
Lack-of-Fit	5	0.7443	0.7443	0.14887	0.36	0.855
Pure Error	5	2.0521	2.0521	0.41042		
Total	19	21.3761				

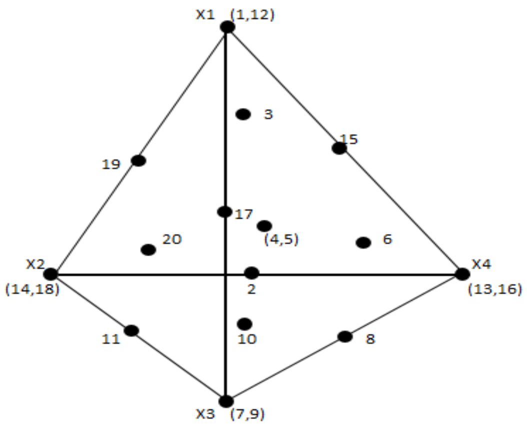

Fig 1: an augmented {4, 2} Simplex lattice showing the design points

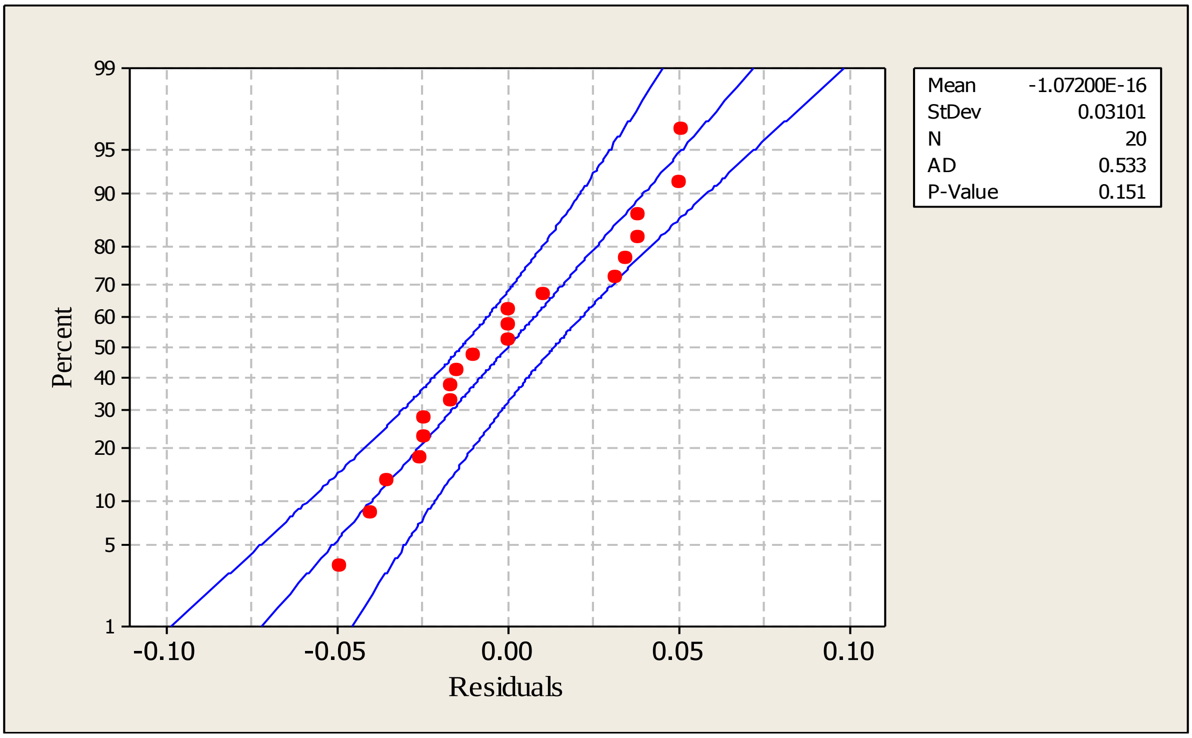

Fig 2: Normal probability plot for compressive strength residual (Scheffe's pseudo component model)

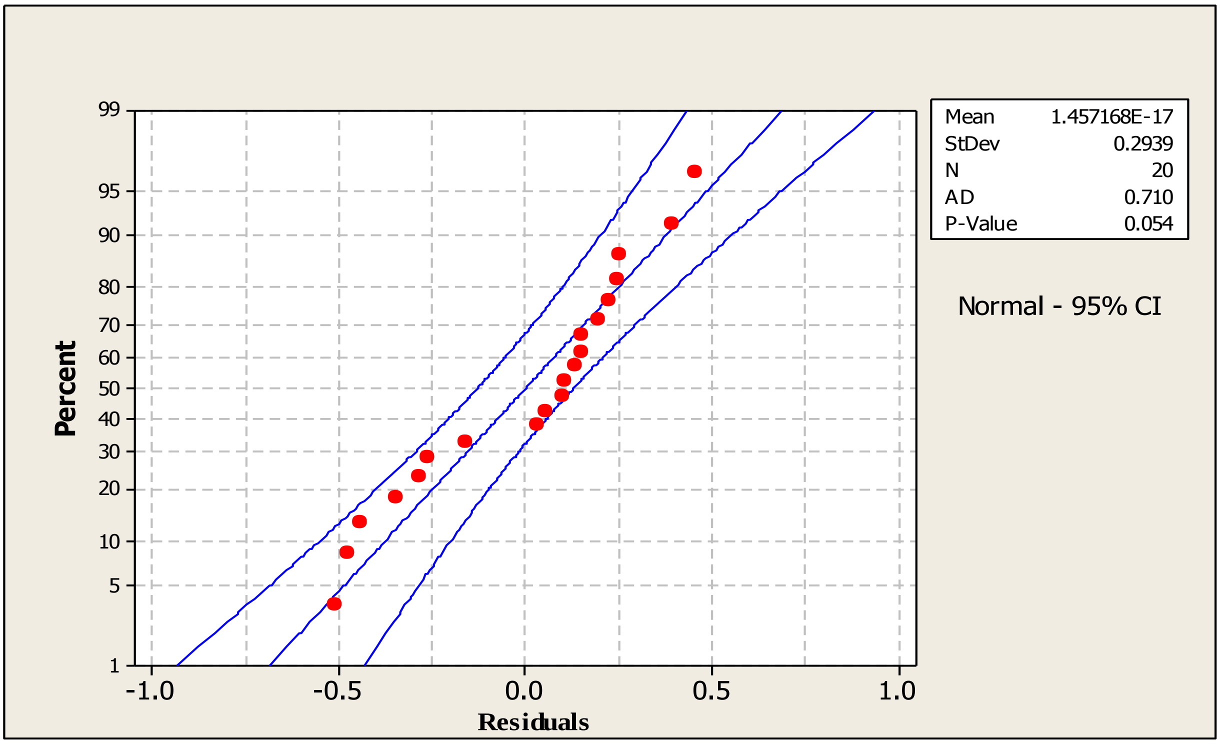

Fig 3: Normal probability plot for water absorption residual (Scheffe's pseudo components model)

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