Quest Journals
Journal of Architecture and Civil Engineering
Volume 9 ~ Issue 8 (2024) pp: 25-37
ISSN(Online) : 2321-8193
www.questjournals.org

Research Paper

The mathematical model for the optimization of compressive strength of sawdust ash geopolymer concrete

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***ABSTRACT**: Geopolymer concrete offers an eco-friendlier option compared to traditional cement, as it lowers greenhouse gas emissions during production. It consists of an alkaline solution with sodium or potassium silicate and sodium or potassium hydroxide, as well as a source material abundant in silica and alumina. For this study, thirty geopolymer concrete samples were produced in the lab using a mix design approach from Scheffe's (5,2) model. The focus of the research was on maximizing the compressive strength of the concrete, especially when incorporating sawdust ash as the source material. The findings indicated that subjecting sawdust ash to pyrolysis in the absence of oxygen significantly impacts its pozzolanic properties and, consequently, the characteristics of the concrete. The research determined the optimal compressive strength of geopolymer concrete incorporating sawdust ash to be 21.673 MPa, along with specific concentration ratios of NaOH, Na2SiO4 to NaOH, sawdust ash in the binder, water to binder, and activator to sawdust ash at 10.5415, 2.0446, 38.6307, 0.0363, and 2.5882 respectively. Furthermore, MATLAB-based computer programs were utilized to optimize and forecast the ideal mixture proportions for sawdust ash-based geopolymer concrete.*

***Keywords:** Sawdust ash, geopolymer, pozzolanic property, Optimization, Prediction, optimum parameter*

***R**eceived 13 Aug., 2024; **R**evised 25 Aug., 2024; **A**ccepted 27 Aug., 2024 © The author(s) 2024.*
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I. INTRODUCTION

Throughout an extended period, ordinary Portland cement has served as a binding element in the creation of ordinary Portland concrete (OPC). The growing infrastructure needs in numerous developing nations, coupled with the rising number of aging, deteriorating concrete structures in urgent need of repair and rehabilitation, are adding to the expected surge in demand for OPC. Nevertheless, Mehta [1] disclosed that the cement industry contributes to nearly seven percent (7%) of global greenhouse gas emissions and generates millions of tons of waste annually. Pearce [2] recently declared that anthropogenic greenhouse gas emissions from the cement industry represent 8% of the world's annual greenhouse gases. In line with the findings of Hardjito [3], the production of one metric ton of Portland cement discharges approximately one ton of carbon dioxide (CO_2) into the environment.

The originator of geopolymer concrete, Davidovits [4], introduced the concept of developing binders by combining silicon (Si) and aluminum (Al) in a geologically-derived source material or in by-product materials like flue ashes and rice husk ash. He termed these binders "geopolymers" to signify the polymerization process involved in the chemical reaction. Geopolymer binders, an alternative to traditional cement, are formed by blending pozzolanic precursors such as flue ashes and occasionally sawdust ash, which are abundant in silica and alumina, with an alkaline solution to initiate the process [5], [6], [7], [8] & [9].

The cement industry cannot be deemed sustainable due to its dependence on raw materials acquired through mining, which adversely impacts land use patterns. Furthermore, the products manufactured by this industry are non-recyclable. By considering waste management principles, the by-products of a thermal power plant, such as flue ashes, and the by-products of the steel industry, like slag, can be utilized as binders instead of cement. Additionally, the wood industry's by-product, sawdust, can also function as a binder. This substitution holds the potential to significantly reduce the energy required for cement production. This approach can result in energy conservation and a reduction in greenhouse gas emissions by conserving both raw materials and energy

resources within a specific threshold. By implementing this method, we can convert waste by-products into a useful and valuable substance, namely geopolymers in concrete.

In a study by Ivindra [10], the influence of the molarity of an alkaline activator solution (AAS) on the compressive strength of geo-polymer concrete was investigated. The study utilized NaOH solutions with 10M, 12M, and 14M concentrations, and determined that higher NaOH concentrations enhanced the compressive strength. The optimal NaOH concentration for geo-polymer concrete was identified as 12M.

Jeremiah [11] studied the utilization of geo-polymers produced from industrial wastes such as PFA, GGBS, MK, GP, POFA, SF, RHA, VA, and MP to stabilize weak clays. They discovered that the treated clays exhibited increased resistance, making them suitable for road pavement construction. Additionally, other studies [12], [13], [14], [15], [16], [17] & [18] have made noteworthy contributions to the concepts of geopolymer concrete and its impact on properties. This work utilized a range of guidelines, codes, standards, and specifications [19], [20], [21], [22], [23], [24], [25], [26], [27], and [28]. The primary objective of the study was to identify the optimum mixture proportions for sawdust ash concrete geopolymers, as well as to evaluate the pozzolanic properties of sawdust ash and create mathematical models and a MATLAB program for predicting and optimizing the compressive strength of sawdust ash concrete geopolymers.

II. MATERIALS AND METHODS

A. Materials

The study utilized locally sourced materials within the City of Port Harcourt Metropolis. The constituents used in the study included sawdust ash, water, alkaline liquid, fine aggregates, coarse aggregates, and super-plasticizer.

1. Sawdust ash

The sawdust ash samples were obtained from wood waste treated in Rumuosi sawmills and were converted into ash through open burning. The pozzolanic property and cementation characteristics of the samples were determined through oxide composition tests and X-ray diffraction analysis.

2. Water

Clean tap water without impurities, color, or odor was used in the study to prevent adverse effects on concrete properties.

3. Alkaline liquid

Alkaline liquid, consisting of SiO_2 solutions and 8–14M NaOH, was used to activate the sawdust ash alkaline. The sodium silicate and sodium hydroxide were sourced from Mile 3 market in Port Harcourt, Nigeria.

4. Fine aggregates

The fine aggregate used in the study was sourced from the riverbank Choba sand dump and underwent a particle size distribution test before use.

5. Coarse aggregates

Coarse aggregates were collected from Mile 3 Market and underwent particle size distribution analysis before being used in the research. The research included the use of coarse aggregates of crushed granite with nominal maximum sizes of 7mm, 10mm, and 20mm.

6. Super-plasticizer

A super-plasticizer utilizing naphthalene at a continuous dose of 1.25 percent of the binder weight was used in the concrete formulations to achieve the desired slump.

B. Methods

The methods employed in this study included experimental method and mathematical model development.

i. Experimental Method

Laboratory tests were conducted for the geopolymer concrete derived from sawdust ash, including particle size distribution, oxide composition test, specific gravity, density of constituent materials, and compressive strength tests.

The concrete specimens' compressive resistance was measured experimentally following the guidelines of BS 1881 [29]. At 28 days old, a 100mm concrete cube was tested for compressive resistance using the control MCC8 machine, which provided a load with a constant rate of 0.333 MPa/sec (equivalent to 20±2MPa compressive stress per minute) until failure. The compressive strength of the specimens was calculated using the equation (1).

$$f_c = {}^{P}/_{A} \quad (1)$$

Where;

f_c = Compressive strength (MPa)
P = maximum force applied (KN),
A = Cross sectional area (mm^2)

Figure 1: Compressive strength with sample under loading

ii. Mathematical Model development

1. Trial and Control Mixes

Scheffe, [30] states that Equation 2 can be used to calculate the sum of experimental data points.

$$N = \frac{(q+m-1)}{(q-1)!m!} \quad (2)$$

Where;

q = sum of the variables;

m = maximum summation of interactions

Keep the following information in mind:

When Equation (2) is utilized, mixtures containing five and two components yield a total of fifteen (15) experimental data points. The study examined the following five ratios: activator/SDA, water/binder, percentage of SDA in binder, NaOH concentration (M), and Na2SiO4/NaOH ratio. The study employed a simplex lattice design, as illustrated in Figure 2.

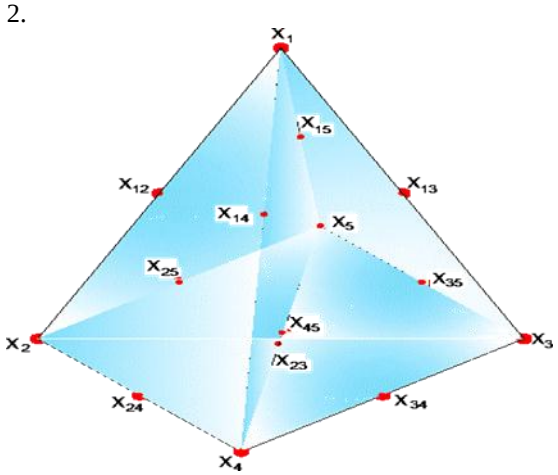

Figure 2: Scheffe's (5, 2) simplex lattice adopted in this study.

In his research, Scheffe [30] explains that theoretical mix ratios, also referred to as pseudo mix ratios, are utilized to express mixture proportions. Each vertex represents a pure substance, and this method assumes that the total of all pseudo mix ratios equals 1. This technique is used to illustrate mixture compositions from a mathematical perspective;

$$\sum_{i=1}^{q} x_i = 1 \quad (3)$$

In order to satisfy Equation (4), the actual mix ratios need to be transformed into pseudo mix ratios. There exists a relationship between the two sets of mix ratios:

$$Z = [A]X \quad (4)$$

Where;

Z = column matrix of real constituent ratio.

X = column matrix of pseudo constituent ratio.

[A]= co-efficient matrix which is the transpose of the permutation matrix.

The matrix A is derived from flipping the permutation matrix. The permutation matrix for NaOH concentration (M) ranged from 8M to 15M, resulting in a Na2SiO4/NaOH ratio between 1.5 and 3. The binder SDA content was confined to a range of 35 percent to 45 percent. The activator/SDA ratio fell within the range of 2.3 to 3.1, while the water/binder ratio was between 0 and 0.1. At the pure substance points assumed, the mix ratios are as follows: (8, 9.75, 11.5, 13.25, 15), (1.5, 1.875, 2.25, 2.625, 3), (35, 37.5, 40, 42.5, 45), (0, 0.025, 0.05, 0.075, 0.1), and (2.3, 2.485, 2.671, 2.856, 3.1). These points are indicated by the permutation matrix [P0].

$$P_o = \begin{bmatrix} 8 & 1.5 & 35 & 0 & 2.3 \\ 9.75 & 1.875 & 37.5 & 0.025 & 2.485 \\ 11.5 & 2.25 & 40 & 0.005 & 2.671 \\ 13.25 & 2.625 & 42.5 & 0.075 & 2.856 \\ 15 & 3 & 45 & 0.1 & 3.1 \end{bmatrix}$$

Transpose of Po becomes

$$A = \begin{bmatrix} 8 & 9.75 & 11.5 & 13.25 & 15 \\ 1.5 & 1.875 & 2.25 & 2.625 & 3 \\ 35 & 37.5 & 40 & 42.5 & 45 \\ 0 & 0.025 & 0.05 & 0.075 & 0.1 \\ 2.3 & 2.485 & 2.671 & 2.856 & 3.1 \end{bmatrix}$$

Below is the pseudo mix ratios of the central or interaction locations depicted in Figure 2:

$$X = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0.5 & 0.5 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.5 & 0 & 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.5 & 0 & 0.5 & 0 & 0.5 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.5 & 0 & 0.5 & 0.5 \end{bmatrix}$$

The trail mix matrix, Z, becomes;

$$Z = \begin{bmatrix} 8 & 9.75 & 11.5 & 13.25 & 15 & 8.875 & 9.75 & 10.625 & 11.5 & 10.625 & 11.5 & 12.375 & 12.375 & 13.25 & 14.125 \\ 1.5 & 1.875 & 2.25 & 2.625 & 3 & 1.6875 & 1.875 & 2.0625 & 2.25 & 2.0625 & 2.25 & 4.4375 & 2.4375 & 2.625 & 2.8125 \\ 35 & 37.5 & 40 & 42.5 & 45 & 36.25 & 37.5 & 38.75 & 40 & 38.75 & 40 & 41.25 & 41.25 & 42.5 & 43.75 \\ 0 & 0.025 & 0.05 & 0.075 & 0.1 & 0.0125 & 0.025 & 0.0375 & 0.05 & 0.0375 & 0.05 & 0.0625 & 0.0625 & 0.075 & 0.0875 \\ 2.3 & 2.485 & 2.671 & 2.856 & 3.1 & 2.3925 & 2.4855 & 2.578 & 2.7 & 2.578 & 2.6705 & 2.7925 & 2.7635 & 2.8855 & 2.978 \end{bmatrix}$$

Tables 1 below represent the trial mix matrix of SDA concrete mixes respectively after proper application of Equation 5.

Table 1: Trial mix matrix points owing to Scheffe's (5, 2) factor space

N	Pseudo constituent					Actual constituent				
	X_1	X_2	X_3	X_4	X_5	Z_1 = NaOH conc. (M)	Z_2 = Na2SiO4/ NaOH	Z_3 = percent SDA in binder	Z_4 = water/binder	Z_5 = Activator/ SDA
1	1	0	0	0	0	8	1.5	35	0	2.3
2	0	1	0	0	0	9.75	1.875	37.5	0.025	2.485
3	0	0	1	0	0	11.5	2.25	40	0.05	2.671
4	0	0	0	1	0	13.25	2.625	42.5	0.075	2.856
5	0	0	0	0	1	15	3	45	0.1	3.1
6	½	½	0	0	0	8.875	1.6875	36.25	0.0125	2.3925
7	½	0	½	0	0	9.75	1.875	37.5	0.025	2.4855
8	½	0	0	½	0	10.625	2.0625	38.75	0.0375	2.578
9	½	0	0	0	½	11.5	2.25	40	0.05	2.7
10	0	½	½	0	0	10.625	2.0625	38.75	0.0375	2.578
11	0	½	0	½	0	11.5	2.25	40	0.05	2.6705
12	0	½	0	0	½	12.375	2.4375	41.25	0.0625	2.7925
13	0	0	½	½	0	12.375	2.4375	41.25	0.0625	2.7635
14	0	0	½	0	½	13.25	2.625	42.5	0.075	2.8855

15	0	0	0	½	½	14.125	2.8125	43.75	0.0875	2.978

Similarly, for the control mix matrix, the pseudo mix proportion adopted in line with Scheffe's criteria is given as;

$$Xc = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & \frac{3}{10} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & \frac{3}{20} & \frac{1}{5} & \frac{1}{4} \\ \frac{1}{3} & \frac{1}{3} & 0 & \frac{1}{3} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{10} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & \frac{1}{4} & \frac{1}{5} & \frac{1}{5} \\ \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{4} & \frac{1}{4} & 0 & \frac{1}{4} & \frac{1}{5} & \frac{1}{10} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & \frac{3}{20} & \frac{1}{5} \\ 0 & \frac{1}{3} & \frac{1}{3} & 0 & \frac{1}{4} & 0 & \frac{1}{4} & \frac{1}{4} & \frac{1}{5} & \frac{3}{10} & \frac{3}{10} & \frac{1}{5} & \frac{1}{5} & \frac{1}{4} & \frac{1}{5} \\ 0 & 0 & 0 & \frac{1}{3} & 0 & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{5} & \frac{1}{5} & \frac{1}{10} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & \frac{3}{20} \end{bmatrix}$$

Multiplying the pseudo mix proportions for control, X_c by A, the control mix matrix, Z_c, becomes;

$$Zc = \begin{bmatrix} 9.75 & 10.33 & 10.92 & 10.92 & 10.63 & 11.06 & 11.50 & 12.38 & 11.33 & 11.68 & 11.33 & 11.50 & 11.59 & 11.59 & 11.15 \\ 1.88 & 2.00 & 2.13 & 2.13 & 2.06 & 2.16 & 2.25 & 2.44 & 2.21 & 2.29 & 2.21 & 2.25 & 2.27 & 2.27 & 2.18 \\ 37.50 & 38.33 & 39.17 & 39.17 & 38.75 & 39.38 & 40.00 & 41.25 & 39.75 & 40.25 & 39.75 & 40.00 & 40.13 & 40.13 & 39.50 \\ 0.03 & 0.03 & 0.04 & 0.04 & 0.04 & 0.04 & 0.05 & 0.06 & 0.05 & 0.05 & 0.05 & 0.05 & 0.05 & 0.05 & 0.05 \\ 2.49 & 2.55 & 2.61 & 2.63 & 2.58 & 2.64 & 2.69 & 2.78 & 2.66 & 2.70 & 2.66 & 2.68 & 2.69 & 2.69 & 2.64 \end{bmatrix}$$

The control mix design matrix and the trial mix design for concrete that are geopolymers adopted in this study is given in table 2 and table 3 respectively.

Table 2: Control mix matrix owing to Scheffe's (5, 2) factor space

N	Pseudo constituent					Actual constituent				
	X_1	X_2	X_3	X_4	X_5	Z_1 = NaOH conc. (M)	Z_2 = Na2SiO4/ NaOH	Z_3 = percent SDA in binder	Z_4 = water/binder	Z_5 = Activator/ SDA
1	1/3	1/3	1/3	0	0	9.75	1.88	37.50	0.03	2.49
2	1/3	1/3	0	1/3	0	10.33	2.00	38.33	0.03	2.55
3	1/3	0	1/3	1/3	0	10.92	2.13	39.17	0.04	2.61
4	1/3	1/3	0	0	1/3	10.92	2.13	39.17	0.04	2.63
5	¼	¼	¼	¼	0	10.63	2.06	38.75	0.04	2.58
6	¼	¼	¼	0	¼	11.06	2.16	39.38	0.04	2.64
7	¼	¼	0	¼	¼	11.50	2.25	40.00	0.05	2.69
8	0	¼	¼	¼	¼	12.38	2.44	41.25	0.06	2.78
9	3/10	1/10	1/5	1/5	1/5	11.33	2.21	39.75	0.05	2.66
10	1/5	1/5	1/10	3/10	1/5	11.68	2.29	40.25	0.05	2.70
11	1/5	1/5	1/5	3/10	1/10	11.33	2.21	39.75	0.05	2.66
12	1/5	1/5	1/5	1/5	1/5	11.50	2.25	40.00	0.05	2.68
13	3/20	¼	1/5	1/5	1/5	11.59	2.27	40.13	0.05	2.69
14	1/5	1/5	3/20	¼	1/5	11.59	2.27	40.13	0.05	2.69
15	¼	1/5	1/5	1/5	3/20	11.15	2.18	39.50	0.05	2.64

Table 3: Trial mix design of Sawdust ash geopolymer and OPC concrete

GEO-POLYMER CONCRETE MIX DESIGN												
S/NO	**Mix ID**	**Conc. Of NaOH (M)**	**SS/SH**	**Activator /SDA**	**Super-Plasticizers (percent of Binder)**	**Binder (Kg)**	**percent of SDA in Binder**	**SDA (Kg)**	**Cement (Kg)**	**SAND (Kg)**	**Aggregates (Kg)**	**Water/ Binders**
1	GPC1	8	1.5	2.3	0.05	2.1	35	0.74		4.1	8.2	0
2	GPC2	9.75	1.875	2.485	0.05	2.1	37.5	0.79		4.1	8.2	0.025
3	GPC3	11.5	2.25	2.671	0.05	2.1	40	0.84		4.1	8.2	0.05
4	GPC4	13.25	2.625	2.856	0.05	2.1	42.5	0.89		4.1	8.2	0.075
5	GPC5	15	3	3.10	0.05	2.1	45	0.95		4.1	8.2	0.1
6	GPC6	8.875	1.6875	2.39	0.05	2.1	36.25	0.76		4.1	8.2	0.0125
7	GPC7	9.75	1.875	2.49	0.05	2.1	37.5	0.79		4.1	8.2	0.025
8	GPC8	10.625	2.0625	2.58	0.05	2.1	38.75	0.81		4.1	8.2	0.0375
9	GPC9	11.5	2.25	2.70	0.05	2.1	40	0.84		4.1	8.2	0.05
10	GPC10	10.625	2.0625	2.58	0.05	2.1	38.75	0.81		4.1	8.2	0.0375
11	GPC11	11.5	2.25	2.67	0.05	2.1	40	0.84		4.1	8.2	0.05
12	GPC12	12.375	2.4375	2.79	0.05	2.1	41.25	0.87		4.1	8.2	0.0625
13	GPC13	12.375	2.4375	2.76	0.05	2.1	41.25	0.87		4.1	8.2	0.0625
14	GPC14	13.25	2.625	2.89	0.05	2.1	42.5	0.89		4.1	8.2	0.075
15	GPC15	14.125	2.8125	2.98	0.05	2.1	43.75	0.92		4.1	8.2	0.0875

2. Optimization Model Development

Theoretical mix ratios based on Scheffe's (5,2) simple lattice represent mixture proportions, and pure substances are found at the vertices point. At any point, the sum of all theoretical mix ratios must equal 1, which is a constraint in the optimization process as shown in Equation 3.

The (q, m) polynomial have a general form represented by Equation 5 (Scheffe, 1958);

$$Y = b_o + \Sigma b_i x_i + \Sigma b_{ij} x_i x_j + \Sigma b_{ijk} x_i x_j x_k + \cdots + \Sigma b_{i1,i2..im} x_{i1} x_{i2} x_{im} \quad (5)$$

Where; $1 \le i \le q$, $1 \le i \le j \le q$, $1 \le i \le j \le k \le q$

b_o is a constant coefficient

For (5, 2) polynomial problem as adopted in this study, Equation (5) becomes;

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_{12}X_{12}X_2 + b_{13}X_1X_3 + b_{14}X_1X_4 + b_{15}X_1X_5 + b_{25}X_2X_5 + b_{24}X_2X_4 + b_{23}X_2X_3 + b_{34}X_3X_4 + b_{35}X_3X_5 + b_{45}X_4X_5 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{44}X_4^2 + b_{55}X_5^2 \quad (6)$$

For a ternary mixture, Equation (7) is obtained from Equation (3).

$$X_1 + X_2 + X_3 + X_4 + X_5 = 1 \quad (7)$$

Multiplying through by constant, b_0, yields Equation (8).

$$b_0X_1 + b_0X_2 + b_0X_3 + b_0X_4 + b_0X_5 = b_0 \quad (8)$$

Again, multiplying Equation (8) by X_1, X_2, X_3, X_4 and X_5 in succession and rearranging, Equation (9) is produced.

$$\left.\begin{aligned} X_1^2 &= X_1 - X_1X_2 - X_1X_3 - X_1X_4 - X_1X_5 \\ X_2^2 &= X_2 - X_1X_2 - X_2X_3 - X_2X_4 - X_2X_5 \\ X_3^2 &= X_3 - X_1X_3 - X_2X_3 - X_3X_4 - X_3X_5 \\ X_4^2 &= X_4 - X_1X_4 - X_2X_4 - X_3X_4 - X_4X_5 \\ X_5^2 &= X_5 - X_1X_5 - X_2X_5 - X_3X_5 - X_4X_5 \end{aligned}\right\} \quad (9)$$

Substituting Equations (8) and (9) into Equation (6), Equation (10) was obtained after necessary transformation.

$$Y = (b_0 + b_1 + b_{11})X_1 + (b_0 + b_2 + b_{22})X_2 + (b_0 + b_3 + b_{33})X_3 + (b_0 + b_4 + b_{44})X_4 + (b_0 + b_5 + b_{55})X_5 + (b_{12} - b_{11} - b_{22})X_1X_2 + (b_{13} - b_{11} - b_{33})X_1X_3 + (b_{14} - b_{11} - b_{44})X_1X_4 + (b_{15} - b_{11} - b_{55})X_1X_5 + (b_{23} - b_{22} - b_{33})X_2X_3 + (b_{24} - b_{22} - b_{44})X_2X_4 + (b_{25} - b_{22} - b_{55})X_2X_5 + (b_{34} - b_{33} - b_{44})X_3X_4 + (b_{35} - b_{33} - b_{55})X_3X_5 + (b_{45} - b_{44} - b_{55})X_4X_5 \quad (10)$$

Denoting; $\beta_i = b_0 + b_i + b_{ii}$ and

$\beta_{ij} = b_{ij} - b_{ii} - b_{jj}$

With five variables, the simplified second-degree polynomial may be seen in Equation (11).

$$Y = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 + \beta_{15} X_1 X_5 + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{25} X_2 X_5 + \beta_{34} X_3 X_4 + \beta_{35} X_3 X_5 + \beta_{45} X_4 X_5 \quad (11)$$

Equation (11) uses fifteen (15) coefficients instead of the many coefficients in Equation (6). Therefore, Equation (12) shows the reduced second-degree polynomial in q-variables.

$$Y = \sum_{1 \le i \le q} \beta_i X_i + \sum_{i \le j \le q} \beta_{ij} X_i X_j \quad (12)$$

Where;
Y = Expected response
β_i, β_{ij} = Co-efficient of the quadratic polynomial
X_i, X_j = Pseudo proportion of factors considered
Equation (13) is obtained by substituting the coordinates of the vertices from Figure 2 into Equation (9).

$$\left.\begin{aligned} Y_1 &= \beta_1 \\ Y_2 &= \beta_2 \\ Y_3 &= \beta_3 \\ Y_4 &= \beta_4 \\ Y_5 &= \beta_5 \end{aligned}\right\} \quad (13)$$

For interaction point X_{12} of Figure 2;

$$Y_{12} = {}^1/_2 X_1 + {}^1/_2 X_2 + {}^1/_4 X_1 X_2$$
$$= {}^1/_2 \beta_1 + {}^1/_2 \beta_2 + {}^1/_4 \beta_{12} \quad (14)$$

In congruent with Equation (7), β_i is equal to Y_i, where i ranges from 1 to n. By plugging the values into Equation (8), the ensuing upshot was obtained:

$$Y_{12} = ({}^1/_2) Y_1 + ({}^1/_2) Y_2 + ({}^1/_4) \beta_{12} \quad (15)$$

Simplifying Equation (15), yielded:

$$B_{12} = 4Y_{12} - 2Y_1 - 2Y_2 \quad (16)$$

Equations (17) to (20) were derived in a similar manner. Therefore:

$$B_{13} = 4Y_{13} - 2Y_1 - 2Y_3 \quad (17)$$
$$B_{14} = 4Y_{14} - 2Y_1 - 2Y_4 \quad (18)$$
$$B_{15} = 4Y_{15} - 2Y_1 - 2Y_5 \quad (19)$$
$$B_{23} = 4Y_{23} - 2Y_2 - 2Y_3 \quad (20)$$

By generalizing equations (16) to (20), equation (21) was derived.

$$\left.\begin{aligned} \beta_i &= Y_i \\ \beta_{ij} &= 4Y_{ij} - 2Y_i - 2Y_j \end{aligned}\right\} \quad (21)$$

The numbers mentioned above are utilized as the co-efficient for the second-degree polynomial with coordinates (5, 2) in Equation (9).

3. Optimization models validation

Models generated using Equation (11) were subjected to the Fisher test (F-test) to validate and ensure their appropriateness. The F-statistic was used to compare the variance of the experimental value with the expected model response value, and the resulting hypotheses were accepted to validate the models. The null hypothesis (H0) stated that there is no substantial difference between the experimental and calculated responses, while the alternate hypothesis (H1) suggested that there is a substantial difference between the experimental and calculated responses. The F-test can be expressed mathematically as Equation (22).

$$F = \frac{S_1^2}{S_2^2} \quad (22)$$

Where; S_1^2 = Larger of both variances
S_2^2 = Smaller of both variance
S2 is calculated utilizing the ensuing equation:

$$S^2 = \frac{1}{n-1}[\sum (Y - \bar{Y})^2] \quad (23)$$

Where: $\bar{Y}$= Average mean of response, Y
Y = Mean of response

In order for the models to be deemed adequate, the F-values calculated using Equation (22) should be less than the values listed in the F-distribution table.

III. RESULTS AND DISCUSSION

1. Results

In this section, the findings from the analysis of the component materials, as well as the outcomes of fifteen (15) experimental geopolymer concrete mixtures and fifteen (15) control mixes for compressive strength, are provided and deliberated.

Table 4: Oxide composition text

Chemical properties Parameter	Hardwood sawdust ash		Softwood sawdust ash	
	Sample 1 (with oxygen)	Sample 2 (without oxygen)	Sample 3 (with oxygen)	Sample 4 (without oxygen)
CaO (%)	6.13	4.18	5.46	5.11
SiO2 (%)	69.84	71.02	66.79	72.57
Al2O3 (%)	3.78	4.32	4.81	5.16
Fe2O3 (%)	1.94	1.82	2.27	2.36
MgO (%)	3.20	3.47	4.10	4.43
Na_2O (%)	0.28	0.19	0.11	0.15
K2O (%)	2.95	3.11	2.88	3.28
Loss of Ignition	2.92	3.11	3.56	3.44

Table 5a: Specific Gravity of Sawdust ash and Fine aggregate

Bottle/Test Number	Sawdust ash		Fine aggregate	
	1	2	1	2
Weight of Bottle only(g) - M_1	28.0	26.5	28.0	26.5
Weight of Bottle and dry sample(g) - M_2	36.0	35.0	64	64.5
Weight of Bottle, sample and water(g) - M_3	82.0	80.0	102	100
Weight of Bottle and water(g) - M_4	78.0	78.0	78.0	78.0
$G_s = M_2 - M_1/(M_4 - M_1) - (M_3 - M_2)$	2.0	1.308	3.0	2.375
AVERAGE(Gs)	**1.654**		**2.6875**	

Table 5b: Density of Sawdust ash and Fine aggregate

		Sawdust ash		Fine aggregate	
Volume of Mould		$2.2 * 10^{-4} m^3$		$2.2 * 10^{-4} m^3$	
TEST		**1**	**2**	**1**	**2**
Wt. of Specimen + Mould	gms	678.0	776.0	864.0	872.0
Wt. of Mould only	gms	444.0	444.0	444.0	444.0
Wt. of Specimen	gms	234.0	332.0	420.0	428.0
Density of Specimen	g/m^3	1.045	1.482	1.875	1.910
Average Density	g/m^3	1.2635			1.8925
Bulk Density	Kg/m^3	1.2635			1.8925
Unit Weight	KN/m^3	**12.609**		**18.560**	

The results of the oxide composition test on softwood and hardwood sawdust ash are presented in Table 4. It was found that softwood sawdust ash, produced through pyrolysis, demonstrates superior pozzolanic properties and was thus chosen for further laboratory investigation. The XRD test conducted on the sawdust ash sample provided additional support for the selection of softwood sawdust ash. Tables 5a – 5b contain information on the specific gravity and density of sawdust ash and fine aggregate, indicating their suitability for further testing.

Table 6 displays the compressive strength results from laboratory experiments using the trial mix design outlined in Table 3. In these experiments, the geopolymer binder entirely replaced cement, while the fine and coarse aggregate remained constant throughout the testing. Other variables, such as rest period, superplasticizer, and curing temperature, were also kept consistent. The samples were cured in an oven at 90°C for three days and then aged for 28 days before undergoing crushing.

Table 6: Compressive Strength of Sawdust ash geopolymer concrete Experimental Result for Trial mixes at 28 days curing age

N	Pseudo component					Actual component					Response	
	X_1	X_2	X_3	X_4	X_5	Z_1 = NaOH conc. (M)	Z_2 = Na2SiO4/ NaOH	Z_3 = % SDA in binder	Z_4 = water/binder	Z_5 = Activator/ SDA	Symbol	Compressive Strength (N/mm²)
1	1	0	0	0	0	8	1.5	35	0	2.3	Y_1	21.00
2	0	1	0	0	0	9.75	1.875	37.5	0.025	2.485	Y_2	12.67
3	0	0	1	0	0	11.5	2.25	40	0.05	2.671	Y_3	21.00
4	0	0	0	1	0	13.25	2.625	42.5	0.075	2.856	Y_4	14.00
5	0	0	0	0	1	15	3	45	0.1	3.1	Y_5	16.33
6	½	½	0	0	0	8.875	1.6875	36.25	0.0125	2.3925	Y_{12}	18.67
7	½	0	½	0	0	9.75	1.875	37.5	0.025	2.4855	Y_{13}	14.00
8	½	0	0	½	0	10.625	2.0625	38.75	0.0375	2.578	Y_{14}	18.67
9	½	0	0	0	½	11.5	2.25	40	0.05	2.7	Y_{15}	21.00
10	0	½	½	0	0	10.625	2.0625	38.75	0.0375	2.578	Y_{23}	18.67
11	0	½	0	½	0	11.5	2.25	40	0.05	2.6705	Y_{24}	21.00
12	0	½	0	0	½	12.375	2.4375	41.25	0.0625	2.7925	Y_{25}	21.00
13	0	0	½	½	0	12.375	2.4375	41.25	0.0625	2.7635	Y_{34}	21.00
14	0	0	½	0	½	13.25	2.625	42.5	0.075	2.8855	Y_{35}	14.00
15	0	0	0	½	½	14.125	2.8125	43.75	0.0875	2.978	Y_{45}	7.00

2. Modeling the Compressive Strength of sawdust ash Geopolymer Concrete

The outcomes of the compressive strength test for the geopolymer concrete trial mix are shown in Table 6. Through the use of this table and Equation 11, the model coefficients for the Scheffe's (5, 2) optimization models for the compressive strength of geopolymer concrete incorporating sawdust ash were determined. The optimization model for the compressive resistance of sawdust ash blended geopolymer concrete using Scheffe's (5,2) is formulated in the following manner;

$\beta_1 = Y_1 = 21.00$
$\beta_2 = Y_2 = 12.67$
$\beta_3 = Y_3 = 21.00$
$\beta_4 = Y_4 = 14.00$
$\beta_5 = Y_5 = 16.33$
$\beta_{12} = 4Y_{12} - 2Y_1 - 2Y_2 = 4(18.67) - 2(21) - 2(12.67) = 7.34$
$\beta_{13} = 4Y_{13} - 2Y_1 - 2Y_3 = 4(14) - 2(21) - 2(21) = -28$
$\beta_{14} = 4Y_{14} - 2Y_1 - 2Y_4 = 4(18.67) - 2(21) - 2(14) = 4.68$
$\beta_{15} = 4Y_{15} - 2Y_1 - 2Y_5 = 4(21) - 2(21) - 2(16.33) = 9.34$
$\beta_{23} = 4Y_{23} - 2Y_2 - 2Y_3 = 4(18.67) - 2(12.67) - 2(21) = 7.34$
$\beta_{24} = 4Y_{24} - 2Y_2 - 2Y_4 = 4(21) - 2(12.67) - 2(14) = 30.66$
$\beta_{25} = 4Y_{25} - 2Y_2 - 2Y_5 = 4(21) - 2(12.67) - 2(16.33) = 26$
$\beta_{34} = 4Y_{34} - 2Y_3 - 2Y_4 = 4(21) - 2(21) - 2(14) = 14$
$\beta_{35} = 4Y_{35} - 2Y_3 - 2Y_5 = 4(14) - 2(21) - 2(16.33) = -18.66$
$\beta_{45} = 4Y_{45} - 2Y_4 - 2Y_5 = 4(7) - 2(14) - 2(16.33) = -32.66$

The values of the coefficients mentioned can be utilized in Equation (24) for predicting the best mixture ratios for sawdust ash concrete geopolymers based on the compressive strength using an optimization model.

$$Y = 21x_1 + 12.67x_2 + 21x_3 + 14x_4 + 16.33x_5 + 7.34x_1x_2 - 28x_1x_3 + 4.68x_1x_4 + 9.34x_1x_5 + 7.34x_2x_3 + 30.66x_2x_4 + 26x_2x_5 + 14x_3x_4 - 18x_3x_5 - 32.66x_4x_5 \quad (24)$$

The optimization model used in equation (24) is for estimating the compressive resistance of sawdust ash blended geopolymer concrete with parameters (5, 2). This model has the capability to predict the compressive resistance of sawdust ash concrete for any given value within the range of compressive strength values in the trial mix.

By utilizing MATLAB code developed during this research, the modified pseudo coefficients, denoted as x1 to x5, were determined. These values can also be calculated using Excel Solver.

$$\begin{matrix} X_1 & X_2 & X_3 & X_4 & X_5 & \sum x \end{matrix}$$
$$[0.549743 \quad 0.1336 \quad 0 \quad 0 \quad 0.316657] = \quad 1$$

After plugging in the best pseudo coefficients into equation 24, the optimal compressive strength for the geopolymer concrete based on sawdust ash is determined to be;

$$F_{op} = 21.67326$$

The optimized mix design for sawdust ash blended geopolymer concrete is shown in Table 7 using the adjusted pseudo coefficient.;

Table 7: Compressive Strength Optimum mix design for sawdust ash based geopolymer concrete

Pseudo component					Actual component					Optimum compressive strength (N/mm^2)
X_1	X_2	X_3	X_4	X_5	Z_1 = NaOH conc. (M)	Z_2 = Na2SiO4/ NaOH	Z_3 = % SDA in binder	Z_4 = water/ binder	Z_5 = Activator/ SDA	
0.54974	0.1336	0	0	0.31666	10.5415	2.0446	38.6307	0.0363	2.5882	21.67326

3. Validation and verification of optimization model

Adequacy tests were conducted on the optimization models from the previous section, utilizing F-statistics, and verification tests were performed using R2 statistics. The study used the compressive resistance laboratory response values for the control mix design matrix presented in Table 2. Table 8 displays the experimental results for the compressive resistance of the control mix. The average compressive resistance values found in Table 8 were compared with the predicted values shown in Table 9. These predicted values were obtained by substituting the pseudo matrix for control in Table 2 into the previously developed optimization model (Equation 24). Figure 2 illustrates the graphical representation (R2 statistics) of the predicted values compared with the control mix values in Table 9, used to determine the R2 value. Lastly, Table 10 presents the F-statistics validation and is used to calculate the variances of the experimental value and predicted value.

Table 8: Control mix Compressive Strength Experimental Results at 28 days curing age

N	Pseudo component					Actual component					Response symbol	Compr. Strength (N/mm^2)		Average Compressive strength (N/mm^2)
	X_1	X_2	X_3	X_4	X_5	Z_1 = NaOH conc. (M)	Z_2 = Na2SiO4/ NaOH	Z_3 = % SDA in binder	Z_4 = water/binder	Z_5 = Activator/ SDA		Sample 1	Sample 2	
1	1/3	1/3	1/3	0	0	9.75	1.88	37.50	0.03	2.49	Y_1	16	18	17
2	1/3	1/3	0	1/3	0	10.33	2.00	38.33	0.03	2.55	Y_2	21	19	20
3	1/3	0	1/3	1/3	0	10.92	2.13	39.17	0.04	2.61	Y_3	18	18	18
4	1/3	1/3	0	0	1/3	10.92	2.13	39.17	0.04	2.63	Y_4	20	22	21
5	¼	¼	¼	¼	0	10.63	2.06	38.75	0.04	2.58	Y_5	18	20	19
6	¼	¼	¼	0	¼	11.06	2.16	39.38	0.04	2.64	Y_{12}	16	19	17.5
7	¼	¼	0	¼	¼	11.50	2.25	40.00	0.05	2.69	Y_{13}	20	18	19
8	0	¼	¼	¼	¼	12.38	2.44	41.25	0.06	2.78	Y_{14}	16	18.5	17.25
9	3/10	1/10	1/5	1/5	1/5	11.33	2.21	39.75	0.05	2.66	Y_{15}	16	18.5	17.25
10	1/5	1/5	1/10	3/10	1/5	11.68	2.29	40.25	0.05	2.70	Y_{23}	17	19	18
11	1/5	1/5	1/5	3/10	1/10	11.33	2.21	39.75	0.05	2.66	Y_{24}	18	19	18.5
12	1/5	1/5	1/5	1/5	1/5	11.50	2.25	40.00	0.05	2.68	Y_{25}	18.5	16	17.5
13	3/20	¼	1/5	1/5	1/5	11.59	2.27	40.13	0.05	2.69	Y_{34}	19	18	18.5
14	1/5	1/5	3/20	¼	1/5	11.59	2.27	40.13	0.05	2.69	Y_{35}	18	18	18
15	¼	1/5	1/5	1/5	3/20	11.15	2.18	39.50	0.05	2.64	Y_{45}	17	19	18

Table 10: Comparison of Predicted Compressive Strength values with the Experimental values

N	Pseudo component					Actual component					Response symbol	Compr. Strength (N/mm²)	
	X_1	X_2	X_3	X_4	X_5	Z_1 = NaOH conc. (M)	Z_2 = Na2SiO4/ NaOH	Z_3 = % SDA in binder	Z_4 = water/binder	Z_5 = Activator/ SDA		Experiment result	Predicted value
1	1/3	1/3	1/3	0	0	9.75	1.88	37.50	0.03	2.49	Y_1	17.000	16.7433
2	1/3	1/3	0	1/3	0	10.33	2.00	38.33	0.03	2.55	Y_2	20.000	20.6322
3	1/3	0	1/3	1/3	0	10.92	2.13	39.17	0.04	2.61	Y_3	18.000	17.6311
4	1/3	1/3	0	0	1/3	10.92	2.13	39.17	0.04	2.63	Y_4	21.000	21.4089
5	¼	¼	¼	¼	0	10.63	2.06	38.75	0.04	2.58	Y_5	19.000	19.4188
6	¼	¼	¼	0	¼	11.06	2.16	39.38	0.04	2.64	Y_{12}	17.500	17.9600
7	¼	¼	0	¼	¼	11.50	2.25	40.00	0.05	2.69	Y_{13}	19.000	18.8350
8	0	¼	¼	¼	¼	12.38	2.44	41.25	0.06	2.78	Y_{14}	17.250	17.6675
9	3/10	1/10	1/5	1/5	1/5	11.33	2.21	39.75	0.05	2.66	Y_{15}	17.250	17.0016
10	1/5	1/5	1/10	3/10	1/5	11.68	2.29	40.25	0.05	2.70	Y_{23}	18.000	17.8016
11	1/5	1/5	1/5	3/10	1/10	11.33	2.21	39.75	0.05	2.66	Y_{24}	18.500	18.5484
12	1/5	1/5	1/5	1/5	1/5	11.50	2.25	40.00	0.05	2.68	Y_{25}	17.500	17.8016
13	3/20	¼	1/5	1/5	1/5	11.59	2.27	40.13	0.05	2.69	Y_{34}	18.500	18.1466
14	1/5	1/5	3/20	¼	1/5	11.59	2.27	40.13	0.05	2.69	Y_{35}	18.000	17.8366
15	¼	1/5	1/5	1/5	3/20	11.15	2.18	39.50	0.05	2.64	Y_{45}	18.000	18.1052

Where; X_1, Z_1= pseudo and actual constituent of NaOH concentration; X2, Z2 = pseudo and actual constituent of Na2SiO4/NaOH ratio; X3, Z3 = pseudo and Actual constituent of percent of SDA in binder; X4, Z4 = pseudo and actual constituent of water/binder ratio; X5, Z5 = pseudo and actual constituent of Activator/SDA ratio

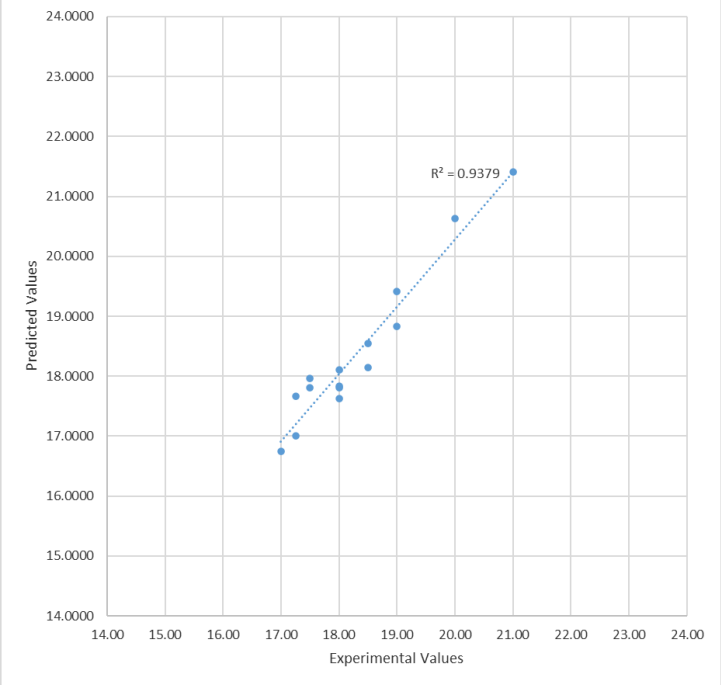

Figure 3: R^2 Statistics of sawdust ash blended geopolymer concrete Compressive Strength model

Table 10. F-Statistics for Validation of Sawdust Ash concrete that are geopolymers Compressive Strength Optimization Model

Experiment Value = Y_e	Pred. value = Y_m	Y_e-$\hat{Y}_e$	Y^m-$\hat{Y}^m$	$(Y_e$-$\hat{Y}_e)^2$	$(Y^m$-$\hat{Y}^m)^2$
17.0000	16.7433	-2.0667	-0.2036	4.2712	0.0414
20.0000	20.6322	0.9333	3.6853	0.8710	13.5816
18.0000	17.6311	-1.0667	0.6842	1.1378	0.4681
21.0000	21.4089	1.9333	4.4620	3.7376	19.9093
19.0000	19.4188	-0.0667	2.4719	0.0044	6.1100
17.5000	17.9600	-1.5667	1.0131	2.4545	1.0264

19.0000	18.8350	-0.0667	1.8881	0.0044	3.5649
17.2500	17.6675	-1.8167	0.7206	3.3004	0.5193
17.25	17.0016	-1.8167	0.0547	3.300399	0.00299209
18	17.8016	-1.0667	0.8547	1.137849	0.73051209
18.5	18.5484	-0.5667	1.6015	0.321149	2.56480225
17.5	17.8016	-1.5667	0.8547	2.454549	0.73051209
18.5	18.14655	-0.5667	1.19965	0.321149	1.439160123
18	17.8366	-1.0667	0.8897	1.137849	0.79156609
18	18.10515	-1.0667	1.15825	1.137849	1.341543063
$\hat{Y}_e$ = 18.300	$\hat{Y}^m$ =18.3692			∑= 25.5924	∑= 52.8222

With the aid of Table 10 and Equation (23) the following was deduced:

$$S_e^2 = {}^{16.7750}/_{14} = 1.1982$$

$$S_m^2 = {}^{22.4773}/_{14} = 1.6055$$

The F-value which is the ratio of the two squared variances was computed using Equation (22) as;

$$F = {}^{1.6055}/_{1.1982} = 1.3399$$

The value of F-calculated (F-cal) is 1.3399, which is lower than the critical F-value (F-tab) of 2.4986. As a result, we can conclude that the null hypothesis is accepted, and the model is deemed suitable.

Furthermore, the R-squared (R^2) statistics presented in Figure 3 demonstrate an R^2 score of 93.79%. This indicates that the optimization model accounts for more than 93% of the dataset.

IV. CONCLUSIONS

Following this research, the subsequent findings were derived:

1. When subjected to pyrolysis in an oxygen-free environment, sawdust ash exhibits superior pozzolanic properties compared to when it is burned in the presence of oxygen.
2. Softwood sawdust outperforms hardwood sawdust as a pozzolanic material.
3. A mathematical model has been created for forecasting the Compressive Strength of geopolymer concrete made from sawdust ash as; $Y = 2.956x_1 + 2.413x_2 + 2.956x_3 + 2.413x_4 + 2.685x_5 + 0.002x_1x_2 - 2.172x_1x_3 + 0.002x_1x_4 + 0.542x_1x_5 + 0.002x_2x_3 + 2.172x_2x_4 + 1.628x_2x_5 + 1.086x_3x_4 - 1.630x_3x_5 - 3.368x_4x_5$.
4. The fresh sawdust ash-based geopolymer concrete can be managed for up to 120 minutes without showing any signs of setting or experiencing a decline in Compressive strength.
5. Increasing the molar ratio of H2O to Na2O results in a reduction in the compressive strength of geopolymer concrete made with sawdust ash.
6. The compressive strength of sawdust ash-based geopolymer concrete decreases as the mass ratio of water-to-geopolymer solids increases.
7. The compressive strength of heat-cured sawdust ash-based geopolymer concrete does not depend on age.
8. Mixing sawdust ash-based geopolymer concrete for up to sixteen minutes increases the compressive strength.
9. The average density of sawdust ash-based geopolymer concrete is similar to OPC concrete.

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