

Prediction and Optimization of Poisson's Ratio of Sawdust Ash Geopolymer Concrete

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Abstract

Introduction: Geopolymer concrete is a more environmentally friendly option than traditional cement because it reduces greenhouse gas emissions during production. It is composed of an alkaline solution with sodium or potassium silicate and sodium or potassium hydroxide, as well as a source material rich in silica and alumina.

Objectives: The primary focus of the study was to predict maximize the Poisson's ratio of the concrete, particularly when incorporating sawdust ash as the source material.

Methods: In this investigation, thirty geopolymer concrete samples were created in the laboratory using a mix design approach based on Scheffe's (5,2) model.

Results: The research developed a mathematical model for prediction and also identified the optimal Poisson's ratio of geopolymer concrete incorporating sawdust ash to be 0.2695, as well as specific concentration ratios of NaOH, Na₂SiO₄ to NaOH, sawdust ash in the binder, water to binder, and activator to sawdust ash at 141937, 2.8272, 43.8481, 0.0885, and 2.9876 respectively. Additionally, MATLAB-based computer programs were used to optimize and predict the ideal mixture proportions for sawdust ash-based geopolymer concrete.

Conclusion: The results revealed that subjecting sawdust ash to pyrolysis in the absence of oxygen significantly affects its pozzolanic properties and, consequently, the characteristics of the concrete. Models for prediction and optimization of the Poisson's ratio of sawdust ash geopolymer concrete were developed alongside a MATLAB code.

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

1. Introduction

Over an extended period, ordinary Portland cement has been used as a binding agent in the production of ordinary Portland concrete (OPC). The increasing infrastructure demands in many developing countries, along with the growing number of deteriorating concrete structures in urgent need of repair and rehabilitation, are contributing to the anticipated increase in demand for OPC. However, Mehta [1] has revealed that the cement industry is responsible for nearly seven percent (7%) of global greenhouse gas emissions and generates millions of tons of waste annually. Pearce [2] has recently stated that human-caused greenhouse gas emissions from the cement industry account for 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 releases approximately one ton of carbon dioxide (CO₂) into the atmosphere.

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

The cement industry cannot be considered sustainable due to its reliance on raw materials obtained through mining, which has adverse effects on land use patterns. Moreover, the products manufactured by this industry are non-renewable. By taking waste management principles into account, the by-products of a thermal power plant, like flue ashes, and the by-products of the steel industry, such as slag, can be used as binders

instead of cement. Additionally, the by-product of the wood industry, sawdust, can also serve as a binder. This substitution has the potential to significantly reduce the energy needed for cement production. This approach can lead to 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, waste by-products can be transformed into a useful and valuable substance, namely geopolymers in concrete.

In a study by Ivindra [10], the impact of the molarity of an alkaline activator solution (AAS) on the compressive strength of geopolymer concrete was examined. The study utilized NaOH solutions with concentrations of 10M, 12M, and 14M, and found that higher NaOH concentrations improved the compressive strength. The optimal NaOH concentration for geopolymer concrete was identified as 12M.

Jeremiah [11] investigated the use of geopolymers produced from industrial wastes such as PFA, GGBS, MK, GP, POFA, SF, RHA, VA, and MP to stabilize weak clays. They found 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 significant contributions to the concepts of geopolymer concrete and its impact on properties. This work utilized a variety of guidelines, codes, standards, and specifications [19], [20], [21], [22], [23], [24], [25], [26], [27], and [28]. In our recent publication [29], the mathematical model for the optimization of compressive strength of sawdust ash geopolymer concrete was detailed and the model was adequate for the prediction of compressive strength of the geopolymer concrete. This study aimed to identify a model that can predict and optimize the Poisson's ratio for sawdust ash concrete geopolymers. Additionally, it sought to assess the pozzolanic properties of sawdust ash and create a MATLAB program to forecast and optimize the Poisson's ratio of sawdust ash concrete geopolymers.

2. MATERIALS AND METHODS

A. Materials

The study made use of locally available materials from the City of Port Harcourt Metropolis; Sawdust

ash, water, alkaline liquid, fine aggregates, coarse aggregates, and super-plasticizer were among the constituents used in the study.

1. Sawdust ash

The sawdust ash samples were converted to ash through open burning and pyrolysis. The properties of the samples were determined through oxide composition tests and X-ray diffraction analysis to assess their pozzolanic and cementation characteristics.

2. Water

Clean tap water without impurities, color, or odor was utilized in the study to avoid any negative impact on concrete properties.

3. Alkaline liquid

An alkaline liquid, composed of SiO₂ solutions and 8–14M NaOH, was used to activate the sawdust ash alkaline.

4. Fine aggregates

The fine aggregates underwent a particle size distribution test before being used.

5. Coarse aggregates

Coarse aggregates were washed, sun-dried and underwent particle size distribution analysis before being used in the research. Various sizes of crushed granite coarse aggregates with nominal maximum sizes of 7mm, 10mm, and 20mm were used.

6. Super-plasticizer

A super-plasticizer, containing naphthalene at a constant dose of 1.25 percent of the binder weight, was utilized in the concrete formulations to achieve the desired slump.

B. Methods

The methods utilized in the study encompassed an experimental method and the development of a mathematical model.

i. Experimental Method

Laboratory tests were carried out for the geopolymer concrete derived from sawdust ash, including particle size distribution, oxide composition test, specific gravity, density of constituent materials, and Poisson's ratio tests.

To determine the Poisson's ratio, the concrete specimens' compressive and flexural resistances were measured experimentally following the guidelines of BS 1881 [30]. 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, while 100 mm x 100 mm concrete beam that had a span length of 500 mm was used for the flexural test. The Poisson's ratio of the specimens was calculated using the equation (1).

$$v = f_c / f_f \quad (1)$$

Where;

f_c = Compressive strength (MPa)

f_f = Flexural strength (MPa)



(a)



(b)

Figure 1: Test setup; (a) Compressive strength, (b) Flexural strength

ii. Mathematical Model development

1. Trial and Control Mixes

Scheffe, in his article [31], asserts that Equation 2 is applicable for computing the total of the 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:

Using Equation (2) produces a total of fifteen (15) experimental data points when working with mixtures containing five and two components. The research investigated five ratios: activator/SDA, water/binder, percentage of SDA in binder, NaOH concentration (M), and Na₂SiO₄/NaOH ratio. A simplex lattice design, as shown in Figure 2, was utilized for the study.

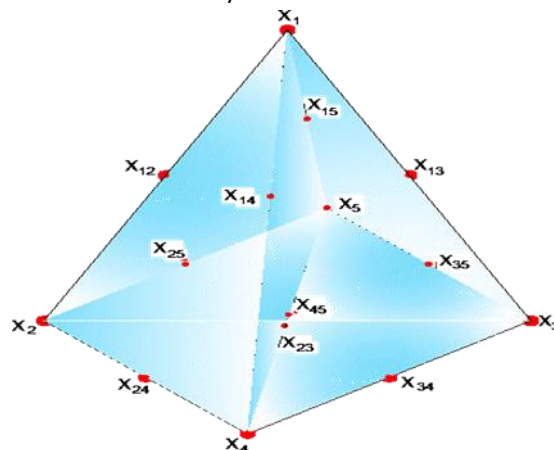


Figure 2: Scheffe's (5, 2) simplex lattice adopted in this study.

Scheffe [31] describes in his study that theoretical mix ratios, also known as pseudo mix ratios, are employed for expressing mixture proportions. Each corner denotes a pure substance, and this approach assumes that the sum of all pseudo mix ratios is equal to 1. This method is employed to depict mixture compositions from a mathematical standpoint;

$$\sum_{i=1}^q x_i = 1$$

(3)

To meet the requirements of Equation (4), the real mix ratios must be converted to pseudo mix ratios. There is a connection between the two groups of mix ratios:

$$Z = [A]X$$

(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 created by flipping the permutation matrix, which is based on a range of 8M to 15M for NaOH concentration (M), leading to a Na₂SiO₄/NaOH ratio between 1.5 and 3. The binder

SDA content is limited to 35 percent to 45 percent. The activator/SDA ratio is within the range of 2.3 to 3.1, and the water/binder ratio ranges from 0 to 0.1. At the assumed pure substance points, 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 represented by the permutation matrix [P₀].

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

$$P_0 = \begin{bmatrix} 8 & 1.5 & 35 & 0 & 2.3 \\ 9.75 & 1.875 & 37.5 & 0.025 & 2.485 \\ 11.5 & 2.25 & 40 & 0.005 & 2.671 \\ 13.25 & 2.625 & 42.5 & 0.075 & 2.856 \\ 15 & 3 & 45 & 0.1 & 3.1 \end{bmatrix}$$

Transpose of P₀ becomes

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

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

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 = Na ₂ SiO ₄ /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;

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

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

Table 2 contains the control mix design matrix and Table 3 shows the trial mix design for concrete, which utilizes geopolymers, as specified in this study.

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

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 = Na ₂ SiO ₄ /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	1/4	1/4	1/4	1/4	0	10.63	2.06	38.75	0.04	2.58
6	1/4	1/4	1/4	0	1/4	11.06	2.16	39.38	0.04	2.64
7	1/4	1/4	0	1/4	1/4	11.50	2.25	40.00	0.05	2.69
8	0	1/4	1/4	1/4	1/4	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	1/4	1/5	1/5	1/5	11.59	2.27	40.13	0.05	2.69
14	1/5	1/5	3/20	1/4	1/5	11.59	2.27	40.13	0.05	2.69
15	1/4	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 concrete

GEO-POLYMER CONCRETE MIX DESIGN											
S/N	Mix ID	Conc. Of NaOH (M)	SS/SH	Activator /SDA	Super-Plasticizers (percent of Binder)	Binder (Kg)	percent of SDA in Binder	SDA (Kg)	SAND (Kg)	Aggregate s (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

Mix ratios in the theoretical sense, as per Scheffe's (5,2) simple lattice, indicate the proportions of mixtures, with pure substances located at the vertices. The sum of all theoretical mix ratios must always equal 1 at any given point, serving as a constraint in the optimization process, as depicted in Equation 3.

The general form of the (q, m) polynomial is given by Equation 5 as explained in Scheffe's work;

$$Y = b_0 + \sum b_i x_i + \sum b_{ij} x_i x_j + \sum b_{ijk} x_i x_j x_k + \dots + \sum b_{i_1, i_2, \dots, i_m} x_{i_1} x_{i_2} x_{i_m} \quad (5)$$

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

b_0 is a constant coefficient

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

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{14} X_1 X_4 + b_{15} X_1 X_5 + b_{25} X_2 X_5 + b_{24} X_2 X_4 + b_{23} X_2 X_3 + b_{34} X_3 X_4 + b_{35} X_3 X_5 + b_{45} X_4 X_5 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 + b_{44} X_4^2 + b_{55} X_5^2 \quad (6)$$

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).

$$b_0 X_1 + b_0 X_2 + b_0 X_3 + b_0 X_4 + b_0 X_5 = b_0 \quad (8)$$

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.

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

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).

$$\begin{aligned} Y &= \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_{12}X_1X_2 + \beta_{13}X_1X_3 + \beta_{14}X_1X_4 + \beta_{15}X_1X_5 + \beta_{23}X_2X_3 + \beta_{24}X_2X_4 \\ &\quad + \beta_{25}X_2X_5 + \beta_{34}X_3X_4 + \beta_{35}X_3X_5 + \beta_{45}X_4X_5 \end{aligned} \quad (11)$$

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.

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

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;

$$\begin{aligned} Y_{12} &= \frac{1}{2}X_1 + \frac{1}{2}X_2 + \frac{1}{4}X_1X_2 \\ &= \frac{1}{2}\beta_1 + \frac{1}{2}\beta_2 + \frac{1}{4}\beta_{12} \end{aligned} \quad (14)$$

Aligned with Equation (7), β_i equals Y_i , where i varies from 1 to n . Substituting the values into Equation (8) resulted in the subsequent outcome:

$$Y_{12} = \left(\frac{1}{2}\right)Y_1 + \left(\frac{1}{2}\right)Y_2 + \left(\frac{1}{4}\right)\beta_{12} \quad (15)$$

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

Equation (11) was used to generate models, which were then tested with the Fisher test (F-test) to confirm their suitability. The F-statistic was employed to compare the experimental value's variance with the expected model response value, and the resulting hypotheses were accepted to validate the models. The null hypothesis (H0) proposed that there is no significant difference between the experimental and calculated responses, while the alternate hypothesis (H1) indicated that there is a notable difference between the experimental and calculated responses. The F-test can be represented mathematically by 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

To determine if the models are sufficient, the F-values obtained from Equation (22) must be lower than the values specified in the F-distribution table.

3. RESULTS AND DISCUSSION

1. Results

The analysis results of the component materials and the results of fifteen (15) experimental geopolymer concrete mixtures and fifteen (15) control mixes for Poisson's ratio are presented and discussed in this section.

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
Na2O (%)	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	$2.2 * 10^{-4} m^3$	$2.2 * 10^{-4} m^3$

N	Pseudo component					Actual component					Response	
	X ₁	X ₂	X ₃	X ₄	X ₅	Z ₁ = NaOH conc. (M)	Z ₂ = Na ₂ SiO ₄ / NaOH	Z ₃ = % SDA in binder	Z ₄ = water/binder	Z ₅ = Activator/ SDA	Symbol	Poisson's Ratio
1	1	0	0	0	0	8	1.5	35	0	2.3	Y ₁	0.1554
2	0	1	0	0	0	9.75	1.875	37.5	0.025	2.485	Y ₂	0.2283
3	0	0	1	0	0	11.5	2.25	40	0.05	2.671	Y ₃	0.1554
4	0	0	0	1	0	13.25	2.625	42.5	0.075	2.856	Y ₄	0.1903
5	0	0	0	0	1	15	3	45	0.1	3.1	Y ₅	0.2117
6	½	½	0	0	0	8.875	1.6875	36.25	0.0125	2.3925	Y ₁₂	0.1728
7	½	0	½	0	0	9.75	1.875	37.5	0.025	2.4855	Y ₁₃	0.1903
8	½	0	0	½	0	10.625	2.0625	38.75	0.0375	2.578	Y ₁₄	0.1728
9	½	0	0	0	½	11.5	2.25	40	0.05	2.7	Y ₁₅	0.1554
10	0	½	½	0	0	10.625	2.0625	38.75	0.0375	2.578	Y ₂₃	0.1728
11	0	½	0	½	0	11.5	2.25	40	0.05	2.6705	Y ₂₄	0.1554
12	0	½	0	0	½	12.375	2.4375	41.25	0.0625	2.7925	Y ₂₅	0.1554
13	0	0	½	½	0	12.375	2.4375	41.25	0.0625	2.7635	Y ₃₄	0.1554
14	0	0	½	0	½	13.25	2.625	42.5	0.075	2.8855	Y ₃₅	0.1903
15	0	0	0	½	½	14.125	2.8125	43.75	0.0875	2.978	Y ₄₅	0.2691
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			

Table 4 presents the findings of the oxide composition test conducted on softwood and hardwood sawdust ash. The results revealed that softwood sawdust ash, obtained through pyrolysis, exhibits excellent pozzolanic properties, leading to its selection for further laboratory investigation. Additionally, the XRD test performed on the sawdust ash sample provided further confirmation of the superiority of softwood sawdust ash. Information on the specific gravity and density of sawdust ash and fine aggregate, essential for subsequent testing, is detailed in Tables 5a - 5b. The Poisson's ratio results from laboratory experiments utilizing the trial mix design described in Table 3 are presented in Table 6. During these experiments, the geopolymer binder entirely replaced cement, while the fine and coarse aggregate remained constant. Other variables, including rest period, superplasticizer, and curing temperature, were maintained consistently. The samples were cured in an oven at 90°C for three days and then aged for 28 days before undergoing crushing. Table 6: Poisson's ratio of Sawdust ash geopolymer concrete Experimental Result for Trial mixes at 28 days curing age

2. Modeling the Poisson's ratio of sawdust ash Geopolymer Concrete

Table 6 displays the results of the Poisson's ratio test for the trial mix of geopolymer concrete. By utilizing this table and Equation 11, the coefficients of the model for the optimization of Scheffe's (5, 2) for the Poisson's ratio of geopolymer concrete containing sawdust ash were calculated. The optimization model for the Poisson's ratio of geopolymer concrete with sawdust ash using Scheffe's (5, 2) is expressed in the following way;

$$\begin{aligned} \beta_1 &= Y_1 = 0.1554 \\ \beta_2 &= Y_2 = 0.2283 \\ \beta_3 &= Y_3 = 0.1554 \\ \beta_4 &= Y_4 = 0.1903 \\ \beta_5 &= Y_5 = 0.2117 \\ \beta_{12} &= 4Y_{12} - 2Y_1 - 2Y_2 \\ &= 4(0.1728) - 2(0.1554) - 2(0.2283) = -0.0761 \\ \beta_{13} &= 4Y_{13} - 2Y_1 - 2Y_3 \\ &= 4(0.1903) - 2(0.1554) - 2(0.1554) = 0.1397 \\ \beta_{14} &= 4Y_{14} - 2Y_1 - 2Y_4 \\ &= 4(0.1728) - 2(0.1554) - 2(0.1903) = 0 \\ \beta_{15} &= 4Y_{15} - 2Y_1 - 2Y_5 \\ &= 4(0.1554) - 2(0.1554) - 2(0.2117) = -0.1126 \\ \beta_{23} &= 4Y_{23} - 2Y_2 - 2Y_3 \\ &= 4(0.1728) - 2(0.2283) - 2(0.1554) = -0.0761 \\ \beta_{24} &= 4Y_{24} - 2Y_2 - 2Y_4 \\ &= 4(0.1554) - 2(0.2283) - 2(0.1903) = -0.2158 \\ \beta_{25} &= 4Y_{25} - 2Y_2 - 2Y_5 \\ &= 4(0.1554) - 2(0.2283) - 2(0.2117) = -0.2586 \\ \beta_{34} &= 4Y_{34} - 2Y_3 - 2Y_4 \\ &= 4(0.1554) - 2(0.1554) - 2(0.1903) = -0.0698 \end{aligned}$$

$$\begin{aligned} \beta_{35} &= 4Y_{35} - 2Y_3 - 2Y_5 \\ &= 4(0.1903) - 2(0.1554) - 2(0.2117) = 0.0271 \\ \beta_{45} &= 4Y_{45} - 2Y_4 - 2Y_5 \\ &= 4(0.2691) - 2(0.1903) - 2(0.2117) = 0.2725 \end{aligned}$$

The coefficients' values given can be used in Equation (24) to predict the optimal mixture ratios for sawdust ash concrete geopolymers, considering the Poisson's ratio, through an optimization model.

$$\begin{aligned} v &= 0.1554x_1 + 0.2283x_2 + 0.1554x_3 + 0.1903x_4 + 0.2117x_5 - 0.0761x_1x_2 + 0.1397x_1x_3 - 0.1126x_1x_5 - 0.0761x_2x_3 - 0.2158x_2x_4 - 0.2586x_2x_5 - 0.0698x_3x_4 + 0.0271x_3x_5 + 0.2725x_4x_5 \end{aligned} \quad (24)$$

The equation (24) optimization model is used to predict the Poisson's ratio of sawdust ash blended geopolymer concrete using parameters (5, 2). It has the capacity to forecast the Poisson's ratio of sawdust ash concrete for any Poisson's ratio value within the trial mix range.

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

$$\begin{matrix} X_1 & X_2 & X_3 & X_4 & X_5 & \sum x \\ [0 & 0 & 0 & 0.46077 & 0.53937] & = 1 \end{matrix}$$

Upon inserting the most effective pseudo coefficients into equation 24, the optimum Poisson's ratio for the geopolymer concrete utilizing sawdust ash is calculated to be;

$$v_{op} = 0.2695$$

Table 7 displays the optimized mix design for geopolymer concrete blended with sawdust ash, utilizing the adjusted pseudo coefficient;

Table 7: Poisson's ratio Optimum mix design for sawdust ash based geopolymer concrete

Pseudo component					Actual component					Optimum Poisson's Ratio
X ₁	X ₂	X ₃	X ₄	X ₅	Z ₁ = NaOH conc. (M)	Z ₂ = Na ₂ SiO ₄ /NaOH	Z ₃ = % SDA in binder	Z ₄ = water/binder	Z ₅ = Activator/SDA	
0	0	0	0.46077	0.5392	14.1937	2.8272	43.8481	0.0885	2.9876	0.2695

3. Validation and verification of optimization model

The optimization models from the previous section underwent adequacy tests using F-statistics, and verification tests were conducted using R2 statistics. The study utilized the Poisson's ratio from laboratory response values for the control mix design matrix as outlined in Table 2. The experimental results for the Poisson's ratio of the control mix are presented in Table 8. The average Poisson's ratio values in Table 8 were compared to

the predicted values shown in Table 9. These predicted values were derived by inputting the pseudo matrix for control from Table 2 into the optimization model developed earlier (Equation 24). The graphical representation (R2 statistics) in Figure 2 illustrates the comparison of the predicted values with the control mix values in Table 9, which was used to determine the R2 value. Finally, Table 10 showcases the F-statistics validation, which is used to calculate the variances of the experimental value and predicted value.

Table 8: Control mix Poisson's Ratio Experimental Results at 28 days curing age

N	Pseudo component					Actual component					Response symbol	Compre. Strength	Flexural Strength	Poisson's Ratio
	X ₁	X ₂	X ₃	X ₄	X ₅	Z ₁ = NaOH conc. (M)	Z ₂ = Na ₂ SiO ₄ /NaOH	Z ₃ = % 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	Y ₁	17.00	2.9340	0.1726
2	1/3	1/3	0	1/3	0	10.33	2.00	38.33	0.03	2.55	Y ₂	20.00	3.1830	0.1592
3	1/3	0	1/3	1/3	0	10.92	2.13	39.17	0.04	2.61	Y ₃	18.00	3.0210	0.1678
4	1/3	1/3	0	0	1/3	10.92	2.13	39.17	0.04	2.63	Y ₄	21.00	3.2620	0.1553
5	1/4	1/4	1/4	1/4	0	10.63	2.06	38.75	0.04	2.58	Y ₅	19.00	3.1020	0.1633
6	1/4	1/4	1/4	0	1/4	11.06	2.16	39.38	0.04	2.64	Y ₁₂	17.50	2.9760	0.1701
7	1/4	1/4	0	1/4	1/4	11.50	2.25	40.00	0.05	2.69	Y ₁₃	19.00	3.1020	0.1633
8	0	1/4	1/4	1/4	1/4	12.38	2.44	41.25	0.06	2.78	Y ₁₄	17.25	2.9550	0.1713
9	3/10	1/10	1/5	1/5	1/5	11.33	2.21	39.75	0.05	2.66	Y ₁₅	17.25	2.9550	0.1713
10	1/5	1/5	1/10	3/10	1/5	11.68	2.29	40.25	0.05	2.70	Y ₂₃	18.00	3.0200	0.1678
11	1/5	1/5	1/5	3/10	1/10	11.33	2.21	39.75	0.05	2.66	Y ₂₄	18.50	3.0620	0.1655
12	1/5	1/5	1/5	1/5	1/5	11.50	2.25	40.00	0.05	2.68	Y ₂₅	17.50	2.9550	0.1689

13	3/20	1/4	1/5	1/5	1/5	11.59	2.27	40.13	0.05	2.69	Y ₃₄	18.50	3.0620	0.1655
14	1/5	1/5	3/20	1/4	1/5	11.59	2.27	40.13	0.05	2.69	Y ₃₅	18.00	3.0210	0.1678
15	1/4	1/5	1/5	1/5	3/20	11.15	2.18	39.50	0.05	2.64	Y ₄₅	18.00	3.0200	0.1678

Table 10: Comparison of Poisson's Ratio Strength values with the Experimental values

N	Pseudo component					Actual component					Respo nse symbol	Poisson's Ratio	
	X ₁	X ₂	X ₃	X ₄	X ₅	Z ₁ = NaOH conc. (M)	Z ₂ = Na ₂ SiO ₄ / NaOH	Z ₃ = % SDA in binde r	Z ₄ = water/bin der	Z ₅ = Activat or/ SDA		Experim ent result	Predict ed value
1	1/3	1/3	1/3	0	0	9.75	1.88	37.50	0.03	2.49	Y ₁	0.1726	0.178
2	1/3	1/3	0	1/3	0	10.33	2.00	38.33	0.03	2.55	Y ₂	0.1592	0.159
3	1/3	0	1/3	1/3	0	10.92	2.13	39.17	0.04	2.61	Y ₃	0.1678	0.175
4	1/3	1/3	0	0	1/3	10.92	2.13	39.17	0.04	2.63	Y ₄	0.1553	0.149
5	1/4	1/4	1/4	1/4	0	10.63	2.06	38.75	0.04	2.58	Y ₅	0.1633	0.164
6	1/4	1/4	1/4	0	1/4	11.06	2.16	39.38	0.04	2.64	Y ₁₂	0.1701	0.165
7	1/4	1/4	0	1/4	1/4	11.50	2.25	40.00	0.05	2.69	Y ₁₃	0.1633	0.172
8	0	1/4	1/4	1/4	1/4	12.38	2.44	41.25	0.06	2.78	Y ₁₄	0.1713	0.176
9	3/10	1/10	1/5	1/5	1/5	11.33	2.21	39.75	0.05	2.66	Y ₁₅	0.1713	0.178
10	1/5	1/5	1/10	3/10	1/5	11.68	2.29	40.25	0.05	2.70	Y ₂₃	0.1678	0.177
11	1/5	1/5	1/5	3/10	1/10	11.33	2.21	39.75	0.05	2.66	Y ₂₄	0.1655	0.170
12	1/5	1/5	1/5	1/5	1/5	11.50	2.25	40.00	0.05	2.68	Y ₂₅	0.1689	0.173
13	3/20	1/4	1/5	1/5	1/5	11.59	2.27	40.13	0.05	2.69	Y ₃₄	0.1655	0.171

1 4	1/5	1/5	3/2 0	1/4	1/5	11. 59	2.27	40. 13	0.05	2.69	Y ₃₅	0.1678	0.175
1 5	1/4	1/5	1/5	1/5	3/2 0	11. 15	2.18	39. 50	0.05	2.64	Y ₄₅	0.1678	0.171

Where; X₁, Z₁= 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 rat

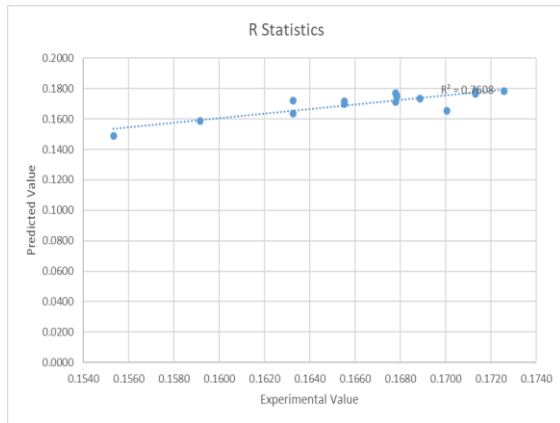


Figure 3: R² Statistics of sawdust ash blended geopolymer concrete Poisson's Ratio model

Table 10. F-Statistics for Validation of Sawdust Ash concrete that are geopolymers Poisson's Ratio Optimization Model

Experiment Value = Y _e	Pred. value = Y _m	Y _e - Ŷ _e	Y _m - Ŷ _m	(Y _e - Ŷ _e) ²	(Y _m - Ŷ _m) ²
0.1726	0.1783	0.0166	0.0080	0.0003	0.0001
0.1592	0.1589	0.0031	0.0114	0.0000	0.0001
0.1678	0.1748	0.0018	0.0045	0.0000	0.0000
0.1553	0.1488	0.0007	0.0215	0.0000	0.0005
0.1633	0.1637	0.0007	0.0066	0.0001	0.0000
0.1701	0.1654	0.0047	0.0049	0.0002	0.0000

0.1633	0.1720	0.0073	0.0017	0.0001	0.0000
0.1713	0.1764	0.0153	0.0061	0.0002	0.0000
0.1713	0.1784	0.0153	0.0081	0.0002	0.0001
0.1678	0.1769	0.0118	0.0066	0.0001	0.0000
0.1655	0.1697	0.0095	0.0006	0.0001	0.0000
0.1689	0.1734	0.0129	0.0031	0.0002	0.0000
0.1655	0.1715	0.0095	0.0012	0.0001	0.0000
0.1678	0.1750	0.0118	0.0047	0.0001	0.0000
0.1678	0.1711	0.0118	0.0008	0.0001	0.0000
Ŷ _e =	Ŷ _m			Σ =	Σ =
0.1665	=0.1703			0.0020	0.0009

Using Table 10 and Equation (23), the following conclusions were drawn:

$$S_e^2 = 0.0020/14 = 0.00014$$

$$S_m^2 = 0.0009/14 = 0.0001$$

The ratio of the two squared variances, known as the F-value, was calculated using Equation (22);

$$F = 0.00014/0.0001 = 2.1101$$

The F-calculated (F-cal) value is 2.1101, which is less than the critical F-value (F-tab) of 2.4986. This indicates that we can accept the null hypothesis, confirming the suitability of the model. In addition, the R-squared (R²) statistics shown in Figure 3 reveal an R² score of 76.08%. This suggests that the optimization model explains over 76% of the dataset.

4. Conclusions

The following findings were made from this study:

1. Sawdust ash displays enhanced pozzolanic properties when exposed to pyrolysis in an environment devoid of oxygen, as opposed to when it undergoes combustion in the presence of oxygen.
2. As a pozzolanic material, softwood sawdust demonstrates better performance than hardwood sawdust.
3. A predictive model has been developed for estimating the Poisson's ratio of geopolymer concrete produced using sawdust ash; $Y = 2.956x_1 + 2.413x_2 + 2.956x_3 + 2.413x_4 + 2.685x_5 + 0.002x_1x_2 - 2.172x_1x_3 + 0.002x_1x_4 + 0.542x_1x_5 + 0.002x_2x_3 + 2.172x_2x_4 + 1.628x_2x_5 + 1.086x_3x_4 - 1.630x_3x_5 - 3.368x_4x_5$.
4. The fresh sawdust ash-based geopolymer concrete shows no signs of setting or decrease in structural and elastic properties for up to 120 minutes.
5. An increase in the molar ratio of H₂O to Na₂O leads to a increase in the Poisson's ratio of geopolymer concrete using sawdust ash.
6. As the mass ratio of water-to-geopolymer solids increases, the Poisson's ratio of sawdust ash-based geopolymer concrete increases.
7. The elastic properties of heat-cured sawdust ash-based geopolymer concrete remains independent of age.
8. Mixing sawdust ash-based geopolymer concrete for up to sixteen minutes enhances the elastic property.
9. The average density of sawdust ash-based geopolymer concrete closely resembles OPC concrete.

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