



# **Optimizing Physical and Mechanical Properties of Metakaolin and Calcium Carbide Residue – Geopolymer Concrete Using the Taguchi Method**

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## **Authors' contributions**

*This work was carried out in collaboration among all authors. Authors JO and SA designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AA and MA-A managed the analyses of the study. Author JO managed the literature searches. All authors read and approved the final manuscript.*

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## **ABSTRACT**

The construction industry is seeking alternative sustainable materials for construction due to the increased demand on the conventional construction materials. Investigations into environmentally friendly binders, most predominantly geopolymer, have intensified in the past few years. The

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Taguchi method is used in this present study to optimize the properties of geopolymer concrete mix. Three factors at 2 levels each, that is, liquid-to-binder ratio (0.8 and 0.6), coarse aggregate sizes (14 mm and 16 mm) and curing regime (ambient temperature with and without wet hessian mat) were considered to produce four concrete mixes. The workability, density, compressive strength and flexural strengths of the geopolymer concretes were evaluated. The slump values of the fresh geopolymer concrete were classified as S1 and S2. The optimum geopolymer concrete that produced the highest density, compressive strength and flexural strength was obtained at mix T3 (liquid-to-binder ratio of 0.6, 16 mm coarse aggregate and cured with wet hessian mat). Based on the signal-to-noise ratio, the size of the coarse aggregate had the most influence on the density. The liquid-to-binder ratio had the most impact on the compressive and flexural strengths.

*Keywords: Geopolymer concrete; Taguchi method; compressive strength; flexural strength; ANOVA.*

## 1. INTRODUCTION

Geopolymer concrete is an environmentally friendly concrete material. The ordinary Portland cement (OPC) in conventional concrete is replaced with geopolymer as a binding material in geopolymer concrete. Beyond the environmental advantages of geopolymer over OPC, other added benefits include improved mechanical and durability performance [1-3]. The geopolymer is an amorphous or semi-crystalline binding material produced through the reaction between aluminosilicate sources and alkali activators [4].

Metakaolin is an aluminosilicate material produced through the calcination of kaolin clay and is low in calcium [5,6]. Calcium-rich aluminosilicate materials (high calcium fly ash, and slag) used as precursors for synthesizing geopolymers results in the formation of calcium aluminate silicate hydrates (C-A-S-H) and /or calcium silicate hydrates (C-S-H) in addition to the geopolymer gels [7,8]. These reaction products together with the geopolymer gels improves the mechanical strength and durability of the geopolymers [9,10].

Recent studies have focused on the use of waste materials in concrete formulations to reduce their negative impact on the environment. In this regard, waste materials that have significant calcium contents can be added to metakaolin to promote a sustainable environment. An example of a waste calcium source is calcium carbide residue (CCR) which is produced as a byproduct in acetylene gas production [11]. The main composition of the CCR is calcium hydroxide. The addition of CCR to geopolymer mix formulations have been comprehensively investigated [12-16]. The studies have found that aluminosilicate sources that have partially been substituted with CCR

resulted in improved performance. When used as replacement of aluminosilicate materials, optimal proportions have ranged from 10 % to 30% [12, 17]. Higher replacements with CCR results in detrimental effects on the resulting material [17].

The manufacturing of geopolymer concrete has been researched from several perspectives, including particle sizes of aluminosilicate sources [18], type of hydroxides and silicates [19], concentrations of hydroxides and alkali activator ratios [20], and aggregate type and amount [21], among many other parameters. Few studies have considered the effect of liquid-to-solid ratios (L/S) on the properties of geopolymer concrete. It has been reported that L/S significantly affects the mechanical strength of geopolymer [22]. For example, [23] observed that the L/S was found to be influential on the mechanical performance of geopolymer paste produced among the other factors investigated. Therefore the focus of this research is on the effect of the L/S on the mechanical strength of geopolymer concrete. Also, coarse aggregates contributes about 70% of the total volume of concrete [24], therefore it plays significant role on the properties of concrete [25]. The different sizes of coarse aggregates also influences the mechanical strength of concrete, therefore it is crucial to study the effect of the commonly available coarse aggregate sizes used in construction in the geopolymer concrete studied in this research. Many researchers have studied the curing of geopolymers above room temperatures. This particular type of curing is mostly observed in fly ash based geopolymers, which requires curing above ambient temperatures (60 – 120 °C) for complete geopolymerization and improved compressive strength [26,27]. In metakaolin based geopolymers on the other hand, with different microstructure compared to fly ash, complete

geopolymerization is achieved under ambient conditions. For wider applications of geopolymers which includes in situ construction, curing under ambient conditions are favorable with the added advantage of reduction in energy and cost of production associated to heating. Besides curing under ambient conditions, the use of wet hessian mats to provide moist in curing has been reported to improve compressive strength in concrete which is explored in this research [28].

The Taguchi approach is employed to analyze how combinations of different factors at varying levels interact and influence the response characteristics used in designing concrete mixtures [29]. For example, [30] investigated influence of four factors namely, content of binder, concentration of sodium hydroxide, alkali activator ratio and amount of superplasticizer at different levels on the strength properties of geopolymer concrete [31]. Conducted a study on factors influencing the density of geopolymer concrete, including aggregate type, sodium hydroxide concentration, silica-alumina ratio, and solid-to-liquid ratio. The geopolymer concrete mixture yielding the highest density was identified as optimal in the research experiment. The Taguchi method, a statistical approach, is utilized to optimize concrete based on specific property requirements. Depending on the context, the optimal concrete property may prioritize highest, medium, or lowest values [32]. However, for most concrete materials, particularly concerning mechanical properties such as compressive strength and flexural strength, their highest values are typically considered optimal [33].

Current literature shows limited research on the use of metakaolin combined with CCR to produce geopolymer materials especially as concrete [34,14]. This knowledge gap is addressed in this research studies. The objective of this research experiment is to study the feasibility of producing geopolymer concrete from metakaolin clay and CCR. The influence of L/S of the geopolymer, curing regimes and different coarse aggregate sizes on the properties of geopolymer concrete were investigated. The Taguchi approach is employed to determine the optimum mix design of geopolymer concrete which produces the highest density, compressive and flexural strengths. The concrete produced would be applied for structural applications under field or in-situ conditions.

## 2. MATERIALS AND METHODS

### 2.1 Materials

Metakaolin and CCR were used as precursors. The kaolin clay used for the production of the metakaolin was obtained from Mfensi in the Ashanti region of Ghana. The chemical components of the clay are given in Table 1. Alumina and silica are the major oxides in the Mfensi clay. The clay was dried in an electric oven at 110 °C for 24 hours and then milled. After passing the milled clay through 125 µm sieve, the clay was then calcined for four (4) hours at a temperature of 700 °C. The CCR used in this study was obtained as waste from an artisanal welding shop in Sunyani, Ghana. The CCR was dried at 100 °C for 24 hours in an electric oven. The dried CCR was ground into a fine powder and sieved through 125 µm sieve to obtain a smaller particle size. Calcium oxide is the major component of the CCR (see Table 1). Alkaline activators used in this study were commercially available sodium hydroxide (NaOH) pellets with >98% purity from VWR BDH Chemicals and sodium silicate solution (Na<sub>2</sub>SiO<sub>3</sub>). The NaOH and Na<sub>2</sub>SiO<sub>3</sub> were combined, however, the concentration of the NaOH and the ratio of the NaOH:Na<sub>2</sub>SiO<sub>3</sub> adopted was obtained from previous research work [14]. Distilled water was used to prepare 10 M NaOH 24 hours prior to the preparation of the geopolymer concrete. Pit sand and crushed granite were used as fine and coarse aggregates, respectively. The fine and coarse aggregates used were under saturated surface dry conditions. The fine aggregate had specific gravity of 2.65. Two different coarse aggregate sizes were used. The 14 mm coarse aggregate size had specific gravity and water absorption of 2.7 and 0.56%, respectively. The 16 mm coarse aggregate size on the other hand, had specific gravity and water absorption of 2.7 and 0.52%, respectively.

### 2.2 Methods

In traditional concrete, factors like the water-cement ratio, coarse aggregate sizes, and curing conditions have a significant impact on their strength properties [35-39]. However, in geopolymer concrete design, the liquid-to-binder ratio, akin to the water-cement ratio in conventional concrete, is noted to influence their strength properties [40]. Hence, the factors selected for investigation on the density,

compressive strength and flexural strength of the geopolymer concrete were the liquid-to-binder ratio, coarse aggregate sizes and curing conditions, as shown in Table 2. The chosen levels for the selected influencing factors were determined based on the prevailing practical conditions under which concrete is used in structural applications and the available coarse aggregate sizes. The liquid-to-binder ratios of 0.8 and 0.6 used were obtained from trial mixes. The readily available coarse aggregate sizes were 14 mm and 16 mm. To ensure that the geopolymer concrete produced in this study would be well suited for field applications, ambient curing conditions were chosen. Also, to avoid excessive moisture loss, the concrete was covered with wet hessian mat and cured under ambient conditions. The optimization of the formulation was conducted using a partial factorial design based on the Taguchi orthogonal array. The parameters are outlined in Table 3. Four concrete mixes were generated using the Taguchi Orthogonal array L4 (2<sup>3</sup>), involving four factors at three levels. The details of the concrete mixtures for the four combinations resulting from the Taguchi

approach are presented in Table 4. Table 5 summarizes the geopolymer concrete mixture proportions.

All the dried materials (i.e. metakaolin, CCR (binders), fine and coarse aggregates) were mixed. The alkaline solution was then added and mixed further followed by addition of water to promote a workable mixture. The mixing of all the materials continued until a uniform mixture was obtained. A slump test was used to determine the workability of the fresh geopolymer concrete mixes produced. Slump testing was performed in line with BS EN 12350-2 [41]. The specimens were then cast into 100×100×100 mm cubes for density and compressive strength test. For the flexural strength test the specimens were poured into the 100×100×300 mm prisms. The specimens were removed after 24 hours casting and cured in ambient temperature with and without wet hessian mat until the testing day. Temperatures ranged between 24°C and 30°C, with relative humidity ranging between 77 and 85 %. All specimens were cured for 28 days. The density of the geopolymer concrete was

**Table 1. Chemical composition (wt%) of clay and CCR samples**

Materials	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	K <sub>2</sub> O	MnO	MgO	SO <sub>3</sub>	TiO <sub>2</sub>
Clay	65.25	18.10	2.72	0	0.49	0.01	0	0	1.04
CCR	0.34	0.91	0.2	64.64	0	0.01	0	0.18	0

**Table 2. Factors and values at corresponding levels**

Factors	Levels	
	1	2
A. Liquid /Binder Ratio	0.8	0.6
B. Coarse Aggregate Size	16 mm	14 mm
C. Curing Regime	Ambient without hessian mat	Ambient with wet hessian mat

**Table 3. The Taguchi orthogonal array L4 (2<sup>3</sup>)**

Trial Number	Factor A	Factor B	Factor C
T1	1	1	1
T2	1	2	2
T3	2	1	2
T4	2	2	1

**Table 4. Geopolymer concrete mixes**

Trial	Factors		
	Liquid/binder ratio	Coarse Aggregate Size	Curing Regime
T1	0.8	16 mm	Ambient without hessian mat
T2	0.8	14 mm	Ambient with wet hessian mat
T3	0.6	16 mm	Ambient with wet hessian mat
T4	0.6	14 mm	Ambient without hessian mat

**Table 5. Geopolymer concrete mixture proportions**

MIXES	Unit Weight(kg/m <sup>3</sup> )							
	Cement	Metakaolin	CCR	NaOH	Na <sub>2</sub> SiO <sub>3</sub>	Fine Aggregates	Coarse Aggregates	Water
T1 –T4		288	72	72	144	705.6	1410	80

measured in accordance to the BS EN 12390-7 [42]. The compressive strength and the flexural strength were conducted according to the BS EN 12390-3 [43] and BS EN 12390-5 [44], respectively. A loading rate of 0.3KN/s were used to test for the compressive strength and flexural strength of the hardened geopolymer concrete. At least three samples were tested and the average values recorded.

### 3. RESULTS AND DISCUSSION

#### 3.1 Fresh Properties of Geopolymer Concrete Mixes

In order to evaluate the fresh properties of the geopolymer concrete mixes, the workability of the mixes was examined. The slump of fresh geopolymer concrete is shown in Fig. 1. The slump values for the various geopolymer concrete mixes are shown in Fig. 2. The slump values for each geopolymer concrete mix are classified in accordance with BS 8500 [45] and shown in Table 6. The slump classes S1 – S5, are used to identify the ranges of the slump, and their specific applications in construction. From Table 6, it can be seen that the slump values fall within class S2 for mixes T1 and T3, and class S1 for mixes T2 and T4. The T1 and T3 mixes which is made from 16 mm nominal coarse aggregates have higher workability than the T2 and T4 mixes made from relatively smaller coarse aggregate size thus, 14 mm nominal coarse aggregates. This is because concrete made from bigger coarse aggregate sizes have less requirement of water for mixing due to their smaller total surface area. Therefore they are more workable than smaller coarse aggregates sizes [46]. The effect of the liquid-to-binder ratios on the slump of the geopolymer concrete mixes shows that mixes T1 and T2 with liquid-to-binder ratio of 0.8 are within the higher limits of their classes compared to mixes T3 and T4 with liquid-to-binder ratio of 0.6. This is because there is more liquid for mixing at liquid-to-binder ratio of 0.8 compared to liquid-to-binder ratio 0.6 [47].

#### 3.2 Optimization of Geopolymer Concrete Mixes

After combining the various factors at differing levels, the impact on the responses, which are density, compressive strength, and flexural strength, is evaluated. The Taguchi approach optimizes responses depending on their specific requirements by using the S/N ratio. The S/N ratio is calculated using formulae that classify the optimal response as lower-the-better, medium-the-better, or higher-the-better. The density of concrete may be lighter or heavier depending on the specific concrete use [48]. The higher density was prioritized in this study. Furthermore, high compressive and flexural strengths are generally required for concrete applications. For this reason, the concrete mix that produced the highest density, compressive strength and flexural strength were appropriate for the aim of this study. Consequently, the S/N ratio which classifies the response as the higher-the-better is used to select the response which gives the optimum geopolymer concrete mix. The equation used to compute this S/N ratio is presented in equation 1 as follows:

$$S/N = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (1)$$

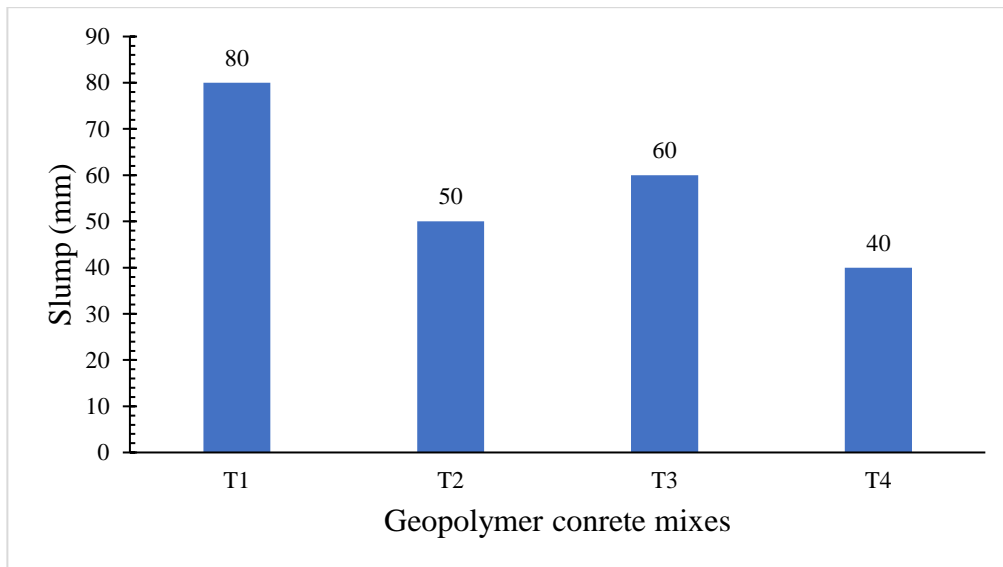
Where n is the number of observations and y<sub>i</sub> is the results of the experiment. The results from the experiments performed on the density, compressive strength and flexural strengths (responses) of the four different geopolymer concrete mixes cured after 28 days are provided in Table 7. Additionally, Table 7 includes the S/N ratios for these various responses, which have been calculated using Equation 1. The Minitab 19.1 analytic tool was used to evaluate the S/N ratios for each response (density, compressive strength and flexural strength) and construct the response index for each factor at each level, as shown in Table 8. The factors were ranked at the various levels based on the highest S/N ratios, as shown in Table 8. As a result, for each factor, the level that elicited the maximum response was recorded.

**Table 6. Slump values of geopolymer concrete and their respective slump classes**

Mix	Slump (mm)	Slump Class	Limit (mm)
T1	80	S2	50-100
T2	50	S1	0-50
T3	60	S2	50-100
T4	40	S1	0-50



**Fig. 1. Slump of fresh geopolymer concrete mix**



**Fig. 2. Slump values for the various geopolymer concrete mixes**

Fig. 3a and 3b shows the densities of the geopolymer concrete mixes after 28 days of curing and the effect of the control factors on the densities. The maximum density, 2435kg/m<sup>3</sup>, is observed at geopolymer concrete mix T3, as shown in Fig. 3a. T3 geopolymer concrete mix has a 0.6 liquid-to-binder ratio, coarse aggregate size of 16 mm, and is cured in ambient temperature with wet hessian mat. In contrast, geopolymer concrete mix T2 had the lowest density of 2052 kg/m<sup>3</sup>. The geopolymer concrete

mix T2 was formulated with 0.8 liquid-to-binder ratio, coarse aggregate size of 14 mm, and is cured in ambient temperature with wet hessian mat. From Fig. 3b, factor B which is the coarse aggregate size at level 1 thus, 16 mm coarse aggregate size was the most influential on the density of the geopolymer concrete. This is because concrete mixes produced with larger coarse aggregates improves the density of concrete due to their heavier weights [46]. The larger coarse aggregate size 16 mm

**Table 7. Density, compressive strength and flexural strength at 28<sup>th</sup> day of curing with respective S/N ratios**

Mix	Control Factors			28 -Day	S/N ratio	28 -Day	S/N ratio	28 -Day	S/N ratio
	A	B	C	Density (kg/m <sup>3</sup> )	Density	Compressive Strength (MPa)	Compressive Strength	Flexural Strength (MPa)	Flexural Strength
T1	0.8	16 mm	Ambient without hessian mat	2412	67.65	31.7	30.02	3.97	11.98
T2	0.8	14 mm	Ambient with wet hessian mat	2052	66.24	30	29.54	3.79	11.57
T3	0.6	16 mm	Ambient with wet hessian mat	2435	67.73	35.3	31.00	4.4	12.87
T4	0.6	14 mm	Ambient without hessian mat	2248	67.04	33.6	30.53	4.01	12.08

**Table 8. Response index for S/N ratios for density, compressive strength and flexural strength**

LEVELS	28 - day Density			28 - day compressive strength			28 - day flexural strength		
	Factor A	Factor B	Factor C	Factor A	Factor B	Factor C	Factor A	Factor B	Factor C
level 1	66.95	67.69	67.34	30.03	30.51	30.03	11.77	12.66	12.42
level 2	67.38	66.64	66.99	30.61	30.27	30.27	13.11	12.22	12.46
Delta	0.44	1.05	0.35	1.20	0.69	0.22	1.33	0.44	0.04
Rank	2	1	3	1	2	3	1	2	3

**Table 9. ANOVA of density, compressive strength and flexural strength**

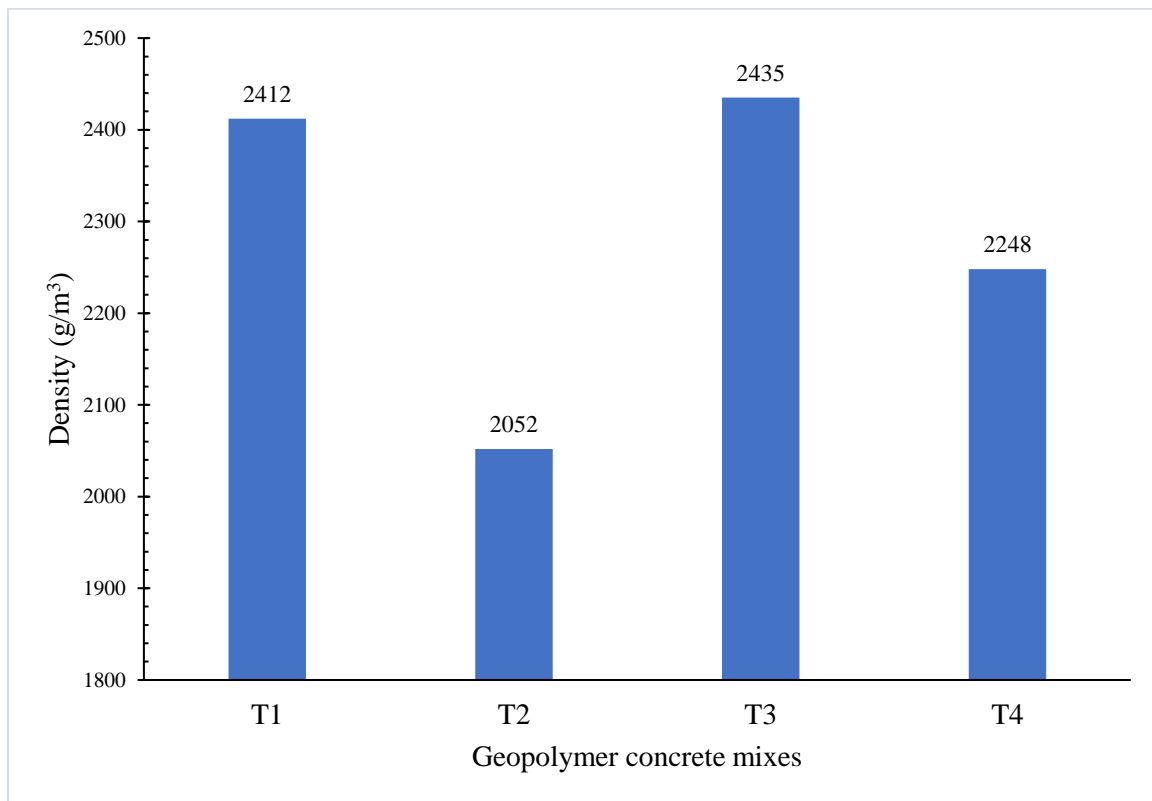
Factor	Degree of Freedom	Sum of Squares	Mean Squares	% Contribution	Density			Compressive strength			Flexural strength		
					Sum of Squares	Mean Squares	% Contribution	Sum of Squares	Mean Squares	% Contribution	Sum of Squares	Mean Squares	% Contribution
Liquid/Binder Ratio	1	0.19127	0.19127	13.49	1.62683	1.62683	73.26842	1.78158	1.78158	90.06977			
Coarse Aggregate Size	1	1.10013	1.10013	77.62	0.54296	0.54296	24.45358	0.19494	0.19494	9.85541			
Curing Regime	1	0.12597	0.12597	8.89	0.05058	0.05058	2.277999	0.00148	0.00148	0.074823			
Total	3	1.41736		100.00	2.22037		100	1.978		100			

in T3 results in higher density than the smaller coarse aggregate size 14 mm in T2, which contradicts most study findings that smaller coarse particles pack more aggregates and so result in denser concretes [49]. Among the factors studied, the curing regime had the least influence on the density of the geopolymer concretes. The concrete mix T2, with a recorded density of 2052 kg/m<sup>3</sup>, falls within the classification of lightweight concrete [50]. Conversely, mixes T1, T3, and T4 have densities classified as normal weight concrete [51]. This suggests that lightweight geopolymer concrete, like T2, can be suitable for applications requiring lower dead loads [52]. On the other hand, normal weight geopolymer concrete, like T1, T3, and T4, can be utilized in various concrete applications such as buildings, road construction, and water-retaining structures [53,24]. However, it is essential to recognize that despite the classification based on density, the compressive strength requirement for a specific concrete application will significantly influence its suitability for that particular concrete work. Thus, both density and compressive strength considerations are vital in determining the appropriate use of geopolymer concrete in construction projects [54,55].

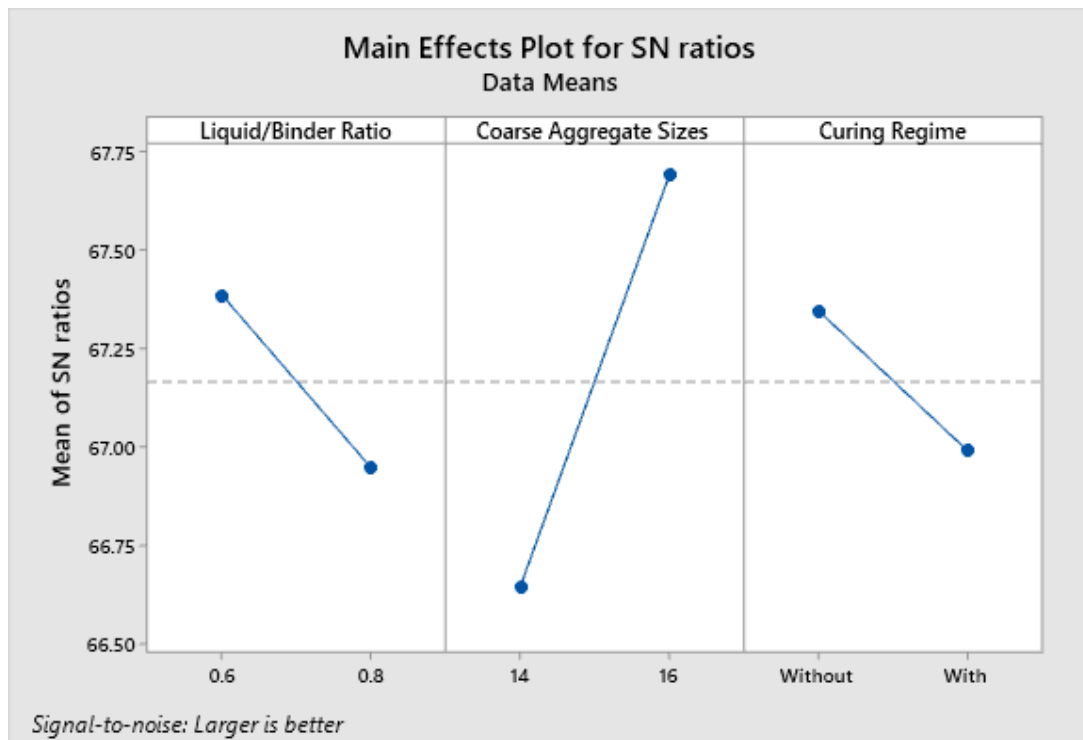
Fig. 4a depicts the average compressive strength of the three specimens for each geopolymer concrete mix. The effect of the liquid-to-binder ratio, coarse aggregate size, and curing regime on the compressive strength of four geopolymer concrete mixes (T1- T4) was examined. According to Fig. 4a, the geopolymer concrete mix identified as T3 had the maximum compressive strength of 35.3 MPa. Geopolymer concrete mix T3 is made up of a liquid-to-binder ratio of 0.6, coarse aggregate size of 16 mm, and is cured at ambient temperature with wet hessian mat. On the other hand, the geopolymer concrete mix with the lowest compressive strength T2 had a liquid-to-binder ratio of 0.8, coarse aggregate size of 14 mm, and was cured at ambient temperature with wet hessian mat. According to Table 7, the liquid-to-binder ratio was the most influential factor in the compressive strength of geopolymer concrete mixtures. The maximum compressive strength geopolymer concrete mix T3 was made with a liquid-to-binder ratio of 0.6. (See Fig. 4b). The lower liquid-to-binder ratio of 0.6 contrary 0.8 implies that there is less liquid, and hence activators (NaOH and Na<sub>2</sub>SiO<sub>3</sub>) at equal binder content. Interestingly, the geopolymerization process may be hampered when geopolymers with high quantities of

activator are used, resulting in decreased compressive strength. This is observable in this study, since the geopolymer concrete with the lowest compressive strength was made with a liquid-to-binder ratio of 0.8. Evidently, the geopolymer concrete mix T3 made with a liquid-to-binder ratio of 0.6 did not contain excess activator than was required for geopolymerization, and hence it had the maximum compressive strength. The findings of this study are comparable to those of previous studies where lower liquid-binder ratios resulted in the best compressive strengths [56,57]. The coarse aggregate size was the secondary greatest influential factor. Fig. 4b shows that the coarse aggregate size of 16 mm generated the highest compressive strength. Similar to the findings of [58], concrete produced with bigger coarse aggregate sizes had higher compressive strength than concrete produced with smaller coarse aggregate sizes. It is worth noting that the improvement in compressive strength with increasing coarse aggregate size is only up to a specific size. This includes coarse aggregate sizes of 12.5 mm [59] and 18.5 mm [60]. Despite such reports that confirm the findings of this study, other researchers [61] have observed that smaller coarse aggregate sizes utilized in concrete had greater compressive strength than bigger coarse aggregate sizes. According to Table 7, the curing regime has the least influence on compressive strength. In general, geopolymer materials are cured above ambient temperatures to increase mechanical strength [62,63], especially in fly ash based geopolymers than metakaolin-based geopolymers. However, to assure in-situ application of the geopolymer concrete produced in this study, all geopolymer concrete was cured at ambient temperatures. Curing OPC concrete with moisture prevents quick water loss, which might be harmful to mechanical strength [64]. Considering that, the addition of calcium to metakaolin to make geopolymer resulted in the development of hydrates (C-A-S-H) similar to OPC-based materials, the curing method similar to OPC, which is moisture condition curing at ambient temperature, were applied here. The least impact of the curing regimes becomes more evident when considering that geopolymer concrete mixes exhibiting both highest and lowest compressive strengths were cured under identical conditions, specifically at ambient temperature with wet hessian mat. Geopolymer concrete, achieving compressive strengths ranging from 30 MPa to 35.5 MPa as demonstrated in this research, proves suitable



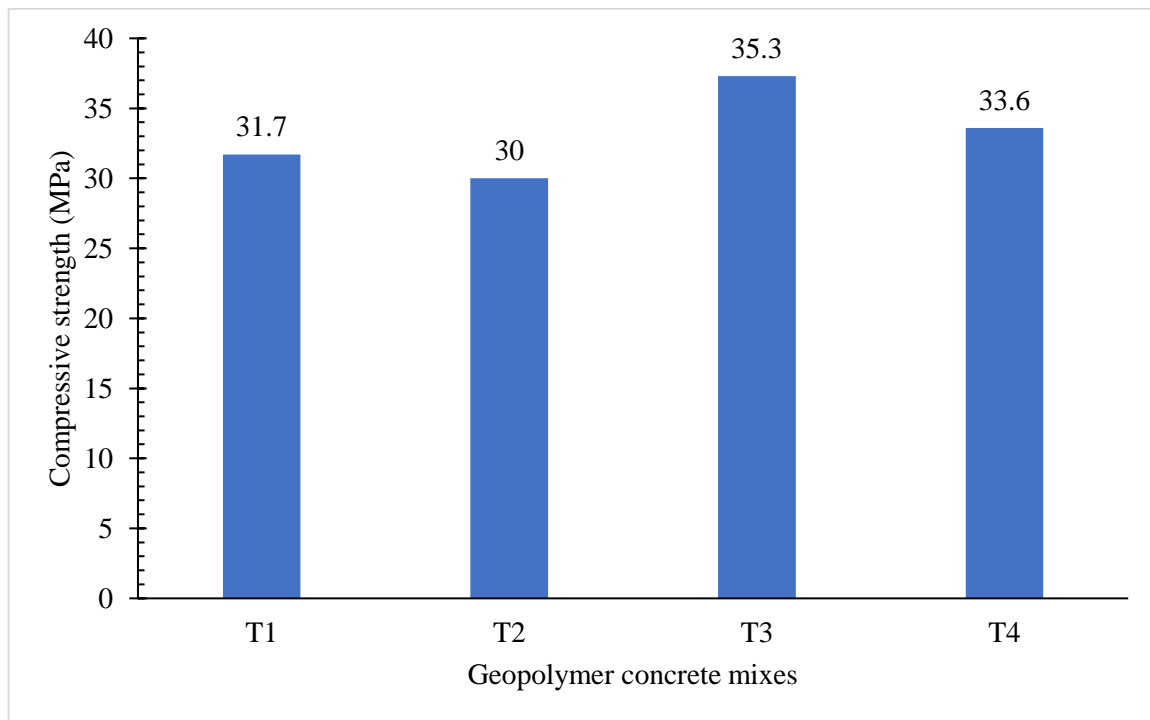


(a)

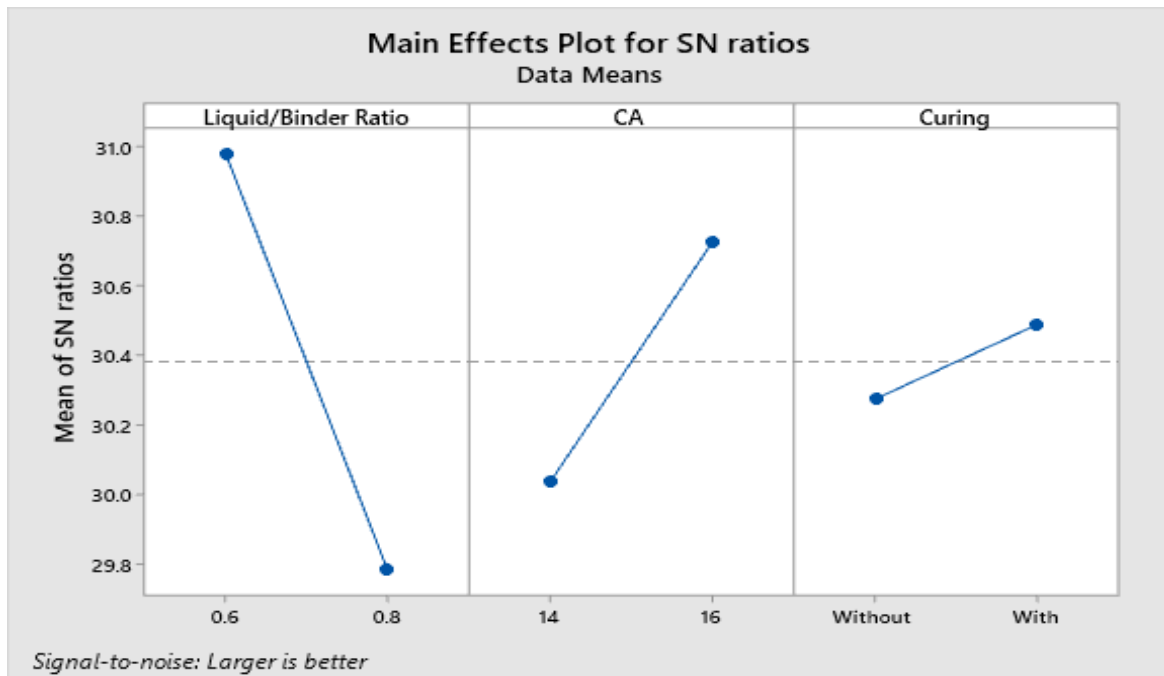


(b)

**Fig. 3. (a) Density of geopolymer concrete mixes after 28 days of curing (b) Effect of control factors on density of geopolymer concrete mixes**



(a)

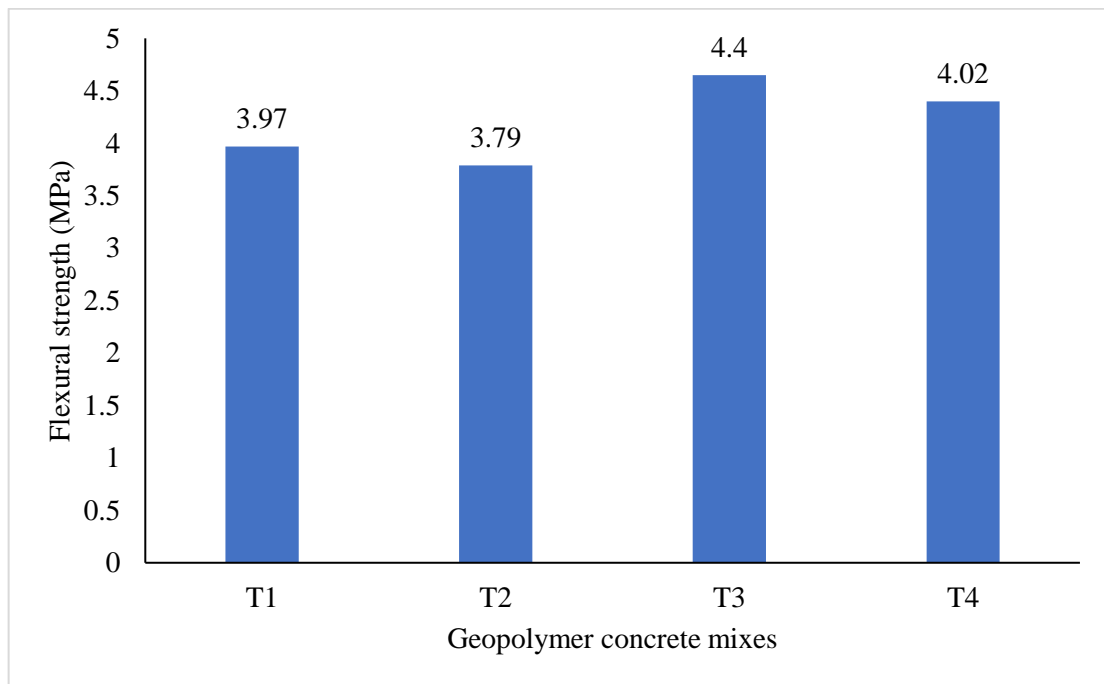


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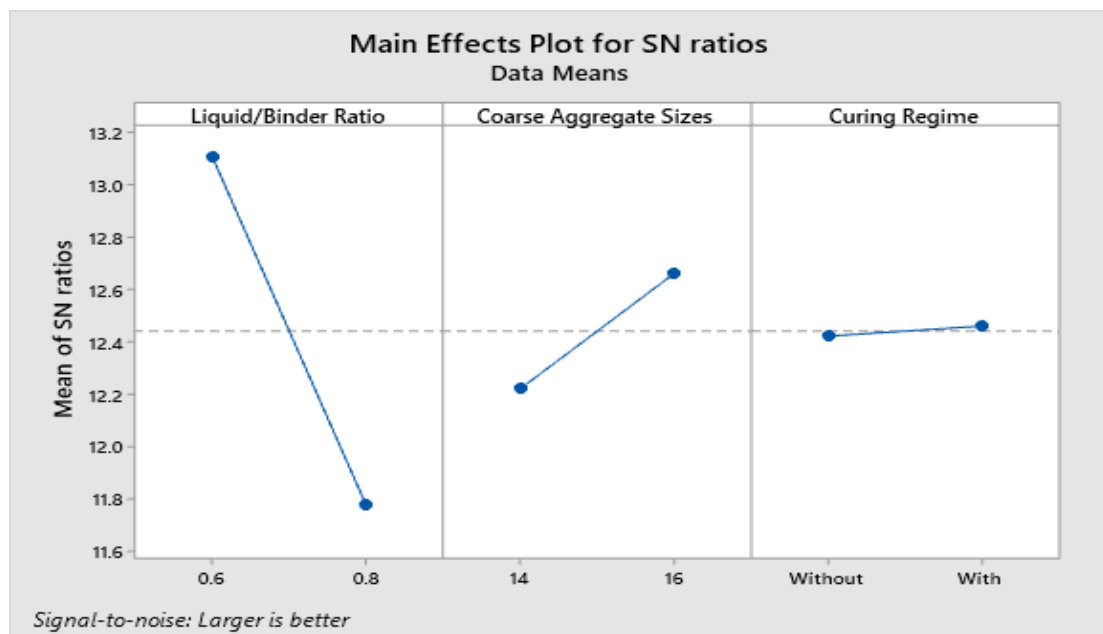
**Fig. 4. (a) Compressive strength of geopolymer concrete mixes after 28 days of curing (b) Effect of control factors on compressive strength of geopolymer concrete mixes**

for structural construction in buildings and highways requiring high compressive strength [65,66].

Fig. 5a depicts the flexural strength of each geopolymer concrete mix. The highest flexural strength of 4.4 MPa was attained using



(a)



(b)

**Fig. 5. (a) Flexural strength of geopolymer concrete mixes after 28 days of curing (b) Effect of control factors on flexural strength of geopolymer concrete mixes**

geopolymer concrete mix T3, which had a liquid-to-binder ratio of 0.6, a coarse aggregate size of 16 mm, and was cured at ambient temperature with wet hessian mat. Fig. 5a shows the lowest flexural strength of geopolymer concrete mix T2, which was prepared with a liquid-to-binder ratio of 0.8, coarse aggregate size of 16 mm, and

cured at ambient temperature with wet hessian mat. As with compressive strength, the parameter that has the greatest impact on flexural strength is factor A, which is the liquid-to-binder ratio, as illustrated in Fig. 5b. Level 2 of the liquid-to-binder ratio of 0.6 provided the highest flexural strengths, according to Fig. 5b,

which was developed from Table 7. Accordingly, geopolymer concrete mix T4, which had the second highest flexural strength of 4.02 MPa, was formulated with a liquid-to-binder ratio of 0.6, same as geopolymer concrete mix T3. The implications of this confirm prior research that highlight the importance of liquid-to-binder ratios, which is simply increasing or decreasing the quantity of liquid alkali activators in the geopolymer formulation, on the mechanical characteristics of geopolymer materials [67,68]. In addition, analogous to this study, [67] observed that lowering the liquid-to-binder ratio from 0.5 to 0.25 increased mechanical strength. Reduced mechanical strength as the liquid-to-binder ratio progressed was due to excess liquid, which inhibits interaction between the geopolymers components. Although the previous study's [67] mechanical strength was compressive strength, similar conclusions can be drawn in this study because flexural strength is also classified as a mechanical property. Furthermore, several building codes [69,70] reflect a link between compressive strength and flexural strength.

### 3.3 ANOVA Results

The Minitab 19.1 analytical tool was used to conduct an analysis of variance (ANOVA) on the experimental results. Taking into account the effect of the various factors at various levels on the response characteristics, the ANOVA reveals the percentage contribution of each factor on the density, compressive strength, and flexural strength shown in Table 9. The coarse aggregate size contributed the most to density, accounting for 77.62 %. This meant that in order to achieve higher density values in the geopolymer concrete mix, the coarse aggregate size had to be a significant aspect to consider in the design of the geopolymer concrete mix. In terms of compressive and flexural strengths, the same factor, the liquid-to-binder ratio, contributed the most; however, the proportion of contribution differed for the compressive and flexural strengths. The liquid-to-binder ratio contributed 73.27 % to the compressive strength and 90.07 % to the flexural strength. According to [71], the solid-to-liquid ratio which is similar to the liquid-to-binder ratio significantly affected the strength of calcined kaolin geopolymer by contributing to their microstructure and strength growth. This demonstrates that if the geopolymer concrete mix emphasizes the requirement to make concrete with good mechanical properties, the liquid-to-binder ratio must be carefully examined.

With a substantially lower percentage contribution, the curing regime was determined to contribute the least to the all the response characteristics. The curing regime specifically contributed 8.89%, 2.28%, and 0.07% to the density, compressive strength, and flexural strength, respectively. More coarse aggregate sizes may be investigated in future research to analyze their influence on response characteristics, particularly density, because this study only considered the most generally available coarse aggregate sizes for concrete use in the construction industry.

## 4. CONCLUSION

The Taguchi orthogonal array L4 was effective in determining the optimum geopolymer concrete mixes that produced the highest density, compressive strength and flexural strength. The conclusions made from the experimental and analytical studies are as follows:

- The workability of the geopolymer concrete mixes were evaluated from the slump values which showed that the geopolymer concrete mixes produced from 16 mm coarse aggregates were more workable than the geopolymer concrete mixes produced from 14 mm coarse aggregates.
- The optimum geopolymer concrete mix for obtaining the highest density was made from 0.6 liquid-to-binder ratio, 16 mm coarse aggregate size and cured in ambient temperature with wet hessian mat.
- In terms of the compressive and flexural strengths, the geopolymer concrete mix that produced the maximum strength values is produced from liquid-to-binder ratio of 0.6, 16 mm coarse aggregate size and cured in ambient temperature with wet hessian mat. The maximum compressive and flexural strengths are 35.3 MPa and 4.4 MPa, respectively after 28 days of curing.
- From ANOVA analysis, the percentage of contribution of each of the factors was determined. Results showed that the coarse aggregate size contributed the most to the density of the geopolymer concrete with 77.62%. The liquid-to-binder ratio also contributed the most to the compressive strength and the flexural strength by 73.27% and 90.07%, respectively.

## DATA AVAILABILITY

The datasets generated during and/or analyzed during the current study are available from the corresponding author on request.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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