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

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 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 ratiohad the most impact on the compressive and flexural strengths.

Keywords: Geopolymer concrete, Taguchi method, compressive strength, flexural strength, ANOVA

1. Introduction

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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 (Darmawan et al., 2022; Nazari et al., 2019; Thirumakal et al., 2020). Thegeopolymer is an amorphous or semi-crystalline binding material produced through the reaction between aluminosilicate sources and alkali activators (Davidovits & Quentin, 1991).

Metakaolin is an aluminosilicate material produced through the calcination of kaolin clayand is low in calcium(Allali et al., 2016; Tchakouté et al., 2017). 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 (X. Guo et al., 2010; Mallikarjuna Rao & Gunneswara Rao, 2018). These reaction products together with the geopolymer gels improves the mechanical strength and durability of the geopolymers (Kurtoğlu et al., 2018; Yip et al., 2005).

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(Castillo et al., 2021). The main composition of the CCR is calcium hydroxide. The addition of CCR to geopolymer mix formulations have been comprehensively investigated (Hanjitsuwan et al., 2017; Mohammadinia et al., 2019; Obeng et al., 2023; Phummiphan et al., 2014; Somna et al., 2011). The studies have found that

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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% (Hanjitsuwan et al., 2017; Phoo-ngernkham et al., 2020). Higher replacements with CCR results in detrimental effects on the resulting material (Phoo-ngernkham et al., 2020).

The manufacturing of geopolymer concrete has been researched from several perspectives, including particle sizes of aluminosilicate sources (Assi et al., 2018), type of hydroxides and silicates (Satpute et al., 2016), concentrations of hydroxides and alkali activator ratios (Kumar et al., 2019), and aggregate type and amount (Le et al., 2021), 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 (Jaya et al., 2018). For example, Kwek, Awang & Cheah, (2021) 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 (Duggal, 2008), therefore it plays significant role on the properties of concrete(Guo et al., 2020). 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 ℃) for complete geopolymerization and improved compressive strength (Görhan et al., 2016; Li et al., 2022). In metakaolin based

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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 favorablewith 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 (Naderi et al., 2002).

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(Singh & Saini, 2024). For example, Dave & Bhogayata, (2020)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. Candra, Agung and Ufafa, (2018) 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(Şimşek & Uygunoğlu, 2016). However, for most concrete materials, particularly concerning mechanical properties such as compressive strength and flexural strength, their highest values are typically considered optimal(Joseph et al., 2023).

Current literature shows limited research on the use ofmetakaolin combined with CCR to produce geopolymer materials especially as concrete (Alnajjar et al., 2023; Obeng et al., 2023).

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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 ofL/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_2SiO_3). The NaOH and Na_2SiO_3 were combined,

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however, the concentration of the NaOH and the ratio of the NaOH:Na_2SiO_3adopted was obtained from previous research work (Obeng et al., 2023). Distilled water was used to prepare 10M 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.

Table 1 Chemical Composition (wt%) of clay and CCR samples

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MnO	MgO	SO_3	TiO_2
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

2.2 Method

In traditional concrete, factors like the water-cement ratio, coarse aggregate sizes, and curing conditions have a significant impact on their strength properties (Namyong et al., 2004; Panda et al., 2020; Rmdan Amer et al., 2020; Wang et al., 2022; Wedatalla et al., 2019). 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 (Pham et al., 2023). Hence, the factors selected for investigation on the density, compressive strength and flexural strength of the geopolymer concrete were theliquid-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 theprevailing 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 areoutlined in **Table 3**. Four concrete mixes were generated using the Taguchi Orthogonal array L4 (2^3), 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.

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 (2^3)

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

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	Unit Weight(kg/m^3)							
MIXES	Cement	Metakaolin	CCR	NaOH	Na_2SiO_3	Fine Aggregates	Coarse Aggregates	Water
T1 –T4		288	72	72	144	705.6	1410	80

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 (British Standard Institute, 2009).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 after24 hours casting and cured in ambient temperaturewith 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 measured in accordance to the BS EN 12390-7(British Standards Institute, 2000). The compressive strength and the flexural strength were conducted according to the BS EN 12390-3(BS EN 12390-3:2001, 2001)and BS EN 12390-5(BS EN 12390-5, 2019), 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.

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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 **Figure 1**.The slump values for the various geopolymer concrete mixes are shown in **Figure 2**. The slump values for each geopolymer concrete mix are classified in accordance with BS 8500(BSI Standards Publication, 2019) 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 (Salau & Busari, 2015). 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 0.8compared to liquid-to-binder ratio 0.6 (Arafa et al., 2018).

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Figure 1. Slump of fresh geopolymer concrete mix

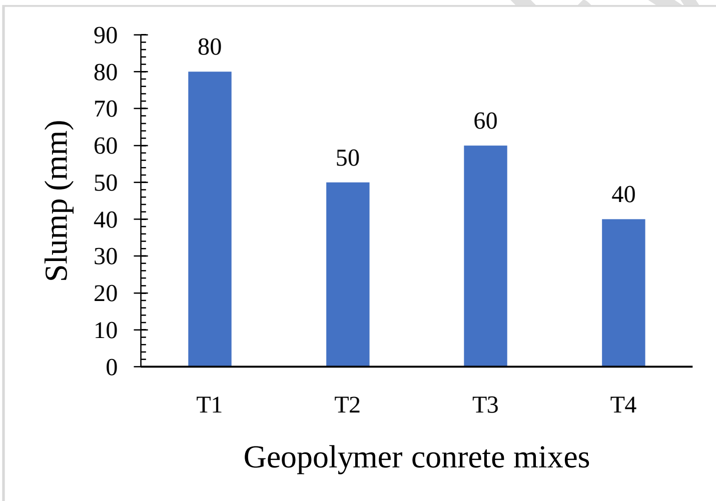

Figure 2. Slump values for the various geopolymer concrete mixes

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

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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 (Ouda, 2015). 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:

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

Where n is the number of observations and yt 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, **Table7** 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

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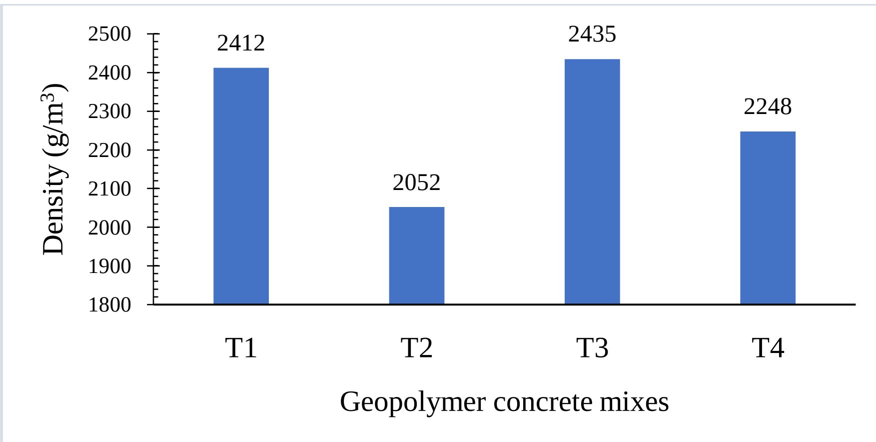
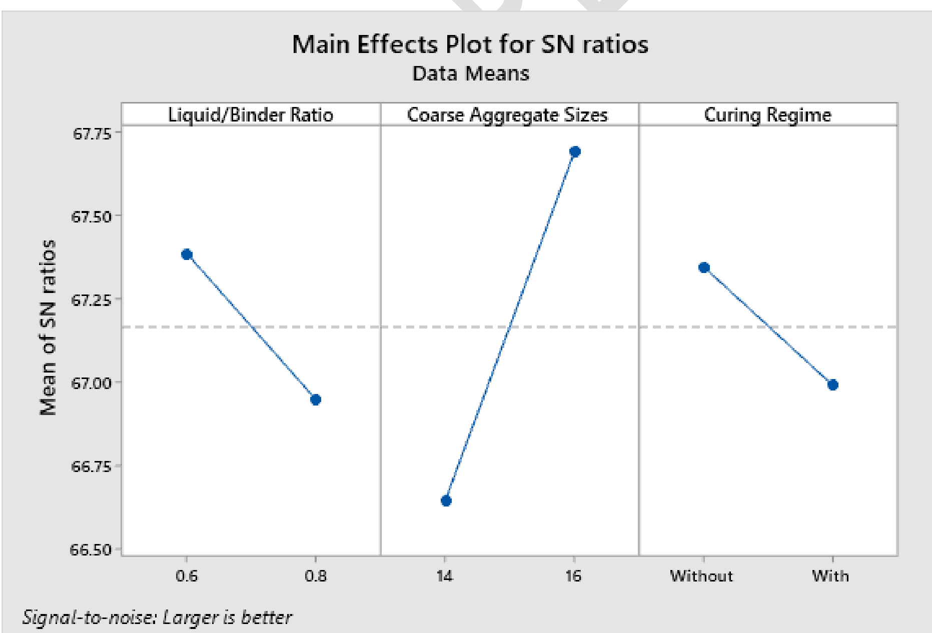
various levels based on the highest S/N ratios, as shown in **Table 8**. As a result, for each factor, the level that elicited the maximum response was recorded.

Figure 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^3, is observed at geopolymer concrete mix T3, as shown in **Figure 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^3. 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 **Figure 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 (Salau & Busari, 2015). The larger coarse aggregate size 16 mm 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 park more aggregates and so result in denser concretes (Korat et al., 2015). 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^3, falls within the classification of lightweight concrete (Peñaranda et al., 2021). Conversely, mixes T1, T3, and T4 have densities classified as normal weight concrete (Rafi, 2013). This suggests that lightweight geopolymer concrete, like T2, can be suitable for applications requiring lower dead loads (Lu et al., 2021). 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 (Dong et al., 2020; Duggal, 2008). 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 (Al-Lami & Abdul-Majeed Al-saadi, 2021; Azunna, 2019).



(a)



(b)

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

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Table 7 Density, compressive strength and flexural strength at 28th 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^3)	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

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Table 9ANOVA of density, compressive strength and flexural strength

Factor	Degree of Freedom	Sum of Squares	Mean Squares	% Contribution	Sum of Squares	Mean Squares	% Contribution	Sum of Squares	Mean Squares	% Contribution
		Density			Compressive strength			Flexural strength		
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

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Figure 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 **Figure 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 **Figure 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_2SiO_3) 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(Barbosa et al., 2000; Heah et al., 2012).The coarse aggregate size was the secondary greatest influential factor.**Figure 4b** shows that the coarse aggregate size of 16 mm generated the highest compressive strength.Similar to the findings ofPertiwi, Theresia and Komara, (2021), concrete produced with bigger coarse aggregate

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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 (Ogundipe et al., 2018) and 18.5 mm (Guades, 2019). Despite such reports that confirm the findings of this study, other researchers (W. Xie et al., 2012) 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 (Cai et al., 2020; Yuan et al., 2016), 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 (Han et al., 2018). 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 for structural construction in buildings and highways requiring high compressive strength (Humaidi et al., 2023; Mansor et al., 2020).

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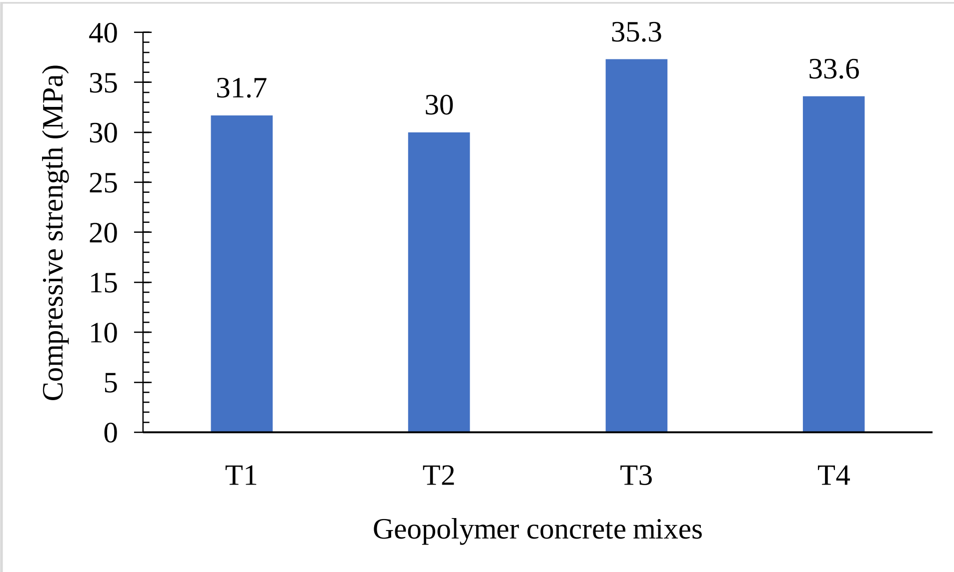
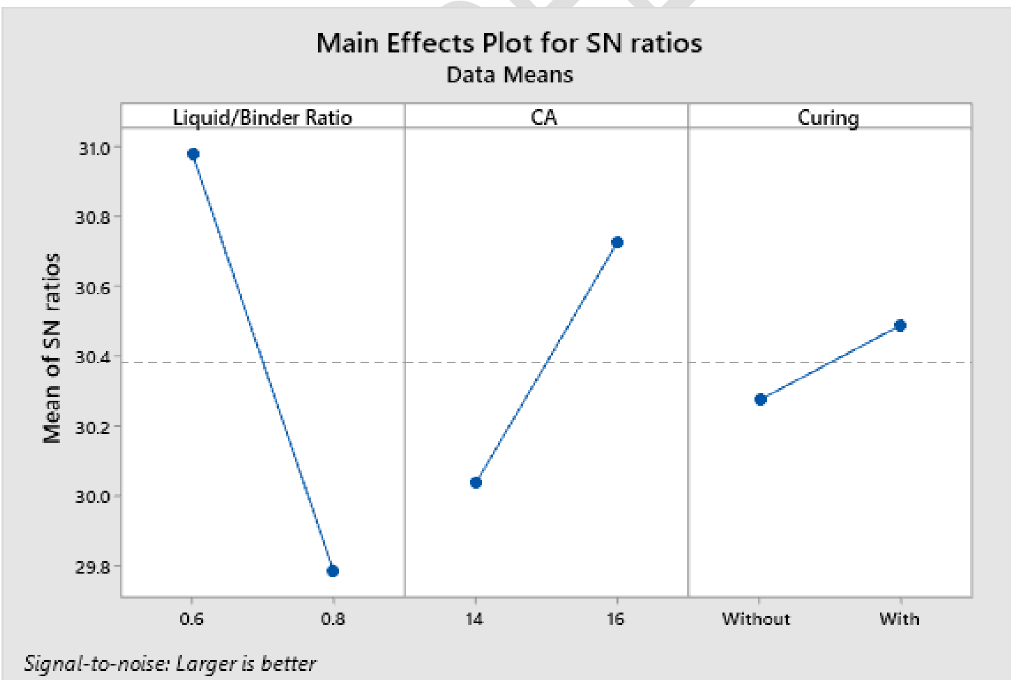

Compressive strength (MPa)
40
35
30
25
20
15
10
5
0
31.7
30
35.3
33.6
T1
T2
T3
T4
Geopolymer concrete mixes

(a)


Main Effects Plot for SN ratios
Data Means
Liquid/Binder Ratio
CA
Curing
Mean of SN ratios
31.0
30.8
30.6
30.4
30.2
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29.8
0.6
0.8
14
16
Without
With
Signal-to-noise: Larger is better

(b)

Figure 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

Figure 5a depicts the flexural strength of each geopolymer concrete mix. The highest flexural strength of 4.4 MPa was attained using 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.**Figure 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 **Figure 5b**.Level 2 of the liquid-to-binder ratio of 0.6 provided the highest flexural strengths, according to **Figure 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 (T. Xie & Ozbakkaloglu, 2015; Xu et al., 2021). In addition, analogous to this study, Xie and Ozbakkaloglu, (2015) 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 (T. Xie & Ozbakkaloglu, 2015) mechanical strength was compressive strength, similar conclusions can be drawn in this study because flexural strength is also classified as a

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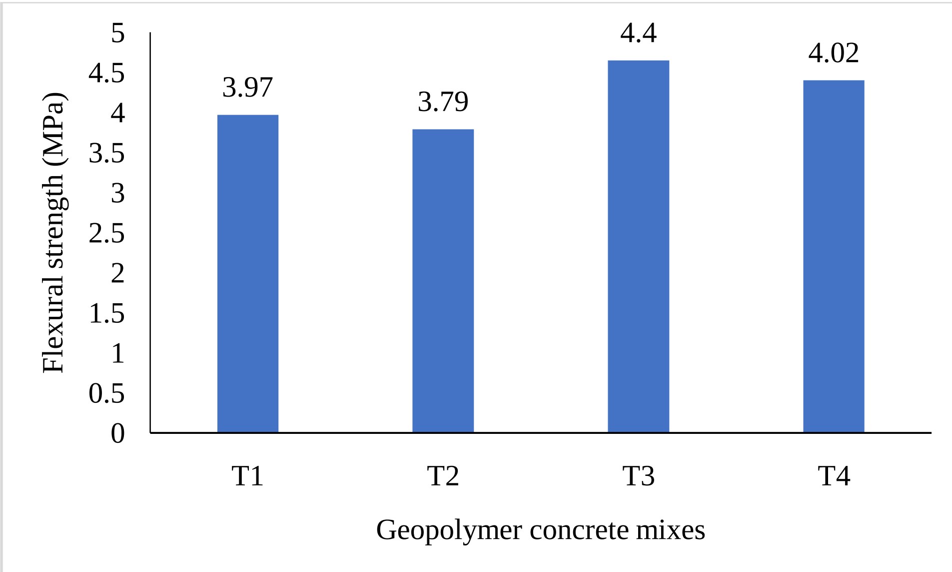
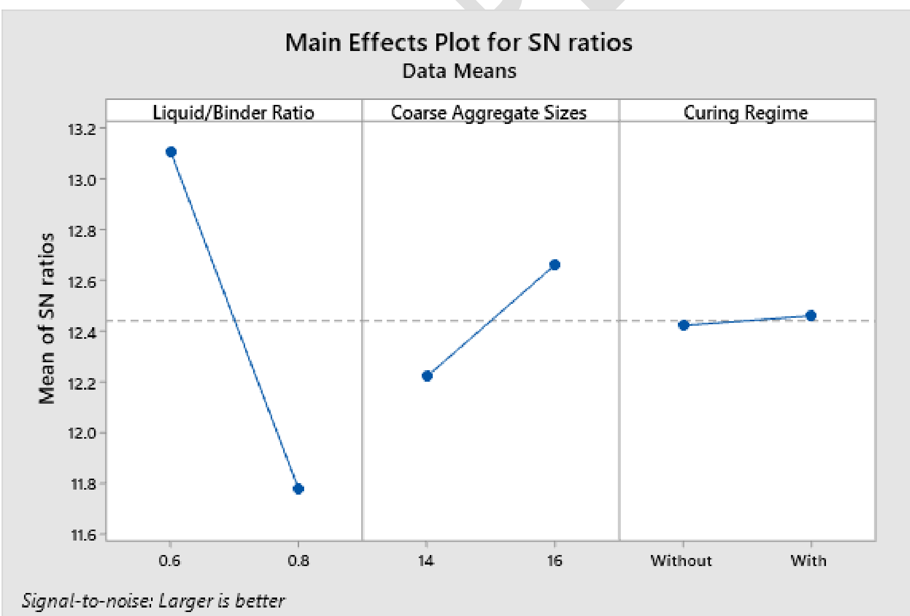
mechanical property. Furthermore, several building codes (American Concrete Institute, 2004; BS 8110, 1985) reflect a link between compressive strength and flexural strength.



(a)



(b)

Figure 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

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 Liew *et al.*, (2012), 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

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this study only considered the most generally available coarse aggregate sizes for concrete use in the construction industry.

3 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

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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.

REFERENCES

Al-Lami, M. S., & Abdul-Majeed Al-saadi, E. (2021). The relationships between compressive strength and density of polystyrene lightweight concrete and their component ratios. *Journal of Applied Engineering Science*, *19*(1), 175–185. https://doi.org/10.5937/jaes0-27471

Allali, F., Joussein, E., Kandri, N. I., & Rossignol, S. (2016). The influence of calcium content on the performance of metakaolin-based geomaterials applied in mortars restoration. *Materials and Design*, *103*, 1–9. https://doi.org/10.1016/j.matdes.2016.04.028

Alnajjar, H. M., Khater, H. M., Shaker, N. O., & Farag, A. A. (2023). Asses the Use of Calcium Carbide for Increasing Mechanical and Thermal Properties of Alkali Activated GGBFS-MK Precursor. *European Journal of Advanced Chemistry Research*, *4*(1), 6–14. https://doi.org/10.24018/ejchem.2023.4.1.125

American Concrete Institute. (2004). Building code requirements for structural concrete and commentary. *ACI 318-1995 and ACI 318R-1995, Detroit*.

Arafa, S. A., Ali, A. Z. M., Awal, A. S. M. A., & Loon, L. Y. (2018). Optimum mix for fly ash geopolymer binder based on workability and compressive strength. *IOP Conference Series: Earth and Environmental Science*, *140*(1). https://doi.org/10.1088/1755-1315/140/1/012157

Assi, L. N., Eddie Deaver, E., & Ziehl, P. (2018). Effect of source and particle size distribution

UNDER PEER REVIEW

on the mechanical and microstructural properties of fly Ash-Based geopolymer concrete. *Construction and Building Materials*, *167*, 372–380. https://doi.org/10.1016/j.conbuildmat.2018.01.193

Azunna, S. U. (2019). Compressive strength of concrete with palm kernel shell as a partial replacement for coarse aggregate. *SN Applied Sciences*, *1*(4), 342. https://doi.org/10.1007/s42452-019-0334-6

Barbosa, V. F. F., MacKenzie, K. J. D., & Thaumaturgo, C. (2000). Synthesis and characterisation of materials based on inorganic polymers of alumina and silica: Sodium polysialate polymers. *International Journal of Inorganic Materials*, *2*(4), 309–317. https://doi.org/10.1016/S1466-6049(00)00041-6

British Standard Institute. (2009). BS EN 12350-2: Testing fresh concrete; Slump test. *BSI Standards Publication*, 5–8.

British Standards Institute. (2000). BS EN 12390-7:2000 Testing hardened concrete — Part 7: Density of hardened concrete. *BSI Standards Publication*, *3*(1), 13.

BS 8110. (1985). Structural use of concrete, part 1, 2. *British Standard Institute.*

BS EN 12390-3:2001. (2001). BS EN 12390-3:2001 Testing hardened concrete - Part 3: Compressive strength of test specimens. In *BSI Standards Publication* (pp. 4–10). file:///C:/Users/hp/Downloads/dlscrib.com-pdf-bs-en-12390-3-dl_b8a9ef69ed054e431ee2df7d05824cb9.pdf

BS EN 12390-5. (2019). BS EN 12390-5:2009 Testing hardened concrete — Part 5: Flexural strength of test specimens. *BSI Standards Publication*, *August*, 1–22.

BSI Standards Publication. (2019). BS 8500-1:2015+A2:2019 Concrete - Complimentary British Standard to BS EN 206. *The British Standards Instituition 2020*, *3*, 72.

Cai, J., Li, X., Tan, J., & Vandevyvere, B. (2020). Thermal and compressive behaviors of fly ash and metakaolin-based geopolymer. *Journal of Building Engineering*, *30*, 101307. https://doi.org/10.1016/j.jobe.2020.101307

Candra, S. N., Agung, P. A., & Ufafa, A. (2018). Optimization density of geopolymer concrete

UNDER PEER REVIEW

based on taguchi method. *Research Journal of Chemistry and Environment*, *22*(Special issue II), 134–138.

Castillo, H., Collado, H., Droguett, T., Sánchez, S., Vesely, M., Garrido, P., & Palma, S. (2021). Factors affecting the compressive strength of geopolymers: A review. *Minerals*, *11*(12), 1–28. https://doi.org/10.3390/min11121317

Darmawan, M. S., Tajunnisa, Y., Suprobo, P., Sutrisno, W., & Aziz, M. W. (2022). Comparative Study of Flexural Performance of Geopolymer and Portland Cement Concrete Beam Using Finite Element Analysis. *International Journal of GEOMATE*, *23*(95), 1–9. https://doi.org/10.21660/2022.95.j2340

Dave, S. V., & Bhogayata, A. (2020). The strength oriented mix design for geopolymer concrete using Taguchi method and Indian concrete mix design code. *Construction and Building Materials*, *262*, 120853. https://doi.org/10.1016/j.conbuildmat.2020.120853

Davidovits, J., & Quentin, S. (1991). *GEOPOLYMERS Inorganic polymerie new materials*. *37*, 1633–1656.

Dong, M., Feng, W., Elchalakani, M., Li, G. K., Karrech, A., & Sheikh, M. N. (2020). Material and glass-fibre-reinforced polymer bond properties of geopolymer concrete. *Magazine of Concrete Research*, *72*(10), 509–525. https://doi.org/10.1680/jmacr.18.00273

Duggal, S. K. (2008). *Building Materials* (New Age International Publishers (ed.); Third Revi).

Görhan, G., Aslaner, R., & Şinik, O. (2016). The effect of curing on the properties of metakaolin and fly ash-based geopolymer paste. *Composites Part B: Engineering*, *97*, 329–335. https://doi.org/10.1016/j.compositesb.2016.05.019

Guades, E. J. (2019). Effect of coarse aggregate size on the compressive behaviour of geopolymer concrete. *European Journal of Environmental and Civil Engineering*, *23*(6), 693–709. https://doi.org/10.1080/19648189.2017.1304276

Guo, X., Shi, H., & Dick, W. A. (2010). Compressive strength and microstructural characteristics of class C fly ash geopolymer. *Cement and Concrete Composites*, *32*(2), 142–147. https://doi.org/10.1016/j.cemconcomp.2009.11.003

UNDER PEER REVIEW

Guo, Y., Wu, J., Wang, C., & Zhang, F. (2020). Study on the influence of the shape and size of coarse aggregate on the strength of concrete. *IOP Conference Series: Materials Science and Engineering*, *780*(4). https://doi.org/10.1088/1757-899X/780/4/042008

Han, J., Li, Z., Liu, H., Zhang, G., Tan, C., & Han, J. (2018). Study on the process of isothermal continuous drying and its effect on the strength of concrete of different strength grades. *Construction and Building Materials*, *187*, 14–24. https://doi.org/10.1016/j.conbuildmat.2018.07.167

Hanjitsuwan, S., Phoo-ngernkham, T., & Damrongwiriyanupap, N. (2017). Comparative study using Portland cement and calcium carbide residue as a promoter in bottom ash geopolymer mortar. *Construction and Building Materials*, *133*, 128–134. https://doi.org/10.1016/j.conbuildmat.2016.12.046

Heah, C. Y., Kamarudin, H., Mustafa Al Bakri, A. M., Bnhussain, M., Luqman, M., Khairul Nizar, I., Ruzaidi, C. M., & Liew, Y. M. (2012). Study on solids-to-liquid and alkaline activator ratios on kaolin-based geopolymers. *Construction and Building Materials*, *35*(April), 912–922. https://doi.org/10.1016/j.conbuildmat.2012.04.102

Humaidi, M., Yanuar, K., & Fajar, R. A. (2023). Correlation between Compressive Strength of Concrete and Flexural Strength of Concrete Using Local Aggregates. *Journal of Mechanical, Civil and Industrial Engineering*, *4*(2), 11–17. https://doi.org/10.32996/jmcie.2023.4.2.2

Jaya, N. A., Liew, Y. M., Heah, C. Y., & Abdullah, M. M. A. B. (2018). Effect of solid-to-liquid ratios on metakaolin geopolymers. *AIP Conference Proceedings*, *2045*(December). https://doi.org/10.1063/1.5080912

Joseph, H. S., Pachiappan, T., Avudaiappan, S., & Guindos, P. (2023). Prediction of the mechanical properties of concrete incorporating simultaneous utilization of fine and coarse recycled aggregate. *Revista de La Construccion*, *22*(1), 178–191. https://doi.org/10.7764/RDLC.22.1.178

Korat, L., Ducman, V., & Netinger, I. (2015). *Influence of aggregate type and size on properties of pervious concrete*. *78*, 69–76. https://doi.org/10.1016/j.conbuildmat.2014.12.073

UNDER PEER REVIEW

Kumar, S., Gautam, P. D., & Sarath Chandra Kumar, B. (2019). Effect of alkali activator ratio on mechanical properties of GGBS based geopolymer concrete. *International Journal of Innovative Technology and Exploring Engineering*, *8*(12), 947–952. https://doi.org/10.35940/ijitee.J9539.1081219

Kurtoğlu, A. E., Alzeebaree, R., Aljumaili, O., Niş, A., Gülşan, M. E., Humur, G., & Çevik, A. (2018). Mechanical and durability properties of fly ash and slag based geopolymer concrete. *Advances in Concrete Construction*, *6*(4), 345–362. https://doi.org/10.12989/acc.2018.6.4.345

Kwek, S. Y., Awang, H., & Cheah, C. B. (2021). Influence of liquid-to-solid and alkaline activator (Sodium silicate to sodium hydroxide) ratios on fresh and hardened properties of alkali-activated palm oil fuel ash geopolymer. *Materials*, *14*(15). https://doi.org/10.3390/ma14154253

Le, H. B., Bui, Q. B., & Tang, L. (2021). Geopolymer recycled aggregate concrete: From experiments to empirical models. *Materials*, *14*(5), 1–22. https://doi.org/10.3390/ma14051180

Li, Q., Chen, S., Zhang, Y., Hu, Y., Wang, Q., Zhou, Q., Yan, Y., Liu, Y., & Yan, D. (2022). Effect of Curing Temperature on High-Strength Metakaolin-Based Geopolymer Composite (HMGC) with Quartz Powder and Steel Fibers. *Materials*, *15*(11). https://doi.org/10.3390/ma15113958

Liew, Y. M., Kamarudin, H., Mustafa Al Bakri, A. M., Bnhussain, M., Luqman, M., Khairul Nizar, I., Ruzaidi, C. M., & Heah, C. Y. (2012). Optimization of solids-to-liquid and alkali activator ratios of calcined kaolin geopolymeric powder. *Construction and Building Materials*, *37*, 440–451. https://doi.org/10.1016/j.conbuildmat.2012.07.075

Lu, J.-X., Shen, P., Ali, H. A., & Poon, C. S. (2021). Development of high performance lightweight concrete using ultra high performance cementitious composite and different lightweight aggregates. *Cement and Concrete Composites*, *124*, 104277. https://doi.org/https://doi.org/10.1016/j.cemconcomp.2021.104277

Mallikarjuna Rao, G., & Gunneswara Rao, T. D. (2018). A quantitative method of approach in

UNDER PEER REVIEW

designing the mix proportions of fly ash and GGBS-based geopolymer concrete. *Australian Journal of Civil Engineering*, *16*(1), 53–63. https://doi.org/10.1080/14488353.2018.1450716

Mansor, A. A., Mohammed, A. S., & Mansor, M. A. (2020). Reinforced Concrete Beams Capacity with Various Concrete Compressive Strengths. *IOP Conference Series: Materials Science and Engineering*, *978*(1). https://doi.org/10.1088/1757-899X/978/1/012036

Mohammadinia, A., Arulrajah, A., Phummiphan, I., Horpibulsuk, S., & Mirzababaei, M. (2019). Flexural fatigue strength of demolition aggregates stabilized with alkali-activated calcium carbide residue. *Construction and Building Materials*, *199*, 115–123. https://doi.org/10.1016/j.conbuildmat.2018.12.031

Naderi, M., Sheibani, R., Shayanfar, M. A., Azad, T., & Student, P. G. (2002). *Comparison of Different Curing Effects on*.

Namyong, J., Sangchun, Y., & Hongbum, C. (2004). Prediction of Compressive Strength of In-Situ Concrete Based on Mixture Proportions. *Journal of Asian Architecture and Building Engineering*, *3*(1), 9–16. https://doi.org/10.3130/jaabe.3.9

Nazari, A., Bagheri, A., Sanjayan, J., Yadav, P. N. J. A., & Tariq, H. (2019). A Comparative Study of Void Distribution Pattern on the Strength Development between OPC-Based and Geopolymer Concrete. *Advances in Materials Science and Engineering*, *2019*. https://doi.org/10.1155/2019/1412757

Obeng, J., Andrews, A., Adom-asamoah, M., & Adjei, S. (2023). Effect of calcium carbide residue on the sulphate resistance of metakaolin-based geopolymer mortars. *Cleaner Materials*, *7*(February), 100177. https://doi.org/10.1016/j.clema.2023.100177

Ogundipe, O. M., Olanike, A. O., Nnochiri, E. S., & Ale, P. O. (2018). Development of Soil Distribution and Liquefaction Potential Maps for Downtown Area in Yangon, Myanmar. *Civil Engineering Journal*, *4*(4), 836. https://doi.org/10.28991/cej-0309137

Ouda, A. S. (2015). Development of high-performance heavy density concrete using different aggregates for gamma-ray shielding. *Progress in Nuclear Energy*, *79*, 48–55. https://doi.org/10.1016/j.pnucene.2014.11.009

UNDER PEER REVIEW

Panda, S., Sarkar, P., & Davis, R. (2020). Effect of Water-Cement Ratio on Mix Design and Mechanical Strength of Copper Slag Aggregate Concrete. *IOP Conference Series: Materials Science and Engineering*, *936*(1), 12019. https://doi.org/10.1088/1757-899X/936/1/012019

Peñaranda, J. F. M., Cáceres, J. R., & Palacios, J. D. (2021). Density, Compressive Strength, and Modulus of Elasticity: Three Properties that Influence the Efficiency of Structural Concrete. *Journal of Physics: Conference Series*, *2046*(012051), 1–7. https://doi.org/10.1088/1742-6596/2046/1/012051

Pham, T. T., Nguyen, N. L., Nguyen, T. T., Nguyen, T. T., & Pham, T. H. (2023). Effects of Superplasticizer and Water–Binder Ratio on Mechanical Properties of One-Part Alkali-Activated Geopolymer Concrete. *Buildings*, *13*(7). https://doi.org/10.3390/buildings13071835

Phoo-ngernkham, T., Phiangphimai, C., Intarabut, D., Hanjitsuwan, S., Damrongwiriyanupap, N., Li, L. yuan, & Chindaprasirt, P. (2020). Low cost and sustainable repair material made from alkali-activated high-calcium fly ash with calcium carbide residue. *Construction and Building Materials*, *247*, 118543. https://doi.org/10.1016/j.conbuildmat.2020.118543

Phummiphan, I., Ph, D., Horpibulsuk, S., Ph, D., Phoo-ngernkham, T., Arulrajah, A., Ph, D., Shen, S., & Ph, D. (2014). *Marginal Lateritic Soil Stabilized with Calcium Carbide Residue and Fly Ash Geopolymers as a Sustainable Pavement Base Material*. 1–10. https://doi.org/10.1061/(ASCE)MT

Rafi, S. M. (2013). Analytical Study on Special Concretes with M20 & M25 Grades for Construction. *International Journal of Current Engineering and Technology*, *2*(2), 338–343. https://doi.org/10.14741/ijcet/spl.2.2014.62

Rmdan Amer, A. A., Mustafa Al Bakri Abdullah, M., Yun Ming, L., Faheem Mohd Tahir, M., Wazien Ahmad Zailani, W., & Ahmad Faris, M. (2020). Low Density, High Compressive Strength: Experimental Investigation with Various Particle Sizes of Sand for Different Mix Designs of Cement Mortar Manufacturing. *IOP Conference Series: Materials Science and Engineering*, *864*(1). https://doi.org/10.1088/1757-899X/864/1/012010

UNDER PEER REVIEW

Salau, M. A., & Busari, A. O. (2015). Effect of different coarse aggregate sizes on the strength characteristics of laterized concrete. *IOP Conference Series: Materials Science and Engineering*, *96*(1). https://doi.org/10.1088/1757-899X/96/1/012079

Satpute, S., Shirasath, M., & Hake, S. (2016). Investigation of Alkaline Activators for Fly-Ash Based Geo- Polymer Concrete. *International Journal of Advance Research and Innovative Ideas in Education (IJARIIE)*, *2*(5), 2395–4396.

Şimşek, B., & Uygunoğlu, T. (2016). Multi-response optimization of polymer blended concrete: A TOPSIS based Taguchi application. *Construction and Building Materials*, *117*, 251–262. https://doi.org/10.1016/j.conbuildmat.2016.05.027

Singh, G., & Saini, B. (2024). Appraisal on mechanical, durability and ecological performance of sustainable cementitious mortar by using Taguchi optimization technique. *European Journal of Environmental and Civil Engineering*, *28*(3), 736–751. https://doi.org/10.1080/19648189.2023.2223252

Somna, K., Jaturapitakkul, C., & Kajitvichyanukul, P. (2011). Microstructure of Calcium Carbide Residue–Ground Fly Ash Paste. *Journal of Materials in Civil Engineering*, *23*(3), 298–304. https://doi.org/10.1061/(asce)mt.1943-5533.0000167

Tchakouté, H. K., Rüscher, C. H., Kamseu, E., Djobo, J. N. Y., & Leonelli, C. (2017). The influence of gibbsite in kaolin and the formation of berlinite on the properties of metakaolin-phosphate-based geopolymer cements. *Materials Chemistry and Physics*, *199*, 280–288. https://doi.org/10.1016/j.matchemphys.2017.07.020

Thirumakal, P., Nasvi, M. C. M., & Sinthulan, K. (2020). Comparison of mechanical behaviour of geopolymer and OPC-based well cement cured in saline water. *SN Applied Sciences*, *2*(8), 1–17. https://doi.org/10.1007/s42452-020-3154-9

Wang, X., Jia, L., Jia, Z., Zhang, C., Chen, Y., Ma, L., Wang, Z., Deng, Z., Banthia, N., & Zhang, Y. (2022). Optimization of 3D printing concrete with coarse aggregate via proper mix design and printing process. *Journal of Building Engineering*, *56*, 104745. https://doi.org/https://doi.org/10.1016/j.jobe.2022.104745

Wedatalla, A. M. O., Jia, Y., & Ahmed, A. A. M. (2019). Curing Effects on High-Strength

UNDER PEER REVIEW

Concrete Properties. *Advances in Civil Engineering*, *2019*, 1683292. https://doi.org/10.1155/2019/1683292

Xie, T., & Ozbakkaloglu, T. (2015). Behavior of low-calcium fly and bottom ash-based geopolymer concrete cured at ambient temperature. *Ceramics International*, *41*(4), 5945–5958. https://doi.org/10.1016/j.ceramint.2015.01.031

Xie, W., Jin, Y., & Li, S. (2012). Experimental research on the influence of grain size of coarse aggregate on pebble concrete compressive strength. *Applied Mechanics and Materials*, *238*, 133–137. https://doi.org/10.4028/www.scientific.net/AMM.238.133

Xu, Z., Yue, J., Pang, G., Li, R., Zhang, P., & Xu, S. (2021). Influence of the Activator Concentration and Solid/Liquid Ratio on the Strength and Shrinkage Characteristics of Alkali-Activated Slag Geopolymer Pastes. *Advances in Civil Engineering*, *2021*. https://doi.org/10.1155/2021/6631316

Yip, C. K., Lukey, G. C., & Deventer, J. S. J. Van. (2005). *The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation*. *35*, 1688–1697. https://doi.org/10.1016/j.cemconres.2004.10.042

Yuan, J., He, P., Jia, D., Yang, C., zhang, Y., Yan, S., Yang, Z., Duan, X., Wang, S., & Zhou, Y. (2016). Effect of curing temperature and SiO2/K2O molar ratio on the performance of metakaolin-based geopolymers. *Ceramics International*, *42*(14), 16184–16190. https://doi.org/10.1016/j.ceramint.2016.07.139

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