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Effect of the Mortar Volume Ratio on the Mechanical Behavior of Class CI Fly Ash-Based Geopolymer Concrete

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Abstract

This research described the effect of the mortar volume ratio on the mechanical behavior of Class CI fly ash-based geopolymer concrete. The absolute volume ratio parameters were designed to determine the effects on the mechanical properties of the geopolymer concrete. The volume ratio of the mortar to coarse aggregate voids (Rc) was increased by 0.25 increments, from 1 to 1.75, using constant parameters of 10 M NaOH at a ratio of Na_2SiO_3 to NaOH (R). Furthermore, the alkaline to fly ash ratio (A) of 0.35 and the volume ratio of paste to fine aggregate voids (Rm) of 1.5 were based on geopolymer paste and mortar investigations previously published. The test results showed that 1) the Rc ratio influences the workability and compressive strength of geopolymer concrete; 2) the increase in the Rc ratio by 1.75 is not linear with the rise in compressive strength but produces better mechanical properties; 3) it does not affect the tensile strength of both geopolymer and OPC concretes; 4) the lower the Rc ratio, the higher the flexural strength; 5) the Rc ratio does not affect the OPC concrete and GC tensile strength; 6) the bond stress in geopolymer concrete with an Rc ratio of 1.75 is higher than in OPC concrete; and 7) Rc ratio does not affect the early strength of geopolymer concrete. The geopolymer concrete experienced an increase in compressive strength after 28 days, while the OPC concrete remained flat. The results will help develop an optimal mix design of Class CI fly ash with moderate calcium oxide in the production of geopolymer concrete. This will improve the future applications of using this process in new binding materials.

Keywords: Mortar Volume Ratio; Fly Ash; Class-CI; Geopolymer Concrete; Mechanical Behavior.

1. Introduction

Fly ash is a waste product of a steam power plant that uses coal as fuel, and its production in the country is increasing yearly. According to the Indonesian National Power Plant (PLN) data, its production rate is expected to reach 180 to 209 million tons annually by 2021. This is due to the government's implementation of the 35,000 MW program in the electricity sector. Although, if not properly managed, its increased production is undoubtedly bound to have a negative impact because fly ash is classified as a B3 waste under PP No. 85 of 1999. However, chemically, it typically contains several oxide elements such as SiO_2, Al_2O_3, and CaO. These are the primary ingredients for producing geopolymer concrete and reusing it as a more valuable product.

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This study classified fly ash according to the Canadian Standard (CAN/CS A-A3000-03) [1, 2], and there are three classes based on the percentage by weight of calcium oxide. These include classes F, Cl, and CH with weight percentages of CaO < 8%, CaO of 8% to 20%, and CaO of > 20%, respectively. Class F fly ash generally contains more amorphous SiO_2 and Al_2O_3 (reactive phase) than crystalline SiO_2 and Al_2O_3. Meanwhile, Class-CI fly ash has a less amorphous phase of SiO_2 and Al_2O_3. Xu and Van Deventer [3], including Winnefeld et al. [4], stated that polymerization reactions involving Class F fly ash are more stable. It was further reported that geopolymer binder has better mechanical and durability properties than conventional OPC. Almost all publications reported using Class F fly ash as its primary base material. These properties are only achieved if the curing temperature ranges from 50 to 90^{o}C, and its relative humidity (RH) is either greater than or equivalent to 90%. This is because polymerization is an endothermic reaction, hardens more slowly at room temperature, and has a low compressive strength at the initial age. Heat curing is essential for developing the microstructure of Class-F fly ash-based geopolymer concrete at an early age. Palomo et al. [5] stated that its costs are relevant because it is one of the reasons why the development and utilization of geopolymer concrete technology are still limited and only available on a laboratory scale and in the precast concrete industry.

On the contrary, the volume of production of Class-CI fly ash is large, and it has not been optimally utilized in geopolymer technology. Typically, it has more than 8% calcium oxide and low amorphous phase content. The main reactive products for high calcium fly ash-based geopolymer are calcium silicate hydrate (C-S-H) and calcium aluminosilicate (C-A-S-H), which tend to coexist with sodium aluminosilicate hydrate (N-A-S-H). In contrast, sodium aluminosilicate hydrate (N-A-S-H) is the main reactive product for low calcium fly ash-based geopolymer. It implies that the high-calcium fly ash has pozzolanic and cementitious properties. The literature review on geopolymer stated that the calcium oxide content in fly ash increases the speed of the polymerization reaction [6-8]. It is desirable to make geopolymer binders because they tend to enhance the strength when cured at ambient temperatures [9, 10]. This is the reason high calcium fly ash-based geopolymer binders are used in practical work.

Some recent research on Class-C fly ashes in geopolymers includes Chindaprasirt and Chareerat [8], Guo et al. [11], Chindaprasirt et al. [12], Hanjitsuwan et al. [13], Ridzuan et al. [14], Tennakoon et al. [15], and Dirgantara [16]. The majority are still limited in understanding calcium's role in strong base media and aluminosilicate gels. Although, only a few discuss the mechanical behavior of geopolymers that uses Class-CI fly ash for concrete. Additionally, specific problems are attributed to high calcium oxide on fly ash, such as triggering rapid setting and flash set issues that limit its application. A secondary calcium silicate gel could also occur, potentially altering the geopolymer network system. However, assuming the calcium oxide content is not too high, approximately 10 to 12%, in fly ash, there is a possibility of producing geopolymers as an environmentally friendly binder. It has several advantages similar to Portland cement, such as having high strength early, being stable and cured at high and ambient temperatures, and increased durability. This condition is in line with some initial research on geopolymer paste and mortar using Class-CI fly ash with a calcium oxide content of approximately 10%. The results showed that setting time was shorter, and the initial compressive strength of geopolymer for both paste and mortar was higher even though it was cured at an ambient temperature. This study showed that both classes CI fly ash-based geopolymer paste and mortar are cured at room temperature and produce a 28-day compressive strength of relatively 60 MPa and excellent durability.

One of the main problems of using Class CI fly ash-based geopolymer concrete in practical works is that there is no standard mix design as ordinary Portland cement [17]. This is caused by the mix design, and the proportion of geopolymer concrete binders seems complex due to the involvement of more variables [18]. These include alkaline activator solution volume, H_2O to Na_2O ratio, fly ash content, the weight ratio of activator solution to fly ash, sodium hydroxide to sodium silicate solution ratio, and volume ratio of fly ash to the fine aggregate void [9, 19]. The data collected from previous studies was insufficient to understand the relationship between raw materials and concrete properties comprehensively. No article discusses the effect of the volume ratio of mortar to aggregate void on the mechanical properties of geopolymer concrete. Therefore, the subject of optimizing the geopolymer concrete composition by selecting the appropriate amounts of various elements is an exciting topic. The particles need to be carefully selected to fill up the voids between the large and smaller ones, obtain a dense and stiff structure, and optimize the packing density of concrete [20]. There is a need to determine the proper volume of such geopolymer mortar required to fill the voids between the coarse aggregate particles that enhance the mechanical properties, as reported in previous research. The result is necessary to understand the effect of particle packing and ultimately to optimize geopolymer concrete mix design that used Class-CI fly ash as an alternative material to replace Portland cement (OPC). This study focuses on the effect of the mortar volume ratio on the mechanical behavior of geopolymer concrete based on class-CI fly ash cured under normal conditions without additional heat. It differs from the results of previous research, especially on class-CI fly ash-based-geopolymer concrete.

2. Raw Materials and Details of Experimental

This experimental study was carried out at Gadjah Mada University, Yogyakarta, Indonesia. The humidity and room temperature in the laboratory range from 80% to 95% and 26°C to 37°C, respectively. The fundamental processes include material preparation, concrete mixing, and mechanical testing. In addition, the slump test was conducted before the concrete casting relevant ASTM C143 codes [21].

2.1. Raw Materials

2.1.1. Fly Ash

The fly ash was originally obtained from the Paiton, East Java power plant, available in Yogyakarta local market, Indonesia. It was used as a prime aluminosilicate source material. Moreover, it is brown, and the fly ash oxides are composed of 40.5% Fe_2O_3, 37.3 % SiO_2, 10.7% CaO, and 6.37 % Al_2O_3. This was analyzed using X-ray fluorescence (XRF), and the cumulative SiO_2, Fe_2O_3, and Al_2O_3 compounds are greater than 70% and are classified as Class C concerning ASTM C618-12 [22]. Incidentally, it has a bulk-specific gravity (Gs_{fa} in SSD) of 2.86.

2.1.2. Alkali Solution

The alkali solution was used for the geo-polymerization process, and it was prepared by mixing sodium hydroxide (SH) and sodium silicate (SS) solutions at predetermined proportions. The sodium hydroxide solution was made by mixing NaOH pellets with aquadest in desired molarity (M) and stirred till all the pellets were dissolved. These pellets are 98% pure, and it has a bulk specific gravity (Gs_{sh}) of 1.52. The sodium silicate solution (Na_2SiO_3) comprised of Na_2O 7.89%, SiO_2 19.86 %, and 72.25 % H_2O, and it has a bulk-specific gravity (Gs_{ss}) of 1.59. Afterward, the alkali solution was left for one hour before use. Meanwhile, Bratachem, Bandung, Indonesia, supplied all the chemical materials.

2.1.3. Fine Aggregate

The fine aggregate comprises the local natural river sand, subsequently referred to as river sand. ASTM C128-15 [23] calculated its specific gravity, density, and absorption. The sieve analysis was also carried out as per ASTM C136-06 [24] and ASTM C33-16 [25]. The physical parameters of the river sand with a unit weight of 1,599.14 (kg/m^3) are shown in Table 1. Additionally, Figure 1 shows the sieve analysis test result, revealing that the river sand was coarse.

Table 1. Physical parameters of local natural river sand

Material	Specific Gravity (SSD)	Absorption (%)	Fineness Modulus
Natural river sand	2.706	2.07	3.085

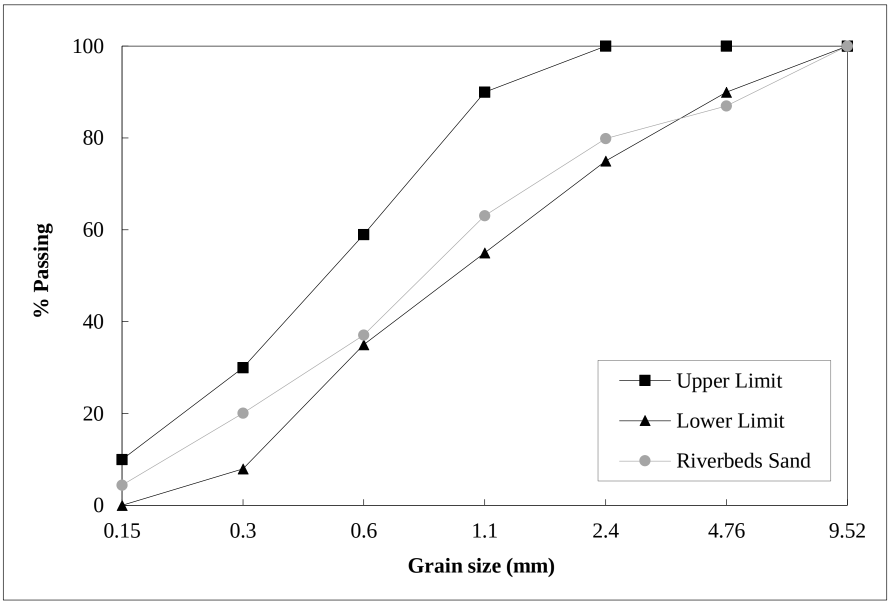

Figure 1. The result of river sand sieve analysis

2.1.4. Coarse Aggregate

The local coarse aggregate, subsequently called CA, was obtained from the Celereng area of Kulon Progo Regency, Yogyakarta. ASTM C127-88 [26] was the standard for analyzing its specific gravity, density, and absorption. The sieve analysis was carried out as per ASTM C136-06 [24] and ASTM C33-16 [25]. Table 1 shows the physical parameters of the local CA with a unit weight of 1,570 (kg/m^3). The sieve analysis results proved that the CA complies with specification requirements, as shown in figure 2. A Los Angeles machine obtained the aggregate abrasion test result of 11.25%, a fraction between 9.6 to 19.2 mm. Based on the Indonesian Standard SNI 03-6891 [27], this CA complies with the requirements of normal concrete, which is greater than 200 kg/m^3.

Table 2. Physical properties of local coarse aggregate

Material	Specific Gravity, SSD	Absorption,%	Max Diameter, mm
Coarse aggregate (CA)	2.6	1.96	20

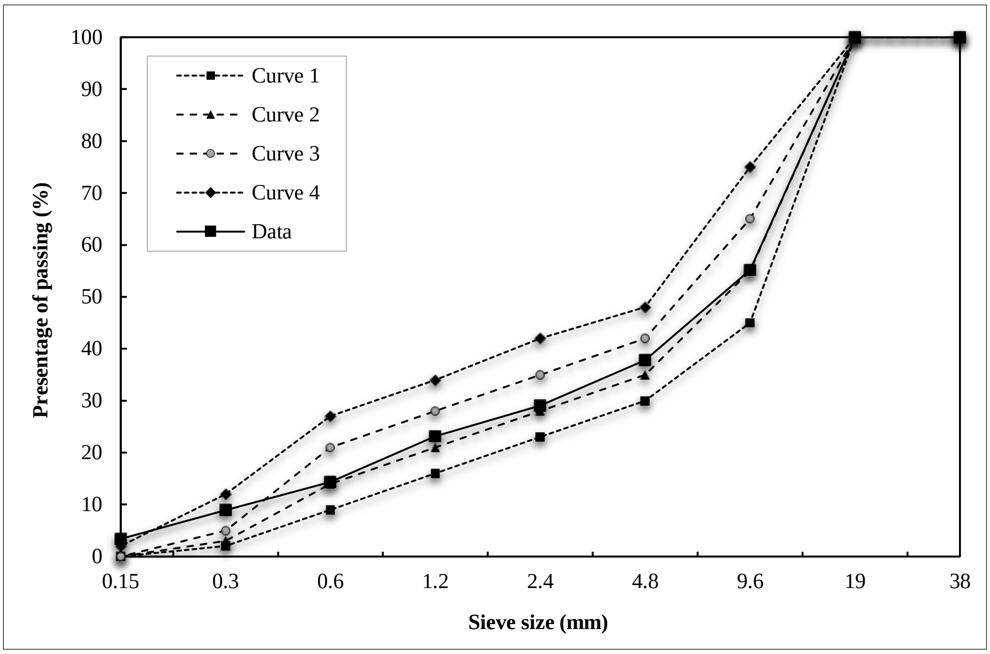

Figure 2. Gradation of coarse aggregate (CA)

2.2. Method and Mix Proportions Procedure

The procedures employed in the present study are shown in Figure 3. In this article, geopolymer concrete is called GC while OPC concrete is OPCC. Currently, there is no standard mix design for geopolymer concrete. Therefore, the absolute volume method [28, 29] was adopted in this research to design GC mixtures and OPC concrete (OPCC) (Figure 4).

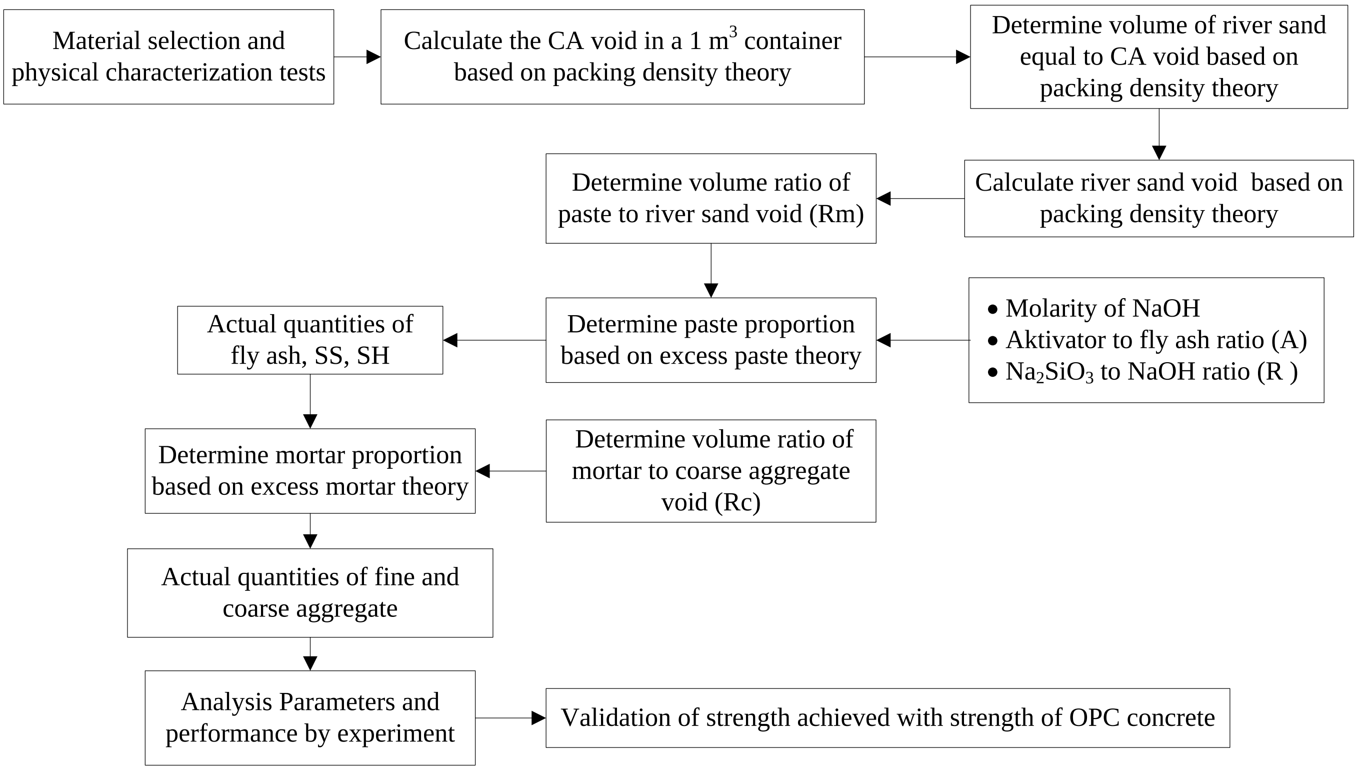

Figure 3. Flow Chart for the principle for geopolymer mix design

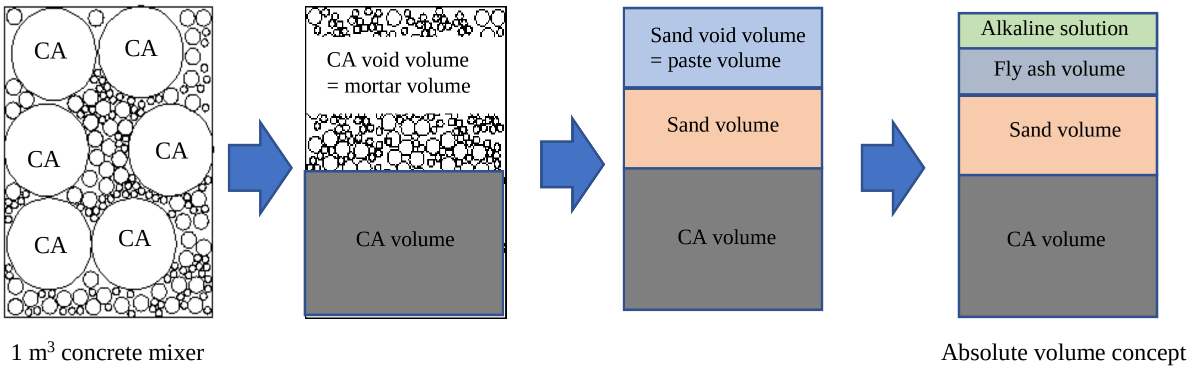

Figure 4. Concept of absolute volume method

Based on Figures 3 and 4, the first step is to calculate the volume of the aggregate void. It was assumed that the void volume of CA in a 1 m^3 container was precisely filled with mortar, and there was a perfect bond between the aggregates[30]. Aggregating the contact area, size, and shape to determine the bond between aggregates. Meanwhile, discerning the apparent specific gravity of CA (Gs_{ca}) and its unit weight in SSD (W_{ca}), then the theoretical CA void volume (Vv_{ca}) is calculated as follows:

$$Vv_{ca} = 1 - \frac{W_{ca}}{Gs_{ca}\gamma_w}, \quad (1)$$

where γ_w is the water unit weight of 1000 kg/m^3. Moreover, assuming the void capacity of CA (Vv_{ca}) is precisely filled with river sand, then the theoretical river sand void volume (Vv_{rs}) is calculated as follows:

$$Vv_{rs} = Vv_{ca} - \frac{W_{rs}}{Gs_{rs}\gamma_w}, \quad (2)$$

where Gs_{rs} is the apparent river sand specific gravity, and W_{rs} is the river sand unit weight in SSD.

The paste was presumed to act as a binder in mortar and concrete. It binds the aggregates into a rock-like mass as it hardens. According to the excess paste theory [31], shown in Figure 5, an increase in volume triggers the distance between the sand particle as well as improves the fresh GM's workability. Therefore, the paste volume significantly influences mechanical properties, dimensional stability, and production cost.

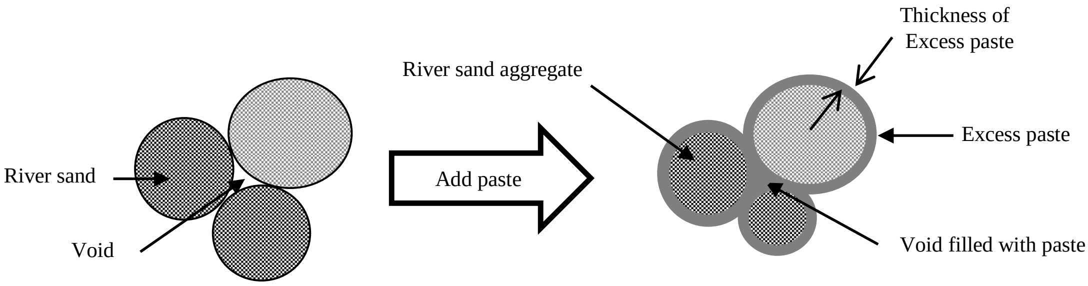

Figure 5. The filling concept of paste in geopolymer mortar

Highly dense aggregate packing decreases the paste that filled the voids, thereby reducing the frictional resistance and interlocking at a given paste content. Theoretically, it improves the workability of fresh concrete, and as a result, the paste strength also tends to change due to a reduction in its maximum thickness. The relationship between workability and mechanical properties at different excess paste levels was observed in detail based on the absolute volume ratio of paste to river sand void, Rm. Some previous research on GM stated that the highest mortar compressive strength is attained if the value of the Rm ratio is 1.5 [32]. The following equation is used to calculate the constituents of the GM mix needed to appropriately fill in the total void volume of CA (Vvca):

$$\frac{W_{fa}}{Gs_{fa}\gamma_w} + \frac{W_{ss}}{Gs_{ss}\gamma_w} + \frac{W_{sh}}{Gs_{sh}\gamma_w} = R_m Vv_{rs}, \quad (3)$$

where Gs_{fa} is the fly ash specific gravity, Gs_{fa} is the SH specific gravity, Gs_{fa} is the SS specific gravity, W_{fa} is the weight of fly ash in kilograms per cubic meter, W_{ss} is the weight of SS solution in kilograms per cubic meter, W_{sh} is the weight of SH solution in kilograms per cubic meter. Equation 3 was further modified as follows:

$$\frac{W_{fa}}{Gs_{fa}\gamma_w}+\frac{\frac{W_{ss}}{W_{fa}}W_{fa}}{Gs_{ss}\gamma_w}+\frac{\frac{W_{sh}}{W_{fa}}W_{fa}}{Gs_{sh}\gamma_w}=R_mVv_{rs}. \quad (4)$$

Assuming the weight ratio of SH to SS (R) and that of fly ash to alkali solution SS + SH (A) are known, like the water-cement ratio in the OPCC system, then Equation 4 is simplified as follows:

$$\frac{W_{fa}}{Gs_{fa}\gamma_w}+\frac{\frac{A.R}{(1+R)}W_{fa}}{Gs_{ss}\gamma_w}+\frac{\frac{A}{(1+R)}W_{fa}}{Gs_{sh}\gamma_w}=R_mVv_{rs}. \quad (5)$$

Furthermore, the weight of fly ash needed in the GM mixture is calculated using Equation 5.

The same concept of excess paste is then applied to the design of the GC mix, where the void of CA is assumed to be appropriately filled with the GM mixture. Furthermore, the relationship between workability and mechanical properties at different excess mortar was observed in detail based on the absolute volume ratio of mortar to CA void, Rc. Subsequently, the weight of river sand (W_{rs}) in a 1 m^3 mixture of GC is calculated as follows:

$$R_mVv_{rs}+\frac{W_{rs}}{Gs_{rs}\gamma_w}=R_cVv_{ca}. \quad (6)$$

hence

$$W_{rs}=\left(\frac{R_cVv_{ca}-R_mVv_{rs}}{Gs_{rs}\gamma_w}\right). \quad (7)$$

assuming Rc is known, then the weight of CA (W_{ca}) is calculated as follows:

$$R_cVv_{ca}+\frac{W_{ca}}{Gs_{ca}\gamma_w}=1.m^3. \quad (8)$$

therefore

$$W_{ca}=\left(\frac{1.m^3-R_cVv_{ca}}{Gs_{ca}\gamma_w}\right) \quad (9)$$

The previous research on geopolymer paste (GP) and geopolymer mortar (GM), has several parameters that resulted in high mechanical strength. These include the molarity of NaOH of 10 M, the ratio of Na_2SiO_3 to NaOH (R) of 2, the weight ratio of alkaline to fly ash (A) of 0.35, and the volume ratio of paste to sand voids (Rm) of 1.5 [32, 33]. Furthermore, the Rc parameter was raised by 0.25 increment from 1 to 1.75 to determine the effect of the volume ratio of mortar to CA void on the GC mechanical properties. A detailed explanation of all mixes per meter cubic is shown in Tables 3 and 4. All samples are curing at ambient temperature, and no superplasticizer and additional water were used.

Table 3. Geopolymer concrete mixture proportions by weight (kg/m^3)

No.	ID Sample	Volume ratio of mortar to CA void	Coarse Aggregate	Fine Aggregate	Fly Ash	Na_2SO_3	NaOH
		[Rc]	[Wca]	[Wsr]	[Wfa]	[Wss]	[Wsh]
1	GC1	1	1,477.43	403.83	513.46	119.81	59.90
2	GC2	1.25	1,183.43	504.79	641.83	149.76	74.88
3	GC3	1.5	888.65	605.75	770.19	179.71	89.86
4	GC4	1.75	594.25	706.71	898.56	209.66	104.83

Table 4. OPC concrete mixture proportions by weight (kg/m^3)

No.	ID Sample	Volume ratio of mortar to CA void	Coarse Aggregate	Fine Aggregate	OPC	Water
		[Rc]	[Wca]	[Wsr]	[Wopc]	[Ww]
1	OPCC	1.5	888.65	605.75	575.2	258.84

2.3. Specimens Preparations and Testing

The alkaline solution was prepared according to the mixes in previous research. The modulus of SS was adjusted to the targeted values by mixing NaOH solution with a liquid activator, then allowed to cool at an ambient temperature. The medium and small CAs, including river sand, were mixed for 3 minutes. Furthermore, fly ash was added to the pot and mixed for 3 minutes till the mixture became uniform. Then the alkaline solution was added and stirred for the next 5 minutes, while the mixture of GC and OPCC was performed according to the absolute volume method. After the casting procedure, the samples were kept in the room at an ambient temperature of 24 ± two °C and humidity higher than 90% for 24 hours. Later, the demolded samples were divided into two groups (Figure 6). GC samples were kept in wrapped plastic film, while that of the OPCC were treated in water.

Figure 6. Sample of geopolymer concrete and OPC concrete

In this study, slump and flow tests were used to measure fresh GC and OPCC workability, as shown in Figure 7. The slump and flow tests were guided according to ASTM C143 [21] and ASTM C 230 [34], respectively. These were performed immediately after mixing the solution under ambient conditions.

The mechanical properties are measured by the compressive strength, splitting tensile, flexural strength, and pull-out tests. In details, the compressive strength tests were conducted as per ASTM C39 [35], and the size of the specimens was 150 mm × 300 mm. These are cured and evaluated under normal conditions for 3, 7, 28, and 56 days and the reported outcome served as the average strength of the three samples. The tensile strength tests were conducted as per ASTM C496 [36] with the size of the three specimens was 150 × 300 mm, tested after 28 days and the reported outcome was its average. Flexural strength tests were conducted as per ASTM C78-02 [37], with the three samples measured in 15 × 15 × 60 cm and tested on the 28th day. The reported outcome was also the average of the three specimens. The bond strength was based on the pull-out test results as per ASTM C900-02 [38] and RILEM/CEB/FIP Part 2 RC 6 [39]. In this study, the plain reinforcement diameter varies, 8 mm, 10 mm, and 12 mm, to discern their impact on the concrete bond strength. The geopolymer sample with the highest strength used for the pull-out tests is GC3.

3. Result

This section is divided into subsections and tends to provide a concise and precise description of the experiment's results, its interpretation, and the practical conclusions.

3.1. Workability

The workability method was measured using the slump and flow tests as in Figure 7. However, both analyses were conducted because the flow properties of the GC2, GC3, and GC4 tend to move continuously, unlike the OPC concrete mixture as in the study conducted by sofry [19]. The slump values of the GC2, GC3, and GC4 are equivalent to the ones obtained before the geopolymer mixture moved downward. The workability measurement mechanism is shown in Figure 7. Table 5 shows that the minimum flow value of GC mixture that is easy to work with is 43 cm. Low flow value results in high compressive strength, but the mixture is not workable, causing problematic in practice. The higher the absolute volume ratio between the GM and the CA voids, the greater the flow value. The higher total volume is due to the increasing quantity of mortar, and when in excess, it increases the distance between the aggregates, thereby improving the fresh GC's workability. Consequently, the mixture tends to be easier to handle.

(a) (b) (c)

Figure 7. Slump test on a) OPCC, b) GC, and c) flow test on GC

Table 5. The result of the slump test on OPCC and GC

No.	ID Sample	Volume ratio of mortar to CA void	Slump	Flow	Compressive strength	
					28 days	56 days
		[Rc]	[mm]	[mm]	[MPa]	[MPa]
1	GC1	1.00	0.00	0.00	43.67	53.63
2	GC2	1.25	50.00	370.00	42.84	49.59
3	GC3	1.50	100.00	430.00	40.20	41.90
4	GC4	1.75	160.00	470.00	43.76	53.56
5	PCC	1.50	120.00	390.00	44.79	47.91

3.2. Compressive Strength

The compressive strength of GC and OPCC test results and its mechanisms are shown in Figure 8. Meanwhile, the compressive strength of OPCC is higher on the third and seventh days, although after 28 days, its development tends to be slower. These results align with most of the previous research on OPCC. By contrast, the compressive strength of GC is lower on the third and seventh days, but its development after 28 days tends to increase significantly than in the OPC concrete [40]. This is because the rate of geopolymerzation in alkaline solution was prolonged during the early conditions, although it increased after 28 days. In the geopolymerization reaction, the dissolution rate of the fly ash particles was relatively slow at ambient temperature [20]. The diffusion of hydroxide and silicate ions in the geopolymer gel is controlled mainly by the curing temperature [41]. The lower polymerization at ambient temperatures results in a low compressive strength of the geopolymer. In the OPC concrete, the hydration reaction tends to be fast at the initial condition and constant after 28 days [19].

(a) (b)

Figure 8. Compressive strength test on a) GC, and b) OPCC

Figure 9 shows that GC1 and GC4 attained the maximum compressive strength of more than 50 MPa at age 56, which is higher than that of the OPCC. However, the compressive strength of GC1 is due to the high packing density of the mixture and compactness of the microstructure, where the aggregate volume fraction is approximately 71.7%. At the same time, the proportion of paste that functions as a lubricant and binder are not sufficient enough to increase the mixture's workability. In the case of GC4, the aggregate volume fraction is relatively 49%. In comparison, the paste proportion is relatively 51%, which results in good mix workability when in excess. The high compressive strength of GC4 caused by the amount of paste is sufficient to produce excess thickness, thereby allowing a perfect geopolymer reaction and an adequate amount of binding gel [31]. This is consistent with the previous study that geopolymer paste and mortar compressive strength amounted to 60 MPa after 56 days [32, 33]. The condition is slightly different from the OPCC because an increase in the cement paste raises the volume of water needed for the hydration process, resulting in higher workability and lower compressive strength. In geopolymer system, water does not react as well as hydration in OPC. It only serves as a medium for the geopolymerization reaction and spells out after the procedure [42]. This implies excess paste in GC, resulting in high workability and compressive strength. In GC2 and GC3, the effect of excess paste is not enough to wet and lubricate the aggregate surface, and it seems like workability is lower, resulting in lower compressive strength.

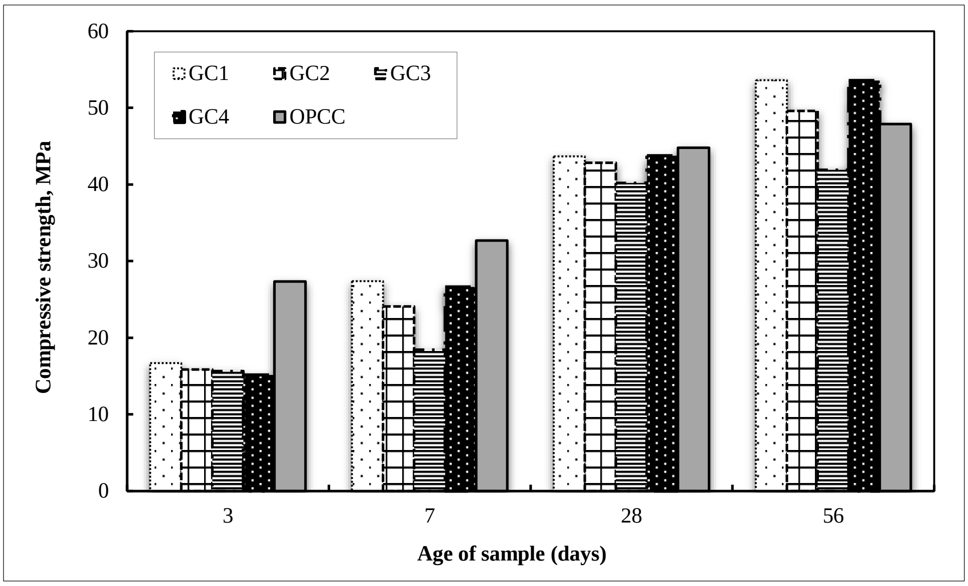

Figure 9. Compressive strength of GC and OPCC

Figure 10 shows that the characteristics of the stress-strain relationship of both OPCC and GC at 28 days are nonlinear. This is because they constitute composite materials. The modulus elasticity of OPCC is slightly higher than GC, which tends to be more ductile. Furthermore, its ultimate strain is higher than that of OPCC. This is because the chemical bond structure in the geopolymer system allows for increased strain during loading. On the contrary, the chemical structure in the OPC system is firmly bound, and the strain is hard to expand and becomes brittle if the strength gets high. The increase in the compressive strength of GC is slower than that of OPCC. This is comparable to the research carried out by Nath et al. [40].

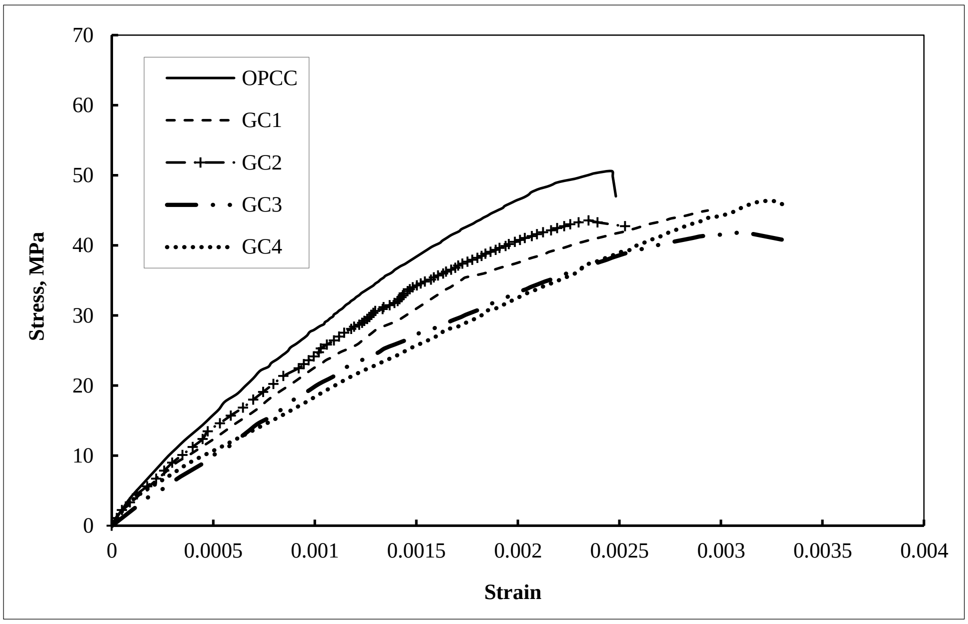

Figure 10. Stress-strain relationship of OPCC and GC

3.3. Splitting Tensile Strength

The tensile strength of OPCC is slightly higher than that of GC. Slower polymerization reactions in the early stage cause a reduction in the GC tensile strength. The tests in Figure 11, shows that the tensile strength of OPCC similar to that of the GC. The results of these analyses are shown in Figure 12.

(a) (b)

Figure 11. Splitting tensile test on a) GC, and b) OPCC

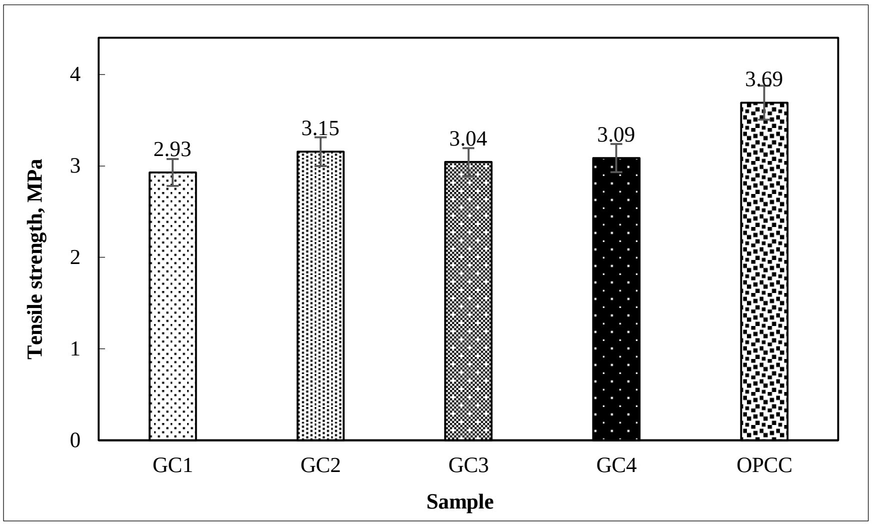

Figure 12. Effect of Rc ratio on tensile Strength of OPCC and GC

Some research carried out by Hardjito et al. [43], and Sofi et al. [44] also reported similar characteristics, as shown in Figure 13.

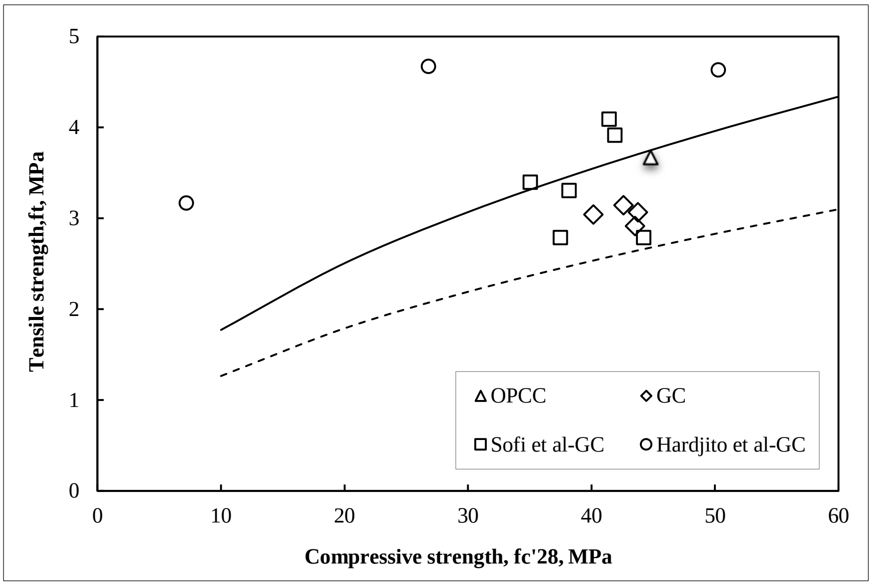

Figure 13. Tensile strength and compressive strength of OPCC and GC

Figure 13 shows that the split tensile strength of the GC is mainly located below the predicted ACI 318 equation used for obtaining the value of the OPCC. It is still above the results of Neville's empirical equation prediction. Therefore, the predicted tensile strength of GC is more realistic using the Neville equation, ft = 0.4 (fc'_{28}) 0.5. The results obtained indicate that the OPCC tensile strength is similar to that of the GC.

3.4. Flexural Strength

Flexural strength tests are shown in Figure 14, and the results are shown in Figure 15. The flexural strength of the GC is higher than the OPCC. GC sample with an Rc ratio of 1.25 has a maximum flexural strength that is more significant than the others. These tests reveal that GC with good flexural strength is obtained if the volume of its mortar is 1.25 times the aggregate void. It was critically discovered that when cured under normal conditions, its flexural strength tends to be better than that of the OPC concrete. The results are inline with works of Muthadi et.al [45].

(a)

(b)

Figure 14. Splitting tensile test on a) OPCC, and b) GC

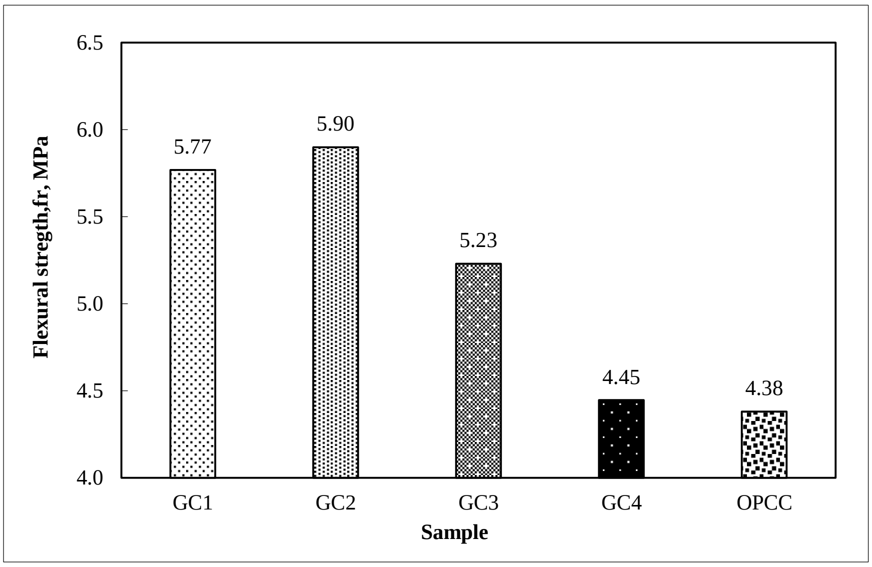

Figure 15. Flexural strength of geopolymer concrete and OPC concrete

The outcome of some research carried out by Fernandez et al. [46], Sofi et al. [44], and Diaz et al. [47] are also stated in this work. The flexural strength of OPC concrete is similar to that of the geopolymer. There are insignificant differences, and the results obtained also have a similar trend, as shown in Figure 16.

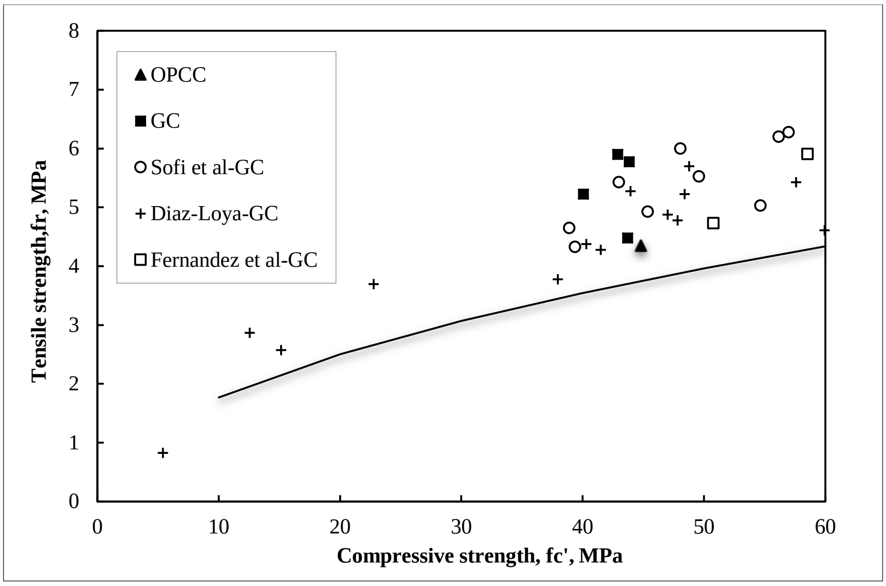

Figure 16. Flexural strength and compressive strength of OPCC and GC

The flexural strength of the GC is above the ACI 318 prediction curve. Therefore, this formula could be used to predict the flexural strength of the GC. The test on the GC beam shows that this system is better than the OPCC. It also indicates that geopolymer can be used as an alternative to OPCGC.

3.5. Bond Strength

The bond strength of GC and OPCC were also investigated, as shown in Figure 17. The pull-out test results are shown in Figure 18. The greater the diameter of the reinforcement bar, the higher the bond strength for both GC and OPCC. However, the bond stress in GC is higher than OPCC.

(a)   (b)

Figure 17. Pull out tests on a) OPCC, and b) GC

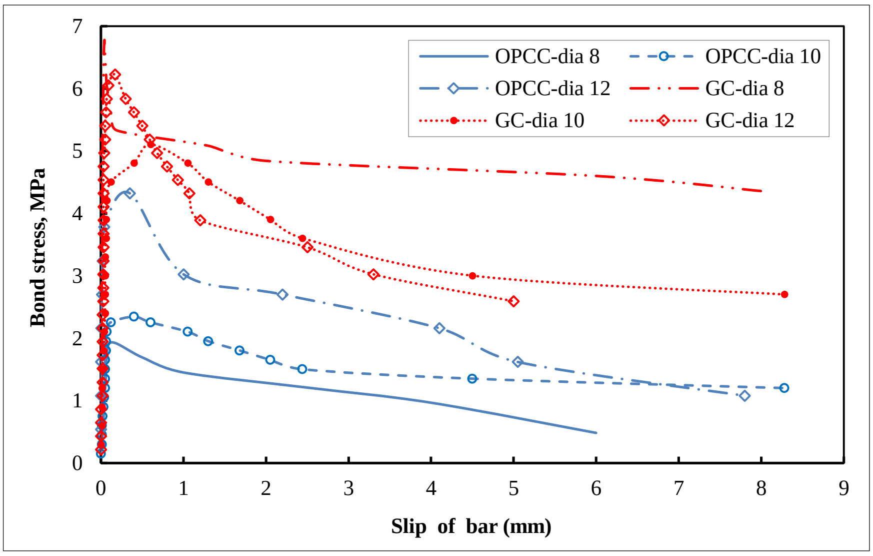

Figure 18. The relationship between bond stress and slip of the bar

The results obtained by Sarker et al. [48] and Filho et al. [49] proved that the bond strength of the plain reinforcement was reduced due to an increase in its diameter. This study's outcome contrasts with previous ones, where the bond strength becomes stronger as the bar reinforcement diameter increases. This difference is because previous research used a larger diameter of 12, 16, and 19 mm to obtain a significant cover effect, which was confirmed by the failure mode. On the contrary, the failure mode in this research is a slip and not a splitting failure.

Figure 19 shows that the bond strength of the GC is greater than that of the OPCC. The difference was relatively 42, 75, and 76% for 8, 10, and 12 mm of reinforcement. The failure mode of pull-out plain bar reinforcement tests in OPCC and GC slip failure. These results indicate that geopolymer can be used as an alternative material to replace OPC.

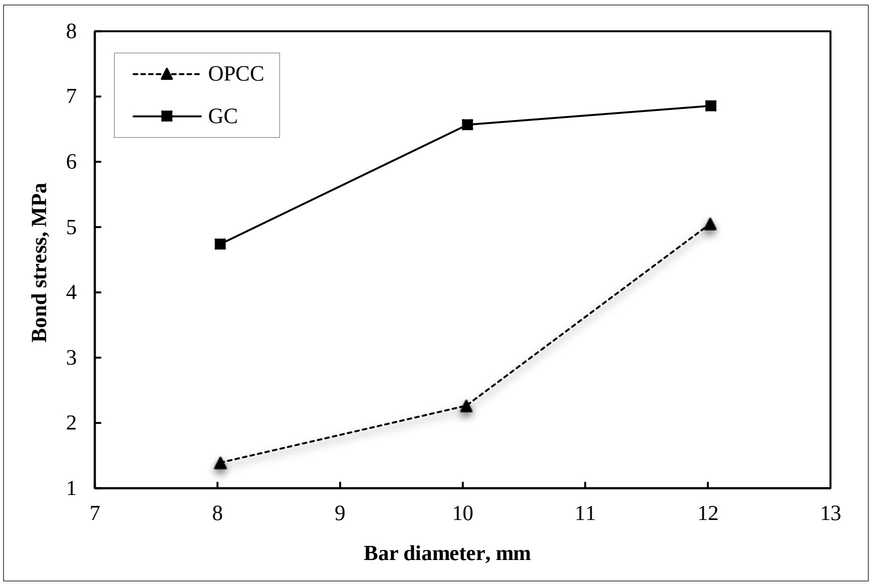

Figure 19. The relationship between bond strength and diameter of plain steel bar

4. Conclusion

Class CI fly ash contains moderate calcium oxide and makes geopolymer concrete cure under normal conditions. The following is the effect of the aggregate volume ratio on its mechanical properties. The volume ratio of Rc does not affect the early strength of GC, but rather strongly influences its workability and compressive strength. The increase in the value of the Rc ratio does not align with that of the compressive strength. However, the Rc ratio of 1.75 triggers high workability and compressive strength. It does not affect the OPC and GC tensile strength. The lower the Rc ratio, the higher the OPC concrete's and GC's flexural strength. An increase in the diameter of the reinforcement bar, the higher the bond strengths of both geopolymer and OPC concretes. The bond stress in geopolymer is higher than in OPC concrete. It was significantly discovered that the mortar volume ratio affects the workability and compressive strength of Class CI fly ash-based geopolymer concrete, and it does not require high-temperature curing or admixture. Irrespective of this, its compressive and tensile strength is comparable to that of OPC concrete and it has greater flexural and bond strengths. This led to the knowledge of optimizing the mix design geopolymer and making it suitable for use as an alternative concrete material.

5. Declarations

5.1. Author Contributions

R.C., H.P., I.S., and R. contributed to the study's conception, methodology, and research design. R.C. performed numerical studies and analyzed the experimental data. I.R. contributed, guided, reviewed, and commented on the previous version of the manuscript; R.R. wrote the first draft of the manuscript; H.P., I.S., and R. added review and editing in the discussion. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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