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Mustafa Sameer Abdulkareem Al-azzawi
University of Wollongong, msaaa374@uowmail.edu.au

Tao Yu
University of Wollongong, taoy@uow.edu.au

Muhammad N. S Hadi
University of Wollongong, mhadi@uow.edu.au

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Abstract

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Factors affecting the bond strength between the fly ash-based geopolymer concrete and steel reinforcement

Mustafa Al-Azzawi¹, Tao Yu², Muhammad N.S. Hadi^{3*}

¹ PhD Candidate, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia

^{2*} Associate Professor, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia

³ Associate Professor, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia

Correspondence:

Muhammad N. S. Hadi

School of Civil, Mining & Environmental Engineering

University of Wollongong, Australia

E-mail: mhadi@uow.edu.au

Telephone: + 61 2 4221 4762

Facsimiles: + 61 2 4221 3238

* Corresponding author

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Keywords: Geopolymer concrete; Bond strength; Fly ash; steel reinforcement; Alkaline activator.

1. Introduction

Geopolymer concrete is developing as an environmentally friendly alternative to Portland Cement Concrete (PCC). The geopolymer concrete is synthesised by mixing a geopolymer binder (aluminosilicate material and alkaline activator) with aggregate. In general, the geopolymer binder is prepared by mixing an aluminosilicate material (i.e. fly ash and blast furnace slag) with an alkaline activator, i.e. sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The chemical reaction (geopolymerization) between the aluminosilicate material and the alkaline activator forms a three-dimensional inorganic polymer with coherent and adhesive properties [1].

The use of fly ash (by-products of coal combustion in power stations) in producing geopolymer concrete is gaining more interest by many researchers across the world. This is because the fly ash is one of the cheapest aluminosilicate materials which is rich in silica (SiO_2 40%-70% by weight) and alumina (Al_2O_3 15%-30% by weight) [2, 3]. Moreover, the use of fly ash in the geopolymer concrete contributes in reducing the environmental impacts due to disposing fly ash in landfills [4]. However, fly ashes produced from different power stations have different characteristics because of using different fuel types (bituminous and lignite coal) and different techniques in collecting the fly ashes making the fly ash a non-standard material [5, 6]. As such, fly ashes from different sources will have different extent of geopolymerization with alkaline activators that affects the properties of the Fly Ash-Based Geopolymer Concrete (FBGC). This is due to the differences in the fly ash characteristics in terms of particle size distribution, amorphous SiO_2 and Al_2O_3 content and CaO content [7-10]. Consequently, using fly ash from different sources in producing FBGC has different performance in structural members. Thus, understanding the factors that affect the

performance of the FBGC with steel reinforcement is necessary to promote the use of FBGC as a potential alternative to the PCC.

Reinforced concrete members generally rely on the interfacial bond between the reinforcing bars and the surrounding concrete [11, 12]. Transferring the forces between a steel rebar and the surrounding concrete depends on chemical adhesion, friction and the mechanical interlocking between steel ribs and the concrete [11]. The performance of the concrete to resist stresses transferred from the reinforcing bars is dominated by the compressive and the tensile strengths of the surrounding concrete [11].

The bond strength between the FBGC and steel reinforcement has been investigated in different studies [13-18]. The effects of the bar size of steel reinforcement, the embedded length of the steel bar, the thickness of the concrete cover and curing conditions of FBGC on the bond strength between the FBGC and steel reinforcement were investigated by several studies. However, the existing studies did not investigate the effect of using different fly ash sources (different characteristics) and different mix proportion on the bond strength between the FBGC and steel reinforcement. The present study examines the effect of different fly ash sources (five different Australian fly ash sources) and different mix proportion of the FBGC (three different fly ash contents and three different weight ratios of $\text{Na}_2\text{SiO}_3/\text{NaOH}$) on the bond strength between the FBGC and steel reinforcement.

2. Experimental work

2.1 Materials

2.1.1 Fly ash

Fly ashes (Type F) from Eraring (ER), Mt Piper (MP), Bayswater (BW), Gladstone (GL), and Collie (CL) power stations were used in this study. The X-Ray Fluorescent (XRF) was

carried out on samples of fly ash in the laboratories of the School of Earth & Environmental Sciences, University of Wollongong, Australia. The particle size distribution analysis for the fly ash samples were carried out using laser diffraction particle size analyser. The results of the XRD and XRF analysis of the fly ash are summarised in Table 1, respectively. The particle size distribution of the fly ash samples is illustrated in Figure 1.

The analysis of the XRF showed that all fly ash samples were Type F based on the definition of ASTM-C618 (2015). The amount of SiO_2 , Al_2O_3 and Fe_2O_3 content for all fly ashes were higher than 70%. The CaO content in all fly ash samples were less than 8%. The percentages of the Loss on Ignition (LOI) for the unburned particles in all fly ashes ranged from 0.7% to 1.7%. The median particle size (d_{50}) of the fly ashes Eraring, Mt Piper, Bayswater, Gladstone, and Collie were 24.8, 20.5, 17.0, 3.5 and 9.0 μm , respectively.

2.1.2 Alkaline activator

The alkaline activator utilised in this study was composed of different proportions of NaOH and Na_2SiO_3 . The NaOH solution was prepared by diluting caustic soda, which contained about 98% by weight Na_2O in water. The Na_2SiO_3 composed of 29.4% SiO_2 , 14.7% Na_2O and 55.9% water by weight.

The optimum concentration of the NaOH and the weight ratio of the alkaline activator to the fly ash content (AL/FA) for each fly ash source were determined by conducting sets of geopolymer trial mixes. For this aim, five sets of fly ash-based geopolymer mortar (FGBM) mixes were prepared and tested for compressive strength. The details of the mix proportion of the geopolymer mortar are summarised in Table 2. The weight ratio of fly ash to sand was fixed at 1:2.75 according to [19]. The results of the compressive strength of the FGBM show

that the optimum concentration of NaOH and the optimum AL/FA for ER, MP and BW fly ashes were 16 mole/L and 0.6, respectively. While the optimum NaOH concentration and the optimum AL/FA for GL and CL fly ashes were 12 mole/L and 0.5, respectively. The results showed that fly ash with a high percentage of fine particles and amorphous components (SiO_2 and Al_2O_3) such as GL and CL fly ashes required a low dosage of alkaline activator to achieve the highest compressive strength. While ER, MP and BW fly ashes required a high concentration of the NaOH and AL/FA to achieve the highest compressive strength.

The effect of using an alkaline activator with different content of Na_2SiO_3 and NaOH on the bond strength between the FBGC and steel reinforcement was investigated. For this aim, the Na_2SiO_3 and the NaOH were blended into three $\text{Na}_2\text{SiO}_3/\text{NaOH}$ weight ratios which are 1.5, 2.0 and 2.5. These ranges of the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratios were used previously in several studies [20-22].

2.1.3 Aggregate

Coarse aggregate with a maximum size of 14 mm and specific gravity of 2.6 was utilised in the geopolymer concrete mixes. The coarse aggregate used in this study was crushed basalt aggregate with water absorption of 0.77%. Fine aggregate (< 4.75 mm) with a specific gravity of 2.5 and a fineness modulus of 3.2 was also used in the geopolymer concrete mixes. Both coarse and fine aggregates were used in the saturated surface-dry (SSD) condition.

2.1.4 Steel bar

To investigate the bond behaviour between the geopolymer concrete and steel reinforcement, deformed steel bars with a nominal diameter of 16 mm were used in this study. The nominal tensile strength of the deformed steel bar was 500 MPa.

2.2 *Mixing, casting and curing of the FBGC*

In this study, mixes of the FBGC were prepared by mixing fly ashes (Type F), alkaline activators (mix of NaOH and Na₂SiO₃), water, fine aggregate and coarse aggregate in different mix proportions. These mixes were divided into five groups according to the source of fly ash, which are ER, MP, BW, GL and CL. Nine mixes of FBGC were prepared for each group. Fly ash in the FBGC groups was blended with Na₂SiO₃/NaOH ratios of 1.5, 2.0, and 2.5; the mixes of the FBGC in each group were mixed with 300, 400, and 500 kg/m³ of fly ash. The maximum reduction in the total volume of aggregate due to increasing the fly ash content from 300 to 500 kg/m³ was 24%. Water was used to control the slump of the FBGC. The fine and coarse aggregates were selected based on the method prescribed in ACI-211.1 [23] for normal concrete. The details of the geopolymer concrete mixes are listed in Table 3. The fly ash and aggregate were dry mixed for three minutes, then the pre-mixed alkaline activator was added and blended for another four minutes. Water was added to the geopolymer concrete mixes to maintain a slump between 80 to 100 mm, after which the mixes were poured into moulds and compacted by a vibrating table. These specimens were kept at ambient temperature for 24 hours as proposed by Vora and Dave [24], then cured in an oven at 70° C for 24 hours as recommended by Gunasekara et al. [25] and Soutsos et al. [26]. During heat curing, the specimens were covered with plastic sheets to prevent loss of moisture. The specimens were then taken out of the moulds and kept at room temperature before being tested.

The mixes of the FBGC were identified according to the fly ash source, fly ash content and Na₂SiO₃/NaOH ratio. The sources of fly ash were labelled ER, MP, BW, GL, and CL, which denotes the Eraring, Mt-Piper, Bayswater, Gladstone and Collie, respectively; while the amount of fly ash was denoted by values of 300, 400 and 500 kg/m³. The ratio of

Na₂SiO₃/NaOH was expressed by the letter R, followed by the ratios (1.5, 2.0, and 2.5). For example, Mix ER500R2.5 refers to geopolymer concrete that was mixed with fly ash from Eraring power station, with 500 kg/m³ fly ash and Na₂SiO₃/NaOH in the ratio of 2.5.

2.3 Test procedure

2.3.1 Bond strength test

Direct pull-out tests were carried out according to European Standard EN-10080 [27] to determine the bond strength between FBGC and steel reinforcement. The bond test was carried out on cubic specimens 160 mm sides in accordance to the EN-10080 [22]. A 16 mm diameter deformed steel bar was embedded in the middle of the cubic specimens to a length of five times its diameter, as recommended by EN-10080 [22]; details of the test specimens are shown in Figure 2. Three specimens from each mix were tested at the age of 7 days. In total, 45 mixes of the FBGC were examined for the bond strength test. These bond tests were carried out in the Highbay laboratory, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia.

The type of failure was identified, and the bond stress-slip relationship was recorded by a computer mounted onto the testing machine (Instron 8033 testing machine). According to EN-10080 [22], the bond strength was calculated using the following formula:

$$\tau = \frac{F_U}{5d^2\pi} \quad (1)$$

where τ is the bond strength, F_U is the ultimate pull out force, and d is the bar diameter.

2.3.2 Compressive strength tests

The 100 mm diameter by 200 mm high cylinders were tested for compressive strength of concrete according to AS1012.9 [28] at the age of 7 days. The average compressive strength of three specimens was reported for each mix. The compressive strength was obtained using a W&T Avery Testing Machine with a loading capacity of 1800 kN. The test was carried out in the Highway laboratory, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia.

2.3.3 Scanning Electron Microscopy (SEM) analysis

The Scanning Electron Microscope (SEM) was performed on the crushed FBGC. Neoscope SEM-JSM 6000 at the Nanotechnology laboratory at the School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Australia was used for the SEM analysis. The SEM was conducted to investigate the effect of different fly ashes on the microstructure of the FBGC. Also, the SEM was used to examine the effect of increasing the fly ash content in the FBGC on the microstructure.

3. Results and discussion

3.1 Bond strength

The failure mode of pull-out specimens of the FBGC and the effects of test parameters (fly ash type, fly ash content and $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio) on the bond strength were evaluated. The results of the pull-out test of the FBGC are summarised in Table 3.

3.1.1 Failure mode of the pull-out specimens

All FBGC pull-out specimens failed when the concrete cover split along the steel bar referring to the brittle nature of the FBGC as shown in Figure 3. The splitting failure occurs when the forces induced between the steel ribs and the surrounding concrete exceeds the maximum tensile strength of the FBGC. The splitting failure of the FBGC in the pull-out test was also reported by Sofi et al. [13], Sarker [14] and Topark-Ngarm et al. [17].

It was observed that the mode of splitting failure was significantly influenced by the fly ash content in FBGC mixes. Typically, the propagation of cracks in the FBGC with high fly ash content (500 kg/m^3) occurred suddenly through the geopolymer paste and resulted in splitting the specimens, as shown in Figure 3a. On the other hand, the propagation of cracks in the FBGC with low fly ash content (300 kg/m^3) took a time before splitting the FBGC, as shown in Figure 3b. The effect of the fly ash content in the FBGC on the failure mode may be attributed to the variance in the total volume of the aggregate that was replaced by the fly ash in the FBGC mixes. Increasing the fly ash content in the FBGC from 300 to 500 kg/m^3 reduced the total volume of aggregate by about 24%. The aggregate, especially the coarse aggregate, works on delaying the crack propagation that initially occurred at the interfacial transition zone (ITZ) between the aggregate and the geopolymer paste [11].

The mode of the splitting failure of the FBGC in the pull-out test was influenced by the compressive strength of the FBGC. It was found that increasing the fly ash content in the FBGC promoted the compressive strength of the produced FBGC (see Table 3). The increase in the compressive strength of the concrete correlates to the increase of the brittleness of the concrete [11]. As a result, increasing the fly ash content in the FBGC results in increasing the

brittleness of the FBGC, which in turn affects the mode of failure of the FBGC during the pull-out test.

3.1.2 Bond strength of the FBGC

3.1.2.1 Effect of fly ash type on the bond strength of the FBGC

The effect of using different fly ash sources on the bond strength between the FBGC and steel reinforcement is shown in Figure 4. The bond strength between the FBGC and steel reinforcement was significantly influenced by the source of fly ash. The FBGC that was mixed with GL fly ash exhibited the highest bond strength between the FBGC and steel reinforcement where the average bond strength was 25 MPa. On the other hand, The FBGC that was mixed with BW fly ash showed the lowest bond strength between the FBGC and steel reinforcement where the average bond strength was 10.3 MPa. The high average bond strength of the FBGC that were mixed with GL fly ash may be attributed to the lowest median particle size, the high content of amorphous component (SiO_2 and Al_2O_3) and the highest CaO content. The different characteristics of different fly ashes lead to different extent of geopolymerization between the fly ash and the alkaline activator, which in turn influences properties of the produced FBGC.

The different extent of the geopolymerization affects the microstructure of the FBGC that consequently affects the bond with a steel bar. This is true when comparing the microstructure of the FBGC that were mixed with different fly ashes. Figure 5 a-e show the SEM images of the microstructure of Mixes ER500R2.5, MP500R2.5, BW500R2.5, GL500R1.5 and CL500R1.5 that achieved the highest bond strength of the FBGC that were mixed with ER, MP, BW, GL and CL fly ashes, respectively. The results show that using different fly ashes exhibited different microstructure of the FBGC. The microstructures of

Mixes ER500R2.5, MP500R2.5 and BW500R2.5 (Figures 5 a-c) were less homogeneous and contained a higher amount of unreacted particles, voids and cracks between the aggregate particles than those observed in Mixes GL500R1.5, CL500R1.5 (Figure 5 d and e). The weakest microstructure was observed in FBGC that was mixed with BW fly ash (Figure 5 c) where the highest amount of unreacted fly ash particles, a large amount of irregular voids and cracks were found, which is consistent with the lower average bond strength.

The presence of unreacted particles, voids and cracks in the microstructure of the FBGC represent weak points that failure may start and/or pass through it [29]. Because of this, the bond performance between the FBGC and steel reinforcement declines significantly. These results suggested that the bond strength is essentially dependent on the fly ash characteristics.

3.1.2.2 Effect of fly ash content on the bond strength of the FBGC

The effect of the fly ash content in the FBGC on the bond strength between the FBGC and the steel reinforcement is illustrated in Figure 4. An increase in the amount of fly ash from 300 to 500 kg/m³ in the FBGC mixes increased the bond between the FBGC and steel reinforcement. The maximum increase in the bond strength of the FBGC that were mixed with ER, MP, BW, GL and CL fly ashes were 36%, 16%, 29%, 26% and 29%, respectively.

This improvement in the bond between the FBGC and the steel reinforcement may be attributed to the improvement in the microstructure of the FBGC that is associated with increasing the fly ash content in the FBGC as shown in Figure 6 a-d. Using a lower content of fly ash (300 kg/m³) in the FBGC resulted in forming a non-homogeneous and loosely structured matrix. Unreacted particles and large irregular voids are likely to be found, as shown in Figure 6 a and c. As discussed above, the presence of unreacted fly ash particles,

voids, and crakes in the microstructure of the FBGC reduces the bond between the FBGC and steel bar.

The poor microstructure of the FBGC that used the lower content of fly ash (300 kg/m^3) may be attributed to the poor consolidation of FBGC components. Fly ash particles facilitate flow between the aggregate particles owing to the spherical shape and smooth surface of the fly ash particles [8]. Thus, lowering the fly ash content (300 kg/m^3) reduces the ability of the FBGC components to consolidate properly around the steel bar which in turn leads to less integration between the FBGC and the steel bar.

The use of high fly ash content (500 kg/m^3) in the FBGC resulted in a dense and compacted microstructure, as shown in Figure 6 b and d. This improvement in the microstructure of the FBGC that was mixed with high fly ash content (500 kg/m^3) may be attributed to the increase in the packing density (the ratio of volume fraction occupied by the solids to the volume of the surrounding container) of the FBGC matrix. Increasing the fly ash content increases the volume of the fine fraction particles in the FBGC matrix which in turn fill the voids between the aggregate particles and the steel bar. As a result, increasing the fly ash content in the FBGC improves the microstructure of the FBGC which in turn improves the bond between the FBGC and the steel reinforcement.

3.1.2.3 Effect of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio on the bond strength of the FBGC

The increase of the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio in the alkaline activator from 1.5 to 2.5 in the FBGC that were mixed with ER, MP and BW fly ashes increased the bond strength between the FBGC and steel reinforcement, as shown in Figure 4. The increase in the bond strength between the FBGC and steel reinforcement reached 36%, 29%, and 16% for FBGC

that were mixed with ER, MP and BW fly ashes, respectively, which is in line with the findings of Sarker [14]. However, Figure 4 shows that an increase in the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio from 1.5 to 2.5 caused a considerable reduction in the bond between FBGC and steel reinforcement by 19% and 13% for the FBGC that were mixed with GL and CL fly ashes, respectively. As a result, increasing the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio in the FBGC does not show a clear effect on the bond strength of the FBGC due to using different fly ashes that required different optimum $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratios to achieve the highest bond strength of the FBGC.

The alkaline activator components (Na_2SiO_3 and NaOH) are mainly composed of the molecules including SiO_2 and Na_2O in different ratios. In order to understand the effect of the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio on the bond strength of the FBGC, relationships between bond strength of the FBGC and the liquid SiO_2 as well as with Na_2O in the alkaline activator were performed. The relationship between the content of the liquid SiO_2 in the Na_2SiO_3 , which represents 29.4% by weight, and the bond strength of the FBGC were conducted as shown in Figure 7. The results show that the bond strength of the FBGC increased significantly with increasing the amount of the liquid SiO_2 in the FGBC. The increase of the liquid SiO_2 content results in increasing the reactive silica in geopolymer matrix forming a silicon-rich gel which has compacted and higher mechanical properties [30]. As a result, the higher bond strength of the geopolymer is associated with the higher liquid SiO_2 in the FBGC matrix.

In addition, the effect of the total Na_2O content in alkaline activator components (14% by weight of Na_2SiO_3 and 28%-35% by weight of NaOH) on the bond strength between the FBGC and steel reinforcement was evaluated. Figure 8 shows the relationship between the total Na_2O of the alkaline activator on the bond strength of the FBGC. The results show that increasing the Na_2O in the alkaline activator reduced the bond strength of the FBGC, irrespective of the type and content of the fly ash. In fact, the Na_2O content controls the

extent of leaching the fly ash components (SiO_2 and Al_2O_3) in the geopolymer mix while the fly ash is being geopolymerised [31, 32]. Consequently, the Na_2O content affects the cohesion of geopolymer structure, which in turn affects the bond strength of the FBGC with steel reinforcement.

3.1.2.4 Effect of the water content in the FBGC on the bond strength with steel reinforcement

The increase of water content in the normal concrete reduces the bond strength with steel reinforcement; increasing the water content in concrete increases the bleed of water that occurs due to concrete consolidation resulting in forming open pores between concrete and steel [33]. In the FBGC, the alkaline activator is the main source of water (55.9% by weight of the Na_2SiO_3 and about 60% by weight of the NaOH) in the mix. Also, water is added to the geopolymer mix to control the slump of the geopolymer concrete mix. In this study, the effect of added water on the bond strength of the FBGC was evaluated.

The effect of the added water on the bond strength of the FBGC is illustrated in Figure 9. For all FBGC specimens, increasing the added water in the FBGC resulted in a significant decrease in the bond strength. The amount of reduction in the bond strength between the FBGC and steel reinforcement was significantly influenced by the fly ash source. The maximum reduction was observed in the FBGC that was mixed with CL fly ash where the reduction in the bond strength between the FBGC and steel reinforcement reached 38% due increasing the amount of the added water from 7 to 15 kg/m^3 . While the maximum reduction in the bond strength of the FBGC that was mixed with ER fly ash was 25% when the added water increased from 5 to 14 kg/m^3 .

This reduction in the bond strength of the FBGC due to increasing the amount of the added water in the mixes may be attributed to evaporation of the water from the concrete, when curing at high temperature, leaving pores and cavities within geopolymer matrix. In addition, the added water may affect the alkalinity (pH value) of the geopolymer matrix that could lead to reducing the rate of the geopolymerization between fly ash and alkaline activator.

3.2 Compressive strength

The results of the compressive strength of the FBGC are summarised in Table 3. The compressive strength of the FBGC at the age of 7 days was in the range between 16 MPa to 64 MPa. The results show a substantial difference in the compressive strength of the FBGC due to effects of the tested parameters including the type and content of fly ashes, the dosage of the alkaline activator in terms of liquid SiO_2 and Na_2O and the added water. The results showed that the tested parameters influenced the compressive strength of the FBGC similarly to that was observed in the bond strength between FBGC and steel reinforcement. The compressive strength of the FBGC that was mixed with GL fly ash was in the range of 34.4 MPa to 64 MPa, whereas the compressive strength of FBGC that was mixed with BW fly ash was from 16 MPa to 23.2 MPa.

3.3 Relationship between the bond strength and the compressive strength of the FBGC

The bond strength between the FBGC and the steel reinforcement and the corresponding compressive strength are plotted in Figure 10. The results show that the bond strength between the FBGC and the steel reinforcement increases significantly with increasing the corresponding compressive strength. Different models were proposed to estimate the bond strength between the PCC and the steel reinforcement in terms of the compressive strength. A comparison was carried out with the models proposed for the bond strength of the PCC by

Orangun et al. [34], Hadi [35] and CEB-FIP [36] in Eqs 2, 3 and 4, respectively. These models were plotted along with the experimental results of the bond strength between the FBGC and steel reinforcement in this study as shown in Figure 10. It can be seen that the experimental results of the bond strength between the FBGC and the steel reinforcement in this study were generally higher than those calculated by Eqs 2, 3 and 4. However, models of Orangun et al. [34] and CEB-FIP [36] in Eqs 2 and 3, respectively gave comparable values of the bond strength at a range of compressive strength lower than 25 MPa. While, the bond strength values that were estimated by the model of Hadi [35] in Eq 4 were 37% to 66% lower than the experimental results in this study. These results imply that the bond strength of the FBGC is significantly higher than the bond strength of the PCC in the range of compressive strength higher than 25 MPa.

$$\tau = 2.18f_c'^{0.5} \quad (2)$$

$$\tau = 1.33f_c'^{0.5} \quad (3)$$

$$\tau = 2.51f_c'^{0.5} \quad (4)$$

where τ is the bond strength (MPa), f_c' is the compressive strength of the FBGC (MPa).

As a result, a model was derived based on the results of the bond strength of 45 FBGC mixes. For this aim, power regression law was used in fitting the relevant best fit line. The model parameters (intercept and power values) were determined using logarithm method [37]. As a result, a model with a correlation factor (R^2) of 0.84 was developed as shown in Eq 5.

$$\tau = 1.35 f_c'^{0.75} \quad (5)$$

The $\pm 95\%$ confidence intervals were calculated by using Eq 6 while $\pm 95\%$ prediction intervals were determined by using Eq 7 [38]. The confidence and prediction intervals at a

probability level of $\pm 95\%$ for the power regression line were calculated and plotted along with the relevant best fit line.

$$\tau_{95\% \text{ confidence}} = \tau_{\text{predicted}} \pm t_{0.05} \left(\sqrt{\frac{\sum(\tau - \tau_{\text{predicted}})^2}{i - 2}} * \sqrt{\frac{1}{i} + \frac{(f'_c - f'_{c \text{ ave}})^2}{ss_x}} \right) \quad (6)$$

$$\tau_{95\% \text{ prediction}} = \tau_{\text{predicted}} \pm t_{0.05} \left(\sqrt{1 + \frac{\sum(\tau - \tau_{\text{predicted}})^2}{i - 2}} * \sqrt{1 + \frac{1}{i} + \frac{(f'_c - f'_{c \text{ ave}})^2}{ss_x}} \right) \quad (7)$$

where $\tau_{95\% \text{ confidence}}$ is the 95% confidence interval value of the predicted bond strength, $\tau_{95\% \text{ prediction}}$ is the 95% prediction interval of the predicted bond strength, $\tau_{\text{predicted}}$ is the predicted bond strength using the developed model in Eq 5, $f'_{c \text{ ave}}$ is the average of the compressive strength. The $t_{0.05}$ is the *t-test* critical value for 95% interval, and ss_x is the sum of the squares of the standard error of input values.

The model in Eq 5 was evaluated using the available experimental data from studies were conducted on the bond strength of the FBGC by Sofi et al. [13] Topark-Ngarm et al. [17] and Dahou et al. [18]. The data were plotted along with the results of the bond strength between the FBGC and the steel reinforcement of this study as shown in Figure 10. It can be seen that the experimental data of Sofi et al. [13] and Topark-Ngarm et al. [17] were significantly lower than that estimated by developed model in Eq 5. This is because of the low curing temperature ($< 60^\circ\text{C}$) that was used by Sofi et al. [13] and Topark-Ngarm et al. [17] in their experimental which in turns affecting the developing of the bond strength between the FBGC and steel reinforcement bar. In contrast, the experimental data of Dahou et al. [18] shows a good consistency with the model in Eq 5 where the data were between the ± 95 prediction intervals as shown in Figure 10.

4. Conclusion

This study investigated the effects that the fly ash characteristics, amount of fly ash and different $\text{Na}_2\text{SiO}_3/\text{NaOH}$ had on the bond between FBGC and steel reinforcement. The following conclusions can be drawn as based on the analysis of the results:

1. The bond strength between FBGC and steel reinforcement was from 7.5 to 30 MPa, and the source of fly ash affects the strength of the bond between the FBGC and the steel reinforcement quite considerably. The fly ash characteristics including particle size distribution, the content of the amorphous components (SiO_2 and Al_2O_3) and the CaO have a significant effect on the bond strength of the FBGC. The FBGC that was mixed with GL fly ash exhibited the highest average bond strength between the FBGC and steel reinforcement (25 MPa), while the FBGC that was mixed with BW fly ash showed the lowest average bond strength between the FBGC and steel reinforcement 10 MPa.
2. An increase in the amount of ash content from 300 to 500 kg/m^3 increased the brittleness of the FBGC that affects the mode of failure of the FBGC due to pull-out of the steel bar.
3. An increase in the amount of ash content from 300 to 500 kg/m^3 increased the bond between FBGC and steel reinforcement in the range between 16% to 36%.
4. The strength of the bond between FBGC and steel reinforcement differed according to the increase in the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio in the alkaline activator. An increase in the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio in the FBGC that were mixed with GL and CL fly ashes reduced the strength of the bond between FBGC and steel reinforcement by 13% to 19%, respectively. Increasing the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio in the alkaline activators of the FBGC that were mixed with ER, MP, and BW fly ashes increased the strength of the bond between the FBGC and steel reinforcement up to 36%.

5. The bond strength of the FBGC increased with increasing the SiO_2 used in the alkaline activator. While it decreases significantly with increasing the total content of the Na_2O in the NaOH and the Na_2SiO_3 .
6. The increase of the amount of added water in the FBGC reduced the bond strength between the FBGC and steel reinforcement.

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Table 1 Chemical composition of the fly ash samples

Composition	Eraring (ER)	Mt-Piper (MP)	Bayswater (BW)	Gladstone (GL)	Collie (CL)
SiO ₂ (%)	62.9	66.6	77.2	43.4	52.7
Al ₂ O ₃ (%)	25.8	25.9	15.2	26.2	33.4
CaO (%)	2.3	0.4	0.6	5.4	1.0
Fe ₂ O ₃ (%)	3.1	0.9	2.5	17.4	9.0
K ₂ O (%)	1.2	2.7	1.5	0.5	0.3
MgO (%)	0.3	0.1	0.3	1.4	0.6
LOI (%)	1.7	1.3	0.7	0.7	0.4

Table 2 Details of the mix proportion of the geopolymer mortar

Fly ash Source	Mix No.	Na ₂ SiO ₃ /NaOH wt. ratio	Alkaline activator/ fly ash wt. ratio	Average Compressive Strength (MPa)
Eraring (ER)	1	2.0	0.5	14
	2			16
	3			21
	4		0.6	26
	5			28
	6			32
	7		0.7	13
	8			18
	9			24
Mt-Piper (MP)	1	2.0	0.5	15
	2			20
	3			25
	4		0.6	27
	5			30
	6			33
	7		0.7	19
	8			23
	9			29
Bayswater (BW)	1	2.0	0.5	12
	2			18
	3			16
	4		0.6	20
	5			24
	6			25
	7		0.7	14
	8			17
	9			21
Gladstone (GL)	1	2.0	0.5	62
	2			58
	3			56
	4		0.6	59
	5			56
	6			54
	7		0.7	45
	8			43
	9			38
Collie (CL)	1	2.0	0.5	46
	2			43
	3			40
	4		0.6	45
	5			40
	6			37
	7		0.7	34
	8			31
	9			30

Table 3 Details of mix proportion and results of the fly ash based geopolymer concrete

Mix ID	Fly ash		Alkaline activator Na ₂ SiO ₃ / NaOH wt. ratio	Aggregate		Water (kg/m ³)	Slump (mm)	Average Compressive strength (MPa)	Bond strength (MPa)
	Fly ash type	Fly ash content (kg/m ³)		Fine (kg/m ³)	Coarse (kg/m ³)				
ER300R1.5	Eraring (ER)	300	1.5	627	1333	14.5	92	17	9.5
ER300R2.0			2.0	628	1335	14.0	91	18	10.2
ER300R2.5			2.5	629	1336	14.0	91	21	10.4
ER400R1.5		400	1.5	554	1177	10.0	93	19	10.0
ER400R2.0			2.0	555	1179	10.0	93	20	12.0
ER400R2.5			2.5	556	1181	9.5	92	22	14.0
ER500R1.5		500	1.5	480	1020	6.5	94	22	10.4
ER500R2.0			2.0	482	1023	6.0	95	25	12.0
ER500R2.5			2.5	483	1026	5.7	94	26	14.0
MP300R1.5	Mt-Piper (MP)	300	1.5	622	1321	12.7	93	19	8.6
MP300R2.0			2.0	623	1323	12.2	89	20	10.0
MP300R2.5			2.5	623	1324	12.0	91	20	11.7
MP400R1.5		400	1.5	546	1161	9.5	95	20	9.2
MP400R2.0			2.0	548	1164	9.5	96	21	10.6
MP400R2.5			2.5	548	1165	9.2	94	22	12.6
MP500R1.5		500	1.5	471	1000	7.0	95	21	13.7
MP500R2.0			2.0	475	1005	6.7	92	25	14.0
MP500R2.5			2.5	475	1005	6.7	93	26	15.0
BW300R1.5	Bayswater (BW)	300	1.5	627	1333	16.5	88	16	7.5
BW300R2.0			2.0	628	1335	16.2	89	18	8.3
BW300R2.5			2.5	629	1336	16.2	88	19	9.8
BW400R1.5		400	1.5	554	1177	13.7	90	18	9.5
BW400R2.0			2.0	555	1179	13.0	91	19	10.5
BW400R2.5			2.5	556	1181	13.0	91	20	11.2
BW500R1.5		500	1.5	480	1020	10.0	93	21	10.5
BW500R2.0			2.0	482	1023	9.5	92	21	11.8
BW500R2.5			2.5	483	1026	9.2	92	23	13.0
GL300R1.5	Gladstone (GL)	300	1.5	622	1321	11.0	95	45	24.0
GL300R2.0			2.0	623	1323	10.5	94	39	22.0
GL300R2.5			2.5	623	1324	10.2	94	34	20.0
GL400R1.5		400	1.5	546	1161	9.5	98	58	26.0
GL400R2.0			2.0	548	1164	8.0	96	47	25.0
GL400R2.5			2.5	548	1165	7.7	97	42	24.0
GL500R1.5		500	1.5	471	1000	6.5	100	64	30.0
GL500R2.0			2.0	475	1005	5.7	99	62	29.6
GL500R2.5			2.5	475	1005	4.8	97	53	27.9
CL300R1.5	Collie (CL)	300	1.5	663	1408	12.3	91	30	17.0
CL300R2.0			2.0	663	1410	11.5	89	28	16.0
CL300R2.5			2.5	664	1411	11.5	92	27	14.0
CL400R1.5		400	1.5	601	1277	9.0	92	35	21.0
CL400R2.0			2.0	602	1279	9.0	93	30	19.6
CL400R2.5			2.5	602	1280	9.0	92	28	18.3
CL500R1.5		500	1.5	539	1145	7.0	98	43	25.8
CL500R2.0			2.0	540	1148	7.0	98	41	25.1
CL500R2.5			2.5	541	1150	7.0	98	36	22.7

Figure 1 Particle size distribution of the fly ash samples

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Figure 2 Details of the bond strength test specimen
(All dimensions are in mm)

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Figure 3 Typical splitting failure of the pull-out test specimens (a) Mix GL500R2.0, (b) Mix GL300R2.0

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Figure 4 Variation of the bond strength with fly ash content of the FBGC mixes at different Na₂SiO₃/NaOH ratios

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Figure 6 The SEM images for Mixes; (a) ER300R2.5, (b) ER 500R2.5, (c) GL300R1.5 and (d) GL 500R1.5

Figure 7 Relationship between the liquid SiO₂ and the bond strength of the FBGC

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Figure 8 Relationship between the total Na₂O and the bond strength of the FBGC

Figure 9 Relationship between the added water and the bond strength of the FBGC

Figure 10 Bond strength of the FBGC versus the compressive strength