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The Influence of Plain Bar on Bond Strength of Geopolymer Concrete

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Abstract. This paper presents some results of experimental study of bond strength of plain bar embedded in geopolymer concrete. Fly ash class F was used as a raw material activated with alkali solutions. The combination of 8 Molar of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as alkali activators was examined in the mixture with ratio of 2.5 by weight. Nine cubical specimens with a size of 150 x 150 x 150 mm were prepared to measure bond strength and slip between reinforcement and concrete. The influential factors studied for the experimental investigation were the diameter of reinforcement bar, bond area, and concrete cover to diameter (c/d) of reinforcement. The result showed that the average bond strength decreased as the diameter of plain bar and bonded length were increased from 16 mm to 19 mm. However, the 12 mm showed the different result allegedly caused by the effect of bond area and the passive confined provided by the concrete. Based on several equations used to compare the bond strength, it is clear that deformed bar of 12 mm in diameter is potential to increase the bond strength.

INTRODUCTION

Concrete is the most common and essential material in the construction of infrastructure application. The worldwide consumption of concrete is enhanced due to the increase of infrastructure in countries such as India and China [1]. Ordinary Portland cement is conventionally used as the main binder to product concrete. The problem with Ordinary Portland cement is that it requires large amount of natural resource and energy causing air pollution and carbon emission. Approximately 5% to 8% of all human-generated atmospheric carbon dioxide is the result of the concrete industry. Among the greenhouse gases, carbon dioxide contributes about 65% of global warming [2]. Thus, it is important to seek for environmentally friendly binding agents for concrete. Currently, geopolymer concrete has been introduced as a solution for this problem.

Geopolymer is an aluminosilicate inorganic polymer synthesized from alkaline activator of various aluminosilicate materials of geological origin or by product materials like fly ash, metakaolin and blast-furnace slag. Several researches showed that geopolymer can act as a binding agent in concrete [3, 4]. Fly ash is one of the construction materials which is used to produce geopolymer concrete [5]. In previous study, low calcium fly ash (class F) was investigated as a material for geopolymer because of its abundant availability, pertinent silica and alumina composition, and less water demand.

In application, the bond strength is critical contribution factor to strengthen the section of concrete which has low tensile strength. Bond behavior is described as the transfer of force from the reinforcement to the surrounding concrete by adhesion between the bar and concrete, frictional force at the interface and the ribs of deformed bar against the concrete [6]. Bond ensured that there is no slip of the reinforcement relative to the concrete which stress is transferred across the steel concrete [7]. Generally, bond strength is governed by different factors such as compressive and tensile strength of concrete, the concrete cover to bar, confinement due to transverse reinforcement, surface condition of the bar and bar geometry [8].

Research using the pull-out test has shown that geopolymer mortars generally perform well [9, 10, 11]. Another experimental study reported the development length of reinforcement embedded in fly ash-based on geopolymer concrete for various compressive strengths of concrete and deformed reinforcement diameters [12]. Other recent studies [13, 14] reported bond behavior of reinforcing fly ash-based geopolymer concrete beams with an emphasis on the effect of concrete compressive strength, bar diameter, and splice length of deformed

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bars on the bond strength. In another study, the performance of pull out test on reinforced geopolymer concrete was found a better bond performance than the use of reinforced OPC concrete [15]. A similar result was also observed and the increase of bond strength by decreasing deformed bar diameters was reported [16, 17]. However, there were only few results discussing about bond performance of plain bar. This paper discussed the influence of plain bar on bond strength of geopolymer concrete and compared the results with previous researches on bond strength of OPC concrete [12, 18, 19, 20].

EXPERIMENTAL STUDIES

Materials

Low calcium fly ash type F was obtained from *PT. Petrokimia Gresik* Indonesia as the base material. Fly ash used in this study was composed of 85% ($SiO_2 + Al_2O_3 + Fe_2O_3$), 5% SO_3, and 10% of CaO. Based on the [21], those compositions of fly ash can be classified as Type F. The chemical compositions of this material are shown in Table 1.

The combination of Sodium hydroxide (NaOH) and Sodium silicate (Na_2Si0_3) was used as the alkaline activator. Sodium hydroxide was prepared by dissolving sodium hydroxide flakes in distilled water. The concentration of NaOH was 8 M. Sodium silicate with a chemical composition of 15% Na_2O, 30% SiO_2 and 55% H_2O was obtained from *PT. Kasmaji Utama* (*PTKIU*), Indonesia. The mass ratio of Na_2SiO_3 to NaOH was kept at 2.5. A commercially available superplasticizer from *PT. Sika* Indonesia with a dosage of 3% by weight of fly ash was used to improve the workability of fresh concrete.

TABLE 1. The Chemical Composition of Fly Ash (%)

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Cr_2O_3	K_2O	Na_2O	SO_3	Mn_2O_3
48.47	26.05	12.54	0.92	5.18	2.77	0.02	1.66	0.47	1.05	0.19

The aggregates were prepared in saturated-surface-dry (SSD) conditions before mixing them with the concrete, which was determined from the absorption and the moisture content test as described in ASTM C127 [22] and ASTM C566 [23], respectively. Locally available aggregates comprising of 10 mm coarse aggregates and fine aggregates sand were collected from *PT. Surya Beton Indonesia*. The mix proportion of geopolymer concrete is given in Table 2.

TABLE 2. The Mix Proportion

Material	Mass (kg/m^3)
Coarse Aggregate	1080
Fine Aggregate	720
Fly Ash (Type F)	390
NaOH (8 M)	60
Na2SiO3	150
Superplaticizer (3% of fly ash)	11.7

The reinforcement bar embedded in concrete used geopolymer paste as bonding material. The nominal reinforcement plain bar diameter were 12 mm, 16 mm, and 19 mm with 3 (three) specimens were made for each series of specimen. Samples of reinforcement bar were tested in laboratory to obtain the actual yield strength and ultimate strength. The results are given in Table 3.

TABLE 3. Properties of Reinforcement Bar

Diameter	Nominal Area (mm^2)	Yield Strength (MPa)	Ultimate Strength (MPa)
12	91.8	390	544
16	184	389	492
19	269	340	505

Preparation of Specimens

There are three types of test to investigate the bond behavior of reinforcing bar, namely pull out test, beam end test, beam anchorage and splice test [24]. In this study, the pull out test was selected to investigate bond behavior of each variation of plain bar diameter. Each bar was embedded in 150 mm x 150 mm x 150 mm concrete cube and the embedded length was five times bar diameter (5d). Standard 100 mm x 200 mm concrete cylinders were used for compressive strength test. As shown in Fig.1, the contact between the concrete and the bar was eliminated through the use of PVC tubing to achieve the desired embedment length.

Mixing was conducted with a pan mixer. The pan was cleaned and in wet condition, the materials were placed into the mixer by hand. The specimens were put in a horizontal position and were compacted by a vibrating table, it was necessary to hold the reinforcement during the compaction. The aggregates and base material of fly ash were mixed previously. Furthermore, the alkali activators with superplasticizer were mixed together. After the mixing, the fresh geopolymer concrete was placed into the mold. After demolding, the geopolymer concrete specimens were stored under wet condition using gunny-sack until the test day, which was 28 days after the preparation as shown in Fig.2.

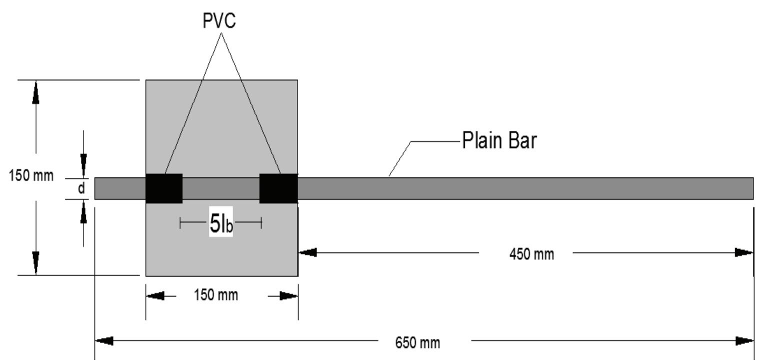

FIGURE 1. Pull Out Specimen

FIGURE 2. Curing Specimen

Test Setup

The test was performed by using universal testing machine with a tensile capacity of 2.000 KN. The load was applied at the bottom side of the reinforcement until the failure of specimens was identified. The slip of the bar relative to concrete at the free end was measured with linear variable displacement transducers (LVDT). The force and displacement were recorded by using an automatically data acquisition system. The test setup is shown in Fig.3.

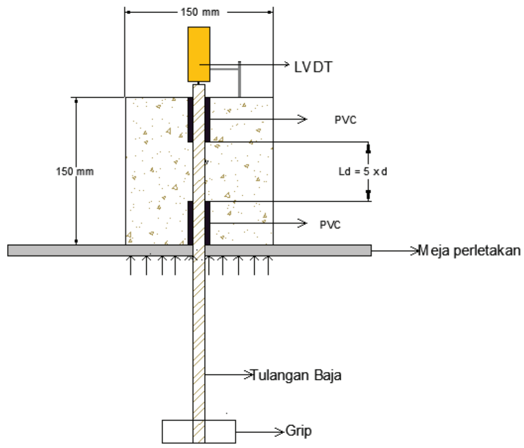

FIGURE 3. Setup of pull out test

RESULT AND DISCUSSION

The average bond strength calculated from the peak pull out load is assumed at the ultimate bond strength between two materials. This definition of average bond strength is followed throughout the analysis, and it is calculated as:

$$\tau = \frac{F}{\pi * d_b * L_b} \tag{1}$$

The bond area is depended on the diameter of reinforced bar and the bonded length of reinforcement embedded in concrete**.** The bond area calculated by using Eq. (2).

$$A = \pi * d_b * l_d \tag{2}$$

Where P is the maximum pull out load and d_b and l_d are the diameter and the bonded length of the plain bar, respectively. The experiment results for geopolymer are given in Table 4. The average curve from each variation group of three samples was chosen as the representative of the bond slip behavior and is plotted in Fig. 4. The bond slip curve displays the characteristic stages of the typical bond-slip curve of geopolymer concrete. When the failure occurs at the maximum bond stress point, softening of the bond stress follows. The failure of bond strength rapidly decreases at the slip increases.

TABLE 4. Bond Test Result for GPC Concrete.

Specimen	**Bar diameter db(mm)**	**Cover c (mm)**	**c/db**	**Bond Length ld = 5* db (mm)**	**Bond Area A (mm)**	**Bond Strength (Mpa)**
GPC 12	12	150	5.75	60	2261	3.11
GPC 16	16	150	4.19	80	4019	6.34
GPC 19	19	150	3.45	95	5668	6.77

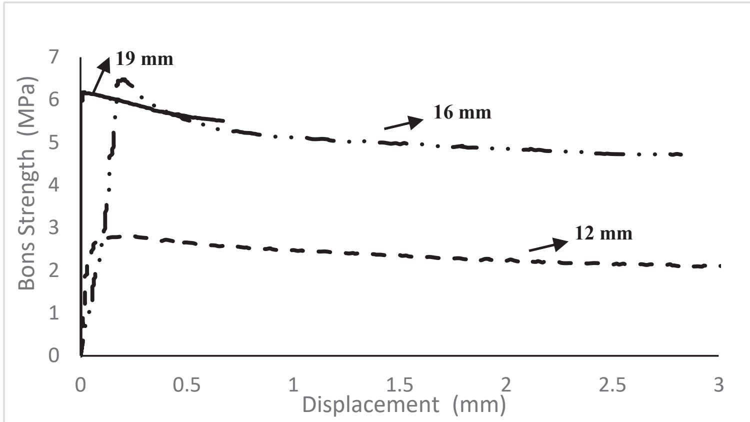

FIGURE 4. Bond Strength-Slip Curve

Table 4 and Fig.5 illustrate the influences of concrete cover to diameter ratio (c/d) of reinforcement bar for each variation. The result shows that concrete cover to diameter ratio (c/d) is depended on bond area and the thickness of concrete cover as the passive confined of concrete**.** In general, bond strength increases as the concrete cover to diameter ratio is also increased. This study showed the same result as the increase from 3.45 to 4.19 indicates the increase of bond strength. However, the bond strength of 12 mm plain bar with cover to diameter ratio 5.75 shows less value. The different results also indicated that the increase of c/d with the smaller bond area and friction between concrete and reinforcement influence this behavior.

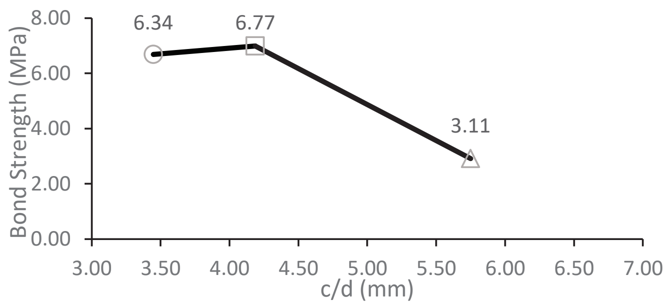

FIGURE 5. Bond Strength with variation of concrete cover to diameter ratio (c/d)

The effect of bonded length (l_d) on bond strength of geopolymer concrete is shown in Fig.6. The trend of the experimental results indicated the increase of bond length and the decrease of average bond strength. The increase of bond length from 80 mm into 95 mm indicated a decrease of bond strength. This behavior is possibly caused by the lack of the concrete thickness. In addition, the smallest bond strength was obtained by 60 mm of bond length.

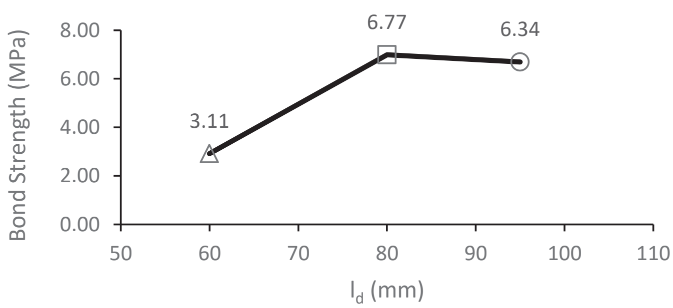

FIGURE 6. Bond strength with variation of bond lengths

The similar trend of increased bar diameter that leads to decreased bond strength of geopolymer and OPC concrete have been reported previously [12]. Fig. 7 shows bond strength decreases as diameter of plain bar is increased from 16 mm to 19 mm. Different results of bond strength as shown by diameter of 12 mm is caused by the bond area and the thickness of concrete cover. Based on previous discussion in this paper, the behavior that influences bar diameter is similar with the behavior that influences concrete to cover diameter ratio and bond length. The bond area and the thickness of concrete cover were main factors that influenced bond strength in this research. The uniformity of the thickness concrete cover with the variation of bond areas contributed by bar diameter and bond length is shown by other results of bond strength of geopolymer concrete.

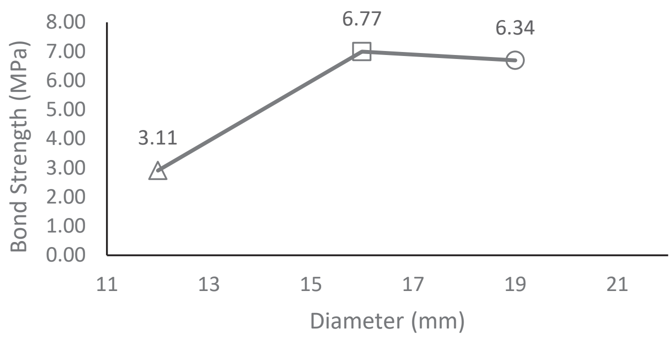

FIGURE 7. Bond Strength with variation of plain bar diameters

Several researchers have attempted to formulate equations that represent the bond between the reinforcing bars and the concrete. Below is a brief description of those equations:

Oragun *et al,* [18] proposed the following formula:

$$u = 0.083045\sqrt{f'c}\left[1.2 + 3\frac{c}{d_b} + 50\frac{d_b}{L_b}\right] \quad (3)$$

The previous research [12] proposed the equation for bond strength related to length development in geopolymer concrete. The new equation of bond stress was required for geopolymer concrete.

$$u = \sqrt{f'c}\left[2.07 + 0.20\frac{c_{min}}{d_b} + 4.15\frac{d_b}{l_d}\right] \quad (4)$$

TABLE 5. The Summary of Pull out Results

Diameter (mm)	Cover (mm)	Pmax (N)	Calculated Bond Strength (MPa)		
			Experimental	Oragun *et al.*, [18]	Kim and Park [12]
12	150	6590	3.11	14.12	24.20
16	150	28125	6.34	11.79	22.33
19	150	36953	6.77	10.69	21.45

The summary of the pull out test results by using the several equations are given on Table 5 and Fig. 8. The equation developed by Kim and Park [12] was used to compare the bond strength of geopolymer concrete for each variation in this experiment. The results of the calculation with those from previous formula showed significant differences. Using equation developed by Oragun *et al.* [18], the trend showed to decrease of bond strength in accordance with the increase of bar diameter. Those significant differences of bond strength were possiblycaused by the differrent specimens and type of bar. This experiment used the cube concrete specimen while Oragun *et al.,* [18] used the beam specimen. Furthermore the equation is particularlyproposed for calculating bond strength of beam specimen and deformed reinforcement bar.

The results of equation by Kim and Park [12] showed similar trend with Oragun [18] where the increase of bar diameter is in accordance with the decrease of bond strength. Additionally, similar trend also occured in this experiment with bond strength in diameter of 16 mm to 19 mm. Different results of 12 mm plain bar indicated the lowest bond strength. The result showed that 12 mm of plain bar is not recommended as the reinforcement embedded in geopolymer concrete. It is evident that deformed bar with 12 mm diameter is potential to increase bond strength as illustrated in Fig. 8.

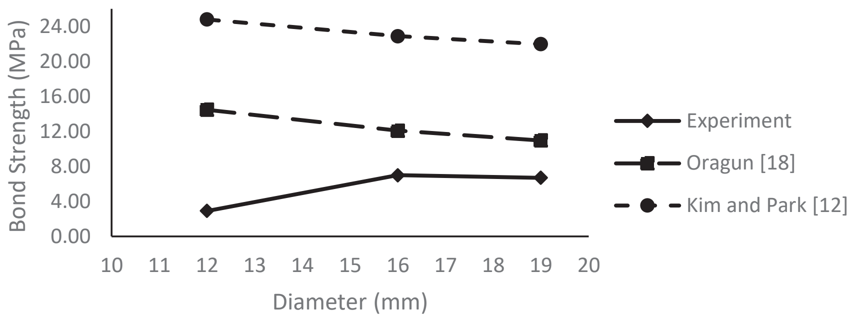

FIGURE 8. Comparison of bond strength generated from the equations.

CONCLUSIONS

The bond strength as the results of plain bar was investigated in this research. The variation of concrete cover to diameter ratio (c/d), bond length (l_d), and diameter of plain bar was examined. The bond slip curve and the average of bond strength for each specimen were observed. The following conclusions are drawn from the experimental results:

1. The bond strength increases in accordance with the increase of diameter reinforcement (c/d) from 3.45 to 4.19 of concrete cover. However, the c/d of 5.75 showed less bond strength. The bond area and the thickness of concrete cover caused this behavior.
2. The increase of bond length (l_d) from 80 mm to 95 mm led to the decrease of bond strength. It is possibly caused by the lack of passive confined provided by concrete. In addition, less bond strength was indicated by a diameter of 12 mm on a bond legth of 60 mm.
3. Several equations were employed to compare the generated bond strengths. The results showed that similar trend showed by diameter of 16 mm and 19 mm. However, a diameter of 12 mm showed the different result. It indicated that the bar is not recommended as reinforcement embedded in geopolymer concrete.

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