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Effect of Embedment Length on Bond Strength of Geopolymer Concrete

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Abstract. The evaluation of the pull-out experimental result of the steel reinforcing bar on fly ash-based geopolymer concrete prism is presented in this study. A single reinforcing bar with the nominal diameter (d_b) of 13mm was pulled out from the geopolymer concrete prism. Three sizes of geopolymer concrete prism were presented, 100x100x200, 150x150x200, and 180x180x200 m^3. Hence the ratio of cover thickness to diameter of the bar (c/d_b) were 3.4, 5.4, and 6.6. The effects of embedment length (L_d) that were $3d_b$, $5d_b$, and $7d_b$ were investigated. The results showed that the embedment length changed the mode of failure. The pull-out failure occurred on the specimens with the short embedment length ($3d_b$), splitting failure occurred on the long embedment length, and the bar ruptured on the large specimens with longer embedment length ($7d_b$). The highest of maximum pull-out load and the bond strength obtained were 77.58 kN and 42.13 MPa, respectively. The maximum pull-out load increased with increasing the embedment length. The bond strength decreased as the embedment length increased.

INTRODUCTION

Cement production increases every year to fulfill the cement demand in concrete construction. Cement production requires high energy and releases carbon dioxide into the air. Seven percent of total man-made carbon dioxide emissions are produced by cement production [1]. The cement industry contributes around 3% of global greenhouse gas emission [2]. Various attempts have been made to reduce the use of cement, such as replacing cement with pozzolan material partially or entirely from the contents of cement. Silica-fume, granulated blast furnace slag, rice husk ash, and fly ash are classified as the pozzolanic materials that are waste material. This dumping of industrial waste materials should be eliminated due to the environmental issue. Geopolymer concrete is one of this effort. This concrete is popular as green concrete cause geopolymer concrete is applied to minimize the cement production and utilize the waste material[3]. Geopolymer concrete for structural members has been used widely in recent years. As a new material, evaluation on bond behavior between reinforcing bar and geopolymer is required[4].

The bond between steel reinforcing bar and geopolymer concrete was studied by several researchers. Various types of testing were conducted, such as pull-out test[4-8], beam-end test[9], and splice specimens test[10]. Nurwidayati et al.[11] evaluated bond behavior between deformed steel reinforcing bar and geopolymer concrete. The influences of deformed reinforcing bar diameter and the ratio of concrete cover thickness to the bar diameter to bond behavior were analyzed. However, the effect of embedment length on bond strength in geopolymer concrete was not evaluated by previous studies.

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Pour and Alam[12] investigated the effects of embedment length and concrete cover to bar diameter ratio to the bond strength between deformed steel bar and recycled concrete aggregate (RCA). Meanwhile, the effects of self-compacting concrete (SCC) compressive strength, the bar diameter, and the embedded length were examined by Pop et al. [13]. Moreover, the effects of embedment length and bar diameter on bond strength behavior on geopolymer concrete had been conducted by Maranan et al. [14]. However, this investigation used sand-coated glass fiber-reinforced polymer (GFRP) bars instead of steel reinforcing bar.

On the other hand, Dewi and Ekaputri [15] studied the bond strength between a plain steel reinforcing bar and geopolymer concrete. The variation of embedment length (five-times of bar diameter) in this research was obtained from the different diameter of the bar (12, 16, and 19mm). Bonding behavior in the study was influenced by reinforcing bar diameter and concrete cover not by embedment length. The information about the effect of embedment length of the steel reinforcing bar on geopolymer concrete was limited. Hence investigation of the influence of embedment length with the same diameter of the bar to the bond strength on geopolymer concrete was required to evaluate.

Hadi[16] developed bond strength expression in Ordinary Portland Cement (OPC) concrete based on the experimental result. The wide range of reinforcing bar diameter was evaluated. However, only one embedment length was analyzed (150mm). Another expression developed by Kim and Park [6] in geopolymer concrete. The expression was a function of compressive strength, ratio of concrete cover to bar diameter, and embedment length. However, the different bond length was obtained from the same reinforcing bar diameter ($5d_b$). Hence, effect of embedment was required to evaluate. In this research, three different embedment lengths and three different cross-sections of geopolymer concrete prism were considered to evaluate the effect of embedment length and the ratio of cover concrete thickness to bar diameter to bond strength.

EXPERIMENT PROGRAM

The pull-out test was conducted to evaluate the effect of embedment length to maximum pull-out load and bond strength between steel reinforcing bar and geopolymer concrete. Fly ash-based geopolymer concrete was used.

Materials, Mixture Proportions, and Procedures

Deformed reinforcing bars were used in this research. The nominal diameter of the reinforcing bar was 13mm and effective diameter around 12.7mm. The yield and ultimate strengths were 503.8MPa and 641.7MPa, respectively. The reinforcing bars were cut to a length of 900mm.

Geopolymer concrete mixes consisted of fly ash, coarse aggregate, fine aggregate, and alkaline activator. Class F of fly ash was used as raw material that was collected from Banten Suralaya Power Station. Alkaline activator was a combination of sodium silicate (Na_2SiO_3) and 8M Sodium hydroxide (NaOH Solution). Coarse aggregate and fine aggregate were obtained from the local quarry with a maximum size of coarse aggregate was 10mm. Plastiment-VZ was applied around 2% by fly ash mass to improve the workability and delay the setting time of fresh geopolymer concrete.

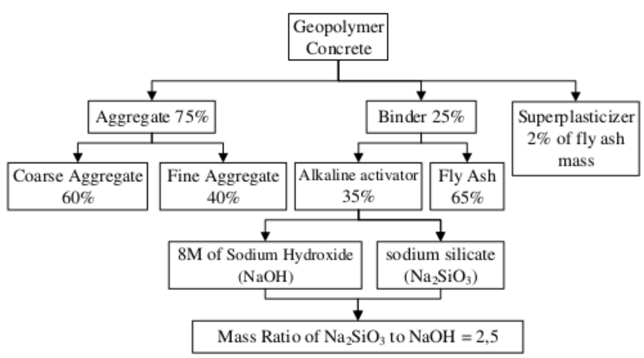

FIGURE 1. The mixture proportions of geopolymer concrete.

The mixture proportion of the geopolymer concrete based on the percentage of the mass ratio of all material, as shown in Fig. 1. The mixing proportions of geopolymer concrete that were developed by Dewi et al. in the previous research as shown in TABLE 1 [15].

An 8M of NaOH solution was prepared 24 hours before mixing. Alkaline activator was blended before mixed with other materials. The mixing procedure of geopolymer concrete: first, put fly ash and coarse aggregate into mixer machine and mixed around two minutes. Then poured the alkaline activator until well blended. Then put in the fine aggregate and mixed for approximately five minutes. In the middle of the mixing, poured the Plastiment-VZ. The material which was stuck on the side of the mixer machine was cleaned and then mixed again for one minute. The fresh geopolymer concrete poured into a cylinder mold specimen with a diameter of 100mm and height 200mm for the compressive strength test and prism specimens for the pull-out test.

TABLE 1. Geopolymer concrete compositions per $1m^3$.

Material	weight (kg)
Coarse aggregate	1080
Fine aggregate	720
Fly ash	390
Na_2SiO_3	150
NaOH 8M	60
Plastiment-VZ	7.8

The specimens were unmolded 24 hours after cast. All samples were wrapped up by using wet gunny-sack and covered with a plastic sheet to protect the moist of geopolymer concrete for 28 days. The reinforcing bars outside the concrete prism were coated to protect the corrosion occurred on the reinforcing bar while curing session.

Descriptions of Test Specimens

Three series of pull-out test were carried out corresponding to three embedment lengths (L_d) of the bond area that depended on the diameter of the reinforcing bar. Three-, five- and seven-times of the bar diameter (d_b) were analyzed in this research. To achieve a specific length of bond between steel bar and geopolymer concrete, two pieces of PVC pipe were applied on the reinforcing bar to cover some area of the reinforcing bar. One-piece of 60mm PVC pipe placed on lead-length on all specimens to avoid the conical failure at an early stage of the pull-out test and to prevent the influence of lead-length to bond strength. Bond strength increased when lead-length increased [17]. The second piece of PVC pipe was adjusted following a predetermined length.

Prism steel molds were prepared to produce the pull-out specimens. A single reinforcing bar was embedded horizontally and centrally in the pull-out prism concrete mold that had a length of 200 mm. Three sizes of the prism cross-section (B) were 100x100, 150x150, and 180x180 mm^2 consequently, the ratio of the concrete cover thickness (c) to a diameter of reinforcing bar (d_b) were 3.4, 5.4, and 6.6, respectively. FIGURE 2 shows the details of the prism geopolymer concrete specimen. A strain gauge type of FLA-2-11 with a gauge length of 2mm was installed on the reinforcing bar to evaluate the bar behavior. The strain gauge set up around 300mm outside the geopolymer concrete prism. Pull out test specimens before testing are shown in FIGURE 3.

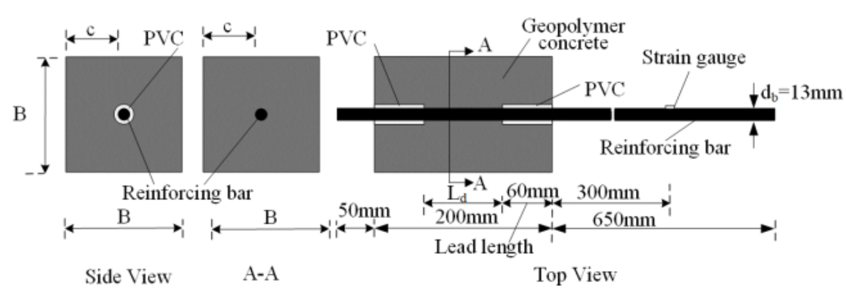

FIGURE 2. Details of pull-out prism specimen.

Experiment Set-Up

The pull-out tests were carried out on a universal testing machine (UTM) with a maximum capacity of 2.000kN at Laboratorium of Concrete and Building Material Institut Teknologi Sepuluh Nopember, Surabaya. The specimens were put vertically on a 3cm-thickness steel plate with a longer length of reinforcing bar on the bottom that was used for gripped by machine, as shown in FIGURE 4 The steel plate had a hole in the center of the plate that was larger than the diameter of the PVC tube and the diameter of the bar. Therefore the reinforcing bar could pass through. The geopolymer concrete was restrained by steel plate while the loaded-end bar was gripped by machine and pulled down on with displacement control of 1mm/min until the specimen failed. The maximum pull-out load (P_{max}) dan the mode of failure was observed.

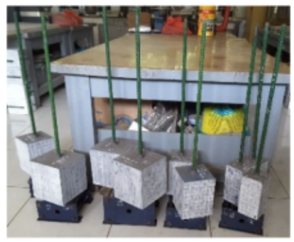

FIGURE 3. The pull-out specimens prepared before the test.

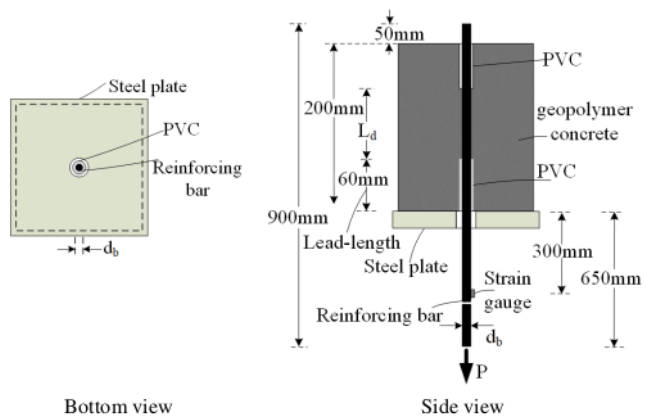

FIGURE 4. The set-up of the pull-out test.

RESULT AND DISCUSSION

A total of 27 prism concrete specimens were tested, and the results of the experiments were summarized in Table 2. It should be noted that each result for different sample sizes in Table 2 represented the average of three prism concrete specimens. Specimens name in this research (Table 2) based on the type of concrete, followed by the bar diameter, the cross-section of the concrete prism and the embedment length. For example, GP13-100-3d_b was a geopolymer concrete (GP) which used a reinforcing bar diameter of 13mm, a cross-section of a prism 100x100 and the embedment length of three-times the reinforcement diameter. In this table, ε_{max} is the strain corresponding to the peak pull-out load that was recorded by the strain gauge. The steel tensile stress is calculated by dividing the maximum pull-out load over the surface area of the bar. τ is the bond strength. It was assumed that the bond stress along the whole embedded length of the steel reinforcing bar is a uniform distribution. The bond strength between steel reinforcing bar to geopolymer concrete that was obtained by dividing the maximum pull-out load to the bond area as follow:

$$\tau = \frac{P_{max}}{\pi d_b L_d} \tag{1}$$

Where τ is the bond strength in MPa, P_{max} is the maximum pull-out load in Newton, d_b is the diameter of steel reinforcing bar, 13mm was used in this research. L_d is the embedment length of reinforcing bar on geopolymer concrete in mm. The average compressive strength of geopolymer concrete (f_c') was 46 MPa. The effects of embedment length to the failure mode, maximum pull-out load, and the bond strength are discussed below.

TABLE 2. Detail of specimens, maximum pull-out load, bond strength, dan failure mode.

Specimens	c (mm)	c/d_b	L_d (mm)	P_{max} (kN)	τ (MPa)	ε_{max}	Steel Tensile Stress (MPa)	Failure
GP13-100-3d_b	46.3	3.4	38.2	59.67	39.07	0.00264	468.2	Bar Pull-out
GP13-100-5d_b	46.3	3.4	63.7	67.13	26.37	-	547.2	Splitting Concrete
GP13-100-7d_b	46.3	3.4	89.1	74.03	20.77	-	581.7	Splitting Concrete
GP13-150-3d_b	68.6	5.4	38.2	61.11	40.01	0.00250	480.1	Bar pull-out
GP13-150-5d_b	68.6	5.4	63.7	73.89	29.12	-	591.1	Bar pull-out
GP13-150-7d_b	68.6	5.4	89.1	75.70	21.24	-	614.3	Bar rupture
GP13-180-3d_b	83.6	6.6	38.2	64.35	42.13	0.00264	501.5	Bar pull-out
GP13-180-5d_b	83.6	6.6	63.7	76.21	29.94	-	608.1	Bar pull-out
GP13-180-7d_b	83.6	6.6	89.1	77.58	21.77	-	601.1	Bar rupture

Failure Mode

In this study, the failure patterns of all the specimens were divided into three types, including bar pull-out failure, splitting of concrete and yielding of the steel bar (steel rupture). Clearly, from Table 2, the increasing bond length changed the failure mode of the pull-out test of a steel reinforcing bar on geopolymer concrete in all sizes of the prism. All specimens in short bond length (3d_b) failed cause of pull-out the bar from the surrounding concrete. The reinforcing bar still on the elastic condition, where the tensile stress from the pull-out test was less than the bar yield strength.

The pull-out failure mode also occurred on moderate embedment length (5d_b) on large specimens of 150x150x200 and 180x180x200 m^3 where the covers around the bar were 5.4 and 6.6 times the diameter of the bar, respectively. The confinement was high; the shear stress occurred along the tops of ribs; hence, the failure occurred on the concrete between the ribbed bars [18] as shown in FIGURE 5a. While the small samples (100x100x200m^3) where the cover was 3.4 times the bar diameter failed because of cracking the concrete cover and propagating parallel with the length of the bar as shown in Fig. 5b. For small samples, the thickness of concrete cover insufficient confined the bar; hence, the crack reached the surface of concrete and the concrete split. However, the bars were rupture on the long embedment length (7d_b) on the large concrete prism (150x150x200 and 180x180x200 m^3) as shown in FIGURE 5c. The rupture of bars occurred before the crack reached the concrete surface, or the bar pulled out from the concrete prism. The failure mode changed from pull-out to splitting the concrete and from pull-out mode to fracture of the reinforcing bar as the embedment length increased at small specimens and large specimens, respectively.

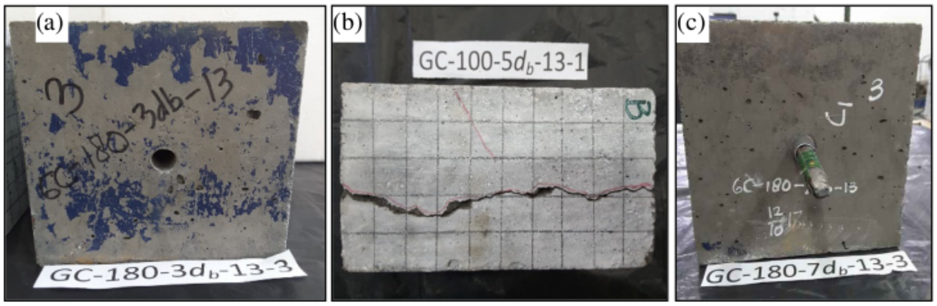

FIGURE 5. Type of failure mode (a). Pull-out failure; (b). Splitting failure; (c). Reinforcing bar rupture.

The Maximum Pull-out Load

The maximum pull-out load in this research was in the range of 59.67kN to 77.58kN. The lowest of the maximum pull-out load was on GP13-100-3d_b specimen that was the shortest length of the bond in the smallest concrete prism. In contrast, the highest of the maximum pull-out load was on GP13-180-7d_b that was the longest of the embedment length in the largest concrete specimen. The comparison of all embedment length between the reinforcing bar and geopolymer concrete is shown in FIGURE 6.

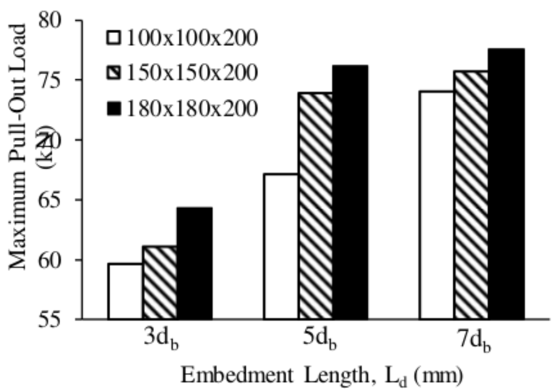

FIGURE 6. The effect of embedment length to the maximum pull-out load.

It is observed from Figure 6 that the maximum pull-out load of the concrete prism with an embedment length of 3d_b was lower than concrete prism with an embedment length of 5d_b and 7d_b. The maximum pull-out load increased around 13-21% and 21-24% as the embedment length of specimens increased from 3d_b to 5d_b and from 3d_b to 7d_b, respectively. The peak load increased with increasing the embedment length. This result implied that higher contact surface between reinforcing bar with geopolymer concrete, the higher load was required to pull-out the steel bar from the surrounding geopolymer concrete. The bond area significantly increased by about 67% and 133% on the embedment length of 5d_b and 7d_b as compared to 3d_b, respectively.

Bond Strength

The bond strength, as in equation (1) of all specimens, is listed in Table 1, and a comparison of bond strength is shown in Fig. 7. The highest bond strength was obtained in this study around 42.13MPa that was gained on the large specimen and short embedment length (GP13-180-3d_b). A better bond resistance was obtained on a large cross-section of concrete prism due to bigger concrete cover that means higher confinement. This specimen failed because the bar pulled out from the concrete prism while the smallest bond strength was achieved on the small samples, long embedment length (GP13-100-7d_b), and the concrete prism split. The bond strength on geopolymer concrete that was gained in this research is significantly higher than similar studies in the literature [4-6,9].

It can be seen that the bond strength indicated to decrease significantly with the increasing the embedment length. On the test of 100x100x200 m^3 prism concrete specimens, the bond strengths with an embedment length of 5d_b and 7d_b were decreased by 33% and 47%, respectively compared to the embedment length of 3d_b. For the same size specimens of 150x150x200 m^3, the bond strengths reduced around 27% and 47% as the embedment length increased of 3d_b to 5d_b and 7d_b, respectively. While on 180x180x200 m^3 concrete prism, the bond strengths on embedment length of 5d_b and 7d_b were approximately 29% and 48%, respectively lower than embedment length of 3d_b. The bond strength on the long-embedment length and small prism concrete exhibited concrete splitting failure that caused low bond strength. The nonlinear stress distribution occurred along the embedment length. The stress on the steel reinforcing bar reduced from the loaded end bar to the unloaded end bar [19].

Effect of Concrete Cover to Reinforcing Bar Diameter Ratio (c/d_b)

The different size of the concrete prism cross-section caused the vary of concrete cover thickness to bar diameter ratio (c/d_b). The effect of ratio c/d_b to peak pull-out load and bond strength is presented in FIGURE 8. On the short embedment length (3d_b) and the long embedment length (7d_b), an increase in c/d_b ratio was followed by an increase in bond strength slightly that was less than 8%. While on L_d=5d_b, the increasing c/d_b=3.4 to 5.4 and 3.4 to 6.4 caused the increasing the bond strength approximately 10% and 14% respectively. This result indicated that the ratio of c/d_b small affected the bond strength. It should be noted that the diameter of the reinforcing bar that was used in this research was 13mm; as a result, the c/d_b ratio in the range of 3.4 to 6.6. A more extensive range of bar diameter is needed to clarify the effect of c/d_b ratio to bond strength behavior.

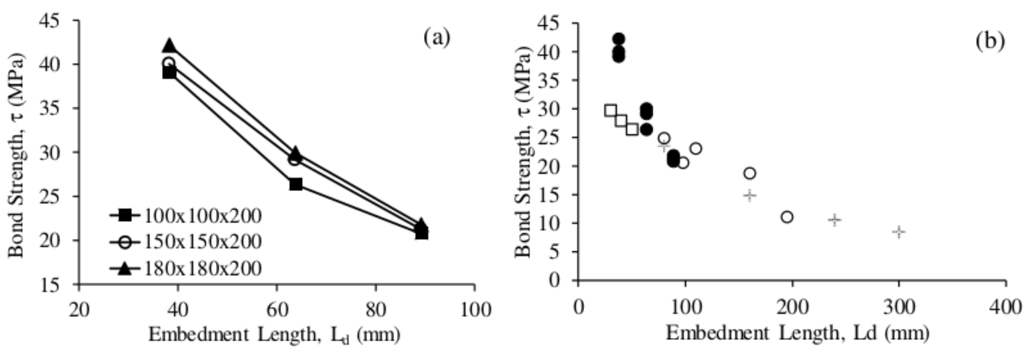

FIGURE 7. Influence of embedment length (L_d) to bond strength; (a). Result experiment on different sizes of concrete prism (b) Comparison to others author: + [14], □[13], ○[12], ● result experiment.

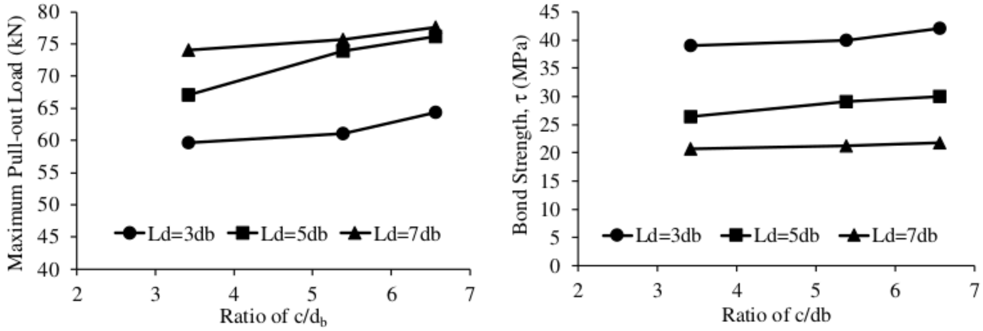

FIGURE 8. The effect ratio of c/d_b to (a). Maximum pull-out load; (b). Bond strength.

Bond Strength Equation

Hadi [16] developed a bond strength equation based on experimental results on high strength steel reinforcing bar on high strength concrete OPC as following:

$$\tau = \sqrt{f_c'}\left(1{,}893 - 0{,}017\left(\frac{c}{d_b}\right) - 3{,}173\left(\frac{d_b}{L_d}\right)\right) \quad (2)$$

While Kim and Park [6] proposed a bond strength equation to predict bond strength between the steel reinforcing bar and geopolymer concrete.

$$\tau = \sqrt{f_c'}\left(2{,}07 + 0{,}20\left(\frac{c}{d_b}\right) + 4{,}15\left(\frac{d_b}{L_d}\right)\right) \quad (3)$$

Eq. (2) and Eq. (3) were used to build a comparison between the experiment results and expressions for bond strength as shown in FIGURE 9.

FIGURE 9 shows the bond strength based on Hadi equation, increased as the embedment length increased. While the equation of Kim and Park shows the bond strength decreased as the embedment length increased that was similar to the experiment results. However, the expression of Kim and Park underestimated the experiment result particularly on short embedment length ($3d_b$).

The bond strength was obtained from this research higher significantly than the predictions based on Hadi[16]. The Hadi expression was developed by using pullout tests on OPC with large values of d_b but only one embedment length. Hence the effect of embedment length insignificant affected the bond strength. The lowest scatter was exhibited by the expressions obtained by Kim and Park[6] on embedment length $5d_b$ (L_d=63.7mm). Kim and Park developed the expression on different steel reinforcing bar diameter (10, 16, 25mm) but only one embedment length ($5d_b$).

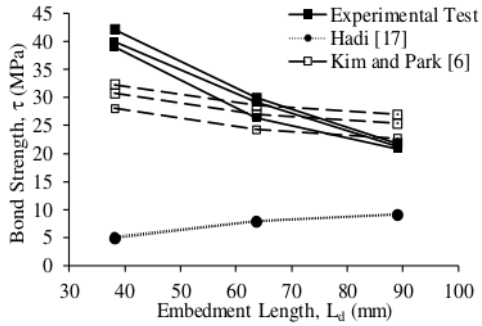

FIGURE 9. Comparison of the experiment result and bond strength equation on different size of the concrete prism.

CONCLUSIONS

Three different sizes of geopolymer concrete prism were analyzed, with three different embedment length for each dimension of the geopolymer concrete prism. Based on the results of the experimental study, the following conclusions can be drawn:

1. The failure mode of geopolymer concrete prism was influenced by the embedment length and the ratio of the thickness concrete cover to reinforcing bar diameter.
2. As the embedment length of steel reinforcing bar increased, the average maximum pull-out load increased. The contact surface between the reinforcement and the geopolymer concrete was greater in a longer embedment length than in a shorter embedment length.
3. The bond strength of the steel reinforcing bar on geopolymer concrete decreased as the embedment length increased. The nonlinear stress distribution occurred along the embedment length
4. The bond strength from the experiment results higher than the bond strength based on the expression of previous research. Geopolymer concrete provides a better bond to reinforcing bar than concrete that was used as the based-formulation of equations.

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