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An Experimental Investigation of Bond Properties of Reinforcements Embedded in Geopolymer Concrete

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***Abstract*—**Geopolymer concretes are new class of construction materials that have emerged as an alternative to Ordinary Portland cement concrete. Considerable researches have been carried out on material development of geopolymer concrete; however, a few studies have been reported on the structural use of them. This paper presents the bond behaviors of reinforcement embedded in fly ash based geopolymer concrete. The development lengths of reinforcement for various compressive strengths of concrete, 20, 30 and 40 MPa, and reinforcement diameters, 10, 16 and 25 mm, are investigated. Total 27 specimens were manufactured and pull-out test according to EN 10080 was applied to measure bond strength and slips between concrete and reinforcements. The average bond strengths decreased from 23.06MPa to 17.26 MPa, as the diameters of reinforcements increased from 10mm to 25mm. The compressive strength levels of geopolymer concrete showed no significant influence on bond strengths in this study. Also, the bond-slip relations between geopolymer concrete and reinforcement are derived using non-linear regression analysis for various experimental conditions.

***Keywords*—**Bond-slip relation, bond strength, geopolymer concrete, pull-out test.

I. Introduction

GOPOLYMER concrete is concrete which does not utilize any Portland cement in its production. Rather, the binder is produced by the reaction of an alkaline liquid with a source material that is rich in silica and alumina. It is being studied extensively and shows promise as a greener alternative to Portland cement concrete [1]. It has high compressive strength, little drying shrinkage, low creep and good resistance to acid and sulphate attacks. The experimental and analytical works show that the performances of geopolymer concrete structural members such as beams and columns under load are similar to those of ordinary Portland cement concrete members [2]. The design of reinforced concrete members starts with the assumption that there exist perfect bond between embedded reinforcements and concrete to prevent slips. It is essential to investigate the bond properties when new binding materials and/or new reinforcements are used for structural applications.

Geopolymer concrete is a type of alumino-silicate product and shows good bonding properties. In a fly ash-based geopolymer binder, fly ash reacts with and alkaline solution to create an alumino-silicate binder; no cement is used. The geopolymer binder binds aggregates to produce geopolymer concrete. The basic ingredients of fly ash-based geopolymer concrete are fly-ash, sodium silicate, water, fine aggregates and coarse aggregates.

Bond in reinforced concrete members is described as the transfer of force from the reinforcement to the surrounding concrete. The force is transferred by adhesion and friction between concrete and reinforcing bar, and the bearing of the ribs of deformed bars against concrete surface. It is generally recognized that bond strength is governed by different factors such as the strength of concrete, the thickness of the concrete surrounding the reinforcing bars, the gap between reinforcements, the transverse confinement and the bar geometry [3].

This paper presents some experimental findings obtained from the pull-out tests on geopolymer concrete and ordinary reinforcements. The influence of design parameters such as compressive strength of geopolymer concrete and diameter of reinforcing bars are studied by using the test results. The equation for determination of basic development length in geopolymer concrete is proposed based on this experiment and compared with that in current design code for Ordinary Portland Cement (OPC). Also, bond-slip relations are studied to assess the cracking behaviors of geopolymer concrete, which were expressed in non-linear form as most design codes do.

II. Experimental Works

A. Specimens

The pull-out test according to EN 10080:2005[4] was used to investigate bond behavior of geopolymer concrete in this paper for 27 specimens. The specimens were fabricated with varying compressive strength and reinforcement bar diameters. The compressive strengths are varied as 20, 30 and 40 MPa and the nominal bar diameters are 10, 16 and 25mm and 3 specimens are made for each series of specimens. The plywood molds were used for easy removal and the rubber hammer compaction was applied. The specimens are cured at atmospheric conditions for 24 hours after molding and then cured for 24 hours at 70°C. The mix proportions are summarized in Table I as a weight ratio to fly ash.

The reinforcements embedded in geopolymer concrete were covered by PVC tube to control the bonded length, which is 5 times the diameter of reinforcement as shown in Fig. 1.

B. Loading and Measurements

The 2,000kN capacity UTM was used to give axial load with displacement control of 1mm/min. The load was applied at bottom side of the reinforcement till the failure of specimens was observed. The test setup was shown in Fig. 2. The relative

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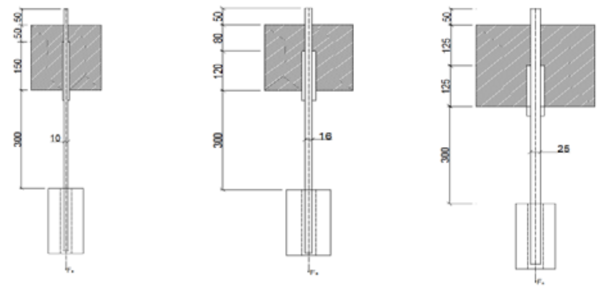
slips between concrete surface and reinforcement were measured at top side with two electric dial gages.

TABLE I
MIX PROPORTIONS OF GEOPOLYMER CONCRETE

Compressive Strength (MPa)		G20	G30	G40
Water		0.19	0.17	0.18
Binder	Fly Ash	1.00	1.00	1.00
	Slag	0.00	0.04	0.11
	$Ca(OH)_2$	0.00	0.00	0.00
Activator	Sodium Silicate	0.33	0.40	0.43
	NaOH (Solid)	0.06	0.06	0.06
Fine Aggregate		1.75	1.83	1.95
Coarse Aggregate		2.51	2.62	2.80



(a) D10 (b) D16 (c) D25

Fig. 1 Pull-out specimens

Fig. 2 Experimental setup

TABLE III
SUMMARY OF PULL-OUT TEST

Bond Stress (MPa)		G20	G30	G40
D10	1	19.81	35.61	29.23
	2	21.08	25.76	23.15
	3	28.35	32.60	23.12
D16	1	18.58	23.63	21.50
	2	14.48	23.34	22.58
	3	21.14	27.12	23.22
D25	1	18.76	19.76	21.62
	2	14.93	23.47	16.14
	3	18.09	27.80	21.58

III. BOND STRESSES AND DEVELOPMENT LENGTHS

A. Bond Stresses

The bond stresses are obtained from failure loads with (1), in which, F_a is failure loads in N and d_b is diameter of reinforcement in mm.

$$U = \frac{1}{5\pi}\frac{F_a}{{d_b}^2} \tag{1}$$

The bond stresses are summarized in Table II with compressive strengths and bar diameters.

The bond average stresses of G20 specimens were 23.06MPa, 21.14MPa and 17.26 MPa for reinforcement diameters of 10mm, 16mm and 25mm, respectively. The bond stresses decreased as the diameter of reinforcement increased in the other compressive strength specimens also. The larger bar requires larger forces to cause a bond failure for bars not confined by transverse reinforcement [3]. In this experiment, the same proportions of bar diameters were given to the specimens, and which result smaller contact areas and smaller bond stresses. The bond stresses assessment for various transverse confinement conditions may be needed for future uses.

B. Development Lengths

The structural applications of geopolymer concrete require some provisions for reinforcement details such as bar spacings, cover depths, development lengths and so on. The development lengths are influenced by structural characteristics, bar properties and concrete properties. The major concerns are from concrete strength, cover depths and bar diameters as shown in (2), in which U is bond stress in MPa, f'_c is compressive strength of concrete in MPa, c_{min} is smaller of minimum concrete cover of 1/2 of the clear spacing between bars in mm, d_b is bar diameter in mm and l_d is development or splice length in mm [5].

$$\frac{U}{\sqrt{f_{c'}}} = 0.1 + 0.25\frac{c_{min}}{d_b} + 4.15\frac{d_b}{l_d} \tag{2}$$

The bond stresses or development lengths in geopolymer concrete are much larger than those in normal concrete obtained by (2). The new equation of bond stress estimation for geopolymer concrete was required to proper and economic design and analysis of geopolymer concrete members. Equation (3) was derived from the data of this experiment.

$$\frac{U}{\sqrt{f_{c'}}} = 2.07 + 0.20\frac{c_{min}}{d_b} + 4.15\frac{d_b}{l_d} \tag{3}$$

The new equation is compared with (2) in Fig. 3 and experimental results are also plotted.

The bond stresses normalized with square root of concrete compressive strength of geopolymer concrete are 1.5 – 2 times higher than those of normal concrete strengths. The grey points in Fig. 3 are experimental results obtained from normal concrete specimens of same conditions given for reference. Within the experimental results of this study, it may be concluded that geopolymer concrete requires much smaller development and splice length compared to normal concrete.

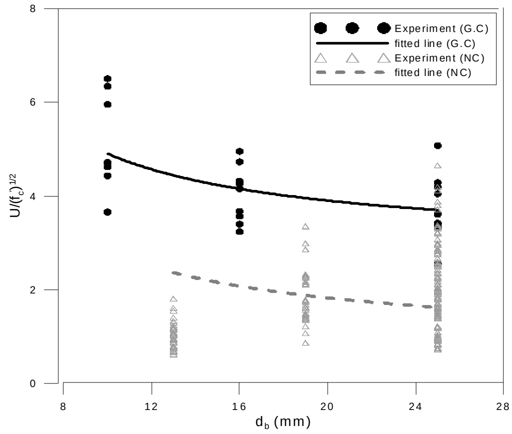


Fig. 3 Normalized bond stress

IV. Bond-Slip Relations

Bond of reinforcing bars to concrete influences the behavior of reinforced concrete structures in many respects. In an obvious way, bond plays an important role in the cracking behavior (crack widths and crack spacing) and the tension stiffening [6]. CEB-FIP Model Code 1990 uses a non-linear law to relate the applied bond stress, τ, to bar slip, s as in the form of (4) and Fig. 4, in which τ_{max} is bond strength, τ_f is residual bond capacity and s_1, s_2 *and* s_3 are characteristic slip values dependent on the state of confinement of concrete, concrete strength, quality of bond and geometry of reinforcing bars.

$$\tau = \tau_{max} \cdot (\frac{S}{s_1})^{\alpha} \quad (4)$$

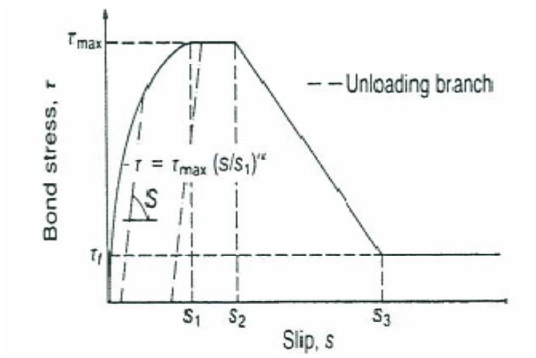
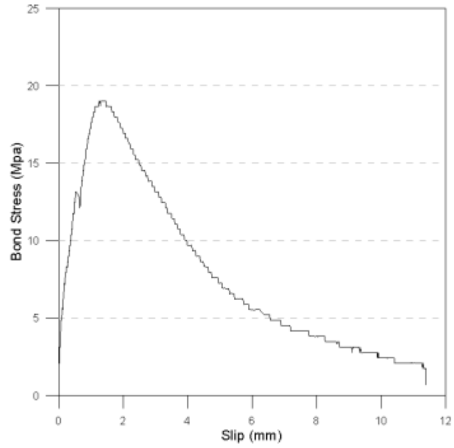
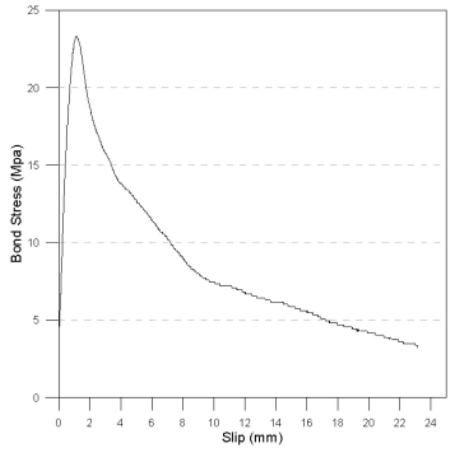


Fig. 4 Analytical bond stress-slip relationship according MC90 [7]

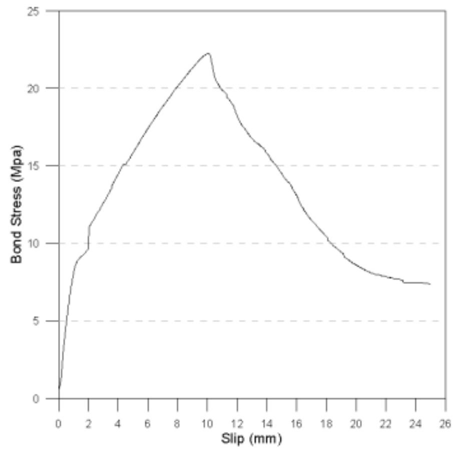
The bond-slip curves for various reinforcing bar diameters were derived for geoplolymer concrete as in Fig. 5, which shows similar shapes those of normal concrete. The transverse confinements were not applied to specimens, which results in abrupt descending of curves after peak stresses.



(a) D10



(b) D16



(c) D25

Fig. 5 Bond-slip curves for geopolymer concrete

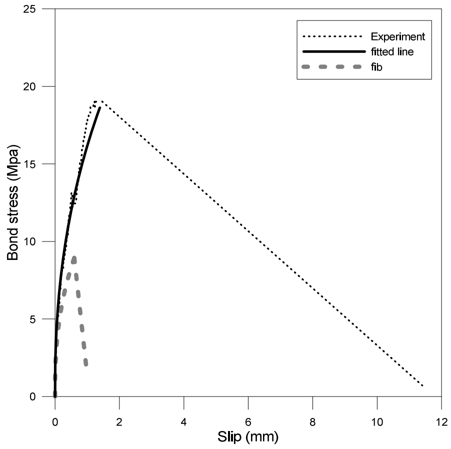
The slips are the average values of relative slips between concrete and reinforcing bars measured by two LVDT's attached front and back of specimens. The axial loads were measured using load cell of UTM system and converted to stress by (1).

A non-linear regression analysis was performed to obtain bond-slip relations for typical geopolymer concrete specimens with maximum bond stress, τ_{max}, and slip at failure, τ_f for various bar diameters. The average values were used for each bar diameter and summarized in Table III.

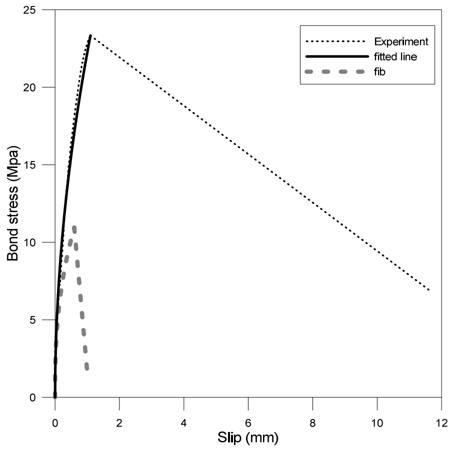
TABLE III
SUMMARY BOND-SLIP CURVES

Reinforcements	Max. Bond Stress (MPa)	Slip at Failure(mm)	α
D10	19.03	1.46	0.43
D16	23.33	1.10	0.51
D25	19.09	2.10	0.78

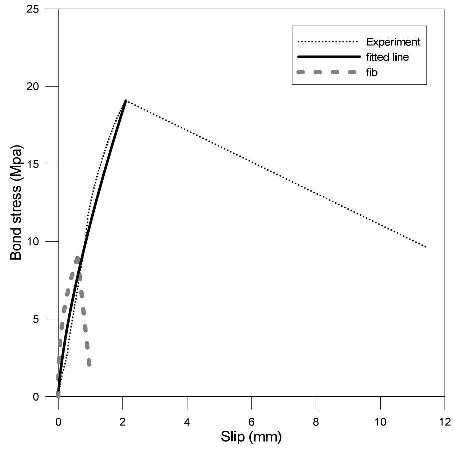
The derived equations for each bar diameter are shown in Fig. 6.



(a) D10



(b) D16



(c) D25

Fig. 4 Bond-slip models for geopolymer concrete

The solid lines are fitted line with parameters in Table III and dotted lines are smoothed experimental results and dashed-grey lines are fib model equations for normal concrete. The descending parts are drawn as linear lines with slopes in fib model. Because the bond capacity of geopolymer concrete is much higher than that of normal concrete as shown in Fig. 3, the bond-slip model of geopolymer concrete gives higher bond stress and slip. The accumulation of experimental data may refine the bond-slip models for geopolymer concrte.

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