10th International Conference on Composite Science and Technology
ICCST/10
A.L. Araújo, J.R. Correia, C.M. Mota Soares, et al. (Editors)

BOND PROPERTIES OF GLASS FIBRE REINFORCED POLYMER BARS WITH FLY-ASH BASED GEOPOLYMER CONCRETE

Biruk Hailu Tekle1*, Amar Khennane[†], Obada Kayali[††]

*PhD student
School of Engineering and Information Technology, Univ. of New South Wales, Canberra
biruk.tekle@student.adfa.edu.au

[†]Senior Lecturer
School of Engineering and Information Technology, Univ. of New South Wales, Canberra
a.khennane@adfa.edu.au

[††]Associate Professor
School of Engineering and Information Technology, Univ. of New South Wales, Canberra
O.Kayali@adfa.edu.au

Key words: Geopolymer concrete, GFRP rebar, bond properties, bond slip.

Summary: *Bond behavior is an important issue in the design and performance of reinforced concrete structures. In this research the bond property between glass fibre reinforced polymer (GFRP) bars, a corrosion resistant substitute to steel bars, and fly-ash based Geopolymer Cement (GPC) concrete, a more environmental friendly alternative to Ordinary Portland Cement (OPC) concrete, is investigated. When compared to OPC concrete, fly-ash based GPC concrete has a different micro structures and hydration process, which may affect its bond performance. A total of 18 pull-out specimens containing 16 mm GFRP rebar embedded in GPC and OPC concrete cylinders with 100 mm diameter and 170 mm height were prepared. Embedment lengths of three, six, and nine times the rebar diameter were taken as the main test variables. For each specimen, the test results include the bond failure mode, the average bond strength, the slip at the loaded and free end and the bond–slip relationship curves. With these test results, the performance of GFRP in GPC and OPC concretes are compared. Furthermore, the effect of embedment length on bond strength of GPC and OPC concrete is carefully investigated. The average bond strength values revealed the higher bond performance of GFRP bars in GPC concrete.*

1 INTRODUCTION

Corrosion of steel reinforcement in different structural members results in a premature deterioration and failure of the structure. This especially happens when the reinforced concrete structure is exposed to aggressive environments such as those encountered in coastal areas, chemical plants, or involving de-icing salts. So far, methods such as concrete additives, galvanization and epoxy coating of the reinforcing steel, and the use of cathodic protection systems have been applied. However, corrosion issues are yet to be completely eliminated. Fibre reinforced polymer (FRP) composites and geopolymer concrete currently stand out as ideal replacements for steel and OPC concrete respectively. FRP is mainly based on thermoset polymers vinyl ester and glass (GFRP) or carbon fibers (CFRP) and are characterized by high tensile strength, high durability, light weight, and electromagnetic permeability [1]. Geopolymer binders are commonly produced using alkali liquids (usually a soluble metal hydroxide and/or alkali silicate) to react with silica (SiO_2) and alumina (Al_2O_3) rich natural materials, like metakaolin or with industrial by-products, such as Fly Ash (FA), Silica Fume (SF), Rice Husk Ash (RHA) or Slag [2].

The composite action of reinforced concrete structure is maintained by load transfer between the concrete and the reinforcement bar. This load transfer is referred to as bond and is mainly provided by the adhesion between the bar and the concrete, frictional forces at the interface and bearing on the ribs of the deformed bar [3]. Various studies have been carried out on steel reinforced OPC concrete, steel reinforced GPC, and GFRP reinforced OPC concrete to better understand their bond performance [4, 5, 6, 7, 8, 9]. However, to the knowledge of the authors, the bond property of GFRP reinforced GPC concrete is still to be studied. Due to the difference in the properties of the constituent materials i.e. GFRP and GPC, the bond behavior of these materials may be completely different from that of steel and OPC, hence the need for this research. The aim of this research therefore is to compare the bond performance of GFRP in GPC and OPC concretes, to understand the bond mechanism in GFRP reinforced GPC, to study the effect of bar embedment length in such concrete, and to determine its bond-slip relationship.

2 MATERIAL PROPERTIES

2.1 GFRP

The GFRP rebars used in this study were supplied by Pultral Inc., a Canadian company which specializes in the manufacturing of parts made of composite materials. Sand coated GFRP rebars with a nominal diameter of 16 mm are used. The bars are reinforced by continuous E-glass fibers with a minimum volume of 65 percent while the binding material is modified vinyl ester with a maximum volume of 35 percent. The manufacturer specifications for the mechanical and physical properties of the rebar are summarized in Table 1.

Property	Manufacturer
Tensile strength (MPa)	1184 (Nominal)
Elastic modulus in tension (GPa)	62.6±2.5(Nominal)
Tensile strain at failure (%)	1.89
Poisson’s ratio	0.25
Coefficient of longitudinal thermal expansion (/^{o}C)	6.2×e-6
Coefficient of transverse thermal expansion (/^{o}C)	23.8×e-6
Weight (g/m)	558

Table 1: Mechanical and physical properties of GFRP bars

2.2 CONCRETE

As is the case with OPC concrete, the properties of the constituents in GPC also affect its property. The properties of aggregates used are summarized in Table 2. The sieve analysis of fine and coarse aggregates is as shown in Fig. 1.

Material	Specific Gravity	Absorption (%)
14 mm Coarse Agg.	2.7	0.7
10 mm Coarse Agg.	2.67	0.7
7 mm Coarse Agg.	2.65	1.3
Fine Agg.	2.6	1.2

Table 2: Physical properties of coarse and fine aggregates

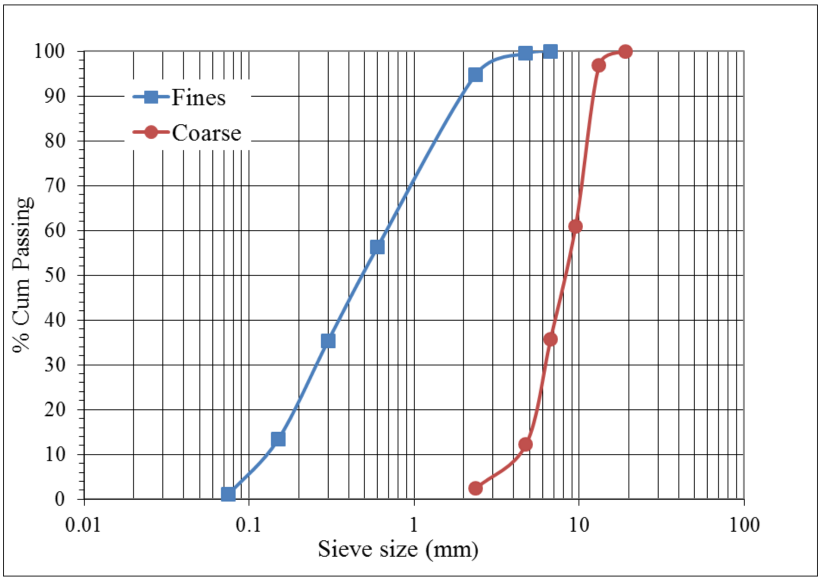

Figure 1: Particle size distribution for fine and coarse aggregate

A general purpose cement and class F fly ash were used. The laboratory grade D sodium silicate solution with SiO_2/Na_2O between 1.95 and 2.05 from IMCD Australia Limited and 98 % caustic soda flakes from Redox Pyt Ltd, Australia, were used.

The mix proportions of the GPC and OPC concrete adopted from [10] are given in Table 3.

Ingredient	OPC	GPC
Cement (kg/m^3)	357	-
Fly Ash (kg/m^3)	-	420
Coarse aggregate[a] (kg/m^3)	944	1090
Fine Aggregate (kg/m^3)	814	630
12M NaOH (kg/m^3)	-	60
Na_2SiO_3 (kg/m^3)	-	150
Water (kg/m^3)	225	31
SP (kg/m^3)	-	4
VM (kg/m^3)	-	4
Density (kg/m^3)	2320	2240
Compressive strength (MPa)	42.04	49.33
Elastic modulus (GPa)	29.24	20.37
Indirect Tensile strength (MPa)	3.88	4.61

[a]Maximumaggregatesizeof 14 mm

Table 3 : Mix proportions and properties of concrete

3 SPECIMEN PREPARATION AND TEST SETUP

Pull out tests with GFRP rebars embedded in a 100 × 170 mm concrete cylinder were used. The embedment lengths were three, six and nine times the rebar diameter. All the rebars were 1000 mm long with a special anchorage on one end to avoid premature failure of the GFRP bars due to the grip. To achieve the desired embedment length, contact between the concrete and the rebar was broken using PVC (polyvinyl chloride) tubing as shown in Fig. 2. Three nominally identical specimens were tested for each embedment length. The GPC specimens were then allowed to rest for 24 hours after which they were placed to cure in an oven for 3 days at 80^{o}C. The specimens were de-moulded and placed in a temperature and humidity chamber (23^{o}C and 50%RH) until the time of testing. They were tested at 7 days after casting. The OPC specimens on the other hand were stored in a fog room until the test day which was done at 28 days.

Fig.2. Moulds and GFRP bars with special anchor before assembly (left) and Setup of pull-out test (right)

Fig.2. also shows the setup of the experiment. A small frame was set up on the universal testing machine to hold the pull out specimens. The load was applied to the reinforcement bar in displacement control at a rate of 1 mm/min. The slips of the rebar relative to concrete at the loaded end and at the free end were measured with four linear variable displacement transducers (LVDT), two at each end. Forces and displacements were recorded using an automatic data acquisition system.

4 TEST RESULTS AND DISCUSSION

Table 4 and 5 shows the experimental result for OPC and GPC concretes respectively. The specimens are identified by the type of concrete used (OPC or GPC), the embedment length as a multiple of rebar diameter (3d_b, 6d_b and 9d_b) and the specimen number. Using the assumption that the bond strength is proportional to the square root of the compressive strength [11, 12], the bond stresses were normalised to a concrete compressive strength of 45 MPa to account for the strength difference between the two concretes.

Specimen	Compressive strength f'_c (MPa)	Splitting load T (MPa)	Load P_{max} (kN)	Average bond stress τ (MPa)	Free end slip (mm)	Loaded end slip (mm)	Adjusted loaded end slip(mm)	Modified bond stress (MPa)	Failure mode
OPC-3d-1	42.04	3.88	42.13	17.47	0.41	1.06	0.57	17.04	P
OPC-3d-2			40.59	16.83	0.24	0.98	0.50	16.42	P
OPC-3d-3			31.19	12.93	0.24	0.65	0.29	12.61	P
OPC-6d-1	42.04	3.88	74.60	15.47	0.22	1.30	0.58	15.13	S
OPC-6d-2			66.02	13.69	0.27	1.20	0.56	13.22	S
OPC-6d-3			63.90	13.24	0.43	-	-	12.91	S
OPC-9d-1	42.04	3.88	89.24	12.33	0.18	1.50	0.81	12.03	S
OPC-9d-2			70.61	9.76	0.04	1.11	0.56	9.52	S
OPC-9d-3			92.53	12.79	0.29	1.61	0.90	12.48	S

P=Pull out failure
S=Splitting failure

Table 4 : Bond test results for OPC concrete

Specimen	Compressive strength f'_c (MPa)	Splitting load T (MPa)	Load P_{max} (kN)	Average bond stress τ (MPa)	Free end slip (mm)	Loaded end slip (mm)	Adjusted loaded end slip(mm)	Modified bond stress (MPa)	Failure mode
GPC-3d-1	49.33	4.61	45.82	19.00	0.24	0.91	0.37	18.15	P
GPC-3d-2			43.32	17.96	0.37	0.99	0.49	17.15	P
GPC-3d-3			47.20	19.57	0.35	1.08	0.53	18.69	P
GPC-6d-1	49.33	4.61	89.11	18.48	0.29	1.59	0.73	17.65	S
GPC-6d-2			76.70	15.90	0.14	1.32	0.58	15.19	S
GPC-6d-3			90.75	18.81	0.18	1.52	0.65	17.96	S
GPC-9d-1	49.33	4.61	121.90	16.85	0.06	1.64	0.73	16.09	S
GPC-9d-2			93.67	12.95	0.05	1.42	0.70	12.37	S
GPC-9d-3			109.92	15.19	0.07	1.71	0.86	14.51	S

P=Pull out failure
S=Splitting failure

Table 5 : Bond test results for GPC concrete

4.1 Bond failure mode

As can be seen in Tables 4 and 5, both pull out and splitting types of failure were observed in the specimens. Pull out failure occurs when adequate amount of confinement is provided by the concrete. Besides, a relatively small embedment length and a small bar diameter also lead to this type of failure. Failure occurs when the shear strength of the bond between the concrete and the reinforcement is exceeded. This failure was observed for both OPC and GPC with $3d_b$ embedment length. When the embedment length is increased to $6d_b$ and $9d_b$, the failure mode changed to splitting. In this case the confinement provided by the concrete is not enough to support the splitting stress.

4.2 Average bond strength

Assuming uniform bond strength distribution along the embedment length, the average bond strength is defined as the shear force per unit surface area of the rebar. The average bond stress calculated from the peak pull out load is taken as the ultimate bond strength for the two materials [11, 13]. This definition of average bond strength is followed throughout the paper, and it is calculated as

$$\boldsymbol{\tau = \frac{P}{\pi d_b l_b}} \qquad (1)$$

where, τ is average bond strength in MPa; P is applied pull out load in N; d_b is diameter of the rebar in mm; and l_b is bonded/embedded length in mm.

4.3 Slip at the loaded end

The LVDT at the loaded end measures both the slip and elongation of the rebar. The low elastic modulus of GFRP bars calls for consideration of the elongation of the bar. Therefore, the loaded end slip should be adjusted by deducting the displacement due to the elongation of the loaded end rebar outside the bonded region; this will give the reading of the LVDT when placed at the actual loaded end of the embedment length. For this, the length between the point of attachment of the LVDT and the actual loaded end of the embedment length was measured, and its elongation calculated.

$$\boldsymbol{\delta_l = \delta_m - \delta_e} \qquad (2)$$

$$\boldsymbol{\delta_e = \frac{Pl}{A_b E_b}} \qquad (3)$$

where, $\delta_l$is the adjusted slip at the actual loaded end in mm; δ_m is the measured slip in mm; δ_e is the slip correction due to elongation in mm; P is the pull-out load in N; l is the length between the actual loaded end and the point of attachment of the LVDTs; E_b is the modulus of elasticity of GFRP in MPa; and A_b is the nominal cross-sectional area of GFRP in mm^2.

4.4 Bond–slip relationship curves

A typical average bond stress-slip relationship of some of the specimens is shown in Fig. 3 and 4 for both GPC and OPC. The bond-slip curve starts with a steep initial slope and has small free and loaded end slip in this range. Once the failure occurred, in case of $3d_b$ specimens, softening of the bond stress follows. This is accompanied by a large slip at both free and loaded ends. Most importantly, however, is the higher bond strength displayed by GPC as compared to OPC concrete that can also noticed on the Figures.

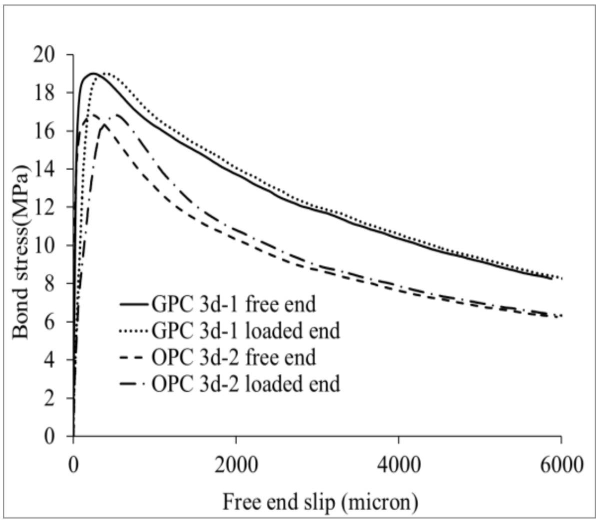

Fig.3._Typical bond stress-slip curve for GPC 3d and OPC 3d_

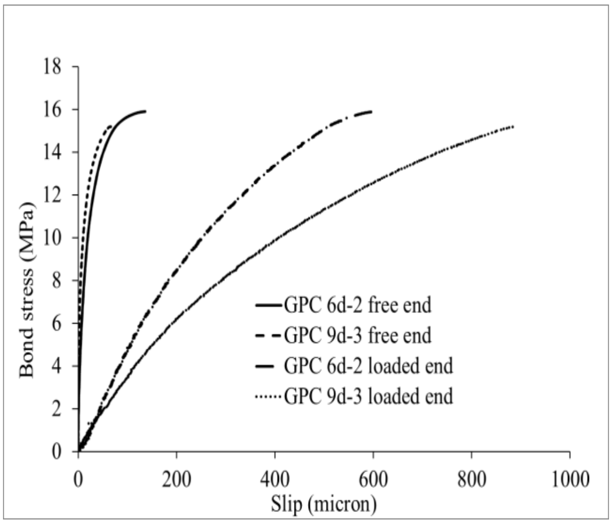

Fig.4. _Typical bond stress-slip curve for GPC6d and GPC 9d_

The main contribution for the bond in straight bars comes from adhesion and friction between the rebar and the concrete [11, 12, 14], and this appears to be better in the case of GPC. This is due to the improvement of chemical bond between the GPC concrete and the GFRP rebar [14]. Furthermore sand coating improves the friction coefficient between the two materials. Once the peak bond stress is reached, for pull out failure mode, friction reduces as pull out continues. In case of splitting failure, as can be seen in Fig. 4, the bond-slip curves don't have a softening branch because of the brittle nature of the failure. In this case, the confinement provided by the concrete was not enough to result in a pull out failure. As a result of this, the concrete failed before the bond attains its maximum bond value unlike the $3d_b$ specimens.

4.5 Effect of embedment length

Larger embedment length resulted in a higher loaded end displacement for both OPC and GPC. The higher failure load as the embedment length increases coupled with the lower elastic modulus of GFRP bars caused elongation of the bar and thus increment of the loaded end displacement as the embedment length increases.

The general trend of the test results also indicates that the longer the embedment length, the smaller the value of the apparent average bond strength. The splitting failure of the longer embedment length specimens, which causes the sample to fail before the full bond strength is developed, coupled with the non-linear distribution of bond along the embedment length is believed to cause this lower bond strength values. Various researches on GFRP reinforced OPC concretes also suggest the non-linear distribution of bond along the embedment length to be the possible explanation for the lower average bond strength [11, 14, 15, 16]. This phenomenon is also observed in steel bars [17].

5 CONCLUSIONS

In this research the bond properties between sand coated GFRP bars and fly-ash based GPC concrete were investigated. The results of this study can be summarized as follows:

1. The bond performance of GPC is better than that of OPC concrete. This is shown by the higher failure loads and bond strengths of GFRP reinforced GPC specimens for all embedment lengths.
2. Pull out loads increase with increasing embedment length, but the average bond strength decreases due to the splitting failure mode because of the nonlinear distribution of the bond along the embedment length.
3. The failure mode is dependent on the embedment length. Lower embedment lengths result in pull out failure, whereas longer embedment lengths showed splitting failure. In the pull out failure, the crushing of the concrete interface between the concrete and the rebar was suggested to be the main cause of failure in both GPC and OPC concrete, whereas the splitting failure is caused by the radial stress generated by the bond. Furthermore, GPC's splitting failure was found to be more brittle than that of OPC concrete.

REFERENCES

[1]. Focacci F, Nanni A, Bakis CE, *Local bond-slip relationship for FRP reinforcement in concrete*. Journal of Composites for Construction,4(1), 24-31,2000
[2]. Hardjito D, Rangan BV, *Development and properties of low calcium fly ash-based geopolymer concrete*. Research Report GC 1, Curtin University of Technology, Perth, Australia, 2005
[3]. Sarker PK, *Bond strength of reinforcing steel embedded in fly ash-based geopolymer concrete*. Materials and Structures, 44(5), 1021-1030,2011
[4]. Tepfers R. *Cracking of concrete cover along anchored deformed reinforcing bars*. Magazine of Concrete Research, 31, 3-12,1979
[5]. Eligehausen R, Popov EP, Bertero VV, *Local bond stress-slip relationships of deformed bars under generalized excitations: experimental results and analytical model*. University of California, Earthquake Engineering Research Centre, Berkeley, 1983.
[6]. Malvar LJ, *Bond of reinforcement under controlled confinement*. ACI Materials Journal,89(6), 593-601,1992
[7]. Chang EH, Sarker P, Lloyd N, Rangan BV, *Bond behaviour of reinforced fly ash-based geopolymer concrete beams*. Concrete solutions, The 24th Biennial Conference of the Concrete Institute of Australia, Sydney, 17-19 September 2009.
[8]. Cui Y, Kayali O, *Bond performance of steel bar and fly ash based geopolymer concrete*. Understanding concrete, Concrete Institute of Australia Biennial National Conference, Gold Coast, 16-18 October 2013.
[9]. Sofi M, van Deventer JSJ, Mendis PA, Lukey GC, *Bond performance of reinforcing bars in inorganic polymer concrete (IPC)*. Journal of Material Science, 42(9), 3107-3116, 2007
[10]. Cui Y, *Experimental study and finite element simulation of bond behaviour between reinforcing steel bars and fly-ash based geopolymer concrete*. Undergoing PhD thesis, The University of New South Wales, 2015
[11]. Okelo R, Yuan R, *Bond strength of fiberreinforced polymer rebars in normal strength concrete*. Journal of Cmposites for Construction, 9(3), 203–213, 2005
[12]. Sooriyaarachchi H, *Tension stiffening effect in GFRP reinforced concrete elements*. PhD Thesis, The University of Sheffield, July 2006.
[13]. Hao Q, Wang Y, He Z, Ou J. *Bond strength of glass fiber reinforced polymer ribbed rebars in normal strength concrete*. Construction and Build Materials, 23, 865-871, 2009;
[14]. Cosezna E, Manfredi G, Realfonzo R, *Behaviour and modellng of bond of FRP rebars to concrete*. Journal of Composites for Construction, 1(2), 40-51, 1997
[15]. Lee YH, Kim MS, Kim H, Lee J, Kim D. *Experimental study on bond strength of fiber reinforced polymer rebars in normal strength concrete*. Journal of Adhesion Science and Technology, 27, 508-522, 2013
[16]. Tighiouart B, Benmokrane B, Gao D, *Investigation of bond in concrete member with fiber reinforced polymer (FRP) bars*. Construction and build materials, 12, 453-462, 1998
[17]. Larralde J, Silva-Rodriguez R, *Bond and slip of FRP rebars in concrete*. Journal of Materials in Civil Engineering, 5(1), 30-40, 1993