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An Investigation of Bond Strength of Reinforcing Bars in Fly Ash and GGBS Based Geopolymer Concrete

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Abstract. Geopolymers are amorphous aluminosilicate materials. Geopolymers are binders formed by alkali activation of Geopolymer Source Materials (GSM) using an alkaline activator solution. Concretes made using Geopolymer binders are excellent alternative to the Ordinary Portland Cement concretes from strength, durability, and ecological considerations. Especially, usage of industrial waste materials such as Fly Ash and Slags as GSMs considerably lower the carbon footprint of concrete and mitigate the damage due to the unscientific dumping/disposal of these materials. To use the Geopolymer concrete (GPC) for reinforced structural members, the composite action of reinforcing bars with Geopolymer concrete i.e. the bond behaviour should be well understood. This paper describes the bond behaviour of 12mm and 16mm dia. bars embedded in Fly ash and GGBS based Geopolymer concrete and conventional Portland Pozzolana cement concrete specimens investigated using the pull-out tests as per Indian Standard Code IS:2770(Part-I); the bond stresses and corresponding slips were found out. The bond stress increased with increase in compressive strength. The peak bond stress was found to be 4.3 times more than the design bond stress as per IS:456-2000. The Geopolymer concretes possess higher bond strength compared to the conventional cement concretes.

1 Introduction

Creating structures of modern world is quite impossible without concrete. Huge structures are constructed using cement concrete, which leads to the heavy usage of Portland cement. Concrete is the second most consumed substance on earth after water. Therefore, any improvement in concrete technology would influence the economy and ecology of the world over. The Portland cement, an important component of concrete, accounts for nearly 7% of the world's CO_2 emission [1], needed mining, manufacturing process, plant and machinery and transportation etc. The production of concrete involves utilization of billion

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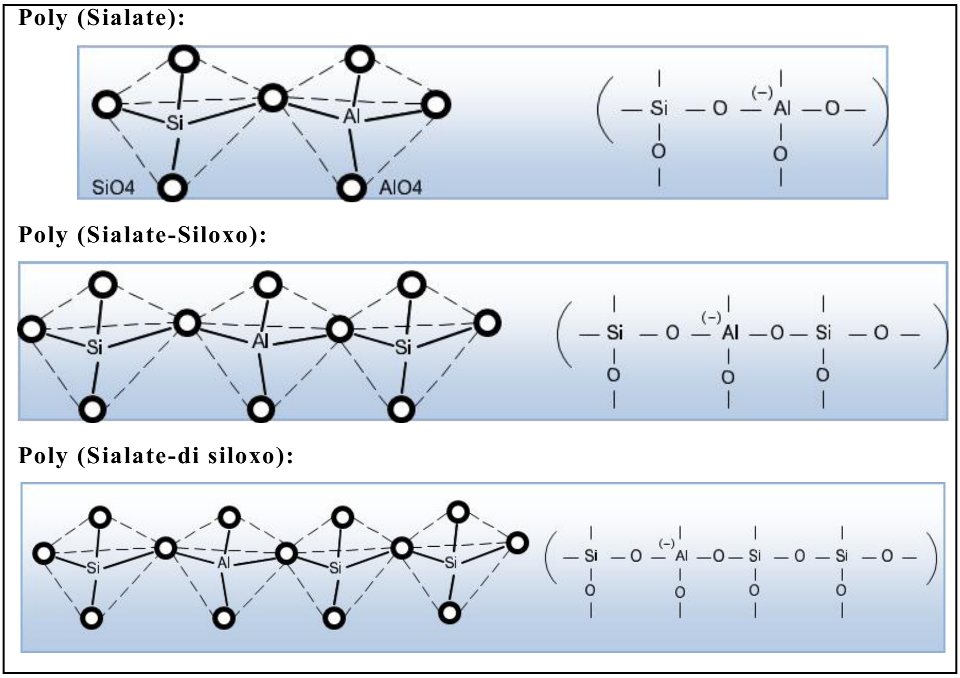
tons of natural resource materials such as lime stone, shale, clay, etc., which are actually non-renewable. Also the environment must be protected by preventing the unscientific dumping of industrial waste materials [2] such as Fly Ash (FA), Slags, Red mud etc., and in this regard, it is seen that the R&D efforts all over the world confirm that these materials have potential for converting them into binder for producing concrete. This way, the harmful environmental hazards due to these materials can be eliminated. In respect of the above environmental concerns, the Geopolymer based concretes, with much lower carbon footprint compared to that with Portland cement, show considerable promise for application in the construction industry [3].

Geopolymer concrete (GPC) utilizes Fly Ash and Blast Furnace Slag powder (generally known as GGBS), which are abundantly available as industrial waste materials as a result of the burning of coals (in Thermal Power Plants) and making of iron and steel (in Steel plants). These industrial by-products are good candidate materials [4] for creating eco-friendly binder called as geopolymers to function as cement in concretes. When compared to Ordinary Portland Cement concretes, higher compressive and tensile strengths can be achieved in GPCs which also have very low shrinkage and creep, besides being resistant to aggressive chemicals, acids, sulphates and corrosive chloride and salt water.

For the practical application of geopolymer concrete in structural members, the effectiveness of bond between the reinforcing bars and the geopolymer concrete should be established. In Reinforced concrete members, steel reinforcement receives its share of loads only from the surrounding concrete [5]. Therefore, the bond stress between concrete and steel must be ensured under various loads such as tension, compression, flexure etc., The bond action is mainly due to adhesive force of steel bar with the surrounding concrete and the mechanical interlocking of ribs on the deformed bars. This paper presents the experimental findings of bond strength obtained from pull-out test on reinforcing bars embedded in geopolymer concrete and Portland pozzolana cement concrete specimens. The bond stress versus various slip values for 12mm and 16mm diameter bars were studied and compared with geopolymer concrete and Portland pozzolana cement concrete specimens.

2 Geopolymers

In general, geopolymers are amorphous alumino silicate binder materials formed by alkali activation of silica and alumina containing powdery materials. The term ‘geopolymer’ was introduced in 1970’s by French Scientist and Engineer Joseph Davidovits. The defining characteristics of a geopolymer is that the binding phase comprises an alkali alumino silicate gel, with Aluminium and silicon linked in a three dimensional tetrahedral gel frame work as described by sialate nomenclature of Aluminosilicate structure as represented in Fig. 1[1];



Poly (Sialate):

Poly (Sialate-Siloxo):

Poly (Sialate-di siloxo):

Fig. 1. Alumino Silicate Structure [1].

An alkaline liquid (NaOH or KOH) used to react with Silicon (Si) and Aluminium (Al) in a source material such as metakaolin, Fly Ash or Slags to produce gel binders. During the process of formation of geopolymer binder gel, alumino silicate materials are dissolved in alkali solution to form free SiO4 and AlO4 tetrahedral units and these units are linked alternatively. The source materials can be of geological origin i.e. naturally occurring clays are also used for geopolymerisation. Major efforts are being made worldwide to use waste materials such as fly ash, slags, red mud etc., instead of naturally occurring materials from resource conservation point of view.

2.1 Production of geopolymer concrete

The main difference between the geopolymer concrete and cement concrete is the geopolymer binder gel instead of cement paste. The geopolymer binder binds the coarse aggregate (stone jelly) and fine aggregate (sand) together to form the geopolymer concrete. Conventional methods used in the manufacture of cement concrete can also be utilized for geopolymer concrete. The alkaline liquid mixed with superplasticiser and the extra water if any, is added to the dry materials and mixed well. The fresh concrete could be handled up to 120 minutes without any setting and degradation. After moulding, the concrete can be heat cured or steam cured at 60°C for 24 hours [2]. Low calcium fly ash based geopolymer concrete can be cured in ambient condition with the addition of ground granulated blast furnace slag (GGBS) to reduce the energy needed in case of heat curing.

2.2 Properties of Geopolymer Concrete

Geopolymer concrete undergoes less creep, low shrinkage, sulphate resistance, corrosion resistance, acid resistance [4], fire resistance and no alkali-aggregate reaction. Experimental studies [6] have shown that the aggregate-binder interfaces are strong in geopolymer concretes than in the case of cement concretes. The stronger interface leads to superior mechanical properties.

Experimental investigations show that the geopolymer concrete can be well adopted for reinforced concrete structural members [3,5,7,8]. The behaviour of geopolymer concrete members such as columns and beams are similar to the reinforced concrete members. The basic assumption of reinforced concrete design of the structural members is the good composite action between the reinforcing bars and the surrounding concrete. Therefore, it is very important to study the bond behaviour of reinforcing bars. This paper presents some experimental investigations by conducting pull-out test of reinforcing bars embedded in geopolymer concrete (GPC) specimens and Portland pozzolana cement concrete (PPCC) specimens.

3 Bond strength

The mechanics of bond stresses ensure the reinforcement is solidly anchored to the surrounding concrete. Analysis and design of the reinforced concrete composite members are based on the assumption that no slippage will occur in the interface of steel and concrete. Bond stress is the shear stress at the reinforcing bar – concrete interface which by transferring load between the reinforcing bar and the surrounding concrete, modifies the steel stresses. This bond stress enables the two materials to form a composite member. The efficiency of a reinforced concrete structural member is based on the adequate composite action between the steel and concrete.

3.1 Bond stress distributions

Bond stress in reinforced concrete member arises due to two distinct situations:
1. The Anchorage bond of bars in tension or compression.
2. The Flexural bond of bars in flexural members.

3.2 Anchorage bond

The generation of bond stress is idealized as shown in Fig. 2:

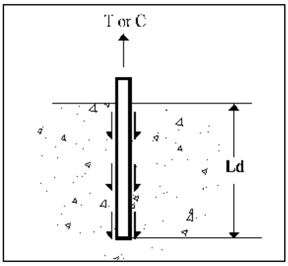


Fig. 2. Bar Anchorage.

A reinforcing bar must extend a length L_d beyond any section at which it is required to develop its full yield strength so that sufficient bond resistance is mobilized. Let τ_{ba} is the uniform bond stress along the anchorage length L_d in tension or compression,

$$\pi/4 \text{ x } d^2 x f_s = \tau_{ba} x \; \pi d \text{ x } L_d$$
$$L_d = (d\ f_s) / (4\tau_{ba}) \quad (1)$$

where f_s=stress in steel; d=bar diameter.

3.3 Flexural Bond Stress

The magnitudes of bond stresses along the reinforcing bars are a function of the rate of change of tensile force in the reinforcing bars from section to section in flexural members. Change in the bending moment and the development of tension cracks cause the tensile force in the reinforcing bar to vary and induce variable bond stresses.

In flexural members, in regions, where the bending moment changes rapidly and the shear is consequently high, the tensile force in reinforcing bar necessarily under goes significant change in a short distance Δx as shown in Fig. 3, therefore large bond stresses called flexural bond stresses are required to equilibrate the difference in tension ΔT between the sections. This increased ΔT is capable of being transferred to the surrounding concrete without slip between the reinforcing bar and the concrete by the bond stresses between the reinforcing bar and the concrete.

Expressions for bond stresses are related to the shear, that is the measure of the rate at which the moment changes i.e. V=ΔM/Δx,

$$\sum_0 \text{ x } \Delta x \text{ x } \tau_{bf} = \Delta T = \Delta M / jd$$
$$\tau_{bf} = V/\sum_0 jd \quad (2)$$

where τ_{bf} = Flexural bond stress
$\sum_0$ = Surface area of a bar
jd = Internal lever arm

This paper deals with the anchorage type bond test in the form of pull out and comparison of mixes using this test is likely to be valid for flexural bond also.

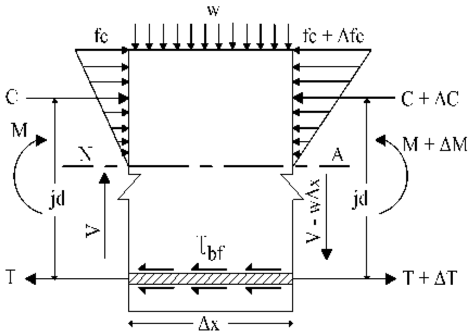


Fig. 3. Flexural Bond Stresses created by a Moment Gradient.

4 Investigation

The aim of this paper is to present some experimental findings on bond strength of embedded reinforcing bars of 12mm and 16mm dia. into geopolymer concrete cubes of 150x150x150mm size and compared with similar size cubes with Portland pozzolana Cement Concrete (PPCC). The effect of compressive strength of concretes on the bond stresses and the bond-slip relations were studied. The relation between slip and bond stresses were plotted and ultimate bond strength was found. The method of testing was carried out according to the Indian Standard Code IS: 2770(Part-I)-1997 [9].

4.1 Materials

Fly Ash and GGBS based geopolymer concrete mixes were used to make test specimens. The mixes were referred as GPC25g, with 25% GGBS and 75% FA and as GPC50g, with 50% GGBS and 50% FA contents. The Alkali Activator Solution (AAS) was prepared with the %Na_2O, %SiO_2& %H_2O for the mix GPC50g were 5.91%, 3.63% and 45.46% respectively and these values for mix GPC25g were 7.53%, 4.62% and 57.86% respectively. Typical PPCC mixes with 28% FA contents referred as PPCC35 and PPCC45 with W/C ratios 0.35 and 0.45 respectively were used to make test specimens for comparative study. The compressive strength levels of GPC and PPCC mixes are within the range of 2 to 7%. The GPC and PPCC mix proportions and details are summarized in Table 1&2.

Table 1. GPC Mix Proportion.

GPC Mix	**GPC50g**		**GPC25g**	
AAS / GSM	0.55		0.7	
	Wt Proportion	Content [Kg/m^3]	Wt Proportion	Content [Kg/m^3]
Fly Ash	0.5	212	0.75	308
GGBS	0.5	212	0.25	103
Sand	1.5	635	1.5	616
Coarse Aggregate	2.5	1059	2.5	1026
Density [kg/m^3]	2350		2340	
28day Strength [MPa]	55		45	

Table 2. PPCC Mix Proportion.

Mix ID	**PPCC35**		**PPCC45**	
W/C ratio	0.35		0.45	
	Wt Proportion	Content [kg/m^3]	Wt Proportion	Content [Kg/m^3]
Fly Ash	0.28	111	0.28	94
OPC	0.72	287	0.72	242
Sand	2.0	796	2.5	839
Coarse Aggregate	2.7	1075	3.2	1074
Density [kg/m^3]	2412		2402	
28day Strength [MPa]	56		41	

4.2 Specimens

The testing of bond in geopolymer concrete was carried out as per Indian standard Codal provision IS 2770(Part-I)-1997 [9]. Test specimens of 150x150x150 mm cubes with 12mm and 16mm dia. deformed bars conforming to IS 1786 with characteristic yield strength of 415MPa (Fig. 4). For each mix, three specimens for bond study and three 100x100x100 mm cubes for obtaining compressive strength were cast. The reinforcing bar was embedded vertically along the centre in each of cube specimen, and projected down by about 10 mm from the bottom face of the cube, and projected 650 mm upwards from the top surface of the cube for gripping the specimen while applying the load. The projecting lower end of the reinforcing bar was used to fix the dial gauge as shown in Fig. 5. The cubes were reinforced with a helix of 6 mm diameter plain mild steel reinforcing bar at 25 mm pitch. The test bar was aligned vertically at the time of compaction of the concrete. The geopolymer concrete specimens were covered with gunny clothes for 3 days to avoid loss of AAS in the mix and allowed for ambient temperature curing.

Fig. 4. Specimens after Casting.

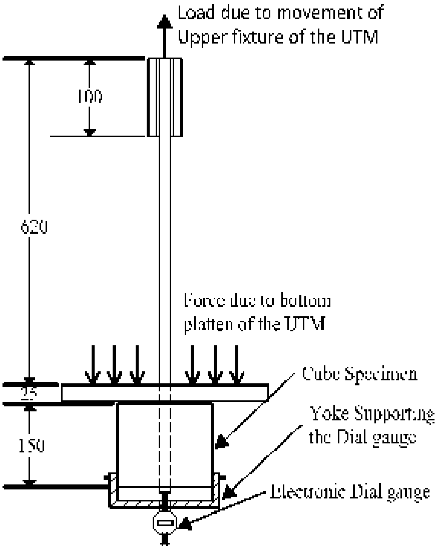


Fig. 5. Schematic Line Sketch of Test Setup.

4.3 Description of test method

The pull-out test setup shown in Fig. 6. The specimen was mounted in UTM of 40T capacity in such a manner that the bar was pulled axially from the cube. The top surface of cube was supported on plate with a hole at the centre to accommodate the reinforcing bar, which was projecting from the bearing surface. An electronic dial gauge of 0.001 mm least count was used for measuring the slip of the bar with respect to the free end of the bar.

The dial gauge was mounted on a suitable yoke, which was attached to the specimen. The pull-out action of the bar was indicated in the dial gauge

readings at different loads and loading was continued and readings were recorded until:
a) The yield point of reinforcing bar had reached.
b) The enclosing concrete failed or
c) A slip of 2.5mm occurred at the free end.

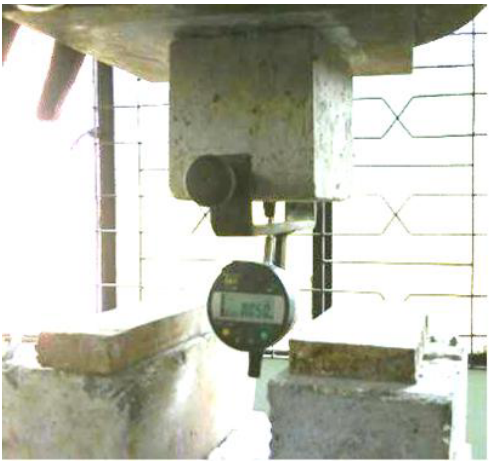


Fig. 6. Pull-out Test Setup

5 Bond test results

The average bond stress along the entire embedded length of the bar is obtained by dividing the applied load at the specified slip, by the surface area of the embedded length of bar and the expression is τbd = P / (πdl); Where τbd = Bond stress in MPa; P = load in N; d = Dia of Reinforcing bar; l = Embedded length. The mean values of bond strengths on minimum of three specimens are used. The bond slip relationships for the concretes are shown in Table 3.

Table 3. Test Data on slip vs Bond Stresses.

	GPC		**PPCC**	
	GPC50g	**GPC25g**	**PPCC35**	**PPCC45**
AAS/GSM ratio (or) W/C for PPCC	0.55	0.7	0.35	0.45
28 days compressive strength, fc [MPa]	55	45	56	41
Slip value in mm	Test on 12mm dia deformed bar Bond stress value in MPa			
0.025	7.1	6.9	6.7	5.7
0.25	10.2	10.1	9.8	8.4
1.25	12.4	12.3	11.9	10.2
1.5	13.5	13.2	12.2	10.4
2.0	12.6	12.5	10.5	9.2
2.5	10.5	10.3	8.4	7.2
τ in IS 456:2000 0.45xSQRT(fc)	3.3	3.0	3.3	2.9
τ(Peak) / τ(IS 456)	4.1	4.4	3.6	3.6

Slip value in mm	Test on 16mm dia deformed bar Bond stress value in MPa			
0.025	7.3	7.4	7.4	6.3
0.25	10.7	10.8	10.9	9.3
1.25	12.8	13.1	13.2	11.2
1.5	13.8	14.2	13.5	11.5
2.0	13.1	13.2	11.6	10.0
2.5	10.8	11.0	9.4	8.0
τ in IS 456:2000 0.45xSQRT(fc)	3.3	3.0	3.3	2.9
τ(Peak) / τ (IS 456)	4.2	4.7	4.0	4.0

6 Conclusion

From the test data, the following observations (Fig. 7 to 10) were made:

a) Increase of GGBS content increases the geopolymerisation and enhances compressive strength in GPC. In case of GPC with higher FA content, AAS/GSM ratio needs to be increased to enhance geopolymerisation and compressive strength. Bond stress increases with increase in compressive strength for both GPC and PPCC.

b) Bond stress in GPC is more than that of PPCC at similar strength levels. This can be due to the better adhesive bond of GPC with reinforcing bar.

c) The Bond stress increases marginally with bar diameter for both GPC and PPCC.

d) Peak Bond stress corresponding to slip for GPC were found to be higher than PPCC.

e) The design bond stress as per IS 456:2000 are presented in table. The peak bond stress obtained from investigation were found to be 4.3 times more than the design bond stress as per IS:456-2000 for GPC mixes and the same is 3.6 times more for PPCC mixes. Thus GPCs was found to possess higher bond strength compared to conventional Portland cement concretes.

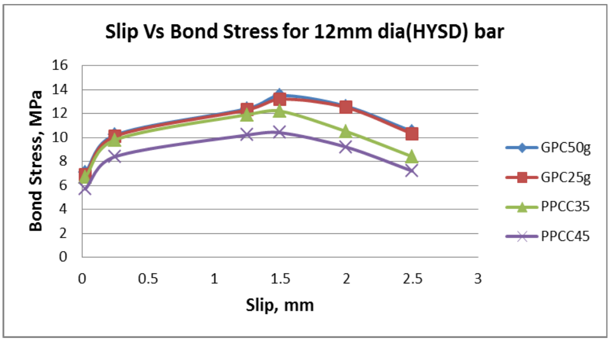


Fig. 7. Effect of Compressive strength on Bond Stress for GPC & PPCC.

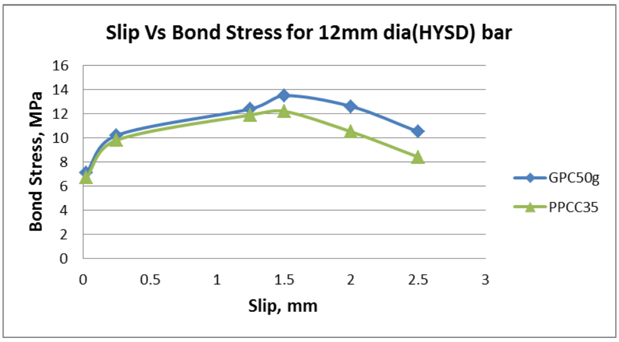


Fig. 8. Comparison of Bond strength of GPC and PPCC.

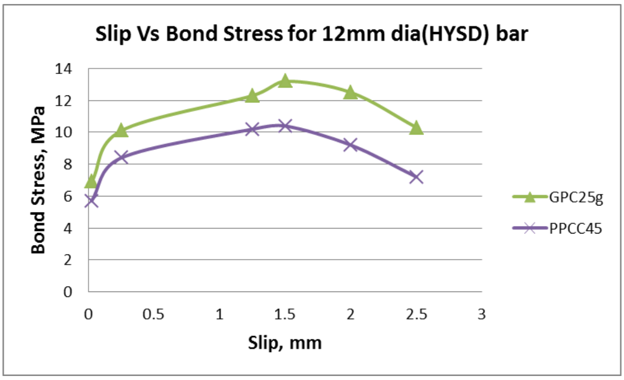


Fig. 9. Comparison of Bond strength of GPC and PPCC.

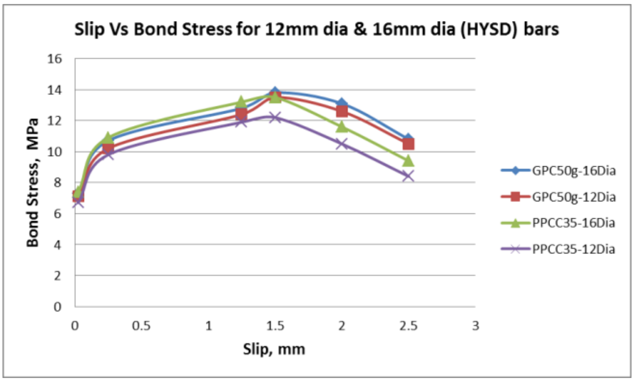


Fig. 10. Effect of bar diameter on Bond Strength for GPC & PPCC.

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