Technical report

Adhesive Bond Strength of Steel Bars Embedded in Fly Ash-GGBS-based Geopolymer Concrete

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Abstract

The bond behaviour of plain rebars embedded in ambient cured geopolymer concrete (GPC) prepared with a mix of fly ash and ground granulated blast furnace slag (4:1 by mass) was studied to evaluate the adhesive bond between these rebars and concrete. As GPC is an inorganic polymer concrete, the adhesive bond strength of concrete is evaluated for its suitability to reinforced concrete applications. Pull-out tests were conducted to measure the slip of the applied load. Diameters of the embedded bars were varied as 12, 16 and 20 mm, providing compressive strengths of 39 to 68 MPa. Chemical adhesion occurs between the bar and concrete as the bar surface is polished. We observed a gain in adhesive bond stress as bar diameter is increased. The bond stress-slip curves of GPC and ordinary Portland cement concrete were different and the peak bond stress was about 70% higher in GPC. Regression analysis showed that the adhesive bond strength in GPC is about one-fourth of the bond strength of the deformed rebars. Higher bond strength in GPC is due to chemical bonding and formation of both sodium aluminosilicate hydrate and calcium aluminosilicate hydrate gels besides the denser interface as seen from scanning electron microscopy and the ordering of silicon and aluminium as identified in MAS-NMR.

1. Introduction

In the production of the most commonly used binder, ordinary Portland cement (OPC), widely employed in infrastructure projects in India and across the world, natural materials such as limestone are used and the process involves high energy. OPC use contributes to nearly 7% of the world’s carbon dioxide (CO2) emission, which is detrimental to environment, and its production also requires consumption of natural resources, the depletion of which is not conducive to life. Among all the binders suggested as an alternative to OPC, geopolymer (GP) stands out because of its low CO2 emission and due to its preparation from industrial wastes such as fly ash and blast furnace slags (Davidovits 2011; Palomo et al. 1999; Swanepoel 2002; Hardjito 2005). In India, fly ash and ground granulated blast furnace slag (GGBS) can be easily procured as they are the by-products of thermal coal power generation and metallurgical operation, respectively, and hence geopolymers derived from these waste materials can be considered as an environmentally cleaner and energy-efficient alternative. The microstructure formation in geopolymers differs depending upon the nature of the raw materials and therefore different types of binding gels are formed. However, issues like lower compressive strength and need for elevated temperature curing for hardening the fly ash-based geopolymers were addressed by blending it with GGBS. The higher reactivity of GGBS is due to its high calcium content and very fine powdery glassy nature. In geopolymers prepared from a blend of GGBS and fly ash, the calcium aluminosilicate hydrate type gel (CASH-type gel) along with sodium aluminosilicate hydrate type gel (NASH-type gel) are formed, thereby imparting significantly advanced engineering properties to final binding systems (Yip and Van Deventor 2003). The geopolymerisation process involved in the formation of binding gel is widely discussed in the literature and geopolymer concretes (GPCs) were found to possess a higher compressive strength, lower creep, lower shrinkage and better acid and heat resistances (Wallah and Rangan 2006; Kong and Sanjayan 2010). Various studies have shown that GPCs can be used as reinforced concrete structural members (Sumajouw et al. 2007; Dattatreya et al. 2011; Rajamane 2013; Mo et al. 2016).

The structural behaviour of reinforced concrete mem-
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bers mainly depends on the bonding mechanism of reinforcing bars with the surrounding concrete matrix. Bond strength refers to the restraint on steel offered by the surrounding concrete. Adhesion, friction and mechanical interlocking action are observed to be the common mechanisms of bonding. Without the formation of this bond, the design and construction of many concrete structures would not be possible. The satisfactory performance of a reinforced concrete structural member depends on the bond strength of concrete with steel rebars, which needs to be well understood. The development of a bond between rebar and concrete is complex, depending upon the characteristics of concrete and the reinforcing bars, and their mutual interactions. Park and Paulay (1975) explained the process of the development of bond strength in deformed bar. Bond strength, in their assessment, depends upon the shear stress ($\tau_a$) developed through adhesion along the surface of the bar, bearing stresses ($f_b$) against the face of the rib and shear stresses ($\tau_c$) acting on the cylindrical concrete surface between the ribs as shown in Fig. 1.

In case of surface-smooth polished steel bars, the bond is formed due to chemical adhesive forces whereas the plain bars with factory finish derive their bond strength with concrete from both adhesion and friction. However, the deformed rebars, which are commonly used, transfer their load to surrounding concrete mainly due to physical bearing strength of their ribs. The bond strength due to bearing strength in practical deformed bars is very high as it is capable of inducing splitting and crushing actions in the surrounding concrete. But even then, chemical adhesion and friction forces assist in the initial stage of load transfer (Ferguson 1966). Lutz and Gergely (1967) explained adhesive bond as that formed before cracking and slip. Initially the steel bar adheres chemically to the concrete. This adhesion holds until slip of the bar and cracking of the surrounding concrete occur. Goto (1971) experimentally observed the sloping cracks radiating from each rib and in the separation between the bar and concrete as shown in Fig. 2. The strain on the concrete resulting from stresses tend to pull the concrete away from the bar in the vicinity of the primary cracks. When the threshold tensile strength of the adhesive bond between the bar and the mortar is then reached, the surrounding concrete separates from the bar surface.

Choi et al. (1991) reported the effects of epoxy-coating of the steel bar on its bond strength. The uncoated bars showed evidence of good adhesion to the concrete, whereas in epoxy-coated bars, there was virtually no evidence of adhesion between the bar and surrounding concrete (as the concrete in contact with the bar had a smooth glassy surface). Further, a tendency for increased crack width and crack spacing was observed. Epoxy coatings significantly reduce the bond strength of deformed bars with concrete. Research has shown the addition of polymer (latex 20% by weight of cement) to OPC concrete (OPCC) increased the bond strength of concrete with bars because of the formation of a polymer interface layer, which helps in the adhesion process (Fu and Chung 1999). These studies have shown that adhesive bond with reinforcing bar aid the initial stage of load transfer to the surrounding concrete. It is clearly visible that higher adhesion can reduce crack width and number of cracks developing around the bar. Thus the separation of concrete from bar surface is reduced, which can improve the durability of reinforced concrete.

Abrishami and Mitchell (1996) reported that bond

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![Fig. 1 Bond stresses of a deformed bar.](image1)

![Fig. 2 Formation of cracks around the deformed bar.](image2)
stress distributions are dependent on embedment length, bar size, concrete properties and the size of the specimen. de Almeida et al. (2008) analysed the bond behaviour of self-compacting and vibrated concretes. They concluded that both concrete specimens displayed a similar behaviour. Chapman and Shah (1987) reported load-slip characteristics of smooth and deformed bars with OPCC. The bars were made smooth by slowly turning them in a lathe. The load-slip curve of smooth bars suddenly rose to a peak value, and once the adhesive bond is broken, the bond stress drops off quickly. They also reported that the adhesive bond is relatively independent of the compressive strength. The test data showed the adhesive bond strength is about one-sixth of the bond strength of deformed bars. Xing et al. (2015) studied the bond behaviour of plain bars, deformed bars and plain aluminium alloy rods with OPCC. They concluded that bond transfer in the plain bar is due to adhesive force and friction arising from surface roughness of the bar. But the bond transferred by the plain aluminium alloy rod (whose surface is very smooth, thereby making frictional bond negligible) is mainly due to adhesive bond whose magnitude is about one-tenth of that of plain steel bars.

A pioneering work was carried out in early part of last century by Abrams (1913) on bond strength of polished bars with 200 mm embedment length in OPC concrete having a compressive strength of 13 MPa. He reported that adhesive bond is formed at small slip values of 0.0125 to 0.025 mm and then the bar is pulled out rapidly. The bond resistance of polished bar fully depends upon chemical adhesion. The bond-slip curve shown in Fig. 3 was experimentally obtained by Abrams (1913).

In later years, similar studies were conducted on plain bars with various surface roughness characteristics by Feldman and Bartlett (2005). The surface roughness of around 3.1 μm of polished bars were similar to that reported by Abrams. The typical load-slip curve in Fig. 4 does not feature any significant peak up to maximum load. The CEB-FIP Task Group on Bond Models (fib 2000) on plain bars confirmed that evidently the bond forces arise from both adhesion and micro interlocking (Mylrea 1948). Therefore, at lower chemical adhesive strength, a reduction in the magnitude of bond stress occurs since the transfer of loads occurs only through surface friction of the bar.

A few studies have compared the bond strength of OPCC with that of GPCs, which are also called inorganic polymer concrete (IPC) (Sofi et al. 2007). Ambient cured fly ash and GGBS-based GPCs have been the subject of several investigations (Rajamane 2013; Sarker 2011; Hu et al. 2008; Boopalan et al. 2018; Vinothini et al. 2015). Bond strengths of steel bars with GPCs that were produced from fly ash, metakaolin, rice husk ash or in combination with other aluminosilicate raw materials were comparable to those of OPCC (Cui et al. 2017; Kim and Park 2015; Castel and Foster 2015). Balcikanli et al. (2017) studied the bond and abrasion behaviour of alkali-activated concrete (AAC) by central composite design method and concluded that increasing the sodium concentration increased the compressive strength, bond strength and abrasion resistance. However, studies on GPCs in which adhesive bond strength of surface-polished smooth bar’s bond with concrete is the main focus are very scarce. Therefore, the present study aims to investigate the bonding behaviour of blended fly ash-GGBS geopolymer concrete with polished steel bars by performing pull-out tests as prescribed in Indian standards. A simple regression analysis has been carried out to predict the relationship between the adhesive component of the bond and total bond strength of deformed bars from the literature. The nature of geopolymeric network formed was also investigated using analytical techniques such as scanning electron microscopy (SEM) and nuclear magnetic resonance (NMR) spectroscopy. We aim to contribute to an understanding the adhesive bond strength of steel bars with GPC with a specific focus on structural engineering applications to determine how this adhesive bonding contributes to durability of reinforced concrete structures.

2. Significance of the study

For building reinforced concrete structures using eco-
friendly geopolymer concrete, an understanding of its bonding to the reinforcing bars is essential. The composite action between the reinforcing bar and the concrete matrix contributes to a better performance of a reinforced concrete member. The adhesive bond formed between the concrete and the bar improves the composite action and reduces cracks formed around the reinforcing bars, thereby increasing the durability of the reinforced concrete structures. The main objective of this study is to study the bond-slip behaviour and to quantify the adhesive bond strength that arises from bond due to friction and bearing component of ribs of the reinforcing deformed bars. For this purpose, specially prepared polished steel bars were used. For our study, we chose GPCs prepared using blend of fly ash and GGBS mixed in the mass ratio of 4:1 to which was added an optimally formulated mixture of sodium hydroxide and sodium silicate solution (SSS) called the alkaline activator solution (AAS). The test specimens were self-cured at ambient conditions for a duration of 7 and 28 days before conducting the pull-out tests, in which the concrete-embedded polished steel bar was pulled out of the bar containing concrete cube specimen mounted on a Universal Testing Machine (UTM).

3. Experimental programme

3.1 Materials and methods

The GPC used in this experiment was prepared using Class F fly ash from the Ennore thermal power station in Chennai, Tamil Nadu, India, and GGBS was obtained from an integrated steel plant. The chemical compositions of GPC and OPCC mixes are shown in Table 1. As presented in the table, fly ash (FA) and GGBS (ground granulated blast furnace slag) were the primary raw materials for the GPC mix. The FA was from the Ennore power station, and the GGBS was obtained from an integrated steel plant. They were mixed in a mass ratio of 4:1. The alkaline activator solution (AAS) was prepared using sodium hydroxide and sodium silicate (SSS) solutions, which were added to the FA and GGBS at a mass ratio of 0.6 and 0.4, respectively. The materials proportions for the GPC and OPCC mixes are shown in Table 2. The fresh concrete density was measured and is reported in Table 3.

Table 1 Chemical composition of fly ash and GGBS by EDXRF.

| Constituents | SiO₂ | Al₂O₃ | CaO | MgO | Fe₂O₃ | Na₂O | K₂O | P₂O₅ | SO₃ |
|--------------|------|-------|-----|-----|-------|------|-----|------|-----|
| Fly ash (mass %) | 65.10 | 21.29 | 1.39 | 0.66 | 4.61 | 0.15 | 1.18 | 0.68 | 0.51 |
| GGBS (mass %) | 34.88 | 14.88 | 37.93 | 7.12 | 1.78 | 0.015 | 0.48 | – | – |

Table 2 Chemical proportions of alkali activator solution.

| Alkaline activator solution (AAS) | Silica modulus SiO₂/Na₂O | Na₂O (mass %) | SiO₂ (mass %) | Water (mass %) |
|-----------------------------------|--------------------------|---------------|---------------|---------------|
| AAS-1                             | 0.9                      | 13.8          | 12.0          | 74.3          |
| AAS-2                             | 1.2                      | 18.3          | 21.0          | 60.8          |

Table 3 Materials mixes proportions: GPC and OPCC.

| ID | GPC-1 | GPC-2 | OPCC |
|----|-------|-------|------|
| AAS | AAS-1 | AAS-2 | –    |

| Materials | Weight proportion | Content (kg/m³) | Weight proportion | Content (kg/m³) | Weight proportion | Content (kg/m³) |
|-----------|-------------------|----------------|-------------------|----------------|-------------------|----------------|
| Fly ash   | 0.8               | 336            | 0.8               | 338            | –                 | –              |
| GGBS      | 0.2               | 84             | 0.2               | 85             | –                 | –              |
| Cement    | –                 | –              | –                 | –              | 1.0               | 460            |
| Sand      | 1.5               | 630            | 1.5               | 635            | 1.2               | 550            |
| Coarse aggregate | 2.5 | 1050        | 2.5               | 1058           | 2.5               | 1150           |
| AAS       | 0.6               | 252            | 0.6               | 254            | –                 | –              |
| Water     | –                 | –              | –                 | –              | 0.4               | 185            |
| Water/GSM | 0.36              | 0.24           | –                 | –              | –                 | –              |
| Fresh concrete density (kg/m³) | 2352 | 2370 | 2345 |
kept submerged in water for curing. The average compressive strength of this reference concrete at 7 and 28 days of water curing is 38 and 57 MPa respectively. Machine-polished bars of diameter 12, 16 and 20 mm (see Fig. 5) were used in our pull-out tests. The surface of the bars was tested using Mitech Surface Tester and an average roughness of 1.9 μm was obtained. In accordance with the recommendations of clause 3.1 of the Indian Standard IS 2770 (IS 1967), cube moulds of size 100 × 100 × 100 mm were used for the embedment of 12 mm diameter bars and 150 × 150 × 150 mm cubes for 16 and 20 mm diameter bars.

3.2 Testing program
Pull-out test specimens were prepared as specified by IS 2770 by embedding the polished bars vertically along the central axis of the cube moulds as shown in Figs. 6 and 7. The bar was kept in such a way that about a length of 10 mm was projecting from bottom face and about 900 mm projecting from top face, i.e., load-bearing face of the cubes. While applying the load, the 900 mm projecting bar facilitates the gripping of the specimen on the UTM. The entire size (100 or 150 mm) of the cube was utilised as the embedment length. Steel spirals of 6 mm diameter plain bar at 25 mm pitch with a helix diameter equal to the size of the cube was provided around the embedded steel bar as lateral confinement as recommended in IS 2770. The average of test results of three specimens was considered.

The specimens were tested at 7 and at 28 days of casting. A digital servo-controlled UTM of 100-ton capacity was used to conduct the experiments. Test specimens were mounted on UTM in such a way that the loadbearing face of the cube was supported on the machined plate that is 20 mm thick with a hole of 35 mm diameter at the centre to accommodate the bar. The cube with the plate was placed over a spherically seated steel bearing block with a central hole of 35 mm diameter. For measuring free end slips of the projecting bar, a digital dial gauge was mounted on the cube as shown in Fig. 8. The pull-out load was applied by gripping the projecting bar from the loadbearing face in the movable block of the UTM as shown in Fig. 9. The pull-out load was applied and the free end bar slip values were recorded. It was assumed that the entire embedment length of the bar subjected to uniform average bond stress and the bond stresses were calculated as,

$$\tau_{ba} = \frac{P}{\pi dl}$$

where $\tau_{ba}$ is the adhesive bond stress in MPa, $P$ the load

![Fig. 5 Polished bar.](image)

![Fig. 6 View before casting.](image)

![Fig. 7 View after casting.](image)

![Fig. 8 Pull-out schematic illustration.](image)
in Newtons, \(d\) the diameter of the bar in mm and \(l\) the embedment length in mm.

### 3.3 Characterisation of the geopolymer

Field emission scanning electron microscopy (FE-SEM) using JEOL JSM 6300 microscope with a tungsten filament electron source and 20 kV accelerating voltage on a fractured surface of the concrete was employed to study the microstructure of geopolymers. \(^{29}\)Si and \(^{27}\)Al MAS-NMR (magic angle spinning nuclear magnetic resonance) spectra were obtained at a frequency of 300 MHz with a Brucker 7 mm probe turned to 79.48 MHz for silicon and 104.1 MHz for aluminium. Samples were placed in zirconia rotors and chemical shifts were measured with respect to zero reference from tetramethylsilane (TMS) for \(^{29}\)Si, and aluminium nitrate for \(^{27}\)Al.

### 4. Results and discussion

#### 4.1 Effect of silica modulus on strength

As shown in Table 4, the effect of silica modulus (Ms) of AAS on the compressive and bond strengths at room temperature in the binary system was found to be significant. The compressive strength of GPC prepared with 0.9 Ms of AAS-1 was 39 MPa at 7 days of curing and increases further to 50 MPa at 28 days. Concurrently, increasing Ms to 1.2 as in AAS-2, the strength gain increases from 59 to 68 MPa as curing age increases from 7 to 28 days.

In general, the dissolution of GGBS and fly ash upon alkali activation would produce a higher degree of cross-linking in binder systems consisting of both calcium aluminosilicate hydrate (CASH) and sodium aluminosilicate hydrate (NASH) gels. Higher soluble silicate species in AAS with higher Ms increase the dissolution of fly ash besides contributing to the formation of more NASH-type and CASH-type gels that cause enhancement in strength as observed in GPC-2. An increase of concentration of AAS promotes the polycondensation reaction rate and degree of geopolymerisation, leading to less porous and stronger geopolymer binding gel, which is reflected in the scanning electron micrographs of the paste samples of GPC-1 and GPC-2 (Figs. 10a and 10b). The improved microstructure resulting from the optimum GGBS blending ratio of 20 to 30% in low calcium fly ash is in accordance with what has already been reported in the literature (Palomo et al. 1999; Chi 2012).

#### 4.2 MAS-NMR characterisation of binder gel

Reactions of blended fly ash and GGBS with silicate anions during geopolymerisation were studied using \(^{29}\)Si and \(^{27}\)Al MAS-NMR spectral data for the GP 1 and 2 (see Fig. 11). The chemical shifts of the products were compared with those of starting raw materials to gain an insight into the reaction. The broad peak ranging from \(-80\) to \(-100\) ppm and from \(-100\) to \(-120\) ppm in \(^{29}\)Si MAS-NMR spectral data are from different Q structural units of fly ash assigned to Si-Al-O systems represented by Q4 \((nAl)\) for \(^{29}\)Si, and aluminium nitrate for \(^{27}\)Al. The
The chemical shift values agree with those presented in the literature reports (Duxson et al. 2007; Barr et al. 1997).

The $^{27}$Al MAS-NMR signal of fly ash shows a strong and broad asymmetric signal around +60 ppm, which is associated with the coordination of Al(IV) and Al(V) in fly ash. The second peak between +16 to +18 ppm shows the presence of Al(VIII). Mullite phase identified with higher intensity in fly ash is absent in GGBS as expected (Criado et al. 2016; Park et al. 2016). Structural investigations of geopolymer networks using NMR and interpretation of NMR have been done before as well (Criado et al. 2016; Singh et al. 2005). The chemical shift is more negative corresponding to a high/up field, representing a high degree of condensation reaction of SiO$_4$ tetrahedra and a connection between each AlO$_4$ to a SiO$_4$ group. Based on these observations, the formed silicate networks can be explained with two different geopolymers prepared using different silica moduli of AAS. On comparing the spectra of raw fly ash and slag with geopolymers, the main chemical shift occurs in the range –104 to –101 ppm and –98 to –94 ppm, indicating the presence of Q$_4$ (2Al) and Q$_4$ (3Al). Further, peak at –108 ppm corresponding to the Q$_4$ (0Al) coordination had a lower intensity in the geopolymer, which points to the penetration of Al in the [SiO$_4$] T-skeleton.

The electron density of Si is different in NASH and CASH environments, which can be explained from the chemical shift values. The mixes contain 80% of fly ash, and hence upon activation, the nature of the gel formed predominantly is NASH, which shows a chemical shift between –70 to –91 ppm. The peaks can be assigned to various silicon environments such as Q$^1$(1Al), Q$^2$(1Al), Q$^2$, Q$^2$(1Al) and Q$^4$(4Al). A broad signal around –95 to –110 ppm in CASH corresponds to Q$^2$, Q$^2$(0Al), Q$^2$(1Al) and Q$^3$(1Al) environments. The Q$^2$(4Al) peak found to be in the range of 20% arises from the silicate activation of GSM, which is absent in raw material. The Q$^2$(4Al) peak is observed in geopolymers, which is absent in the GSM while the chemical shift move towards

![Fig. 10 Scanning electron micrographs of paste sample (a) GPC-1 (b) GPC-2.](image)

![Fig. 11 $^{29}$Si NMR spectra of (a) fly ash and GGBS and (c) geopolymer. $^{27}$Al NMR spectra of (b) fly ash and GGBS and (d) geopolymer.](image)
lower values in GP 2.

On comparing the Al NMR spectra of both geopolymers, it is clear that there is no change in the peak position corresponding to Al(IV). A broad resonance centered between 60 and 61 ppm is observed in each sample and assigned to Al in a significantly, distorted tetrahedral environment. This can be attributed to poorly crystalline mixed types of C(N)ASH and amorphous NASH gel products. The octahedral environment of Al at approximately 6 to 14 ppm in all samples can be attributed to octahedral Al in mullite phases (0 ppm) as seen in raw fly ash particles. The signal at around 14 ppm likely is due to Al(VI) of remnant slag particles. A small variation in the shielding of tetrahedral and octahedral resonances in GP1 and GP2 are as a consequence of structural differences due to the variation in the degree of reaction as well their crystallinities.

4.3 Pull-out test results

An ideal pull-out failure occurred in all the test specimens as shown in Figs. 12 and 13. The main results of pull-out specimens of GPC-1 and GPC-2 and OPC are shown in Table 4 and Figs. 14 to 16.

4.3.1 Effect of bar size

Figures 14 and 15 show bond stress-slip curves for different bar sizes in GPC-1 and GPC-2. The 12 mm bars with 100 mm embedment length experience low bond stresses and as the diameter and embedment length increases, the bond stress values also move to higher values. This observation is found to be contradictory with the results of experiments on plain Al alloy bars, which are considered to be smooth bars with negligible surface friction, embedded in OPC ($f_c = 41$ MPa). There was no apparent change in bond stress upon increasing the diameter and embedment length in the case of Al bars incorporated in OPC (Xing 2015). In the present study, the reference OPC with polished bar specimens showed the trend of no obvious change in bond stresses with the increase of diameter and embedment length with respect to 12 and 16 mm bars. However, bond stress was found to be increased for 20 mm bars at initial slips as depicted in Fig. 16. The peak bond stresses occurred at a very small end slip of 0.03 and 0.05 mm. There were no prominent ascending portion of curve or significant stress plateau. As the slip occurs, the bond stress then dropped asymptotically to residual stress values at slips between 5 and 6 mm. The maximum bond stress calculated using the empirical relationship $T_s = 0.09f_{c,0.67}$ (Boopalan et al. 2018) matches with the peak bond stress value of 28 days test from this experiment.

According to these test results, at lower slip ranges,
GPC bonded to steel bars behaved significantly different from OPCC bonded to steel bars. As diameter and embedment length increase, the surface area of embedment increased, which has an influence on the contact surface between the matrix and the steel bar. The chemical network stability and binding properties of mixed types of gel in fly ash/GGBS blended geopolymers highly influence the strength of the mix as well as its bonding strength. Therefore, the higher bond stress of the all the bars in both GPC specimens is attributed to chemical bonding with the network formed. At the same time, higher sliding forces overcome this chemical bonding, which bring down the bond strength. In other words, the size effects of bars play a vital role beyond certain slip values and the behaviour of geopolymers then follow the trend of OPCC.

4.3.2 Effect of ageing on strength

The bonding behaviour of the adhesion of the geopolymer with steel bars was studied with materials having two different silica moduli. A longer curing time improves the degree of reaction irrespective of the Ms values. The solubility of raw materials strengthens the geopolymeric network as evident in the compressive strength of the formed geopolymer (see Fig. 17). The interfacial zone strength between the concrete and metal is affected by ageing. So its impact on the bond strength was evaluated for different aged specimens at critical slip values as given in Table 4. The bond strength variations at 7 and 28 days of curing are shown in Fig. 18. The results indicate that increasing the duration of curing time increases the compressive strength, which in turn, increases bond strength. This observation seems to be contradictory with the results of pull-out test on smooth bars with OPCC, where the adhesive bond is relatively independent of the compressive strength (Chapman and Shah 1987).

The average of bond-slip curves of GPC-1 and GPC-2 are shown in Fig. 19. In case of the 7-day test ($f_c = 39$ MPa), GPC-1 showed an ascending curve with a 12% increase in bond stress from 0.025 mm slip to peak stress ($\tau_{\text{max}}$) at maximum stress plateau attained at 0.1 mm slip. Further, the pull-out load decreases and the corresponding slip increases. Thus the curve gradually moves to a ‘strain-softening type’ of response. This type of bond-slip response with maximum stress plateau and strain-softening behaviour as observed in the bond-slip curve of plain bars with OPC concrete had been reported earlier in the literature (Abrams 1913). In contrast to the 7-day test results, the 28-day test results ($f_c = 50$ MPa) showed an ascending curve with a 15% increase in bond strength from 0.025 mm slip to $\tau_{\text{max}}$ at 0.1 mm slip. Further the curve dips to a bond stress of 84% of $\tau_{\text{max}}$ at 0.75 mm slip. Then the curve raises gradually to bond stress of 100% of $\tau_{\text{max}}$ at 6 mm slip. Thus the curve displayed a ‘strain-hardening type’ of behaviour.
At 7 days of curing of GPC-2 ($f_c = 59$ MPa), a 18% increase of bond stress beyond 0.025 mm slip up to $\tau_{\text{max}}$ at maximum stress plateau at 0.25 mm slip was observed. The increase in bond stress in case of 28-day curing ($f_c = 68$ MPa) is 23%. In both cases, at 7 and 28 days of curing, the post peak response curves experienced a small dip in bond stress of 97% of $\tau_{\text{max}}$ at an average of 0.6 mm slip. Then the curves surged to bond stress values of 118% of $\tau_{\text{max}}$ at 6.0 mm slip. Thus GPC-2 showed a distinct strain-hardening type of behaviour at both 7- and 28-day pull-out test results. This indicates a sustained bond transfer from steel rod to surrounding concrete in a gradual manner after a peak bond stress level is reached.

From the above observations, it can be concluded that geopolymeric specimens having compressive strength below 50 MPa experienced a ‘strain-softening type’ stress transfer whereas at higher compressive strengths, ‘strain-hardening’ type of behaviour is observed. Increase in load, which is required to produce an additional slip or otherwise called ‘strain-hardening’, probably due to an increased resistance to sliding. These phenomenal changes can be explained in terms of the geopolymeric binding network formed during the reaction. As silica modulus of AAS increases, the higher sodium concentration contributes to a better molecular network formation, which is much stronger as seen from the incorporation of Al(IV), the evidence for which is observed from the Al NMR spectral data, in GPC-2. This kind of variation in strength against the type of hardening in OPCC matrix is not reported earlier. Our studies also confirm the same behaviour for the OPCC matrix.

4.4 Comparison of adhesive bond stress of GPC with OPCC

Figure 20 shows the average bond stress-slip plots for both GPC and OPC concrete at the same compressive strength. The maximum stress plateau and ‘strain-hardening stages’ were attained in the GPC mix due to adhesive bond-slip response with $f_c$ above 50 MPa. GPC with $f_c = 39$ MPa showed gradual ‘strain softening’ with maximum stress plateau. The OPCC did not show any significant maximum stress plateau and bond stress values dropped continuously with corresponding increase in slip values for both $f_c = 38$ and $f_c = 57$ MPa. The increase of adhesive bond stress beyond 0.025 mm slip (a parameter as per IS 2770) up to the peak bond stress at similar compressive strength level is 12 and 18% for GPC and only 2 and 4% for OPC concrete (see Table 4).

Thus the geopolymer, GPC-2 (Ms: 1.2), the adhesive bond is 70% stronger than that of OPC concrete, confirming a higher level of adherence of GPC with steel bars and GPC-1 (Ms: 0.9) attained only 5% higher bond compared to OPCC with similar $f_c$ as shown in Fig. 18.

4.5 Adhesive bond strength of deformed bars with GPC

In the work of Balci et al. (2017), the bond strength of alkali-activated (also called geopolymer) concretes with deformed reinforcing bars were examined experimentally by using the central composite design method. The relationship between the bond strengths from pull-out test of deformed bars and the compressive strength is defined by the equation below.

\[ \tau = 0.0203f_c^{1.5071} \]  

This equation was taken as the basis for assessing the relationship between adhesive bond of polished bars and bond strength of deformed bars based on compressive strength of the surrounding GPC matrix. The above equation is modified as $\tau = kf_c^{1.5071}$ for ascertaining the mentioned relationship.

The present test data was used to find out the value of $k$ by regression analysis and the following equation was derived from Fig. 21 to be applicable adequately for the present data on polished bars:

\[ \text{Adhesive bond strength} = 0.0055f_c^{1.5071} \]  

Since the coefficient of correlation for the above equation was 0.922, it shows a strong relationship between the adhesive bond and bond strength of deformed bars based on the compressive strength of concrete. The value of $k = 0.0055$ is 27% of the value of $k = 0.0203$ given for the deformed bars. This indicates that the bond resistance in the polished bars is mainly due to the adhe-
sive force between GPC matrix and bar surface at the interface, whereas the bond resistance offered by the deformed bar is due to chemical adhesion along with mechanical interaction and bearing against the face of the ribs. When the reinforced concrete members are loaded, the deformed bars attempt to slip initially. Adhesive bond combined with mechanical interaction prevents the slip. After the breakdown of the adhesive bond, the ribs of the bar restrain the slip. The higher adhesive bond component of the deformed bar transfers the bond force to the ribs with increased ductility. It can be hypothesised that the adhesive bond in GPC minimises the cracks at the interface and improves durability of reinforcing bars.

4.6 Scanning electron microscopy
SEM studies were performed on the fractured specimens after the pull-out tests to investigate the morphological changes in the bulk matrix and interfacial zone. From Figs. 22a and 22b, it is clearly seen that GPC-1 at the interface and the inner matrix have a more or less dense microstructure with minor cracks at the interface as compared to that of GPC-2. They also show comparatively more surface homogeneity. The interface surfaces formed due to steel bar contact (shown by arrow in the Fig. 22b) have transferred the load such that the integrity of the matrix is not affected much and hence the bar has slipped through without more surface deformations. In case of GPC-2 (Figs. 23a and 23b), the matrix is denser because of a high degree of polycondensation reaction (due to higher Ms of the activating solution), which generates greater interface surface contact areas (shown by arrow in the Fig. 23b) to the bar, which could be the reason for its higher bond strength. The mechanical forces acting on the matrix exerts high frictional forces creating more areas of stress concentrations. Therefore SEM shows more microcracks that destabilise the network. The differences in matrix structures generated from two different mixes having additives (AAS-1 and AAS-2) with two different values of Ms can be observed from unreacted fly ash particles.

![Fig. 22a](image1.png)  ![Fig. 22b](image2.png)

Fig. 22 Scanning electron micrographs of GPC-1 (a) inner matrix (b) at matrix-bar interface.

![Fig. 23a](image3.png)  ![Fig. 23b](image4.png)

Fig. 23 Scanning electron micrographs of GPC-2 (a) inner matrix (b) at matrix-bar interface.
seen as many spherical particles in case of lower Ms solution (Fig. 22) whereas the higher Ms solution had produced more intense and higher degree of polymerisation, resulting in almost all fly ash particles undergoing dissolution and hence showing almost absence of raw spherical unreacted fly ash particles (Fig. 23).

SEM images of the inner and bar interface matrices of OPCC are shown in Figs. 24a and 24b. The images show the hydration products of the CSH gel, which are spread over the surfaces along with calcium hydroxide in a small crystalline size. The microstructure of the inner matrix is less dense and a large number of pores are found. Almost negligible cracks or failure surfaces are seen in the inner matrix zone. The interface matrix shows only a few contact areas (shown by arrow in the Fig. 24b), which are not prominent as in GPCs. No major distortions, but only a few cracks, are found at the bar interface zone. In OPCC, the adhesive bond strength is low and therefore, the load transfer from steel to concrete is less. As a result, the energy needed for creating failure surfaces is low, as evident from a few cracks at the interface.

Larger number of failure surfaces generated in GPCs compared to OPCC, as explained above, indicate that the nature of chemical adhesion bond generated in GPCs is such that ‘strain hardening’ type of portion occurs in the bond stress - slip curves i.e., after peak bond stress is generated, the continued bond contributes to further transfer of load from steel to concrete so that there is no sudden decrease in bond stress as it happens in OPCC. This kind of load carrying capacity after peak stress is attained, is observed in tensile strength - elongation curves of ultra-high performance fibre reinforced concretes (UHPFRC) where microfibers help in reducing the micro crack widths and making denser matrix by bonding action generated thereby there is no dropping of stress and stresses continue to rise marginally with larger elongations. Thus, the present GPCs are found to generate very special adhesive bonding with steel and thereby exhibiting bond-slip behaviour different from that of OPCC.

5. Conclusions

Ascertaining the bond strength of polished steel bar embedded in GPC and traditional OPCC was the main objective of this study. GPC was prepared from the blend of geopolymeric raw materials, fly ash and GGBS (4:1 by mass), to which two different sodium silicate solutions of silica modulus 0.9 and 1.2 were added as the activator. The compressive strength achieved in GPC is in the range of 39 to 68 MPa against that of reference OPCC, which was about 38 and 57 MPa. The adhesive bond strength of GPC increased on ageing and on increase of compressive strength.

GPC-1 with lower compressive strength (below 50 MPa) achieved a maximum stress plateau and gradual ‘strain-softening’ behaviour. But GPC-1 and GPC-2 with higher compressive strengths showed maximum stress plateau and ‘strain-hardening’ type of bond-slip relationships. In GPC, ‘strain hardening’ increases the adhesive bond resistance. But OPCC showed rapid ‘strain-softening’ type of bond-slip without significant maximum stress plateau. Increase in steel bar diameter and embedment length resulted in a higher bond strength.

Test results on bond-slip relationship indicated the transfer of the load between steel bar and surrounding concrete and the bond involved here was mainly chemical adhesion, which is about 70% higher than adhesive bond strength of reference OPCC at the same compressive strength level.

The relationship between adhesive bond and the bond strength of deformed bars based on the compressive strength of GPC was determined. We found that the adhesive bond component is about one-fourth of total bond resistance of the deformed bars and compares favourably higher than OPCC. This is an indicator of a much better adherence of GPC on reinforcing bars.

Si and Al MAS NMR spectra clearly provide evidence for the formation of silicate hydrate gels with aluminium in the structures of NASH and CASH with a variety of Q4 (nAl) environments. While comparing
spectra of geopolymers, GPC-2 prepared with a higher silica modulus solution was found to form stronger loadbearing gels and have better space filling properties.

Microstructural studies performed using SEM confirmed the denser matrix of GPCs. However, microcracks at the interfacial zone occurred while applying load in the pull-out tests. In GPC matrix with higher compressive strength, more compact interfacial zone surface area is formed due to higher degree of polycondensation reactions. The microstructural characteristics of geopolymers that we studied indicated their superior chemical adhesive nature with steel bars as compared to conventional Portland cement. We therefore conclude the GPCs that have a greater bonding capacity with steel can be used in reinforced concrete structures.

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Abbreviations and notations
AAC: Alkali-activated concrete
AAS: Alkali activator solution (sodium silicate solution prepared from mixing commercial sodium silicate solution with laboratory-prepared sodium hydroxide solution)
GGBS: Ground granulated blast furnace slag
GP: Geopolymer
GPC: Geopolymer concrete
OPCC: Ordinary Portland cement concrete
CASH: Calcium aluminosilicate hydrate
NASH: Sodium aluminosilicate hydrate
CSH: Calcium silicate hydrate
FA: Fly ash
f_c: Compressive strength
FE-SEM: Field emission scanning electron microscopy
IPC: Inorganic polymer concrete
MAS-NMR: Magic angle spinning nuclear magnetic resonance
Ms : Silica modulus (SiO_2 / Na_2O): molar ratio
SSS: Sodium silicate solution
TMS: Tetramethylsilane
UTM: Universal testing machine