Bond characteristics of reinforcing steel embedded in geopolymer concrete

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Abstract. The force transferring between reinforcing steel and the surrounding concrete in reinforced concrete is influenced by several factors. Whereas, the study on bond behaviour of geopolymer concrete (GPC) is lagging. In this paper, an experimental attempt has been made to evaluate the geopolymer concrete bond with reinforcing steel of different diameter and embedded length using standard pull out test. The geopolymer concrete is made of ground granulated blast furnace slag (GGBFS) as geopolymer source material (GSM). The tests were conducted to evaluate the development of bond between steel and concrete of grade M40 and M50 with 12 and 16 mm diameter reinforcing steel for geopolymer and cement concrete mixes and to develop a relation between bond strength and compressive strength. From the experimental results, it has been observed that the bond strength of the geopolymer concrete mixes was more compared to the cement concrete mixes and increases with the reduction in the diameter of the bar.

Key words: Geopolymer Concrete, Ground Granulated Blast Furnace Slag, Ambient Curing, Pull-Out Test and Compressive Strength.

1. Introduction
Over the past two decades, geopolymer concretes have developed as novel construction materials with a possibility to become a significant component in construction industry and environmentally sustainable construction [1, 2]. Geopolymer concrete is resulting from the reaction between aluminosilicates present in the GSM and alkalis to develop an inorganic polymer as binder. The materials of geological origin and industrial byproducts such as fly ash, GGBFS, etc. [3, 4] which are rich in Silica and Alumina can be used as a GSM in the development of geopolymer concrete. In spite of their diverse chemical composition and reactions [5, 6] geopolymer concretes shows a number of attributes similar to conventional cement concrete whereas, a least number of works were attempted in the past to evaluate the bond behaviour steel reinforcement in geopolymer concrete. Hence, in this investigation, the bond behaviour of GPC with deformed reinforcing steel was evaluated using standard pull out test for 12 and 16 mm diameter bars as reinforcement for the grades of M40 and M50. Since very few literatures are available to study the bond behaviour of GPC made of GGBFS, this study was carried out by employing stress-slip relation and compressive-bond strength relation. The results were compared with the performance of ordinary Portland cement (OPC) based concrete. Considering the GPC is appropriate for precast applications, this work was focused to evaluate the
bond strength of GPC under ambient temperature condition to assess its ability under cast in-situ conditions.

2. Materials and methods

2.1 Materials

Ordinary Portland Cement (OPC) of grade 53 confirming to IS 12269 was utilized in the study. The specific gravity of the OPC sample was found to be 3.12 with an initial setting time of 40 minutes and a standard consistence of 28% with its chemical composition is given in Table 1. GGBFS a byproduct of iron and steel industry is one of the most commonly used mineral binder as it continues to gain strength over time and is chemically stable. Another interesting property about GGBFS is, when incorporated it shows latent hydraulic properties. In this experimental study with a specific gravity of 2.90, fineness 438 m²/kg and bulk density of 1231 kg/m³ was used as geopolymeric source material.

Table 1. Chemical composition of OPC and GGBFS.

| Oxide     | CaO | SiO₂ | Al₂O₃ | MgO | SO₃ | Fe₂O₃ | Na₂O | K₂O |
|-----------|-----|------|-------|-----|-----|-------|------|-----|
| OPC (%)   | 63.12 | 24.52 | 6.88 | 2.16 | 1.43 | 3.51 | 0.44 | 0.63 |
| GGBFS (%) | 36.77 | 30.97 | 17.41 | 9.01 | 1.82 | 1.03 | 0.69 | 0.46 |

A mixture of Sodium hydroxide and Sodium Silicate with silica to alkali molar ratio (SiO₂/Na₂O) of 2.5 was as used for the alkali activation. Commercial grade Sodium Hydroxide in the form of flakes of almost 99% purity and sodium silicate solution having 28% SiO₂, 11.2% Na₂O and 60.8% H₂O by mass were taken. Locally available river sand was used as fine aggregates. The grading of the aggregate was categorized using sieve analysis test, and the results are detailed in Table 2 and accordingly the aggregate was categorized as graded under Zone III.

Table 2. Properties of aggregates used in the mixes.

| Properties          | Fine Aggregate | Coarse Aggregate |
|---------------------|----------------|-----------------|
| Specific gravity    | 2.58           | 2.72            |
| Fineness modulus    | 2.56           | 6.97            |
| Bulk density, kg/m³ | 1696           | 1485            |
| Water absorption, % | 1.37           | 0.77            |

Coarse aggregates from locally available quarry and crushed blue granite chips with a nominal size of 16 mm were used in this study. The aggregates were tested and the results obtained are detailed in Table 2. The steel bars of 12 and 16 mm high yield strength deformed bars were used as reinforcement in the cube specimens.

2.2 Methodology

The cement concrete and geopolymer concrete mixes were prepared for the grade of M40 and M50 with the concentration of NaOH solution used in geopolymer mixes were taken as 14 M and an alkaline ratio of 2.0 and the detailed mix proportioning is given in Table 3, with a liquid-binder ratio of 0.40. The cube of size 150 mm x 150 mm x 150 mm were cast with the bar was placed at the centre with a projection of 25 mm at the bottom. The cement concrete specimens were water cured, whereas the geopolymer mixes were cured under ambient temperature condition.
### Table 3. Mix proportioning of the concrete mixes used in the study.

| Mix  | Cement | GGBFS | Sand  | Aggregate | Water | NaoH Solution | Na₂SiO₃ Solution |
|------|--------|-------|-------|-----------|-------|---------------|-----------------|
| CC40 | 400    | ---   | 660   | 1168      | 160   | ---           | ---             |
| CC50 | 425    | ---   | 648   | 1087      | 170   | ---           | ---             |
| GP40 | ---    | 387   | 432   | 1368      | ---   | 106.5         | 106.5           |
| GP50 | ---    | 400   | 432   | 1368      | ---   | 66.7          | 133.3           |

For the compressive strength test, cubes of size 150 mm x 150 mm x 150 mm were tested in compression testing machine of 3000 kN capacity at the age of 7 and 28 days ambient curing condition in accordance with IS 516-1959. Pull out test was carried out as per the guidelines specified by IS 2770-1. The test specimens are mounted in a Universal testing machine in such a manner that the bar is pulled axially from the cube and a mechanical dial gauge was used to measure the slip rate of the reinforcing steel with the load increment from the surface of the cube specimen. The cube specimens were reinforced with 12 and 16 diameter bars to study the bond behaviour of geopolymer and cement concrete mixes with no confining reinforcement.

### 3. Results and discussion

The variation in the compressive strength of the cement concrete and geopolymer concrete mixes at the age of 7 and 28 days are shown in Figure 1. The 7 days compressive strength of the cement concrete mixes were found to be around 60-70% of its 28 days strength, whereas for geopolymer concrete mixes, it was found to be more than 70% of its 28 days strength. Also, the compressive strength results of the geopolymer concrete mixes were found to be superior to the cement concrete mixes.

![Figure 1. Compressive Strength of the mixes at 7 and 28 Days curing.](image)

Table 4 shows the bond-slip behaviour of cement concrete and geopolymer concrete mixes at various stages of testing.
Table 4. Bond-slip results at various stages of the concrete mixes used in the study.

| Mix No. | Diameter of Bar (mm) | @ 0.25 mm Slip | @ 2.5 mm Slip | @ Ultimate Level |
|---------|----------------------|----------------|---------------|-----------------|
|         | Load (kN)           | $T_{bd}$ (MPa) | Load (kN)     | $T_{bd}$ (MPa)  | Load (kN) | Slip (mm) | $T_{bd}$ (MPa) |
| CC40    | 12                   | 1.11           | 7.13          | 1.26            | 50.80     | 6.97      | 8.99        |
|         | 16                   | 1.03           | 4.93          | 0.65            | 47.70     | 6.39      | 6.33        |
| CC50    | 12                   | 1.18           | 5.10          | 0.90            | 66.50     | 9.13      | 11.77       |
|         | 16                   | 1.31           | 7.90          | 1.05            | 61.55     | 8.13      | 8.17        |
| GP40    | 12                   | 1.46           | 9.00          | 1.59            | 59.20     | 8.04      | 10.47       |
|         | 16                   | 1.46           | 8.85          | 1.17            | 55.95     | 6.78      | 7.42        |
| GP50    | 12                   | 1.84           | 9.48          | 1.68            | 84.80     | 7.89      | 15.00       |
|         | 16                   | 1.44           | 10.28         | 1.36            | 74.40     | 9.30      | 9.87        |

Table 4 details the load-bond-slip behaviour of geopolymer and cement concrete mixes at various stages of loading. The load at 0.25 mm and 2.5 mm slip and at ultimate level was observed.

Figure 2a. Load-Slip behaviour of M40 grade cement concrete mixes.

Figure 2b. Load-Slip behaviour of M50 grade cement concrete mixes.

Figure 2a and 2b, shows the load-deflection behaviour of cement concrete mixes for M40 and M50 grade mixes. The behaviour was found to be similar irrespective of grade of concrete and diameter of the reinforcement. The mixes with 12 mm diameter bars show slightly higher energy absorption capacity than the mixes with 16 mm diameter bars.
Figure 3a. Load-Slip behaviour of M40 grade geopolymer concrete mixes.

Figure 3a and 3b shows the load-deformation behaviour of geopolymer concrete mixes for M40 and M50 grade mixes reinforced with 12 mm and 16 mm diameter bars. There was a slight deviation in the curve for the mix with M40 grade in which the mix with 12 mm diameter bar experiences slightly higher slip than with the mix reinforced with 16 mm diameter bar.

Figure 4a. Bond-Slip behaviour of M40 grade cement concrete mixes.

Figure 4 and Figure 5, shows the bond-slip relation for cement concrete and geopolymer concrete mixes respectively for M40 and M50 grade concrete. The behaviour was found to be similar to the load-slip behaviour.
The bond characteristics of geopolymer shows superior behaviour than cement concrete mixes irrespective of grade of concrete mix and diameter of reinforcement used, which is similar to the results observed from other studies [7,8]. This is mainly due to the strong adhesion between the aggregates and activator solution. The reason behind this improved performance is mainly attributed to the strong interfacial transition zone between aggregate and geopolymer matrix in geopolymer concrete leads to denser matrix results in higher bond strength that cement concrete mixes of similar grade [7]. It was also observed that the bond strength increase with the decrease in the diameter of the reinforcement. Similar behaviour was also observed [9]

4. Conclusion
The use of ambient temperature curing in geopolymer mixes result its ability to use in cast in-situ conditions. The compressive strength of the geopolymer mixes was found to be higher than the cement concrete mixes. There was a superior bonding between the geopolymer concrete and the reinforcement compared with the cement concrete mixes. The bond strength was found to reduce with the increase in the diameter of the reinforcement. The failure of all the specimens was observed to be splitting rather than delamination of the surface concrete.

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