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Bond-slip Behavior of Geopolymer Concrete after Exposure to Elevated Temperatures

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ABSTRACT

The bond-slip behavior of geopolymer concrete equivalent to M40 grade, being exposed to high-temperature conditions is discussed using pull-out test results. The alumino-silicate materials considered in the geopolymer concrete are ground granulated blast furnace slag (GGBS) and fly ash, hence heat curing has been avoided. A ribbed reinforcing bar of 8 mm diameter has been used in the pull-out specimen. Parameters like different GGBS content (50%, 75% and 100%), exposure temperature (Ambient to 800°C) and method of cooling after temperature exposure (air and water) are considered in this study. The result in comparison with bond-slip behavior of OPC (Ordinary Portland Cement) concrete is an approximate grade of M40. It has been seen that the bond strength of geopolymer concrete containing fly ash and GGBS is higher than that of OPC with almost the same compressive strength. Also, when exposed to higher-temperature conditions, the bond strength reduction in geopolymer concrete, primarily due to the formation of geopolymer structure, is less than in OPC. However, while OPC concrete shows uniform rate reduction in bond strength till 800°C, the more or less uniform decrease in the bond strength of geopolymer concrete till 600°C changes to a higher rate beyond 600°C. Further, after water cooling, the decrease in bond strength is significantly higher in geopolymer concrete compared to OPC concrete. A possibility of sudden bond failure has been noted in geopolymer concrete when it is exposed to high-temperature conditions, as the critical strength between the bonds approaches the decisive bond strength with exposure to high temperatures.

KEYWORDS: Bond strength, Geopolymer, GGBS, Fly ash, Bond-slip, Concrete.

INTRODUCTION

Portland cement-based concrete is a versatile material in construction around the world even though the release of CO_2 associated with cement production is a major environmental concern. Cement industry alone contributes nearly 10% of the CO_2 released to the atmosphere(Zhang et al., 2015; VahidShobeiria Bree Bennetta et al., 2021).

However, since the 1990s, geopolymer concrete has evolved as an environmentally sustainable construction material alternative to cement concrete (Rangan, 2014; Voraa and Urmil, 2013). The total carbon footprint of geopolymer concrete has been reported to be 9% less than OPC concrete (Latawiec and Woyciechowski, 2018). As it is well known, geopolymer concrete is made by alkali activation of alumino-silicate materials. The most widely used alumino-silicate material is fly ash and the alkali material is a blend of Na_2SiO_3 and NaOH. However, amongst the main hurdles in the acceptance of geopolymer concrete with fly ash in construction industry is the requirements of heat curing. Researchers have circumvented this problem by introducing other cementitious materials, like GGBS, metakaolin, … etc., as partial replacements of fly ash (Lateef et al., 2019; Pavithra et al., 2016; Khuito Murumi and Supratic Gupta, 2019).

Material characterization of geopolymer concrete has been a major research focus in the past, with little

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emphasis on structure of geopolymer-reinforced concrete. The primary factor that makes a reinforced concrete structural member effective is the bond between concrete and steel. An effective bond between concrete and steel ensures proper force transmission between the materials, ensuring composite action and strain compatibility (Diab et al., 2014).

Hence, it is important to evaluate the behavior of geopolymer concrete for using it as a structural material (Faye and Ye, 2017). There is a consensus among researchers that bond strength improves with the compressive strength of the conventional cement concrete. However, unlike conventional concrete where the parameters that govern the strength development are limited in number, many parameters affect the strength development mechanism of the geopolymer concrete. The ratio of coarse-to-fine aggregate, alkali activators' ratio (Na_2SiO_3 and NaOH), sodium hydroxide molarity, the ratio of alumino-silicate material (fly ash) to alkaline solution, the curing temperature effect and the amount of other alumino-silicate materials added in place of fly ash are some parameters. These factors highlight the importance of the performed study.

Studies on the bond strength of geopolymer concrete are few. It has been reported that the bond strength of geopolymer concrete is higher in comparison to cement-based concrete (Doguparti, 2015; Dewi, 2017). The dense transitional interfacial zone between geopolymer and aggregate in comparison with the cement matrix has been cited as the cause of its high bond strength (Zailani et al., 2017; Prabir Kumar Sarker, 2011). These studies are conducted on geopolymer fly ash concrete; however, studies on the bond property when GGBS is also added as an alumino-silicate material in geopolymer concrete are still limited.

The better strength performance of geopolymer concrete compared to OPC concrete when exposed to high temperature conditions may be because of the ceramics-like properties of alumino-silicate compounds used in its preparation (Hussin et al., 2015; Naus, 2005). Still, only a few research studies have been conducted on the behavior of bond strength of geopo1ymer concrete after it is exposed to higher-temperatures. Some of the studies considered the temperature as the only variable while proposing expressions for the geopo1ymer concrete bond strength when exposed to higher-temperature conditions (Yeddula and Karthiyaini, 2020; Junru et al., 2019). However, these studies considered conventional geopolymer concrete that requires temperature curing. Studies conducted on the effect of parameters like (curing in ambient temperature) on the bond strength characteristics after it is exposed to higher temperatures is lacking.

Therefore, we focused on the bond-slip performance of medium-strength geopolymer concrete (containing fly ash and GGBS as alumino-silicate materials) equivalent to M40 grade (cube compressive strength of 40 MPa on the 28th day) that does not require heat curing after heating the specimens to a high temperature and testing the effect after exposure to elevated temperature.

Experimental Program

Materials

Geopolymer concrete equivalent to M40 (cube compressive strength of 40 MPa) was prepared. The coarse aggregate is crushed granite stone (well-graded) and the fine aggregate is river sand conforming to zone II. The alumino-silicate materials used are class F fly ash and ground granulated blast furnace slag (GGBS). Table 1 lists the chemical contents of fly ash and GGBS (as per the supplier).

Table 1. Chemical contents of GGBS and fly ash

Sl. No.	Parameter	Value (%)	
		Fly ash	GGBS
1	SiO_2	50.22	34.28
2	Al_2O_3	29.61	13.84
3	Fe_2O_3	10.72	0.54
4	Sodium oxide as Na_2O	0.25	0.69
5	Sulphur trioxide as SO_3	0.65	1.83
6	CaO	3.47	36.77
7	MgO	1.30	9.01
8	TiO_2	1.76	0.42
9	P_2O_5	0.53	0.04
10	K_2O	0.54	0.21
11	Loss on ignition	0.80	0.83

Preliminary studies carried out with the materials considered show that geopolymer concrete with maximum compressive strength could be achieved with 10 molar NaOH solutions; 65% aggregate content, fine-to-the-total aggregate ratio of 0.35 and with 2.5 ratio of Na_2SiO_3 and NaOH. Fly ash has been replaced with GGBS by mass by 50%. Accordingly, Table 2 presents the basic mixture proportions (with fly ash alone) considered for further study.

Table 2. Basic geopolymer mixture proportions (for 1 m^3concrete)

Sl. No.	Material	Value
1	Na_2SiO_3	150 kg
2	10 molar NaOH solution	60 kg
4	Fine aggregate	574 kg
3	Fly ash	420 kg
5	Admixture	2.94 kg
6	Coarse aggregate	1082 kg

Conventional geopolymer concrete, in which only fly ash has been mixed as the alumino-silicate material, has less acceptance for general construction, primarily due to the heat curing it requires for strength development. However, it has been reported that mixing GGBS as a partial replacement of fly ash eliminates the need for heat curing (Antonyamaladhas et al., 2016).

Therefore, in this study, the quantity of fly ash was replaced with GGBS by mass (0%, 25%, 50%, 75% and 100%) to understand its influence on the strength of geopolymer concrete. We also prepared pull-out specimens with OPC concrete of almost equal grade of a geopolymer concrete cube that had the GGBS content of 50%. Standard cubes were cast with each mixture proportion and after 24h, these specimens were demolded. Then, they were kept in the laboratory environment till they were tested on the 28th day. Figure 1 depicts the impact of mixing GGBS on the strength of geopolymer concrete.

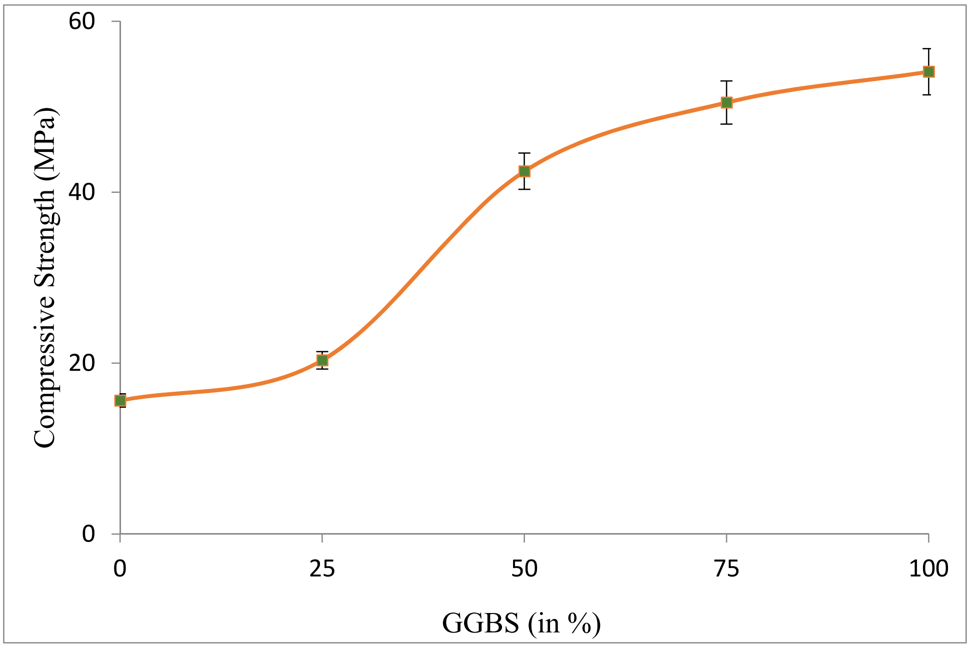


Figure (1): Effect of GGBS content on the strength of a geopolymer concrete cube

Preparation of Pull-out Specimens

Specimens of the pull-out test, consisting of 100 mm×100 mm ×100 mm (as per BIS 2770-2017, the size of concrete cube for a pull-out test when the bar diameter is less than 12 mm is 100 mm ×100 mm ×100mm) geopolymer concrete with 8 mm diameter embedded ribbed rebar were prepared. Fig. 2 shows the test samples prepared for the pull-out test.

Figure (2): Pull-out specimens

After casting, the pull-out samples were kept for curing for 28 days. Two methodologies were adopted for the curing of geopolymer pull-out specimens: ambient curing and heat curing. Heat curing is carried out by keeping the specimens in an electrically operated furnace at a temperature of 90°C for 24 hours. Then, these samples were extracted from the furnace and exposed to high temperature till conducting the pull-out test on the 28th day after casting.

The pull-out specimens are kept under high-temperature conditions (200 °C to 800 °C) on the 27th day of their casting. A constant rate of heating (7°C/minute) was used in an electrically operated furnace. After achieving the specified temperature, the specimens were kept in the furnace for further 60 minutes for making sure that a constant temperature is achieved using these specimens. These specimens were then extracted from the furnace and were cooled following either water -or air- cooling. Special concrete end blocks were used to protect the reinforcement from direct heat exposure in the furnace. The assembly of pull-out specimens with concrete end block is shown in Figure 3.

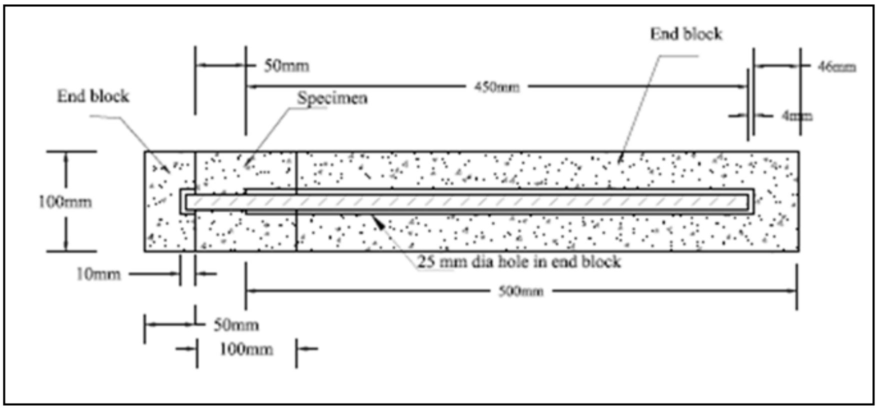


Figure (3): Assembly of a pull-out specimen with end blocks

The pull-out test, as per standards (BIS, New Delhi, 2017), was carried out in UTM (Universal Testing Machine). Figure 4 shows the laboratory setup for the pull-out test. SEM and XRD analyses were carried out on the representative geopolymer samples taken from steel and concrete interface, after the pull-out test.

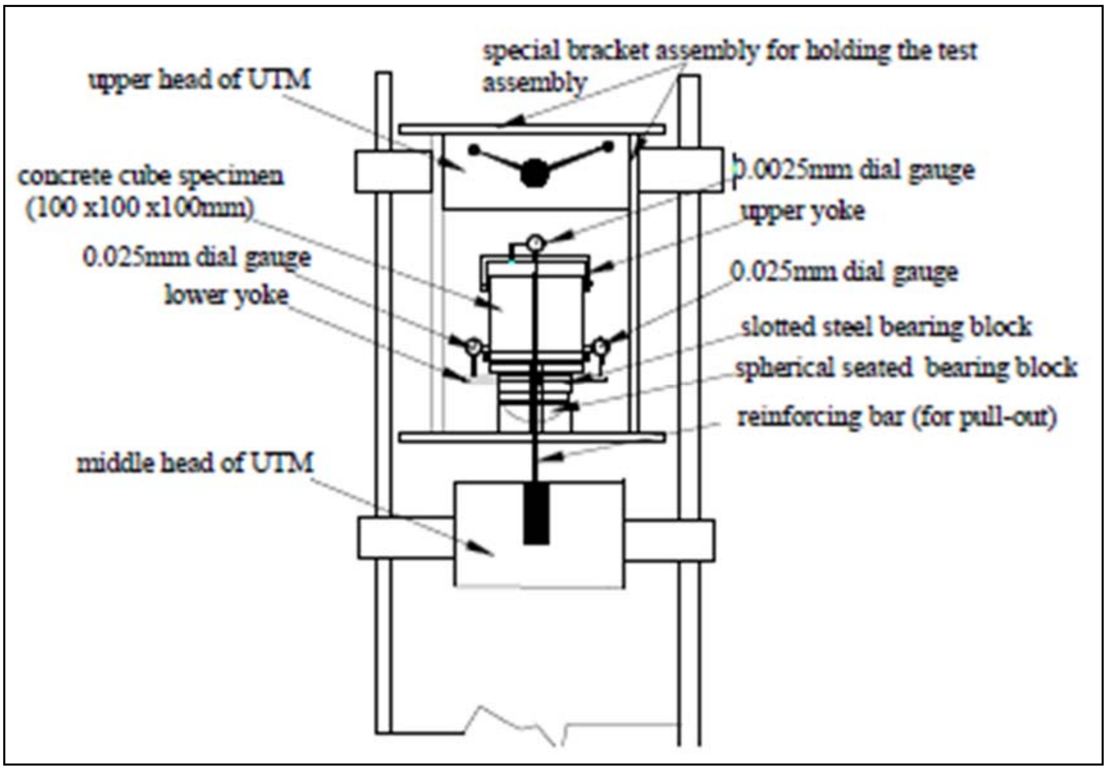


Figure (4): Pull-out test set-up

RESULTS AND DISCUSSION

Four groups of pull-out specimens were cast and tested. The first group of specimens was made of geopolymer concrete with 50% fly ash and 50% GGBS (abbreviated as F50GP). The second group was made of geopolymer concrete having 25% fly ash and 75% GGBS (abbreviated as F25GP). The third group was made of geopolymer concrete with 100% GGBS (abbreviated as F0GP). The fourth group was made of OPC concrete (abbreviated as OPCC). Depending on whether the specimens have been subjected to heat curing or not, the abbreviation letters N and H have been used. The elevated temperature to which the specimens were heated has been included in the specimen identification number. Further, abbreviations A and W have been considered respectively for air-cooled and water-cooled specimens. Thus, for instance, a specimen identification number F25GPN600W means a geopolymer concrete specimen with 25% fly ash (that is, 75% GGBS), cured normally, heated to 600 °C and water-cooled.

Table 3 shows the bond strength of geopolymer concrete specimens when kept under high temperatures and cooled under the two different conditions. Each value in the table was the test result of average ultimate bond strength of five samples in each category. It could be observed from Table 3 that the bond strength of geopolymer concrete containing fly ash and GGBS is more than the corresponding OPC with almost the same compressive strength. Similar behavior has been reported by others as well (He, Dai and Wang, 2020; Boopalan and Rajamane, 2017).

Table 3. The bond strength of geopolymer concrete after higher temperature exposure

Exposure temperature in °C	Nature of curing	Bond strength in MPa							
		F50 GP		F25GP		F0GP		OPCC	
		Air-cooled (A)	Water-cooled (W)	Air-cooled (A)	Water-cooled (W)	Air cooled (A)	Water-cooled (W)	Air - cooled (A)	Water cooled (W)
Ambient (28)	NC	20.38	-	21.06	-	22.29	-	18.68	-
	HC	20.86	-	21.86	-	23.17	-	-	-
200	NC	20.06	18.47	20.66	19.75	20.70	19.35	17.32	16.18
	HC	20.62	18.71	20.95	20.47	20.86	20.54	-	-
400	NC	18.59	16.00	18.95	17.83	19.90	18.39	14.51	14.02
	HC	18.67	16.61	19.09	18.04	20.22	18.87	-	-
600	NC	17.04	15.53	17.60	15.76	17.83	15.84	12.30	11.96
	HC	17.83	14.49	18.35	16.56	19.12	17.44	-	-
800	NC	7.01	5.73	7.25	5.73	7.32	5.14	9.80	8.85
	HC	10.03	8.80	9.45	7.73	8.92	7.01	-	-

Note: NC: Normal curing; HC: Heat curing.

F50 GP-Geopolymer concrete with 50% fly ash, F25 GP- Geopolymer concrete with 25% fly ash, F0GP- Geopolymer concrete with 0% fly ash (100% GGBS), OPCC- OPC cement concrete.

Generally, the bond strength of geopolymer concrete decreases when exposed to high temperatures. It may be noted that geopolymer concrete heat-cured specimens show higher bond strength in comparison with the normally cured specimens because of the impact of further polymerization of the specimen when kept under high temperatures.

It has been reported that under exposure to higher-temperature conditions, the "Si-OH in" geopolymer concrete is released and gives Si–O–(Si or Al) bond, which increases stability, connectivity and strength (Burduhos Nergis, Vizureanu and Corbu, 2019; Takeda et al., 2014). The average variation in bond strength of heat-cured specimens in the present case comes to 3% (the value varies between 0.4% and 10.1%) for a temperature exposure up to 600°C. However, this variation is higher at 800°C and heat-cured specimens showed average bond strength 36.7% higher than normally cured specimens (the value varies between 21.9% and 53.6%). It has been reported that sintering of un-reacted materials occurs at around 600°C and thereby a strong particle bonding develops, leading to increased strength (Rickard et al., 2015). It could also be noted that the degree of polymerization in geopolymer concrete is higher for heat-cured specimens and the corresponding enhancement in strength is related to the increased interconnectivity of particles through a densification process. However, for ambient-cured specimens, cellular destruction occurs at elevated temperatures (it is not severe in heat-cured specimens), resulting in micro-cracks and thereby strength reduction (Kong and Sanjayan, 2010). Because the residual bond strength of these specimens exposed to 800°C is very much less (less than 50% of the strength at ambient temperature), it could be inferred that heat-curing geopo1ymer concrete containing GGBS and fly ash has practically less effect on its bond strength.

Table 3 compares the effect of type of cooling when kept under higher-temperature conditions on bond strength and it can be inferred that specimens cooled with water have lower bond strength than air-cooled specimens, majorly because of the induced thermal shock and the resulting formation of micro-cracks in water-cooled specimens. Further, the rate of loss of bond stress in the case of geopolymer concrete is distinctly different after exposure to 600°C. However, the OPC concrete specimen showed more or less uniform reduction in bond strength up to 800°C. In the case of

OPC concrete, other researchers have also reported a similar observation (Yeddula and Karthiyaini, 2020; Li et al., 2017). In the present study, water-cooled geopolymer concrete showed a reduction in bond strength between 2.3% and 18.7% for samples that were heated at 600°C in comparison to the bond strength of air-cooled specimens. However, the corresponding bond strength reduction varied between 12.3% and 29.8% at 800°C, whereas, reduction in the bond strength in water-cooled OPC concrete is between 2.8% and 6.8% for specimens heated to 600°C and 9.7% for those heated to 800 °C. This shows that, in comparison with OPC, the bond strength in geopolymer concrete is affected more when it is exposed to sudden water cooling when subjected to high-temperature conditions. Dense and compact structure of the geopolymer concrete would have resulted in a greater number of cracks within the matrix due to thermal shock induced while water-cooling it.

The effect of temperature on residual bond strength of both geopolymer concrete and OPC concrete is presented in Fig. 5.

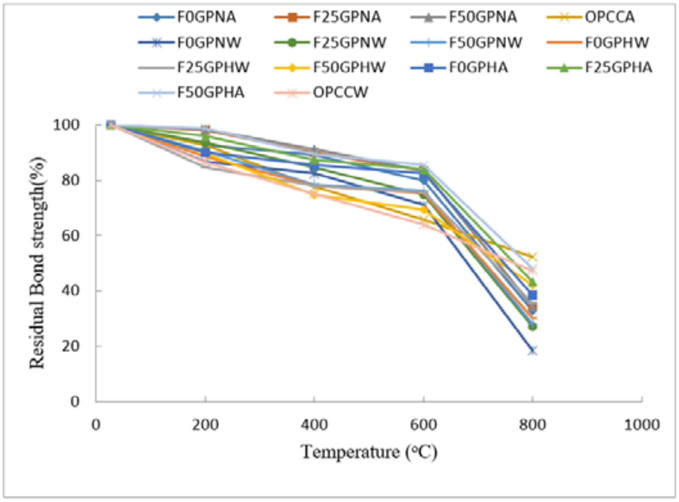


Figure (5): Effect of temperature on bond strength of OPC and geopolymer concrete

From Figure (5) above, it can be seen that, for geopolymer concrete, there is a more or less linear and gradual reduction in bond strength at 600°C, beyond which it reduces rapidly. It may further be noted that, in comparison with the bond strength of OPC concrete, the percentage strength reduction is less in geopolymer concrete up to 600°C. For the present case, while geopolymer concrete had a loss of 20% bond strength, the corresponding OPC concrete lost about 34% bond strength at 600°C. Better performance of geopolymer concrete may be because of the formation of a dense interfacial zone of transition between geopolymer matrix and aggregates in comparison with the cement matrix (Arioz, 2007; Zhang et al., 2005). However, beyond 600°C, the alumino-silicate network gets damaged, which is evident in the SEM images of geopolymer concrete, whereas reduction in bond strength in OPC remains uniform till 800°C. It has also been reported elsewhere that the bond strength of OPC concrete shows a linear reduction up to 800°C (Pofale and Wanjari, 2013; Sureshbabu and Mathew, 2020). This behavior of geopolymer concrete indicates that a sudden failure in bond strength is possible in the case of geopolymer concrete with fly ash and GGBS if exposed to a temperature above 600°C.

Considering the deformed reinforcing bars in concrete, their bond-slip behavior can be explained in three distinct stages. In the first stage, optimal bond strength is achieved, wherein only a fewer concrete shear keys amongst the ribs of reinforcements get crushed. Slip occurs in the next stage, but the bond strength developed at the first stage prevails for slip until most of the shear keys are crushed or sheared off. In the third stage, increased slip and associated reduced bond strength occur (CEB-FIP, 2009).

Figure 6 shows the bond-slip behavior of normal-cured geopolymer concrete with different fly ash contents (0%, 25% and 50%) and OPC concrete specimens that are not subjected to elevated temperatures.

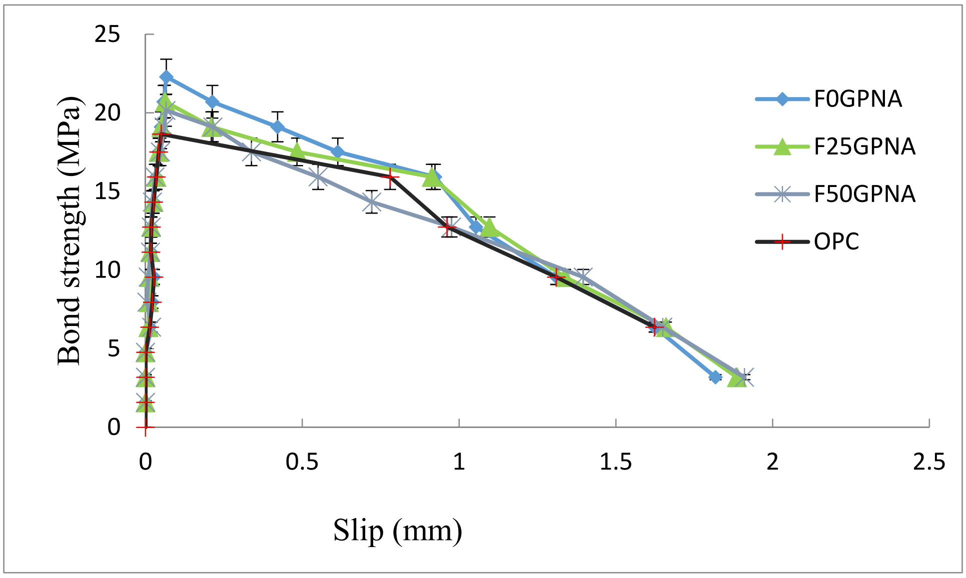


Figure (6): Normally cured geopolymer and OPC concrete bond-slip behavior

It is clear from Fig. 6 that while OPC concrete exhibits almost all three stages of the bond-slip relationship, the second stage is missing in geopolymer concrete. This could be due to the fact that the dense geopolymer structure and the resulting good bonding between the rebar surface and geopolymer concrete would have caused better bond strength development, leading to crushing of more shear keys at the peak bond strength of geopolymer concrete in comparison with OPC.

Figures 7 and 8 present the bond-slip graph of normal-cured geopolymer concrete with different fly ash contents (0%, 25% and 50%) and OPC concrete after they were kept under 600˚C and 800˚C, respectively.

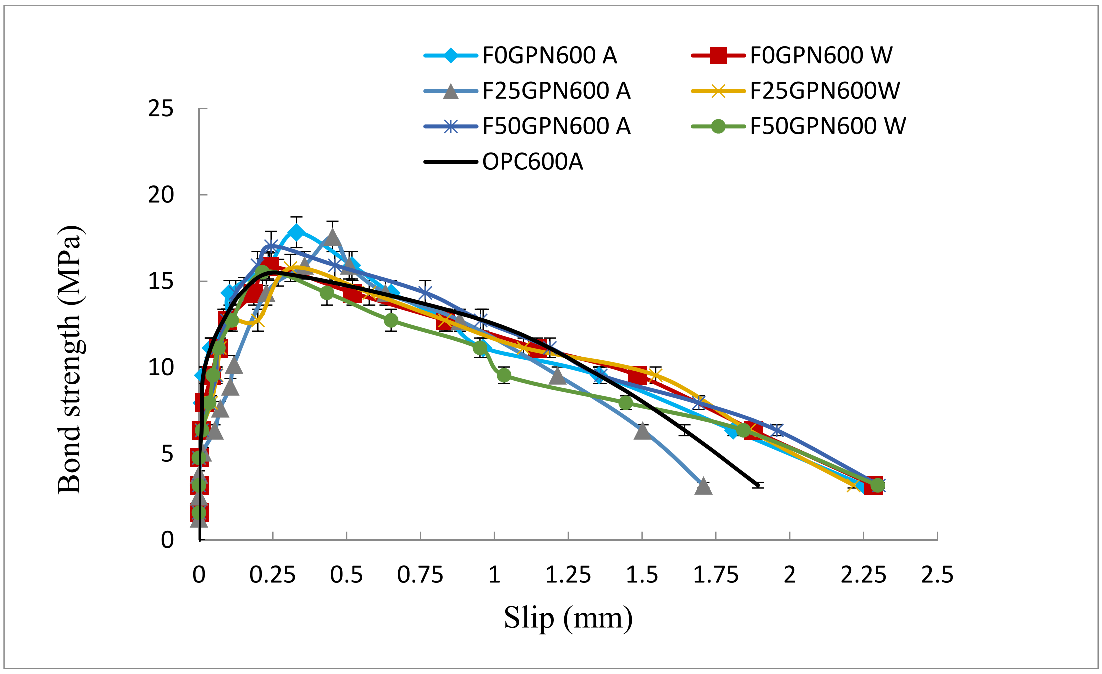


Figure (7): Relationship of geopolymer concrete (normally cured) and OPC concrete bond-slip after being exposed to 600˚C

It may be observed from Figs. 6 to 8 that, in comparison to OPC exposed under high-temperature conditions, geopolymer concrete undergoes more slip for ultimate bond strength, primarily due to crushing of more concrete shear keys at this stage.

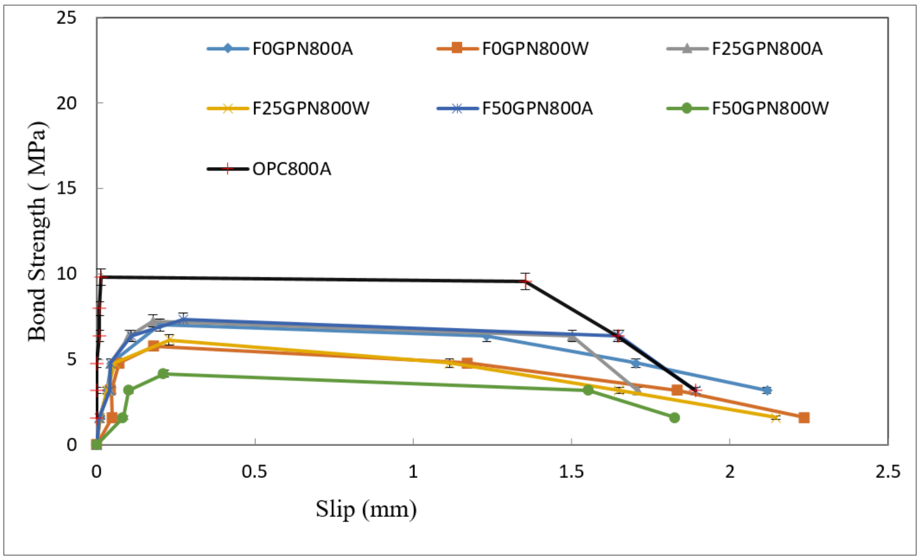


Figure (8): Bond-slip behavior of OPC and geopolymer (normally cured) concrete after exposure to 800°C

It may further be noted that, while OPC concrete shows almost all the three stages of bond-slip relationships till 800°C, this three-stage relationship is evident in geopolymer concrete only at 800°C. Beyond 600°C in geopolymer concrete, the bond gets weakened due to physical changes in the geopolymer structure, which results in low peak bond strength. At this stage, only fewer shear key failures occur and thus the peak value prevails for some specific slip value.

Critical bond strength of concrete may be considered as the bond strength corresponding to a 0.25 mm slip on loaded-end (Sofi et al., 2007; Pothisiri and Panedpojaman, 2012; Kim Hung et al., 2018; Melichar et al., 2017). The critical-to-ultimate bond strength ratio indicates the reserve strength in the specimen before it fails. The critical-to-ultimate bond strength ratios of the test specimens are listed in Table 4.

From Table 4, it can be seen that the ratio of critical to the ultimate bond strength of geopolymer concrete is more or less the same as that of OPC.

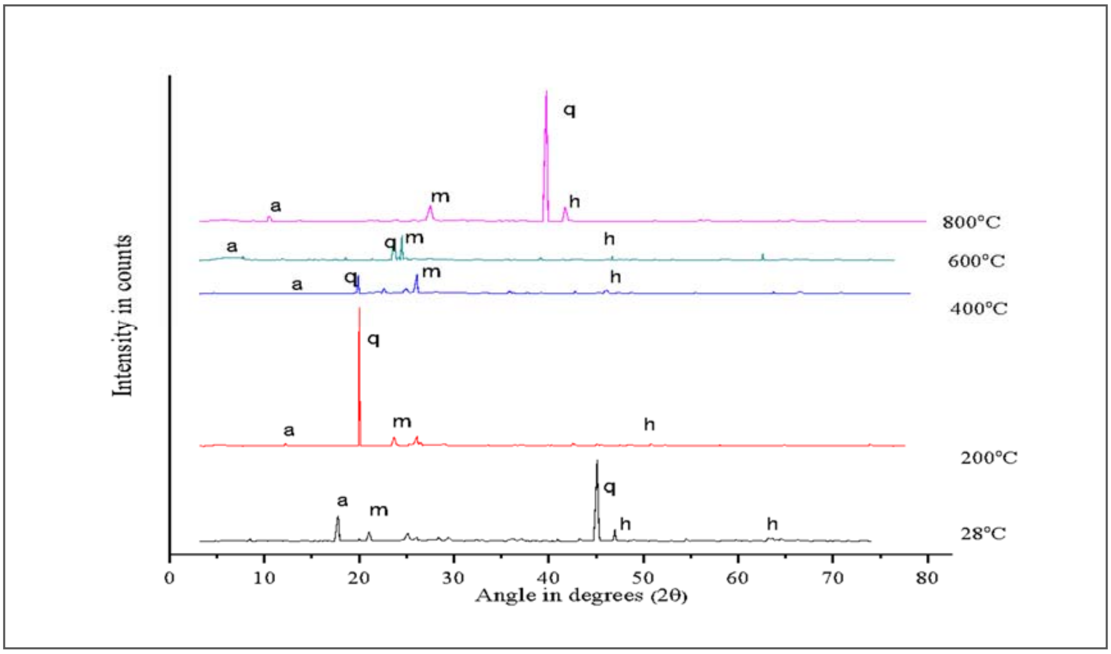
Table 4. Critical-to-ultimate bond strength ratios of test specimens

Exposure Temperature (°C)	Critical to ultimate bond strength ratio													
	F50GP				F25GP				F0GP				OPCC	
	NA	HA	NW	HW	NA	HA	NW	HW	NA	HA	NW	HW	NA	NW
Ambient (28)	0.89	0.91	0.86	0.87	0.73	0.76	0.71	0.73	0.70	0.74	0.70	0.72	0.68	0.67
200	0.86	0.88	0.82	0.85	0.82	0.85	0.79	0.82	0.80	0.83	0.76	0.79	0.68	0.66
400	0.93	0.94	0.89	0.91	0.92	0.94	0.89	0.91	0.91	0.93	0.88	0.89	0.77	0.76
600	0.98	0.99	0.91	0.93	0.93	0.96	0.90	0.91	0.92	0.93	0.89	0.91	0.78	0.77
800	0.99	0.99	0.94	0.97	0.95	0.97	0.91	0.93	0.93	0.94	0.90	0.92	0.81	0.80

NA: Natural curing, ambient cooling, HA: Heat curing, ambient cooling, NW: Natural curing, water cooling, HW: Heat curing, water cooling.

A lower value indicates more reserve strength before failure and as the value approaches 1.0, there is practically no reserve strength and failure could be sudden like a brittle failure. It may be noted that as the temperature increases, the critical bond strength approaches the ultimate bond strength. At 800˚C, the critical-to-ultimate bond strength ratio of geopolymer concrete is between 0.90 and 0.99. As opposed to this, the same in the case of OPC is between 0.98 and 0.99.

Figure 9 shows a typical XRD diffractogram of the geopolymer concrete, F50GPNA, after exposure to elevated temperatures.



a:albite m:mullite q:quartz h:halite

Figure (9): Typical XRD diffractogram of geopolymer concrete (F50GPNA)

It may be noted from Figure 9 that the crystalline phase of albite (a) and halite (h) changes towards the amorphous phase when heated to 200˚C, which creates a dense and compact polymeric matrix. On the other hand, the crystalline phase of quartz (q) and mullite (m) detected in the initial materials remains unaltered even up to 800˚C, which contributes to the friction in the inter-transition zone between concrete and the rebar. The bond strength is retained due to the existence of the crystalline phase. It may further be noted that the geopolymer concrete becomes mostly amorphous when heated to 800˚C. The amorphous nature provides a dense and compact polymeric matrix.

Typical SEM analysis results of geopolymer (F50GPNA) and OPC concrete (OPCCA) after being exposed to high-temperature conditions are as shown in Fig. 10.

From Fig. 10, it can be observed that geopolymer concrete matrix under ambient temperature remains homogeneous and dense and consists of alumino-silicate gel resulting from this polymerization method.

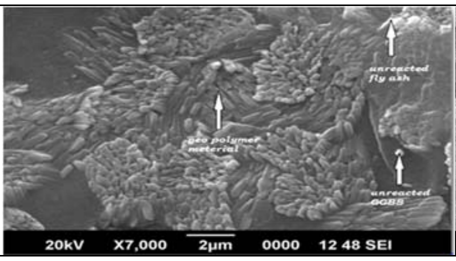
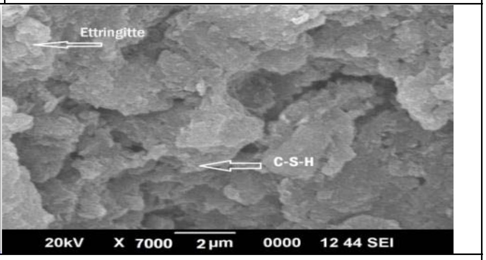
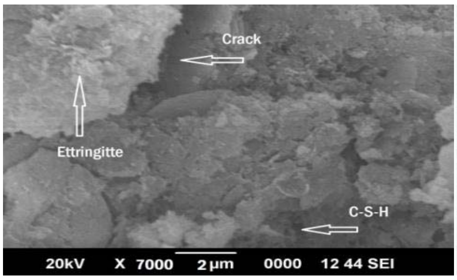
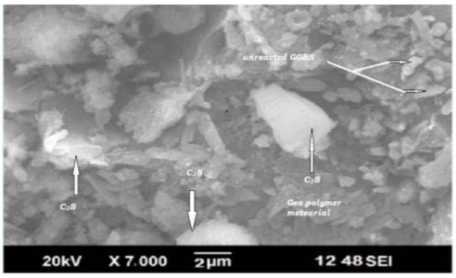
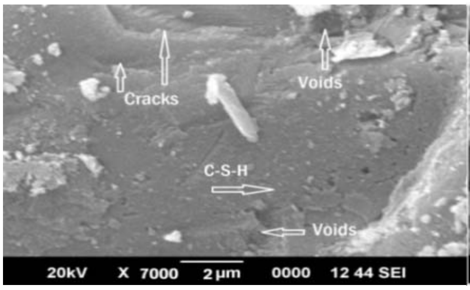
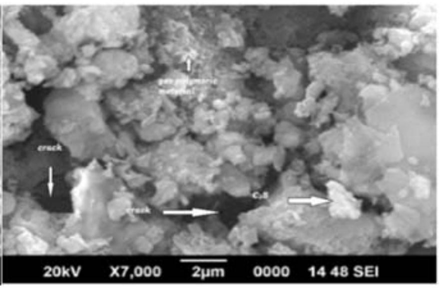
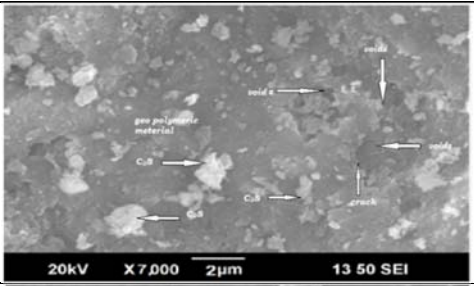
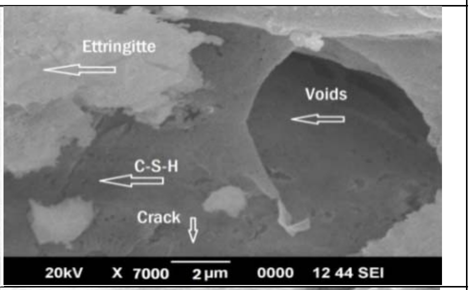
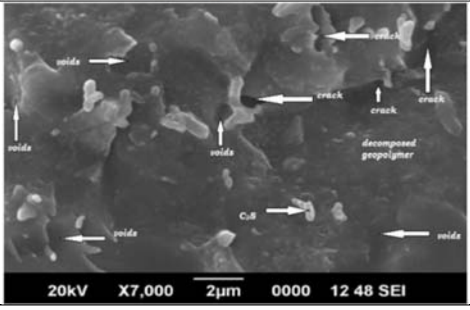
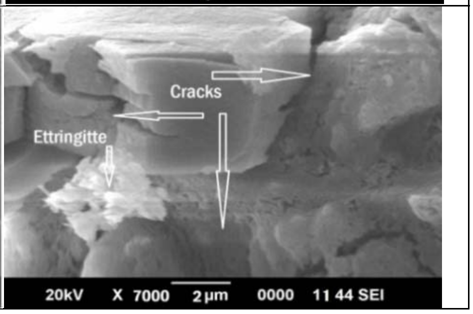
Exposure Temperature	Geopolymer concrete –F50GPNA	OPC concrete -OPCCA
Ambient (28 °C)		
200 °C		
400 °C		
600 °C		
800 °C		

Figure (10): SEM analysis results of geopolymer concrete F50GPNA and OPCCA when exposed to high temperature values

The SEM image of geopolymer concrete specimens at ambient temperature shows needle-like structures, indicating that it is more crystalline. Some un-reacted GGBS and fly ash crystals also could be observed at ambient temperature. At 200°C, C_2S could be observed in geopolymer concrete, which would have been formed by the reaction between Ca and Si present in the GGBS and fly ash. At 400°C, the dense compactness of the microstructure of geopolymer concrete decreases and starts developing cracks. At 600°C, cracks and voids, primarily due to the removal of chemically bound water and thermal incompatibility, could be observed in geopolymer concrete. At 800°C, the gel matrix of geopolymer concrete changes, which is evident from the damaged alumino-silicate network. The micro-cracks and voids increased at this stage; the samples became more porous and the structure became weak. A morphological change is evident in geopolymer concrete at this stage, which results in the reduction of compressive strength and bond strength.

However, in OPC concrete, crack formation could be noticed at 200°C. When the temperature reaches 400°C, the formation of wider cracks and voids could be observed. Other researchers have also observed similar behavior for OPC concrete exposed to elevated temperatures (Kumar and Ram, 2019). This stage could be visible in geopolymer concrete only at 600°C.

Numerous researchers have proposed bond strength prediction equations for conventional geopolymer concrete (with fly ash alone) after being subjected to higher temperatures (Chen et al., 2018; Zhang and Kodur, 2018). The experimental values when compared with predicted values using the available equations are as shown in Fig. 11.

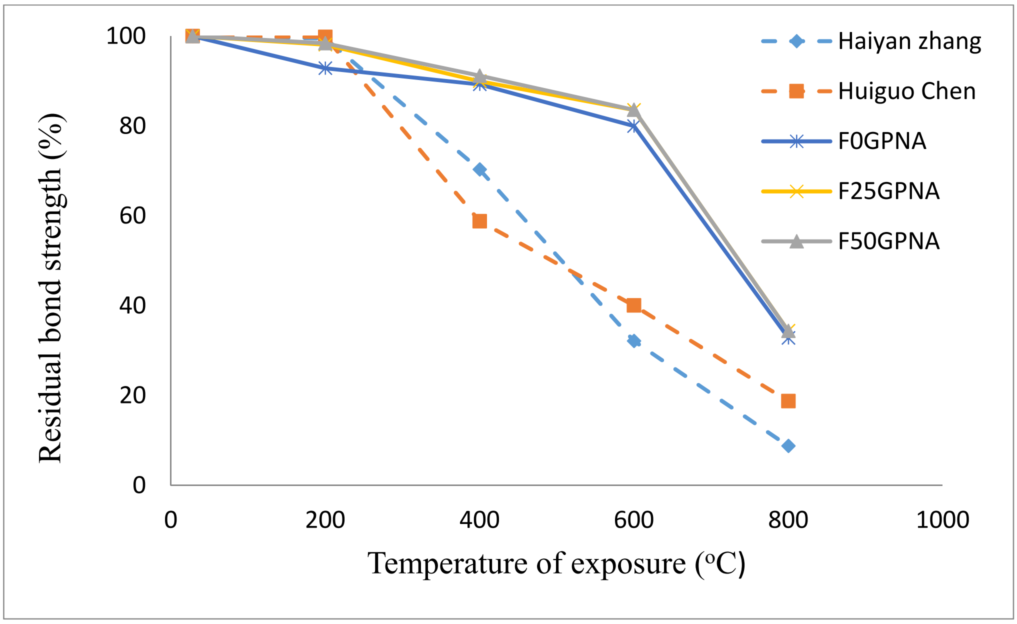


Figure (11): Experimental and theoretical prediction of bond strength: A comparison

From Fig. 11, it can be seen that the predicted geopolymer concrete bond strength is comparable with the experimental values up to 200˚C. However, beyond 200 ˚C, the bond strength of geopolymer concrete with GGBS and fly ash as alumino-silicate constituents is underestimated by the available equations. Hence, there is a need to have a better prediction model that will also consider the influence of GGBS on the bond strength of geopolymer concrete when exposed to higher temperatures.

Results of 270 geopolymer concrete specimens tested for the present study have been considered for the statistical analysis of proposed bond strength prediction model. Of these, 135 specimens were subjected to normal curing and 135 specimens were subjected to 90°C curing temperature for a total time of 24h. The parameters like the percentage replacement of GGBS with fly ash (0%, 25% and 50%), temperature exposure (ambient, 200˚C, 400˚C, 600˚C and 800˚C) and cooling procedures (water and air) are varied in each set. The ANOVA test was conducted with bond strength as the dependent variable. The percentage of fly ash and temperature exposure are the independent variables. The analysis has been done including the calculation of marginal means, pair-wise comparison and *post hoc* test by Tukey HSD method. The homogeneous subsets also were prepared as per Tukey HSD.

After the analysis, it is observed that there are significant differences ($p<0.001$) between mean bond strengths responding to various temperatures and fly ash percentages. The results of the one-way ANOVA test are presented in Table 5.

Table 5. Results of ANOVA conducted on geopolymer concrete bond strength

Model	Degree of freedom	Sum of squares	Mean square	F	Level of significance
Regression	2	475.402	241.4	200.437	0.00
Residual	267	86.353	1.182	-	-
Total	269	561.755	-	-	-

Dependent variable: bond strength.

Table 5 indicates that fly ash content and exposure temperatures are significant variables ($p<0.001$) and about 84% of the variance is explained using the regression test ($R^2=0.842$).

A linear equation, based on the regression analysis, was used to find a relation for bond strength at different temperature levels and percentages of fly ash content. A linear equation was derived concerning linear regression by a statistical analysis of the experimental results obtained for bond stress at high temperatures.

Linear regression analysis was carried out to find a relation between bond strength at different temperature levels and percentages of fly ash. The details are presented in Table 6.

Table 6. Regression analysis on bond strength of geopolymer concrete

Model	Un-standardized coefficient		Standardized coefficient	t	Level of significance
	B	Std. Error	Beta		
Bond strength	21.14	0.296	-	64.095	0.000
Temperature	-0.0031	0.000	-0.821	-18.061	0.000
Fly Ash	-0.006	0.011	-0.3024	-7.023	0.000

Dependent Variable: bond strength.

Equation (1) was used for predicting the bond strength of geopolymer concrete when it was exposed to high-temperature conditions, according to the regression analysis.

$$f_{bT} = f_{bo} - (0.0031*T) - (0.006P_{fa}), \text{ for } 28 < T < 600 \text{ and } 0<P_{fa}<25 \quad (1)$$

where,

f_{bT} = The bond strength of geopolymer concrete after exposure to temperature (T ˚C).

f_{bo}= The bond strength of geopolymer concrete in MPa under ambient temperature.

T = Exposure temperature (˚C).

P_{fa}= Fly ash percentage with GGBS (fly ash content).

(Example: the bond strength of F50 GP exposure to 400 ˚C, the bond strength at ambient temperature is 20.38 N/mm^2. as per the given equation.

f_{b400} = 20.38- (0.0031 x 400) - (0.006 x50) = 18.84, in Table 3, the experimental value obtained for the same is 18.59, this value is at par with the value obtained as per equation).

CONCLUSIONS

1) Geopolymer concrete that does not require temperature curing could be made effectively by replacing at least 50% fly ash and using GGBS by mass instead.
2) The bond strength of geopolymer concrete containing fly ash and GGBS, which does not require temperature curing, is more than that of OPC concrete with almost similar compressive strength.
3) While the bond strength of geopolymer concrete with GGBS and fly ash reduces more or less linearly up to 600°C, a high reduction rate is observed in bond strength beyond 600°C. On the other hand, OPC concrete shows a more or less uniform reduction in bond strength up to 800°C.
4) The influence of sudden cooling with water, after being subjected to higher temperatures, is significantly higher in geopolymer concrete with GGBS and fly ash in comparison with OPCC. The geopolymer concrete exhibited a bond strength reduction of 20.2% and 8.6% for specimens heated up to 800°C and 600°C, respectively as against the bond strength of air-cooled specimens. For OPC, the corresponding values were 4.3% and 9.7%.
5) In comparison with OPCC, there exists a high slip corresponding to an ultimate bond strength in geopolymer concrete, once it was subjected to higher temperatures.
6) The second stage of the generally observed three stages of a bond-slip relationship in conventional concrete (initial stage on which maximum bond strength is observed; second-maximum values are still prevailing for a specific slip; and third-when bond strength decreases with increasing slip) is missing in geopolymer concrete with GGBS and fly ash content. A dense geopolymer structure and the resulting good bonding between the rebar surface and geopolymer concrete would have caused most of the shear keys to crush on the peak bond strength of geopolymer concrete. However, when the temperature increases to 800 °C, all three stages are observed in geopolymer concrete.

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