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INTERFACE SHEAR STRENGTH OF FLY ASH BASED GEOPOLYMER CONCRETE

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ABSTRACT: This paper presents an experimental investigation conducted to study the influence of aggregate content on the interface shear strength of geopolymer concrete and to compare it with that of Ordinary Portland cement concrete. Further, it has been proposed to check the suitability of existing equations for OPC concrete for assessing the shear capacity of geopolymer concrete. Push-off specimens were used to study the interface shear strength. Both reinforced and unreinforced concrete specimens were used for the study. It has been observed that the shear strength of geopolymer concrete is inferior to OPC concrete and that an aggregate content less than 65% in geopolymer concrete leads to a drastic reduction in its shear capacity. A 50% reduction in the value has been suggested to predict the shear strength of geopolymer concrete (with an aggregate content at and above 65%) if it is predicted based on the equations available for the shear capacity of OPC concrete.

KEYWORDS: Aggregate, Interface Shear, Fly ash, Geopolymer concrete

INTRODUCTION

Cement is one of the most energy intensive construction material and its production involves very high temperature (1400°C to 1500°C) processing and leads to the uncontrolled quarrying of natural resources and emission of CO_2 (green house gas). Many efforts are being made to reduce the use of Portland cement in construction. These efforts include the utilization of supplementary cementitious materials as well as use of alternate materials in place of Portland cement. Geopolymer (GP) concrete is one of such alternatives to replace the Portland cement in concrete.

Geopolymers are formed by alkaline activation of an aluminosilicate material. The formation of three dimensional structure of geopolymer involves the basic chemical reactions such as dissolution, hydrolysis and condensation. Depending on the ratio of Silica to Alumina, there could be geopolymer with either Si-O-Al or Si-O-Si bond [1-3]. Review of literature shows that Fly ash, metakaolin, rice husk ash, red mud etc. are the generally used alumino-silicate material and the alkali solutions include sodium hydroxide, potassium hydroxide, sodium silicate, calcium silicate etc.[4-8] .

GP concrete is best suited for precast construction. However, the connective distress found in precast construction is centered around the shear interfaces (Place where shear stress causes sliding type of failure along a well defined plane) associated with corbels, bearing shoes, ledger beam bearing, coupled shear wall, wall to foundation, deep beams etc.[9-11]. Study of shear- slippage at the interface of both monolithic and precast construction is very important in such instances.

Studies have been conducted in the past to understand the interface shear strength in ordinary portland cement (OPC) concrete. Birkeland et al. [12] proposed a shear friction concept to evaluate the interface shear strength of concrete block. Their hypothesis suggests that the external shear load tends to produce slippage along the interface plane and it is resisted by the shear friction and not by bond. They further proposed that, the reinforcement across the interface is stressed in tension and that the dowel action is insignificant. Accordingly, the ultimate shear capacity across the interface of a monolithic concrete with reinforcement across the shear plane has been calculated as $A_s \times f_y \times \tan ø$, where A_s and f_y are the total cross sectional area of the reinforcement across the shear plane and yield strength of reinforcement respectively. The angle of internal friction, ø varies with the nature of interface and is to be determined by tests. They have suggested a value of 1.7 for 'tan ø'. Mast [13], based on the experimental study on monolithic concrete and concrete having crack at the interface, has suggested that the value of 'tan ø' ranges between 1.4 and 1.7. He proposed a lower bound value of 1.4 for design purposes. Hofberck [14] reported a study on the shear strength of reinforced concrete with and without a crack existing along the shear plane of push off specimens and concluded that shear transfer stress depends on initial crack condition, product of reinforcement ratio and yield strength of shear reinforcement. It is suggested that, the dowel action of reinforcing bars *crossing the shear plane is insignificant in initially uncracked concrete, but is substantial in concrete with a pre-existing crack along the shear plane.*

The shear-friction design proposed by ACI suggested the value of coefficient of friction (μ or tanø) for monolithically placed concrete as 1.4λ, where the value of λ for normal weight concrete is one[15]. The value of λ depends on the type of concrete; namely normal weight (λ =1), sand lightweight (λ = 0.85) and all lightweight (λ = 0.75). On the basis of experimental investigations using push-off specimen, Mattock [16] proposed an alternate equation for predicting the ultimate interface shear capacity, given by $V_u = 0.8 (A_s f_y) + (A_c\ 400\ \text{psi})$*. Mattock [17] and Lawrence [18] have conducted experimental research and proposed modification to the ACI equation [15] to predict the interface shear strength of high strength concrete. It could be concluded that, the interface shear strength of concrete depends on various parameters such as type of concrete, type of aggregate, cohesive strength of concrete, percentage of reinforcement across the shear plane, etc.. However, the study on shear transfer strength of geopolymer concrete has not been reported in literature. Hence, it has been proposed to carry out an experimental investigation to study the interface shear behavior of geopolymer concrete.*

EXPERIMENTAL PROGRAM - Materials

☐ *Cement*

53 Grade Ordinary Portland Cement conforming to BIS [25] was used in the present study.

☐ *Fly ash*

Low calcium fly ash (ASTM Class F), having a specific gravity of 1.9, was used as the alumino-silicate source material for making geopolymer binder. The chemical composition of fly ash as determined by XRF analysis is presented in Table 1. The particle size distribution of fly ash is presented in Fig. 1. From the X-ray Diffraction analysis, it is observed that the of fly ash used was amorphous with very small percentage of crystalline material like Quartz, Mullite and Sillimanite and the result of this analysis is depicted in Fig. 2.

Table 1: Chemical composition of fly ash

Sl. No	*Parameter*	*Content (% by mass)*
1	SiO_2	59.70
2	Al_2O_3	28.36
3	Fe_2O_3+Fe_2O_4	4.57
4	CaO	2.10
5	Na_2O	0.04
6	MgO	0.83
7	Mn_2O_3	0.04
8	TiO_2	1.82
9	SO_3	0.40
10	Loss of ignition	1.06

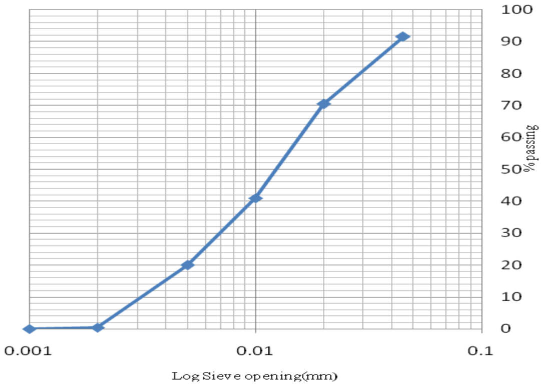

Fig .1 Particle size distribution of fly ash

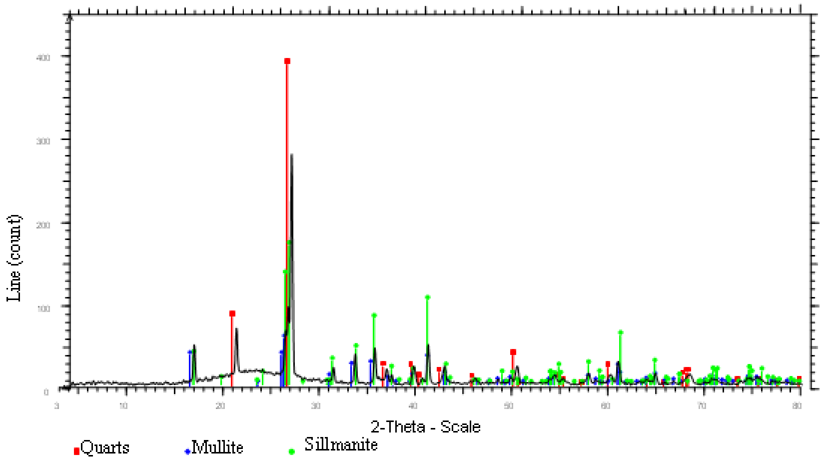

Fig 2 . XRD of Fly ash

☐ *Alkali*

A mixture of NaOH and Na_2SiO_3 *solution (*SiO_2 *= 34.64%,* Na_2O*= 16.27%, water 49.09%) was used as alkali. NaOH pellets of 98% purity were used to make sodium hydroxide solution of molarity 10. The specific gravity of the made up solution was 1.54*

☐ *Aggregates*

Crushed granite aggregate of nominal size 20mm was used as coarse aggregate. Natural river sand was used as fine aggregate. The specific gravity of course and fine aggregates was 2.72 and 2.64 respectively. The fine aggregate had a fineness modulus of 2.36.

☐ Mixture Proportioning

The quantity of different constituents of the mixture has been arrived based on a preliminary study conducted and its details are presented elsewhere [26]. Accordingly, the ratio of fine aggregate to total aggregate (=0.35), ratio of alkali to fly ash (=0.55), molarity of NaOH (=10), ratio of $Na_2 SiO_3$ to NaOH (=2.5), ratio of water to geopolymer solid (=2.5) were kept constant in the present investigation. The total aggregate content in the mixture was varied from 60% to 75% of the volume of GP concrete. A reference OPC concrete mixture proportion has also been arrived base on a trial and error method, such that, its compressive strength is almost the same as that of the GP concrete having maximum compressive strength. Table 2 shows the quantity of materials required to produce 1m^{3}of GP concrete and OPC concrete.

☐ Mixing and casting

The prepared solution of NaOH was first mixed with the calculated amount of Na_2SiO_3. The resulting alkali liquid was stirred well and kept for 24 hours before use. The required quantities of fly ash, coarse and fine aggregates in saturated surface dry conditions were dry mixed in a pan mixture. The alkali liquid, after mixing with 2% (by weight of fly ash) of Naphthalene based Superplastisizer was then added to the dry mix and the whole mixture was mixed well for another 5 minutes.

Table 2. Quantity of materials for 1 m^3 of geopolymer concrete

Sl.No.	Mix ID	Total Aggregate %by volume	Fine aggregate/ Total agg.	Coarse aggregate (kg)	Sand (kg)	Fly ash (kg)	Alkali Content (kg)	Super Plasticizer (kg)
1	GP60	60	0.35	1031.99	555.73	420.57	231.31	8.41
2	GP65	65	0.35	1117.99	602.04	365.16	210.84	7.3
3	GP70	70	0.35	1203.99	648.35	309.85	170.41	6.2
4	GP75	75	0.35	1289.99	694.66	254.54	139.99	5.1
5	OPC	0.67	0.39	1279	500	-	-	1.9

100 mm x 200 mm x 500 mm size push-off specimens were cast in steel moulds. V-groves of 4mm deep were made on either sides of the specimen along the shear plane with the help of standard angles. The push-off specimens were cast with and without dowel bars. Two numbers of 8 mm diameter dowel bars, having yield strength of 435 MPa, were placed across the shear plane (0.99 %), in the form of closed link. Additionally, 10 mm diameter bars and 8 mm diameter stirrups were provided to prevent the premature failure at the loading points for all specimens. Schematic diagram of push-off specimen showing the dimensions and details of reinforcements is presented in Fig.3.

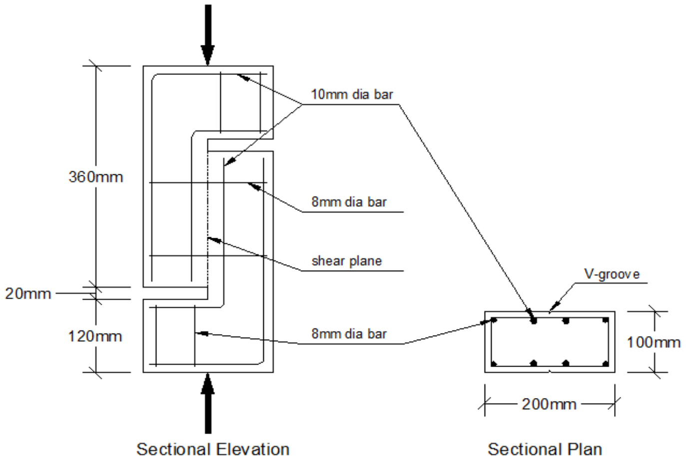

Figure 3. Details of Push -off specimen

In addition to the push-off specimens, cubes of size 150mm; beams of size 100mm x 100mm x 500mm; and cylinders of size 150 mm diameter and 300 height were cast in standard steel moulds to determine various strength properties.

The concrete, after placing in moulds, were compacted with the help of a table vibrator. In the case of specimen with GP concrete, the top side of moulds was covered with a steel plate and edges were sealed properly to avoid the loss of moisture from specimens during heat curing. The GP concrete specimens were subjected to heat curing in an electric oven at 100 °C for a period of 24 hours. The curing temperature and period were arrived at based on a preliminary study [20]. After the temperature curing, the specimens were de-moulded and were kept in room temperature till it was tested (on 28th day).The specimen with OPC concrete were removed from moulds after 24 hours from the time of casting and were then kept for water curing till the day of testing (on 28th day).

TESTING OF PUSH-OFF SPECIMEN

The experimental set up for the push-off specimen is presented in fig. 4. Axial load was applied on push- off specimens at regular intervals until failure occurred. Average shear strength of the concrete was calculated on the basis of the area of shear plane. Dial gauges were used to measure the relative slip at the shear plane.

ANALYSIS OF TEST RESULT

The values presented in tables and the points shown in figures correspond to the average test result of three sample specimens.

Table 3. Mechanical properties of Concrete (28th day)

S.l. No.	Mix ID	Cube compressive Strength MPa	Split Tensil Strength MPa	Flexural Strength Mpa
1	GP60	45	3.1	3.79
2	GP65	47	3.34	3.82
3	GP70	56	3.45	4.74
4	GP75	49	4.51	4.95
5	OPC	58	4.39	4.79

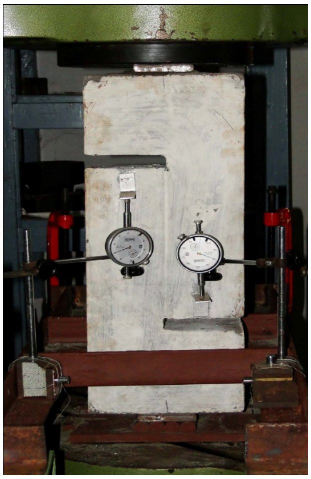

Fig.4 Test Setup for slip measurement

Different strength test results on various concrete specimen cast are presented in Table 3. From this table, it may be noted that the OPC concrete and GP70 concrete have almost the same cube compressive strength. Their aggregate contents are respectively 67% and 70%.

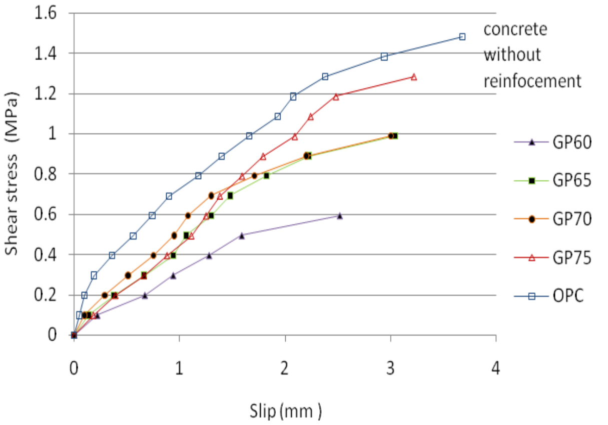

Figure 5. Variation of slip with interface shear stress in specimen without shear reinforcement

Figure 5 presents the variation of slip with interface shear stress in push-off specimens in which no shear reinforcement across the shear plane has been provided. From this figure, it is clear that, for a given value of shear strength of geopolymer specimen, the slip is more with lower aggregate content. Further, as the aggregate content increases, the ultimate shear strength also increases. This is primarily due to the improvement of the cohesive strength of concrete and better aggregate interlocking at the interface with higher percentage of aggregate content. It has been reported that, for low steel ratio cohesive strength of concrete have considerable influence on interface shear strength [13].

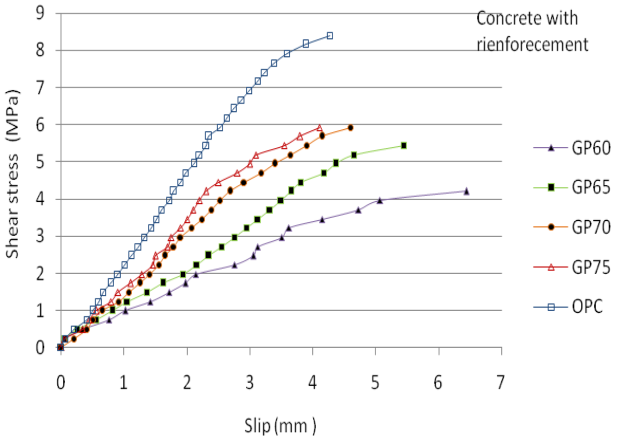

Figure 6. Variation of slip with interface shear stress in specimen with shear reinforcement

Figure 6 depict the variation of slip with shear stress in push- off specimen with 0.99% shear reinforcement. This also shows a similar behavior as that of the specimen without shear reinforcement. Hence, it could be stated that, for a given interface shear stress, a GP concrete with an aggregate content less than 65% shows large slip values. It may be further noted from Fig. 5 and 6 that, for a given shear strength, the slip of GP specimen is more than that of the OPC specimen which has almost the same compressive strength of GP specimen (GP70) for specimens with and without shear reinforcement. The OPC and GP70 had respectively 67% and 70% total aggregate content. This clearly shows that the cohesive strength of GP concrete is inferior to OPC concrete as far as the interface shear resistance is concerned.

The ultimate shear strength of specimens tested is presented in Table 4. From this table, it could be observed that, the shear strength of both the types of GP specimens (unreinforced and reinforced) reduces rapidly when the total aggregate content is lower than 65%. Further, while unreinforced GP specimen shows an increase in shear strength with increase in aggregate content, the GP specimen with shear reinforcement shows no significant variation (about 8% only) in shear strength for an aggregate content more than 65%. This proves that, the contribution of cohesive strength in the development of ultimate interface shear *resistance of GP concrete is negligible if its aggregate content is more than 65%. (one of the assumptions in the development of interface shear friction theory).*

From Table 4, it could be observed that with 0.99 %, shear reinforcement, the ultimate shear strength of OPC specimen is increased by about 4.5 times and that of GP70 is increased by about 5 times. The other GP concrete specimen had an average increase by about 4.5 times when shear reinforcement was provided.

Table 4. Ultimate shear stress in Push-off specimen

Specimen ID	Un reinforced specimen		Reinforced specimen	
	Ultimate Load (kN)	Ultimate shear Strength (MPa)	Ultimate Load (kN)	Ultimate shear Strength (MPa)
GP60	12	0.59	85	4.19
GP65	19	0.94	110	5.43
GP70	20	0.99	120	5.92
GP75	26	1.28	120	5.92
OPC	30	1.48	170	8.34

The crack pattern at failure load for both unreinforced and reinforced GP concrete specimens were the same and a typical crack pattern is shown in Fig.7. Comparing OPC concrete that has almost same compressive strength of GP concrete (GP70), it could be observed from table 4 that, the ultimate shear strength of GP concrete is inferior to OPC concrete. For the present study, compared to OPC concrete, a reduction in the strength by 33% and 29% was observed for unreinforced and reinforced GP specimens respectively. Hence, the equations available to calculate shear capacity of OPC concrete may overestimate the shear capacity of GP concrete.

Figure 7. Crack pattern in reinforced push-off specimen GP60

Table 5 compares the experimental shear capacity of reinforced specimen with the empirical formula available in literature [13, 15,16]. From this table, it may be observed that the empirical formula proposed for OPC concrete, when used in GP concrete overestimates the shear capacity for GP concrete if its aggregate content is equal to and less than 65%. In the present study, while Mast [13] overestimates the shear strength by about 43% for 60% aggregate content (GP60), the value is only about 2% for GP concrete with 75% aggregate content(GP70). On the other hand, the shear strength of OPC concrete specimen is underestimated by about 28% to 32% when different formulae [13, 15, 16] are used to predict the shear strength. Since no equation is available for the prediction of shear strength of GP concrete it is recommended that, only 50% of the predicted shear strength based on the available equations can be considered as the shear strength of GP concrete which has an aggregate content above 65%. However, further study has to be carried out to propose a more refined estimation of interface shear strength of geopolymer concrete.

Table 5. Comparison of Shear capacity of reinforced concrete with the calculated value using empirical formula

Specimen I D	ULTIMATE LOAD EXPERIMENTAL VALUE $P_{U\,EXP}$ (KN)	Ultimate load Theoretical value P_{Uth} kN)			$P_{u\,exp}/\ P_{U\,the}$		
		Mast	Mattock	ACI	Mast	Mattock	ACI
GP60	85	122	119	116	0.69	0.71	0.73
GP65	110	122	119	116	0.90	0.92	0.94
GP70	120	122	119	116	0.98	1.00	1.03
GP75	120	122	119	116	0.98	1.00	1.03
OPC	170	122	119	116	1.41	1.42	1.46

From this table, it may be observed that the empirical formula proposed for OPC concrete, when used in GP concrete overestimates the shear capacity for GP concrete if its aggregate content is equal to and less than 65% . In the present study, while Mast [17] overestimates the shear strength by about 43% for 60% aggregate content (GP60), the value is only about 2% for GP concrete with 75% aggregate content (GP70). On the other hand, the shear strength of OPC concrete specimen is underestimated by about 28% to 32% when different formulae [17, 19, 20] are used to predict the shear strength. Since no equation is available for the prediction of shear strength of GP concrete it is recommended that, only 50% of the predicted shear strength based on the available equations can be considered as the shear strength of GP concrete which has an aggregate content above 65%. However, further study has to be carried out to propose a more refined estimation of shear strength of geopolymer concrete.

CONCLUSIONS

Following conclusions could be derived based on the present study.

☐ *For a given interface shear stress, geopolymer concrete specimen shows more slip compared to OPC concrete specimen.*

- ☐ *The interface shear strength of geopolymer concrete is inferior to OPC concrete. In the present study, compared to OPC concrete, a reduction in the strength by 33% and 29% was observed for unreinforced and reinforced geopolymer specimens respectively.*
- ☐ *The interface shear strength of both unreinforced and reinforced geopolymer specimens reduces rapidly when the total aggregate content is lower than 65%.*
- ☐ *The enhancement in shear strength of reinforced (with 0.99% steel) geopolymer concrete specimen is not significant (about 8% only) for an increased aggregate content above 65%*
- ☐ *The equations available to calculate shear capacity of OPC concrete very much overestimate the shear capacity of geopolymer concrete if its aggregate content is less than 65%.*
- ☐ *50% of the value obtained using the prediction equation available(Mattock and ACI)for the shear capacity of OPC concrete can be considered as the predicted shear capacity of geopolymer concrete with an aggregate content 65% and above.*

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