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An experimental investigation on shear strength of monolithic geopolymer concrete interface

B. Sumanth Kumar* and D. Rama Seshu*,✉

✉ Email: drseshu@nitw.ac.in

*Department of Civil Engineering , National Institute of Technology, Warangal, INDIA

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In recent times the Geopolymer Concrete (GPC) is gaining significance from the point of development of eco and environment friendly concrete using Industrial by-products. The evaluation of mechanical characteristics of GPC paves the way for its structural use. In this paper the experimental study on shear strength of monolithic GPC interface is presented. This study includes different strength of GPC with and without reinforcement crossing the shear plane. The push off specimen prepared using GPC, were cast and tested. The results indicated that the shear strength of monolithic GPC interface has increased at higher rate up to GPC compression strength of 40 MPa. The presence of reinforcement across shear plane caused an increase of about 28% of the shear resistance against slip. The prediction equation proposed for the shear strength of GPC consists of contribution from friction, cohesion and dowel action of reinforcement at the interface. The push off test results was used to predict the coefficient of cohesion and coefficient of dowel action influencing the shear strength of GPC.

KEYWORDS: Geopolymer concrete; shear strength; binder index; cohesion; friction; dowel action.

Manufacturing of Ordinary Portland cement (OPC) contributes about7% of global green house gas emissions[1]. To minimize the ecological impact and bringing sustainability in concrete production, the industrial by-products like fly ash, ground granulated slag or a mixture of fly ash, slag and other natural waste materials are being used in the production of concrete. In the production of Geo-polymer Concrete (GPC) the source materials such as fly ash, GGBS which are rich in silicon (Si) and aluminum (Al), are stimulated using high alkaline liquids such as Sodium Hydroxide Solution and Sodium Silicate Solution, and produces the alumino silicate gel binders. This process is known as geo-polymerization. As an outcome, a new material was developed and named as 'Geo-polymer Concrete (GPC)'[2-4].The literature available indicates that the research on Geopolymer concrete include its characterization[5], evaluation of mechanical strength[6] and mix design[7,8].

The evaluation of shear friction characteristics of GPC assume the significance from the point of using as structural material and finds applications in concrete corbels, beam column junctions, beam-slab interface. Several types of test specimens like Splitting, Corbel with moment, Pull-off etc. are investigated in the determining the shear strength of concrete. The Push-off specimens (Fig.1) being most appropriate and widely used due to shear transfer across interfaces against other type of specimens, which induces both shear and moment[9,10]. The results of push-off tests were used in proposing shear – transfer models for concrete[11-13]. Different models were available in the literature for calculating the concrete shear transfer strength[14-19]. Numerous design expressions were proposed to envisage the shear stress at the concrete interface. The most significant contributions are presented in Table 1. Majority of design codes considered the shear-friction theory for concrete structures[11,13,20].

Some of the shear strength expressions proposed in literature comprises the influence of three load mechanisms i.e., contribution of cohesion, because of interlocking between aggregates; friction, because of slip among different concrete layers and is effected by normal stress and roughness at the interface; and dowel action, due to the presence of reinforcement across the interface[21,22].

RESEARCH SIGNIFICANCE

The review of literature indicates that the shear strength of concrete is influenced mainly by the effect of cohesion, because of the interlocking between aggregates; friction, because of longitudinal relative slip among concrete layers and influencing by normal stress and surface roughness at shear interface; and dowel action, due to the presence of shear reinforcement across the interface. In present investigation the shear capacity of monolithically cast GPC interface were evaluated by testing of push off specimens. The shear strength was analyzed based on the shear friction concept that includes cohesion, friction and dowel action components[13,20,21].

This paper presents an experimental investigation on the shear strength of monolithic GPC interface by casting and testing of push off specimens. The variables considered in the investigation are the strength of GPC with and without the reinforcement crossing the shear plane. Coefficient of cohesion for GPC has been predicted based on tests conducted on push off specimens without reinforcement across the interface (Unreinforced GPC) in relation to binder index of GPC, further the Coefficient of dowel action reinforcement in GPC is predicted based on tests conducted on push off specimens with reinforcement across the interface (Reinforced GPC), considering shear as function of three mechanisms i.e., cohesion, friction and dowel action.

EXPERIMENTAL PROGRAM

The experimental program consists of casting and testing of 18 push off specimens, which were cast in 3 batches representing three grades (M20, M30 and M40 grades named as GA, GB and GC) of GPC. Each batch consists of two sets of push off specimens representing with or without reinforcement i.e. No reinforcement (NR) and with reinforcement (WR) across the monolithic shear interface. In each set three identical specimens (S1, S2 and S3) were cast and tested and the average behavior is taken to represent the behavior for that set of three

TABLE 1
SHEAR FRICTION CONTRIBUTIONS

Researchers	Design Expression	Remarks
Birkelandand Birkeland[14]	$v_u = \rho f_y \tan\varphi = \rho f_y \mu$	tan φ equals to 1.7 for concrete placed monolithically.
Mattock and Hawkins[17]	$v_u = 1.38 + 0.8\left[\rho f_y + \sigma_n\right]$	For $v_u \le 0.3 f'_c \le 10.34 MPa$, $\rho f_y + \sigma_n \ge 1.38 MPa$
Loov (1978)[23]	$v_u = k\sqrt{f_c\left[\sigma_n + \rho f_y\right]}$	σ_n is the clamping stress $k = 0.5$ for initially uncracked shear interfaces
Walraven, Frenay & Pruijssers (1987)[24]	$v_u = C_1\left[\rho f_y\right]^{C_2}$ $C_1 = 0.822 f_C^{0.406}$; $C_2 = 0.159 f_C^{0.303}$	f_C is the compressive strength of 150mm concrete cubes
Randl (1997)[21]	$v_u = C f_c^{1/3} + \mu\left[\sigma_n + \rho k f_y\right] + \alpha\rho\sqrt{f_y f_c} \le \beta v f_c$	The Values of the design parameters such as *C, μ, k, α* and *β* are dependent on the roughness at the interface.

TABLE 2
CHEMICAL COMPOSITION OF FLY ASH AND GGBS (% BY MASS)

Binder material	SiO_2	Al_2O_3	Fe_2O_3	SO_3	CaO	MgO	Na_2O	LOI
Fly ash	60.11	26.53	4.25	0.35	4.00	1.25	0.22	0.88
GGBS	37.73	14.42	1.11	0.39	37.34	8.71	--	1.41

push off specimens. Each specimen was designated by the grade of GPC, with or without reinforcement across the shear interface and serial number of the identical specimen. Thus the push off specimen whose designation GBNRS2 stands for GB grade (i.e. M30) of GPC concrete having no reinforcement (NR) across the shear interface and second identical specimen in the set. Also three cubes were cast and tested along with each specimen to determine the compressive strength. The details of specimens tested along with respective compressive and shear strength are given in Table 4.

Materials used

Fly ash and GGBSare used as binders which were procured from NTPC power plant, Ramagundam, India and JSW Cements Pvt ltd, Bilakalagudur, India respectively. The Specific gravity of GGBS and Fly ash are 2.90 and 2.17 respectively. Table 2 shows the details of chemical compositions.

Fine Aggregate: River sand conforming to Zone-IIof IS: 383 (2016)[25] was used as fine aggregate. The specific gravity and bulk density of sand are 2.65 & 1.45 g/cm3respectively.

Coarse Aggregate: Well graded aggregate conforming to IS: 383 (2016)[25] with 20mm nominal size of granite is used as coarse aggregate.2.80 and 1.5g/cm^3 are specific gravity and bulk density respectively.

Water: Potable water was used in the experimental work.

Alkaline Solution: Combination of Sodium Hydroxide Solution (8 Molarity) and Sodium Silicate Solution in the ratio of 1:2.5. The alkaline solution is stored at room temperature (25±2°C) for 24 hours with relative humidity of 65% before using it in the casting of GPC push off specimens.

Mix proportions

The GPC Mix proportion methodology proposed by the authors[26] was adopted. The mix proportion shown in Table3 was adopted after making different trials, in casting the GPC push off specimens having different strengths. The Binder index (Bi) which influences the strength of GPC is calculated using the following expression[27] for the different GPC mixes considered in the present investigation. The cohesion parameter influencing the shear strength is related to the binder index of GPC in the subsequent sections.

$$Bi = \frac{MA}{G+F}\left[\frac{G}{F}\right]$$

where, M = molarity of NaOH, A = Alkaline activator (Both NaOH and Na_2SiO_3 together) content, G = GGBS content and F= Fly ash content

Casting of GPC specimens

A rotating drum type pan mixer of 100 kg capacity was used to mix the dry materials, alkaline liquid and super plasticizer. Homogenous mixture was attained after mixing for 5 minutes. Fresh GPC mixture were placed in push off moulds and compacted on jolting table. Top surface of moulds were leveled with a trowel after compaction. After 24 hours of casting, Specimens were de-moulded and cured in open air for a period of 28 days. The average room temperature and relative humidity measured during the period of curing were 35±2°C and 75% respectively.

The push-off specimens of dimensions shown in Fig. 1 were cast with and without reinforcement across the shear interface. The reinforcement consists of three numbers of two legged 6 mm diameter mild steel having yield strength of 250MPa and they were placed across the shear plane in the form of closed link,

TABLE 3
MATERIALS USED IN GPC (PER CU.M)

S.No	Grade of GPC	Materials							
		Coarse agg. (kg)	Fine agg. (kg)	Fly ash (F) (kg)	GGBS (G) (kg)	NaOH solution - 8 molarity (kg)	Sodium silicate (kg)	SP* (kg)	Binder index
1	M20	965	812	294	126	66	165	4.2	1.886
2	M30	965	812	252	168	66	165	4.2	2.933
3	M40	965	812	210	210	66	150	4.2	4.000

*SP: Super plasticizer (SP 430, Make: Fosroc chemicals).

which corresponds to percentage of steel as 0.77. Also 10 mm diameter bars and 6 mm diameter stirrups were provided against the flexural failure at the loading point. The details of reinforcements are shown in Fig. 2.

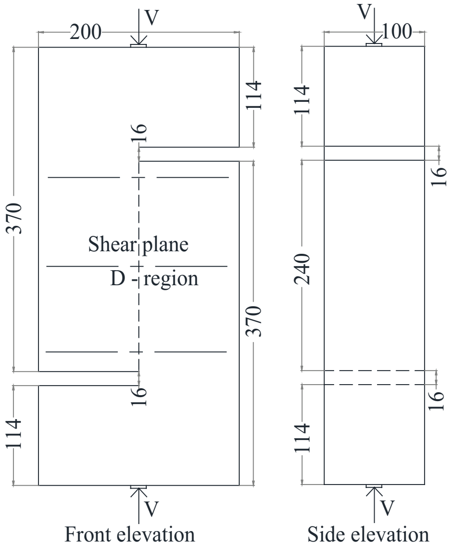

Fig. 1 The push off specimen

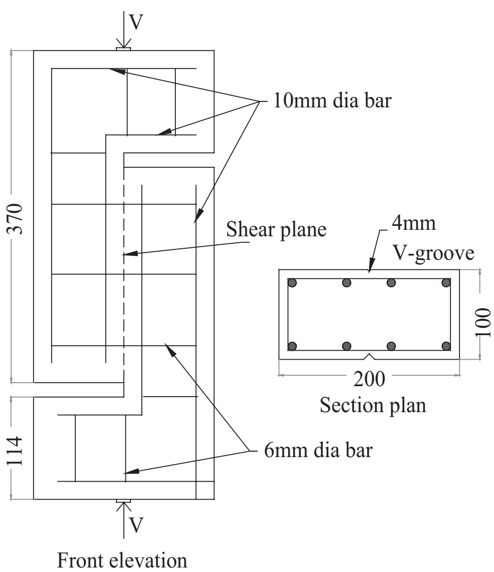

Fig.2. Reinforcement details for push -off specimen

V-groves of 4mm deep were made on either side of the push off specimen along shear plane for ensuring the direction of shear crack.

Testing of GPC push off specimens

The experimental set up in testing the Push-off specimens is shown in Fig. 3. The specimens were loaded axially until failure occurred. The Push off specimens with and without reinforcement across the interface, tested has failed by developing crack along the interface. The experimental shear strength of push off specimens with and without reinforcement across the interface (v_{ur}, v_{up}) was calculated by dividing the failure load (P_u) with the Cross sectional area of the interface. The failure Patterns of the push off specimens are shown in Fig. 4. The axial loads at failure (Ultimate load) was recorded and shown in Table 4 along with shear strength.

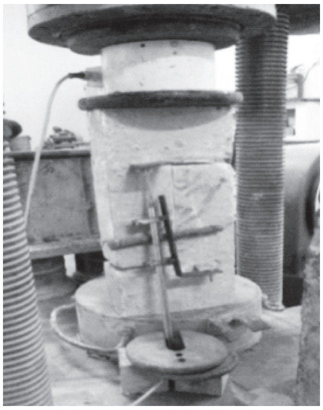

Fig. 3 Test setup

Fig. 4 Failure pattern for unreinforced and reinforced across shear plane

RESULTS AND DISCUSSIONS

During testing the crack along the shear plane was almost sudden in case of push off specimens with no reinforcement across the interface. However in case of push off specimens having reinforcement across the shear interface the visible crack along the shear plane was noticed at about 70 to 80 percent of the ultimate loads. Due to the provision of adequate reinforcement in the both halves of the push of specimen, none of the specimens have failed prematurely due to flexure in horizontal or vertical arms of the push off specimen. In the un-cracked stage, the shear across the interface in push-off specimen is assumed to be resisted mainly by the cohesion due to aggregate interlock of the concrete. After initiation of cracking along the shear plane, the cohesion of concrete reduces and the other actions such as friction and dowel action of reinforcement across the interface come in to action. At ultimate the shear at the interface is mainly resisted by the dowel action of reinforcement across the interface. The variation of shear strength of GPC obtained by testing the push of specimens (with and without reinforcement across the monolithic interface) with compressive strength is shown in Fig.5 and it is observed that the shear strength of GPC has increased with increase in compressive strength of GPC. Also the rate of increase of shear strength has decreased for compressive strength of GPC approximately more than 40 MPa. This may be attributed to the diminishing effect of aggregate interlock with increase in concrete strength[19].There is a higher increase of shear strength with compressive strength in the presence of reinforcement across the interface. The higher increase is due to the dowel action of reinforcement across the interface. There is an increase of shear strength of GPC by about 28% with the provision of constant steel percentage (ρ = 0.77%) across the interface. The average shear strength at the monolithic interface of unreinforced and reinforced push off specimens is about 11% and 24% of respective compressive strength of GPC.

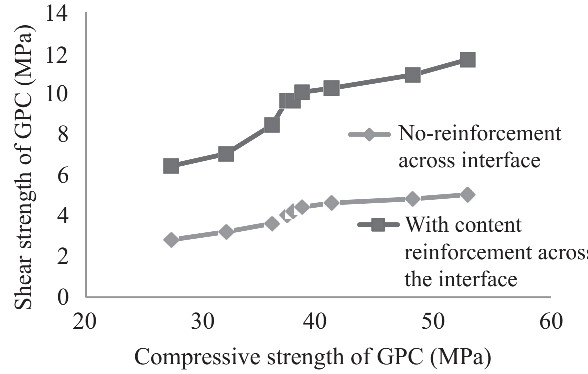

Fig. 5 Shear strength vs. Compressive strength of GPC

Shear strength of push off specimens without reinforcement across the interface

In the push off specimens without reinforcements across the interface, the Shear force is resisted by Cohesion which indirectly depends upon the compressive strength of GPC which in turn influenced by the parameters such as bond between Geopolymer products and aggregate and the interlocking between aggregates. Hence considering Cohesion to depend on the compressive strength of GPC, coefficient of Cohesion is evaluated as given in Table 5.

TABLE 4

THE ULTIMATE LOADS, SHEAR STRENGTH OF GPC PUSH OFF SPECIMENS

f_{ck}	With no reinforcement across the shear interface					With constant % of reinforcement across the shear interface					$(v_{ur} - v_{up}) / v_{up}$
	Specimen ID	P_u	v_{up}	ε (10^{-5})	v_{up}/f_{ck}	Specimen ID	P_u	v_{ur}	ε (10^{-5})	v_{ur}/f_{ck}	
27.29	GANRS1	62.30	2.82	221	0.10	GAWRS1	142.39	6.45	734	0.24	1.29
32.04	GANRS2	71.20	3.22	609	0.10	GAWRS2	155.74	7.05	1449	0.22	1.19
35.99	GANRS3	80.10	3.63	974	0.10	GAWRS3	186.89	8.46	443	0.24	1.33
37.28	GBNRS1	89.00	4.03	660	0.11	GBWRS1	213.59	9.67	1888	0.26	1.40
37.77	GBNRS2	93.45	4.23	435	0.11	GBWRS2	213.59	9.67	793	0.26	1.29
38.57	GBNRS3	97.90	4.43	213	0.11	GBWRS3	222.49	10.08	1333	0.26	1.27
41.10	GCNRS1	102.35	4.64	487	0.11	GCWRS1	226.94	10.28	1503	0.25	1.22
48.11	GCNRS2	106.80	4.84	422	0.10	GCWRS2	241.39	10.93	1076	0.23	1.26
52.86	GCNRS3	111.25	5.04	216	0.10	GCWRS3	258.09	11.69	819	0.22	1.32
			Average		0.11			Average		0.24	1.28

Notes:

f_{ck} = Concrete compressive strength of 150mm cube (MPa);
e = strain at ultimate;
v_{ur} = Shear stress at the reinforced interface (MPa) = P_u / b_h;
P_u = Average experimental peak load (kN)
v_{up} = Shear stress at the unreinforced interface (MPa) = P_u / b_h
b_h = Cross sectional area of the interface = 92 × 240 mm^2

TABLE 5

COEFFICIENT OF COHESION FOR GPC SPECIMENS UNREINFORCED ACROSS SHEAR PLANE

Specimen ID	f_{ck}	f_c'	P_u	v_{up}	B_i	C
GANRS1	27.29	23.20	62.30	2.82	1.886	0.989
GANRS2	32.04	27.23	71.20	3.22	1.886	1.072
GANRS3	35.99	30.59	80.10	3.63	1.886	1.160
GBNRS1	37.28	31.69	89.00	4.03	2.933	1.274
GBNRS2	37.77	32.11	93.45	4.23	2.933	1.332
GBNRS3	38.57	32.78	97.90	4.43	2.933	1.385
GCNRS1	41.10	34.94	102.35	4.64	4.000	1.418
GCNRS2	48.11	40.89	106.80	4.84	4.000	1.404
GCNRS3	52.86	44.93	111.25	5.04	4.000	1.417

Notes:
f_c' = Comp. strength of cylinder (MPa) = $0.85 f_{ck}$
B_i = Binder index of GPC
C = Coefficient of Cohesion = $v_u / (f_c')1/3$ (MPa)

A plot between average binder index and average coefficient of friction for GPC is shown in Fig. 6. It is observed that the coefficient of cohesion varies non-linearly with binder index of GPC. This may due to the decrease in the rate of increase of compressive strength of GPC with increase in the binder index[26].

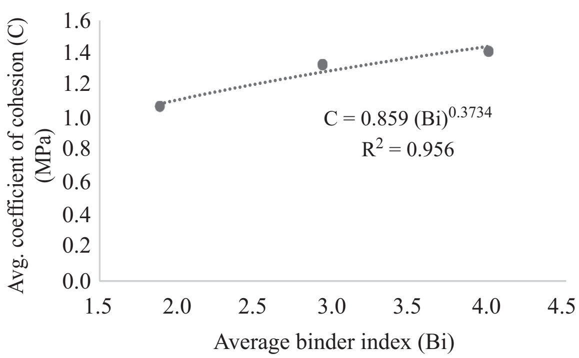

Fig. 6 Average coefficient of Cohesion vs Average binder index

Shear strength of specimens with reinforcement across shear interface

The reinforced push off specimens tested in this investigation consisted of a constant steel reinforcement across the interface in the form of three equally spaced 6mm dia. closed rectangular stirrups with percentage steel equal to 0.77%. The shear across the interface in these specimens is resisted by the combined action of cohesion, friction and dowel Action. Cohesion contribution is calculated by considering coefficient of cohesion from unreinforced specimens developed. Friction contribution is calculated considering friction coefficient and '*k*' in line with Randl[21] assumptions. The normal stress, σn at the interface at failure is taken as zero as there are no clamping forces in the push off specimens tested.

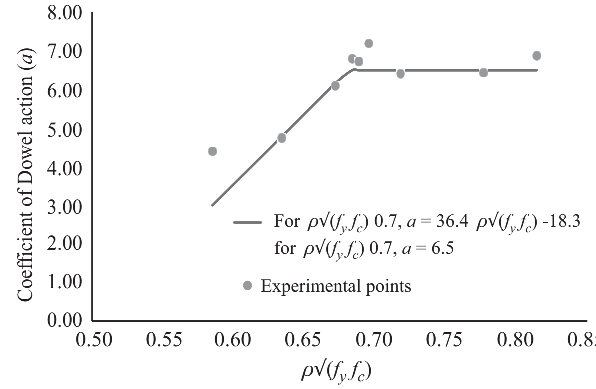

Fig. 7 Variation of coefficient of Dowel action in GPC

Dowel Action contribution is calculated by deducting the cohesion and friction contributions from the experimental shear strength of the reinforced GPC push off specimens. Accordingly, coefficient of dowel action (α) is calculated and the same is tabulated in Table 6. It is observed from the Fig. 7, that the coefficient of dowel action in GPC with constant percent of reinforcement across the shear plane varies bi-linearly with $\rho\sqrt{(f_y f_c)}$ i.e the coefficient of dowel action (α) is linearly increasing up to $\rho\sqrt{(f_y f_c)}$ equals to 0.70 and thereafter it remained more or less a constant. This may be due to the limited resistance of dowel bars in stopping the aggregate interlock crack opening mechanism with increase of slippage at the interface. However this observation requires further studies on shear strength with varying percent of reinforcement across the shear interface. Considering the lower bound values, the predicted equation for the coefficient of dowel action (α) is proposed in terms of $\rho\sqrt{(f_y f_c)}$. The correlation coefficient between the predicted and experimentally obtained values of the coefficient of dowel action is 0.926. Hence the shear strength of monolithic GPC interface (V_u) is proposed as follows:

$$V_u = V_c + V_f + V_d$$

V_c = Shear strength unreinforced GPC due to cohesion = $C^*(f_c')(1/3)^*bh$, $C = 0.8595\ Bi^{0.3734}$

V_f = Shear strength of reinforced GPC due to friction = $\mu[\sigma_n + \rho k f_y]^*bh$,

TABLE 6

COHESION CONTRIBUTION, FRICTION CONTRIBUTION AND CALCULATION OF COEFFICIENT OF DOWEL ACTION OF GPC

Specimen ID	f_{ck}	f_c'	P_u	Bi	C**	V_c (kN)	V_f (kN)	Dowel contribution $V_d = P_u - V_c - V_f$ (kN)	Coefficient of Dowel action $\alpha = V_d / (bh\ \rho\sqrt{(f_y f_c)})$	$\rho\sqrt{(f_y f_c)}$	Coefficient of Dowel action predicted* (α)
GAWRS1	27.29	23.20	142.39	1.886	1.089	68.59	16.96	56.84	4.40	0.585	3.00
GAWRS2	32.04	27.23	155.74	1.886	1.089	72.36	16.96	66.42	4.75	0.634	4.78
GAWRS3	35.99	30.59	186.89	1.886	1.089	75.21	21.21	90.47	6.10	0.672	6.16
GBWRS1	37.28	31.69	213.59	2.933	1.285	89.75	21.21	102.63	6.80	0.684	6.50
GBWRS2	37.77	32.11	213.59	2.933	1.285	90.15	21.21	102.24	6.73	0.688	6.50
GBWRS3	38.57	32.78	222.49	2.933	1.285	90.77	21.21	110.51	7.20	0.696	6.50
GCWRS1	41.10	34.94	226.94	4.000	1.442	104.11	21.21	101.63	6.41	0.718	6.50
GCWRS2	48.11	40.89	241.39	4.000	1.442	109.71	21.21	110.47	6.44	0.777	6.50
GCWRS3	52.86	44.93	258.09	4.000	1.442	113.21	21.21	123.67	6.88	0.814	6.50

**$C = 0.8595\ Bi^{0.3734}$

*Predicted using the proposed equation for coefficient of Dowel action: For $\rho\sqrt{(f_y f_c)} \le 0.7$, $\alpha = 36.4\rho\sqrt{(f_y f_c)} - 18.3$, for $\rho\sqrt{(f_y f_c)} > 0.7$, $\alpha = 6.5$

Correlation coefficient between the predicted and observed values of coefficient of dowel action is 0.926.

$k = 0.5$ and $f_{ck} \ge 20$MPa, $\mu = 0.8$, $f_{ck} \ge 35$MPa, $\mu = 1.0$ and) [Randl (1997)]

V_d = Shear strength of reinforced GPC due to dowel action = $\alpha\rho\sqrt{(f_y f_c)}bh$

$\alpha = 36.4\rho\sqrt{(f_y f_c)} - 18.3$ for the $\rho\sqrt{(f_y f_c)}$ of GPC less than 0.685 and $\alpha = 6.5$ for $\rho\sqrt{(f_y f_c)} > 0.685$

CONCLUSIONS

The following are the conclusions arrived at after the study of Shear strength of monolithic GPC interface.

- The shear strength of monolithic GPC interface has increased with increase in compressive strength of GPC.
- The rate of increase of shear strength has decreased for compressive strength of GPC more than 40 MPa.
- There is an increase in shear strength of GPC by about 28% with the provision of constant steel percentage ($\rho = 0.77\%$) across the interface.
- The average shear strength of unreinforced and reinforced monolithic GPC interface is about 11% and 24% of respective compressive strength of GPC.
- The shear (V_u) across the monolithic interface in GPC specimens is resisted by the combined action of Cohesion, Friction and Dowel Action and can be obtained by
  $V_u = (C^*(f_c')(1/3) + \mu[\sigma_n + \rho k f_y] + \alpha\rho\sqrt{(f_y f_c)})$ bh
- The coefficient of cohesion varies non-linearly with binder index of GPC and can be expressed as: $C = 0.8595\ Bi^{0.3734}$
- Coefficient of dowel action (α) at constant percent ofreinforcement ($\rho = 0.77\%$) across the monolithic GPC interface varies bi-linearly with $\rho\sqrt{(f_y f_c)}$. However further studies are required for different percent of reinforcements across the monolithic interfaces in GPC.

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