A Comparative Study of Shear strength of monolithic Geopolymer Concrete Interface

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Geopolymer Concrete (GPC) is inorganic polymer composites and has prospective potential to become one of the alternatives to conventional concrete. This paper presents an experimental investigation on the shear strength of monolithic GPC interface. A total of 18 push-off specimens with and without reinforcement across interface were cast and tested. The experimental shear strength of GPC is compared with the shear strength evaluated using the available analytical models for normal concrete. The test results indicated that the shear strength of monolithic GPC interface has increased up to certain compression strength GPC. The most of the available analytical models are conservative in estimating the shear strength of GPC.

Keywords: *Geopolymer Concrete, Shear strength, Interface shear transfer, Cohesion, friction, Dowel action.*

1. INTRODUCTION

The development of Geopolymer concrete (GPC) is being visualized as green material and a probable alternative to the normal Cement concrete. To reduce the carbon footprint, cement industry improved the process in cement production, but could not reduce CO_2 emission as it is integral of basic process of calcination of limestone. Through usage of waste by-products from other industries in developing alternate construction materials is increasing day by day. Geopolymer concrete is an innovative material made from minimal processed natural material or industrial by-products to reduce carbon foot print and being very resistant towards durability issues. Geopolymers are blended form silicon and aluminium materials of physical origin or by products. These inorganic alumino–silicate polymers are similar to zeolite but amorphous in microstructure [DavidovitsJ(1999),Palamo MW, Grutzeck MT and Blanco(1999),Lăzărescu A.V, Szilagyi H, Baeră C. and Ioani A(2017)]. The literature existing indicates that the research on Geopolymer concrete include its characterization, evaluation of mechanical strength [Lloyd RR and Van Deventer JSJ (2005), BVRangan (2008), G Mallikarjuna Rao and TD Gunneswara Rao (2015), Sumanth Kumar B and Rama SeshuD (2018)]. Geopolymers, when substituted for OPC, have potential to lower the significant carbon footprint of OPC concrete, however the few past research studies that have been conducted report a wide range of outcomes. The range of reported CO2-e values for geopolymer concrete compared with OPC is considerable, with estimates as high as 80% less than OPC [van Deventer JSJ et.al (2010), Duxson P et al (2007)] to 26–45% lower than OPC concrete [Habert G et al (2011), McLellan BC et al (2011)]. A detailed comparative study reported CO2-e estimates for both geopolymer and OPC concrete [Louise K. Turner et al (2013)], indicated that the CO2 footprint of geopolymer concrete was approximately 9% less than comparable concrete containing 100% OPC binder: much less than predictions by earlier studies. The key factors that led to the higher than expected emissions for geopolymer concrete included the inclusion of mining, treatment and transport of raw materials for manufacture of alkali activators for geopolymers, expenditure of significant energy during manufacture of alkali activators, and the need for elevated temperature curing of geopolymer concrete to achieve reasonable strength.

GPC has significantly used for precast industry where stress is concentrated at interfacial or connective zones associated with corbels, near beam column junctions, beam slab interface etc. Shear transfer across interface is transmitted by friction from compressive stresses, Cohesion because of aggregate interlocking roughness and Dowel action crossing the surfaces. Different models were available in the literature for calculating the concrete shear transfer strength [Birkeland and Birkeland (1966), Mattock and Hawkins (1972), Loov (1978), Walraven JC et al (1987) and Randl (1997)].

<table>
<tr><th colspan="6">Table.1 Shear strength expressions as per different investigators / Codes of practice</th></tr>
<tr><th>Reference</th><th>Shear strength expression</th><th colspan="4">Remarks</th></tr>
<tr><td>Birkeland and Birkeland (1966)</td><td>$v_u = \rho f_y \tan\varphi = \rho f_y \mu$</td><td colspan="4">$\mu$ = 1.7 for concrete placed monolithically</td></tr>
<tr><td>Mattock and Hawkins (1972)</td><td>$v_u = 1.38 + 0.8[\rho f_y + \sigma_n]$</td><td colspan="4">ρ = reinforcement ratio, fy= Yield strength of reinforcement across interface, σ_n = normal stress</td></tr>
<tr><td>Mattock (1974)</td><td>$v_u = 2.76 + 0.8[\rho f_y + \sigma_n]$</td><td colspan="4"></td></tr>
<tr><td>Loov (1978)</td><td>$v_u = k\sqrt{f_c[\sigma_n + \rho f_y]}$</td><td colspan="4">$\sigma_n$ is the clamping stress and k = 0.5 for initially un-cracked shear interfaces.</td></tr>
<tr><td>Walraven, Frenay&Pruijssers (1987)</td><td>$v_u = C_1[\rho f_y]^{C_2}$</td><td colspan="4">$C_1 = 0.822{f_C}^{0.406}$, $C_2 = 0.159{f_C}^{0.303}$</td></tr>
<tr><td>Randl (1997)</td><td>$v_u = C{f_c}^{1/3} + \mu[\sigma_n + \rho k f_y] + \alpha\rho\sqrt{f_y f_c} \le \beta v f_c$</td><td colspan="4">C, μ, k, α and β are dependent on the roughness at the interface</td></tr>
<tr><td>ACI 318 (2014)
Cl. 22.9.4.2 & 3</td><td>$v_n = \mu A_{vf} f_y$
$v_n = A_{vf} f_y(\mu\sin\alpha + \cos\alpha)$</td><td colspan="4">$\mu$=1.4λ For monolithic concrete.
λ = 1 for normal-weight concrete.
ρ_v = greater of 0.75 $\sqrt{f_c'}/f_y$ and $50/f_y$ (SI Units)</td></tr>
<tr><td rowspan="5">Euro code 2 (2004)
Cl. 6.2.5
* Not valid for monolithic Spec</td><td rowspan="5">$v_u = Cf_{ctd} + \mu\sigma_n + \rho f_y[\mu\sin\alpha + \cos\alpha] \le 0.5 v f_{cd}$</td><td>Surface Type</td><td colspan="2">Cohesion Coefficient C MPa</td><td>Friction Coefficient μ</td></tr>
<tr><td>Very Smooth</td><td colspan="2">0.025 – 0.10</td><td>0.50</td></tr>
<tr><td>Smooth</td><td colspan="2">0.20</td><td>0.60</td></tr>
<tr><td>Rough</td><td colspan="2">0.40</td><td>0.70</td></tr>
<tr><td>Indented</td><td colspan="2">0.50</td><td>0.90</td></tr>
<tr><td rowspan="5">FIB Model Code (2010)
Cl. 6.3.4</td><td rowspan="5">$v_u = \tau_c + \mu(\rho k f_y + \sigma_n) + \alpha\rho\sqrt{f_y f_c} \le \beta v f_c$</td><td>Surface Type</td><td>CMPa</td><td>μ</td><td>Average Roughness Ra</td></tr>
<tr><td>Very Smooth</td><td>0.025</td><td>0.50</td><td>NA</td></tr>
<tr><td>Smooth</td><td>0.35</td><td>0.60</td><td><1.50</td></tr>
<tr><td>Rough</td><td>0.45</td><td>0.70</td><td>≥ 1.50</td></tr>
<tr><td>Very Rough</td><td>0.50</td><td>0.90</td><td>≥ 3.00</td></tr>
<tr><td rowspan="2">CSA A23.3 (2014)
Cl. 11.5</td><td>$v_u = \phi_c\lambda(c + \mu\sigma) + \Phi_s\rho_v f_y\cos\alpha_f$</td><td colspan="4">$c$ = 1; μ = 1.4 for monolithic concrete.
λ = 1 for normal density concrete;
$\lambda(c + \mu\sigma) \le 0.25f_c'$, $\rho_{vmin} = 0.06\sqrt{\frac{f_c'}{f_y}}$</td></tr>
<tr><td>$v_u = \lambda k\sqrt{\sigma f_c'} + \rho_v f_y \cos\alpha_f$</td><td colspan="4">$\lambda k\sqrt{\sigma f_c'} \le 0.25f_c'$
k = 0.6 for concrete placed monolithically.</td></tr>
<tr><td colspan="6"></td></tr>
</table>

Several types of test specimens like Splitting, Corbel with moment, Pull-off etc. are studied in determining the shear strength of concrete. Anderson (1960) was first to introduce push-off specimen for evaluating interface shear transfer. The Push-off specimens (Fig.1) is most appropriate and commonly used due to perfect shear transfer across interfaces against other type of specimens, which induce both shear and moment[Mattock et al (1972), Xiao J, Sun C and Lange DA (2016)].The outcomes of push-off investigations were used in recommending shear – transfer models for concrete [ACI 318 (2014), PCI (Precast/Pre-stressed Concrete Institute) (2010), CSA-A23.3-14 (2014)].Numerous design expressions were proposed to envisage the shear stress at the concrete interface. Majority of design codes considered the shear-friction theory for concrete structures [ACI 318 (2014), Euro code 2 (2004), FIB Model Code (2010) and CSA A23.3 (2014)]. Table 1 presents the Shear strength expressions as per different investigators / Codes of practice.

2. RESEARCH SIGNIFICANCE

In present study the shear strength of monolithically cast GPC interface with and without the reinforcement crossing the shear plane were evaluated by testing push off specimens. The shear strength obtained was compared with the models proposed by different investigators and codes of practice.

3. EXPERIMENTAL PROGRAM

3.1 Materials Used

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

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

Fine Aggregate: River sand conforming to Zone-2 of IS: 383 (1970) was used as fine aggregate. The specific gravity and bulk density of sand are 2.65 & 1.45 g/cm^{3}respectively. Well graded aggregate **coarse Aggregate**: conforming to IS: 383 (1970) with 20mm nominal size of granite is used as coarse aggregate.2.80 & 1.50 g/cm^{3}are specific gravity and bulk density respectively. **Potable water** was used in the experimental work. The **Alkaline Solution c**onsist of Sodium Silicate Solution to Sodium Hydroxide Solution (8 Molarity) as 2.5:1. The alkaline solution is stored at room temperature (25±2^{0}C) for 24 hours and relative humidity of 65% before using it in the casting of GPC push off specimens.

3.2 Mix Proportions:

The GPC Mix proportion procedure [G Mallikarjuna Rao, TDGRao, Rama Seshu and Venkatesh (2016)] was adopted. The mix quantity shown in Table.3 was considered after making different trials, in casting the GPC push off specimens having different strengths.

Table.3 Materials used in GPC (per Cu.m)

S.No	Grade of GPC	Materials						
		Coarse Agg.(kg)	Fine Agg. (kg)	Fly Ash (kg)	GGBS (kg)	NaOH Sol. 8 Molarity(kg)	Sodium Silicate (kg)	SP* (kg)
1	A25	965	812	294	126	66	165	4.2
2	B35	965	812	252	168	66	165	4.2
3	C45	965	812	210	210	66	150	4.2

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

3.3 Casting of GPC Specimens

The dimensions of the push-off specimens used for testing are shown in Fig.1. The specimens were cast with and without reinforcement through the shear interface. The reinforcement in the form of closed links across the interface consists of 3 No's of 2-legged 6 mm diameter (percentage of steel of 0.77%) mild steel with yield strength of 250MPa. 10 mm diameter bars and 6 mm diameter links were provided to resist the flexural failure at the loading point. The details of reinforcements are shown in Fig.2. After 24 hours of casting, Specimens were de-molded and are air cured for a period of 28 days. The room temperature and relative humidity are 35 ± 2^{0}C and 75% are respectively. Before testing V-Groves of 4mm deep were made on either side of the push off specimen along shear plane for ensuring the failure at the interface.

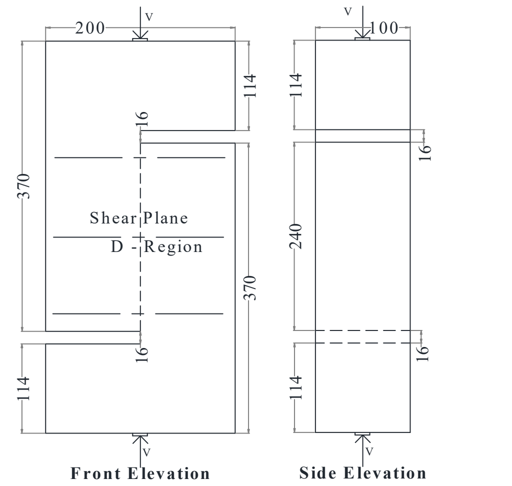

Fig.1. The Push off Specimen

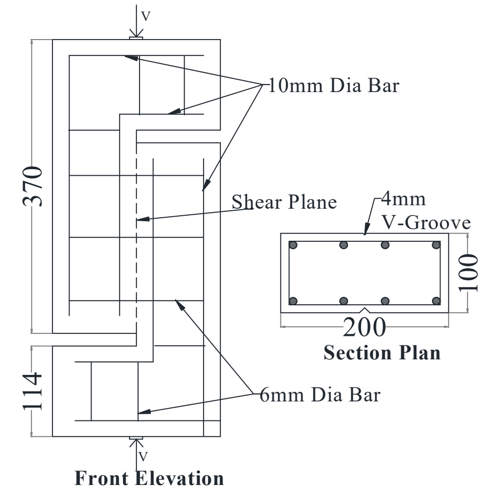

Fig.2. Reinforcement Details for Push -Off specimen

3.4 Testing of GPC Push-off Specimens

The test set up in testing the Push-off specimens is shown in Fig.3. The specimens were loaded axially until failure. The failure loads and the shear strength values are given in Table.4.

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				$(\nu_{ur}-\nu_{up}) / \nu_{up}$
	Specimen ID	P_u	ν_{up}	ν_{up}/ f_{ck}		Specimen ID	P_u	ν_{ur}	ν_{ur}/ f_{ck}	
27.29	GANRS1	62.30	2.82	0.10		GAWRS1	142.39	6.45	0.24	1.29
32.04	GANRS2	71.20	3.22	0.10		GAWRS2	155.74	7.05	0.22	1.19
35.99	GANRS3	80.10	3.63	0.10		GAWRS3	186.89	8.46	0.24	1.33
37.28	GBNRS1	89.00	4.03	0.11		GBWRS1	213.59	9.67	0.26	1.40
37.77	GBNRS2	93.45	4.23	0.11		GBWRS2	213.59	9.67	0.26	1.29
38.57	GBNRS3	97.90	4.43	0.11		GBWRS3	222.49	10.08	0.26	1.27
41.10	GCNRS1	102.35	4.64	0.11		GCWRS1	226.94	10.28	0.25	1.22
48.11	GCNRS2	106.80	4.84	0.10		GCWRS2	241.39	10.93	0.23	1.26
52.86	GCNRS3	111.25	5.04	0.10		GCWRS3	258.09	11.69	0.22	1.32
			Ave=	0.104				Ave=	0.242	

Notation:

f_{ck}	=	Concrete Compressive Strength of 150mm Cube (MPa)	ν_{up}	=	Shear Stress at the unreinforced interface (MPa) = P_u/bh
Pu		Average Experimental Peak Load (kN)	ν_{ur}	=	Shear Stress at the reinforced interface (MPa) = P_u/bh
bh	=	Cross sectional area of the interface = 92 x 240 mm^2			

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The Push-off samples with and without reinforcement through the interface, tested has failed by developing a crack along the interface. The typical failure in the push-off specimens is shown in Fig.4. From the axial loads at failure (Ultimate load) the shear strength was calculated by dividing the ultimate load with the cross sectional area of the interface.

4. RESULTS AND DISCUSSIONS

The GPC push off specimens has failed by developing the crack along the interface. In case of specimens with no reinforcement across the interface the failure occurred suddenly while in the reinforced interfaces the visible cracking along the shear plane was noticed at about 70 to 80 percent of the ultimate loads. Due to the provision of suitable reinforcement in the both halves of push of specimen, none of the specimens have failed prematurely due to flexure in horizontal or vertical arms of the push off specimen. From the observation of the experimental shear strength values given in Table.4 indicate that the shear strength of unreinforced GPC is about 10% of its corresponding compression strength. In the case of reinforced shear interfaces the shear strength has increased and is about 24% of the respective compression strength. In general the shear strength of monolithic interface in GPC has increased with increase in the compression strength of GPC and percent of reinforcement across the interface. In the un-cracked stage, the shear across the interface in Push-off specimen is in general expected to be resisted mainly by the cohesion due to aggregate interlock of the concrete. After the cracking at the shear plane, the cohesion of concrete reduces and the other actions such as friction and dowel action of reinforcement across the interface may come in to action. At ultimate the load is mainly resisted by the dowel action of the reinforcement across the interface.

Fig.3. Test Setup

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

Table.5 presents the comparison of shear strength of GPC obtained with the shear strength of normal concrete predicted by different shear models / shear equations available in literature. The comparison is also shown in Fig.5 and 6 for the unreinforced and reinforced shear interfaces. The comparative study indicates that the available normal concrete shear strength prediction models are highly conservative in estimating the shear strength of unreinforced and reinforced monolithic shear interfaces in GPC. The models by Mattock (1974) and Walraven et al (1987) are seems to give better prediction of shear strength of GPC in the case of unreinforced and reinforced monolithic interfaces respectively.

5. CONCLUSIONS

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

1. The shear strength of monolithic GPC interface has increased with increase in compressive strength of GPC.
2. The average shear strength of unreinforced and reinforced monolithic GPC interface is about 10% and 24% of respective compressive strength of GPC.
3. The available normal concrete shear strength prediction models are highly conservative in estimating the shear strength of unreinforced and reinforced monolithic shear interfaces in GPC.
4. The models by Mattock (1974) and Walraven et al (1987) are seems to give better prediction of shear strength of GPC in the case of unreinforced and reinforced monolithic interfaces respectively.

6. Conflict of Interest:

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Table.5. Comparison of Experimental Shear strength of GPC with the Shear strength predicted by the Design Codes / equations

Specimen ID	GPC	Ref.1		Ref.2		Ref.3		Ref.4		Ref.5		Ref.6		Ref.7		Ref.8		Ref.9		Ref.10	
	vup	vu1	vup/ vu1	vu2	vup/ vu2	vu3	vup/ vu3	vu4	vup/ vu4	vu5	vup/ vu5	vu6	vup/ vu6	vu7	vup/ vu7	vu8	vup/ vu8	vu9	vup/ vu9	vu10	vup/ vu10
GANRS1	2.82	--	--	1.38	2.04	2.76	1.02	--	--	--	--	1.20	2.34	--	--	0.98	2.89	1.05	2.68	0.65	4.34
GANRS2	3.22	--	--	1.38	2.34	2.76	1.17	--	--	--	--	1.27	2.54	--	--	1.06	3.05	1.11	2.90	0.65	4.96
GANRS3	3.63	--	--	1.38	2.63	2.76	1.31	--	--	--	--	1.32	2.75	--	--	1.12	3.24	1.16	3.14	0.65	5.58
GBNRS1	4.03	--	--	1.38	2.92	2.76	1.46	--	--	--	--	1.34	3.02	--	--	1.14	3.53	1.17	3.45	0.65	6.20
GBNRS2	4.23	--	--	1.38	3.07	2.76	1.53	--	--	--	--	1.34	3.15	--	--	1.15	3.69	1.17	3.60	0.65	6.51
GBNRS3	4.43	--	--	1.38	3.21	2.76	1.61	--	--	--	--	1.35	3.28	--	--	1.16	3.82	1.18	3.75	0.65	6.82
GCNRS1	4.64	--	--	1.38	3.36	2.76	1.68	--	--	--	--	1.38	3.36	--	--	1.20	3.87	1.21	3.84	0.65	7.13
GCNRS2	4.84	--	--	1.38	3.50	2.76	1.75	--	--	--	--	1.45	3.32	--	--	1.30	3.73	1.27	3.80	0.65	7.44
GCNRS3	5.04	--	--	1.38	3.65	2.76	1.83	--	--	--	--	1.50	3.36	--	--	1.36	3.71	1.31	3.84	0.65	7.75
GAWRS1	6.45	2.69	2.40	2.92	2.21	4.30	1.50	3.24	1.99	4.18	1.54	2.54	2.54	2.69	2.40	1.94	3.33	2.39	2.69	2.40	2.69
GAWRS2	7.05	2.69	2.62	2.92	2.42	4.30	1.64	3.51	2.01	4.52	1.56	2.66	2.65	2.69	2.62	2.02	3.50	2.50	2.82	2.40	2.94
GAWRS3	8.46	2.69	3.15	2.92	2.90	4.30	1.97	3.72	2.28	4.79	1.77	2.94	2.88	2.69	3.15	2.08	4.07	2.77	3.05	2.40	3.53
GBWRS1	9.67	2.69	3.60	2.92	3.32	4.30	2.25	3.78	2.56	4.87	1.99	2.96	3.26	2.69	3.60	2.10	4.60	2.80	3.46	2.40	4.03
GBWRS2	9.67	2.69	3.60	2.92	3.32	4.30	2.25	3.81	2.54	4.91	1.97	2.97	3.25	2.69	3.60	2.11	4.59	2.81	3.45	2.40	4.03
GBWRS3	10.08	2.69	3.75	2.92	3.45	4.30	2.35	3.85	2.62	4.96	2.03	2.99	3.37	2.69	3.75	2.12	4.75	2.82	3.57	2.40	4.20
GCWRS1	10.28	2.69	3.82	2.92	3.52	4.30	2.39	3.97	2.59	5.12	2.01	3.04	3.38	2.69	3.82	2.16	4.76	2.87	3.58	2.40	4.29
GCWRS2	10.93	2.69	4.07	2.92	3.75	4.30	2.54	4.30	2.54	5.54	1.97	3.17	3.44	2.69	4.07	2.26	4.85	2.99	3.65	2.40	4.56
GCWRS3	11.69	2.69	4.35	2.92	4.01	4.30	2.72	4.51	2.59	5.81	2.01	3.26	3.59	2.69	4.35	2.32	5.04	3.07	3.81	2.40	4.87

Reference:

1. Birkeland & Birkeland (1966)
2. Mattock & Hawkins (1972)
3. Mattock (1974)
4. Loov (1978)
5. Walraven et al (1987)
6. Randl (1997)
7. ACI 318 (2014)
8. Euro code 2 (2004)
9. FIB Model Code (2010)
10. CSA A23.3 (2014)

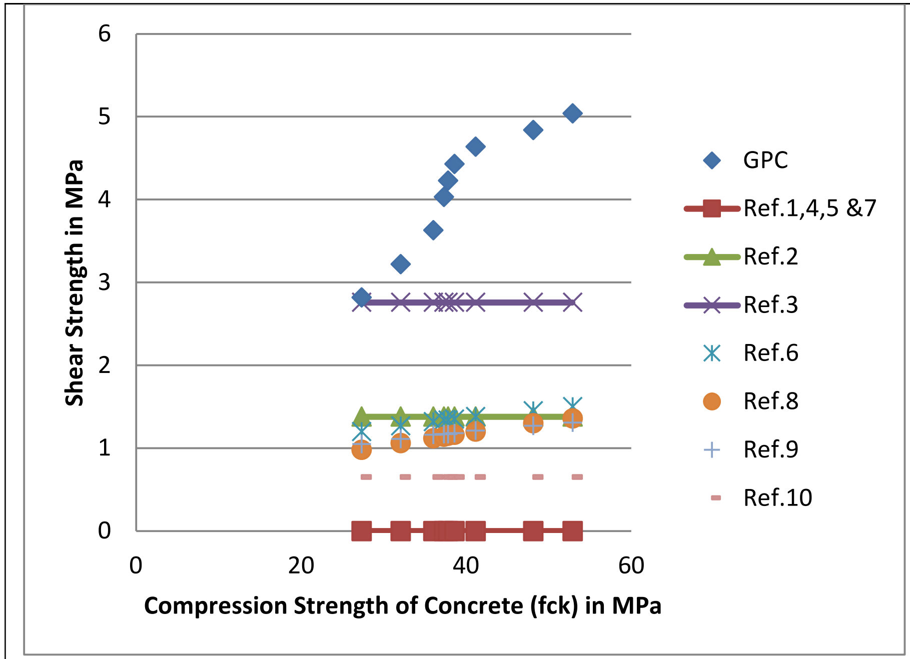

Fig.5. Comparison of Shear strength of GPC unreinforced across the interface

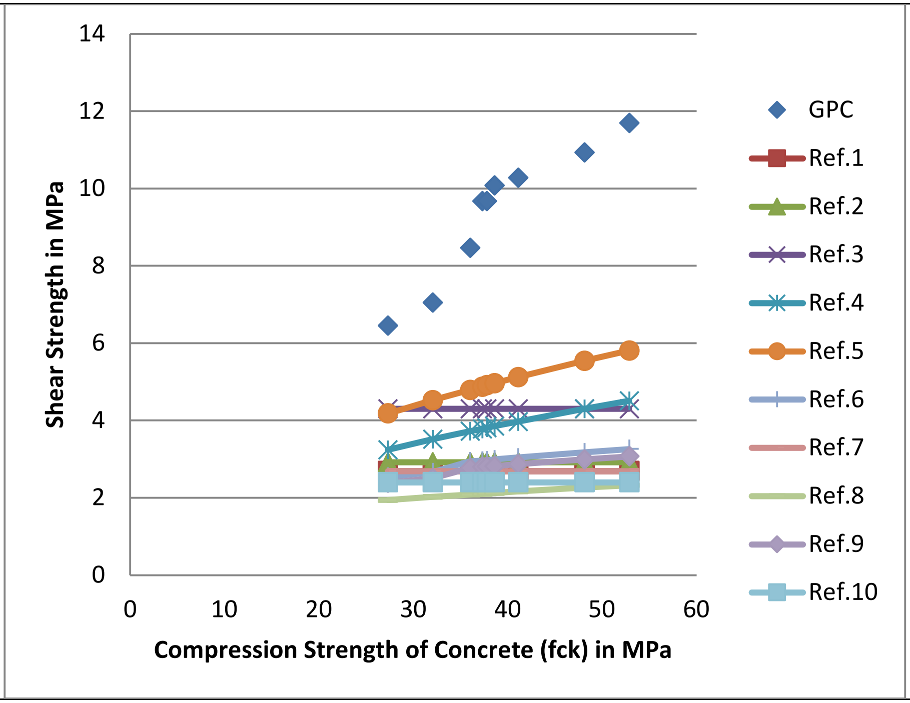

Fig.6. Comparison of Shear strength of GPC reinforced across the interface

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