PULL OUT BEHAVIOUR OF DEFORMED STEEL BARS IN FLY ASH BLENDED SELF COMPACTING GEOPOLYMER CONCRETE

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This study extends the ongoing investigation on bond performance of embedded steel in self consolidating geopolymer concrete, when Class F fly ash is blended with Class C fly ash. 5% OPC and 10% Class C fly ash are replaced to the basic source material Low calcium Fly ash, to facilitate the external exposure curing conditions and thereby aiming for cast in situ concrete production. Synthesising solutions for source material used are combination of sodium hydroxide and sodium silicates. Normal self compacting concrete, Self compacting geopolymer concrete with added OPC and Self compacting geopolymer concrete with OPC and Class C fly ash are the types of concrete selected for experimental investigation. Pull out tests are carried out by varying diameter and bond length of embedded steel in concrete. Comparison of bond stress on 54 pull out specimens was determined using IS: 2770 (Part 1) and studies revealed that inclusion of Class C fly ash in self consolidating geopolymer improves the bond strength tremendously. Results were compared to the latest empirical models proposed by researchers and FIB model code 2010.

Keywords: *Self compacting geopolymer concrete; Ordinary Portland Cement; Class C fly ash; Bond Length; Bond Strength; External exposure curing.*

1. Introduction

Geopolymer technologies are widely used in countries like Australia and New Zealand for precast construction, which has proved to be advantageous in terms of sustainability, economy and durability. Inclusion of heat curing methods for enhancing the mechanical properties are major drawback in case of geopolymer concrete and hence developing countries like India, China etc. are not at all interested in acknowledging the current trends. Need for ambient curing thereby emerged in zero cement concepts and different methods were tried to bring down the curing temperature. It was identified that if Calcium oxide content is increased in fly ash precursors, setting time can be decreased without affecting the strength [1]. This can be achieved by introducing supplementary cementitious materials that are rich in calcium oxide content, to the basic source material of geopolymer. Supplimentary cementitious materials like silica fume and metakaolin was added to fly ash which helped in bringing down curing temperature and enhancing mechanical properties [2, 3]. P. Nath and P. K. Sarker investigated on ambient cured geopolymer by introducing Ground blast furnace slag to Class F ash in different proportions to the mix and enhance the early age properties of concrete. Results were compared for the varying proportions of slag and alkaline activator in the mix. Inclusion of slag reduced the setting time and improved the early-age compressive strength significantly [4]. Ambient cured geopolymer was also made out of Ground Blast Furnace Slag and Bottom Ash as source material, which decreased the setting time and improved compression strength appreciably [5].

Geopolymer in Self compacting concrete (SCGC) marked as a milestone in the field of special concretes which helped in fast production of concrete with environment sustainability. Preliminary investigation of SCGC were done using heat curing methods and proved to exhibit outstanding mechanical and microstructural properties [6, 7]. Addition of 10 % Silica fume into low calcium fly ash was seen to improve mechanical properties in elevated curing conditions of 60 degrees [8]. 100% replacement of GGBS to fly ash was also investigated in heat curing regime of 70 degrees and results proved that mechanical properties tend to be reduce in high molarity concentration of sodium hydroxides [9]. Eventhough supplementary cementitious materials are replaced to class F fly ash in SCGC, the need for addition in

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the area of curing regime was lacking on major researches.

Class C fly ash was omitted in many researches because of its unrecognised properties on geopolymer precursors. But in early 90's use of class C fly ash on structural concrete was adopted to increase the hardened properties [10]. Class C fly ash replaced in proportions upto 60 % of cement on Self Compacting Concrete (SCC), was identified to produce durable concrete with resistance against freezing, thawing and chloride penetration [11]. In another research, SCC was made with 10% High calcium fly ash to the cement replacement and investigation revealed the necessary of grinding the ashes to improve the rheological properties [12]. Class C fly ash geopolymer concrete was prepared with OPC as additive, under ambient curing conditions, and proved to be beneficial in mechanical properties [13]. In India, investigations on Class C fly ash in geopolymer has been reported which gave appreciable properties in strength and durability. However works were carried out in elevated curing conditions. Works on class C fly ash geopolymer was also conducted based on durability and different types of curing conditions, which proved to be advantageous for sustainable construction [14, 15]. Inclusion of OPC as additive in GPC also enhanced the process of geopolymerisation and triggered the curing condition in room environment [16]. These results were incorporated in preparation of SCGC and it was identified that 5% of OPC in binder helped in reducing superplasticiser dosage and altering the curing conditions to external exposure curing [17].

Bond Strength plays an inevitable role in structural applications by anchoring reinforcement to surrounding concrete. Extend of slippage depends on type of concrete the steel is holding and also based on compressive strength and confinement of concrete. In addition, factors such as shape, size, rib inclination of steel bar also depends on bonding characteristics to form as a composite structure. Previous works on bond strength of geopolymer concrete was reported to be superior in bonding properties than ordinary concrete. Efficiency of binding geopolymer concrete to embedded steel was diagnosed using ASTM standard tests for pull out and found to be better than ordinary concrete [18]. Rama Seshu Doguparti experimented on pull tests of geopolymer concrete under ambient curing conditions by changing the bond length in 100 and 75 mm [19]. Results stipulated slight increase in strength, when bond length is decreased. In a distinguished work on pull out tests, 260 specimens were made to develop an empirical model on GP and OPC specimens. The work also compares the previous works on OPC concrete with regression analysis and equations are produced based on those observations [20]. Bond behaviour of Fly ash and GGBS based geopolymer concrete with 12mm and 16mm diameter embedded bars, were also carried out using pull out tests prescribed in Indian Standard Code IS:2770 (Part-I). Results prove that the peak bond stress was found to be 4.3 times more than design bond stress as per IS:456-2000 and geopolymer concrete possess higher bond strength compared to the conventional cement concretes [21, 22].

From the literature it was inferred that, bond strength characteristics of SCGC is still a vague concept and has to be analysed for RCC specimens.The preliminary investigation on pull out tests was performed on SCGC with 5% OPC (SCGC) using 12 and 16mm diameter steel bars [23]. It was identified from previous research that 10% of Class C fly ash in SCGC (SCGC-C) helped in bringing down the curing temperature, and improved its mechanical properties [24]. Hence the present investigation was aimed to compare specimens made of SCC, SCGC and SCGC-C fly ash in terms of Bond strength. The varying factors selected for pull out tests are given as below:

- Change in type of concrete – Normal Self Compacting Concrete (SCC), SCGC without Class C fly ash (SCGC) and SCGC with 10% Class C fly ash (SCGC-C).
- Change in Diameter of reinforcing bar for pull out tests - 10, 12 mm and 16 mm.
- Change in Embedded length of reinforcing bar – 135 mm and 150 mm.

SCC was designed using similar properties of SCGC, in terms of strength and flowability. The test specimens were made using the specification given in IS: 2770 [25]. For each varying factor, 3 specimens were casted and totally 54 specimens were tested to understand the average change in bond strength. The final results were made to compare with empirical equations of bond stress and to identify whether the current equations can be used for validation of bond strength in SCGC.

2. Experimental observations

2.1. Materials

Class F Fly ash of Specific gravity 2.2 and Class C fly ash with specific gravity 2.36 was used for the present study which was directly available from nearby power plants of Tamilnadu, India. The chemical ingredients of both fly ashes are given in Table 1. Referring to the given values it was inferred that fly ash is conforming to IS: 3812 (2013) specifications [26]. The coarse aggregate chosen were of 14 mm and below to ensure proper flowability for SCC and SCGC. River sand is used as a fine aggregate. Physical properties of coarse and fine aggregate are given in Table 2.

Synthesising chemicals used for geopolymerisation are sodium hydroxide (available in pellets) and sodium silicate solution. Sodium Hydroxide pellets with specific gravity 1.47 and of minimum assay-97 %, Carbonate-2%, Chloride-

Table 1.

Chemical composition of Class F and Class C Fly Ash

Content	Class C Fly Ash (% By Mass)	Class F Fly Ash (% By Mass)
SiO_2	60	58
Al_2O_3	32	26.32
CaO	24	3.6
Fe_2O_3	24	3.58
SO_3	6	1.8
Na_2O	1.5	2
MgO	5	1.91
Loss on ignition	2	2

Table 2

Physical properties of Coarse and fine aggregate

Physical Properties	Coarse Aggregate	Fine Aggregate
Bulk Density	1596 kg/m^3	1862 kg/m^3
Specific Gravity	2.72	2.68

0.01%, Sulphate-0.05 %, Potassium-0.1 %, Silicate-0.05 %, Zinc-0.02 %, Heavy metals-0.002 % and Iron-0.002 %, was mixed in water in order to achieve the required molarity in solution. The concentration of NaOH was maintained as 12 M, prepared by dissolving 36.1% solids into 1 litre solution [27].

The sodium silicate solution available in gel form of specific gravity 1.6 is used as surfactant for the present study. Ordinary Portland Cement (OPC) of 53 grade was used as additive in SCGC and 53 grade Portland Pozzolana Cement (PPC) with 35% fly ash was used for preparation of SCC.

MPCE based superplasticiser cum retarder Sika viscocrete 20 HE was selected for which dosage of 1.0 - 2.0% by weight of cement has to be decided according to trials. Relative density noted down is 1.08 g/l.

HYSD deformed bars of minimum yield strength 500 N/mm^2 are taken as reinforcement for pull out specimens. 10mm, 12 mm and 16 mm diameter deformed bars were employed for comparison of bond strength in RCC.

2.2 Mix design

SCGC was designed following EFNARC guidelines and binder content was fixed to 500 kg/m^3 [28]. Trials were done based on workability characteristics in such a way that M30 grade concrete is achieved satisfying codal provisions. Alkaline solution to fly ash and NaOH/ Na_2SiO_3 ratio was fixed to 0.5. Extra water was limited to 12 % of binder. Type of SCGC selected are 5%OPC of source material (SCGC) and 5%OPC+ 10% Class C fly ash of Source material (SCGC-C). Workability and strength properties were checked for SCGC and finally SCC was designed matching to the strength criteria of SCGC for comparison purposes. Proportion of materials taken for SCC, SCGC and SCGC-C are given in Table 3.

Table 3

Mix Proportion of Materials

Materials	SCC (kg/m^3)	SCGC (kg/m^3)	SCGC-C (kg/m^3)
Binder	520	475	427.5
OPC	-	25	22.5
Class C Fly ash	-	-	50
Fine aggregate	960	650	650
Coarse aggregate	821	900	900
NaOH	-	83	83
Na_2SiO_3	-	167	167
Superplasticizer	8.32	10	10
Water	188	60	60

2.3. Mixing and mix proportioning

Sufficient flowability was achieved by premixing alkaline solution to superplasticiser and water, just 1 hour before mixing to aggregates. Dry materials were mixed together and later, solution is poured over dry materials to form a homogenous mixture. The chemical reaction of wet mix played an important role in giving the required workability for SCGC and compressive strength of hardened concrete. The fresh SCGC had a flowing consistency with high tendency of filling ability, passing ability and resistance to segregation. Mixing method of SCC was performed in similar way as given in EFNARC guidelines. Slight differences in mixing of SCGC from SCC were that water along with superplasticiser need not be mixed 1hour prior like SCGC.

2.4. Curing

SCGC and SCGC-C was cured using external exposure techniques [17]. For the purpose of pull out tests, specimens were made in laboratory so as to avoid disturbance of external agencies. After demoulding specimens were kept for external exposure curing. For normal SCC, water curing of 28 days was performed.

3. Fresh and Hardened Properties of SCC and SCGC

Basic workability properties like filling ability, passing ability and segregation resistance for SCC and SCGC was tested, using slump flow, Abrams slump flow, L Box Test and U Box Test, prescribed in EFNARC guidelines, 2002. Trial design was conducted on SCGC and SCGC-C to achieve M30 grade in 28 days and the same was followed for SCC. Details of fresh properties are shown in Table 4.

Table 4

Fresh Properties Results

Type of SCC	T_{500mm} slump flow(sec)	Slump flow dia(mm)	L – Box ratio	U-Box value (mm)
SCC	4	700	0.88	28
SCGC	5	680	0.9	26
SCGC-C	5	700	0.87	28
Range as per EFNARC guidelines	2 - 5	650-800	0.8 - 1	30 mm max

Hardened properties such as cube compressive strength, Splitting tensile strength and Beam flexural strength was carried to evaluate the variation of strength parameters based on IS:516 (1959) and stipulated in Table 5 [29].

Table 5

Hardened Properties Results

Type of SCC	Comp. strength (N/mm^2)	Split tensile strength (N/mm^2)	Flexural strength (N/mm^2)	Cylinder Comp. Strength (N/mm^2)
SCC	32	3.5	3.1	21.6
SCGC	33	2.9	2.9	25.52
SCGC-C	36.4	2.9	3	25.63

4. Pull Out Test

Pull out test measures the force required to pull out a previously cast in steel insert, with an embedded enlarged end in the concrete. In this operation, a cone of concrete is pulled out and the force required is related to the compressive strength of concrete. The failure of RC structures happens primarily due to the deterioration of the bond. Hence it is necessary to study the bond characteristics. Bond stress is calculated as

$$\tau_b = \frac{P}{\pi d_b l_b}$$

where, τ_b - bond stress (MPa),
P - applied load (N),
d_b - diameter of bar (mm)
l_b - embedded length of bar (mm)

4.1. Casting Of Specimen

Concrete cubes of size 150×150×150 mm with a single reinforcing bar (10, 12 mm and 16mm diameter) embedded vertically along the central axis, were used for pull out investigation. Studies are carried out to understand the bonding of steel and concrete when concrete cover is provided, bar was inserted in 150 mm and 135 mm from the top of the mould. 15 mm concrete cover blocks were provided to maintain 135 mm bond length of specimen. Also, the bar was projected upwards by about 85 cm from the top face of the cube to provide an adequate length for gripping the specimen in the testing machine. Illustration showing the arrangement of specimen in different bond length are given in Figure 1.The specimens were also reinforced with a helix of 6mm diameter plain mild steel bar at a pitch of 25mm to prevent splitting failure. Casting arrangement of pull out specimens is shown in Figure 2. De moulding was carried out after 24 hours and then the specimens were kept for external exposure curing. 10mm coating of cement plastering were done one day prior to testing to ensure the exact failure mode.

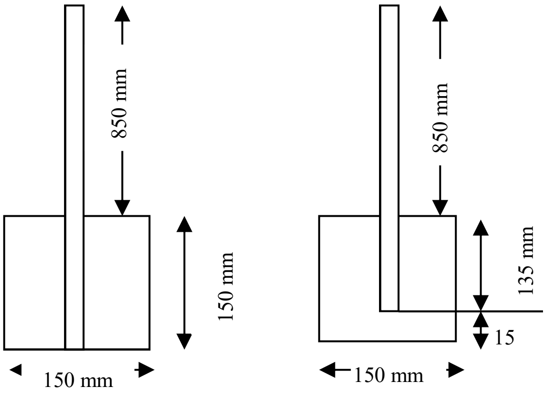

Fig. 1 - Illustration on Bond length of steel for different specimens

Fig. 2 - Casting arrangement of pull out specimens for 135 mm concrete cover

4.2. Testing Of Specimen

The test were conducted based on IS 2770 specifications. Pullout specimen was mounted on the universal testing machine of 2000 kN capacity. Linear variable differential transformer (LVDT) was used to measure the displacement characteristics of the bar. Load was applied to the reinforcing bars monotonically at a rate not greater than 22.5 kN/min. The loading was continued until the specimen failed. The recording of loads and deformations were carried out. The loads recorded were then converted to bond stress. The testing arrangement is shown in Figure 3.

Fig. 3 - Testing of pull out specimens.

5. Results and Discussion

SCC, SCGC and SCGC-C were made of similar hardened properties for the comparison of pull tests and values are noted down. Experimental results for 135 mm and 150 mm bond length are given in Table 6 and Table 7 respectively. Spiral reinforcement provided for each specimen assisted in shear failure mode and are illustrated in Figure 4. Bond stress-slip relation was obtained using displacements observed from LVDT and are plotted down in Figure 5 - 9 and 10. Improved properties of SCGC-C in bonding, helped to exhibit better results for pull out tests than normal SCC and SCGC. 16 mm diameter bars showed better bonding to concrete than other two diameter bars. Change in bond length did not show any appreciable change in bond stress and this was true for all the cases. This depicts that providing change in bond length upto 20mm do not diminish bond strength based on length of embedded steel. However propagation of initial displacement corresponding to the load was slow in 150 mm bond length and increase in load intensity was noted down for 0.025 mm displacement. Hence from above results it proves that SCGC-C is highly recommended for RCC structures where bonding of steel to concrete is prominent factor.

Table 6

Pull test results for 135 mm bond length of steel to concrete

Type of Concrete	Diameter of steel rods (mm)	Bond stress at 0.025mm Slip (N/mm^2)	Max. Bond stress (N/mm^2)	Failure mode
SCC	10	7.62	12.8	Shear
	10	6.88	11.3	Shear
	10	5.42	10.25	Shear
	12	10.62	15.73	Shear
	12	11.4	14.55	Splitting
SCC	12	9.82	13.37	Shear
	16	12.18	16.12	Shear
	16	11.59	14.35	Shear
	16	11.99	16.9	Shear
SCGC	10	7.6	13.6	Shear
	10	8.8	15.68	Shear
	10	7.4	14.9	Shear
	12	14.55	18.68	Shear
	12	15.33	19.68	Shear
	12	15.73	19.27	Shear
	16	15.73	19.66	Splitting
	16	16.12	22.02	Shear
	16	16.32	22.81	Shear
SCGC - C	10	8.2	15.3	Shear
	10	8.33	15.5	Shear
	10	9.45	16.6	Shear
	12	16.3	21.96	Shear
	12	16.8	22.9	Shear
	12	17	23.45	Shear
	16	17	23.57	Shear
	16	17.2	23.97	Shear
	16	16.2	22.92	Shear

Table 7

Pull test results for 150 mm bond length of steel to concrete

Type of Concrete	Diameter of steel rods (mm)	Bond stress at 0.025mm Slip (N/mm^2)	Max. Bond stress (N/mm^2)	Failure mode
SCC	10	8.12	11.5	Shear
	10	10.8	13.3	Shear
	10	9.3	12.18	Shear
	12	12.48	16.2	Shear
	12	11.15	15.3	Shear
	12	10.66	14.2	Shear
	16	12.1	16.2	Shear
	16	13.2	17.2	Shear
	16	12.13	16.6	Shear
SCGC	10	10.66	14.42	Shear
	10	11.45	15.3	Shear
	10	12.9	16.1	Shear
	12	16.55	20.15	Shear

SCGC	12	15.82	19.35	Shear
	12	14.66	18.89	Shear
	16	16.4	21.67	Shear
	16	17.3	22.9	Shear
	16	14.95	19.98	Shear
SCGC -C	10	13.68	15.56	Shear
	10	13.63	15.48	Shear
	10	14.2	16.9	Shear
	12	16.82	22	Shear
	12	17.66	22.34	Shear
	12	18.42	23.68	Shear
	16	21.15	24.25	Shear
	16	20.3	23.67	Shear
	16	20.9	24.1	Shear

Fig. 4 - Failure of specimens in shear due to pull out of bars.

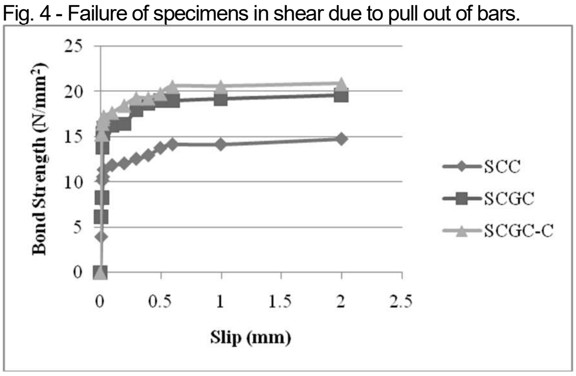

Fig. 5 - Bond Strength Vs slip variation of 10 mm diameter with135mm bond length .

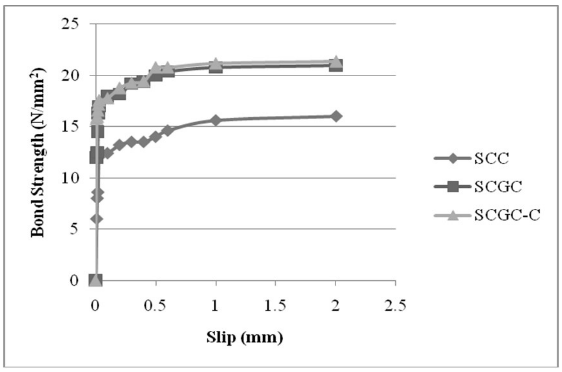

Fig. 6 - Bond Strength Vs slip variation of 12 mm diameter with 135mm bond length.

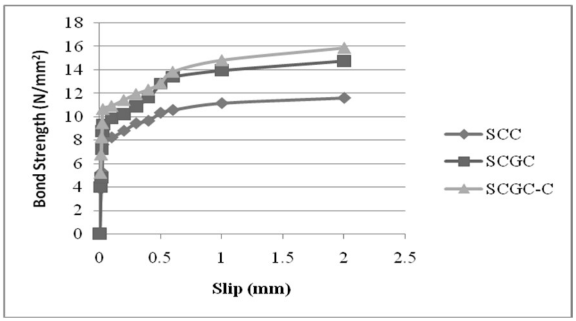

Fig. 7- Bond Strength Vs slip variation of 16 mm diameter with 135 mm bond length.

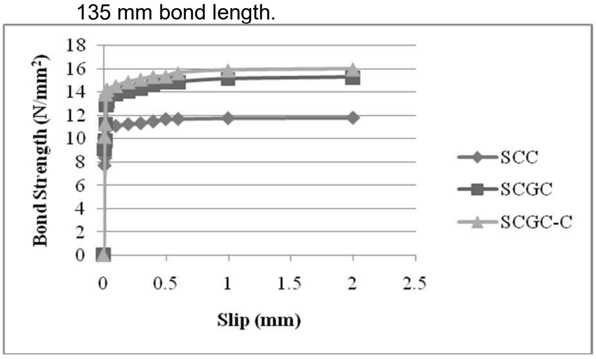

Fig. 8 - Bond Strength Vs slip variation of 10 mm diameter with 150 mm bond length.

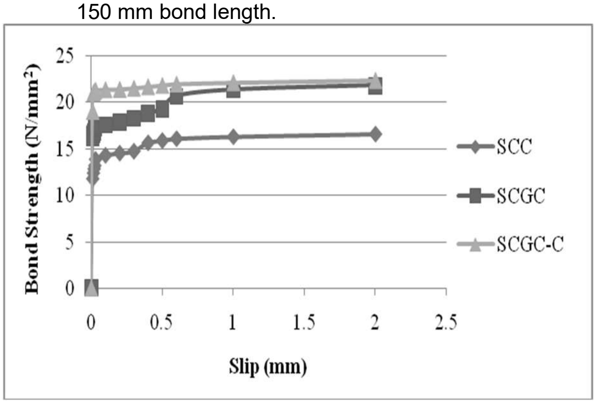

Fig. 9 - Bond Strength Vs slip variation of 12 mm diameter with 150mm bond length.

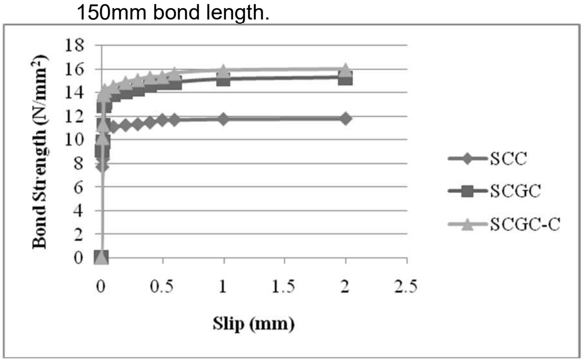

Fig. 10 - Bond Strength Vs slip variation of 16 mm diameter with 150mm bond length.

6. Comparison With Code Recommendations And Empirical Equations

Analytical and numerical methods are presented in many investigations dealing with bond stress of steel to concrete surfaces. Several factors interrelated to bond strength include, concrete cylinder compressive strength, concrete cover, reinforcement diameter, embedded length etc. and empirical equations were categorised with/ without confinement [30]. The influence of the transverse reinforcement is considered as a sum with the bond strength without reinforcement plus the bond strength by the amount of stirrups in the bonded zone. Orangun et al. identified the need of transverse reinforcement to increase the ductility of the anchorage for bond strength requirements [31]. ACI-318 specifies the relation of bond strength to compressive strength as square root of value obtained from cylinder compressive strength (f'c)[32]. This relation seems to be slightly underestimated in case of special concrete. FIB model 2010 clearly explains the need of cylinder compressive strength and differentiates the expression based on confinement, bar dia, spacing of ribs, bar type etc. [33]. Work on SCC and bond strength also laid out empirical expression for bond strength in terms of concrete cover, bar diameter and bond length [34 - 36]. Recently GPC model has been set up using regression analysis and linear relation was laid out for OPC and GPC separately [20]. Table 8 specifies separate expression used by researchers and FIB model code.

Table 8

Bond Stress τ_u Value predicted in FIB model Code and Empirical Equations

Reference	Bond Strength Equation (τ_{max})	
FIB Model equation forconfined concrete	$2.5\sqrt{f'c}$	
Model proposed by Aslani et al. for deformed bar and SCC	$\left(0.672\left(\frac{C}{d_b}\right)^{0.6}+4.8\left(\frac{d_b}{l_d}\right)\right)(f'c)^{0.55}$	
Model Proposed by Bae et al. for deformed bar and SCC	$A\left(\frac{C}{d_b}\right)^{B}(f'c)^{\alpha}$	
Model Proposed by Desnerck et al. for SCC	$\left(1.762+0.514\frac{C}{d_b}\right)\sqrt{f'c}$	
Model Proposed by Dahou et al.	OPC	$0.44f'c$
	GPC	$3.83\sqrt{f'c}$
f'c- Cylinder Compressive strength in MPa, C- Concrete Cover, d_b- Diameter of steel bar, l_d-Embedded length, A- Constant value 0.74 for deformed bars, B- Constant value 0.52 for deformed bars,α -0.58 for deformed bars.		

Based on analytical equations, experimental results for bond stress is matched with varying dia and variations based on bond length are stipulated in Figures 11 to 16.

From figures, it is evident that for SCC, experimental results are matching to Aslani's expression for bond stress and it is valid for 12 and 16 mm diameter. Expression for GP laid out by Dahou et al. matched the experimental results for SCGC and SCGC-C and here also 10 mm diameter did not satisfy the lower limit of expression. Expression defined by Desnerck et al. was found to be slighlty overestimated in case of SCC, SCGC and SCGC-C, whereas FIB model code and Bae's expression underestimated bond stress for SCGC. The empirical equation laid out using concrete cover to steel diameter ratio, proposed decrease of strength for increase of steel diameter This was not valid in case of experimental investigation from 10 to 16 mm diameter specimens. However most of expressions were satisfied for 12 and 16 mm diameter bar specimens.

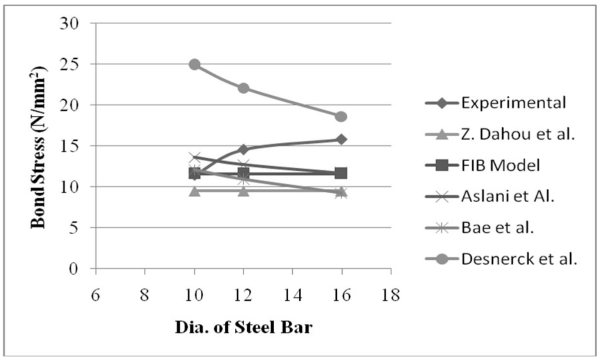

Fig. 11 - Model comparison for SCC specimens with 135 mm bond length.

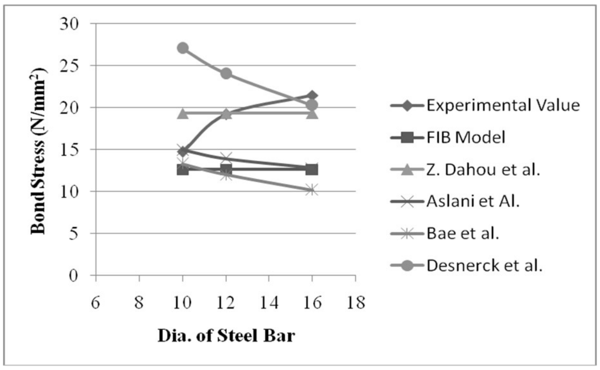

Fig.12 - Model comparison for SCGC specimens with 135 mm bond length.

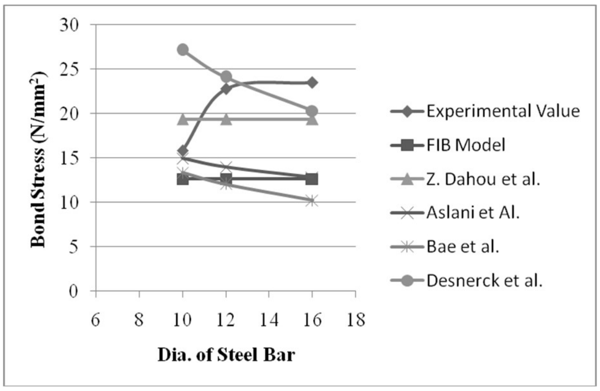

Fig. 13 - Model comparison for SCGC-C specimens with 135 mm bond length.

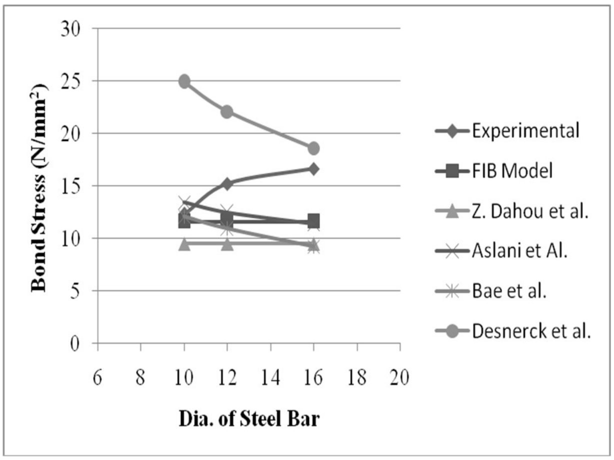

Fig. 14- Model comparison for SCC specimens with 150 mm bond length.

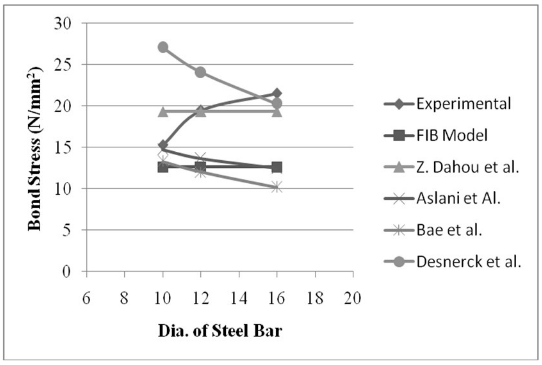

Fig. 15 - Model comparison for SCGC specimens with 150 mm bond length

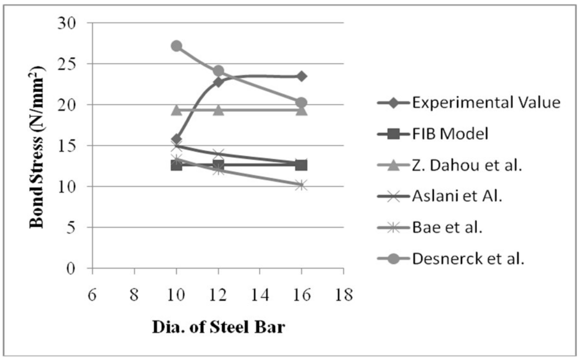

Fig. 16 - Model comparison for SCGC-C specimens with 150 mm bond length

7. Conclusion

Based on Experimental investigation following conclusions can be drawn:

Bond strength between concrete and steel is much higher for SCGC-C when compared to SCC and SCGC of similar mechanical properties. This indicated that blending of fly ashes improved the bonding property of SCGC to steel, which in turn can be useful for R.C.C. structures.

Change in Bonding length for 135 mm and 150 mm length has no direct connection to the bond strength in the case of SCC and SCGC. Bond strength increased by increase in diameter of steel rods.

The authors have tried to evaluate whether concrete cover has any effect on bond strength and proved that, providing concrete cover upto 15 mm does not influence bond strength directly.

The Pull out strength of SCC, SCGC and SCGC-C increased with increase in compressive strength of concrete.

Comparison was made on experimental bond strength values to empirical equations. Result suggests conservative approach for Z.Dahou's model in SCGC& SCGC-C and Aslani's expression in SCC.

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MANIFESTĂRI ȘTIINȚIFICE / SCIENTIFIC EVENTS

ICGCGC 2018: 20th International Conference
on Geopolymer Cement and
Geopolymer Concrete
Tokyo, Japan
October 8 - 9, 2018

The ICGCGC 2018 event aims to bring together leading academic scientists, researchers and research scholars to exchange and share their experiences and research results on all aspects of Geopolymer Cement and Geopolymer Concrete. It also provides a premier interdisciplinary platform for researchers, practitioners and educators to present and discuss the most recent innovations, trends, and concerns as well as practical challenges encountered and solutions adopted in the fields of Geopolymer Cement and Geopolymer Concrete.

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