Studies on the Effect of Top Bar in Bond Strength of Self-Compacting Concrete

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Abstract - Self Compacting Concrete is well known for its strength and uniformity. The mechanical properties and bond strength at the steel –concrete interface of SCC varies with its varying mix design. The aim of this paper is to investigate on the bond strength of the top reinforcement and compare with the bond strength of bottom bars in both SCC and VC through pullout tests. For this SCC and VC of compressive strength 40MPa was designed and achieved through proper mix design procedures. The pullout specimen was designed as an integrated composite comprising of both pullout cubes and cubes for compressive strength test at five different levels. The study concludes that the bond transfer mechanism and the top bar effect in self compacting concrete are similar to that of vibrated concrete up to a 500mm height.

Index Terms – Bond strength, Self Compacting Concrete, Top Bar Effect.

1 INTRODUCTION

Self-compacting concrete (SCC), is a new kind of high performance concrete, with excellent deformability and segregation resistance, developed first in Japan, 1986. With regard to its composition, self-compacting concrete consists of the same components as that of the conventional vibrated concrete (VC), with some additional chemical and mineral admixtures in different proportions. Usually, the chemical admixtures used are high-range water reducers (super plasticizers) and viscosity – modifying agents, which change the rheological properties of concrete. Mineral admixtures are used as extra fine material, besides cement, and in some cases, they also replace cement to some extent.

The application of SCC effectively resolves the difficulties of concreting in situations with complicated formwork and intricate reinforcements. Particularly structures like seismic resistant incorporates heavily congested beam column joints where attaining full compaction is of utmost important for its durability. The entire voids between the reinforcements and the formworks are filled by self compacting concrete enhancing better bond and durability of the structures. SCC is expected to increase the flexural behaviour and loading carrying capacity of moment-resisting members due to the superior filling capability of SCC that may directly enhance the bond between reinforcements and concrete and may also indirectly improve the confinement effect from the lateral reinforcements.

FACTORS INFLUENCING THE BOND PERFORMANCE

The bond behaviour depends on a variety of factors, which refers basically to the reinforcing unit (bar, multi-wire strand, tendon), to the concrete and to the stress state in both the reinforcing unit and the surrounding concrete. Nevertheless, many technological aspects come into play

too, such as concrete cover, clear space between the bars, number of bar layers and bundled bars, casting direction with respect to bar orientation and bar position with respect to the free surface of the fluid concrete.

Therefore, the bond performance is influenced by the following factors:

1. Adhesion.
2. Gripping effect resulting from the drying shrinkage.
3. Frictional resistance.
4. Effect of concrete quality and strength.
5. Mechanical anchorage effect of the ends of bars.
6. Diameter, shape, and splicing of reinforcement.
7. Location of rebar with respect to the concrete depth

And also, the effect of varying degree of consolidation in concrete showed that the

- Concrete-steel bond strength improved with consolidation.
- Over vibration results in bleeding or segregation and decreased the bond strength
- Improper, insufficient vibration results in entrapped air and decreased the bond strength.
- In normally vibrated concretes, when its fluidity is increased or sand rich mixes are used, its bond deteriorates.

The fact that the, no need to compact SCC reduces the risks that accompany with compaction. For the bond behaviour of the rebars in normal concrete several investigations have been done. From these was found, that the main parameters that influence the bond behaviour are, the surface of the rebars, the number of load cycles, the concrete mix design, the direction of concreting and also the location of the rebars.

BOND STRENGTH OF SCC:

A review of bond tests conducted by various researchers is presented here below:

Pull out tests:

In a study dealing with pull-out tests on SCC, Chan et al. [22] reported that, as compared to NC, SCC exhibits higher bond to reinforcing bars and lower reduction in bond strength due to the top-bar effect. Zhu et al. [20] performed bond tests (pullout tests) with 12 and 20 mm deformed bars placed in concrete specimens of 100 × 100 × 150 mm to study the performance of SCC compared to NC. The test results showed 10%-40% higher normalized bond strength in SCC compared to NC. Dehn et al. [23] performed pull out tests with 10mm diameter bars placed centrally in the specimen of size 100 x 100 x 100 mm to investigate the bond strength of SCC. The bond behavior was measured at 1, 3, 7, and 28 days and was reported as all specimens failed from pulling out, no visible cracks in the concrete cover were monitored. Arnaud et al. [2] investigated the bond strength of SCC using 100 x 100 x 150 mm sized pull out specimens and reported that the maximum ultimate bond strengths obtained were approximately 20% higher for SCC than normal concrete, regardless of the concrete strength. Valcuende et al. [28] examined the bond strength between reinforcement steel and concrete, and the top-bar effect in self-compacting concretes through pull out test on 200 mm specimen and reported that at moderate load levels, SCC performed with more stiffness, which resulted in greater mean bond stresses. The ultimate bond stresses are also somewhat greater although, due probably to the negative effects of the bleeding having less impact on failure, the differences between SCC and NVC are reduced considerably, and even disappear completely for concretes of more than 50 MPa.

Failure Mechanism in Pull out Test:

The failure occurred in two different modes for SCC. One mode consisted of splitting of the concrete surrounding the bar, and the other mode consisted of shearing of the reinforcement against the surrounding concrete. The splitting failure is caused by the wedging action of the lugs on the bars. The wedging produces confining pressure from the surrounding concrete and is balanced by circumferential tensile stresses around the bar. These stresses cause formation of radial splitting cracks that lead to a sudden loss of bond strength. The shearing failure occurs after the reinforcement lugs shear or crush the concrete in front of the lug, thus making a pull out along a cylindrical frictional surface possible. The splitting failure is obviously fracture dominated. Different though it might seem at first, the shearing failure is also of fracture mechanics type since it is propagating and progressive. The shearing failure starts from the loaded end and then propagates towards the free end as one lug after another shears or crushes the concrete in front of the lug. After the shearing has progressed over the entire length of embedment of the bar, the force drops and then the remaining pullout is resisted by the friction, which is nonsoftening in nature but occurs at a force lower than its previous maximum. Nevertheless, due to law of friction, the shearing failure is much less abrupt than the splitting failure which is almost purely of fracture mechanics type [26].

Esfahani et al. (2007), reported that the local bond strength of top bars for SCC is about 20% less than that for NC. For the bottom bars, however, the results were almost the same. Comparison of the local bond strength between test results with the values calculated by ACI 318 Code shows that in the case of SCC, the location factor of ACI Code should be increased. Hassan et al. (2009), reported that in both NC and SCC pullout specimens, the bond stress was slightly higher in the bottom bars than that in the top and middle bars at all ages. Also, no significant difference was detected between the top and middle bars at all ages.

SCOPE

The scope of the present experimental work is to

1. Design SCC and VC mix for medium strength concrete with a suitable mix design procedure.
2. Design a specimen to study the top bar effect of steel bars in SCC and VC.
3. To test the specimens through pullout test under monotonic loading.
4. Suggest modifications for the top bar factor ψ_t.

EXPERIMENTAL PROGRAM

MATERIALS

The ingredients for self-compacting concrete (SCC), cement, water, coarse and fine aggregates, are the same as that required for normal or conventional concrete but to attain self flow ability admixtures such as fly ash, glass filler, limestone powder, silica fume with some superplasticizer are added. In the present study mineral addition, fly ash of class – C from “Neyveli Lignite Corporation limited” was used to enhance the powder content of the SCC mix. The material properties of the ingredients of SCC and VC are detailed in the Tables 1, 2 and 3.

Table 1 Properties of Cement and Fly Ash

Properties of Cement	Test results	Properties of Fly Ash	Test results
Standard consistency	33.5%	Loss on ignition, %	1.25
Initial setting time	35 min	Specific gravity	2.25
Final setting time	155 min	Blaine’s Fineness, cm²/g	4350
Specific gravity	3.15	Silicon dioxide (SiO_2), %	45.3
Soundness	1 mm	Calcium oxide (CaO), %	11.2
Strength of Mortar cubes	MPa	Aluminium oxide (Al_2O_3), %	22.95
7th day	22.4	Magnesium oxide (MgO), %	4.00
14th day	31	Sulphur oxide (SO_3), %	Traces
28th day	42.5	Iron oxide	14

Table 2 The physical properties of aggregates

Sl.No.	Properties	Coarse aggreate	Fine agregate
1	Specific gravity	2.74	2.71
2	Losse density, kg/m^3	1315.6	1437.5
3	Rodded density, kg/m^3	1620	1720
4	Fineness modulus	7.9	2.8
5	Water absorption, % mass	0.58	0.32

Chemical admixture

The admixture used in SCC is to reduce water demand and the other is to modify the viscosity of concrete so that segregation could be avoided. Therefore it is customary to add superplasticizer (SP) along with viscosity modifying agent (VMA). Commercially available super-plasticizer (Supaflo special) from Don Chemicals (India) Ltd. was used. Supaflo special is a non toxic brown liquid based on sulphonated naphthalene polymer. It is a superplasticizer (SP) which is premixed with vicosoty modifier.

Table 3: The properties Supaflo special admixture as given by its manufacturer

Physical state	Brown Liquid
Dry material content	42 % ± 3 %
Specific gravity	1.21 ± 0.015 @ 27° C
Chloride content	Nil
pH	7 to 8

The workability test for conventional concrete, using slump cone test, resulted in a slump value of 200 mm. The fresh properties of the final mix proportions of SCC, as evaluated by the above mentioned fresh state assessment tests are presented in Table 4.

MIX PROPORTIONING OF SCC FOR M30

In order to proportion SCC the method proposed by Nan Su, et al., [35] has been followed. The final mix proportions of SCC and VC for 30MPa strength are as given below:

Ingredients		SCC	VC
Cement Content	:	300 kg/m^3	300 kg/m^3
Fly ash Content	:	273 kg/m^3	273 kg/m^3
Powder content, P	:	573 kg/m^3	573 kg/m^3
Coarse aggregate (12.5mm NMS)	:	743 kg/m^3	817 kg/m^3
Fine Aggregate	:	743 kg/m^3	670 kg/m^3
W/P ratio	:	0.43	0.42
Water	:	246.4 lts/m^3	240 lts/m^3
SP (2% of P for SCC and 1% of P for VC)	:	11.5 kg/m^3	5.7 kg/m^3

The mix proportion of both the types of concrete are maintained the same with minimal variation in the contents of conventional concrete's ingredient.

Table 4: Fresh properties of the evolved SCC mix

S.No.	Fresh properties assessment Tests	Results Otained	Aceptance Criteria*	
			Min	Max
1	'V' Funnel, sec	9	6	12
2	'L' Box, ratio	0.85	0.8	1
3	Slump flow time, sec	3.2	0	5
4	Slump spread diameter, mm	700	650	800

* Acceptance criteria from draft European guidelines for testing SCC

DETAILS OF THE SPECIMENS

The specimens for both the type of concretes were designed to consist of the pull out cubes and the cubes for compression strength tests, as a combination in one casting. Each specimen measured 600 mm in length, one meter in depth and 200 mm in width as a whole. The centre of the specimen comprises the concrete cubes for compression strength tests at five elevations. The ends of these concrete cubes are the pullout cubes of length 200 mm, at both the ends of the specimen. The cubes for compression test and the pullout cubes are of same cross section (200 mm x 200 mm) and are separated from each other by 30 mm thick thermacoal sheets. The pullout cubes are designated by their concrete type followed by their depth level of concrete in the specimen from the top. For example the top most pullout cube in SCC specimen is designated as "SCC-Top", the middle as "SCC-Middle" and the bottom as "SCC-Bottom". Therefore, the pullout cube in between the top and middle is designated as "SCC-Top middle" and that in between the middle and the bottom as "SCC-Middle bottom". Same principle is followed in designating the VC pullout cubes.

Fig.1shows the reinforcement details of the specimen in the plan and cross section view. The beam reinforcement comprises of two numbers 16 mm ϕ rods at their bottom and two numbers of 10 mm ϕ rods at the top. The bottom rods, spliced at their midspan, for a length of 320mm. The transverse reinforcement was provided by two legged stirrups of 8 mm ϕ bars at 160 mm centre to centre spacing. The bars used were TMT bars of inclined rib pattern, meeting the IS 1786 of grade Fe415 specification. The average yield stresses were 615 MPa for the 16mm ϕ bars and 564 MPa for 8mm ϕ bars.

EXPERIMENTAL SET-UP AND TESTING PROCEDURE

Pullout test set-up

Pullout tests were conducted in an Universal Testing Machine of 60 Tonnes capacity as shown in Fig.2. Bearing surface of the cube in the pull-out test was capped with a thin layer of Plaster of Paris 24 hours prior to testing. The bearing surface was supported on a 25 mm thick plate of size 200mm x 200mm, with a hole drilled at its centre. To avoid the influence of lateral strains by friction, 6 mm Teflon sheet (250mm x 250mm) was placed between the specimen and the base plate. The test specimen was mounted in the testing machine as shown in Fig.2, in such a manner that the bar is pulled axially from the cube. At the free end of the bar an LVDT, with least count 0.01, was fixed to measure the free end slip. The movement between the reinforcing bar and the concrete cube, as indicated by the LVDT was read at sufficient intervals (100kgf) throughout the test. The loading was continued and readings were recorded until the specimen failed either by splitting of concrete or rupture of the steel bar.

A total of twenty pullout specimens, confirming to the RILEM standards (1973), ten in each type of concretes (SCC and VC) were tested. The pullout specimens measured 200mm x 200mm in cross section. Each of the pullout cubes had a one meter length 16mm ϕ rod, placed concentrically in the cube, with an embedment length of 80mm i.e. 5 times diameter of bar. The bond stress (τ) is calculated using the formula given below.

$$\tau = P / (\pi \, d \, L) \qquad \text{-----(1)}$$

Where

P = applied load (N)
d = diameter of the bar (mm)
L = embedment Length (mm)

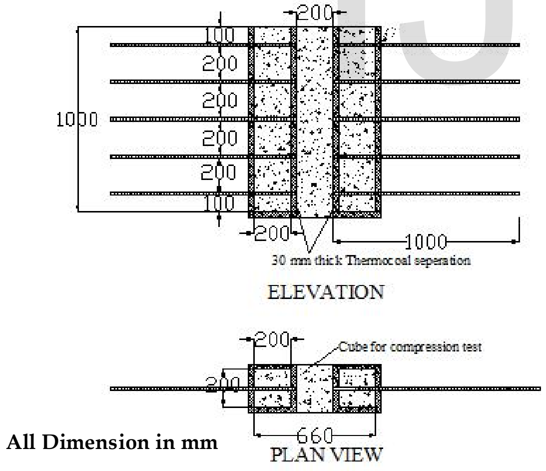


Fig:1 Details of the Specimen

RESULTS AND DISCUSSION

Mode of failure in Pullout Test

Except for a few, all the other specimens have failed in pullout mode. In the VC type, three specimens had splitting failure. One at the top middle level and two at the middle level had splitting failure. Figure 3 (a) shows the full splitting of the VC specimen at the middle level. In the SCC type, one specimen at the middle bottom level had splitting failure (Fig. 3(b)).

And no specimens had failed due to yielding of the bar.

Pullout test results

The pullout test was performed on a total of twenty pullout cubes. Two pullout cubes cast at 100 mm, 300 mm, 500 mm, 700 mm and 900 mm were tested. With the free end slip measurements of the bars for all the specimens, the average of two specimens bond stress vs slip curves were plotted.

Figure 4 to 8 shows the comparison of bond stress vs slip curves of SCC and VC at the five levels (900mm, 700mm, 500mm, 300mm and 100 mm). The initial tangent stiffness of both the concretes are the same at the initial stages, which are tabulated in the table 8. Whereas after cracking of concrete the stiffness of SCC gets reduced to 22 N/mm^3 based on the secant stiffness at 11 MPa bond stress and that of VC to 29.33 N/mm^3 based on the secant stiffness at 10 MPa bond stress. SCC has 75% stiffness degradation from the initial tangent stiffness and that for VC it is 66.67%. From this it is evident that stiffness reduction is less in VC when compared to SCC at the top level and the stiffness degradation in SCC is 24.99% compared to VC.

Fig.9 shows the comparison of bond stress-slip curves of the rods at five levels in vibrated concrete. The curve representing the top bar placed at 900 mm from bottom is found to be the lowest followed by the curves representing the rods at the remaining levels. The sequence of the curves from the lowest to the highest as in graph, is as the top followed by bottom and then by top middle and middle at the same level which is followed by the middle bottom. This irregularity in the sequence of the curves must be the outcome of improper or inadequate vibration at the bottom level of the specimen. The concrete between the middle and the bottom level had good vibration and the bond stress response at this level is maximum. The top middle and the middle levels have received moderate vibration and hence the bond stress response at these two levels is less than that of the concrete at middle bottom level. Thus, it is evident that proper consolidation is required to ensure good bond strength between rod and concrete at their interface for vibrated concrete having sectional depth more than 300 mm.

Figure 10 shows the comparison of bond stress-slip curves of the rods at five levels in Self compacting concrete specimen. The sequence of the five curves is as top, middle, top middle, middle bottom and bottom. Though there is some irregularity in the sequence of curve positions in the graph, the evidence of top bar effect is clear. The curve depicting the rod at the top level is at the lowest position (Fig.5.10) with minimum bond stress response which is followed by the other curves and finally the bottom level curve at the highest position in graph having maximum bond stress response. Hence, SCC the no vibration concrete exhibits top bar effect in it.

Figure 11 shows the comparison of ultimate pullout loads of the specimens positioned at five different heights from the bottom in both the type of concretes. The ultimate load of SCC specimens at the bottom and top levels is greater than that of VC specimens at those levels. For the other remaining levels the VC specimens have taken greater loads than the SCC specimens. Similar to the figure 5.10 the evidence of top bar effect in SCC is seen in this figure also. The ultimate loads taken by the rods at five levels have an increase from the top to bottom. The ultimate loads taken by the middle bottom, middle, top middle and top levels has a decrease of 27.4%, 42.6%, 17.5% and 24.4% compared to the bottom level's ultimate load. For the VC specimens, there is an increase in the ultimate loads from bottom level to the middle level and then decreases to the top level. The ultimate load of the bottom level as reference, the increase in the ultimate loads of the middle bottom and middle level is by 31.8% and 30.5%. The ultimate loads of the top middle and top level has decrease of 3.5% and 26.1% compared to the ultimate load of bottom level.

Top-Bar factor

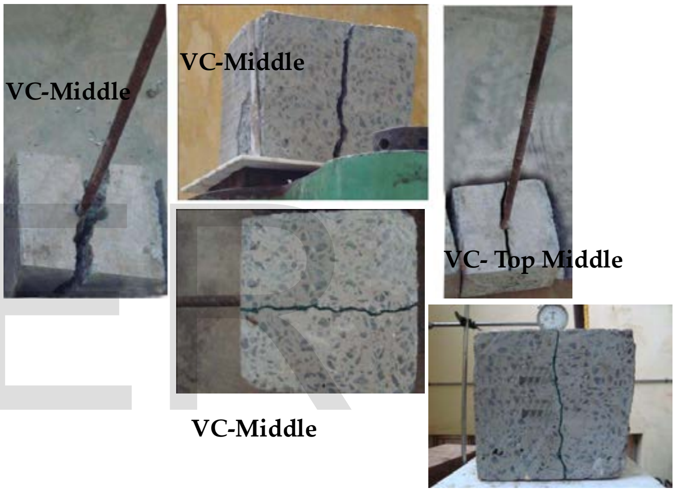
In order to compare the bond strength of SCC and VC, the variation of compressive strength (f_c') has to be taken into account. According to the provisions of ACI 318 (ACI 2005), the development length of the reinforcing bar for sufficient anchorage is inversely proportioned to the square root of the compressive strength, implying that the bond strength should be linearly proportional to the square root of the compressive strength. The bond strength is normalized by dividing it by $\sqrt{f_c}$. The actual bond strength (u) and normalized bond strength ($u_{nz} = u/\sqrt{f_c}$) of SCC and CC are presented in the Table 10.

For the VC specimen, concrete was placed in several layers and thorough mechanical vibration was applied for each layer. Therefore, there are some possibilities of segregation in aggregates and / or local bleeding around the reinforcing bars. As a result, the bond strength of the reinforcing bar at higher elevations is affected. During the pouring of the SCC specimen, no vibration was applied to the concrete. The SCC filled the formwork and space between the reinforcements by self consolidation. Presumably, without vibration or consolidation, the concrete materials in SCC specimens will be more uniform and local bleeding and segregation can be avoided in comparison with those of VC. Therefore, the top-bar effect is expected to be less in the case of SCC. However, the plastic settlement during hardening of SCC may still cause the observed variation in bond strength of SCC at different elevations. All the bars above 300 mm level from bottom are considered to have top bar effect as per ACI recommendations are calculated as shown in Table 10, considering the bond stress calculated at the bottom most level as reference.

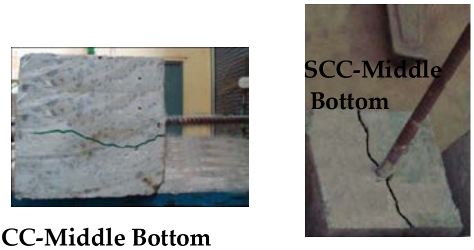
In the case of SCC specimens, the bond strengths of the bars at 300mm, 500mm and 900mm height from bottom, has a decrease of 13%, 31% and 7% compared to that of the bottom bar. But for the rod at the 700mm height from the bottom has an increase of 22% in its bond strength compared to the bottom bar.

In the case of VC specimens, the bond strengths of the bottom bar is found to be less compared to that of the bars above it. As explained in the previous section of this chapter, this is an outcome of inadequate vibration delivered to the bottom layer. Hence, discarding the bottom rod and assuming the middle bottom rod as the bottom most rod, there is evidence of top bar effect in VC. The bars above the middle bottom bar have a decrease in bond strength by 0%, 12% and 47% compared to that of the middle bottom bar.

Figure 2: Pullout test set up



(a) VC Specimens



(b)SCC Specimens

Figure 3: Splitting failure in pullout specimens

Table 7: Pullout test results

Level	Cube strength f_{ck}	Ultimate load, N	Ultimate bond stress, MPa	Slip at ultimate bond stress, mm	Failure
SCC-T	21.40	62337.79	14.27	1.56	pullout
SCC-TM	18.00	68045.06	17.08	1.93	pullout
SCC-M	26.63	47346.18	11.81	1.07	pullout
SCC-MB	23.63	59886.08	14.03	1.92	spliting
SCC-B	29.95	82554.37	18.05	1.36	pullout
VC-T	27.75	55505.15	13.29	0.99	pullout
VC-TM	15.80	72425.98	16.47	0.94	spliting
VC-M	27.47	98068.48	24.82	2.08	spliting
VC-MB	23.49	99073.28	22.90	0.88	pullout
VC-B	28.13	75118.85	18.05	1.54	pullout

Table 8: Degradation in tangent bond stiffness

Level	Initial tangent stiffness (SCC and VC)	Tangent stiffness after cracking		Degradation from initial stiffness, %		Stiffness degradation in SCC compared to VC
		SCC	CC	SCC	VC	
	k_0	k_1	k_2	$((k_0-k_1)/k_0) \times 100$	$((k_0-k_2)/k_0) \times 100$	$((k_2-k_1)/k_2) \times 100$
Top	88	22	29.33	75	66.67	24.99
Top mid	155	20.66	49.6	86.66	68	58.33
Mid	infinite	25	17.64	-	-	-41.72
Mid bot	224	27.27	42.85	87.82	80.86	36.36
Bot	293.34	33.84	33.84	88.46	88.46	0

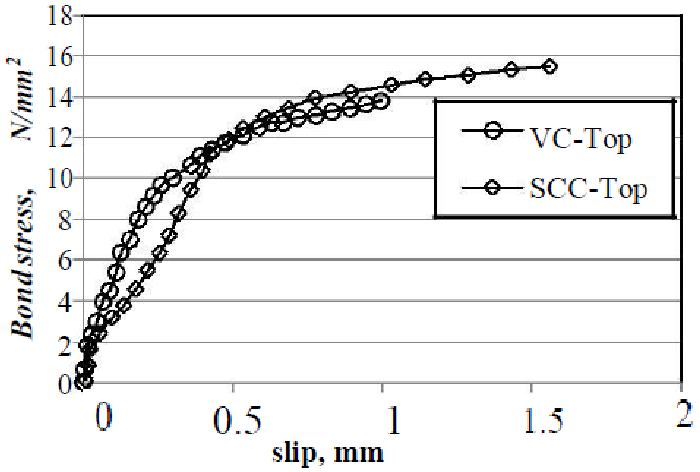


Figure 4:at 900mm

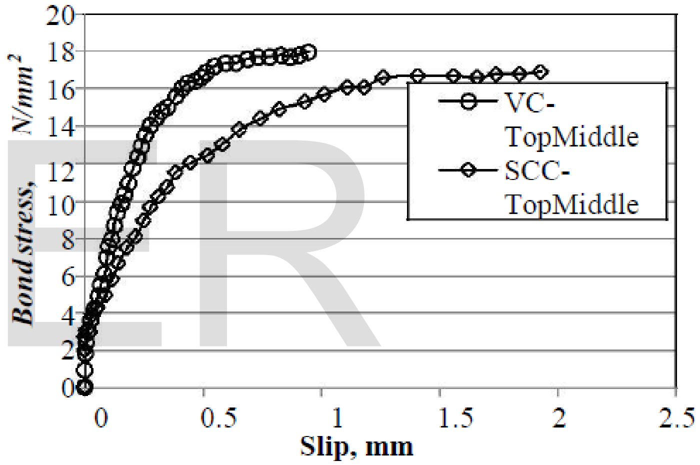


Figure 5: at 700mm

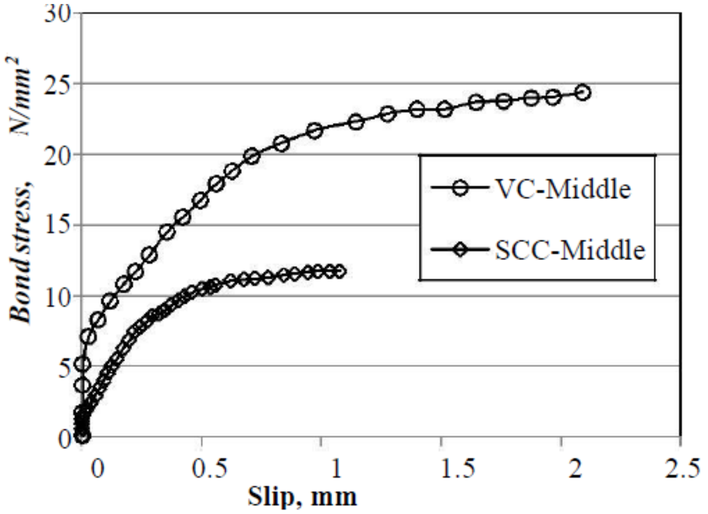


Figure 6: at 500mm

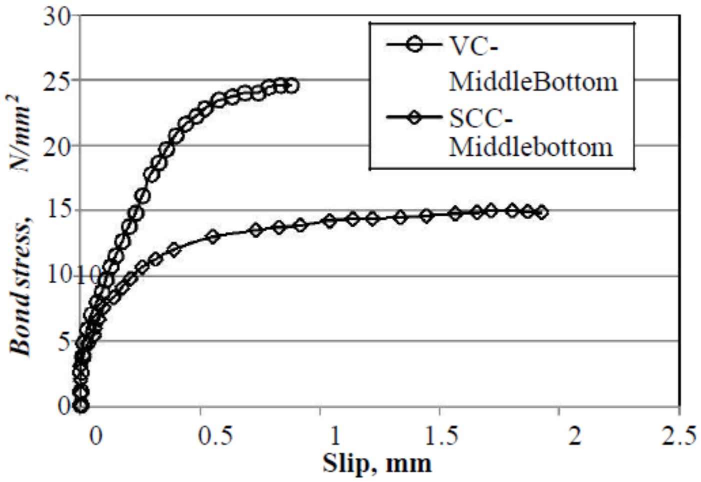


Figure 7: at 300mm

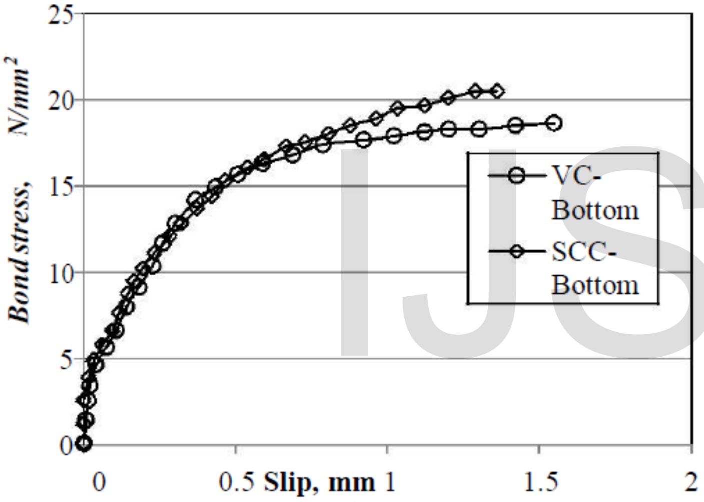


Figure8: at 100mm

Figure 4-8 Bond stress vs slip curves for SCC and VC specimen at respective levels

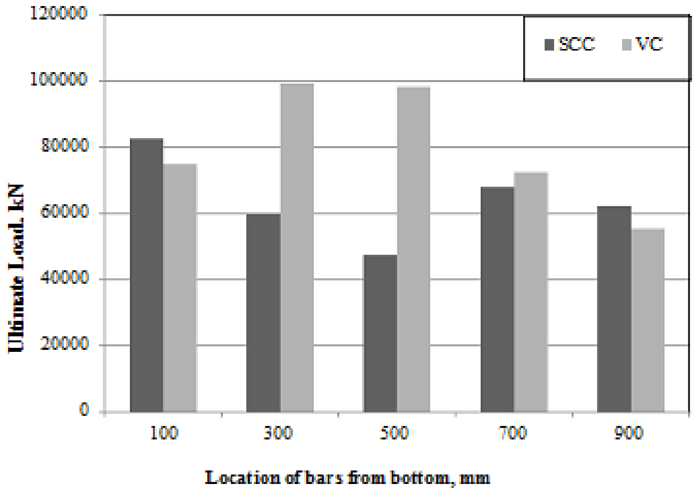


Fig 9: Comparison of ultimate pullout loads in SCC and VC

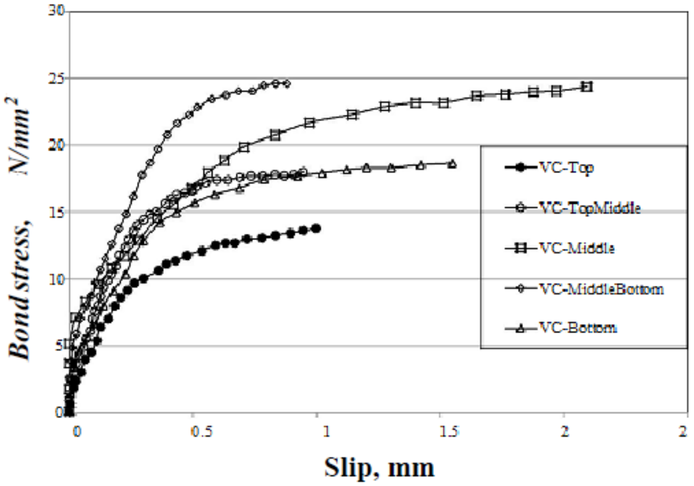


Figure 10: Comparison of bond stress vs slip in VC

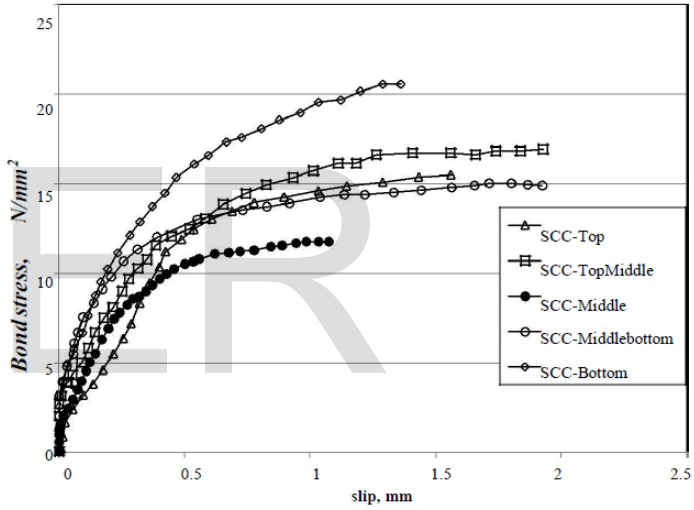


Figure 11: Comparison of bond stress vs slip in SCC

CONCLUSIONS

Stiffness degradation and top bar effect from Pullout test

The ultimate pullout loads in SCC specimens decreases by 27.4%, 42.6%, 17.5%, and 24.4% in middle bottom, middle, top middle and top level compared to bottom level. In VC specimens, there is honey combing in the bottom level specimen due to inadequate vibration at this level. Therefore, discarding this level and assuming the middle bottom level as the bottom level, the ultimate pullout load decreases by 1%, 27% and 44% in middle, top middle and top levels compared to the middle bottom level.

All the bars above the bottom bar are considered as top bars and the top bar factor is calculated as U_{top} / U_{bot}. The top bar factor in SCC and VC are given in table 5.5. In SCC the top bar factor is 31% and for VC it is 47%. Hence, the top bar effect is evident in both SCC and VC, pronounced at the same extent with minimum difference.

Also, the bond stiffness of the concretes were determined and it is found that, the initial tangent stiffness of pullout curves is the same in both type of concretes which increase in its extent from specimen-top to specimen-bottom. After cracking of concrete there is degradation in tangent stiffness of SCC and VC with SCC at lower side compared to that of VC at all levels, except for middle level. However, the degradation of the tangent stiffness from its initial value in both concretes increases from specimen-top to specimen-bottom. Implies the bottom level specimens are stiffer compared to their top level specimens. The stiffness degradation in SCC and VC from top to bottom is as 75%, 86.6% 87.8%, 88.4% and 66.6%, 68%, 80%, 88.4% respectively. Though the VC specimens are found to be stiffer than SCC at the top levels, the stiffness of VC and SCC are the same at the bottom level.

Level	Ultimate load, N	$Load_{re-sp}/Load_{bot}$	Ultimate Bond stress (u)	Normalized Bond stress ($u_{nz}/\sqrt{f_c'}$)	Top Bar Factor $U_{re\,re-sp}/U_{bot}$
SCC-T	62337.79	0.76	14.27	3.45	0.93
SCC-TM	68045.06	0.82	17.08	4.50	1.22
SCC-M	47346.18	0.57	11.81	2.56	0.69
SCC-MB	59886.08	0.73	14.03	3.23	0.87
SCC-B	82554.37	1.00	18.05	3.69	1.00
VC-T	55505.15	0.56	13.29	2.82	0.53
VC-TM	72425.98	0.73	16.47	4.63	0.88
VC-M	98068.48	0.99	24.82	5.29	1.00
VC-MB	99073.28	1.00	22.90	5.28	1.00
VC-B	75118.85		18.05	3.80	

Table 9: Top bar effect based on pullout test results

SCOPE FOR FUTURE WORK

Top bar effect is an important factor for sections with more than 300 mm depth. Only a few studies are available regarding the top bar effect in SCC, more studies in this regard will be needed to substantiate the above conclusions.

The present study is only focused on normal strength SCC. Therefore, SCC as normal, high strength and fiber concrete shall be studied for the top bar effect in them.

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