A COMPARISON OF THE BOND CHARACTERISTICS IN CONVENTIONAL AND SELF-COMPACTING CONCRETE, PART I: EXPERIMENTAL RESULTS

Farhad Aslani (1) and Shami Nejadi (2)

(1) PhD candidate, School of Civil and Environmental Engineering, University of Technology Sydney, Australia

(2) Senior Lecturer, School of Civil and Environmental Engineering, University of Technology Sydney, Australia

Abstract

Self-compacting concrete (SCC) is a very flowing material that can flow through the reinforcement and fill the formworks without any need of vibration during the concrete placement process. The material properties of SCC including bond characteristics must be well understood in order to use this type of high performance concrete in structural members broadly. This paper presents a comparison of the experimental results from the nine recent investigations on the bond strength of SCC and conventional concrete (CC). The comparison is based on the measured bond between reinforcing steel and concrete by utilizing the pullout test on the embedded bars at various heights in mock-up structural elements to assess the top-bar effect and on single bars in small prismatic specimens and conducting the beam tests. The investigated affecting parameters on bond strength are: the steel bar diameter, concrete compressive strength, types of bar (plain or deformed), embedded length of the bar, concrete type, concrete cover, curing age of concrete, casting direction of concrete and height of the embedded bar along the formwork.

1. INTRODUCTION

SCC, a new generation of high performance concrete (HPC) with excellent deformability and segregation resistance, was first developed in Japan in 1986. It is a special type concrete that can flow through and fill the gaps of reinforcement and corners of formwork without any need of vibration and compaction during the placing process. SCC has favourable characteristics such as high fluidity, good segregation resistance and the distinctive self-compacting ability without any need for vibration during the placing process. However, the modified composition of SCC in comparison with conventional concrete (CC) may have some consequences on the properties of the hardened concrete. Therefore, it is important to ensure that all the assumptions and test results on which the structural design models are based for CC structures are also valid for SCC structures. An important property of the hardened concrete is its bond capacity and characteristic with the reinforcing steel. The bond strength between reinforcement and concrete is a basic phenomenon which allows reinforced concrete to behave as a structural material. Forces are transferred between the two materials by two types of actions, those that are physicochemical (adhesion) and those that are mechanical (friction and bearing action), which are activated by various states of stress. To a large extent, the relative importance of those actions depends on the surface texture and the geometry of the bars [1].

Based on extensive experiments, Carrasquillo [2] stated that "in no case the pullout capacity of straight deformed bars embedded in superplaticizered concrete is significantly less than that of the bars embedded in concrete containing no superplasticizer". The bond strength of SCC with Viscosity Modifying Admixtures (VMA) with special focus on the effect of VMA to reduce the top-bar effect of anchored bars has been studied by Khayat [3]. Accumulation of bleed water under the reinforcement and minute separation of fresh paste from the reinforcement due to segregation and settlement can significantly reduce the bond strength. The reduction in bond with horizontally embedded bars located in the upper sections of structural elements as opposed to those located near the bottom is known as the top-bar factor. A total of 25 specimens were prepared to evaluate the effect of specimen height (500, 700, and 1100 mm) and bar anchored length (2.5 and 5 times bar diameter on external bleeding, surface settlement, segregation, and relative bond strength from pullout tests) of horizontally embedded bar. The findings indicate that the use of VMA in SCC reduces the surface settlement (that is related to bleeding and segregation) and significantly reduces the top-bar factor. The results of the pullout tests on 12 and 20 mm diameter steel reinforcing bars which have been conducted by Sonebi et al. [4] show that the bond strength of SCC is about 18 to 38 percent higher than that of CC. In the tests conducted by Attiogbe et al. [5], SCC yielded similar top-bar factors to those of normal concrete with 102 to 152 mm of slump. In a test using air-cured SCC and a VMA, the top-bar factor is actually lower than that of CC. Chan et al. [6] also found that the SCC members have significantly higher bond strength with reinforcing bars than CC members. They also reported that reduction in bond strength due to bleeding and non-homogeneity in CC is prevented with use of SCC. Also, in some studies by Koning et al. [7] and Schiessl and Zilch [8] the CC bond strength is 15% to 20% higher than the SCC bond strength. Conversely, Sonebi and Bartos [9-10] found that SCC bond strength is 15% to 40% higher than the CC bond strength. In other studies performed by Gibbs and Zhu [11] and Lorrain and Daoud [12] no significant differences are observed between the bond strength of both types concrete. The comparison is based on the measured bond between reinforcing steel and concrete by utilizing the pullout test on the embedded bars at various heights in mock-up structural elements to assess the top-bar effect and on single bars in small prismatic specimens; and conducting the beam tests. For this aim the experimental results from the nine recent studies i.e. Zhu et al. [13], Castel et al. [14], Almeida Filho et al. [15], Hossain and Lachemi [16], Esfahani et al. [17], Valcuende and Parra [1], Lachemi et al. [18], Hassan et al. [19] and Desnerck et al. [20], on the bond strength of SCC and CC are investigated and compared.

2. DATABASE FOR BOND CHARACTERISTICS EXPERIMENTAL TESTS

Using experimental results database from various published investigations is an effective tool for studying the applicability of the various bond estimation models of SCC. To apply the estimation models to a particular concrete mixture, it is necessary to use only investigations that adequately define the applied testing methodology. The experimental results included in the database proceed mainly from papers presented at various conferences on SCC and from other published articles. The database includes information regarding the composition of the mixtures, fresh properties of SCC, testing methodology and conditions. It should be emphasized that this aspect has not been investigated as much as the other aspects of SCC, and the published experimental data in the literature is still not very extensive.

Table 1 is a general summary of the concrete experimental tests that contains the specimens and test type, bar type (BT: Plain (P) and Deformed (D)), diameter of steel bar (d_b), embedded length of steel bar (l_d), compressive strength of concrete (f'_c) and casting direction (CD). Various admixtures are used in the mix design of SCC i.e. superplaticizers (SP), high-range water reduces (HRWR), water reducer (WR), viscosity-modifying admixture (VMA), fly ash (FA), slag cement (SC), ground granulated blast slag (GGBS) and air-entraining admixtures (AEA).

As shown in the Table 1, the various type of specimens have been investigated in the literature i.e. pullout test on the prism specimens, pullout test on the cylinder specimens and beam test specimens. Also, the various type of d_b, l_d, f'_c and CD are used and the bar type (P or D) just considered in the Castel et al. [14].

3. RESULTS AND DISCCUSIONS

Table 2 summarizes experimental results of the Zhu et al. [13], Castel et al. [14], Almeida Filho et al. [15], Hossain and Lachemi [16], Esfahani et al. [17], Valcuende and Parra [1], Lachemi et al. [18], Hassan et al. [19] and Desnerck et al. [20]. The experimental results by Zhu et al. [13] show that for both diameters of reinforcement bars, the bond strengths of SCC35 and SCC60 mixes are higher than CC35 and CC60 mixes. According to the Castel et al. [14] conclusion, the optimum ultimate bond strengths (not affected by the casting conditions) are approximately 20% higher for SCC than CC, regardless of the concrete strength of samples reinforced by ribbed bars.

Table 1: SCC and CC experimental tests detailing

Reference		Specimen and test type	BT	d_b(mm)	l_d (mm)	f_c' (MPa)	CD
Zhu et al. (2004)	CC35	pullout test of 100 x 100 x 150 (mm)	D	12 and 20	120	37	V-U
	CC60	pullout test of 100 x 100 x 150 (mm)	D	12 and 20	120	61.5	V-U
	SCC35	pullout test of 100 x 100 x 150 (mm)	D	12 and 20	120	47	V-U
	SCC60	pullout test of 100 x 100 x 150 (mm)	D	12 and 20	120	79.5	V-U
Castel et al. (2006)	CC25	pullout test of 100 x 100 x 500 (mm)	D and P	12	60	34.4	V-U, V-D, H
	CC40	pullout test of 100 x 100 x 500 (mm)	D and P	12	60	48.8	V-U, V-D, H
	SCC25	pullout test of 100 x 100 x 500 (mm)	D and P	12	60	30	V-U, V-D, H
	SCC40	pullout test of 100 x 100 x 500 (mm)	D and P	12	60	43.7	V-U, V-D, H
Almeida Filho et al. (2007)	CC1	pullout test of cylinder with 10 d_b diameter and height	D	10 and 16	5 and 8	35.8	V-U
	CC2	pullout test of cylinder with 10 d_b diameter and height	D	10 and 16	5 and 8	62.25	V-U
	SCC1	pullout test of cylinder with 10 d_b diameter and height	D	10 and 16	5 and 8	38	V-U
	SCC2	pullout test of cylinder with 10 d_b diameter and height	D	10 and 16	5 and 8	70.76	V-U
	CC1	beam specimen test	D	10 and 16	10 d_b	35.8	H
	CC2	beam specimen test	D	10 and 16	10 d_b	62.25	H
	SCC1	beam specimen test	D	10 and 16	10 d_b	38	H
	SCC2	beam specimen test	D	10 and 16	10 d_b	70.76	H
Hossain and Lachemi, (2008)	CC	pullout test of 900 x 200 x100 (mm)	D	25	100	53	V-U, H
	FA SCC	pullout test of 900 x 200 x100 (mm)	D	25	100	62	V-U, H
	SC SCC	pullout test of 900 x 200 x100 (mm)	D	25	100	39	V-U, H
	VMA SCC	pullout test of 900 x 200 x100 (mm)	D	25	100	47	V-U, H
Esfahani et al. (2008)	CC	pullout test of 900 x 200 x100 (mm)	D	25	100	58	H
	CC	pullout test of 900 x 300 x100 (mm)	D	25	100	61	H
	SCC	pullout test of 900 x 200 x100 (mm)	D	25	100	62	H
	SCC	pullout test of 900 x 300 x100 (mm)	D	25	100	68	H
Lachemi et al. (2009)	NG_NS	pullout test of 200 x 200 x 100 (mm)	D	15	100 and 200	38.8	V-U
	BS_BS	pullout test of 200 x 200 x 100 (mm)	D	15	100 and 200	36.2	V-U
	BS_NS	pullout test of 200 x 200 x 100 (mm)	D	15	100 and 200	43.2	V-U
	ES_NS	pullout test of 200 x 200 x 100 (mm)	D	15	100 and 200	43.6	V-U
Valcuende and Parra (2009)	CC32-0.65	pullout test of 200 mm cube	D	16	80	27.75	V-U
	CC32-0.55	pullout test of 200 mm cube	D	16	80	33.76	V-U
	CC42-0.55	pullout test of 200 mm cube	D	16	80	42.4	V-U
	CC42-0.45	pullout test of 200 mm cube	D	16	80	56.5	V-U
	SCC 32-0.65	pullout test of 200 mm cube	D	16	80	30.21	V-U
	SCC 32-0.55	pullout test of 200 mm cube	D	16	80	35.77	V-U
	SCC 42-0.55	pullout test of 200 mm cube	D	16	80	50.18	V-U
	SCC 42-0.45	pullout test of 200 mm cube	D	16	80	61.15	V-U
	CC32-0.65	square cross-section columns of 1500 x150 (mm)	D	12	60	27.75	H
	CC42-0.55	square cross-section columns of 1500 x150 (mm)	D	12	60	42.4	H
	CC42-0.45	square cross-section columns of 1500 x150 (mm)	D	12	60	56.5	H
	SCC 32-0.65	square cross-section columns of 1500 x150 (mm)	D	12	60	30.21	H
	SCC 32-0.55	square cross-section columns of 1500 x150 (mm)	D	12	60	35.77	H
	SCC 42-0.55	square cross-section columns of 1500 x150 (mm)	D	12	60	50.18	H
	SCC 42-0.45	square cross-section columns of 1500 x150 (mm)	D	12	60	61.15	H

Reference		Specimen type	BT	d_b(mm)	l_d (mm)	f_c' (MPa)	CD
Hassan et al. (2010)	CC	pullout test of 4000 x 1200 x 300 (mm)	D	20	150	47	H
	SCC	pullout test of 4000 x 1200 x 300 (mm)	D	20	150	45	H
Desnerck et al. (2010)	CC1	beam specimen test type I	D	12	60	51.8	H
	SCC1	beam specimen test type I	D	12	60	63.7	H
	SCC2	beam specimen test type I	D	12	60	57.5	H
	CC1	beam specimen test type II	D	20 and 25	5 d_b	51.8	H
	SCC1	beam specimen test type II	D	20 and 25	5 d_b	63.7	H
	SCC2	beam specimen test type II	D	20 and 25	5 d_b	57.5	H
	CC1	beam specimen test type III	D	32 and 40	5 d_b	51.8	H
	SCC1	beam specimen test type III	D	32 and 40	5 d_b	63.7	H
	SCC2	beam specimen test type III	D	32 and 40	5 d_b	57.5	H

Almeida Filho et al. [15] reported that the pullout test series with SCC shows better behaviour than the same with CC, which may be explained by the use of filler, which provides a better bond between concrete and steel bar. Comparison between the pullout and beam specimens shows that the presented results are quite close, demonstrating that for this level of concrete strength both specimens, pullout and beam, achieve similar results. Hossain and Lachemi [16] concluded that although the variation in bond strengths at different elevations is observed in SCC, however the extent is less significant than that of CC. This can be attributed to the more consistent nature of SCC and CC processes. If the variation in bond strength of SCC with depth is due to the plastic settlement, this phenomenon would be improved in practical construction situations where the settlement between reinforcement and SCC is minimal. Also, the normalized bond strength of all SCC specimens is found to be higher than CC specimens except for SC SCC specimens casted horizontally. SCCs also exhibit significantly less top-bar effect.

Esfahani et al. [17] demonstrated that the comparison between the results shows that the local bond strength of bottom cast bars is almost the same in both cases of CC and SCC. However, for the top cast bars, the local bond strength for SCC is about 20% less than that for CC. Valcuende and Parra [1] observed that in the four studied mixes, the mean bond strength is greater in SCC than in CC. The ultimate bond strength is greater in SCC than in CC. The differences between the two types of concretes vary with the compressive strength, but are not so great as those recorded for mean stress. In vertically cast pieces, SCC behaves more homogeneously than CC, as the top-bar effect is much more pronounced in the latter stages. Lachemi et al. [18] represented that under the condition of the equivalent compressive strength comparing with the normal weight SCC (NG_NS), the normalized bond strength between the lightweight SCC and reinforcing bars decreases by about 38% for the BS_BS and BS_NS mixtures, and 16% for the ES_NS mixture. Hassan et al. [19] reported that the normalized bond stress was slightly higher in SCC than that in CC at 3, 7, 14 and 28 days. Desnerck et al. [20] observed that the bond strength of SCC is as high as the bond strength of CC when large bar diameters are studied. For smaller bar diameters, the bond strength of SCC is lightly higher, with the largest difference occurring for the smallest bar diameters.

Table 2: SCC and CC bond strength experimental results

Reference	Bond Strength
Zhu et al. (2004)	**Bars with d_b=12mm** • SCC35 24% higher than CC35 • SCC60 30% higher than CC60 **Bars with d_b=20mm** • SCC35 24% higher than CC35 • SCC60 30% higher than CC60
Castel et al. (2006)	**With plain bars** • SCC25 V-U = SCC25 V-D • CC25 V-D 40% higher than CC25 V-U • SCC25 H = 15% SCC25 V-D • CC25 H = 20% CC25 V-D • SCC40 V-D & V-U 15% higher than CC40 V-D & V-U • SCC40 H = 30% SCC40 V-D & V-U • CC40 H = 30% CC40 V-D & V-U **With deformed bars** • SCC25 V-U 10% higher than SCC25 V-D • SCC25 V-U 12% higher than CC25 V-U • SCC25 V-D 13% higher than CC25 V-D • SCC40 V-D 12% higher than SCC40 V-U • SCC40 V-D 16% higher than CC40 V-D • SCC40 V-U = CC40 V-U • SCC25 H 25% higher than CC40 H • SCC40 H = CC40 H
Almeida Filho et al. (2007)	**Pullout test** • SCC1 (d_b=10 mm, l_d=50 mm) 19% higher than CC1 • SCC1 (d_b=10 mm, l_d=50 mm) 16% higher than CC1 • SCC2 (d_b=10 mm, l_d=50 mm) 5% higher than CC2 • SCC2 (d_b=10 mm, l_d=50 mm) 12% higher than CC2 **Beam test** • CC1 14% higher than SCC1 • CC1 12% higher than SCC1 • SCC2 = CC2
Hossain and Lachemi (2008)	**Horizontally cast** • CC normalized bond stress for bottom bars ranges between 1.32 and 1.66 • CC normalized bond stress at the top range between 0.35 and 1.21 • FA SCC normalized bond stress for bottom bars ranges between 1.22 and 1.79 • FA SCC normalized bond stress at the top range between 1.13 and 1.51 • SC SCC normalized bond stress for bottom bars ranges between 0.72 and 1.102 • SC SCC normalized bond stress at the top range between 0.67 and 0.93 • VMA SCC normalized bond stress for bottom bars ranges between 1.10 and 1.30 • VMA SCC normalized bond stress at the top range between 1.11 and 1.36 • FA SCC and VMA SCC show higher bond stress compared with CC. SC SCC develop lower bond stress compared to CC and other SCC mixtures **Vertically cast** • Normalized bond stress from top to bottom bars ranges between 0.33 and 1.13 in CC, between 1.62 and 1.75 in FA SCC, between 0.95 and 1.23 in SC SCC, and between 1.43 and 1.64 in VMA SCC • The normalized bond stresses of all SCCs are higher than CC **Top-bar factor horizontally cast** • The top-bar factor for CC ranges between 1.37 and 3.77, for FA SCC it ranges between 1.08 and 1.29, for SC SCC it ranges between 1.07 and 1.18, and for VMA SCC it ranges between 1.00 and 1.06. • The lower top bar factor is an indication of superior performance of SCCs compared to CC **Top-bar factor horizontally cast** • The top-bar factors of 2.54 and 3.4 for CC, 1.05 and 1.08 for FA SCC, 1.1 and 1.29 for SC SCC, and 1.08 and 1.14 for VMA SCC are found. • The top-bar factor of close to unity along the height of the specimens confirmed the superior performance of SCC compared to CC
Esfahani et al. (2008)	**Top-bar** • SCC is on average about 20% smaller than CC

Lachemi et al. (2009)	• LWSCCs (light-weight) is found to be less (between 16% and 38%) than NWSCC (normal-weight) • The decreases in bond strength are about 38% for BS_BS and BS_NS and 16% for ES_NS • The normalized bond strength is found to increase with the increase of embedded length from 100 mm to 200 mm
Valcuende and Parra (2009)	**Tests with 200 mm cube specimens** • The SCC normalised maximum stress is generally greater than CC in 7%, 17%, 8% and 1% for mixes 1, 2, 3 and 4, respectively **Tests with specimens 1500 mm high (top-bar effect)** • The drop in bond strength between the upper and lower zones of the columns varies from 32% to 55% in SCC and from 60% to 74% in CC • The drop in bond strength at the head of the columns averages 32.1% less in SCC than in CC (differences of 29.1%, 28.6%, 27.89% and 42.9% for mixes 1, 2, 3 and 4, respectively) • In the four mixes studied, the mean bond strength is greater in SCC than in CC • The ultimate bond strength is greater in SCC than in CC • Depending on the mix, the loss in mean bond stress between the upper and lower areas of 1.5 m tall columns varies by between 40% and 61% in SCC and between 70% and 86% in CC • With regard to ultimate stress, the losses vary between 32% and 55% in SCC and between 60% and 74% in CC
Hassan et al. (2010)	• No significant differences are noted between SCC and CC mixes in terms of bond or compressive strength development with age • The normalized bond stress is slightly higher in SCC than that in CC at 3, 7, 14 and 28 days • The ratio of the normalized bond stress of SCC to that of CC is higher in the top bars and late tested ages compared to the bottom bars and early tested ages • The stiffness of the bond stress-slip curve is higher in SCC pullout specimen compared to their CC counterparts and the difference is more pronounced at late age • In both CC and SCC pullout specimens, the bond stress is slightly higher in the bottom bars than that in the top and middle bars at all ages. The difference is more pronounced at late ages rather than early ages
Desnerck et al. (2010)	• The stiffness of the bond stress-slip curve is higher in SCC pullout specimen compared to their CC counterparts and the difference is more pronounced at late age • The bond strength of SCC1 is larger than those of SCC2 and CC1 (as is expected due to the higher compressive strength) at all stress levels • For bar diameters of 40 mm the curves for SCC2 and CC1 are almost identical for small slip values, while the bond stress level for SCC1 for the same slip is higher • The differences in the normalized ultimate bond strength for the CC and the SCC are largest for bar diameters of 12 mm. The difference becomes smaller for higher bar diameters, but the results for SCC are higher in all cases. • By increasing the bar diameter, the slip at maximum bond stress is increasing in all cases

4. CONCLUSIONS

Based on the presented results, the following conclusions can be made:

- The ultimate and mean bond strengths are greater in SCC than in CC.
- The comparison between the pullout and beam specimens shows that the presented results are in good agreement.
- For the top cast bars, the local bond strength for SCC is less than that for CC.
- Comparing the normal and light weight SCC with the equivalent compressive strength shows that the normalized bond strength between the lightweight SCC and reinforcing bass is less.
- The bond strength of SCC is the same with the bond strength of CC when large bar diameters are used.

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