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Influence of pouring techniques and mixture's fresh properties on the structural performance of self-consolidating concrete beams

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An experimental investigation was conducted to study the influence of pouring techniques and mixture's fresh properties on the shear strength, cracking behavior and mid-span deflection of large-scale Self-Consolidating Concrete (SCC) beams. SCC beams were poured in two different techniques: the first technique was to pour the concrete from one side of the formwork only, while the second technique was to move the pouring point along the full beam length. The variables were: the concrete type, length and depth of beams, and the viscosity and yield stress of SCC mixture. The study also included a comparison between the experimental shear strength results and the predictions of some major code-based equations. The results obtained from this investigation proved that different pouring techniques, viscosity and/or yield stress of SCC mixtures did not have a significant effect on the structural performance of SCC beams. However, beams cast with lower yield stress appeared to have slightly higher shear strength and minimum average crack heights. Also, SCC beams with higher viscosity mixture tended to have lower stiffness compared to SCC mixtures with normal viscosity mixture.

Key words: Self-consolidating concrete, pouring techniques, shear strength, structural performance, code-based analysis, cracking, load-deformation response.

INTRODUCTION

Self-Consolidating Concrete (SCC) is a type of concrete which can achieve consolidation under its own weight without compaction or mechanical vibration. It can flow easily through congested reinforcement, filling the formwork without segregation or bleeding problems. The production of SCC is normally achieved by: a) increasing the quantity of fines in the mixture, which could be achieved by incorporating mineral admixtures such as fly ash, ground granulated blast furnace slag, volcanic ash, cement kiln dust etc., b) adding viscosity modifying admixtures (VMA) (Lachemi et al., 2003; Khayat et al., 2001; El-Chabib and Nehdi, 2006), and/or c) decreasing the coarse aggregate content in the mixture (Khayat et al., 1997; Lachemi et al., 2005). The shear strength of

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SCC mixture has gained a great concern among designers/engineers. Because of the reduced size and amount of coarse aggregate in most SCC mixtures, the shear strength of SCC is expected to be less than that of NC. In addition, the substantial difference in the rheology of the cement paste matrix in SCC (compared to NC) may also affect the shear strength of concrete in full-scale elements. However, the shear strength as well as the mechanical properties of SCC is greatly enhanced with lower water-to-cement ratio and the use of supplementary cementing materials (Kim and Han, 1999; Bouzoubaa and Lachemi, 2001). Hassan et al. (2010) compared the shear strength of simply supported beams made of NC and SCC without shear reinforcement. The content of coarse aggregate was higher in NC mixture compared to SCC mixture. The results of their investigation showed that the ultimate shear load of NC beams was greater than SCC beams. This result was attributed to the reduction of the aggregate interlock as a result of the presence of lower coarse aggregate content in SCC beams compared to NC beams. On the other hand, their results did not show a significant difference in the cracking behavior or failure mode between NC and SCC beams.

A four-point bending test was performed by Boel et al. (2010) on NC and SCC beams with different shear span-to-depth ratios. The results of their investigation also confirmed that the shear capacity of SCC beams was lower than those of NC beams at all shear span-to-depth ratios. This was due to the lower aggregate interlock exhibited in SCC beams because of the lower coarse aggregate content in SCC mixture compared to NC mixture. Domone (2007) reviewed the structural performance of SCC beams by using different data collected from various published investigations. Their collected data showed that in mixtures having comparable coarse aggregate contents, most of SCC beams demonstrated slightly greater shear strength compared to NC beams. Another study was carried out by Lachemi et al. (2005) to compare the shear resistance of SCC and NC beams. Different sizes and contents of coarse aggregate were used for NC and SCC mixtures in their investigation. Lachemi et al. (2005) concluded that the increase in size and content of the coarse aggregate improves the post cracking shear transfer mechanisms and increases the ultimate shear strength of SCC beams. The shear strength of SCC beams with and without shear reinforcement was also investigated by Cattaneo et al. (2007). The outcomes of their research were compared to both NC beams experimental results and to standard design equations. The results indicated that NC and SCC had similar stiffness up to cracking, while in the cracked state SCC exhibits a stiffer behavior associated with smaller deflection, denoting a more brittle behavior. The comparison between EC2 predictions and the experimental shear strength for SCC beams showed that EC2 furnishes a lower bound with values closer to those experimentally observed by increasing the shear arm ratio. The uniformity of SCC properties along the length of the structural member is another area of great interest amongst researchers. Although the uniformity of SCC depends on the proper design and the filling ability of the mixtures, the different pouring techniques of SCC may also have some effect in varying the *in situ* mixture properties.

Sonebi et al. (2003) found no significant difference in terms of compressive strength and cracking behavior along 3.8 m SCC beams. However, their investigation showed slightly more cracks, greater crack widths and crack penetrations in NC beams compared to SCC beams. The uniformity of SCC properties was also tested by Khayat et al. (2001) in columns made of NC and SCC mixtures using a uniaxial compression test. They found that SCC columns have more homogeneous distribution of properties than their NC counterparts. On the contrary, Hassan et al. (2010) investigated the durability performance along the length/perimeter of SCC beams. Their results showed that the corrosion distribution was non-uniform in SCC beams compared to NC beams. They attributed their results to the fact that pouring SCC beams from one side only might have caused a lack of compaction in the far end of the beam opposite to the casting point. Throughout this literature, there is a lack of information regarding the uniformity and structural performance of SCC beams especially for different SCC fresh properties and whether or not casting is done from one end of the formwork only.

The objective of this investigation is to study the effect of different pouring techniques and the effect of mixture viscosity and yield stress on the structure performance of SCC beams with respect to shear strength, cracking behavior and deflection characteristics. The results of shear strength and cracking behavior of NC beams are also demonstrated and compared with those of SCC beams made with the same type of materials. The research also includes comparison between the experimental shear strength and those calculated by ACI and CSA code-based equations.

EXPERIMENTAL PROGRAM

Thirteen full-scale beams (3 made of NC and 10 of SCC), having 3 different lengths were tested under four-point loading conditions until shear failure. All beams were cast without shear reinforcement. The shear span-to-depth ratio of each beam was fixed to be 2.5 to ensure shear failure before bending failure (Kani et al., 1979). Only

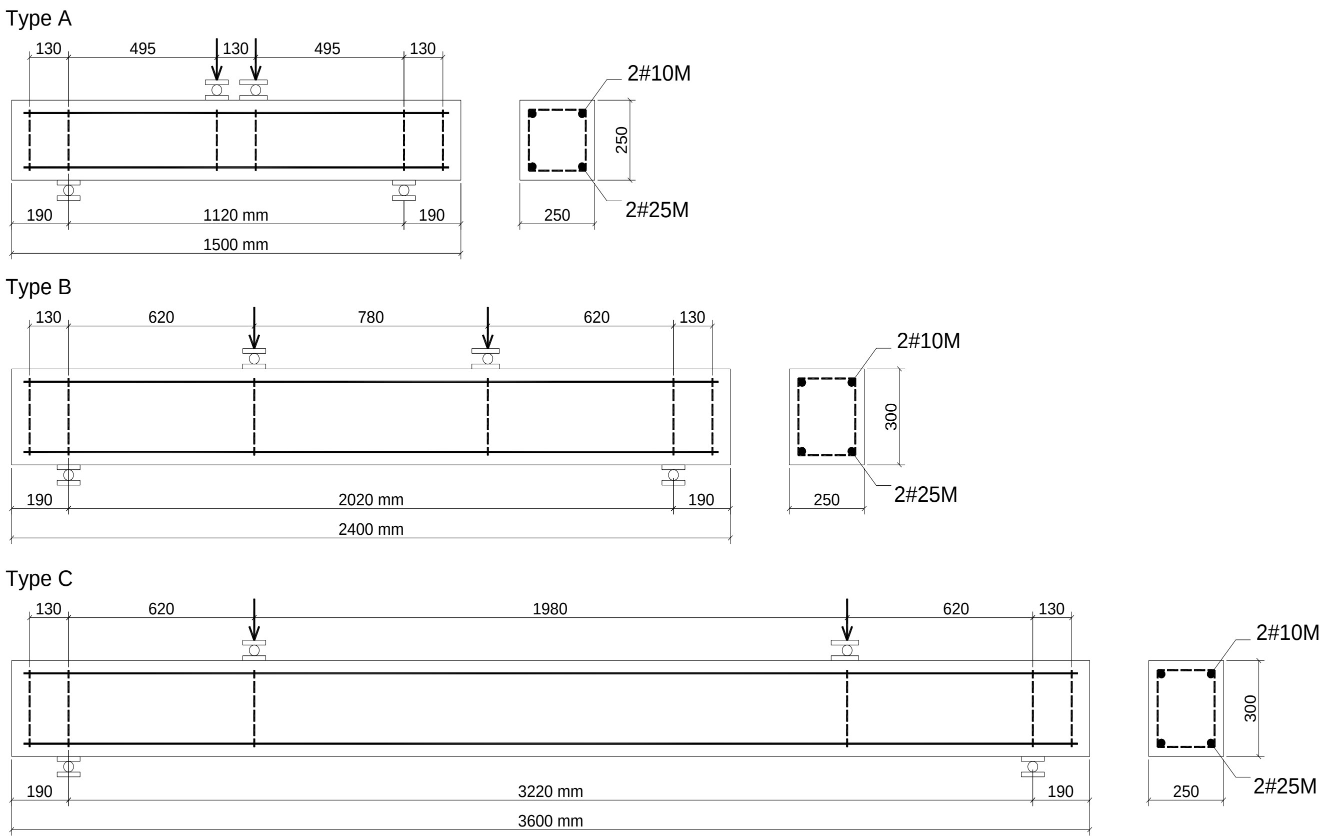

Figure 1. Beams types (Types A, B and C).

6 stirrups were used for each beam to support the top reinforcements. These stirrups were positioned under the loading points, at supports, and away from each support at the beam edges (Figure 1). Three different configurations of beams based on their cross sectional dimensions, lengths and ratios of longitudinal reinforcement (1.6 and 2.0%) were used (Types A, B and C). Three different casting techniques based on the vibration condition and the position of the pouring point were also used. Technique I is associated with NC beams in which a mechanical vibrator was used and the casting was performed along the length of the beam. Techniques II and III were adopted for casting SCC beams without mechanical vibration. The only difference between the two techniques is that in Technique II the concrete was poured from one side of the formwork only, while in Technique III the concrete pouring was distributed along the beam length.

Three different SCC mixtures based on slump flow and time to reach 500 mm slump flow (T_{500}) was selected. SCC1 and SCC2 represent mixtures with low and high slump flow (high and low yield stress), respectively, while SCC3 represents SCC mixture with high T_{500} (high viscosity). The beams were designated according to their dimensions, type of concrete (NC and SCC), yield stress/viscosity (1, 2, and 3), and the casting techniques (I, II and III). For example, SCC beam type A with high yield stress and poured from one side of the formwork only is designated as ASCC1 II.

Materials and mixtures proportions

Three commercial SCC mixtures were chosen to study the effect of slump flow diameter (yield stress) and T_{500} (viscosity) of SCC mixture on the shear strength, cracking behavior and deflection characteristics of simply supported beams. An additional commercial NC mixture was also chosen in this study for comparison. To perform such a comparison, the same coarse aggregate type and size was used in NC and SCC mixtures. The difference between the coarse aggregate content in NC and SCC mixtures was insignificant (886 kg/m^3 in NC versus 830 kg/m^3 in SCC). The water-to-binder ratio was 0.38 for SCC and 0.31 for NC (Table 1). Type GU Canadian Portland cement similar to ASTM Type 1, and fly ash similar to ASTM Type F, were used as binders for both NC and SCC mixtures. Natural sand and 20 mm stone were used as fine and coarse aggregates, respectively. Water reducer (WR) similar to ASTM Type A, was used to adjust the cohesiveness of NC mixture. High range water reducer (HRWR) similar to ASTM Type F and VMA admixtures were used to control the flow and viscosity of SCC mixtures, respectively (ASTM C494). Two different diameters of reinforcing bars were used (10 and 25 mm) designated as #10 and #25 in Figure 1. The bars had an average yield stress of 480 MPa and an average tensile strength of 725 MPa.

Table 1. Mixture proportions for NC and SCC chosen mixtures.

Concrete type	Cement (kg/m^3)	Fly ash (kg/m^3)	20 mm stone (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Chemical admixture (L/m^3)
NC	376	94	886	804	145	0.5 (WR)
SCC1	365	85	830	790	170	2.8 (HRWR)
SCC2	365	85	830	790	170	4.0 (HRWR)
SCC3	365	85	830	790	170	5.4 (VMA)

1 kg/m^3 = 0.0623 lb/ft^3.

Table 2. Fresh and hardened properties of concrete mixtures.

Concrete type	Slump/slump flow (mm)	T_{500} (s)	Compressive strength f'_c (MPa)
NC	85	0	49.58
SCC1	500	2.12	35.15
SCC2	800	2.94	37.88
SCC3	760	8.7	39.24

1 mm = 0.039 in.; 1 MPa = 0.145 ksi.

Fresh and hardened properties of concrete

The fresh and hardened properties of NC and SCC mixtures can be seen in Table 2. A conventional slump test conforming to ASTM C143 was performed for NC mixture. A slump flow test was conducted for SCC mixtures according to ASTM C1611 to evaluate the slump flow diameter and T_{500} of each SCC mixture. The 28-day compressive strength of control cylinders (100 × 200 mm) was measured as specified in ASTM C39, for both NC and SCC mixtures.

Test setup

All beams were tested under a four-point symmetrical vertical loading condition as seen in Figure 1. A single load was applied through a manual hydraulic jack, and then distributed into two point loads using a steel beam. The mid-span deflection was measured using one linear variable differential transformer (LVDT) placed directly under the mid-span of each beam. The load was applied gradually by the same loading rate in three stages (50, 75 and 100% of the theoretical calculated failure load) until failure. After each stage of loading, the crack widths were measured by means of a crack width measuring device. The overall behavior of beams, including the development of cracks, crack patterns, crack widths, crack heights, and failure mode, was observed and sketched for all beams at the three stages as seen in Figure 2.

RESULTS AND DISCUSSION

Cracking behavior and failure mode

As seen in Figure 2, all the beams failed in shear (as expected), and the failure happened after the formation of one major diagonal crack started from one point of the loading application, and then moved downward with angle ranges between 24 to 35°. During the first stage of loading, thin vertical flexural cracks appeared almost on the mid span of the beam. By increasing the load in the second stage, more flexural cracks were formed away from the mid-span on the two sides. Finally, by further increasing the load, the flexural cracks spread diagonally towards the loading point and new diagonal cracks were formed along the beam length. It can be noted that the total number of cracks increases as the beam span increases, and SCC beams had more cracks than NC beams of the same beam type (Table 3). The average height of cracks in NC beams was not significantly different than that of SCC beams. The maximum crack width for each beam at the different loading stages is shown in Table 3. It is clear that type B and C beams have relatively wider cracks compared to type A beams. The reason for that is related to the higher longitudinal steel ratio of type A beams (2.0%), compared to type B and C beams (1.6%) which increased the resistance of the crack to open wider.

Effect of pouring techniques on the cracking behavior of the tested beams

As mentioned earlier, two different techniques were used in casting SCC beams. The first technique was pouring concrete from one side of the formwork only and the second was placing concrete along the beam length. The

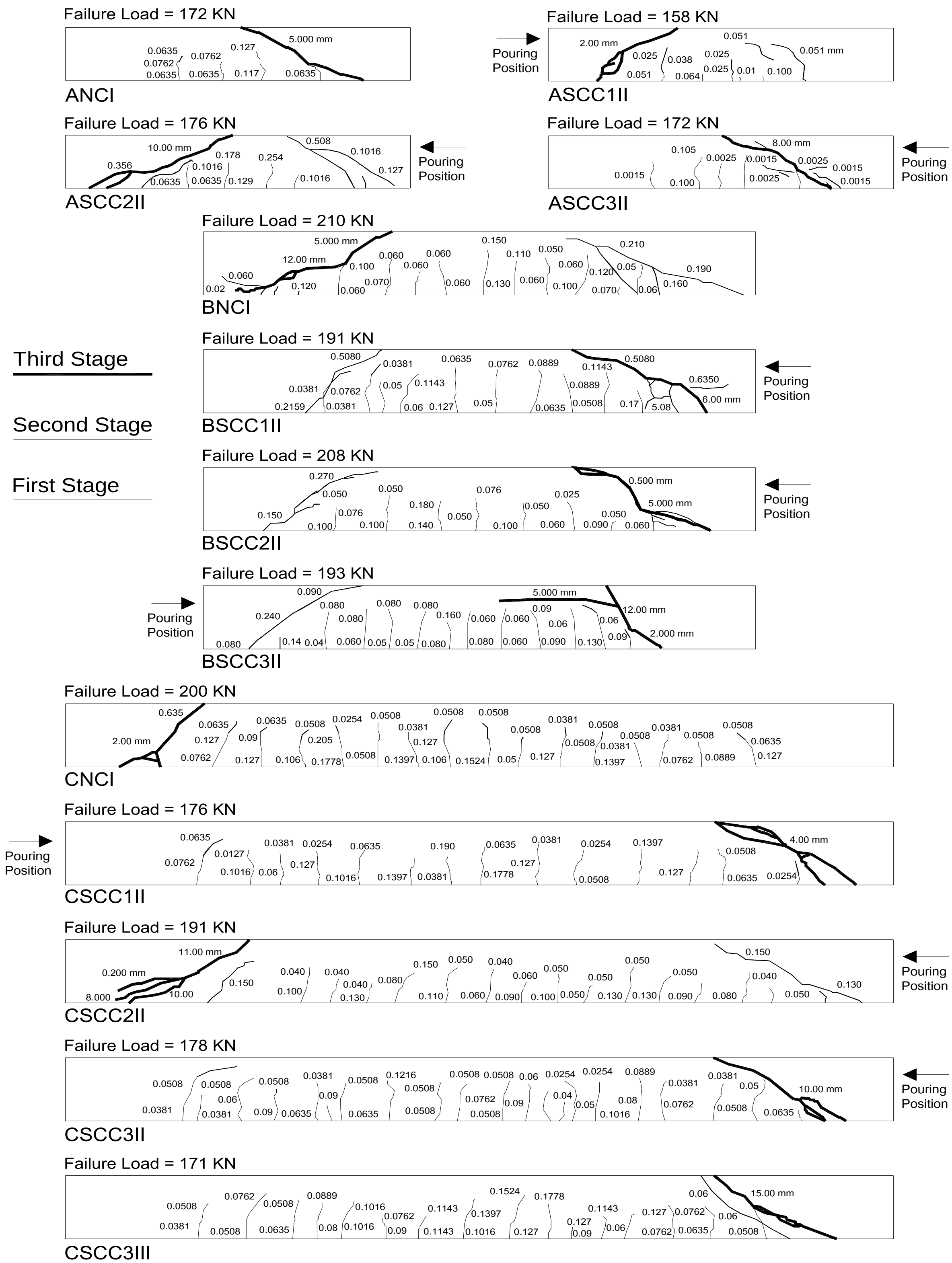

Figure 2. Crack patterns of SCC and NC beams at three stages to failure (Crack width in mm); (1 mm = 0.0394 in.).

Table 3. Pouring, failure position and cracks data for all tested beams.

Beam designation	Pouring position	Failure position	Number of cracks		Crack angle at failure (°)	Maximum crack height (mm)	Maximum crack width (mm)	
			(L)*	(R)*			50%**	75% **
ANCI	All length	Right	2	3	25	136	0.12	0.13
ASCC1II	Left	Left	3	5	31	177	0.07	0.1
ASCC2II	Right	Left	5	5	25	121	0.13	0.18
ASCC3II	Right	Right	2	4	26	161	0.1	0.11
BNCI	All length	Left	6	6	24	148	0.13	0.15
BSCC1II	Right	Right	6	9	31	151	0.12	0.17
BSCC2II	Right	Right	5	5	27	119	0.14	0.18
BSCC3II	Left	Right	8	6	35	135	0.13	0.16
CNCI	All length	Left	8	8	33	153	0.18	0.21
CSCC1II	Left	Right	7	8	30	150	0.18	0.19
CSCC2II	Right	Left	7	10	26	137	0.13	0.15
CSCC3II	Right	Right	10	12	28	181	0.11	0.13
CSCC3III	All length	Right	8	9	29	149	0.13	0.16

* (L) and (R) indicate the number of cracks on the left and right of the center line of the beam; ** 50 and 75% of the theoretical failure load.

position of the pouring is shown in Figure 2 for beams characterized by the second technique (II). It can be seen from Figure 2 and Table 3 that for all tested beams the shear failure crack occurred at one end of the beam only. For beams cast from one side only, the shear failure crack occurred five times on the same side of the pouring point and four times on the opposite side of the pouring point. This result indicates that the uniformity of SCC mixture was not significantly affected by the casting technique. It should be noted that the effect of the casting technique should be manifested more for longer beams (Type C) in which the concrete must travel for a longer time to reach the far end of the formwork. In this type of beams the failure shear crack happened most of the time on the opposite side of the pouring point. However, this result cannot be generalized since only a few beams were compared in this technique. Figure 2 and Table 3 demonstrate the number of cracks at failure and their distribution with respect to the center of the beam. It is clear that the cracks were fairly distributed along the two sides of the beam regardless of the pouring position. These results also show that the casting technique does not affect the uniformity of SCC mixtures. The angle of the failure cracks for all beams ranged between 24 to 35° (with an average of 30°), indicating that there was no significant difference in crack angles at failure between all tested beams. However, the angles of failure cracks for deeper beams (Types B and C) were greater than shallow beams (Type A).

The average heights of cracks for types A, B and C beams before failure were 60, 55 and 62% of the beam height, respectively. The results indicate that the different pouring techniques did not significantly affect the height or width of the cracks.

Effect of the mixture viscosity and yield stress on the cracking behavior of the tested beams

In general, no significant difference was noted between different viscosity and different yield stress SCC mixtures in terms of cracking behavior. However, in longer beams where the effect of the mixture yield stress and viscosity become more manifested, the maximum number of cracks appears to occur for the mixture with the highest viscosity (SCC3) when comparing type C beams as seen in Table 3. The maximum average height of cracks appears to occur in the SCC mixture with high yield stress (SCC1) which was slightly higher than the mixture with the highest viscosity (SCC3). The minimum average crack height happened in the mixture of lower yield stress (SCC2). It should be noted that the change of the mixture viscosity or yield stress may have some effects on the mixture compaction, particles distribution and the uniformity of the whole mixture which in term may affect the hardened properties and cracking behavior of the concrete. Moreover, the effect of the mixture viscosity or yield stress on the hardened properties is expected to be more pronounced when the concrete is poured from one side of the formwork only especially if the formworks

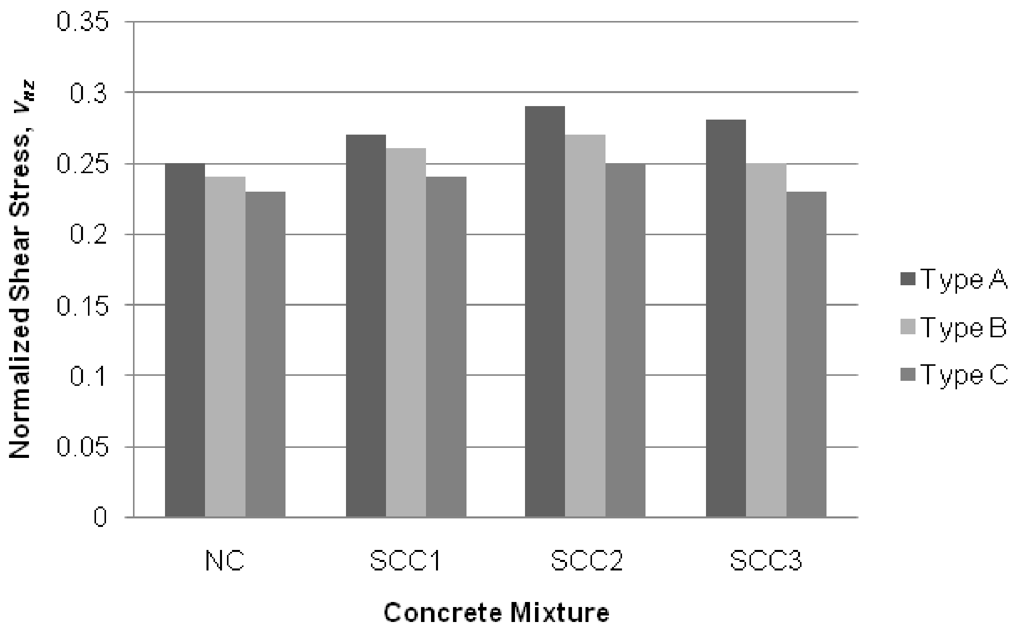

Figure 3. Normalized Shear Stress (*1000 KN/mm^2) vs. Concrete Mixture for all Tested Beams (1 KN = 0.225 kips).

were long, shallow, and/or narrow. This is because in these cases the mixture will have more challenges to travel under its own weight carrying the coarse aggregate in place without segregation while providing enough compaction and maintaining acceptable uniformity for the whole mixture.

Shear strength of SCC and NC beams

In order to compare the shear strength of SCC and NC beams which have different compressive strength, the ultimate shear strength is normalized. Knowing that the shear strength is proportional to the square root of the compressive strength (f'_c), the normalized shear load (V_{nz}) is obtained as follows (Equation 1):

$$V_{nz} = V_u / (f'_c)^{0.5} \quad (1)$$

Then, the normalized shear stress (v_{nz}) is calculated using Equation 2:

$$v_{nz} = V_{nz} / (bd) \quad (2)$$

Where b = beam width, d = beam depth and V_u = the ultimate shear load.

The values of shear load and stress for all SCC and NC beams are shown in Table 4. The normalized shear stress for different concrete mixtures and beam types is shown in Figure 3. As seen from the figure, the average normalized shear stress of all SCC beams was 0.26, while the average normalized shear stress of all NC beams was 0.24. This result indicates that the shear strength of SCC beams is slightly higher than that of NC beams. It should be noted that the volume of the coarse aggregate in SCC mixtures was comparable to that in NC mixture. Therefore, the contribution of the aggregate interlock in transferring the shear strength was not a factor in this comparison. However, the enhanced flowability and homogeneity of SCC mixture could be the reason for the slight enhancement of the shear strength in SCC mixture compared to NC mixture.

Effect of yield stress and viscosity of SCC on shear strength

As seen in Figure 3, the SCC mixture that has the maximum shear strength (0.27) is the mixture of lower yield stress (higher slump flow) which is designated as SCC2. This result matches the result of the average crack heights which indicates that the lower yield stress mixture had the minimum average crack height.

Reducing the crack height increases the shear transfer

Table 4. Shear resistance and mid-span deflection for all tested beams.

Beam designation	Compressive strength, f'_c (MPa)	Failure load (KN)	V_u (KN)	V_{nz}(KN)	v_{nz}(KN/mm^2*1000)	Mid-span deflection (mm)
ANCI	49.58	172	86	12.2	0.25	2
ASCC1II	35.15	158	79	13.3	0.27	3.36
ASCC2II	37.88	176	88	14.3	0.29	3.24
ASCC3II	39.24	172	86	13.8	0.28	3.62
BNCI	49.58	210	105	14.9	0.24	6.25
BSCC1II	35.15	191	95.5	16.1	0.26	5.3
BSCC2II	37.88	208	104	16.9	0.27	6.39
BSCC3II	39.24	193	96.5	15.4	0.25	7.03
CNCI	49.58	200	100	14.2	0.23	12.79
CSCC1II	35.15	176	88	14.8	0.24	13.91
CSCC2II	37.88	191	95.5	15.5	0.25	13.44
CSCC3II	39.24	178	89	14.2	0.23	10.75
CSCC3III	39.24	171	85.5	13.7	0.22	15.69

1 mm = 0.039 in.; 1 MPa = 0.145 ksi; 1 KN = 0.225 kips.

by the un-cracked top part of the beam which contributes to increase the overall shear resistance. The mixtures with higher yield stress and/or higher viscosity (SCC1 and SCC3) have similar average shear strength (0.25). This result indicates that the low yield stress of an SCC mixture seems to improve the mixture quality and consequently enhances the strength behavior of the structural member.

Effect of beam type on the shear strength

Figure 3 shows that the normalized shear stress of the shorter beams (Type A) was greater than that of longer beams (Types B and C). The reason for that is related to the percentage of longitudinal reinforcement used for each beam. Type A beams had 2% longitudinal steel ratio, while Types B and C had 1.6%. The higher percentage of longitudinal steel ratio reduced the shear crack width and allowed the concrete to resist more shear. The other reason for the increased shear strength in type A beams could be related to the size effect between beams. As the depth of a beam increases, the shear strength decreases. This reason is consistent with a number of other research studies (Bentz, 2005; Tompos and Frosch, 2002). However, the difference in depth between type A and type B/C is not significant to manifest the size effect on shear strength. The lower shear strength of Type C beams compared to Type B could be attributed to the higher number of cracks presented in longer beams (Table 3).

Effect of pouring techniques of SCC on shear strength

As seen from Table 4, the normalized shear strengths of beams CSCC3II and CSCC3III which are similar in dimensions, cross section and concrete type, but different in casting technique, were 0.23 and 0.22 respectively. In addition, the failure mode, failure crack width/angle and the average crack widths/heights along the two beams did not show obvious differences. These results indicate that there are no significant differences between casting SCC beams from one side and moving the casting point along the beam's length. It should be noted that longer beams and higher viscosity mixtures in this investigation are expected to strongly manifest the effect of casting technique on the structure behavior of SCC beams (if any). Although CSCC3II and CSCC3III beams were the longest beams and were cast using high viscosity mixtures, the differences between the two beams in terms of shear strength and cracking behavior were insignificant.

Load deflection response

The maximum mid-span deflection before failure and the load mid-span deflection responses of all tested beams are presented in Table 4 and Figure 4 respectively. The excess data after the failure load in the load mid-span deflection graphs were removed from Figure 4 to improve the figure clarity. Both NC and SCC beams showed a

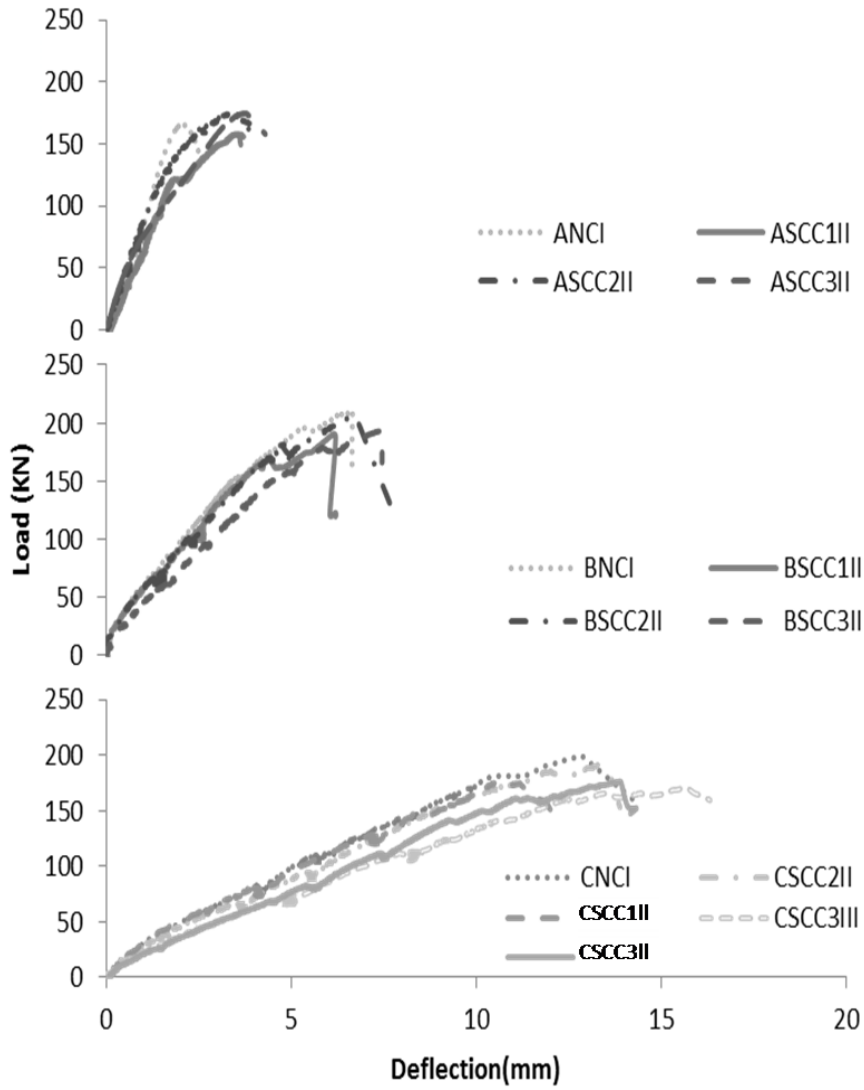

Figure 4. Load mid-span deflection responses for all tested beams (1 KN = 0.225 kips; 1 mm = 0.039 in.).

similar trend of variation throughout loading. However, NC beams exhibited slightly higher stiffness compared to SCC beams in all beams types (Types A, B, and C). Figure 4 also indicate that high viscosity SCC mixtures (SCC3) tend to have lower stiffness compared to SCC mixtures with normal viscosity (SCC1 and SCC2).

Performance of ACI and CSA code equations for predicting the shear capacity

In order to validate the performance of ACI and CSA code equations in predicting the shear strength, the ultimate shear strengths of all tested beams are calculated based on ACI and CSA code equations and compared with the experimental results. As per ACI, the shear resistance (V_u) of beams without shear reinforcement at diagonal cracking can be obtained as (based on SI unit):

$$V_u = 0.158\sqrt{f'_c}bd + 17.24\rho_w \frac{V_f d}{M_f}bd \leq 0.29\sqrt{f'_c}bd \qquad (3)$$

Where V_f is the factored shear force at section; M_f is the

Table 5. Experimental and code based predictions of the ultimate shear resistance.

Beam designation	Experimental V_u (KN)	Code based prediction		Comparison (ratio)	
		ACIV_u (KN)	CSAV_u (KN)	Exp./ACI	Exp./CSA
ANCI	86	61.3	65.31	1.4	1.32
ASCC1II	79	52.51	57.54	1.5	1.37
ASCC2II	88	54.29	56.38	1.62	1.56
ASCC3II	86	55.16	58.1	1.56	1.48
BNCI	105	75.43	70.49	1.39	1.49
BSCC1II	95.5	64.44	62.72	1.48	1.52
BSCC2II	104	66.67	61.97	1.56	1.68
BSCC3II	96.5	67.76	65.87	1.42	1.46
CNCI	100	75.43	72.54	1.33	1.38
CSCC1II	88	64.44	65.65	1.37	1.34
CSCC2II	95.5	66.67	65.11	1.43	1.47
CSCC3II	89	67.76	68.93	1.31	1.29
CSCC3III	85.5	67.76	70.46	1.26	1.21

factored moment at section; M_f occurs simultaneously with V_f at a section; b is the beam width; d is the effective depth of beam cross-section; and ρ_w is the longitudinal steel ratio.

As per CSA specification, shear resistance (V_u) for beams without shear reinforcement can be obtained as (based on SI unit):

$$V_u = \beta \sqrt{f'_c}\, b\, d_v \qquad (4)$$

The factor β can be calculated as:

$$\beta = \frac{520}{(1+1500\,\varepsilon_x)(1000+S_{ze})} \text{ and } \quad s_{ze} = \frac{35 S_z}{15+a_g} \leq 0.85 S_z \qquad (5)$$

Where d_v is effective shear depth which can be taken as the greater of 0.9d or 0.72 h; ε_x is the longitudinal strain at mid-depth of the member due to factored loads which can be derived as: $\varepsilon_x = \frac{M_f/d_v + V_f}{2E_s A_s}$; E_s is the modulus of elasticity of non-prestressed reinforcement; S_z (= d_v) is the crack spacing parameter dependent on crack control characteristics of longitudinal reinforcement and a_g is the maximum size of aggregate in concrete.

Table 5 presents the ultimate shear load derived from experiments and code based predictions. Figure 5 compares the performance of ACI and CSA code based equations in predicting the ultimate shear load. In general, the CSA and ACI calculations are conservative in the prediction of the ultimate shear resistance and can be used safely for any SCC regardless of the mixture viscosity or yield stress. All the values predicted by either CSA or ACI were at least 20% lower than the experimental values (Table 5). Figure 5 indicates that CSA equation was more conservative than ACI equation in type A beams. However, for type B beams, ACI equation becomes more conservative than CSA in predicting the ultimate shear strength. The reason for that could be related to the increased longitudinal steel ratio in type A compared to Type B beams (2.0% in type A compared to 1.6% in type B). However, in longer beams (Type C) where the deflection was relatively high (Table 4), CSA equation tended to become more conservative than ACI equation (Figure 5).

Conclusions

The structural performance of NC and SCC beams were studied and compared using different beam types. Different SCC mixtures having different viscosity and yield stress were used to study the shear strength, cracking behavior and deflection characteristics of large scale SCC beams. The effect of casting technique of SCC mixture was also investigated by fixing the casting point at one side of the formwork and by moving it along the beam's length. From the results described in this paper, the following conclusions are drawn:

i) The same failure mode occurred for both NC and SCC beams. All beams failed after formation of a diagonal crack on one side of the beam.\
ii) SCC beams showed slightly higher shear strength and seem to have higher number of cracks at failure than their

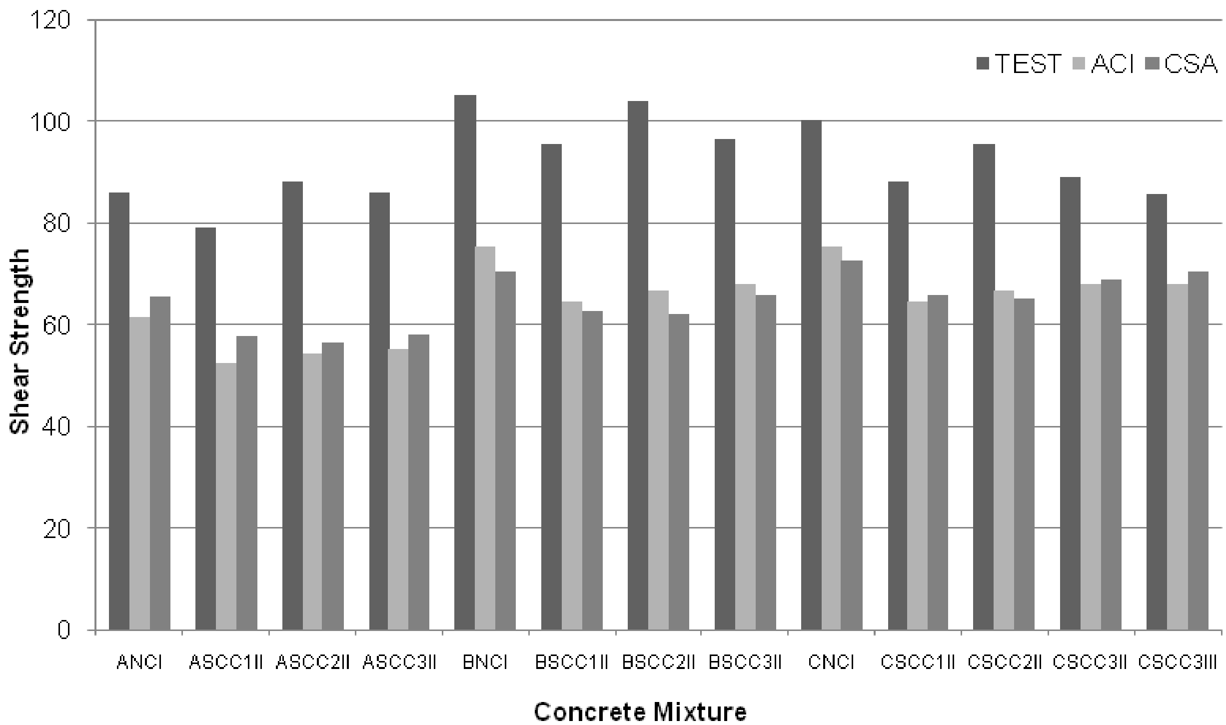

Figure 5. Comparison between the experimental shear results (KN) and ACI and CSA code equations.

NC counterparts.

iii) Using higher percentage of longitudinal steel ratio reduced the crack widths and increased the shear strength in all types of tested beams.

iv) The shear strength and cracking behavior were not significantly affected by the mixture viscosity and/or yield stress. However, beams cast with lower yield stress appeared to have slightly higher shear strength and minimum average crack heights.

v) Casting SCC from one side of the formwork only did not significantly affect the uniformity of SCC mixture. The number of cracks, crack widths, crack heights, failure mode and shear strength did not significantly vary in different pouring techniques, even for long beams with high viscosity mixture.

vi) NC and all SCC beams exhibited a similar trend of variation throughout the load mid-span deflection responses of each beam type. However, NC beams exhibited slightly higher stiffness compared to SCC beams. Also, SCC beams with higher viscosity mixture tended to have lower stiffness compared to SCC mixtures with normal viscosity.

vii) CSA and ACI based equation were found to be conservative in predicting the ultimate shear resistance and can be used safely for any SCC regardless of the mixture viscosity or yield stress.

Abbreviations: SCC, Self-consolidating concrete; **VMA,** viscosity modifying admixtures; **NC,** normal concrete; **ACI,** American Concrete Institution; **CSA,** Canadian Standards Association; **HRWR,** high range water reducer; **ASTM,** American Society for Testing and Materials; **WR,** water reducer; **T500,** time to reach 500 mm slump flow; $f'c$, 28-days compressive strength (MPa); **LVDT,** linear variable differential transformer.

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