Structural Behavior of Self-Compacting Concrete Elements

Ahmed B. Senouci, PhD and
Neil N. Eldin, PhD, PE, CPC, PSP
Department of Construction Management
University of Houston, Houston, Texas, USA

Ala G. Abu Taqa, MSc and
Mohammed S. Al-Ansari, PhD
Department of Civil and Architectural Engineering
Qatar University, Doha, Qatar

Self-compacting concrete (SCC) is a special type of concrete that does not require compaction and vibration for placement. This paper studies the structural behavior of elements made of SCC and compare it to that of elements casted using normally vibrated concrete (NVC). In particular, this research could be considered as a "pilot study" for developing closed-formed equations for the computation of splitting tensile and shear strengths, modulus of rupture, and long term deflection for the structural elements made of SCC. The results showed that the SCC elements could be different than NVC elements and hence, some modifications may be considered in design equations to account for such differences.

Keywords: Self compacting concrete, splitting tensile strength, shear strength, modulus of rupture, normally vibrated concrete

Introduction

Self-compacting concrete (SCC), also known as self consolidating concrete, is an innovative concrete that has the ability to flow under its own weight. It is a highly workable, flowable, and non-segregating concrete that completely fills the formwork space even in the presence of congested reinforcement. SCC provides those desirable properties while maintaining typical mechanical and durability characteristics of normally vibrated concrete (NVC). The materials used in self compacting concrete are the same as those used in conventional concrete except that more fine aggregate and chemical admixtures are used to avoid air pockets within the concrete mass. A viscosity modifying agent (VMA) is used to prevent the segregation of SCC due to the increase of water and fine aggregate.

Several researchers recently studied the mechanical properties of SCC and compared them to those of NVC. Splitting tensile and shear strengths of concrete are important parameters that are used in the design of reinforced concrete structures. While the former is used for computing the development length of the reinforcing steel bars, the latter is needed for the shear design of reinforced concrete elements. Parra et.al. (2011) studied the splitting tensile strength and elastic modulus of SCC at different ages and compared them to those of NVC. They reported that on average the splitting tensile strength of SCC was 15% lower than that of NVC. They recommended that the standard expressions used to compute splitting tensile strength for NVC be modified for SCC. Kim et.al. (2010) studied the influence of the volume of the aggregate and paste on the shear capacity of SCC samples for different coarse aggregate types and volumes and compressive strengths. They proposed new equations for the determination of the concrete shear strength for SCC mixtures. Boel et.al. (2010) examined the shear capacity of SCC and compared it with that of NVC. The results showed decreased shear capacity for SCC compared to that of NVC for a given compressive strength. The percentage of decrease was found lower for higher shear span-to-depth ratios.
While the above studies have provided significant contributions to this important research area, little or no reported research has focused on comparing the experimental values of the mechanical properties of elements made of SCC to those obtained using ACI code equations.

Objectives

This study aims to investigate the splitting tensile strength, shear strength, and modulus of rupture (flexural strength) of reinforced concrete elements made of SCC. It also compares the results obtained experimentally to the values computed using ACI code equation for the elements made of NVC. It could be considered as "pilot" or "guide" study for the behavior of SCC structural elements. Further testing is required in order to formulate equations for closed form design similar to those proposed by ACI code for NVC.

Experimental Testing

Three experiments have been carried out on the SCC specimens. Namely, tensile strength, modulus of rupture (i.e., flexural strength), and shear strength. The specimens were casted and cured at the labs of a ready mix company according to ASTM C192 (ASTM 2013). The specimen were transported to the university lab according to ASTM C31 (ASTM 2012_a) for testing.

Concrete Mixtures

In order to cover the desired range of compressive strengths, six SCC mixes were designed using three concrete grades (i.e., 40, 50 and 60 *MPa)* and two water-cement ratios (i.e., 0.35 and 0.45). The temperature, slump and V-funnel tests were recorded for all mixes and found to be within the acceptable standard limits (see Figure 1).

Figure 1: Slump flow test.

Mixing, Casting, Curing, and Transportation of Specimens

The mixing, casting, and curing of the specimens were done at the ready mix company labs, as shown in Figure 2 (a) and (b), respectively. Following the ASTM standards, at least three samples were tested in each mix/batch.

(a) (b)

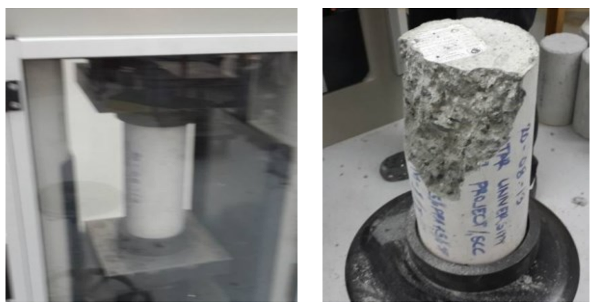
Figure 2: (a) Mixing machine (b) Mixed batch

Testing

Splitting tensile strength, shear strength, modulus of rupture (flexural strength), and long term deflection were recorded for each specimen. The tests are described in the following sections.

Splitting Tensile Strength Test

Standard concrete cylinders were poured according to ASTM C470 (ASTM 2009) (i.e., 152 *mm* in diameter and 304 *mm* in length). A total of 12 specimens were made from each mix. Six cylinders were tested in compression and six in split-tension. The compression and split-tension tests of the specimens were done after 28 days of curing according to ASTM C39 (ASTM 2012_b) and ASTM C496 (ASTM 2011), respectively. Figures 3 and 4 show the specimen failure types in compression and split-tension tests, respectively.



(a) (b)

Figure 3: (a) Compression set up (b) Compression failure type

(a) (b)

Figure 4: (a) Split-tension set up (b) Split-tension failure type

Modulus of Rupture (Flexure Strength) Test

Standard un-reinforced beams of the following dimensions were tested: 1) $100\ mm\ x\ 100\ mm\ x\ 500\ mm$ and 2) $150\ mm\ x\ 150\ mm\ x\ 750\ mm$. Four beams of each size were casted from each mix. The specimens were cured for 28 days according to ASTM C39 (ASTM 2012_b) and ASTM C78 (ASTM 2010), respectively. The flexural strength tests were performed using a simple beam with third-point loading. The beam flexural failure is shown in Figure 5.

Figure 5: Beam flexural failure

Shear Strength Test

Reinforced beams with the following dimensions were tested: 1) $100\ mm\ x\ 100\ mm\ x\ 500\ mm$ and 2) $100\ mm\ x\ 100\ mm\ x\ 750\ mm$. The reinforcement consisted of 2 and 3 T10 bottom steel bars, respectively. No stirrups were provided in the specimens to ensure that the specimens fail under shear.

Four beams for each size were casted from each mix along with four standard cylinders to be tested in compression. The compression strength test was conducted according to ASTM C39 (ASTM 2012_b). On the other hand, the shear strength test was carried out using a four-point loading scheme with two span-depth (a/d) ratios; 1.5 and 2.0 (see Figure 6). The beam shear failure is shown in Figure 7.

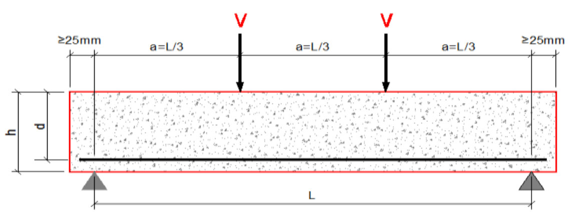


Figure 6: Four points loading scheme

Figure 7: Beam shear failure type

Results and Discussion

Splitting Tensile Strength Test

According to ASTM C39 (ASTM 2012b), the compressive strength is calculated using the following equation:

$$f_c = 4P/\pi d^2 \qquad (1)$$

where f_c is the compressive strength, (MPa), P is the maximum applied load indicated by the testing machine, (N), d is the diameter of the cylindrical specimen, (mm).

According to ASTM C496 (ASTM 2011), the split-tension strength is calculated using the following equation:

$$f_{ct} = 2P/\pi dl \qquad (2)$$

where f_{ct} is the split-tension strength, (MPa), P is the maximum applied load indicated by the testing machine, (N), d is the specimen diameter, (mm), l is the specimen length, (mm).

The loading rate used for both tests, was $0.25MPa/s$, which is the ASTM standard rate for compression testing. The split-tension strength results were modified to accommodate for this loading rate using the following equation suggested by Wright and Garwood (Lamond & Pielert, 2006):

$$\sigma = A + 53log_{10}R \qquad (3)$$

where σ is the strength, $(psi = 1/145.04\ MPa)$, R is the rate of increase of extreme fiber stress (loading rate, psi/min), A is a constant depending on the age.

Considering the test loading rate of $(0.25MPa/s)$ and an average of the standard loading rate of $(1.05MPa/min = 0.018\ MPa/s)$, split-tension strength results need to be modified using the following equation:

$$f_{ct} = Split - tension\ strength\ test\ result - 0.422\ (MPa) \qquad (4)$$

Table 1 summarizes the average of the compressive and split-tension results of all mixes. The results show that the ratio between the average split-tension strength and the square root of the average compressive strengths varies between 0.46 and 0.53 with an average value of 0.50. This ratio decreases as the water/cement ratio increases because of the drop in both strengths. Comparing this ratio to the one specified by the ACI code for NVC, (equal to 0.57) split-tension strength of SCC is found to be lower than that of NVC.

Hence, The ACI code equation related to the split- tension strength of NVC may be modified for SCC using the following equation:

$$f_{ct} = 0.50\sqrt{f'_c} \qquad (5)$$

where f'_c = Cylindrical compressive concrete strength, *(MPa)*.

The ratio of $f_{ct(SCC)}$ to $f_{ct(NVC)}$ is then,

$$f_{ct(SCC)}/f_{ct(NVC)} = 0.50\sqrt{f_c}/0.57\sqrt{f_c} = 0.878$$

This ratio is in a good agreement with the findings of Parra et.al., 2011, who found this ratio to be equal to 0.845.

Table 1
Split- tension strength test results

Mix code	Average compressive strength f'_c, *MPa*	Average split- tension strength f_{ct}, *MPa*	$f_r/\sqrt{f'_c}$
SCC400.35	57.33	3.768	0.50
SCC400.45	42.68	3.018	0.46
SCC500.35	64.74	4.158	0.52
SCC500.45	45.29	3.308	0.49
SCC600.35	65.46	4.298	0.53
SCC600.45	46.2	3.278	0.48
Average	53.62	3.64	0.50

Modulus of Rupture (Flexure Strength) Test

The compressive strength of the cylindrical specimens was calculated using Equation 1. It should be noted that the fracture of all tested beams initiated in the tension surface within the middle third of the span length. Hence, according to ASTM C78 (ASTM 2010), the modulus of rupture was calculated using the following formula:

$$f_r = PL/bd^2 \quad (6)$$

where f_r is the modulus of rupture, (MPa), P is the maximum applied load indicated by the testing machine, (N), b is the average width of specimen, (mm), d is the average depth of specimen, (mm), L is the span length, (mm).

Table 2 summarizes the compressive strength and modulus of rupture average values for all mixes. It shows that the ratio between the average modulus of rupture and the square root of the average compressive strength varies between 0.64 and 0.80 with an average value of 0.71. This ratio also decreases as the water/cement ratio increases. Knowing that the ratio specified by the ACI code for NVC is equal to 0.62, the ACI code equation related to the modulus of rupture of NVC may be **conservatively** used for the SCC without modification.

Table 2
Modulus of rupture test average values

Mix code	Average compressive strength f'_c, *MPa*	Average modulus of rupture f_r, *MPa*	$f_r/\sqrt{f'_c}$
SCC400.35	53.61	5.66	0.77
SCC400.45	41.93	4.14	0.64
SCC500.35	46.93	5.07	0.74
SCC500.45	42.51	4.17	0.64
SCC600.35	51.61	5.72	0.80
SCC600.45	37.94	4.08	0.66
Average	45.76	4.81	0.71

Shear Strength Test

The compressive strength of the cylindrical specimens was calculated using Equation 1. The shear strength of the tested beams was calculated using the following equation:

$$v = P/bd \quad (7)$$

where v is the shear Strength, (MPa), P is the maximum applied load indicated by the testing machine, (N), b is the average width of beam, (mm), d is the distance from top surface of beam to the center of bottom reinforcement, (mm)

Table 3 summarizes the ratios between the NVC shear strength computed using ACI code equation and the experimental SCC shear strength values for two different shear span to depth ratios. The original ACI code equation for shear capacity of normal vibrated concrete is as follows:

$v = 0.167\sqrt{f_c'}$ (8)

It could be noted that the experimental shear values obtained for a shear span to depth ratio of 1.5 were higher than those obtained for a shear span to depth ratio of 2.0. Moreover, for both tested depth/span ratios, equation 8 may be conservative in predicting the shear capacity of SCC. This may be attributed to the fact that it does not consider the effect of shear span to depth ratios which found to have significant effect in predicting the shear strength of concrete beams. Hence, beams with wider range of shear span to depth ratio need to be tested in order to compare the results with those computed using ACI code equation that is applicable for all values of shear span to depth ratios.

Table 3
Shear strength test results

Mix code	**Average compressive strength f'_c, MPa**	**Experimental average shear stress v, MPa**		**Shear stress v, according to ACI equation, MPa**	**Code/Experimental**	
		Shear span/depth ≈1.5	**Shear span/depth ≈2.0**		**Shear span/depth ≈1.5**	**Shear span/depth ≈2.0**
SCC400.35	56.09	4.29	3.11	1.25	0.29	0.40
SCC400.45	46.83	4.93	2.51	1.44	0.29	0.57
SCC500.35	60.54	5.60	2.48	1.30	0.23	0.52
SCC500.45	38.31	4.55	2.21	1.03	0.23	0.47
SCC600.35	54.68	4.16	2.83	1.23	0.30	0.44
SCC600.45	39.48	3.47	2.27	1.05	0.30	0.46
					Avg.=0.27	Avg.=0.48

Conclusions

This study investigated the splitting tensile and shear strengths, and modulus of rupture of elements made of SCC. The results were compared to the values computed using ACI equation for NVC. This investigation suggests the need for new ACI code equations when SCC is used instead of NVC. The following summarizes the findings:

1. Splitting tensile strength of SCC was found approximately equal to 0.875 of that of NVC,
2. The modulus of rupture of SCC elements was found to be similar to that of NVC,
3. The experimental shear values of SCC elements obtained for a shear span to depth ratio of 1.5 were higher than those obtained for a shear span to depth ratio of 2.0. Moreover, for both tested depth/span ratios, ACI equation used for computing the shear capacity of elements made of NVC was found conservative in predicting the shear capacity of SCC. Hence, beams with wider range of shear span to depth ratio need to be

tested in order to compare the results with those computed using ACI code equation that is applicable for all values of shear span to depth ratios,

Acknowledgement

This report was made possible by a UREP award [UREP 13-084-2-031] from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors.

References

American Concrete Institute (ACI), Committee 318 (2011). *Building code requirements for structural concrete and commentary (ACI 318-11)*. USA: American Concrete Institute

American Society for Testing and Materials (2013). *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory (ASTM C192).* USA: ASTM International.

American Society for Testing and Materials (2012). *Standard Practice for Making and Curing Concrete Test Specimens in the Field (ASTM Standard C31).* USA: ASTM International.

American Society for Testing and Materials (2012). *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM Standard C39).* USA: ASTM International.

American Society for Testing and Materials (2011). *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM Standard C496).* USA: ASTM International.

American Society for Testing and Materials (2010). *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading (ASTM Standard C78).* USA: ASTM International.

American Society for Testing and Materials (2009). *Standard Specification for Molds for Forming Concrete Test Cylinders Vertically (ASTM Standard C470).* USA: ASTM International.

Boel, V., Helincks, P., Desnerck, P., and De Schutter, G. (2010). Bond Behavior and Shear Capacity of Self-Compacting Concrete. Design, Production and Placement of Self-Consolidating Concrete. *RILEM State of the Art Reports, 16 (*8), 343-353.

Hoon Kim, Y., Hueste, M. B. D., David Trejo, D., and Cline, D. B. H. (2010). Shear Characteristics and Design for High-Strength Self-Consolidating Concrete. *Journal of Structural Engineering (ASCE),136* (8), 989-1000.

Lamond J. F. and Pielert J. H. (2006). *STP169D, Significance of Tests and Properties of Concrete and Concrete-Making Materials.* USA:ASTM International

Parra, C., Valcuende, M., and Gomez, F. (2011). Splitting tensile strength and modulus of elasticity of self-compacting concrete. *Construction and Building Materials*, *25*(1), 201-207.