Influence of Viscosity Modifying Admixture (VMA) on the Properties of SCC Produced Using Locally Supplied Materials in Bahrain

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ABSTRACT

The reluctance in utilizing the advantages of Self Compacting Concrete (SCC) in Bahrain stems from two contributing factors: Lack of research or published data pertaining to locally produced SCC, and a feeling of doubt and uncertainty in the minds of practicing engineers about reliability and suitability of SCC in hardened stage. The primary aim of this study is to explore the influence of viscosity modifying admixtures available in Bahrain on the fresh and hardened properties of SCC. For this purpose, three self-compacting concrete mixes and one control mix were prepared with same water/powder ratio and other ingredients, but with different fluidity. Control mix is considered to compare the strength of SCC with that of the normal concrete. The fluidity was varied by altering the dosage of VMA in different SCC mixes. The filling ability, passing ability and resistance to segregation were evaluated to make sure that prepared mixes satisfy the SCC basic criteria. From each SCC mix and control mix, 9 cubes were cast to obtain compressive strength of SCC in hardened stage after 3, 7 and 28 days of curing. Also, for each SCC mix and control mix, three prisms were cast and their flexural strength was tested after 28 days of curing. The test results of the specimens were used to carry out a comparison of compressive and flexural strength of different mixes of SCC and the control mix. The study shows that SCC prepared using locally supplied materials is also equally reliable as conventional concrete, provided that it satisfies all the basic requirements of SCC in fresh stage and maintains a minimum slump flow of 600 mm.

KEYWORDS: Self Compacting Concrete (SCC), Viscosity modifying admixtures, VMA, Compressive strength, Flexural strength.

INTRODUCTION

Self Compacting Concrete (SCC), also referred to as self-consolidating concrete, was developed in Japan in the 1980s. SCC is a high-performance material designed to flow into formwork under its own weight, and without the aid of mechanical vibration. At the same time, it is cohesive enough to fill spaces of almost any size and shape without segregation or bleeding.

SCC typically has a higher content of fine particles and different flow properties than the conventional concrete. It has to have three essential properties when it is ready for placement: filling ability, resistance to segregation and passing ability. However, the components of SCC are similar to other plasticized concrete. Self-compacting of concrete can be affected by the physical characteristics of materials, mixture proportioning and moisture content of its ingredients.

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The mixture proportioning is based upon creating a high degree of flow ability, while maintaining a low (< 0.40) w/cm (Okamura and Ouchi, 1999).

The production of SCC is more expensive than regular concrete, and it is difficult to keep SCC in the desired consistency over a long period of time (Kapoor et al., 2003; Essam and Aali, 2009; Akram et al., 2009). However, with SCC, construction time is shorter and production is environmentally friendly (no noise, no vibration). Furthermore, SCC produces a good surface finish. These advantages make SCC particularly interesting for use in precasting plants or surface repair (JRMCA, 1998).

Several different approaches have been used to develop SCC. One method to achieve self-compacting property is to increase significantly the amount of fine materials (e.g., fly ash or limestone filler) (Sakata et al., 1995; Bouzoubaâ and Lachemi, 2001) without changing the water content compared with common concrete. One alternative approach consists of incorporating a Viscosity Modifying Admixture (VMA) to enhance stability (Sari et al., 1999; Rols et al., 1999; Khayat and Guizani, 1997). The use of VMA along with adequate concentration of superplasticizer (SP) (Ouchi et al., 2001) can ensure high deformability and adequate workability, leading to a good resistance to segregation. The SCC currently available on the market is expensive due to higher prices of VMA and high volume of binder in the mixture, and a cost-effective product is desired to produce a competitive concrete in the construction industry. Investigation is therefore necessary to explore the potential use of new and locally available low-cost VMA in the development of SCC. Lachemi et al. (2004) presented the development of SCC with four different types of new VMA. They studied the fresh and hardened properties of different SCC mixes with various dosages of a chosen VMA. The performance of various mixtures was compared with that of known commercial SCC mixtures using a commercial VMA and Walen gum.

Despite its advantages as described above, SCC has not gained much acceptance in the Middle East. Awareness of SCC has spread across the world, prompted by concerns with poor consolidation and durability in case of conventionally vibrated normal concrete. However, the awareness in the Kingdom of Bahrain regarding SCC is somewhat muted, and this explains the lack of any commercial use of SCC in the Kingdom so far. In the Middle East, perhaps only in Dubai, there are a few high-rise structures, where SCC was used in the construction.

The reluctance in utilizing the advantages of SCC, in Bahrain, stems from two contributing factors: Lack of research or published data pertaining to locally produced SCC, and doubts in the minds of practicing engineers about reliability of Self Compacting Concrete (SCC) in hardened stage. The primary aim of this study is to explore the influence of VMA on the fresh and hardened properties of SCC. The filling ability, passing ability and resistance to segregation were evaluated to make sure that prepared mixes satisfy the SCC basic criteria. To compare the properties of SCC with normal concrete having the same cement proportion and other ingredients, a control mix was also prepared. From each SCC mix and control mix, 9 cubes were cast to obtain compressive strength of SCC in hardened stage after 3, 7 and 28 days of curing. Also, for each SCC mix and control mix, three prisms were cast and their flexural strength was determined after 28 days of curing. The test results of the specimens were used to carry out a comparison of compressive and flexural strength of different mixes of SCC and the control mix. The study shows that SCC prepared using locally supplied materials is also equally reliable as conventional concrete, provided that it satisfies all the basic requirements of SCC in fresh stage and maintains a minimum slump flow of 600 mm.

MATERIALS AND MIX PROPORTIONS

Following materials were utilized in the preparation of the SCC and control mixes.

Cement and Fly Ash

In this study, Type-I Ordinary Portland cement meeting ASTM C 150 Standards was used for the preparation of SCC mixes. The physical properties of the cement used are shown in Table 1.

Table 1: Physical properties of the cement*

Properties	Results obtained	Requirements
Setting time		
Initial	129 minutes	Not less than 45 minutes
Final	227 minutes	Not more than 375 minutes
Soundness autoclave	0.05%	Maximum 0.8%
Air content of water (%) by volume	10%	Maximum 12%
Fineness (Specific surface)	342 m^2/kg	Minimum 280 m^2/kg
Compressive strength of mortars:		
3 days	3320 psi (22.9 MPa)	Minimum 1800 psi (12.4 MPa)
7 days	4370 psi (30.1 MPa)	Minimum 2800 psi (19.3 MPa)
28 days	5545 psi (38.2 MPa)	Limit not specified

**Data Supplied by the manufacturer.*

Table 2: Physical properties of aggregates

Properties	Coarse aggregate	Fine aggregate
	20mm and 10 mm	Washed sand
Bulk Specific Gravity (SSD Basis)	2.64	2.6
Bulk Specific Gravity (Oven Dry Basis)	2.50	2.54
Apparent Specific Gravity	2.70	2.71
Unit Weight (kg/m^3)	1542	1591
Absorption (%)	1.50	1.1

In the present study, in addition to cement, a highly pulverized *Class F* fly ash, meeting ASTM C 618 standard and having a specific gravity of 2.15, was also used for partial replacement of the cement.

Aggregates

In all SCC mixes, the coarse and fine aggregates were used. In our study, washed sand was used as fine aggregate. The coarse aggregate used in this study was crushed limestone processed from the local quarries in Saudi Arabia. The maximum size of the coarse aggregate was 20 mm. The physical properties of the coarse and fine aggregates, determined in accordance with ASTM C 127 and ASTM C 128, respectively, are given in Table 2.

Table 3: Salient properties of superplasticizer and VMA used in the SCC mix preparation

Properties	Superplasticizer	VMA
Chemical type	Polycarboxylic ether polymers	Water soluble copolymers
Function	Accelerates the cement hydration.	Maintain right balance between fluidity and resistance to segregation.
Advantages	Earlier development of the heat of hydration, rapid development of the hydration products and, as a consequence, higher strengths at very early age	Refine the rheology of the mixes by increasing cohesiveness and eliminating bleeding.
Ambient temp.	The used superplasticizer is recommended for use at ambient temperature above 15^0C.	It is advisable to keep the product at an ambient temperature above 15^0C.
Dosage	The normally recommended dosage rate is 0.5 to 1.0 liters per 100 kg of the binder and any material (fines or fillers) passing the 0.1 mm sieve.	The used VMA is dosed at the rate of 0.1 to 0.8 liter per 100 kg of cementatious material.

Superplasticizer

High Range Water Reducers (HRWRs), known as superplasticizers, were used in all the three SCC mixes to decrease viscosity and increase fluidity. The level of fluidity is chiefly governed by the dosage of the superplasticizer. However, overdosing may lead to the risk of segregation and blockage. In the present study, a locally available commercial superplasticizer named Glenium Sky 504 was used. The salient properties of the superplasticizer used in our study are shown in Table 3.

Viscosity Modifying Admixtures (VMA)

Viscosity modifying admixtures are used to stabilize the rheology of SCC. They essentially increase viscosity and thus thicken the mix to prevent segregation. This viscosity buildup comes from the association and entanglement of polymer chains of the VMA at a low shear rate, which further inhibits flow and increases viscosity. At the same time, added VMA causes a shear-thinning behavior, decreasing viscosity, when there is an increase in shear rate. There are various types of VMAs, most of which are composed of either polymer or cellulose-based materials, which “grab and hold” water. The most important aspect is that they do not change any properties of the mix besides viscosity. VMAs can be used alone, but are more commonly used with superplasticizers. In this combination, the superplasticizers take on the role of enhancing flow, while VMAs act to provide stability.

In the present study, a locally available high performance viscosity modifying agent, named "Glenium Stream 2" from BASF Chemical Company, specially designed to ensure a good consistency, high segregation resistance and stability in concrete with sufficient fluidity, was used. The viscosity modifying agent was water soluble, chloride free and compatible with all the cements. The salient properties of this VMA are shown in Table 3.

MIX COMPOSITION

The mix composition is chosen to satisfy all performance criteria for concrete in both the fresh and hardened states.

Table 4: Typical range of constituents in SCC (Okamura et al., 1993)

Constituent	Typical range by mass (kg/m^3)	Typical range by volume (l/m^3)
Powder	380-600	
Paste	-	300-380
Water	150-210	150-210
Coarse aggregate (san)	Content balances the volume of the other constituents, typically 48-55% of the total aggregate weight.	
Water/Powder ratio by vol.	-	0.85-1.10

Table 5: Ingredients of self-compacted concrete mixes and control mix (kg/m^3) (case I)

Mix Variables	SCC -1	SCC -2	SCC-3	CM
VMA (l/m^3)	0.0	0.642	1.284	0.0
Cement	530	530	530	600
Flyash	70	70	70	0.0
Water	210	210	210	210
Wash sand	750	300	300	300
Coarse aggregate	750	750	75 750	750
Superplasticizer	0.8%	0.8%	0.8%	0.0%

Table 6: Ingredients of self-compacted concrete mixes and control mix(kg/m^3) (case II)

Mix Variables	MSCC -1	MSCC -2	MSCC-3	MCM
VMA (l/m^3)	0.0	0.642	1.284	0.0
Cement	400	400	400	480
Flyash	80	80	80	0.0
Water	168	168	168	168
Wash sand	550	550	550	550
Coarse aggregate	1150	1150	1150	1150
Superplasticizer	0.8 %	0.8 %	0.8 %	0.0

Basic Mix Design

There is no standard method for SCC mix design and many academic institutions, admixture, ready-mixed, precast and contracting companies have developed their own mix proportioning methods. Table 4 gives an indication of the typical range of constituents in SCC by weight and by volume. These proportions are in no way restrictive and many SCC mixes will fall outside this range for one or more constituents (Su et al., 2001).

MIX PREPARATION

Two case studies were considered for the present study as given in Tables 5 and 6. For each case, four different mixes were prepared. Two mixes were prepared by varying the viscosity modifying admixture dosages in order to study the influence of viscosity modifying admixtures on the properties of self-compacting concrete. Two dosages of VMA = 0.642 l/m^3 and 1.284 l/m^3 of concrete; with fine to coarse aggregate ratio = 1 (by mass), and superplasticizer = 0.8% (by mass of powder) were used for preparing the SCC mixes. For each mix, a constant water/powder ratio of 0.35 (by mass) was taken. A mix was also prepared without using VMA in order to study the properties of SCC in the absence of any viscosity modifying agent. To compare the properties of SCC with those of normal concrete having the same cement proportion and other ingredients, a control mix was also prepared for each case.

MIXING OF CONCRETE

The coarse and fine aggregates were mixed with sufficient water to wet the aggregate for 30 seconds in a pan-type mixer. The cement and fly ash were added together with 70% of the mixing water and mixed for further 2 minutes. Finally, the remaining water mixed with superplasticizer was added and the mixing was continued for one minute. Then, the mixing was halted for 2 minutes and continued for other two minutes.

TESTING OF SELF-COMPACTING CONCRETE

Fresh concrete was subjected to standard and non-standard tests to evaluate the slump flow, bleeding capacity and segregation potential. Standard slump cone (200mm × 100mm × 300mm) was filled with concrete, and the mean diameter of the spread was measured on lifting the cone. V-Funnel test was used to determine the segregation potential. The apparatus used consisted of a V-shaped funnel. It is tapered from the top dimension of 490mm to 65mm over a height of 425mm. The bottom opening has the dimensions of 75mm × 65mm to a depth of 150mm. The funnel is filled with concrete, and the time taken for the concrete to leave the funnel is measured. Then, the funnel is refilled with the same concrete and allowed to settle for 5 minutes. The new time required for the concrete to leave the funnel is measured. The difference in time is a measure of segregation resistance of the concrete mix. J ring test was conducted to measure the filling and passing ability of the self compacting concrete, whereas L box test was carried out to measure the passing ability of the self-compacting concrete.

In addition, compressive and flexural strengths of hardened self-compacting concrete were also determined. A number of standard test cubes (150mm × 150 mm × 150 mm) and prisms were cast and continuously stored in water until testing for compressive strength at the ages of 3,7 and 28 days. The prisms were tested for flexural strength after 28 days of curing.

RESULTS AND DISCUSSION

FRESH PROPERTIES OF SCC

The self-compatibility of the mixes was evaluated using the following tests (EFNARC, 2002). The results of the self-compatibility tests conducted on the three mixes of case I and case II are presented in Tables 7 and 8, respectively.

Slump Flow Test

Slump flow test is performed similar to the conventional slump test (ASTM C143) using the Abrams cone (use of inverted cone is possible). However, instead of measuring the slumping distance vertically, the mean spread of the resulting concrete patty is measured horizontally. This number is recorded as the slump flow. Additional information about the mixture can be obtained by measuring the time it takes for the patty to reach 500 mm (20 in.). This is called the T50 value and is a measure of viscosity.

Figure 1: Slump flow of SCC mix

Table 7: Fresh properties of self-compacting concrete mixes and control concrete (case I)

SCC Mix	VMA l/m^3	Slump flow (mm)	T_{50} (sec)	V-funnel (sec)	J-ring (mm)	L-Box (h_2/h_1)
SCC1	0.0	780	3.80	6.30	7	0.90
SCC2	0.642	625	4.30	7.40	10	0.86
SCC3	1.284	550	6.60	8.20	13	0.83
CM	0.0	65	-	-	-	-

Table 8: Fresh properties of self-compacting concrete mixes and control concrete (case II)

SCC Mix	VMA l/m^3	Slump flow (mm)	T_{50} (sec)	V-funnel (sec)	J-ring (mm)	L-Box (h_2/h_1)
MSCC1	0.0	795	4.50	7.20	8	0.87
MSCC2	0.642	780	5.80	8.30	11	0.85
MSCC3	1.284	755	7.40	9.20	14	0.82
MCM	0.0	65	-	-	-	-

In the present study, the slump flow test was carried out in accordance to ASTM C 1611. The slump flow test was used to determine the flowability of self-compacting concrete mixes (Fig. 1). The diameters of each SCC mix after allowing its full flow was measured and is presented in Tables 7 and 8, respectively for the two case studies. The higher the slump flow value is, the greater is its ability to fill the formwork under its own weight. The acceptable range for SCC is from 500 to 800 mm. At less than 500 mm, the mix may have trouble in flowing in a confined space.

Tables 7 and 8 further illustrate that as the dosage of VMA increases, slump flow decreases. This decrease in slump flow with the increase in VMA dosage may be attributed to the increase in the viscosity of the mix due to VMA. It was observed that when VMA dosage was 1.22 l/m^3, the mix was quite cohesive and slump flow was well within the desirable range of SCC. This shows that VMA plays a significant role in improving the properties of self-compacting concrete. However, the dosage of VMA should be properly designed, as it may change the basic criterion of SCC. In other words, the flowability may fall below 500 mm slump for a very high dosage of VMA. Tables 7 and 8 show the T50 values in seconds. T50 can be directly correlated with slump flow. The values clearly indicate that the higher the flow is, the lesser is the time taken by SCC mix to reach 500 mm diameter (i.e., T50).

Figure 2: V-funnel test for evaluation of segregation resistance

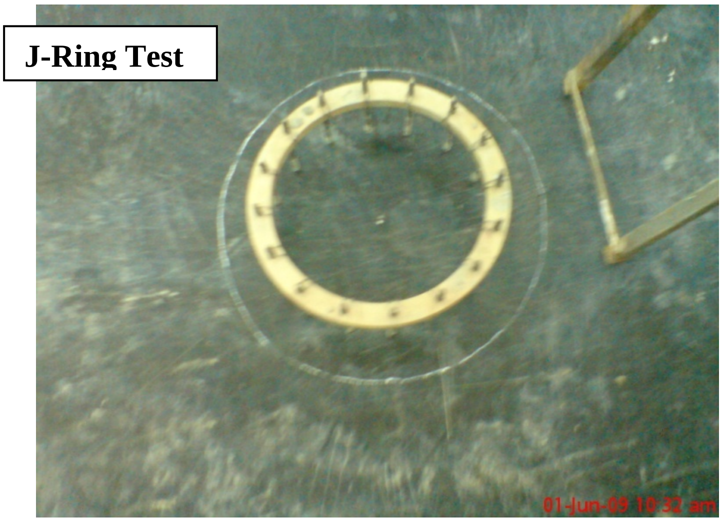

Figure 3: J-ring test for evaluation of passing ability

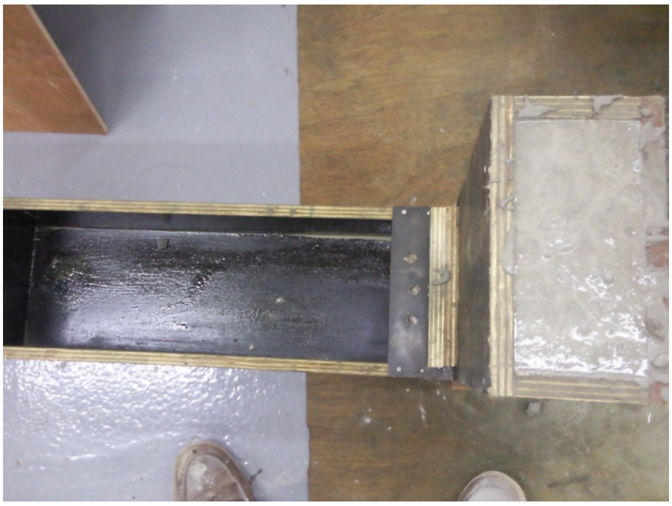

Figure 4: L-box test

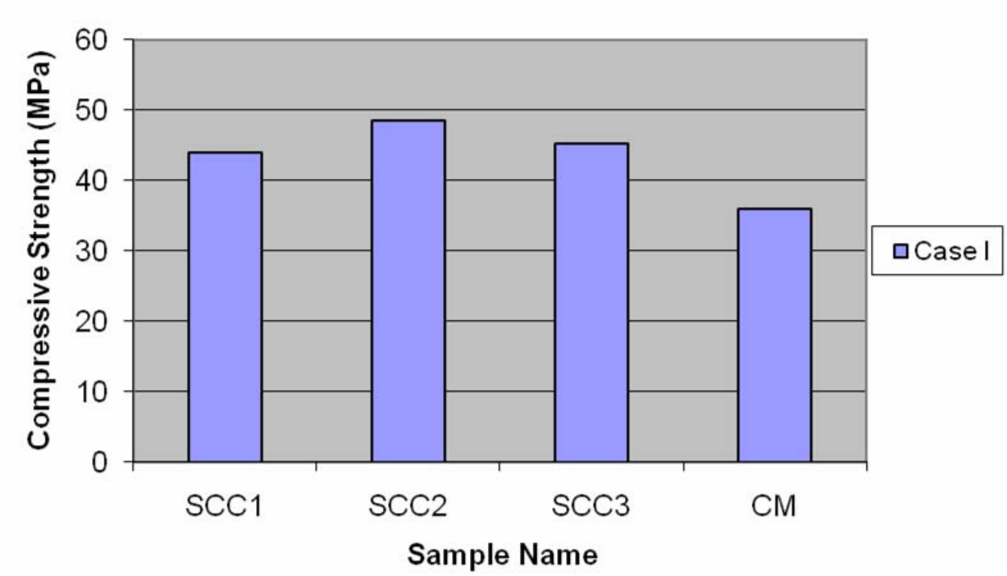

Figure 5: Average compressive strength after 3 days

V-Funnel Test

The V-Funnel consists of a V-shaped apparatus with an opening at its bottom. The time taken to empty the funnel is regarded as a measure of the viscosity (or segregation resistance) of the mixture. Tables 7 and 8 show that for the mixes (SCC-1 and MSCC-1) for both cases with no VMA, the time taken by the mixtures to empty the funnel is the least. This is an expected trend, as superplasticizers increase flowability or decrease viscosity. However, when VMA was also added in the mixes (SCC-2 and 3), the time taken by the mixtures to empty the funnel increased with increasing the dosage of VMA. This is due to the increase in the viscosity of the mixture with the increase in VMA dosage. Figure 2 shows the V-funnel test conducted at the Concrete Lab, Department of Civil Engineering and Architecture, University of Bahrain, Kingdom of Bahrain.

Table 9: Compressive strength of hardened SCC mixes and control mix (case I)

Mix	Specimen	Comp. Strength (MPa) 3 Days	Average Comp. Strength (MPa) 3 Days	Comp. Strength (MPa) 7 Days	Ave. Comp. Strength (MPa) 7 Days	Comp. Strength (MPa) 28 Days	Average Comp. Strength (MPa) 28 Days
SCC1	Cube 1	44.42	43.93	47.43	46.44	50.05	50.29
	Cube 2	43.51		46.36		50.31	
	Cube 3	43.86		45.54		50.52	
SCC2	Cube 1	47.45	48.59	53.07	53.24	58.12	57.73
	Cube 2	48.96		54.64		57.53	
	Cube 3	49.37		52.03		57.54	
SCC3	Cube 1	46.7	45.19	52.33	50.32	53.71	54.33
	Cube 2	44.9		50.19		54.91	
	Cube 3	43.99		48.44		54.39	
CM Control mix	Cube 1	36.20	35.99	44.88	44.39	52.10	52.59
	Cube 2	35.79		44.98		53.86	
	Cube 3	35.98		43.31		51.82	

Table 10: Compressive strength of hardened SCC mixes and control mix (case II)

Mix	Specimen	Comp. Strength (MPa) 3 Days	Average Comp. Strength (MPa) 3 Days	Comp. Strength (MPa) 7 Days	Average Comp. Strength (MPa) 7 Days	Comp. Strength (MPa) 28 Days	Average Comp. Strength (MPa) 28 Days
MSCC1	Cube 1	32.22	33.47	39.58	39.59	44.18	44.28
	Cube 2	34.45		39.41		45.55	
	Cube 3	33.74		39.78		43.11	
MSCC2	Cube 1	37.50	37.17	42.56	43.28	49.31	48.60
	Cube 2	37.90		43.96		48.16	
	Cube 3	36.10		43.33		48.33	
MSCC3	Cube 1	35.85	35.85	41.1	41.25	47.80	47.03
	Cube 2	36.40		40.96		46.31	
	Cube 3	35.30		41.70		46.98	
CM Control mix	Cube 1	28.85	28.52	38.51	38.27	46.84	46.41
	Cube 2	28.40		37.77		45.73	
	Cube 3	28.30		38.54		46.67	

J-Ring Test

The J-Ring consists of a ring of reinforcing bar such that it will fit around the base of a standard slump cone. The J-ring test was conducted in accordance to ASTM C1621 and is shown in Figure 3. This test was conducted to measure the passing ability of SCC mixes. Tables 7 and 8 show that the step size is increasing with the dosage of VMA. This trend can again be attributed to the increase in viscosity of the mix with the increase in VMA. Moreover, for all the SCC mixes of the two cases, standard results are satisfied.

L-Box Test

The L-Box test was conducted in accordance to ASTM C1621 and is shown in Fig. 4. This test was conducted to measure the passing ability of SCC mixes.

Tables 7 and 8 show that the ratio of h_2/h_1 is decreasing with the dosage of VMA. This trend can again be attributed to the increase in viscosity of the mix with the increase in VMA. The ratio of h_2/h_1 for all the SCC mixes of the two cases lies within the standard range (0.8 – 1.0).

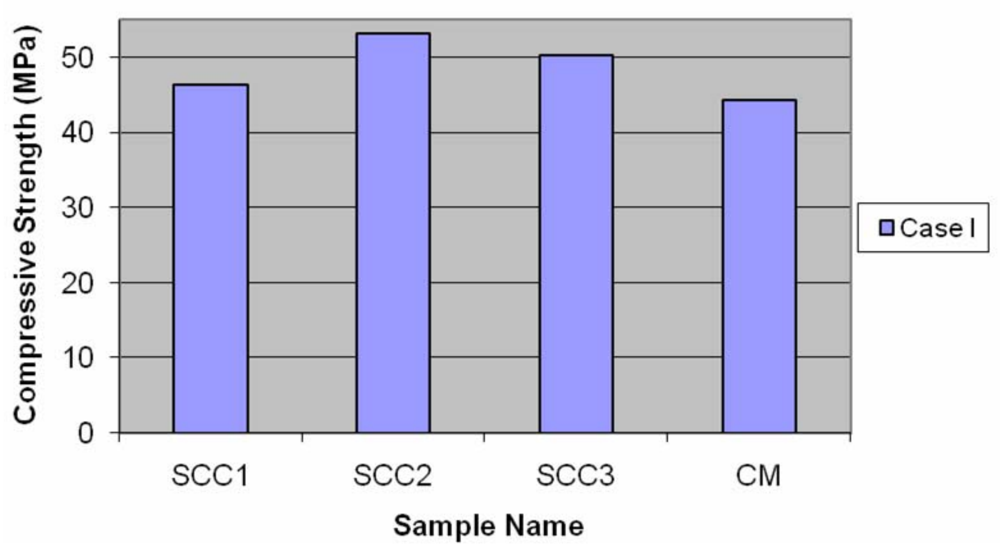

Figure 6: Average compressive strength after 7 days

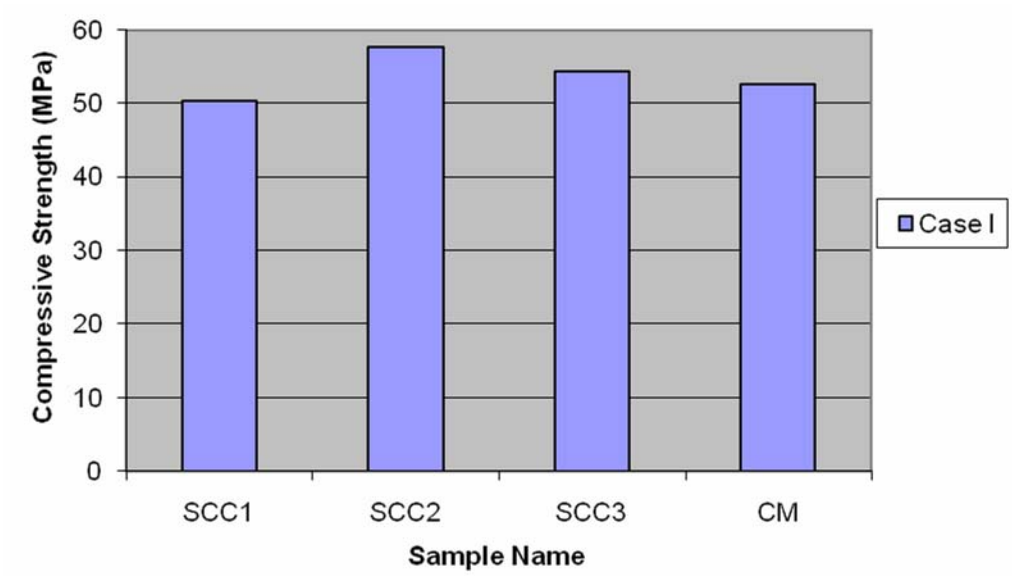

Figure 7: Average compressive strength after 28 days

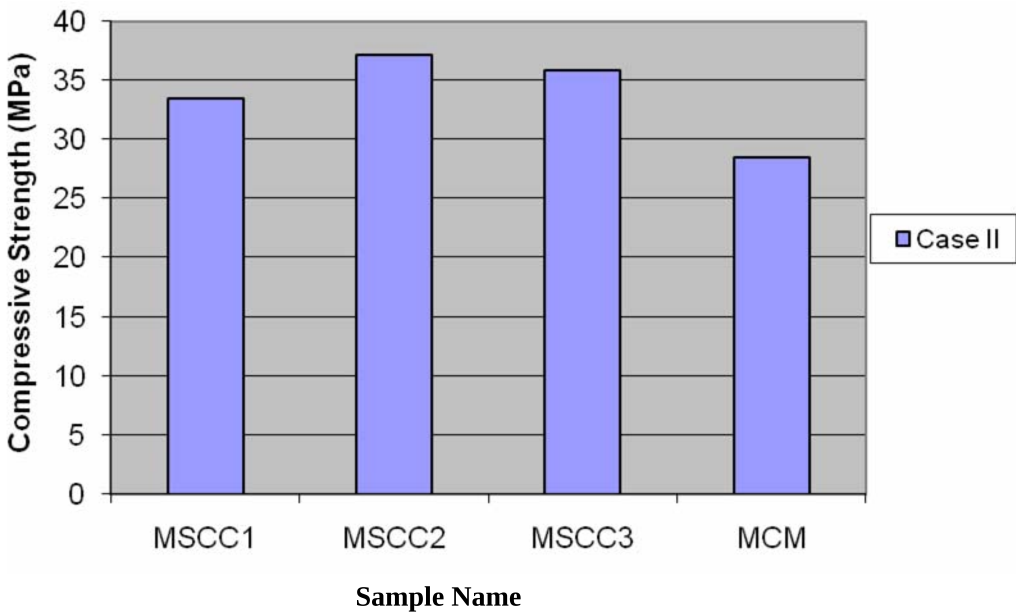

Figure 8: Average compressive strength after 3 days

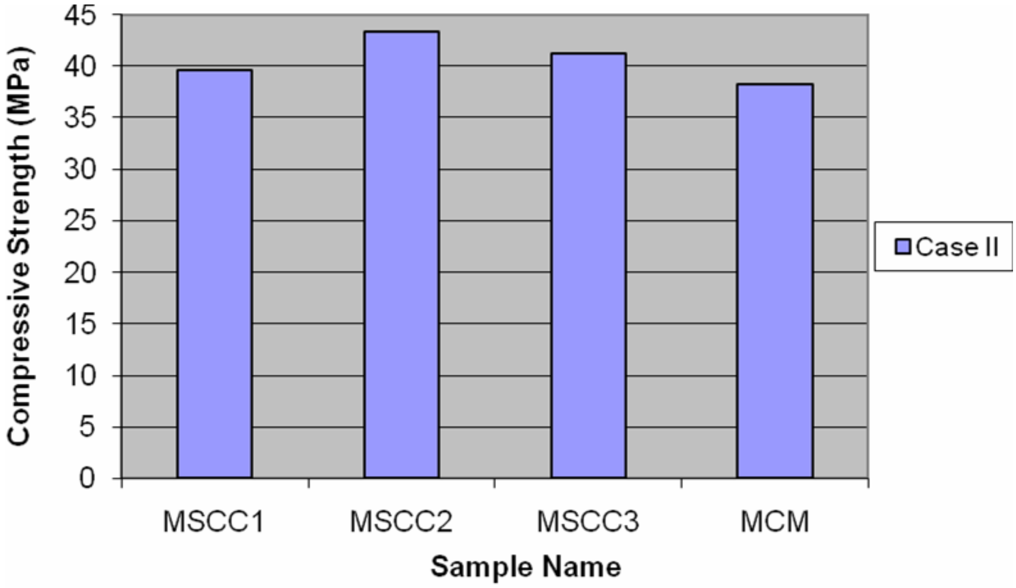

Figure 9: Average compressive strength after 7 days

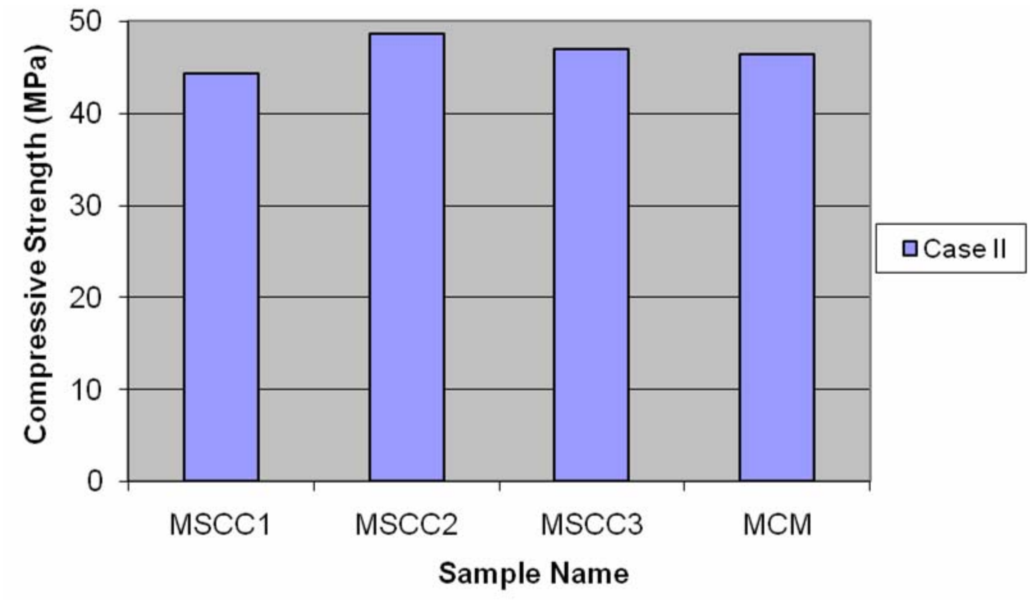

Figure 10: Average compressive strength after 28 days

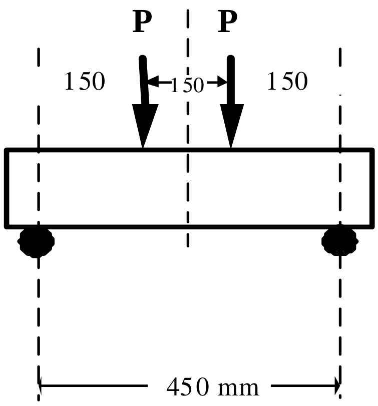

Figure 11: Test set-up for modulus of rupture

HARDENED PROPERTIES OF SCC AND CONTROL MIXES

Compressive Strength

Compressive strength of concrete is a key parameter which indicates the quality of concrete in hardened state. In order to study the quality of self-compacting concrete in hardened state, along with other important parameters, compressive strength of SCC mixes was measured through (150×150×150 mm cubes) tests. As discussed earlier, two different case studies were considered. For each case, four different mixes were prepared, and for each mix a total of 9 concrete cube specimens, 150 mm in size, were cast for determining the compressive strength after 3, 7 and 28 days of water curing. The casting of cubes was made without vibration conditions for self-compacting concrete. Six more cubes of control mix (three each for case I and case II, respectively) were cast with vibration. Before casting, the moulds were oiled properly for easy demolding. After casting and finishing, the specimens were covered with plastic sheet to avoid loss of water due to evaporation. The specimens were demolded after 24 hours of casting, and then they were transferred to a curing tank placed at the laboratory temperature of 18 to 20^0 C. The specimens were cured in the water tank for 3, 7 and 28 days.

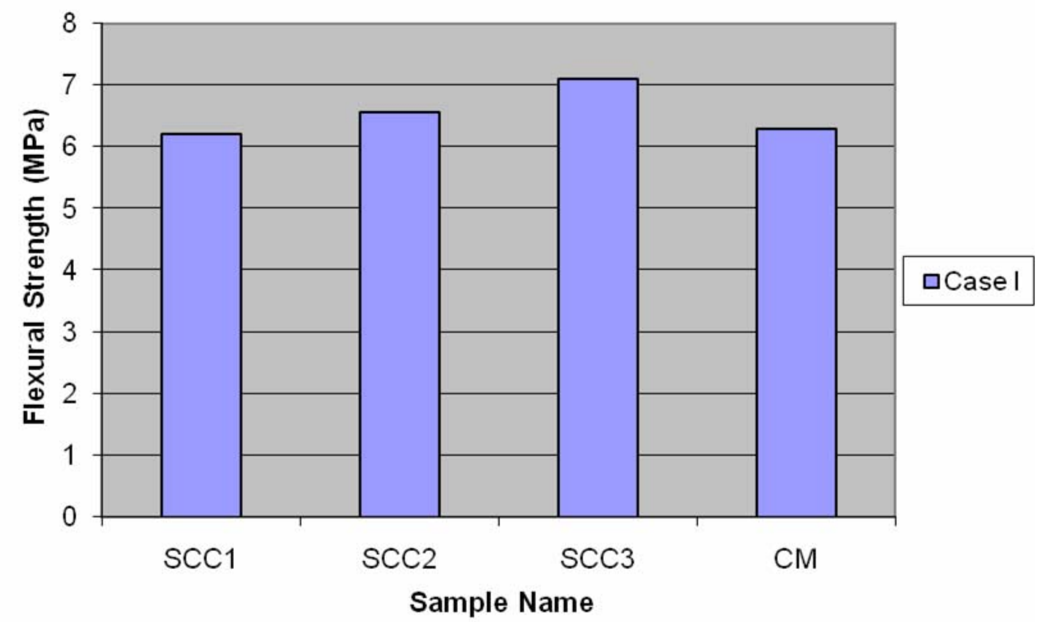

Figure 12: Average compressive strength after 28 days

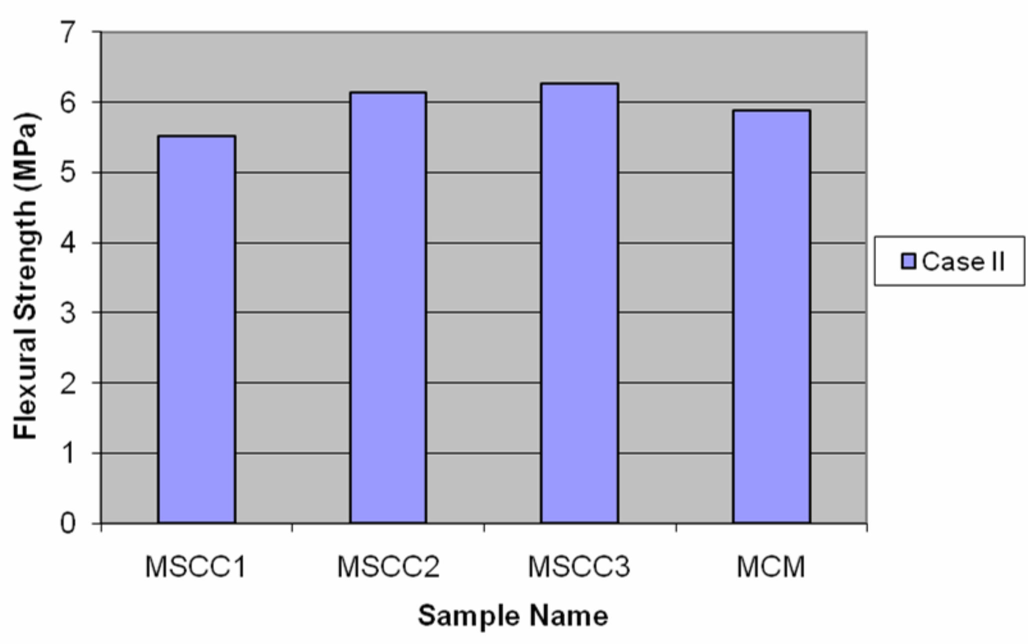

Figure 13: Average compressive strength after 28 days

Table 11: Flexural strength of hardened SCC mixes and control mix (case I)

Type	Sample	Flexural Strength (N/mm^2)	Average (N/mm^2)
SCC1	I	6.30	6.21
	II	6.08	
	III	6.25	
SCC2	I	6.53	6.57
	II	6.63	
	III	6.55	
SCC3	I	7.20	7.11
	II	7.02	
	III	7.10	
CM	I	6.40	6.30
	II	6.20	
	III	6.29	

Table 12: Flexural strength of hardened SCC mixes and control mix (case II)

Type	Sample	Flexural Strength ($Nlmm^2$)	Average (N/mm^2)
MSCC1	I	5.63	5.51
	II	5.40	
	III	5.51	
MSCC2	I	5.85	6.13
	II	6.35	
	III	6.20	
MSCC3	I	6.3	6.27
	II	6.3	
	III	6.20	
MCM	I	5.45	5.88
	II	6.075	
	III	6.10	

The compressive strength of all the SCC mixes and control mix after 3, 7 and 28 days curing are shown in Tables 9 and 10 for case I and case II, respectively. The results are plotted in Figs. 5 to 10. From Table 9 and Fig. 5, one can observe that the average values of the compressive strength of the mixes SCC1, SCC2 and SCC3 after 3 days are 43.93 MPa, 48.59 MPa and 45.19 MPa, respectively for case I; whereas the control mix has only 35.99 MPa. Mix 2 (i.e., SCC2) has maximum strength.

Moreover, after 7 days of curing, there is a marked increase in the strength of samples of all mixes as can be seen in Fig. 6. The strength values of SCC1, SCC2 and SCC3 are 46.44 MPa, 53.24 MPa, and 50.32 MPa, respectively. The strength value of the control mix is 44.39 MPa and is still far less than the strength of samples of all other mixes. The increase in 7 day compressive strength over 3 day compressive strength for the respective mixes is 5.71%, 9.56%, 11.35% and 23.3 %. The strength of the control mix increases rapidly. Strength values of SCC2 and SCC3 are still found to be greater than those of the other mixes. After 28 days of curing, strength values of samples of mixes SCC1, SCC2 and SCC3 are found to be 50.29 MPa, 57.73 MPa and 54.33 MPa, respectively with an increase of 8.29%, 8.43% and 7.96%, respectively over 7 day strength, whereas the increase in strength of the control mix is 18.47%. The comparison of compressive strengths of different mixes after 28 days of curing is shown in Fig. 7. As both mixes SCC2 and SCC3 contain VMA, this means that the presence of VMA enhances the strength of self-compacting concrete. Sample 1 (SCC1) has the minimum compressive strength as compared to the other three samples. On the other hand, the compressive strength of the control mix was found to be smaller than for the two samples containing VMA. This may be due to the fact that SCC samples were not vibrated, thus giving an improved interface between the aggregate and the hardened paste.

As mentioned earlier, compressive strength values for case II after 3, 7 and 28 days of curing are shown in Table 10 and Figs. 8 to 10, respectively. From Table 10 and Fig. 8, one can observe that the average values of the compressive strength of mixes MSCC1, MSCC2 and MSCC3 after 3 days are 33.47 MPa, 37.17 MPa and 35.85 MPa, respectively for case II; whereas the control mix has only 28.52 MPa. Mix 2 (i.e., MSCC2) shows maximum strength. Moreover, after 7 days of curing, there is a marked increase in the strength of samples of all mixes as can be observed from Fig. 9. The strength values of MSCC1, MSCC2 and MSCC3 are 39.59 MPa, 43.28 MPa and 41.25 MPa, respectively. The strength of the control mix is 38.27 MPa and is still far less than the strengths of samples of all other mixes. After 28 days of curing, strength values of samples of mixes MSCC1, MSCC2 and MSCC3 are found to be 44.28 MPa, 48.60 MPa, and 47.03 MPa, respectively (Fig. 10) with an increase of 11.84%, 12.29% and 14.01%, respectively over 7 day strength, whereas the increase in strength of the control mix is 21.27%. The strength values of MSCC2 and MSCC3 are found to be greater than for the other mixes. As both mixes MSCC2 and MSCC3 contain VMA, this shows that the presence of VMA enhances the strength of self-compacting concrete. Sample 1 (MSCC1) has the minimum compressive strength as compared to the other three samples of concrete. The compressive strength of control mix was found to be smaller than for the two samples containing VMA. This may be due to the fact that SCC samples were not vibrated, thus giving an improved interface between the aggregate and the hardened paste.

Thus, we can conclude that the presence of viscosity modifying admixture increases the strength considerably during the first few days of curing. Later on, its effect goes on decreasing. After 28 days of curing, the increase in the compressive strength due to VMA is considerably small.

From Tables 9 and 10, one can observe that mixes containing VMA have better compressive strengths as compared to other mixes. Infact, Mix 1 (SCC1) has the least strength. In both cases, we observed that the control mix has lesser compressive strength than SCC2 and SCC3. This may be due to the fact that SCC samples were not vibrated, thus giving an improved interface between the aggregate and the hardened paste. For both cases, sample 2 (i.e., SCC2) gives the better compressive strengths.

Modulus of Rupture

Modulus of rupture is a measure of flexural strength of concrete. In order to measure flexural strength or modulus of rupture of SCC mixes, 3 beams of size (100 x 100 x 500) mm of the four mixes were cast. As mentioned earlier, self-compacting concrete mixes were cast without vibration, whereas the control mix (Mix 4) was cast with vibration. In this case also, two different cases were considered. The beams were tested after 28 days of curing using the test set-up shown in Fig. 11, and the results are shown in Tables 11 and 12, respectively for the two cases. The results are plotted in Figs. 12 and 13 for case I and case II, respectively.

From Tables 11 and 12, one can observe that mixes containing VMA have better flexural strengths as compared to other mixes. This may be due to the fact that SCC samples were not vibrated, thus giving an improved interface between the aggregate and the hardened paste. For both cases, sample 3 (i.e., SCC3 and MSSC3) gives greater flexural strengths. In the study, we also observed that controlled concrete has greater flexural strength than mix I which is without VMA.

It is worth to mention that VMA is added to modify only the fresh properties of concrete, and ideally it should not have any significant influence on hardened properties of concrete. But, in our study, in general, we observed that mix 2 gives better fresh and hardened properties of self-compacting concrete. This may be due to the fact that in the fresh stage, VMA made the mix more stable compared to other mixes, therefore, hardened strength of VMA added mix was better than for other mixes prepared without VMA.

Further studies are needed to confirm that VMA not only enhances the fresh properties of self-compacting concrete but also gives better hardened properties of self-compacting concrete.

CONCLUSIONS

The following conclusions may be drawn from the results of the present study:

- The SCC is as reliable as conventional concrete for its use in Bahrain, provided that it satisfies all the basic requirements of SCC in fresh stage and maintains a minimum slump flow of 600 mm.
- The magnitude of fluidity has little influence on compressive strength of self-compacting concrete, provided that SCC mix satisfies the basic requirements of flowing ability, passing ability, stability and segregation resistance in fresh stage.
- The locally available Viscosity Modifying Admixture (VMA) has a substantial influence on the fresh properties of SCC. A small change in VMA dose makes a substantial change in SCC properties; i.e., flowing ability, passing ability, stability and segregation resistance.
- The test methods chosen; i.e., Slump flow, T50, V-funnel, J-ring and L-box were sufficient to ascertain all the essential attributes of SCC; i.e., filling ability, passing ability and stability (segregation resistance).
- The dosage of VMA should be properly designed as it may change the basic criterion of SCC. In other words, the flowability may fall below 500 mm slump if the dosage of VMA is more than desired.
- The compressive strength and flexural strength (hardened properties) of SCC are found to better than for normal concrete in the present study.
- Fly ash substitution generally results in favorable outcomes and is highly recommended for all SCC mixes.

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