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Durability characteristics of ultra-high-strength fiber-reinforced self-compacting concrete

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ABSTRACT: Locally available materials in the Gulf region were investigated to produce UHS-SCC. The inclusion of steel fibers with different volume fractions is investigated to produce UHS-FR-SCC. Different mechanical properties are evaluated (compressive strength and splitting tensile strength). The effect of including different steel fiber volume fractions (V_f) on durability characteristics of UHS-FR-SCC were evaluated by the measurement of chloride permeability, bulk chloride diffusion, electrical resistivity and reduction in compressive strength after exposure to high-sulfate high-temperature environment (i.e. resembling Gulf environment). Test results indicate that local material can produce UHS-SCC. The ductility of the concrete is greatly improved by the incorporation of steel fibers and increases as the fiber volume increases. The chloride permeability, bulk chloride diffusion and electrical resistivity were found to be greatly affected by the volume fraction of steel fibers. Insignificant effect was noticed in the reduction in compressive strength after exposure to aggressive sulfate environment.

1 INTRODUCTION

Construction of high-rise buildings and mega projects around the world, and the increasing demands of owners and designers led to growing need on high-strength concrete (HSC). The definition of HSC has changed over the years and with no doubt will continue to change. Progress in concrete materials science and technology during the last 30 years has far exceeded what has been achieved during the previous 150 years (Graybeal 2006). Ultra-high-strength concrete (UHSC) is a new class of concrete that has been the result of such development. This new type of concrete is characterized with very high compressive strength; > than 100MPa using normal moist curing, and > 150MPa for steam or autoclave curing.

Even though UHSC features high compressive strength, it is characterized by its very brittle failure mode and therefore a limited post-crack behavior. UHSC fails explosively without any omen (Bencardino et al. 2008). By the addition of fibers the load-displacement behavior and consequently the ductility and fracture toughness can be improved (Graybeal 2007, Sivakumar and Santhanam 2007 and Köksal et al. 2008). This can be traced back to the fact, that the fibers are able to transfer loads/stresses by bridging cracks. The use of fibers to produce ultra-high-strength fiber-reinforced concrete (UHS-FRC) will enable the structures to have innovative features and open new areas for the application of UHSC.

Mixture proportioning of UHSC mixtures is more critical than that of normal strength concrete (NSC) since, usually, specially selected pozzolanic and chemical admixtures are employed, and a low water-to-binder ratio (*w/b*) is considered essential. Optimum mixture proportions could be obtained after a greater number of trial batches than needed for NSC (Sobolev 2004). There is no single method for proportioning UHSC, and this led to different approaches (Sobolev 2004). Inclusion of steel fibers with UHSC mixtures is more critical than its inclusion in NSC, especially with the very low water-to-binder ratio (*w/b*) of UHSC which is considered essential. Steel fibers will have a great negative impact on the workability of UHSC which will need to increase the water-to-binder (*w/b*) ratio to maintain the workability, thereafter, reducing the concrete strength. The development and use of self-compacting concrete (SCC) has opened the opportunity for resolving the workability issue. The applicability of steel fibers with self-compacting concrete has been investigated and has proven to be feasible (Torrijs et al. 2008 and El-Dieb and Reda Taha 2012).

Ultra-high-strength fiber-reinforced self-compacting concrete (UHS-FR-SCC) seems to be a promising material for special applications and structures. But this would not be achieved without studying its performance before being widely adopted in construction (Graybeal 2006).

2 RESEARCH OBJECTIVES

The main objectives of this study is to investigate producing UHSC with self-compacting characteristics using locally available materials in the gulf region and investigate the effect of variation mixture parameters on the compressive strength. The effect of incorporating steel fibers on the mechanical properties (compressive and splitting tensile strength) and durability characteristics of the concrete was evaluated. Durability performance was assessed by measuring chloride permeability, bulk chloride diffusion, electrical resistivity and resistance to high-sulfate high-temperature exposure.

3 MATERIALS AND TESTING

3.1 Materials

Locally available materials in the gulf region for making ultra-high-strength concrete with self-compacting characteristics were investigated. Also, the effect of incorporating different dosages (i.e. fiber volume) of steel fibers on the mechanical properties and durability characteristics of UHS-FR-SCC is investigated.

Portland cement which conforms to (ASTM Type I) and (BS EN 197 CEM I) was used. Silica fume was used as mineral additive with specific gravity of 2.2, and a specific surface area of 152000cm2/g (according to manufacturer data sheet). Natural crushed stone from Ras Al Khaimah was used as coarse aggregate with nominal size of 10 mm (3/8 inch), a specific gravity of 2.65, and absorption % of 1.3%. Coarse aggregate was washed and left to be air dried (i.e. air temperature 25 to 30^{o}C and R.H. 50 to 60%) to reach saturated surface dry condition before being used. Two types of sand were used; crushed natural stone sand from Ras Al Khaimah with fineness modulus of 3.9 and specific gravity of 2.63, and dune sand from Al Ain area with fineness modulus of 0.88 and specific gravity of 2.63. A modified polycarboxylic ether superplasticizer is used in the study (GLENIUM SKY 504®); it complies with ASTM C 494 Types F and G, and ASTM C1017 Types I and II. The admixture is light-brown in color, with a specific gravity of 1.1, pH value 5-8 and alkali content as Na_2O equivalent of 0.26% (according to manufacturer data sheet).

One type of steel fibers is used in the investigation; (HELIX 5-25®). The fibers are twisted with a triangular cross sectional shape, with an average cross sectional dimension of 0.5mm and average length of 50mm. The aspect ratio of the fibers (L/d) is 50. The specific gravity is 7.9 according to the manufacturer data sheet. The steel fibers are zinc galvanized wires with silver color. The recommended dosages of the fiber volume (V_f) according to the manufacturer are 0.08%, 0.12% and 0.52%.

The effect of variation of different mix proportions on the strength of the concrete is investigated in order to optimize and finalize the UHSC-SCC mix proportions. The UHSC-SCC reference mix proportions are then used to investigate the effect of incorporating various volume fractions of the steel fibers on the mechanical properties and durability of the concrete mix. Three volume fractions (V_f) of the steel fibers are used in the study (0.08%, 0.12%, and 0.52%) as per the recommendation of the manufacturer data sheet.

Slump flow test was used to judge the flowability characteristics of fresh concrete mixtures. The admixture dosage is adjusted for the control mix (i.e. no fibers) in order to have a slump flow higher than the minimum value of 600mm required for self-compacted concrete (SCC) (EFNARC 2005 and ACI-237R-07 2008). The admixture dosage was kept constant in order to evaluate the effect of including steel fibers with different dosages on the slump flow of the mix.

Compressive strength was evaluated using cubes with dimensions of 100x100x100mm. Cylinders with 150mm diameter and 300mm height were used to measure split tensile strength. Strength tests were conducted at different test ages; 28 – 56 – 91 days of age. All experiments were performed on three specimen replicates. The average values are used in the discussion of the test results. The coefficient of variation (COV) for the compressive strength results ranged from 3 to 6 %, and for split tensile strength ranged from 4 to 7%.

Durability performance was evaluated using several tests. Rapid chloride permeability test (ASTM C1202), concrete electrical resistivity and chloride bulk diffusion test are used to evaluate the concrete durability against reinforcement corrosion and chloride attack and chloride induced corrosion. All tests are conducted at different test ages; 28 – 56 – 91 days of age. All experiments were performed on three specimen replicates. The average values are used in the discussion of the test results. The COV for all tests was below 8%. The exposure of concrete to high-sulfate solution (5% by mass) and high-temperature (50^{o}C) was used to evaluate the concrete durability in aggressive sulfate environment which resembles the Gulf environment. In this test concrete cubes were exposed to the sulfate solution after 28 days of age. The compressive strength after exposure for different time intervals was measured (i.e. 3, 6, 9, and 12 months). The compressive strength was compared to the 28 days strength value.

4 RESULTS AND DISCUSIONS

4.1 Mixture proportions

Concrete mixtures with varying mix proportions were examined to evaluate the effect on the concrete compressive strength. Table 1 gives the main mix composition variations and the 28 and 91 days compressive strength for five mixes. From the results it could be seen that Mix III yielded the highest compressive strength to be considered as UHSC (i.e. ≥ 100MPa at 28 days). This mix was used in studying as the reference mix to investigate the effect of incorporating steel fibers on the mechanical properties and durability characteristics.

The inclusion of steel fibers reduced the slump flow of the concrete mixes. The slump flow values remained well above the minimum required value for SCC (EFNARC 2005 and ACI-237R-07 2008). Table 2 shows the slump flow values for different fibers volume fraction (V_f). A reduction of about 12% was observed with the highest steel fiber dosage (0.52%). Admixture dosage could be adjusted if the slump value is required to remain unaffected.

Table 1. Different mixture proportions and its compressive strength

Mix Composition	I	II	III	IV	V
Total Cementing Materials (kg/m^3)	775	775	900	900	900
Silica Fume %	15%	15%	17.5%	17.5%	17.5%
Water/Binder Ratio	0.23	0.23	0.23	0.24	0.24
Water/cement Ratio	0.27	0.27	0.27	0.28	0.28
Fine Aggregate %	45%	60%	60%	50%	100%
Coarse sand %	76%	100%	70%	70%	70%
Dune Sand %	24%	0%	30%	30%	30%
Coarse Aggregate %	55%	40%	40%	50%	0%
28 days Compressive Strength (MPa)	88	92	110	95	85
91 days Compressive Strength (MPa)	105	110	135	115	100

Table 2 – Effect of steel fiber volume fraction (V_f) on slump flow value

V_f (%)	0	0.08	0.12	0.52
Slump Flow (mm)	780	730	710	690

4.2 Compressive and tensile strength

Compressive and splitting tensile strength results with age for mixes with different steel fiber volume fractions and the effect of steel fibers are given in Table 3. The compressive and splitting tensile strength increases with age for all mixes and with the increase of fiber content. The increase in compressive strength differs for different fiber volume content and also differs with test age. For low V_f (0.08%) the increase in strength ranged from 12% to 13% at 28 days and 91 days of age respectively. While for high V_f (0.52%), the increase in strength ranged from 23% to 32% at 28 days and 91 days of age respectively. The most important observation during testing is the significant change of the failure mode of the concrete as the steel fiber are included in the mix and also as the steel fiber volume fraction (V_f) increases. The failure mode changes from sudden explosive failure resulting in complete damage of the specimen into a more ductile failure in which the specimen is still intact even after failure; Figure 1 shows the cube specimens for the different mixes after failure. It could be noticed that as the fiber volume fraction increases the specimens are more intact. This is due to the strong bond between fibers and the concrete which was observed in the microstructure of the concrete (El-Dieb 2009).

The split tensile strength is significantly increased as (V_f) increases. This describes the ductile failure mode observed in compression test for higher (V_f). The ratio between splitting tensile strength and compressive strength expressed as percentage at any age increases as fiber volume fraction (V_f) increases, as shown in Figure 2. The tensile strength results of the concrete without fibers is very low and not improved similar to the improvement achieved in the compressive strength which explains the brittle failure of the concrete. Also, it is observed that the percentage of split tensile strength to compressive strength for UHSC with different fiber volume fractions (V_f) is lower than that of normal strength concrete.

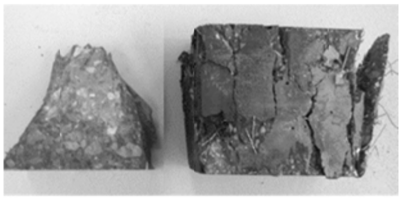

Figure 1. Cube specimens after failure in compression test for mixes with V_f = 0% and 0.52%.

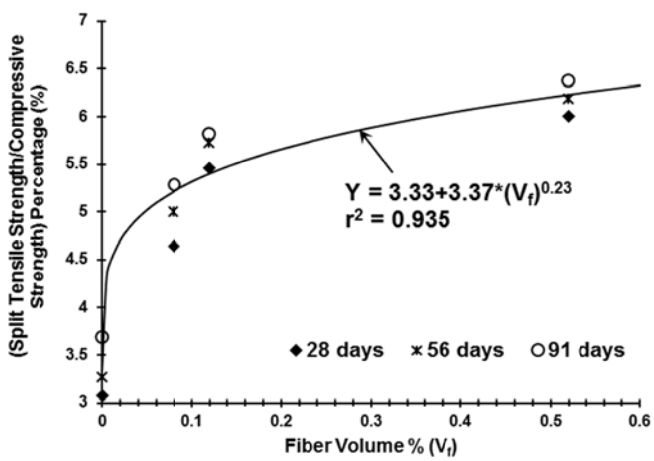

Figure 2. Effect of fiber volume fraction on splitting tensile strength/compressive strength percentage.

Table 3. Compressive and split tensile strength values

Age (days)	Compressive Strength (MPa)				Split Tensile Strength (MPa)			
	V_f=0%	0.08%	0.12%	0.52%	V_f=0%	0.08%	0.12%	0.52%
28	100	112	114	123	3.5	5.2	6.6	7.4
56	107	123	127	135	4.2	5.4	6.9	8.6
91	115	130	138	152	4.9	5.6	7.9	9.4

4.3 Durability

The concrete durability against chloride attack and chloride induced corrosion and protection of reinforcement against corrosion was assessed by measuring rapid chloride permeability test (RCPT), concrete electrical resistivity and chloride bulk diffusion. Table 4 shows the RCPT and electrical resistivity values at different ages and for different steel fiber volume fraction (V_f). It is observed that the total charge passing recorded in the RCPT increases and the electrical resistivity decreases as the fiber volume fraction (V_f) increases at all ages. This could be attributed to the fact that the tests are based on measuring the intensity of the electric current passing through the concrete and the inclusion of steel fibers with its high electrical conductivity contributes to the passing current resulting in an increase of the total charge passing and reduction in the electrical resistivity.

However, all measured RCPT values for the concrete mixture including steel fibers are classified as "very low permeability" according to ASTM C1202. Also, the resistivity values recorded for all mixes at all ages are very high (i.e. ≥ 20 kΩ.cm) which indicates very good protection to steel reinforcement against corrosion and low corrosion rate (ACI-222R-01 2008).

Table 4. RCPT and electrical resistivity values

Age (days)	RCPT (coulombs)				Electrical Resistivity (kΩ.cm)			
	V_f=0%	0.08%	0.12%	0.52%	V_f=0%	0.08%	0.12%	0.52%
28	118	232	480	572	111	87	53	46
56	88	163	253	313	115	93	72	58
91	83	146	167	243	115	97	78	62

Bulk diffusion values decreases with age for all mixes, as seen in Figure 3. It should be noted that the inclusion of fibers did not have significant effect on the bulk diffusion values which is not the case for the results of RCPT and electrical resistivity tests. This could be attributed to the fact that chloride ions diffusion mainly depends on the microstructure of the cement paste rather than the inclusion of steel fibers. The cement paste in all mixes is almost the same (El-Dieb 2009); consequently, there is insignificant change in the bulk chloride diffusion among mixes with different fiber volume fractions (V_f). The difference in the bulk diffusion values ranges from 9% to 25%. Bulk diffusion values also shows high level of resistance to chloride ion diffusion and thus high durability in aggressive environments.

In high-sulfate high-temperature environment condition UHS-FR-SCC showed excellent resistance. Table 5 gives the average compressive strength for each mix at the different immersion periods and the 28 days strength (i.e. strength at time of immersion). Test results showed an increase in strength for early immersion period (3 months), this could be attributed to the high temperature which might have caused further reactions especially the pozzolanic one. The reduction in the strength up to 12 months immersion period for the different mixes is around 12% which indicates slight effect of the concrete by the exposure condition. Also, no significant effect is noticed for including different fiber volume fractions. Figure 4 shows the reduction in compressive strength after immersion in sulfate solution for different mixes.

5 CONCLUSIONS

The following are the main conclusions concluded from the study:

- Steel fibers are necessary in shifting the brittle failure mode of UHSC into a more ductile one. Split tensile strength is improved by incorporating steel fibers. The improvement increases as the fiber volume fraction (V_f) investigated in this study increases.

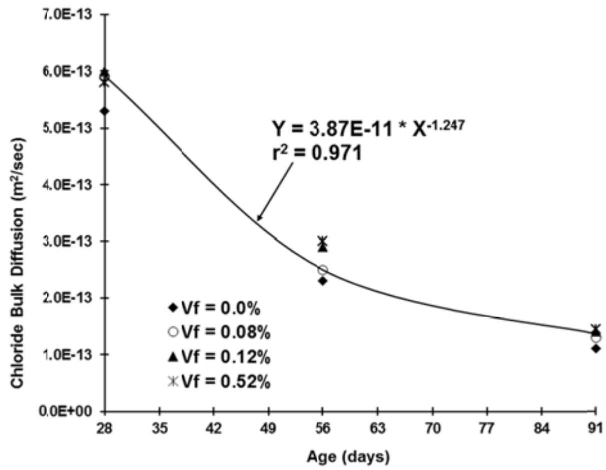

Figure 3. Bulk diffusion with age.

Table 5. Compressive strength after immersion in 5% sulfate solution at 50°C

		Average Compressive Strength (MPa)			
		V_f = 0%	0.08%	0.12%	0.52%
28 days Strength		100	112	114	123
Immersion Period (months)	3	107	120	122	132
	6	101	113	114	125
	9	93.5	104	106	115
	12	88	99	100	109

- Total charge passing in RCPT increases and electrical resistivity decreases as steel fiber fraction (V_f) increases. The change depends on the fiber volume fraction (V_f). Measured total charge passing indicates very low chloride permeability and electrical resistivity values indicate very good protection to steel reinforcement against corrosion.
- Bulk chloride diffusion was not affected by the inclusion of steel fibers.
- Bulk diffusion test is more reliable in evaluating durability characteristics for concretes that includes steel fibers as it mainly depends on the diffusion through microstructure rather than electrical conductivity.
- UHS-FR-SCC exhibits excellent resistance to high sulfate and high temperature exposure condition, the inclusion of steel fibers did not have any significant effect and all mixes have comparable reduction in the strength after exposure.
- Durability characteristics for concretes including steel fibers should be evaluated using test procedures that does not depend on measuring electrical conductivity rather use test procedures that depends on flow/diffusion mechanisms.

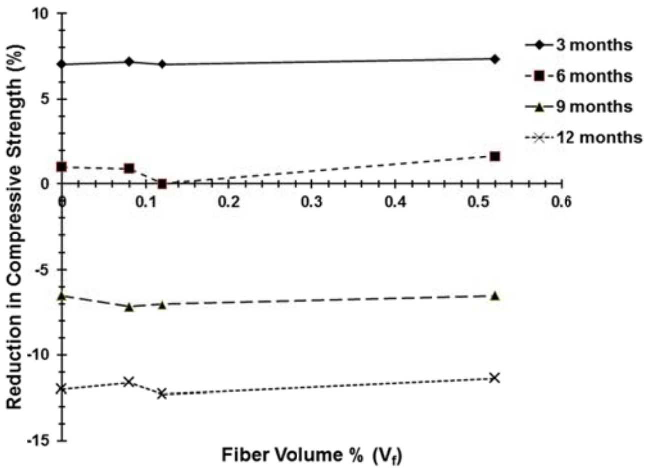

Figure 4. Reduction in compressive strength after immersion in 5% sulfate solution at 50°C.

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