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Original Research Paper

Assessment of Microstructural and Mechanical Properties of Hybrid Fibrous Self-Consolidating Concretes Using Ingredients of Plastic Wastes

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ABSTRACT

This paper focuses on the experimental investigation carried out on self-consolidating concrete (SCC) reinforced with micro-steel fibre and hybrid fibres (combination of micro-steel fibre and recycled high density polyethylene fibre derived from municipal wastes). The physical properties of fresh and hardened concrete including flowability, setting time and durability, the mechanical properties, namely, compressive strength and flexural strength, and microstructural analysis were studied. Micro-steel fibre addition was seen to enhance the flowability of concrete than the non-fibrous and hybrid fibre reinforced concretes. The setting time of SCC mixtures prolonged with the addition of fibres into concrete mixtures. Hybrid fibre reinforced SCC mixtures have displayed reduction in drying shrinkage. The compressive and flexural strengths of the fibre reinforced concretes show a marginal reduction in strength when compared with the strength of unreinforced concrete. The results of the microstructure analysis clearly demonstrate that the hybrid fibres bond well with the cement matrix and stronger than the bonding between micro-steel fibres and cement matrix.

INTRODUCTION

Self-consolidating concrete (SCC), a special type of high performance concrete, is highly workable concrete that could be compacted under its own weight, and fill all voids without any segregation. It has been used since the early 1990's to speed up construction processes by reducing the reliance on equipment and manpower for placing and consolidating concretes (Bentur & Mindess 1990, Okamura & Ouchi 2003). The composition of SCC mixtures includes supplementary cementitious materials (SCM) and high-range water reducing agent (HRWR) to obtain filling, passing and segregation resistance ability as well as to improve strength and durability properties of SCC. Like ordinary concrete, its low tensile strength, strain resistance, low ductility and low energy absorption are the disadvantages of self-consolidating concrete. However, fibres can be added into such concrete mixtures in order to improve the above mentioned properties, and this type of composites are referred to as fibre-reinforced concrete (FRC). Presence of fibres helps to reduce the crack width and increases the ductility of the concrete (Banthia & Trottier 1995, Bentur & Mindess 1990). Previous studies showed that incorporation of short fibres in concretes help to reduce plastic shrinkage cracking and cracking due to restrained drying shrinkage during the service life of concrete (Wang et al. 2000, Alhozaimy & Shannag 2009, Grzybowski & Shah, 1990, Zhang & Li 2013).

Fibres used in FRC are generally categorized as metallic fibres, synthetic fibres and natural fibres. Among metallic fibres, steel fibre is the most commonly employed fibre type in most structural and non-structural applications (Mehta & Monteiro 2006, Li 2002, Ding & Kusterle 2000, Kim et al. 2011). While in terms of synthetic fibre inclusion, wide range of plastic fibres have been employed such as polypropylene (PP), polyethylene (PE), polyvinyl alcohol (PVA), polyvinyl chloride (PVC), nylon, aramid, and polyesters (Li et al. 2000, Zollo 1997, Zheng & Feldman 1995, Won et al. 2010, Wang et al. 1990, Siddique 2008, Silva et al. 2005). Although both virgin and recycled forms of these synthetic fibres are employed in FRC, reuse of plastic wastes as fibre has attracted more widespread attention in recent years to build sustainable solid waste management of these wastes and possibly supply secondary raw material for construction industry (Siddique et al. 2008, Siddique 2008, Alhozaimy & Shannag 2009, Auchey 1998, Foti 2013, Ghernouti et al. 2015, Meddah & Bencheikh 2009, Naaman et al. 1996, Wang et al. 2000). The effects of fibre type, fibre geometry (size and shape) and fibre concentration (volume content) are the most common properties of fibre reinforced concretes investigated in the literature.

Furthermore, it is well known that the increases in the world population and worldwide industrialization result in increasing solid waste amount. In response to this concern, development of effective municipal solid waste management strategies is highly desired. The potentially low price and high quality of recycled products from the solid wastes encourages the construction industry. In recent time, significant research tends to study the possible use of these wastes in cementitious materials and concrete (Siddique 2008, Yang et al. 2015, Rai et al. 2012, Safi et al. 2013, Al-Manaseer & Dalal 1997, Avila & Duarte 2003, Batayneh et al. 2007, Rebeiz & Craft 1995, Rossignolo & Agnesini 2004). From the point of view of developing sustainable and environmental friendly structures, some researchers have studied in the past on the combined strength and durability characteristics of concretes with some proportion of fly-ash particles (Wesche 1991, ACI 232.2, 2003, Ampadu & Torii 2002, Mehta 2002). It is generally captured from the chimneys of coal-fired power plants and also incineration, which is a waste treatment process that involves the combustion of organic substances contained in waste materials and produces fly ash just as in the case of coal combustion. Incineration of waste materials converts the waste into ash and they serve as useful ingredients in the construction industry.

In this study, the effect of fibre incorporation on SCC mixture including municipal solid waste incineration (MSWI) fly ash is studied in details by performing mechanical and physical tests on fresh and hardened concrete. Although the processing of plastic wastes could also result non-fibrous forms of materials such as polythelene particulates, the current work focuses on the application of fibrous plastic wastes in constructing self-consolidating concretes. Two different fibre types including micro steel fibre and hybrid micro steel-recycled polyethylene fibres were incorporated in SCC mixture. The behaviours of micro steel fibres and hybrid fibres in the SCC matrices were also characterized by microstructural studies.

MATERIALS AND METHODS

Materials: An ordinary Portland cement (corresponds to ASTM Type I and comply with CEM I 42.5R) and MSWI fly ash were used as the binder phase of SCC. In addition to these, silica fume was also added to SCC mixture design as a binding material as the chemical composition analysis of MSWI fly ash had earlier shown that it has extremely low silica (1.89%), alumina (0.784%) and iron-oxide (0.6010%) content. Total cementitious materials content and the replacement ratio of silica fume and fly ash were kept constant (10% by weight of Portland cement) in all designed mixtures. The physical properties and chemical analysis of cement, MSWI fly ash and silica fume are presented in Table 1. Sand (or fine aggregate) having specific gravity 2.73, unit weight of 1.45 kg/L and water absorption of 2.15%, and crushed limestone (or coarse aggregate) having specific gravity 3.095, unit weight of 1.93 kg/L and water absorption of 0.62% were procured from the Qatar Sand Treatment Plant and used as the aggregate. Mechanical properties of micro-steel fibres and recycled high density polyethylene (HDPE) fibres, collected from Doha Plastic Company using the municipal wastes of Qatar, are presented

Table 1: Chemical composition and physical properties of portland cement, fly ash and silica fume.

Chemical Composition	Portland Cement	Fly Ash*	Silica Fume
CaO (%)	64.95	45.0	1.05
SiO_2 (%)	21.92	1.89	89.5
Al_2O_3 (%)	4.32	0.784	0.32
Fe_2O_3 (%)	3.78	0.601	0.38
MgO (%)	2.16	0.552	0.1
SO_3 (%)	2.08	8.67	0.1
Alkalies (Na_2O + 0.658 K_2O) (%)	0.68	18.3	-
Loss on Ignition (%)	1.00	1.9	2.3
Insoluble Residue (%)	0.68	1.06	1.0
Physical Properties			
Specific Gravity	3.09	2.25	2.01
Blaine Fineness (cm^2/g)	3527	-	-
Mechanical Properties			
f_c', 2 days (kgf/cm^2)	218	-	-
f_c', 7 days (kgf/cm^2)	295	127	135
f_c', 28 days (kgf/cm^2)	410	186	-

f_c': Compressive Strength
*Obtained by incineration of Qatar municipal solid wastes

Table 2: Properties of the fibres used.

Fiber Type	Micro-Steel	Recycled High Density Polyethylene (HDPE)
Length (mm)	6	3.0 - 10.0
Diameter (μm)	160	100
Cross Sectional Area (mm^2)	0.02	0.0078
Load at Maximum Load (N)	-	74.34
Tensile Strength (MPa)	2.16	25.22
Elastic Modulus (MPa)	210	672.29
% Total Elongation at Fracture	-	152.4

Fig. 1: (a) Micro-steel fiber and (b) recycled HDPE fibers used in SCC mixtures.

Table 3: Mixture proportions of self-consolidating concrete.

			Cementitious Materials (kg/m^3)					Aggregate (kg/m^3)		Fibre (kg/m^3)	
Mix ID	Mix Design Label	w/b	Portland Cement	Fly Ash	Silica Fume	Water (kg/m^3)	SP (kg/m^3)	Fine	Coarse	Steel	r-HDPE
1	Control sample SF0	0.51	320	40	40	204	12	997.7	819.4	0	0
2	SF 2%	0.49	320	40	40	196	12	998.7	831.2	16.6	0
3	SF1% - r-HDPE1%	0.48	320	40	40	192	12	998.9	820.3	8.2	8.2

in Table 2. The straight cylindrical micro steel fibres with a brass coating had 6 mm length and 0.16 mm diameter, and the aspect ratio (L/d) was 40, while the thickness of recycled-HDPE fibre was 0.10 mm, and length of 3.00 mm to 10 mm (Fig. 1). In all concrete mixtures, a polycarboxylic-ether based superplasticizer with a specific gravity of 1.11±0.03 was used to obtain the desired workability, and kept constant for comparison. The amount of superplasticizer (SP) was about 3.5% by weight of cement for all concrete mixtures.

Mixture proportions: The proportions of the different concrete mixes used in this study are given in Table 3. As seen from this table, three concrete mixtures were prepared. The control mixture included only the Portland cement, MSWI fly ash and silica fume as a binder, and named as Mix 1-SF0 which means that there is no steel or polyethylene fibre. The micro steel fibre was used firstly as single and secondly as hybrid in combination of polyethylene fibres and micro steel fibres at the percentage of 50%-50% by weight. Therefore, the second mixture included 2% micro-steel fibre and Mix 3 was designed by including 1% steel fibre and 1% recycled HDPE fibre in order to compare the micro steel fibre and recycled HDPE fibre in SCC, and named as SF1%-R-HDPEF1%. Since the SCC characteristics such as slump flow diameter, V-funnel time were to be examined, water was gradually added to the mixtures and the water to binder ratios (w/b) were kept between 0.48-0.51.

Concrete casting and specimen preparation: The coarse aggregate, fine aggregate, cement, fly ash, silica fume and fibres were mixed to prepare fresh concrete in a concrete mixer for three mixes with steel fibres or hybrid fibres. The 3/4 of mixing water was mixed with the superplasticizer, and added to the mixer. Eventually, remaining water was gradually added into the mixture to provide uniformity in the mixture. After performing the fresh concrete tests, the concrete specimens were cast in cylindrical, prism and shrinkage bar molds. The dimensions of the concrete specimens and the details of the performed tests are presented in Table 4. The concrete specimens were demoulded after 24 hours, and immersed in a water tank until the age of testing for the mechanical properties.

Testing procedure: ***Physical properties of the fresh and hardened concrete:*** The setting time of fresh concrete was recorded using penetration resistance method based on ASTM C 403. The workability properties of SCC mixtures were evaluated through the measurement of slump flow time (T50) to reach a concrete 50 cm spread circle, slump flow diameter and V-funnel flow time according to the methods standardized by Specification and Guidelines for SCC prepared by EFNARC (2005). The results of fresh concrete tests are presented in Table 5. Furthermore, drying shrinkage of the bar specimens with the dimensions of 25×25×280 mm from each mixture was identified by measuring the change in length of the samples according to ASTM C 596 on immediately after demoulding, and 4, 11, 18, and 25 days of air drying by observing the average value of nine specimens per mix.

Mechanical testing: For each mixture, six cylinder specimens (100×200 mm) and six beam specimens (40×40×160 mm) were prepared for compressive and flexural strength tests, respectively. The compressive strength was performed according to the procedure defined in ASTM C 39 and determined at 7 and 28 days of curing by using average measure of three cylinders at each age. The flexural strength of the prism samples was determined according to ASTM C293 by the simple beam with center-point loading test at 7 and 28 days of age by using three prism specimens at each age.

Microstructure analysis: The microstructure of the steel fibre and recycled HDPE fibre, and that of hardened fibre reinforced concrete mixtures was studied by FEI Quanta 200 Environmental Scanning Electron Microscope (ESEM) equipped with an Energy Dispersive X-Ray analysis system (EDX). In this analysis, energy-dispersive x-ray spectrum (EDX) of SEM was used for quantitative chemical analysis

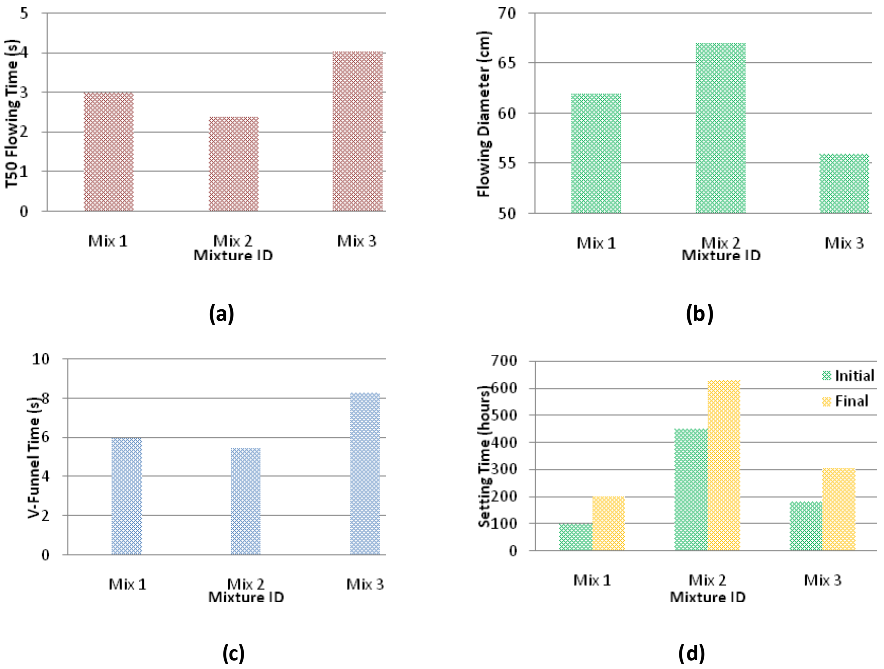


Fig. 2: Fresh state properties of SCC; (a) T50 flowing time, (b) Flowing diameter, (c) V-funnel time, (d) Setting time.

of hardened reinforced concrete samples. The samples for SEM analysis were prepared by firstly being dried and gold coated under vacuum. Investigations were carried out on secondary electron mode under 30 kV voltage.

RESULTS AND DISCUSSION

Physical properties of the fresh and hardened concrete: The physical properties of fresh concrete mixtures were evaluated by performing setting time and flowability tests including slump flow time and diameter, and V-funnel flow time. On the other hand, that of hardened concrete mixtures was evaluated by drying shrinkage test.

Table 5 and Fig. 2 show the flowability properties and average setting time of the mixtures tested. As it is presented in the table, the slump flow diameters of all mixtures were in the range of 56-67.0 cm, slump flow times were less than 5s and more than 2s, the V-funnel flow time was less than 9s and more than 5.47s, and the initial and final setting times of self-consolidating concrete (SCC) ranged from 1:00 to 4:50 h:min., and from 2:00 to 6:30 h:min., respectively. During the mixing procedure, it was observed that the fibre distribution was uniform, and all concrete mixtures filled the molds by their own weight without the need for any additional vibration. Hence the concrete mixtures resulted self-consolidating concretes. As seen from Fig. 2, addition of fibres significantly altered the fresh properties of SCC mixtures. The flow diameter has slightly increased with steel fibre addition and its flowing time has decreased. However, recycled polymer fibre addition increased the flowing time and decreased the flow diameter. This finding is in agreement with findings of Tarun et al. (2013) and Widodo (2012) which showed that the polypropylene fibre inclusion reduce the fluidity and passing ability of SCC in contrast to steel fibre inclusion. Recycled PE fibre has relatively larger dimension compared to 6 mm long steel fibre, therefore prevention of aggregate movement by recycled PE fibre was more likely. Furthermore due to having larger dimensions, recycled PE fibre may block the particles flow which was clearly evident from the V-funnel test results. Although the flowing time and diameter varied with the addition of different fibre types, the flowability values were still in the acceptable range established by EFNARC Specification and Guidelines for SCC. According to EFNARC (2005), a slump flow diameter ranging from 650-800 mm, T50 measurement varying between 2 and 6 seconds, and V-funnel time ranging from 6 to 12 seconds are considered as adequate for fabricating SCC. As micro-steel fibre addition resulted in a better flowability of concrete, it may be concluded that SCC reinforced with micro steel fibre was more workable than control mixture (Mix 1) and hybrid fibre reinforced concrete mixture (Mix 3). In addition, it is clearly seen that adding micro-steel fibre or recycled polyethylene fibre increases the setting time. Although, this result differs from

Table 4:Test methods and specimen size.

Test type	Specimen	Dimensions (mm)
Compression	Cylinder	100×200 (diameter × length)
Flexural	Beam	160×40×40
Drying Shrinkage	Bar	280×25×25

Table 5: Test results of fresh SCC.

	Slump flow			Setting Time	
	T50 Flowing time (s)	Flowing diameter (cm)	V-funnel time (s)	Initial min)	(Final (min)
Mix 1	3	62	6	100	200
Mix 2	2.39	67	5.47	450	630
Mix 3	4.03	56	8.32	180	306

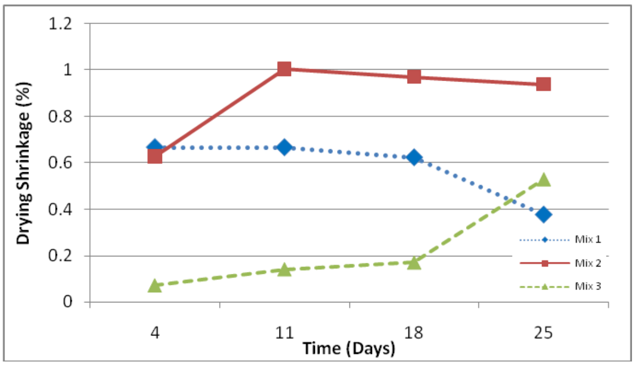


Fig. 3: Effect of fibre type on drying shrinkage.

one published study by Leung et al. (2012), it is consistent with other study performed by Richie et al. (1973) which reported that the setting time of fibre reinforced concrete could increase due to the cohesive nature of fibres, and as a result the internal resistance of fresh fibre reinforced concrete increased.

Fig. 3 represents the results of drying shrinkage test for each concrete mixture tested in the study. It can be noticed that all mixtures containing different fibre types show different shrinkage behaviour. Hybrid fibre reinforced self-consolidating concrete has the least shrinkage up to 18 days, which is almost 11% of control mixture, and then the drying shrinkage increased. Moreover, it can be observed from this figure that although the micro-steel fibre reinforced concrete has the highest shrinkage, after 11 days of casting, micro-steel fibre sample shows a decrease in the shrinkage.

Mechanical testing: The mechanical test results including compressive strength and flexural strength of fibre reinforced SCC mixtures are presented in Figs. 4 and 5, respectively.

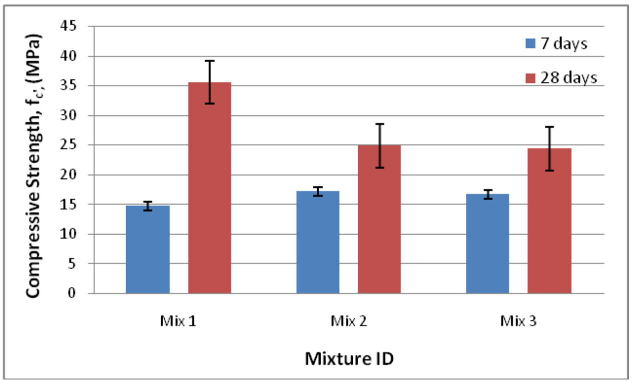


Fig. 4: The effect of fibre types on the compressive strength of SCC mixtures.

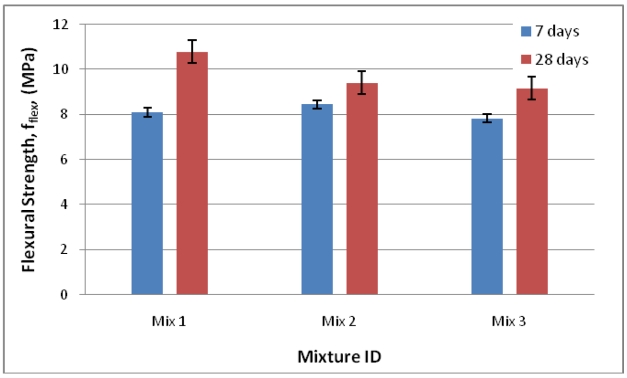
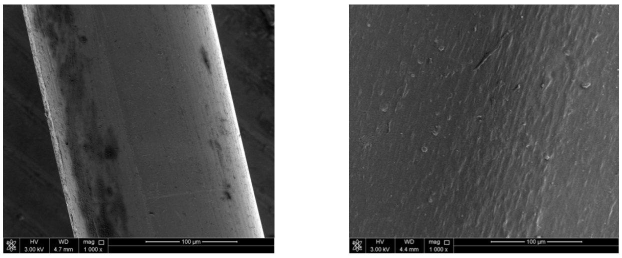


Fig. 5: The effect of fibre types on the flexural strength of SCC mixtures.



(a) (b)

Fig. 6(a): Micro image of micro-steel fiber (×1000), (b)Micro image of r-HDPE fiber (×1000).

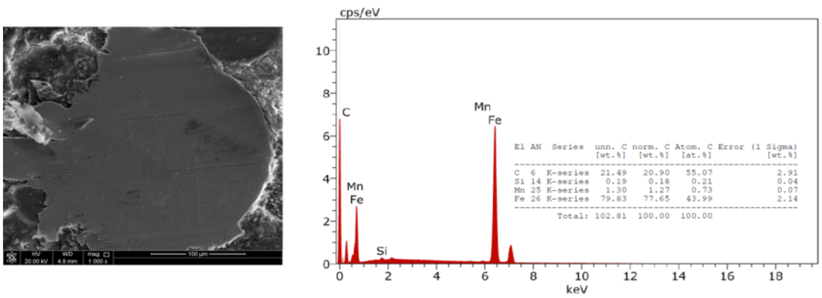
As seen in these figures, the compressive strength of the control mixture was lower than the fibre reinforced SCC mixtures at the early stage, 7 days, which indicates that fibre addition accelerated the hydration and consequently improved the early age compressive strength in fibre reinforced mixtures. However, at 28 days, the control mixture has gained more strength than fibre reinforced mixtures which could be resulted from the low interfacial bond strength of fibre in the composite mixtures. The level of accuracy is shown in the figures by the error bars ranged between 1.2% and 2.6%. The flexural strength test results incorporate the findings of compressive strength test results, i.e. at 28 days, control mixture has the highest flexural strength, although no significant difference was observed at 7 day flexural strength test results of the mixtures which also seems to be consistent with other studies (Bayasi & Zeng 1993, Santos et al. 2005, Suji et al. 2007, Hamedanimojarrad et al. 2011, Sivakumar & Santhanam 2007). The estimated error ranged between 1.80% and 11.72%. The possible reason of this behaviour can be explained by the weaker bonding between fibres and cement matrix at early ages, any local non-homogeneities in the mixes, and the high water content. Furthermore, the addition of fibre to cement matrix increases the porosity of the mixtures which could explain the reduction in flexural strength of fibre reinforced mixtures due to weakened bond strength of fibres. Interestingly, the strength measures of polymeric fibre reinforced concrete (Mix 3), though marginally less, is reasonably comparable to that of steel fibre reinforced concrete (Mix 2).

Microstructure analysis: In order to understand the surface roughness differences between fibres, SEM images were captured at the same magnification and presented in Fig. 6. Surface texture of steel fibre was observed as generally smooth while that of recycled polyethylene was relatively rough. Rough surface texture of recycled polyethylene fibre may increase energy loss during the movement of particles and eventually resulted in workability loss in hybrid fibre reinforced mixture (Mix 3). As seen from the fresh properties, it can be concluded that the geometry of fibres is the influencing factor on the flowability which is consistent with those reported by other researchers (Akcay et al. 2012, Felekoglu et al. 2009).

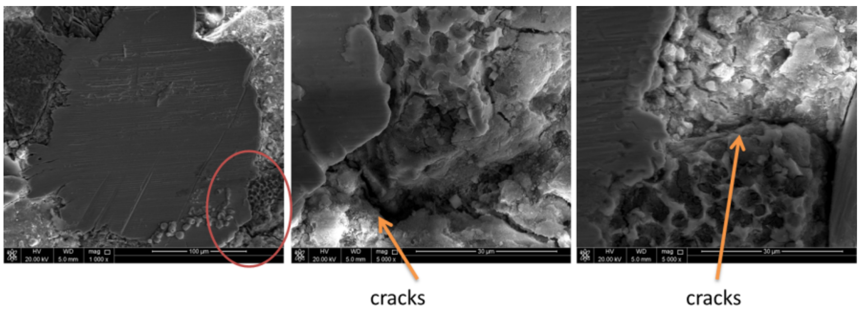
In order to clarify the effect of fibres in composite mechanism, the microstructure of the micro-steel fibre and cement paste and that of hybrid fibre and cement paste were also examined using SEM analyser and represented in Figs. 7 and 8, respectively. Although the bonding between micro-steel fibre and cement paste seems not strong, it was observed that micro-steel fibre prevents the development of micro-cracking through the cement paste as seen in Fig. 7b. On the other hand, the hybrid fibres appear to remain intact with the cement matrix and seem stronger than the bonding between micro-steel fibres and cement matrix.

CONCLUSION

The results of this paper are based on laboratory experiments with three different self-consolidating concrete mixtures reinforced with micro-steel fibre and hybrid fibre including micro-steel fibre and recycled HDPE fibres. Addition of micro-steel fibre has demonstrated better flowability



(a) SEM-EDX of micro-steel fiber



(b) Micro-cracks in interfacial transition zone

Fig. 7: Scanning electron microscope images of micro-steel fibers in SCC mixtures (Mix 2).

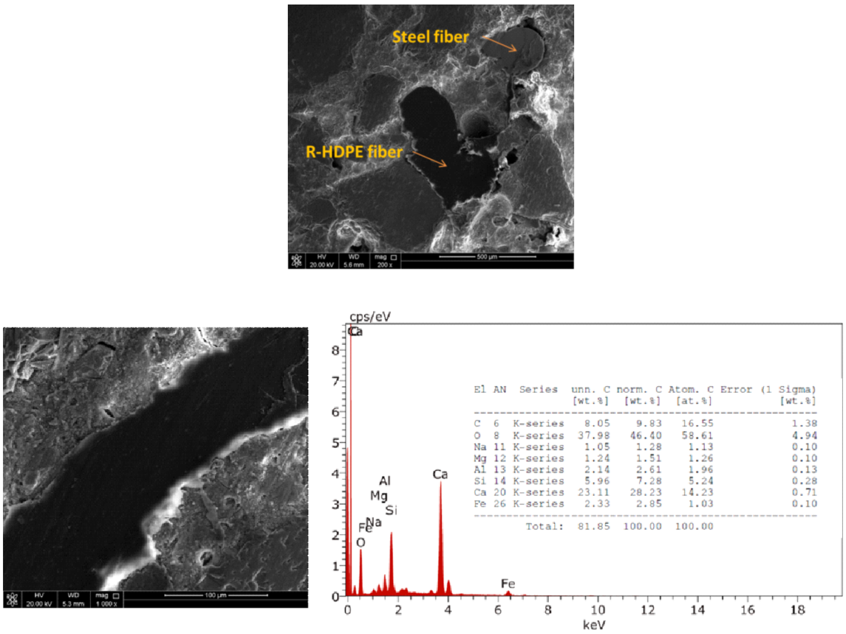


Fig. 8: Scanning electron microscope images of hybrid fibers in SCC mixtures (Mix 3).

than control mixture and hybrid fibre reinforced addition. It can be concluded from the microstructure analysis of fibres that; rough surface texture of recycled polyethylene fibre may increase energy loss during the movement of and eventually resulted in the workability loss in hybrid fibre reinforced mixture. As it is expected, the setting time of SCC mixtures was observed to be prolonged with the addition of fibres into concrete mixtures. Hybrid fibre reinforced SCC mixtures have displayed reduction in drying shrinkage. Results also indicated that micro-steel fibre or hybrid fibre inclusion to concrete mixture resulted in a reduction in 28-day compressive and flexural strength. This phenomenon might be due to the weaker bonding between fibres and cement matrix at early ages. Interestingly, the study shows that the compressive and flexural strength characteristics of steel fibre reinforced and polymeric fibre reinforced concretes are quite comparable. Further studies are required for understanding aging effects of concrete samples for durations greater than 28 days.

The results of the microstructure analysis clearly demonstrate that the hybrid fibres appear to remain intact with the cement matrix and seem stronger than the bonding between micro-steel fibres and cement matrix.

Further work to study on the effect of hybrid fibres on the durability and permeability properties of SCC mixtures is in progress. The results of findings will be reported in the future publications. Further studies could account for different hybrid fibre reinforced SCC mixtures.

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