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Abrasion Properties of Steel Fiber Reinforced Silica Fume Concrete According to Los Angeles and Water Abrasion Tests

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The current study mainly investigated the influence of different tests on the abrasion resistance of concrete mixed with steel fibers and silica fume. The abrasion resistance was assessed at 28, 56 and 91 days on concretes with water-binder ratios of 0.35 and 0.55 where in some mixes silica fume was substituted by 5 % of cement by weight. Steel fibers of 0.5 % and 1.0 % of concrete volume were also added into the test concrete by replacement of coarse and fine aggregates. The results showed that concrete with higher compressive strength in Los Angeles abrasion tests also had better abrasion resistance. The inclusion of steel fibers into test concrete with a water-binder ratio of 0.35 resulted in a significant increase in compressive strength. This concrete also displayed better abrasion resistance and splitting tensile strength than reference concrete; in the test sample with a water-binder ratio of 0.55, the added steel fibers was unable to effectively produce cementation with the concrete. The inclusion of silica fume improved the abrasion resistance of concretes. In water abrasion testing, the abrasion resistance of concrete containing steel fiber was worse than that of concrete without steel fibers. In the water abrasion testing, the surface of steel fiber reinforced concrete was eroded by water and steel balls, and the impact caused the steel fibers to separate from the concrete and led to higher wear loss.
Keywords: abrasion, steel fiber, silica fume, concrete.

1. INTRODUCTION

Concrete is a porous material, which is widely used in construction. Concrete is susceptible to deterioration as a result of abrasion in various environments. The deterioration of concrete due to abrasion occurs progressively, particularly when reinforced concrete structures are in contact with water and sand over longer period of ages [1]. This kind of abrasion occurs as a result of solid particle scraping, rolling, and sliding across the surface. Low durability cement-based composites or concrete has greater permeability or diffusivity, which allows aggressive agents to enter, resulting in a weakening of the matrix [2]. However, the steel fibers can improve the flexural ductility, toughness, split tensile strength, and durability of concrete [3 – 4]. Fiber reinforced composites are defined as composites incorporating relatively short, discrete, discontinuous fibers. Those fibers have been used in cementitious materials since 1960. The steel fiber filling the pores of mortar to reduce micro-crack propagation is the main mechanism that improves the internal tensile strength [5 – 6]. When added to cementitious composites, silica fume produce a strongly pozzolanic reaction with calcium hydroxide resulting in the production of additional calcium hydrate. The pozzolanic phenomenon results in a denser pore structures which would increase the compressive strength, tensile strength, and durability by decreasing the permeability [7 – 8]. The cementitious composites containing fly ash (class C) possessed superior abrasion resistance compared to either ordinary Portland cement composites or composites containing fly ash (class F) [9 – 11] The abrasion resistance of concrete containing silica fume as a cement replacement was better with increasing amounts of silica fume to 10 % [12 – 13]. The resistance to wear of cementitious composites having cement replacement by fly ash up to 30 % was equivalent to the control specimens without fly ash, but beyond 30 % , fly ash composites indicated slightly lower abrasion resistance relative to reference specimens [14 – 15]. This study investigated abrasion resistance of concretes with silica fume and steel fibers by different abrasion tests. This study also presents a series of laboratory tests on the specimens containing various amounts of silica fume and steel fibers. This study reports the compressive strength, splitting tensile strength, and abrasion resistance of the tested concretes. Two water/binder ratios (0.35 and 0.55) were selected in this study. The influence of steel fibers and silica fume on the deterioration of cementitious materials are investigated through Los Angeles abrasion testing [16] and water abrasion tests.

2. EXPERIMENTAL DETAILS

2.1. Materials and mix proportion

Type I Portland cement conforming to the ASTM code no. 150 was used in all mixes. Silica fume with a specific gravity of 2.20 and a surface area of 22500 m^2/kg was used. A diameter of silica fume particle was about 0.10 μm to 0.20 μm according to previous study [17]. Cement was partially replaced with 5 % silica fume. The chemical compositions of cement and silica fume are shown in Table 1. The maximum size of calcareous coarse aggregate was 12.5 mm and the fineness modulus (FM) of calcareous fine aggregate was 2.86. The water/binder ratio (w/b) of 0.35 and 0.55 was selected and the mix proportion for

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Table 1. Composition and specific gravity of Portland cement and silica fume

Chemical composition (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	L.O.I	K_2O+Na_2O (eq.)	others
Portland cement	21.3	5.3	3.3	63.7	2.2	2.0	0.8	0.9	0.5
Silica fume	91.6	0.3	0.8	0.5	1.2	0.4	1.6	1.8	1.8

Table 2. Mix design (kg/m^3)

Mix no.	w/b	Water	Cement	Silica fume	FG*	CG**	Fiber	SP***
A	0.35	189	558	0	908	700	0	6
AF05	0.35	189	558	0	901	694	39	6
AF10	0.35	189	558	0	894	687	78	6
AS5	0.35	189	530	28	908	700	0	6
AS5F05	0.35	189	530	28	901	694	39	6
AS5F10	0.35	189	530	28	894	687	78	6
B	0.55	217	395	0	908	780	0	–
BF05	0.55	217	395	0	901	773	39	–
BF10	0.55	217	395	0	894	767	78	–
BS5	0.55	217	375	20	908	780	0	–
BS5F05	0.55	217	375	20	901	773	39	–
BSF10	0.55	217	375	20	894	767	78	–

* fine aggregate; ** coarse aggregate; *** superplasticizer.

concrete specimens is given in Table 2. The notations used to identify mix no. are constructed as follows: "A" and "B" represents the w/b of 0.35 and 0.55; "S5" represents the replacement of silica fume at 5 %; "F" represents the steel fibers; and "05" and "10" represents the volume fractions of steel fibers at 0.5 % and 1.0 %. Mixture slump was maintained at around 140 mm ±10 mm by using a high range water reducing admixture. Steel fibers used were hooked-end fiber with an aspect ratio (*l*/*d*) of 65. The length of steel fibers was 35 mm and tensile strength of steel fibers was 1100 N/mm^2. Three volume fractions (V_f = 0, 0.5 and 1.0) were selected for each mix.

2.2 Test methods

A total of twelve different mixes were cast. For each mix, twenty-one Ø 100 mm × 200 mm cylindrical specimens were used to test compressive strength, splitting tensile strength, and Los Angeles abrasion testing; three Ø 300 mm × 100 mm circular discs were used for water abrasion test. The test using WAT was conducted following the ASTM code no. 1138 and a previous study [18]. All the specimens were cured in saturated lime-water until testing age of 28, 56 and 91 days. The testing apparatus comprised one agitation paddle, one drill press, and one cylindrical steel-container housing a disk shaped specimen made by concrete; and 65 various sizes grinding steel balls in this apparatus. The container filled with water was run circularly by one immersed agitation paddle which is powered by the drill press operating at 1190 rpm to 1210 rpm. The circulating water in turn operated the abrasive charges (grinding steel balls) transverse upon the concrete surface to realize attritions. The testing period of twenty-four hours was found to be sufficient to realize pronounced abrasions on most of the specimen surfaces. The abrasion testing used in this research comprised two twenty-four hours test periods, totalling forty-eight hours. Besides, the abrasive volume and the abrasive depth were seemed to be the indices in order to evaluate the abrasion resistance. The abrasive volume for a sample was calculated according to equation (1):

$$Vo_t = \frac{We_{air} - We_{water}}{G_w}, \tag{1}$$

where Vo_t is the abrasive volume, We_{air} is the weight for a sample in air, We_{water} is the weight for a sample in water and G_w is the unit weight of water.

The abrasive volume of concrete specimens were measured at 28, 56 and 91 days according to equation (2):

$$VL_t = V_i - V_t, \tag{2}$$

where VL_t is the abrasive volume of a concrete specimen in abrasion test and V_i is the original volume of a concrete specimen before test.

Los Angeles abrasion testing was conducted following the ASTM code no. 131, which is one kind of a modified-version testing for abrasion testing. The test apparatus comprised one steel cylinder and the concrete specimens were placed into the cylinder with 8 steel spheres. Following 500 sample rotations, the percentage of mass loss, which indicated the variation between the weight before abrasion and the weight after abrasion for a sample, was calculated and named as the abrasion index.

3. RESULTS AND DISCUSSION

3.1 Los Angeles abrasion test

The mass loss curves of steel fiber reinforced concrete by Los Angeles abrasion test are shown in Figures 1 and 2, respectively. The addition of steel fibers in composites results in an increase in the abrasion resistance of concrete and steel fiber reinforced cementitious composites with a lower water-binder ratio has better abrasion resistance. This improvement in abrasion resistance is proportional to the amount of steel fibers added. The abrasion resistance of steel fiber reinforced concrete with silica fume and at 28 and 56 days was better than all other test concretes, however the abrasion resistance of the concrete at 91 days was not substantially different except for AF05, AF10, AS5F05, AS5F10, BS5F05 and BS5F10 specimens as shown in Figures 1 and 2. The abrasion resistance of steel fiber reinforced cementitious composites without silica fume was not substantial at the early stage. This could be attributed to the relatively poor cementation of concrete with the steel fibers during the early stage, and this finding was more significant in concrete with higher water-binder ratio. While the abrasion resistance increased with gradual extension of curing time, the poor cementation of steel fibers to concrete with high water-binder ratio led to an abrasion resistance worse than that of reference concrete (mix no. B). In steel fiber reinforced silica fume concrete with low water-binder ratio, the test concrete denseness and cementation of steel fibers with concrete were enhanced after prolonged curing time, which resulted in a significantly increased abrasion resistance, as shown in Figures 1 and 2, respectively.

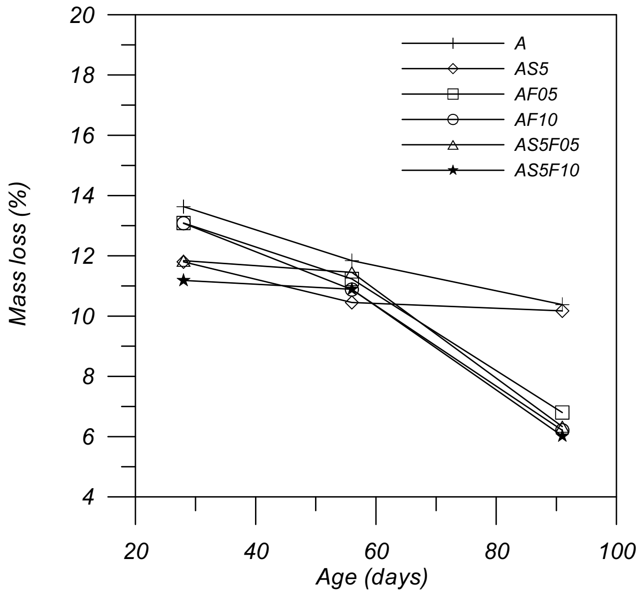

Fig. 1. Mass loss of steel fiber reinforced concrete by Los Angeles abrasion test(w/b = 0.35)

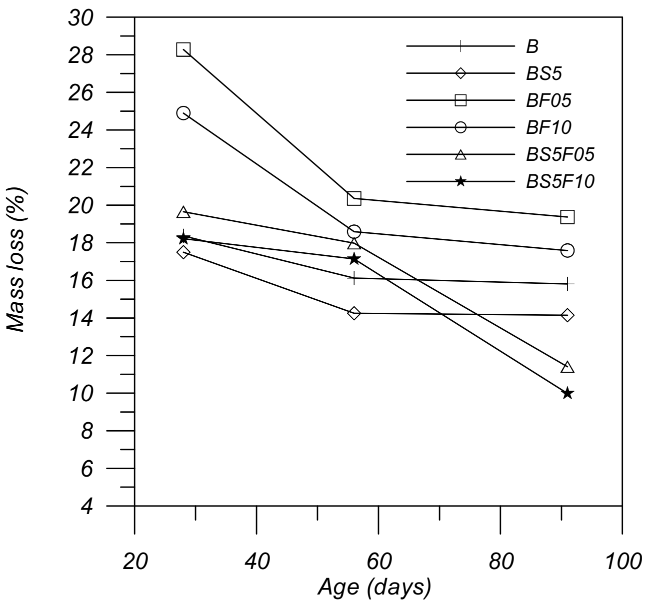

Fig. 2. Mass loss of steel fiber reinforced concrete by Los Angeles abrasion test (w/b = 0.55)

Using linear regression, good correlations ($R^2 = 0.830$) was found between the mass loss and the compressive strength as shown in Figure 3. The relationship between mass loss after 500 rotation cycles and compressive strength for the specimens having w/b ratios of 0.35 and 0.55 are shown in equation (3).

$$Y = -0.27x + 24.87\,, \quad (3)$$

where Y is the compressive strength (MPa) and x is mass loss (%) of specimens after 500 rotation cycles.

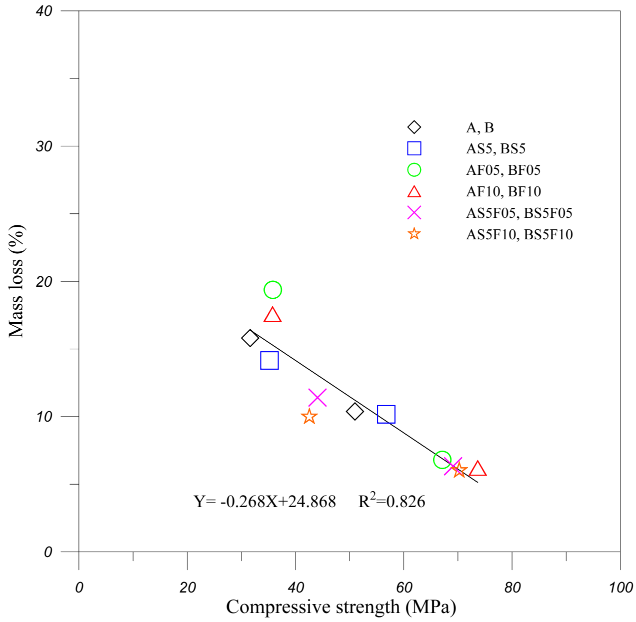

Fig. 3. Relationship between mass loss and compressive strength

The result indicated that the enhancement in compressive strength of cementitious materials led to an increase in abrasion resistance. The bonding strength between the pastes and steel fibers is also an important index on abrasive property.

3.2. Water abrasion test

WAT test was performed at 91 days to investigate the abrasion resistance of concrete by measuring the volume reduction. Test duration was selected as 24 and 48 hours and results are shown in Figures 4 and 5 respectively. As shown in those figures, abrasive volume and the abrasive index increased significantly with an increase in the duration of the rotation period. The AF05 and BF05 specimens presented the highest abrasive volume due to the fiber-balling and the poor fiber dispersion. Those fiber defects may cause the weak bond strength between the fibers and paste, particularly at higher w/b ratios (w/b is 0.55). It was demonstrated that the spalling of concrete could raise the amount of abrasive volume [16]. However, the AS5F05 and BS5F05 specimens with silica fume may help the fibers disperse uniformly in specimens to improve abrasion resistance significantly. Silica fume with nano-size particles helped to enhance the fiber-dispersion all over the paste. As indicated in Figure 4 and 5, test concrete with silica fume possessed better water abrasion resistance. Silica fume added concrete has higher denseness and hence less surface granules are eroded by water current and steel ball. The specimens containing 5 % silica fume can reduce the abrasion resistance about 1 % and 2 % than the reference concrete of mix no. A and B, respectively. The steel fiber reinforced concrete (BF05) suffered higher volume loss, up to 4 %, than reference concrete (mix no. B) in water abrasion test because the surface fibers were eroded by water and steel ball (as shown in Figure 6) which resulted in higher volume reduction. As indicated by the mechanisms mentioned in ASTM C1138, water abrasion is correlated to crushing energy $Q_{crushing}$, shearing energy $Q_{shearing}$, and impact energy Q_{impact}. The positive correlation between $Q_{crushing}$ and the weight of steel ball is represented by $Q_{crushing} \propto W$, where W = Weight of steel ball. $Q_{shearing}$ is correlated to the surface roughness of test concrete, and this correlation is expressed as $Q_{shearing} \propto \mu W$ where μ is the coefficient of friction of test concrete. Q_{impact} is correlated to velocity (U), concrete hardness (H) and the angle of impact (θ), and the correlation is expressed as $Q_{impact} \propto f(\theta) m U^2/H$. These equations help explain the higher abrasion loss suffered by steel fiber reinforced concrete than reference concrete; as evident in Figures 4 and 5, addition of steel fibers to amount of 1 % resulted in the greatest loss in volume.

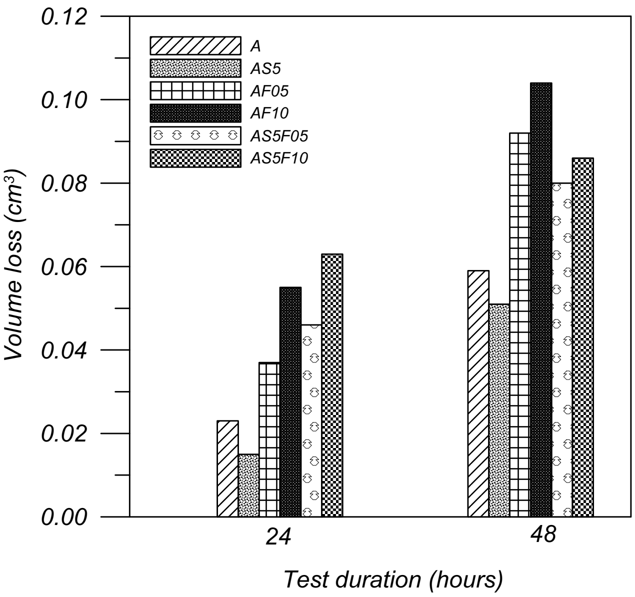

Fig. 4. Volume loss vs. test duration histograms of steel fiber reinforced cementitious composites by WAT (w/b = 0.35)

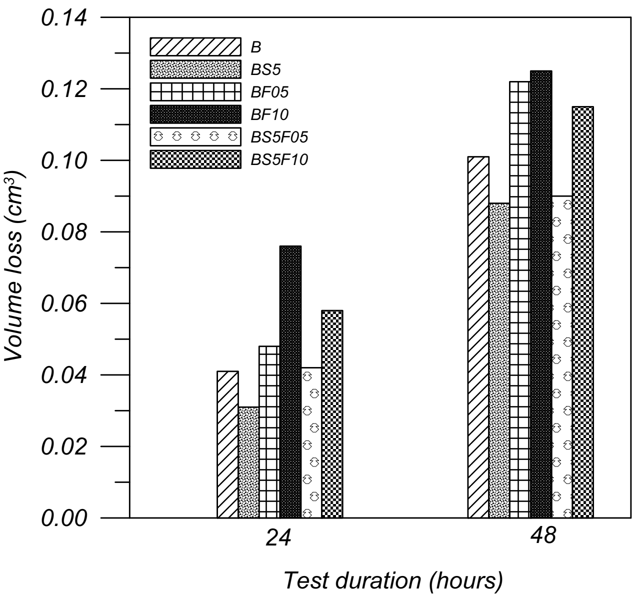

Fig. 5. Volume loss vs. test duration histograms of steel fiber reinforced cementitious composites by WAT (w/b = 0.55)

Fig. 6. Appearance of the specimens after water abrasion test

Erosion of steel fibers by water current and steel ball led to the loss of the entire steel fibers and consequently a greater reduction in volume. Based on the results of WAT, the inclusion of silica fume in the samples underwent less pronounced abrasive volume, compared to the A and B samples. The specimens comprising a mixture of steel fibers and silica fume certified performance superior to the samples with either steel fibers or silica fume separately. The admixture between steel fibers and silica fume was shown to provide the largest resistance on abrasive property. It also indicated that silica fume not only help to enhance the effectiveness of bonding between the paste and steel fibers but also increase fiber-dispersion [16].

According to the previous studies [11, 17 – 18], water abrasion was observed to be less correlated to the compressive and splitting tensile strength of concrete (as shown in Figure 7) and the volume lost ranged between 1 % – 2 % of total volume.

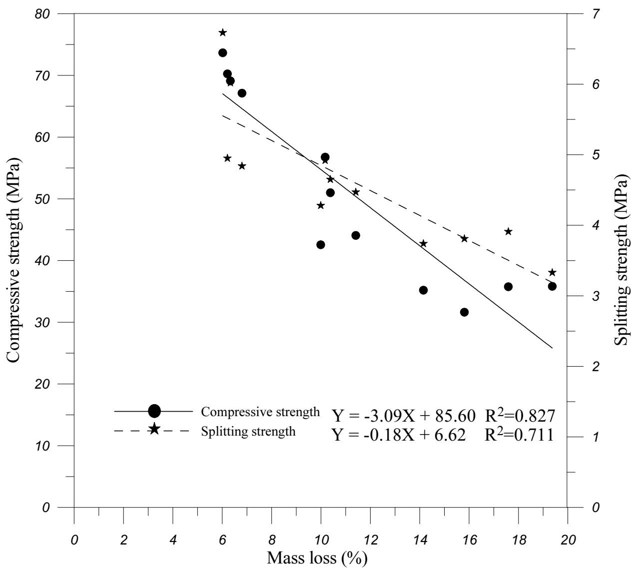

Fig. 7. Relationship between compressive strength and mass loss as well as splitting strength and mass loss

Therefore, water abrasion is less suitable for use in the current study to investigate the general non-water abrasion resistance of fiber reinforced cementitious composites. The abrasion resistance appears to increase with the increase in compressive and splitting strength. Clearly, the compressive strength has a greater effect on abrasive properties of the samples with high water-binder ratio than that of specimens with low water-binder ratio. Equation (4) illustrates the relationship between compressive strength and mass loss for the specimens at 0.35 and 0.55 w/b ratio ($R^2 = 0.827$).

$$Y = -3.09x + 85.6, \qquad (4)$$

where Y is the compressive strength (MPa) and x is mass loss (%) of specimens in WAT.

4. CONCLUSIONS

- Although steel fiber reinforcement enhances the compressive strength of concrete with higher w/b ratio (w/b = 0.55), the enhancement is not substantial. This concrete also experienced the greatest volume loss in the Los Angeles abrasion test and water abrasion test. Therefore, the inclusion of steel fiber to concrete with high water-binder ratio is less suitable considering abrasion properties.
- Addition of steel fiber at lower w/b ratio significantly improved the compressive strength and slightly enhanced the splitting tensile strength of concrete. For Los Angeles abrasion test, the best abrasion resistance was recorded for AS5F10 specimens at the age of 91 days. However, in the water abrasion test, the loss of volume from erosion was higher than that of the control group.
- Addition of silica fume to steel fiber reinforced cementitious composites with higher and lower w/b ratio not only enhanced compressive strength and splitting tensile strength at the age of 28 days but also improved abrasion resistance in both the Los Angeles abrasion and water abrasion tests.
- Steel fiber reinforcement is suitable for applications that demand higher compressive strength and late stage abrasion resistance, and is therefore suitable for use in general land structures. The addition of silica fume can improve the compressive strength and splitting tensile strength of early stage steel fiber reinforced cementitious composites, and the abrasion resistance is also improved at the age of 28 days. Inclusion of steel fiber more than 1 % could further increase the strength of concrete.

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