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## Water-impact abrasion of self-compacting concrete

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**Abstract.** Abrasion erosion is one of the serious problems that encounters the concrete surfaces exposed to speedy water flow in hydraulic structures, affects their service life and poses the need to expensive maintenance works. Some parts of the hydraulic structure like chute blocks and baffle piers in spillways are designed to face direct impact of water and waterborne materials. For such type of loading, the water-jet test method can be used to simulate the abrasion erosion of concrete surfaces. In this study, an experimental work was conducted to evaluate the abrasion erosion of self-compacting concrete under the effect of water impact. Plate specimens from six mixtures with 30, 40 and 50 MPa design strengths and with 0, 0.5, 0.75 and 1.0 % steel fiber contents were tested using the water-jet method. The results showed that increasing the strength from 30 to 40 MPa can reduce the abrasion losses by approximately 17 %, while using steel fibers with volumetric contents of 0.75 and 1.0 % can improve the abrasion resistance by more than 23 %. It was also concluded that the best percentage abrasion resistance improvement was gained when the strength of the plain specimens was increased to 50 MPa, which was 30 % compared to the plain 30 MPa sample.

### 1. Introduction

The reduction in concrete quality in structural members can in several cases be attributed to the inadequate compaction, which affects the strength and durability of the produced structural member. This problem was distinguished in Japan before 1990. Between 1988 and 1999, leading research works [1, 2] were conducted in the University of Tokyo to surpass this problem and produce a durable self-consolidating concrete. This type of concrete was first named as high performance concrete, then after, the term Self-Compacting Concrete (SCC) became more popular [3]. Several favorable characteristics can be named for SCC including self-consolidation under own weight, reduction in number of labor required, reduced noise in site, reduced construction period and avoidance of fresh-state concrete defects, which results in more durable surfaces [3, 4]. Any SCC mixture should have the characteristics of flowability, passing ability and segregation resistance. The limitations of the required SCC fresh properties and their tests are detailed in several standards, among the most important of which are the ACI 237-R [4] and the European Specifications EFNARC [5]. The first application of SCC was in Japan in 1990 where most of the reinforced concrete members of a building structure were cast using SCC. Then in 1991 it was used in the towers of the Shin-Kiba Ohashi prestressed concrete cable-styled bridge [3]. Since that it was extensively used around the world in buildings, bridge structures, tunnels, box-culverts and dam structures. In 2012, several important hydraulic structures in the Upper Gotvand dam in Khuzestan/Iran [6] were constructed using SCC. Among these structures is the pressure tunnel that includes four entrances with 11 m diameter each and total length of more than 5000 m.

One of the serious problems that affect the durability of hydraulic structures is the abrasion erosion of concrete surfaces subjected to high-speed water flow. This flow is mostly accompanied by waterborne materials, which might be as small as sand and gravel and as big as rocks. Such flow with such erodent materials causes shearing or impact abrasion forces that may lead to serious defects in the exposed surfaces. Two tests are being used during the current and last decades to qualitatively evaluate the abrasion erosion of concrete surfaces in hydraulic structures. The first is the standard ASTM C1138 [7] under water abrasion test method, while the second is the non-standard water jet test method developed by liu et al. [8]. The first simulates the abrasion erosion due to the movement of water and waterborne materials, where the direction of this movement is parallel to the concrete surface. In this method, the main cause of abrasion action is the

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shearing frictional forces of water and erodent materials. On the other hand, the water jet method simulates the impact action of water and waterborne materials on surfaces that are normal to the direction of flow. Some valuable experimental research works were found in the literature on the abrasion erosion of different concrete types using the ASTM C1138 method [9–14] and the water jet method [15–20]. However, few trials were found in the literature on the evaluation of SCC abrasion, yet, none of which was under the effect of water and waterborne materials. Turk and Karatas [21] used the ASTM C779 [22] dry abrasion procedure to investigate the effect of the quantity of silica fume and fly ash in the concrete mixture on the SCC resistance to dry abrasion action. Their results showed that SCC was superior to normal concrete in abrasion resistance. The results also revealed that increasing silica fume and decreasing fly ash in the mixture lead to better abrasion resistance. Ghafoori et al. [23] used the same dry abrasion method (ASTM C779) to test SCC specimens. The authors found that SCC exhibited 50–70 % lower abrasion losses than ordinary concrete.

The inclusion of metallic or synthetic fibers to SCC may reduce its flowability, but can positively influence its strength and durability. Fibers are known to improve the physical properties of concrete when applied in sufficient quantities. Steel fiber can noticeably improve the resistance of concrete mixtures and reinforced concrete members to tensile, shear, flexural and torsional loads. It can reduce the crack width and improve the stiffness, ductility, surface hardness and resistance to impact loads [24–29]. Recent researches showed that steel fiber with volumetric contents of 0.3 to 1.0 % can reduce the surface abrasion losses. Liu et al. [15] showed that the inclusion of 1.0% of steel fiber led to lower abrasion losses by 39 %, while Horszczaruk [9] showed that the effect of fiber on abrasion resistance depends on many factors including its aspect ratio and distribution in the mixture, where 30 mm length steel fiber could retained lower abrasion losses by approximately 18% compared to plain mixture. Using the water-jet method, Ristic et al. [16] showed that 0.3 % of steel fiber could reduce the abrasion by approximately 9 to 15 %.

The literature review conducted in this research shows that although several experimental researches were found on the abrasion resistance of concrete under water flow effect, the available experimental data about this problem still much less than required. The response of several new concrete types still not well defined and the influence of several mixture ingredients still not well investigated. There still a need for more research works to improve the knowledge about the problem of abrasion erosion of concrete surfaces in hydraulic structures. Moreover, although SCC was used to construct many hydraulic structures, the reviewed literature reveals that none of the previous experimental researches tried to evaluate the impact abrasion erosion of SCC under water movement effect, especially with the presence of steel fibers. Therefore, this research tries to fill some gap of knowledge in this field by conducting an experimental work on the abrasion erosion of steel fiber-reinforced SCC under direct impact of water and waterborne materials.

## 2. Methods

The water jet test method was used in this work in order to estimate the resistance of SCC to the abrasion erosion that occurs due to direct impact of water and waterborne materials in hydraulic structures. For this purpose, six SCC mixtures were prepared and checked first for their filling, passing and segregation resistance abilities at the fresh state. Then, plate samples were prepared from the mixtures and kept in temperature-controlled water tank until testing date at age of 28 days.

### 2.1. Mixtures and materials

Basically, a SCC mixture was adopted from literature [30], then several trials were made to correct the quantities so that all required mixtures passes all SCC fresh properties tests. Six mixtures were prepared to study both the concrete strength and fiber content effects. The basic mixture has 30 MPa design strength but without fiber. For the same concrete strength, three other fibrous SCC mixtures with fiber contents of 0.5, 0.75 and 1.0 % were prepared, while two mixtures with higher design strengths of 40 and 50 MPa but without fiber were prepared to investigate the strength effect. To evaluate the strength of the prepared SCC mixtures, compressive strength and splitting tensile strength based on the ASTM standards were tested for all mixtures at the same day of abrasion test.

Different dosages of type R42.5 ordinary Portland cement were used in this investigation so as to produce SCC mixtures of different grades. A powder of limestone which is produced locally was added too but with constant small quantity of 70 kg/m<sup>3</sup> as filler in order to provide better homogeneity for all mixtures, while 70 kg/m<sup>3</sup> of silica fume was used with the 50 MPa strength mixture only. The course aggregate was crushed siliceous stone with maximum size of aggregate of 12.5 mm, while local siliceous sand was used as fine aggregate. To accommodate SCC mixtures with required workability and viscosity, Sika Viscocrete-5930 superplasticizer was added with different dosages based on trial mixtures. Straight micro-steel fiber was used with length and diameter of 15 and 0.2 mm, while its tensile strength was 2600 MPa. Table 1 shows the details of the prepared SCC mixtures.

**Table 1. Proportions of SCC mixtures.**

Mixture	Cement (kg/m <sup>3</sup> )	FA (kg/m <sup>3</sup> )	CA (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	W/B	SP (kg/m <sup>3</sup> )	Fiber (kg/m <sup>3</sup> )
C30F0	400	1060	586	185.00	0.394	9.500	0.0
C30F0.5	425	1096	519	196.56	0.397	13.550	38.0
C30F0.75	425	1096	519	196.56	0.397	13.550	58.5
C30F1	435	1110	494	217.00	0.430	15.000	78.0
C40F0	500	990	586	200.00	0.351	10.250	0.0
C50F0	550	950	543	200.00	0.290	17.857	0.0

FA: Fine aggregate, CA: Coarse aggregate, W/B: Water to total binder ratio, SP: Superplasticizer

## 2.2. Fresh SCC tests

To ensure that the prepared mixtures fulfill the required fresh properties of SCC, six SCC fresh tests were adopted to validate the three main test categories which are the flowability, passing ability through steel bar reinforcement and resistance to segregation when cast from to deep sections. Three tests were adopted to check the flowability of the prepared mixtures, which are the slump flow [5, 31], T<sub>50</sub> [5, 31] and V-funnel tests [5]. The former two tests were adopted for all mixtures, while the V-funnel test was carried out for the three plain SCC mixtures (C30F0, C40F0 and C50F0). On the other hand, the J-ring [5, 32] and L-box tests were used to check the passing ability through reinforcement obstacles. The L-shaped box was used in this study as per the standard dimensions of EFNARC [5]. This test was performed to evaluate the three plain mixtures only, while the J-ring test was used for the six SCC mixtures. Finally, the rapid penetration test was used according to the specifications of ASTM C 1712 [33] to evaluate the segregation resistance of the six SCC mixtures. Table 2 lists the acceptable records of the performed fresh properties tests according to both EFNARC and ASTM standards.

**Table 2. Fresh SCC mix limitations.**

Test	Limitations	
	EFNARC	ASTM
Slump flow (mm)	650-800	480-680*
		or 530-740**
T <sub>50</sub> (sec)	2-5	2-5
ΔJ-ring (mm)	0-10	0-25 †
		25-50 ††
Penetration (mm)		0-10 †
		10-25††
L box	0.8-1	
V funnel (sec)	6-12	

\* Single-operator precision \*\* Double-operator precision † No visible blocking †† Minimal to noticeable blocking  
† Resistance to segregation †† Moderately resistance to segregation

## 2.3. The water-jet abrasion test

In this work, the water jet test was considered to experimentally simulate the abrasion of vertical SCC surfaces in hydraulic structures. In order to simulate the abrasion erosion that occurs in hydraulic structures due to the impact effect of the carried sediments, plate samples of 200×200×50 mm were tested under the direct high-pressurized water. The test was conducted at nine time steps of one-hour each. Thus, the specimens were exposed to the abrasion test for nine hours. The weight of the sample was recorded after each time step. The test procedure includes the pumping of water from a tank that contains 1 m<sup>3</sup> of water, that is mixed with erodent materials, through a 200×10 mm nozzle at high pressure. In this test, the same procedure was used but using circular nozzle with a diameter of 50 mm. The velocity of the water jet was 20 m/s and the erodent material was graded sand with a concentration of 30 kg/m<sup>3</sup>. Figure 1 shows the water jet abrasion testing tank used in this investigation.

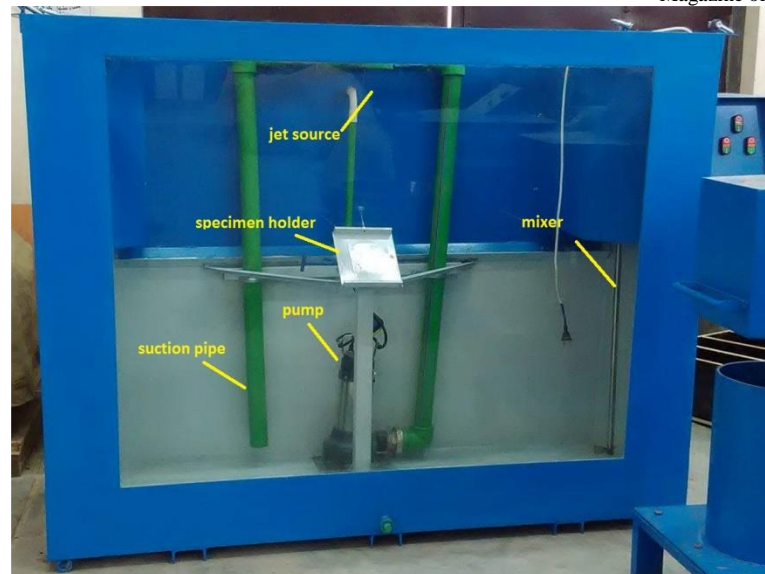


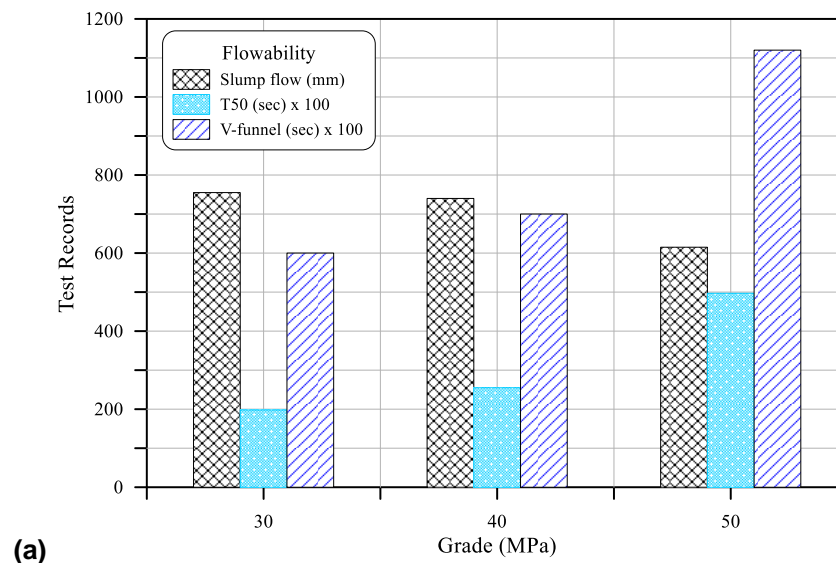
Figure 1. The used water-jet abrasion testing apparatus.

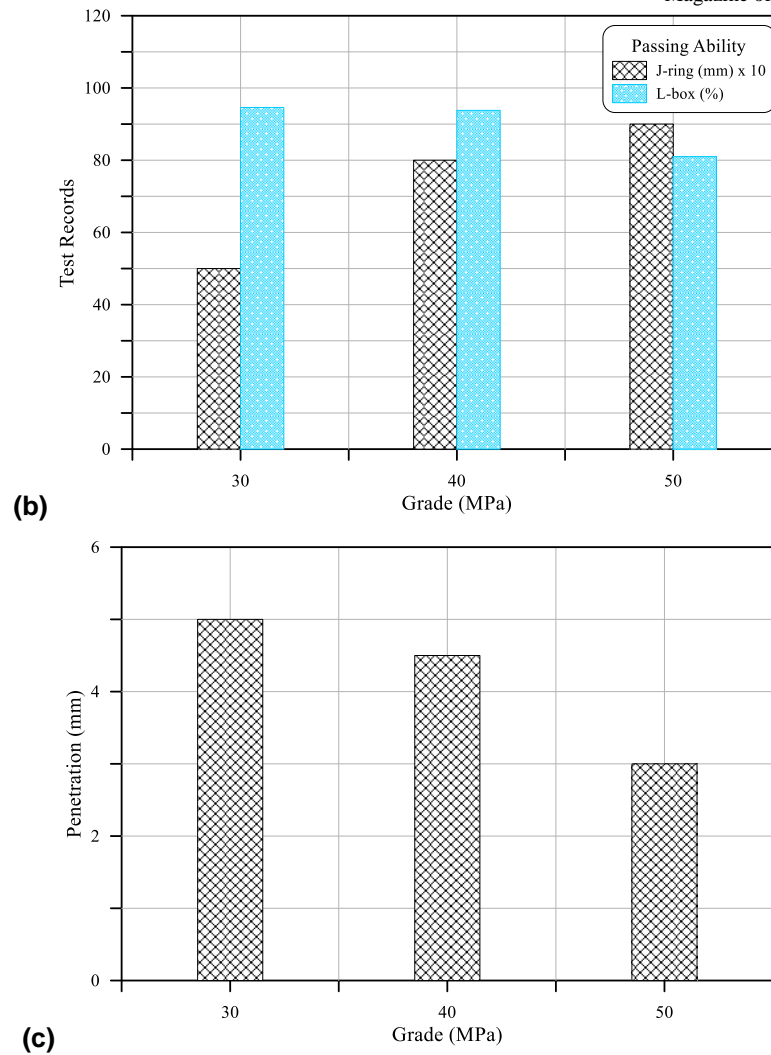
### 3. Results and Discussion

#### 3.1. Results of Fresh Concrete Tests and Control Tests

Figures 2 and 3 display the results of fresh concrete tests. These figures show that the produced SCC mixtures fulfill the requirements of standard SCC with an appropriate flowability, average viscosity which is enough to prevent segregation and finally, acceptable passing ability according to the standards of ASTM and EFNARC.

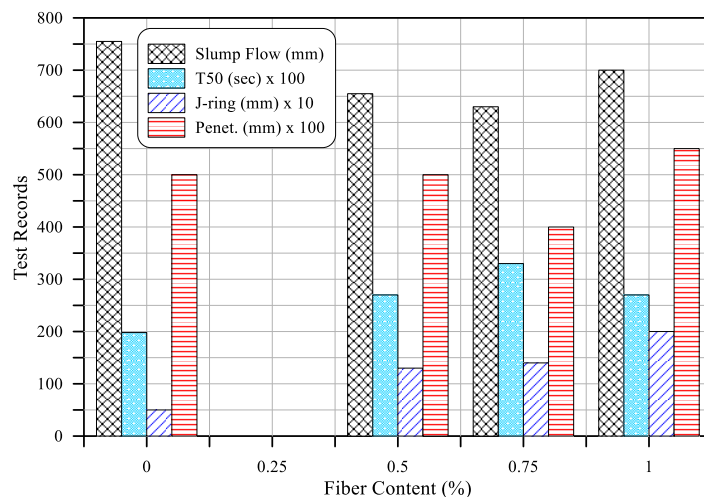
Figure 2 shows that the flowability was reduced as the design strength increased. For mixtures of 40 and 50 MPa (without fiber), where the slump flow diameter was reduced by 2 and 18.54 %, the  $T_{50}$  flow time increased by 28.8 and 150 %, and the V-funnel time increased by 14.3 and 46.4 %, respectively, compared to the mixture of 30 MPa. The decrement of w/b ratio can be considered as the main cause of such behavior in spite of the increment of SP. This result is in agreement with the fact that in the range of acceptable slump deformability, the influence of minimizing the water content appears to be more controlling on flow time than superplasticizer (SP) influence [34]. The obstruction of J-ring increased by 60 and 80 % for grades of 40 and 50 MPa mixtures, respectively, compared to grade 30 MPa mixture, while the height ratio of L-box ( $H_2/H_1$ ) decreased by 1 and 14 %, respectively. This obviously reflects the significant decrement of passing ability and higher blocking occurred by the decrement of water content. On the other hand, the segregation resistance was clearly enhanced as concrete grade increased. For mixtures of 40 and 50 MPa design strengths, the penetration test results reduced by 10 and 40 %, respectively, compared to the 30 MPa mixture. This result can be attributed to the increment in fine materials content and the noticeable reduction in w/b ratio.





**Figure 2. Fresh SCC tests of the mixtures with different design strengths (a) flowability tests (b) passing ability (c) segregation resistance.**

Figure 3 shows that the inclusion of fibers negatively influences the fresh properties of SCC. As steel fiber content increased, slump flow test results clearly decreased in spite of the increase in w/b ratio and superplasticizer dosage. For example, for 1% fiber addition, the w/b ratio and SP increased by approximately 7.8 and 58%, respectively, while the slump flow diameter reduced by about 7.3% as compared with the slump flow for plain mixture. Similarly, the flow time increased due to steel fiber inclusion, while the J- ring obstruction increased by approximately 160, 180 and 300% for mixtures with 39, 58.5 and 78 kg/m<sup>3</sup> of steel fiber, respectively. On the other hand, mixtures segregation was slightly increased but remained in the acceptable range, which returns to the use of larger water and superplasticizer quantities in order to attain appropriate flow and passing abilities.



**Figure 3. Fresh test results of fiber-reinforced mixtures.**

### 3.2. Results of the Water Jet Abrasion Test

The decrease in the specimen weight due to abrasion was recorded in this investigation using the Percentage Abrasion Weight Loss (PAWL). It stands for the weight difference between the primary weight of each sample and its weight after a certain period of testing time, divided by its primary weight and multiplied by 100, as shown in the following equation, in which  $w_p$  and  $w_t$  are the primary weight and the weight of the specimen after (t) hours of testing, respectively:

$$PAWL(\%) = 100(w_p - w_t) / w_p \quad (1)$$

Figure 4 shows that the PAWL of all specimens significantly increased with testing time. The relation of PAWL with time seems to be linear for the 30 MPa specimen, while it is multi-linear for the higher grade specimens. Figure 5 shows that for the test specimens of grade 30 MPa, the PAWLs at testing times of 3, 6 and 9 hours were 0.43, 0.81 and 1.18 %, respectively. On the other hand, the PAWLs of grades 40 and 50 MPa for the same time sequence were 0.45, 0.71 and 0.97 % and 0.39, 0.69 and 0.83 %, respectively. It can be noticed that at all test intervals, the PALWs of grade 30 MPa were the highest except at the first three hours of testing in which grade 40 MPa exhibited higher PAWL, while the PAWLs of grade 50 MPa were permanently the lowest. Comparing the results at the end of the test, it is clear that the abrasion resistances of SCC mixtures with design strengths of 40 and 50 MPa were higher than that of 30 MPa by 17.8 and 30 %, respectively. These results are also shown in the final abraded surfaces shown in Figure 6, which shows that the 30 MPa specimen suffered higher surface abrasion losses.

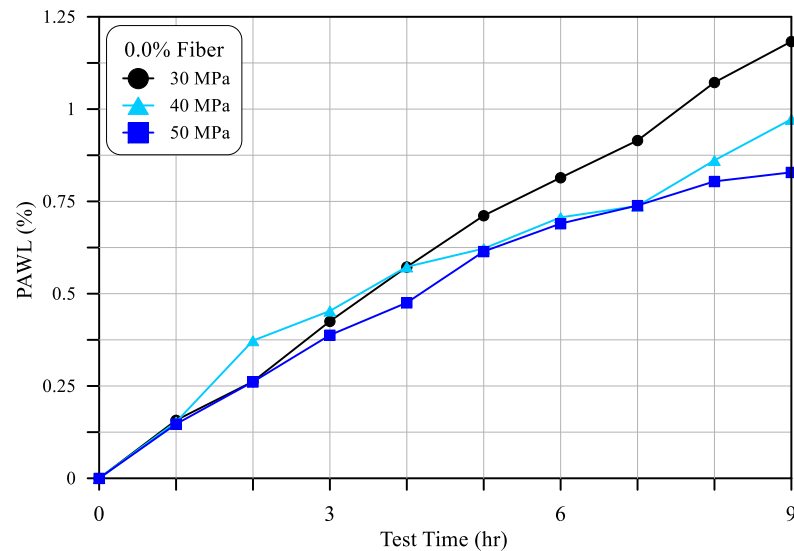


Figure 4. PAWL-testing time for different design concrete grades.

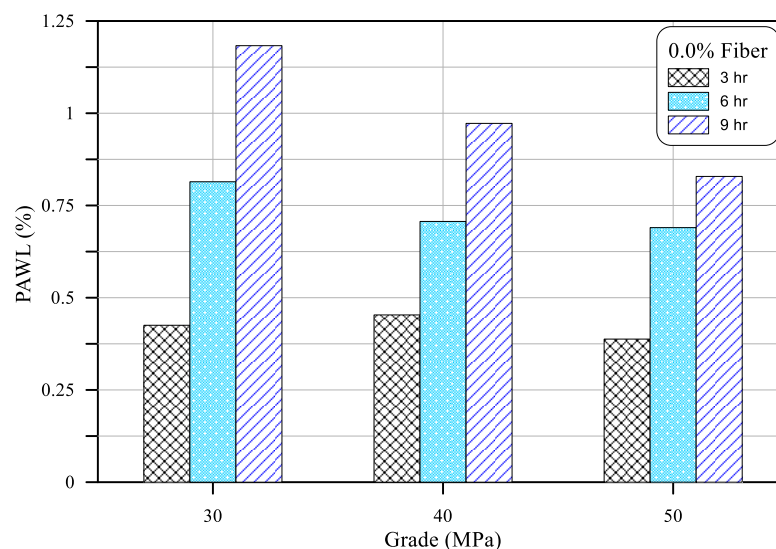
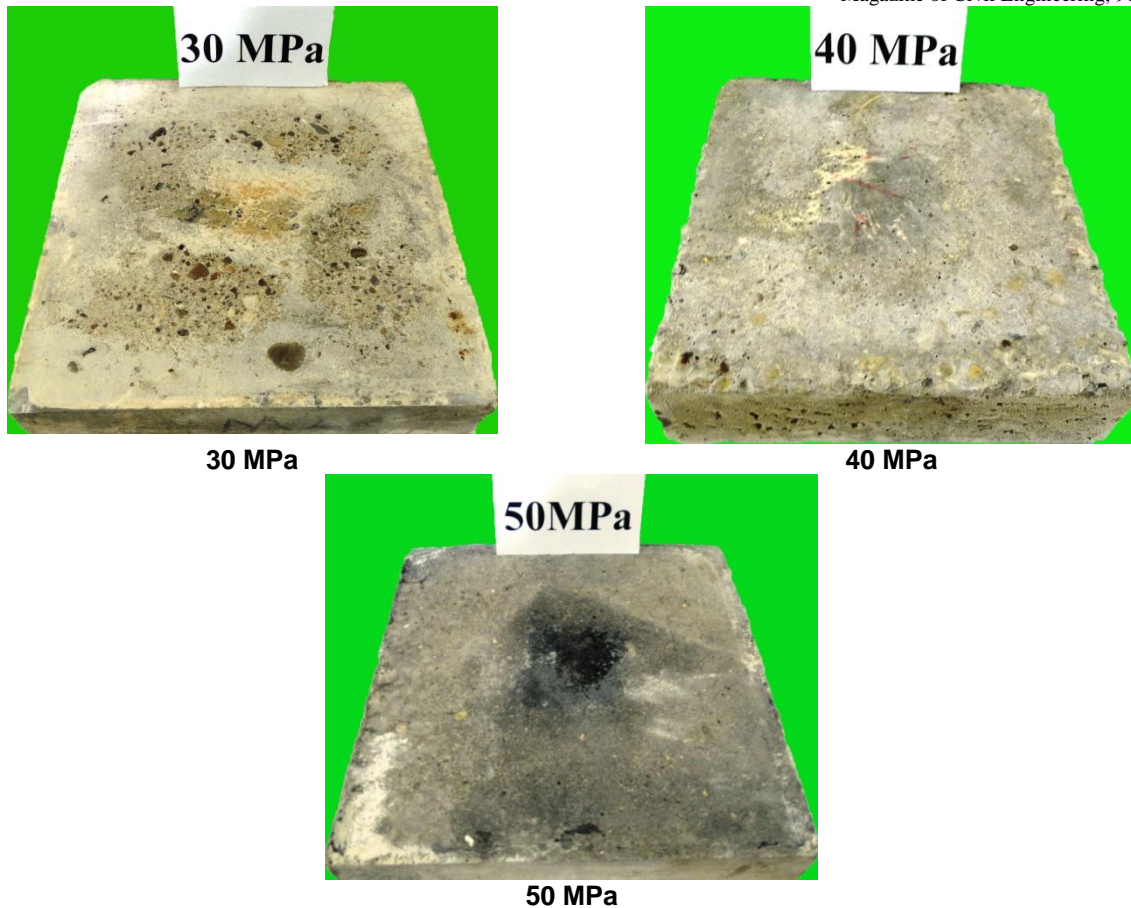


Figure 5. PAWL-concrete design grade after 3, 6 and 9 hours of abrasion testing.





**Figure 6. Abraded surfaces of the specimens with design strengths of 30, 40 and 50 MPa after 9 hours of abrasion testing.**

Figure 7 shows the relation between the PAWL and various testing times for steel fiber contents of 0, 0.5, 0.75 and 1.0 % by volume. It is obvious that the effect of fiber content on the PAWL was not clear during the early hours of abrasion testing, while at the end of the test, the plain specimen with 0 % fiber exhibited the highest PAWL value of 1.18 %, while the specimen with 0.5 % fiber exhibited the second highest PAWL value of 0.95 %. On the other hand, specimens with 0.75 and 1.0 % fiber contents exhibited the smallest PAWL values of 0.906 and 0.903 %, respectively. Figure 8 shows the above discussed influence of steel fiber addition on the PAWL at various testing time intervals of 3, 6 and 9 hours. At the end of the test, the abrasion resistance of fibrous SCC specimens with 0.5, 0.75 and 1.0 % fiber contents was higher than the corresponding plain one by 19.7, 23.4 and 23.7 %. Pictures of the abraded surfaces of the four specimens after 9 hours of abrasion testing are shown in Figure 9. Another notice is that the fibrous specimens, especially those with fiber contents of 0.75 and 1.0 %, exhibited multilinear variation with time, where the slope of this relation changed after 4 hours of abrasion testing, while that of the plain specimen kept having approximately the same slope along the full test period.

From Figures 4 to 9, an important note was observed, that is the final PAWL values for all fibrous specimens of grade 30 MPa were lower than that of plain sample of grade 50 MPa. Specimens of 0.5, 0.75 and 1.0 % fibers have lower PAWL values by 2.4, 6.8 and 7.1 %, respectively. This leads to a conclusion that increasing the strength of SCC has higher impact on abrasion resistance than adding micro-steel fibers with volumetric content up to 1.0 %, which is also a less expensive alternative. This result is more clear in Fig. 10, which shows the Percentage Increase in Abrasion Resistance (PIAR) for the three 30 MPa fibrous specimens (C30F0.5, C30F0.75 and C30F1) and the 40 and 50 MPa plain specimens (C40F0 and C50F0). The PIAR is calculated by dividing the difference of the final abrasion loss of any specimen and that of the reference specimen (C30F0) by the abrasion loss of the reference specimen. The figure obviously shows that the PIAR due to increasing the compressive strength from 30 to 50 MPa was the highest among all specimens, which was 30 %, while the inclusion of 1.0 % of steel fiber improved the abrasion resistance by approximately 24 %. However, it should also be noted that all fiber contents led to better abrasion resistance than increasing the strength by only 10 MPa. As it is shown in Table 1, the C50F0 mixture includes more than 45 % higher cement content and approximately 20 % lower w/b ratio. Such increase in cementitious materials and decrease in water content is enough to significantly improve the surface hardness, which leads to better resistance to impact abrasion forces. However, part of the better behavior of the 50 MPa specimen can be attributed the inclusion of silica fume. Where previous researches [15, 17, 35] showed that silica fume has positive impact on abrasion resistance of concrete.

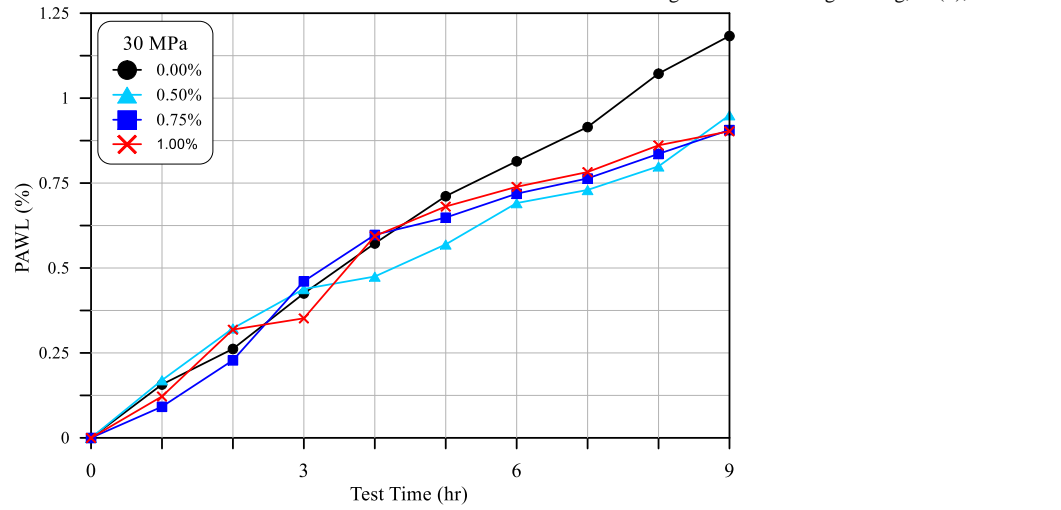


Figure7. PAWL-testing time of various steel fiber contents.

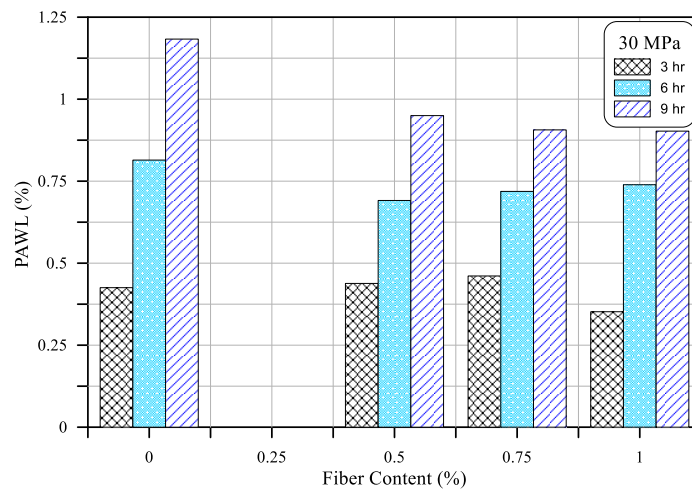


Figure 8. PAWL-fiber content after 3, 6 and 9 hours of abrasion testing.

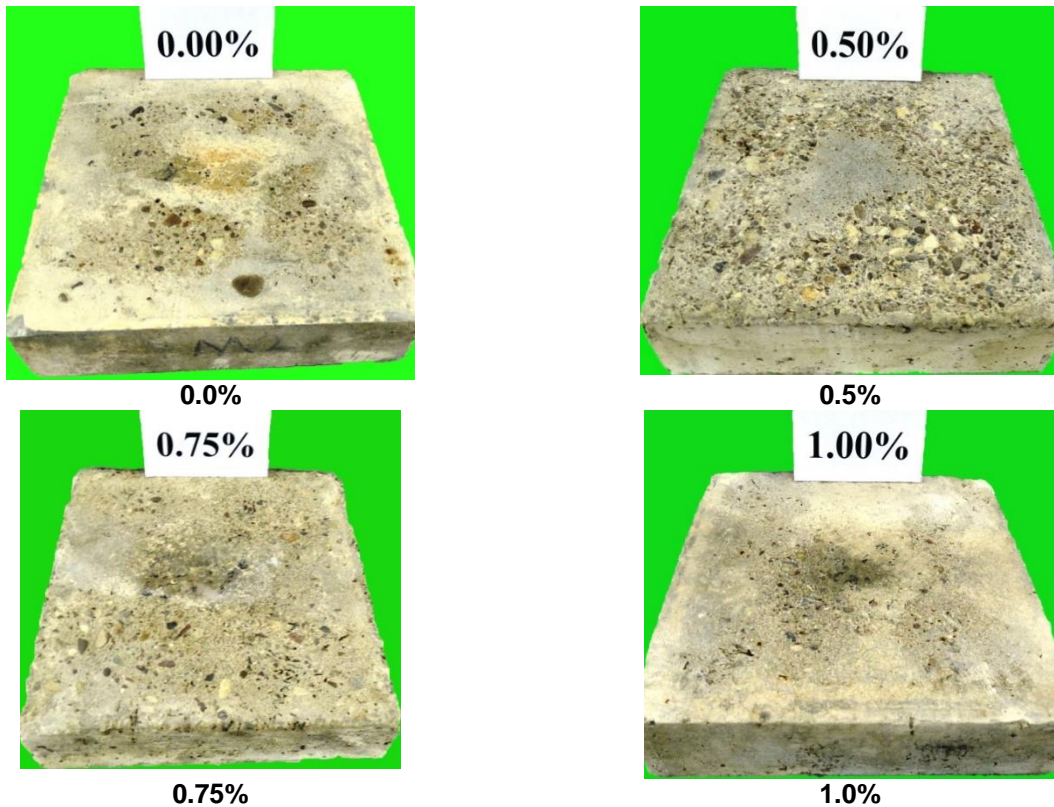
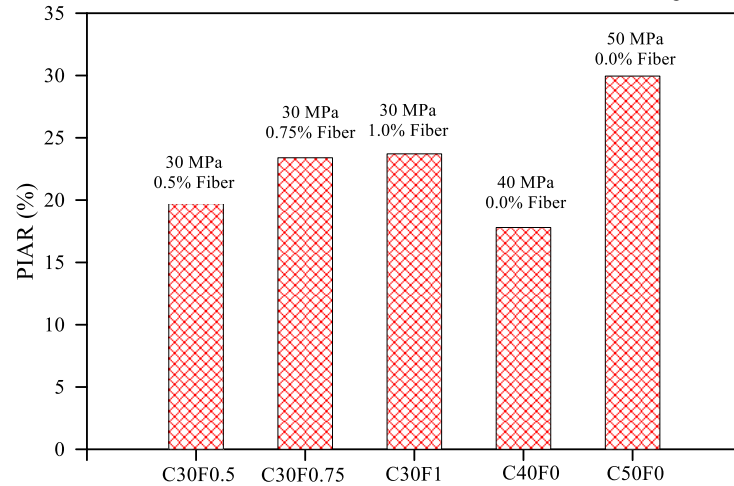


Figure 9. Abraded surfaces of the specimens with fiber contents of 0, 0.5, 0.75 and 1.0 % after 9 hours of abrasion testing.





**Figure10. PIAR of all specimens over the reference specimen with 30 MPa design strength and 0% fiber.**

#### 4. Conclusion

The water-jet method was used in this experimental investigation to conduct abrasion erosion tests on plate samples aiming to evaluate the abrasion resistance of SCC. Plain and steel fiber-reinforced SCC mixtures were prepared and tested. Three design concrete grades of 30, 40 and 50 MPa and four volumetric fiber contents of 0, 0.5, 0.75 and 1.0 % of steel fiber were adopted. Based on the test results of this study, the followings were concluded.

1. For all tested specimens, abrasion erosion weight loss increased as testing time increased. However, the behavior of the relationship between abrasion losses and time was different among the specimens. The reference plain specimen with design grade of 30 MPa exhibited continuous increase in abrasion losses with approximately the same slope, while the plain specimen with 50 MPa design grade and the fibrous specimens with 0.75 and 1.0 % of steel fiber (30 MPa) exhibited approximately a two-step linear behavior with time, where the slope of this relation decreased after 4 hours of abrasion testing indicating higher abrasion resistance.

2. During the full test period, the specimen with 50 MPa design grade showed the lowest abrasion losses among the plain specimens, while that with 30 MPa exhibited the highest abrasion losses along the last two thirds of the test time. At the end of the nine-hour test, the plain specimens with 30, 40 and 50 MPa suffered percentage weight losses of 1.18, 0.97 and 0.83 %, respectively. The better abrasion resistance of the 50 MPa mixture can be attributed to the higher quantity of cementitious materials and lower w/b ratio, which developed the surface hardness. The inclusion of silica fume can also be considered as one of the factors that led to the higher abrasion resistance of this mixture.

3. The effect of steel fiber on abrasion resistance was not clear during the early hours of the test, while it was obvious at the end of the test that the inclusion of 0.75 and 1.0 % of steel fiber can decrease the percentage abrasion losses by more than 23 %. The percentage abrasion losses of specimens with 0, 0.5, 0.75 and 1.0 % of steel fiber at the end of the test were 1.18, 0.95, 0.906 and 0.903 %, respectively.

4. The comparison among all tested specimens showed that increasing the strength by 10 MPa has a positive effect on the abrasion resistance of plain specimens with approximately 17 % decrease in abrasion losses. On the other hand, the inclusion of 0.75 and 1.0 % of steel led to better abrasion resistance by approximately 23 to 24 % compared to the plain specimen with the same grade (30 MPa). However, the best development in abrasion resistance was obtained when the design grade was increased from 30 to 50 MPa (no steel fiber), which was approximately 30 %.

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