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Investigation of steel fiber effects on concrete abrasion resistance

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Abstract. Concrete surfaces, industrial floors, sidewalks, roads and parking lots are typically subjected to abrasions. Many studies indicated that the abrasion resistance is directly related to the ultimate strength of the cured concrete. Chemical reactions, freeze-thaw cycles, and damages under abrasion are among many factors negatively affecting the concrete strength and durability. One of the major solutions to address the abrasive resistance of the concrete is to use fibers. Fibers are used in the concrete mix to improve the mechanical properties, strength and limit the crack propagations. In this study, implementation of the steel fibers in concrete to enhance the abrasive resistance of the concrete is investigated in details. The abrasive resistance of the concrete with and without steel fibers is studied with the sandblasting technique. For this purpose, different concrete samples are made with various hooked steel fiber ratios and investigated with the sandblasting method for two different strike angles. In total, 144 ASTM verified cube samples are investigated and it is shown that those samples with the highest steel fiber ratios have the highest abrasive resistance. In addition, the experiments determine that there is a meaningful correlation between the steel fiber percentage in the mix, strike angle and curing time which could be considered for improving structural behavior of the fiber-reinforced concrete.

Keywords: abrasion resistance; fiber-reinforced concrete; sandblast; compressive strength; steel fiber

1. Introduction

Concrete is typically used for having high compressive strength in various structural applications (Lee *et al.* 2019a, Lee *et al.* 2019b). However, this material loses its resistance under highly abrasive conditions, which leads to micro-crack propagations. One of the useful solutions to prevent the crack initiation is to use fibers in different shapes and mechanical properties which leads to better flexibility and durability (Farzampour 2017, Felekoğlu *et al.* 2007, Paliwal and Marua 2017, Ramesh Kumar *et al.* 2018, Zhang *et al.* 2018). Significant abrasion and erosion damages are previously observed in hydraulic structures subjected to high- velocity water flow (Amini *et al.* 2019a, Amini *et al.* 2019b, El-Hassan *et al.* 2019, Kachouh *et al.* 2019). For achieving satisfactory abrasion resistance, it is recommended to use harder coarse aggregates, improve the ultimate compressive strength, implement impact resistance material and add mineral admixtures (Du *et al.* 2020, Gupta and Kumar 2019, Horszczaruk 2009, Kryžanowski *et al.* 2009). It is shown that adding blast furnace slag and fly ash could be effective for concrete resistance. However, use of mineral admixtures for abrasion resistance purposes is limited and needs to be accompanied with other improvement methods (Duarte *et al.* 2019, Ismail *et al.* 2018, Luhar *et al.* 2019, Mohammed *et al.* 2019).

The importance of high abrasive resistance is more emphasized in hydraulic structures under waterborne silt, gravel, freeze-thaw cycles, and debris circulation (Farzampour 2019, Kiliç *et al.* 2008). Based on the previous studies (Alves *et al.* 2014, Uddin *et al.* 2017), the implementation of the appropriate aggregates, maximum aggregate size, water-cementitious ratio, and hardness of the coarse aggregate in the concrete mix is shown to extensively affect the abrasion resistance. The implicit correlation of the higher compressive strength and abrasive resistance is addressed in previous literature (De Larrard and Belloc 1997). Along the same lines, Kiliç *et al*. (2008) showed that the effect of aggregates types and properties on general compressive of the concrete, flexure tensile strength, and abrasion are significant. It is shown that having less water-cementitious material ratio leads to less porosity and better strength improvements due to the stronger interfacial bond between concrete particles, which results in higher resistance against erosion and abrasion.

Concrete surfaces under different environmental conditions are generally subjected to significant abrasion due to friction, heavy object movement, and abrasive material. In coastal structures, water acts as the abrasive

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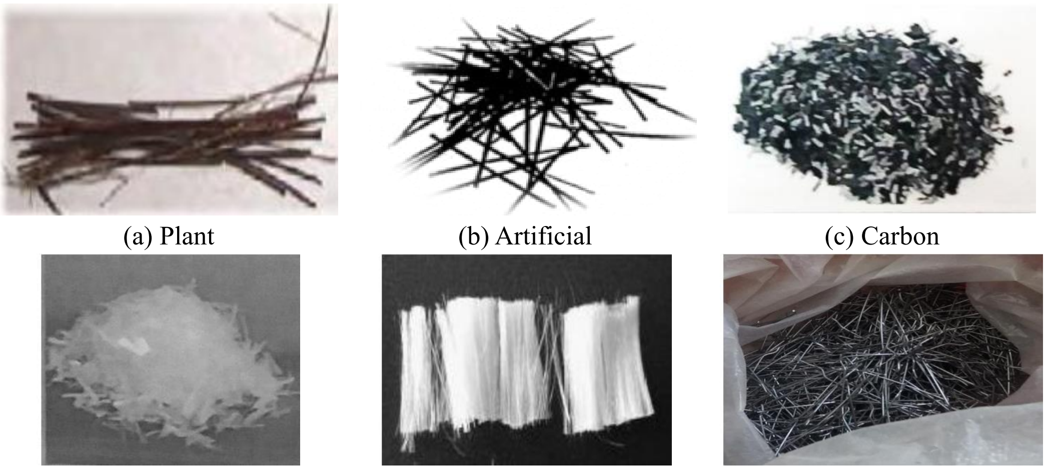


(a) Plant (b) Artificial (c) Carbon

(d) Glass (e) Polypropylene (f) Steel

Fig. 1 Commonly used fiber types in concrete applications

material deteriorating the concrete gradually. In many well-developed countries, the coastal structures are subjected to water abrasion, which eventually results in steel reinforcement corrosion and damages. Hydraulic structures are highly vulnerable due to abrasion caused by material transferred by water (e.g., sand, gravel, ice, and stone), which necessitates the need to appropriately design the concrete mix (ASTM-C1138/97 1997, Simons 1992). For addressing such issues, Romualdi *et al*. (1963) initially used fibers for improving the concrete behavior against impacts by using simple fiber reinforcements and observed that the fibers are able to generally improve the concrete behavior.

Abrasive resistance is correlated with stiffness and strength of the outer layers with a few millimeters thickness, which has a tangible effect on the durability of the concrete (Anderson and Carrasquillo 1995, Ghafoori and Najimi 2015, Zhao *et al.* 2017). To address such issues, fibers with different textured materials are used to improve the compressive strength, tensile strength and shear behavior of the concrete. Different fiber material types are commonly implemented with mixtures (e.g., steel, glass, plastic, etc.), among which the steel fibers are the most common fiber material due to having high elastic modulus, crack resistance, ductility and low cost (Al-Rawi and Tayşi 2018, Gülşan *et al.* 2018, Kaufmann *et al.* 2013, Lou *et al.* 2014, Yang *et al.* 2016). For this type of fibers, the length to diameter ratio has a significant effect on the behavior of the concrete efficiency. In general, to increase energy dissipation performance of the concrete, using steel fibers was investigated to prevent the abrasion in various structural applications and seismic retrofitting techniques including BRBs, and composite structures (Avci-Karatas 2019, Avci-Karatas *et al.* 2019, Avci-Karatas *et al.* 2018).

Fibers could be divided into two groups. First, fibers with lower elastic modulus compared to concrete (e.g., cellulose, nylon, and polypropylene) and fibers with higher elastic modulus (e.g., steel, carbon, and glass). Examples of the different fibers in various shapes and sizes are shown in Fig. 1 (ACI). In addition, Table 1 shows common properties of different fiber types, in which steel and carbon fibers have relatively high elastic modulus compared to concrete material.

Table 1 The common properties of different fiber materials

No.	Fiber type	Tension strength (MPa)	Young's modulus (GPA)	Elongation	Specific density (gr/cm³)
1	Asbestos	560-980	140	0.6	3.2
2	Carbon	1800-2600	380	0.5	1.9
3	Glass	1050-3850	70	1.5-3.6	2.5
4	Nylon	770-840	2.4	16-20	1.1
5	polyester	735-875	4.8	11-13	1.4
6	Polypropylene	560-770	3.5	25	0.9
7	Steel	280-2800	203	0.5-3.5	7.8

Having fibers in the concrete mix reinforces the concrete against crack propagation. After initial cracking, the fibers inside of the concrete resist against tensional stresses. Fibers, in general, prevent crack propagation, which eventually limits the crack widening after occurrence of early cracks. It has been observed that Fiber Reinforced Concrete (FRC) specimens are able to withstand the loading up to higher limits compared the concrete specimens without any fibers (de Castro and Keller 2008, Gopalaratnam *et al.* 1991, Shen *et al.* 2019, Wang *et al.* 2019). It is noted that the general performance of the concrete before crack propagation is related to the fibers distance, angle and density while the ultimate strength of the concrete is directly related to fiber usage ratio and length to diameter factor (*L*/*d*).

Fibers generally change the concrete performance by increasing the energy dissipation capability and tensional strength, improving the impact resistance, allowing bear-loading mechanism after crack occurrence and improving the abrasive resistance. Along the same lines, to achieve the highest FRC quality, the fiber material type and ratio, fiber *L/d* factor, initial compressive strength, and aggregate texture should be considered. This study investigates the experimental behavior of the abrasion resistance for various mix design parameters. The procedures to assess the concrete abrasive resistance are delineated and different steel fiber percentages are used for obtaining the optimal fiber percentage to efficiently resist against abrasion.

Fig. 2 Used hooked steel fibers in concrete mix design

Table 2 Concrete mix design for abrasion study

Material	Weight in 1 cube meter (kg/m^3)
Water	149.2
Cement	379.6
Sand	828.3
Gravel	979.2

Table 3 The properties of steel fibers used in concrete mix design

Specific gravity (gr/cm³)	Tensional Strength (N/mm²)	length (mm)	Diameter (mm)	ratio
7.85	809	50	0.8	62.5

2. Mix design and curing condition

The mix design is conducted based on ACI 211-89, in which the ratios of the gravel, sand, water, and cement are determined to reach the expected compressive strength, durability and required slump. The compressive strength of the concrete is set to be 30 MPA for 28 days cured concrete. The dried specific gravity of the gravel and sand are 1600 Kg/m^3 and the moisture ratio is selected to be 6% with fairness modulus of 3. The slump is selected to be in the range of 80-100 mm, and the maximum gravel size is assumed to be 19mm which results in using 205 Kg water in the mixture with water to cement ratio of 0.54 and 2% air according to ACI 211 0). The properties of the hooked steel fibers are determined in 0 and shown in Table 2.

In this study, 144 concrete ASTM verified cube specimens are made and cured under the same curing condition with different steel fiber ratios. Fig. 3 shows the different stages of curing and demolding for a sample of investigated specimens. The angels of impact and the steel fiber percentage are summarized in 0. The curing procedure used in ACI 211-89 is considered as follows:

Table 4 Specimen properties studied for abrasion

No.	Name	With 5° Impact angle	With 20° Impact angle	Fiber Percentage
1	St 0	A1	B1	0
2	St 0.5	A2	B2	0.5
3	St 0.75	A3	B3	0.75
4	St 1	A4	B4	1

a) 10-liter concrete is poured in the mixture for 5 minutes, and the steel fibers are gradually added to the mixture.
b) The material is mixed for five more minutes.
c) The calculated water needed in the mixture is added gradually to reach the expected slump value.
d) After mixing, the fresh concrete is poured in 100mm cube molds. Shaker is used to remove the extra air and achieve a consistent concrete mix. The surface of the concert specimens is prepared eventually for having sufficient smoothness after the curing process.

Subsequently, sandblasting technique is conducted to evaluate the abrasion effect of the moving vehicles on the concrete structures with the aid of a sandblast machine under two impact angles of 5^o and 20^o which is shown schematically in Fig. 4 with the air pressure of 690 kPa (ASTM-C418 2012).

To investigate the correlation between the compressive abrasion resistance of the concrete, the concrete compressive strength for 1, 3, 7 and 28 days cured specimens are monitored and abrasion resistance is determined for each one of the specimens. The compressive strength of the concrete commonly indicates the general properties of the material which is necessary to be monitored over different curing intervals. The hydraulic jack with 200-ton capacity is used with uniform loading condition for compressive strength evaluations and the loading is applied with a constant rate of 3 kN per seconds. After crack propagation, the maximum strength is reported for each one of the 144 specimens.

3. Discussion of the results

The specimens are evaluated for abrasion resistance for four different steel fiber percentages and two impact angels. It is noted that having different fiber percentages could lead to various shapes of destructions. Generally, the specimens

(a) Mixing (b) Curing (c) Demolding

Fig. 3 The prepared specimens for abrasion investigations

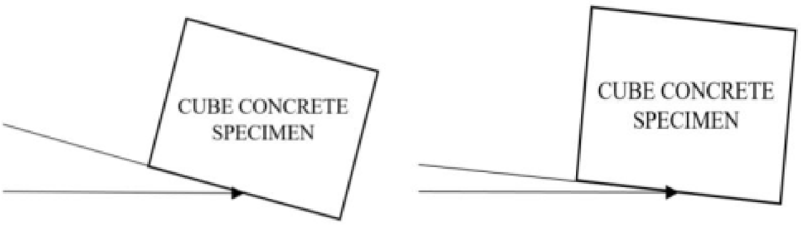
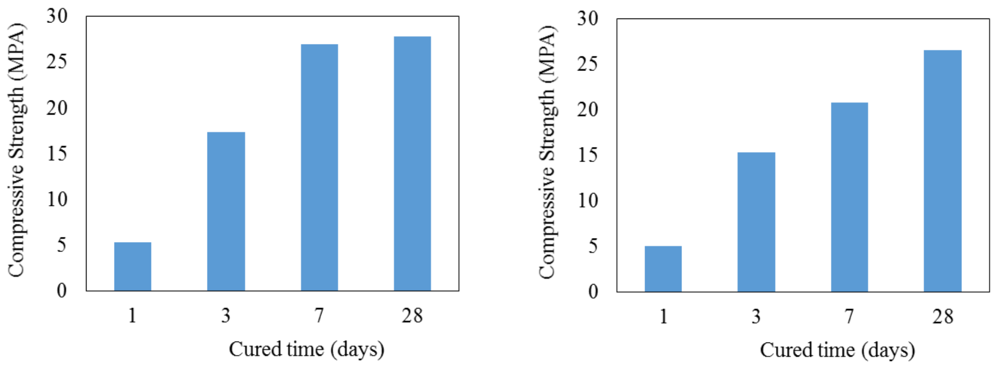


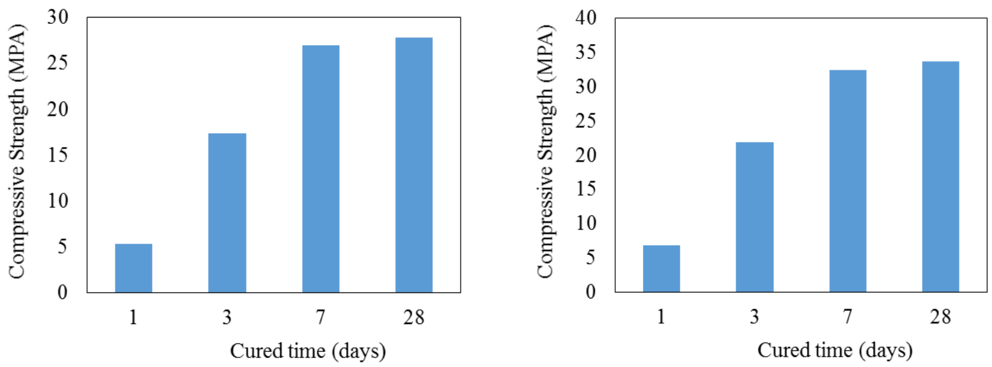
Fig. 4 Different impact angels used for abrasion evaluation

(a) With lower steel fiber ratio and inside large cracks (b) With higher steel fiber ratio and surficial cracks

Fig. 5 Comparison of the abrasion resistance of the concrete



(a) St 0 (b) St 0.5

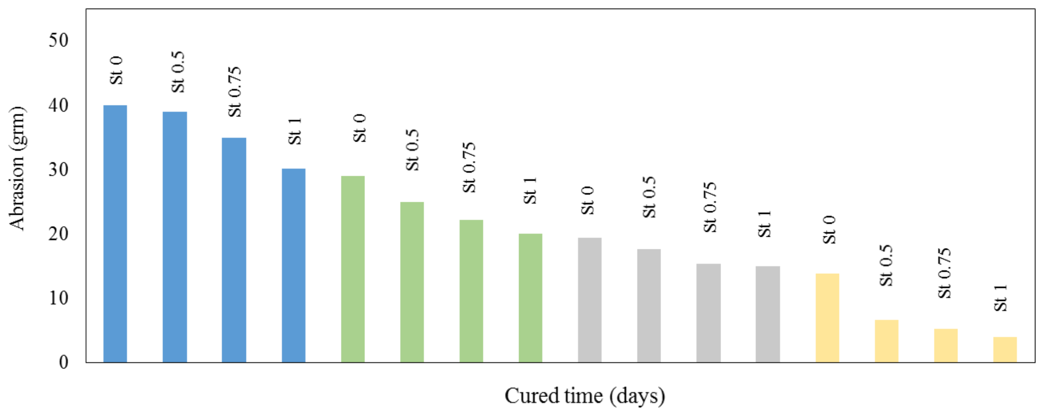


(c) St 0.75 (d) St 1

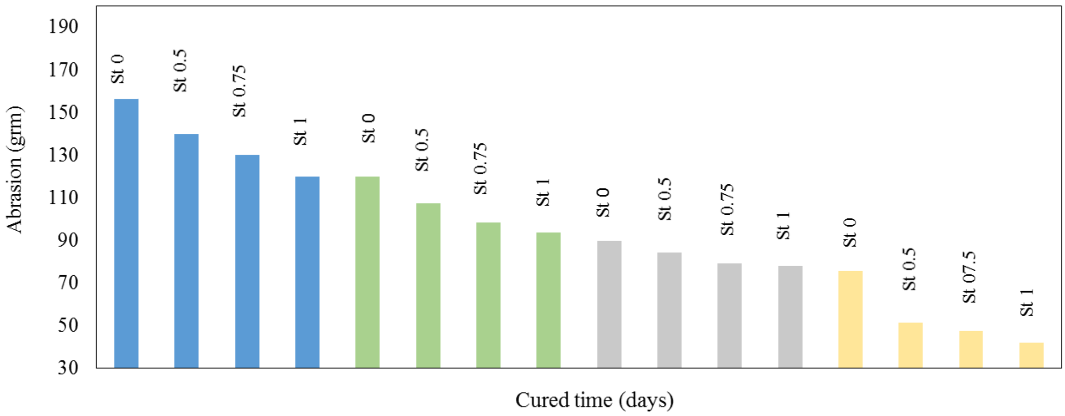
Fig. 6 The effect of steel fibers on the ultimate strength of the concrete

with a high percentage of fibers are shown to have cracks on the corners and outer areas, while the specimens without fibers would have larger cracks at the middle parts causing degradation of the total strength and stiffness of the specimens which is shown in Fig. 5.

The effect of the high steel fiber percentage ratio in increasing the total compressive strength of the concrete is determined in Fig. 6. The sample with one percentage of steel (St 1) has the highest compressive strength compared to the rest of the specimens. In average, an increase of 27.2% (or 9.49 MPA) in ultimate strength for 28 days cured concrete is observed compared to the specimens with 0.5 percentage. Considering all specimens cured in different curing intervals, the average ultimate strength of St 1 is

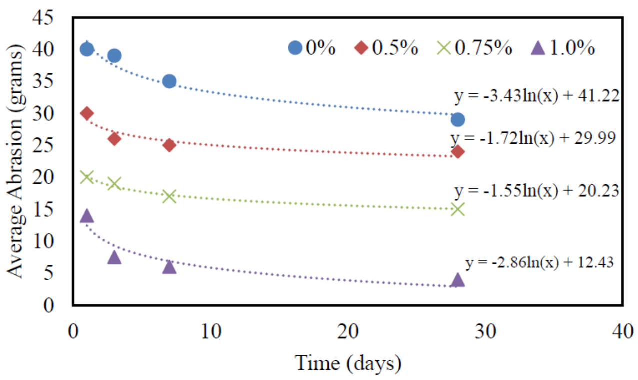


(a) Under 5° impact angle

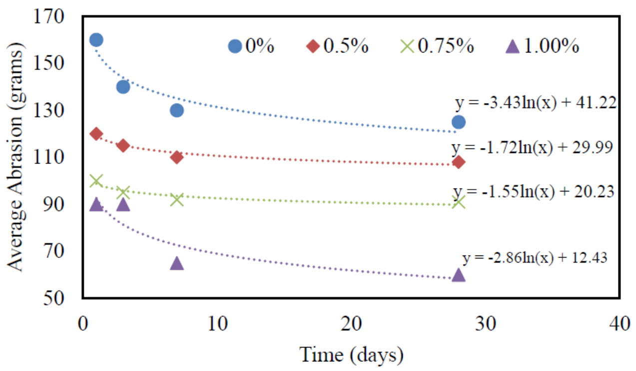


(b) Under 20° impact angle

Fig. 7 The effect of steel fiber percentage in increasing the abrasive resistance of the concrete



(a) With 5° impact angle



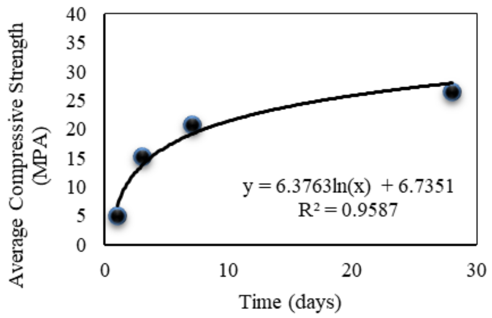
(b) With 20° impact angle

Fig. 8 The abrasive resistance of FRC for different curing time intervals and fiber ratios

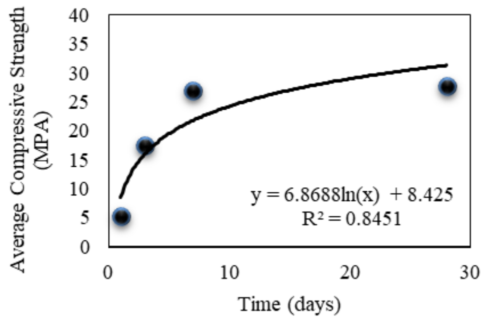
40.38%, 22.45% and 8.96% higher than St 0, St 0.5, and St 0.75, respectively.

In addition, the abrasive resistance of the specimens is calculated based on the ASTM C418 standard. The sandblasting machine is approximately set 75 mm far from the specimens which are held firmly with hangers. For one minute, the abrasive material is released and hit the specimens over the eight points, and the abraded material is weighted with the aid of the clay. The abraded material could be calculated based on the procedures elaborated in ASTM C418. Fig. 7 shows the abraded material in grams for different stages of curing. It is concluded that the specimen with high fiber percentages are able to resist the abrasion with losing less material under sandblasting for two angels of impact. The impact with the angle of 20 ° would eventually result in more material loss compared to the angle of 5° due to higher energy released under the impact loading. The specimens with steel fibers of 1 percentage have approximately 25% more resistance against the abrasion compared to the corresponding specimens with zero steel fibers. In addition, among all the specimens with hooked steel fibers, the St 0.5 has the most material loss under abrasion which shows that the bonding between the cement matrix and steel fibers are not appropriately developed for this case.

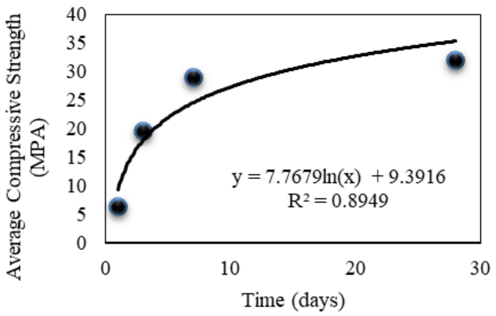
Fig. 8 shows the abrasive resistance of specimens with different steel fiber ratios over the curing time. The abrasive resistance of all the specimens is improved as the curing



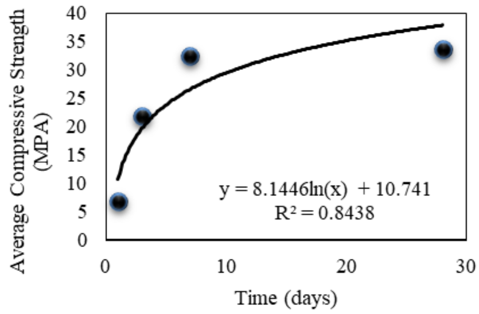
(a) With 0% percent steel fiber



(a) With 0.5% percent steel fiber



(c) With 0.75% percent steel fiber



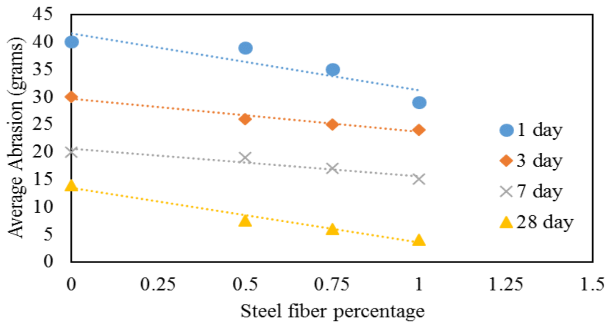
(d) With 1% percent steel fiber

Fig. 9 The strength development of the concrete with various steel fiber percentages

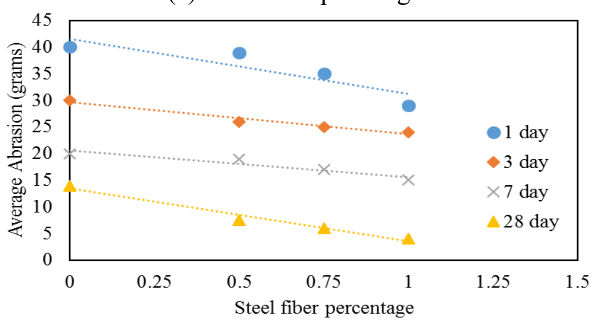
(a) Specimen with 0.5% steel fiber

(b) Specimen with 0.75% steel fiber

Fig. 10 The abrasion depth under impact loading for various steel fiber conditions



(a) With 5° impact angle



(b) With 20° impact angle

Fig. 11 The abrasive resistance of FRC with various fiber percentage ratios

time increases regardless of impact angle. In addition, the abrasive resistance of mixes with higher fiber percentages is higher than the ones with lower fiber ratios. It is noted that the higher the jet impact angle, the more abrasion occurred for all the specimens which are shown in Fig. 8.

The rate of compressive strength development with different fiber percentage ratios are shown in Fig. 9. The logarithmic equation is used to approximate the strength development of the specimens with respect to curing time. It is shown that the rate of strength development is at the highest for the first 14 days, and it decreases more than 50% after two weeks. Based on the Fig. 9 regression analysis, the R^2 values of the proposed strength development equations for specimens with 0%, 0.5%, 0.75%, and 1.0% are 0.95, 0.84, 0.89 and 0.84, respectively. It is concluded that that strength development equations follow the logical trend with respect to curing time of the specimens with various fiber percentages.

Fig. 10 shows the depth of the abrasion for St 0.5 and St 0.75. It is shown that the depth of the abrasion for those specimens with higher steel fiber percentages are less compared to the specimens with less percentage of steel fibers. The abrasive resistance of the concrete is increased over the curing time for all the specimens which linearly correlates with the compressive strength of the specimens. It is noted that as the steel fiber percentage in the concrete mixture increases, the abrasive material loss decreases regardless of the curing time as it is shown in Fig. 11.

5. Conclusions

The effect of the steel fiber on abrasive behavior of the concrete is investigated in this study. It is shown that compressive strength and abrasive resistance of the concrete sample with the highest steel fiber percentage under two impact angels of 5° and 20° are 40%, 48%, and 24% higher than the corresponding concrete specimens without any fibers. This study also corroborates the previous studies indicating the desirable performance improvement of the concrete with steel fibers. The specimens with 1% steel fiber showed the best behavior under abrasion, and by increasing the fiber percentage in the mix, the rate of compressive strength development was higher for those specimens with fibers due to better cement-fiber bonding condition. It is concluded that the abrasion decreases significantly by an increase in steel fiber percentage.

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