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EFFECT OF STEEL FIBER CORROSION ON MECHANICAL PROPERTIES OF STEEL FIBER REINFORCED CONCRETE

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ABSTRACT

In developing countries, usage of steel fiber-reinforced cementitious composites is widely expanding in structures, due to their high mechanical performance and flexibility. In this paper, the behavior of steel fiber-reinforced concrete exposed to corrosive environments has been investigated. Three test programs were conducted: one dealt with the effect of corrosion on steel fiber-reinforced mortar specimens, next considered the effects of using pre-corroded fiber in mortar specimens, and the other dealt with the effect of corrosion on the behavior and the failure modes of a single fiber pull-out test. Different exposure periods, types of solutions and the temperature of environment were taken into account.

Keywords: Concrete durability; corrosion; steel fiber-reinforced concretes; flexural tests; pull-out test; hooked fiber.

1. INTRODUCTION

Concrete has some deficiencies such as low tensile strength, low post cracking capacity, and brittleness [1]. The weakness in tension can be overcome by the use of conventional rod (steel bar) reinforcement and to some extend by the inclusion of a sufficient volume of certain fibers [2]. Fiber addition in the concrete brings a better control of its cracking and improves its mechanical properties. Various types of fiber can be used. The metal and more particularly, steel fibers are most largely employed [3]. Initially used in pavements that may be exposed to deicing salts and chemicals, in repair work, and in marine structures where its toughness properties are desirable [4, 5]. Steel fiber-reinforced concrete (SFRC) is in many ways a well-known construction material, and its use had gradually increased over the last decade. The mechanical properties of SFRC are well described based on the theories of fracture mechanics [6]. SFRC has a high cracking resistance and more progressive post behavior [7]. It is widely used in various types of engineering construction field with its good crack resistance, flexural

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toughness and impact resistance [8]. The long term behavior of structures reinforced with steel fiber in the cracked more depended on their capacity of effort taken by the fiber between the two faces of cracks. This is conditioned, on the one hand, with mechanical creep and fatigue effect, on the other hand, with corrosion of fibers [3].

Important deterioration feature of steel bar corrosion is cracking that may occur at the steel concrete interface because the corrosion product from the steel has a greater volume than the metallic iron from which it was formed. The forces generated by this expansive process exceed the tensile strength of the concrete and result in cracking. However, steel fibers have a relatively small diameter in comparison to reinforcing bars. Thus, although a layer of corrosion may not affect significantly the performance of reinforcing bars, it could lead to serious damage in a steel fiber. Spalling of the concrete, as occurs around corroded areas of steel bars, may not occur if small steel fibers are used because of the much smaller expansive forces due to corrosion [9].

Little information exists on the corrosion characteristics of steel fiber-reinforced concrete [3]. In the literature, all authors agree on the point that the corrosion arising from cracks is less severe in the case of SFRC, also, there is no exact investigation about the effect of corrosion in decrease or increase flexural strength [10-20]. Therefore, this study is about to investigate the behavior of steel fiber-reinforced concrete exposed to corrosive environments and to evaluate the extension of fiber corrosion and its effects on the strength and toughness of steel fiber-reinforced concrete in different exposure periods.

2. EXPERIMENTAL INVESTIGATION

Three different group of tests were performed: 1) accelerated corrosion tests of steel fiber-reinforced concrete specimens, and 2) pre-corroded steel fiber-reinforced concrete test, the main difference between these two groups of tests was that the second one eliminates the effects of deterioration (or improvement) of bond properties due to the expansion of corrosive products at the surface. 3) Single fiber pull-out test to evaluate the effect of corrosion on the behavior and the failure modes.

Table 1 shows the mix proportions utilized in this experimental program. Type 2 cement (Shahrood Factory), PCE super plasticizer, Ottawa silica sand (ASTM C 109) (aggregate sizes are shown in Table 2), hooked steel fiber [with diameter and length of 0.8 and 50 mm, respectively], and crimped steel fiber [0.3 x 20 mm] in volume fraction of 2 percent, were used in this study. Two sizes of flexural specimens used to investigate the effect of specimen minimum dimension on the rate of fiber corrosion were 75x12.5x300mm and 75x37.5x450mm. The small thickness was selected to allow evaluation of corrosion over a shorter period of time, and to simulate thin-sheet applications of fiber-reinforced concrete. In such a case, two dimensional fiber distribution is obtained and the specimen size dose not satisfy the minimum size recommended in ASTM C 1018, i.e., the minimum specimen dimension should be at least three times the fiber length [17]. All specimens that were not pre-cracked were of the smaller size, while the pre-cracked specimens were of two different sizes and all compression cylinders were 75x150mm.

Table 1: Mix design

Mix Design	
Portland Cement	1
Sand (Ottawa)	1.5
Water	0.42, 0.37
Super-plasticizer (PCE)	0.32

Table 2: Aggregate size

Aggregate size(percent passing the sieve)	
1.18 mm (No.16)	100
600 µm (No.30)	96
450 µm (No.40)	65
300 µm (No.50)	20
150 µm (No.100)	0

In order to speed up the process of corrosion in specimens, the following action were taken at initial stages of the experiment:

1. A mortar mix with a high water to cement ratio was used to speed up the sulfate and chloride attacks in a short period of time.
2. Sulfate concentrations and chloride concentrations were kept relatively high in the solutions with high temperature.
3. To speed up the sulfate action further, some of the specimens were pre-cracked after 28 days curing and then immersed in the solutions for a specific period of time.
4. The solutions were changed every two weeks in order to keep same or avoid variations of concentration throughout the experimental work.
5. High volume fraction of steel fibers was used.

The most aggressive environmental agents that affect the long-term durability of field concrete structures are the chlorides (marine environment and deicing salt) and the sulfates (soil, ground-water, and seawater) [18]. Furthermore, the magnesium sulfate used for the preparing the magnesium sulfate solution in this study had anhydrous form of: MgSO4.7H2O, and the sodium chloride used for preparing the chloride solution in this study had the pure form of NaCl.

2.1 Accelerated corrosion tests of fiber-reinforced mortar

A flowchart of the accelerated corrosion tests on steel fiber-reinforced concrete is shown in Fig. 1. The preparation and exposure procedures were as follows:

a. The cement and sand were premixed for about 2 min.
b. 70 percent of water with super-plasticizer (PCE) were then added slowly and mixed for about 5 min.
c. For receiving enough workability, 30 percent of water and fibers were then added slowly and mixed for about 5 min.
d. Specimens were kept in molds for 24 hours, then wet-cured in water at 20oC for six days. Next, it was stored in a laboratory environment for 7 days prior to exposure tests. Bending specimens for the crack-induced tests were cured in water for 14 days and stored

in a laboratory environment for 14 days that loaded in bending up to a mid span deflection of 3mm.

e. After curing, all specimens were exposed to cycles of intermittent wetting and drying. One cycle consisted of 3 days of saturation in 3.5 percent sodium-chloride solution and sulfate solution (of concentration similar to seawater) and 3 days of drying at room temperature.
f. After exposure for 2 and 6 months, flexural and compressive loading test were conducted. Four point loading was applied for the bending tests on a span of 250mm or 400mm, depending on the specimen size.

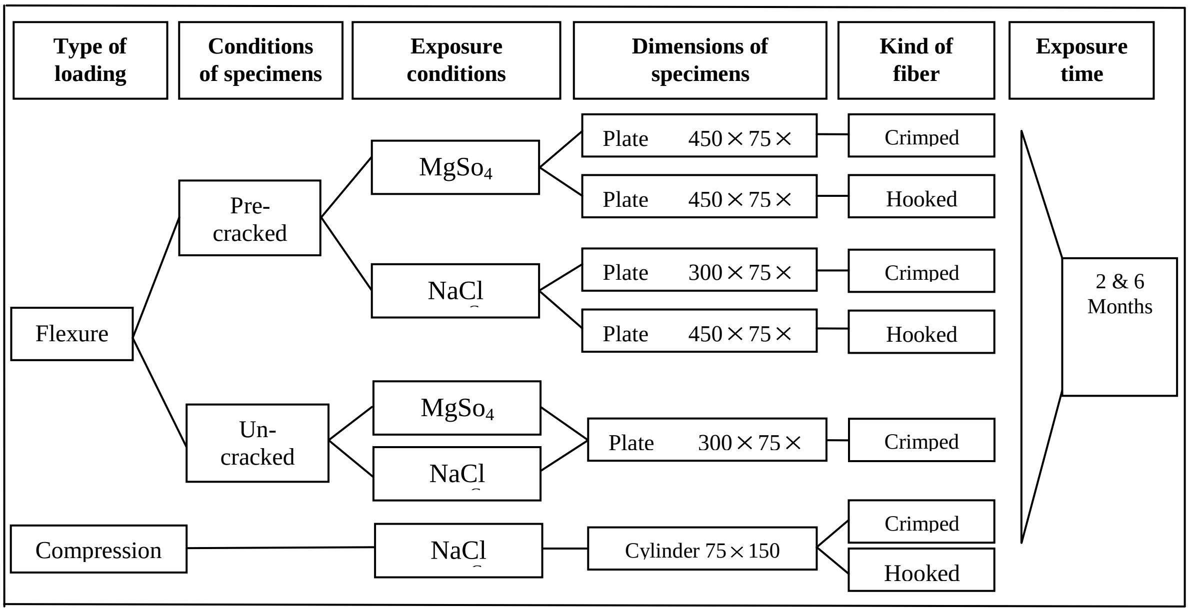

Figure 1. Flow chart for accelerated corrosion tests of SFRM specimens

For both tests, 100mm constant moment zone was maintained. The loading was applied in displacement control manner with the rate of 2.5mm/min. The deflection of mid-span was measured by an LVDT sensor. The details of the test set-up are illustrated in Fig. 2. Using the results the load-deflection curve was plotted on an X-Y recorder. For compression tests, the loading rate was 3mm/min.

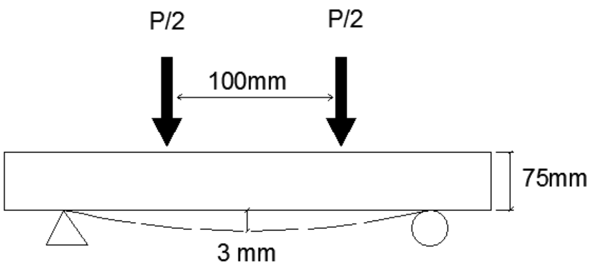

Figure 2. Pre-loading step for crack-induced specimens

2.2 Tests of mortar specimens containing corroded fibers

A flow chart of the experimental program is shown in Fig. 3. Steel fibers were exposed to cycles of intermittent drying and wetting. Each cycle consisted of 3 days of saturation in a 3.5 percent sodium chloride solution at 20C, followed by three days of drying at room temperature.

After 3 months exposure, the average reduction in minimum diameter of the fiber was measured. The fibers were used in flexural specimens with the same mix design of Table 1.

After casting, the specimens were kept in molds for 24 hours, and then wet-cured in water for 6 days. Next, it was air cured at room temperature for 21 days before being tested at 28 days. The correlation between the observed strength and toughness of the composite and the reduction in minimum fiber diameter was then investigated.

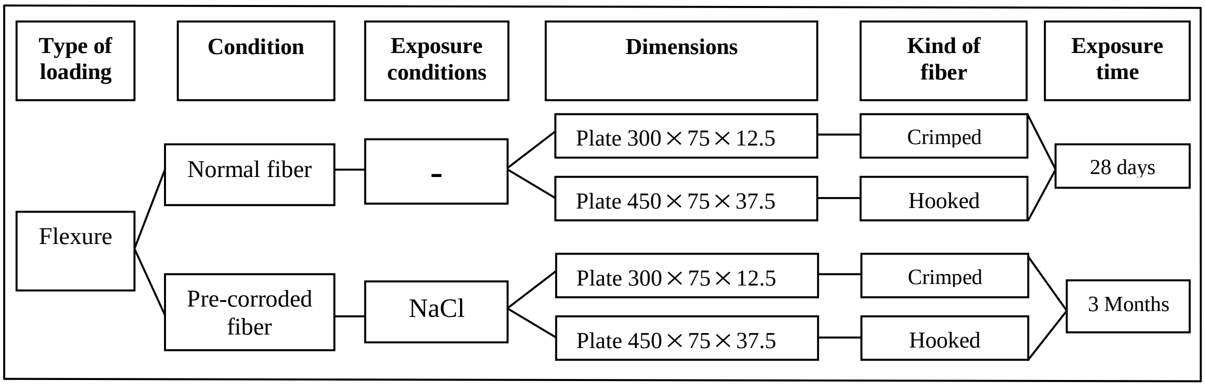

Figure 3. Flowchart for bending tests using pre-corroded fibers

2.3 Fiber pull-out specimen preparation

Fiber pull-out tests are generally used as an indirect method to evaluate bond. A flow chart of this test shown in Fig. 4.

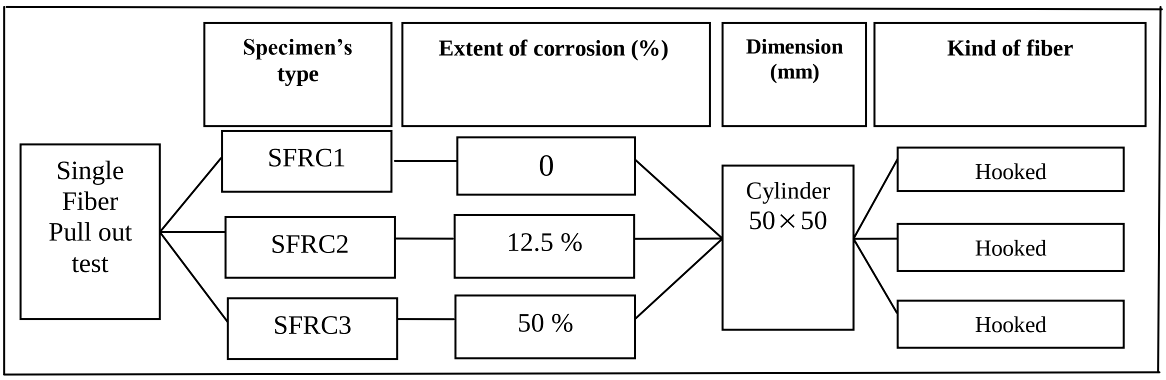

Figure 4. Flow chart for pull-outing tests

The test specimens were prepared using Plexiglas molds having (cylinder) 50 x 50 mm. Fibers were selected from each corrosion extents, with embedded within half length of fibers ($L_f/2$). The pull-out specimen mold preparation is presented in Fig. 5.

Figure 5. Fiber pull-out specimen mold

The concrete (with the mix proportion of Table 1) was poured into the molds and lightly vibrated. Then the specimens were covered by plastic sheet for 24 hours before they were de-molded. As mentioned before, hooked fibers were used in this part of experimental program. These fibers are suitable in shear due to hooked ends and small crimps all over the fiber length [19]. Fig. 6 shows the pull-out test setup.

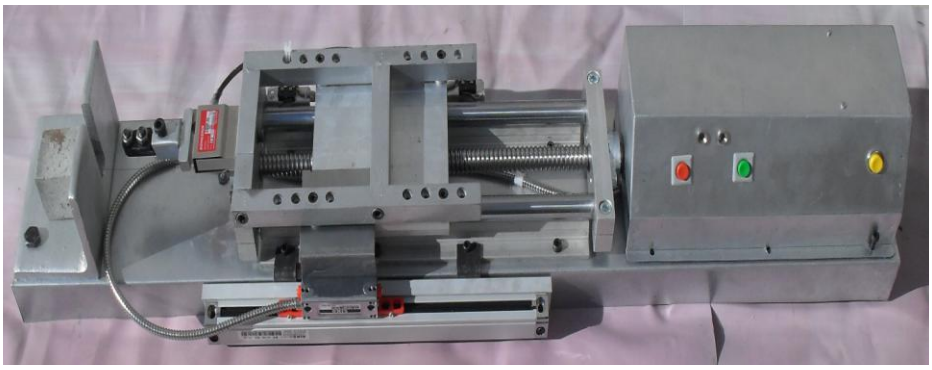

Figure 6. Fibers pull-out test setup

The pull-out resistance of fibers was measured by an accurate device with the ability of pulling out of the fibers with a constant displacement rate. This device would accurately record the pull-out load versus slip. Fibers were embedded vertically over a specified length in the specimen body. The tensile force and fibers were aligned perpendicular to the crack face. It is evident, where the embedded length of a fiber is lower than its critical length (Lc), it is pulled out from its matrix and where this length is longer than Lc, it fractures [20].

3. EXPERIMENTAL RESULT

3.1 Results of accelerated corrosion tests of steel fiber-reinforced concrete

Results of tests were shown in Table 3 and 4. Each parameter in these tables was obtained by calculating the average of three specimens test result. For uncracked specimens, results show that compared to the control specimen cured in laboratory air, peak stress and toughness of the specimens saturated in solution for 2 months increased by 30 percent. This can be the results of long term curing conditions and the early effect of corrosion, which improves the bond strength at the fiber-matrix interface [9].

In contrast, the peak stress and toughness of the specimens saturated for 6 months reduced by 30 percent, compared to the specimens saturated in solution for 2 months. This phenomenon can be due to the intensive effects of corrosion on the steel fibers and accordingly on the mechanical properties of SFRC.

3.2 Results of tests on specimens with pre-corroded steel fibers

In this group, the diameter of fibers was measured after a number of exposure cycles. Fig. 7 illustrates that the longer period of saturation, the more reduction in fiber diameter. Observations show that in the beginning of corrosion (after a few cycles), the thin layer of brass (coating) is vanished. Then, due to the production of corrosion agents a slight expansion in fiber volume and therefore in its diameter is observed. After a considerable number of cycles, measurements show about 50% reduction in fiber diameter.

Table 3: Results of flexural load tests for the pre-cracked specimens

Specimen Type	Maximum Stress (MPa)	Peak Force (N)	Toughness**
Type 1* Control specimens cured in laboratory air for 28 days	9.39	489.1	3.5
	10.86	565.5	4
	8.42	428.7	2.9
Type 1 specimens saturated at 50^{oC} in Sodium chloride water for 2 months	8.31	432.22	3.3
	7.36	400.91	2.73
	7.81	390.32	2.9
Type 1 specimens saturated at 20^{oC} in Mgso4 solution for 2 months	7.6	395.59	4.55
	10.14	421.2	4.87
	8.38	400.33	4.2
Type 1 specimens saturated at 50^{oC} in Sodium chloride water for 6 months	5.37	297.34	1.43
	6.01	312.84	2.3
	5.53	288.18	1.2
Type 1 specimens saturated at 20^{oC} in Mgso4 solution for 6 months	8.35	434.91	3.2
	8.51	442.61	3.65
	7.21	329.55	2.9
Type 2* Control specimens cured in laboratory air for 28 days	8.46	2080	16.2
	8.43	2080	18.75
	8.45	2000	17.48
Type 2 specimens saturated at 50^{oC} in Sodium chloride water for 2 months	7.93	1800	11.87
	7.76	1550	15.64
	7.22	1580	11.93
Type 2 specimens saturated at 50^{oC} in Sodium chloride water for 6 months	6.84	1610	11.93
	8.85	2120	14.23
	5.92	1340	12.14
Type 3* Control specimens cured in laboratory air for 28 days	7.9	1860	17.3
	10.69	2510	22.7
	6.99	1640	16.3

Type 3 specimens saturated at 20^{oC} in Mgso4 solution for 2 months	15.19	3550	21.6
	12.21	2860	17.57
	15.24	3530	22.21
Type 3 specimens saturated at 20^{oC} in Mgso4 solution water for 6 months	11.64	3200	16.92
	11	2570	16.71
	9.57	1690	13.6

* Type 1 specimens had dimensions of (12.5x300x75) mm. and were loaded to deflect up to 3 mm. at the mid-span.(with 2% Crimped Fiber)

Type 2 specimens had dimensions of (37.5x450x75) mm. and were loaded to deflect up to 3 mm. at the mid-span.(with 1.5% Hooked Fiber,(w/c=0.37))

Type 3 specimens had dimensions of (37.5x450x75) mm. and were loaded to deflect up to 3 mm. at the mid-span.(with 2% Hooked Fiber and with w/c=0.42)

**Toughness was calculated from the Flexure-Deflection curve up to 12 mm.

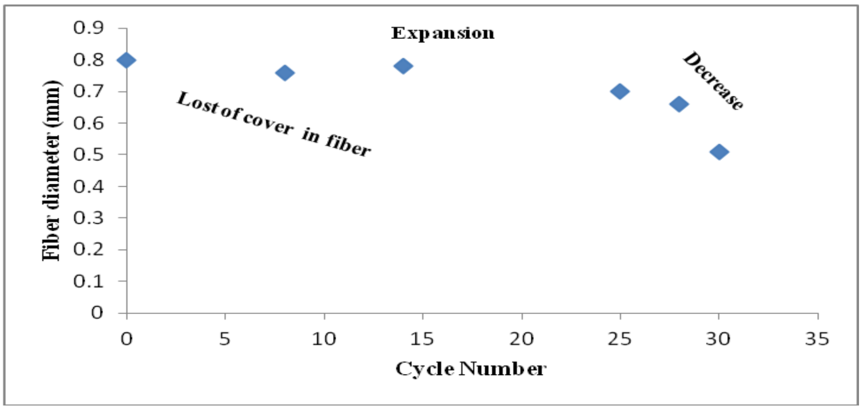

Figure 7. Fiber diameter versus the number of exposure cycles

Table 4: Results of flexural load tests for the uncracked specimens

Specimen Type	Initial crack Stress (MPa)	Peak Stress (MPa)	Toughness** I_5	Toughness** I^*
Control specimens cured in laboratory air for 28 days	6.1	10.2	5.92	3.2
	5.85	9.21	5.3	3.69
	4.48	9.23	4.79	3.45
Specimens saturated at 50c in Sodium chloride water for 2 months	9.13	12.82	5.48	3.92
	12.18	13.33	4.98	5.3
	11.11	13.15	6.14	4.3
Specimens saturated at 50c in Sodium chloride water for 6 months	7.65	10.49	4.7	3.53
	8.77	11.02	5.49	3.63
	6.58	9.56	4.55	3.12
Specimens saturated at 20c in Mgso4 solution for 6 months	6.4	10.81	5.28	3.8
	6.55	8.52	4.26	3.4
	6.4	9.74	4.32	3.5

* Initial crack stress is defined as initial moment divided by the section modulus.

**Toughness index I_5 is defined as the area under the curve up to a deflection of 3.0 times of first crack deflection, divided by the area up to the first crack point. Toughness index I^* is defined as the area under the Flexure-deflection curve for SFRM specimens up to a 12 mm [9].

Table 5 summarizes the results of flexural tests from the specimens with pre-corroded fibers. In this table, amount of initial crack stress, peak stress and toughness were measured in each test.

Table 5: Results of flexural load tests for the specimens using pre-corroded fibers

Specimen Type	Initial crack Stress (MPa)	Peak Stress (MPa)	Toughness**	
			I_5	I^*
Type*** 1 Control specimens cured in laboratory air for 28 days	4.36	5.16	5.65	8.17
Type 1 specimens with using pre-corroded Hooked fibers	4.81	4.81	4.035	4.44
Type 2 specimens with using pre-corroded crimped fibers	7.04	7.04	4.93	41.58
	7.64	7.81	3.71	40.91
Type 2 Control specimens cured in laboratory air for 28 days	6.31	9.63	5.48	61.64
	5.85	9.21	4.98	76.14
	5.48	9.23	6.14	66.27

* Initial crack stress is defined as initial moment divided by the section modulus.

**Toughness index I_5 is defined as the area under the curve up to a deflection of 3.0 times of first crack deflection, divided by the area up to the first crack point. Toughness index I^* is defined as the area under the Flexure-deflection curve for SFRM specimens up to a 12 mm.

***Type 1 specimens had dimensions of (37.5x450x75) mm.(with 1.5% Hooked fiber)

Type 2 specimens had dimensions of (12.5x300x75) mm.(with 2% crimped fiber)

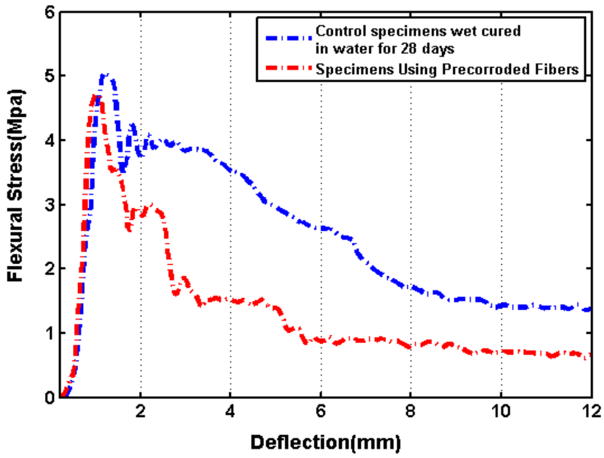

Figure 8. Flexural stress versus deflection chart for specimens using pre-corroded fibers

Flexural stress versus deflection chart depicted in Fig. 8. According to Table 5 and Fig. 8, these illustrate the reduction in post peak stress and toughness. Results show that, for the specimens with 50 percent degree of corrosion, reduction of fiber diameter do not have any considerable effect on maximum flexure stress, but compared to the control specimen wet cured in water for 28 days, its toughness is decreased by 50 percent. In other words, after the appearance of the first crack, the specimen will break suddenly.

3.3 Results of pull-out tests

Table 6 summarizes the results of pull out tests. Each series of test comprises 4 specimens. Amount of peak load, toughness and minimum fiber diameter after exposure were measured (according to the curves in Fig. 8) for each test.

Table 6: Results of pull out tests

Specimens Type	Fiber Type	Degree of Corrosion	Result of Test	Peak Load	Toughness*	Minimum Fiber diameter after exposure (mm)
SFRC1	Hooked	Normal fiber	Pull out	468.1	3487.7	0.8
			Pull out	401.2	3372.5	0.8
			Pull out	445.2	3674.5	0.8
			Pull out	383.5	2889.5	0.8
SFRC2	Hooked	12.50%	Pull out	495.3	3877.5	0.76
			Pull out	387.5	3056.9	0.78
			Pull out	451.6	3470.4	0.74
			Pull out	363.9	2097.6	0.75
SFRC3	Hooked	50%	Breakage	290	1179.1	0.64
			Breakage	222.5	413.94	0.51
			Breakage	270.1	430.94	0.44
			Breakage before testing	0	0	0.32

*Toughness was calculated from the load-slip curve.

Pull-out load versus slip is shown in Fig. 9. The typical pull-out response of hooked fibers can be seen in these charts.

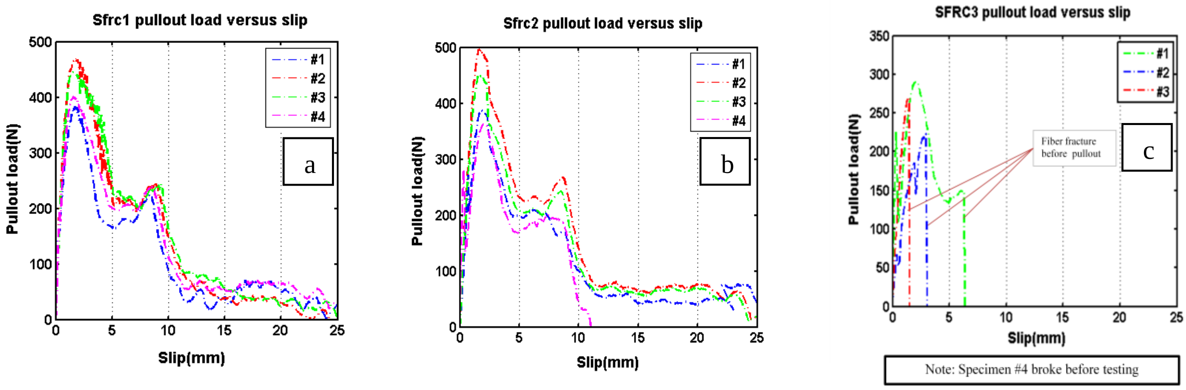

Figure 9. Typical pull out load versus slip chart a) SFRC1, b) SFRC2, c) SFRC3

Behavior of Pull-out charts can be described as following: the ascending part of the curve is caused by the bond between the fiber and the matrix. Afterward due to full debonding of the first hook, there is a sudden drop. Second drop is because of debonding of the second hook at the embedded end. There are two peaks in the curves. First peak indicates the moment that the first hook carried pull-out load and straighten, similarly, the second peek peak indicates this for second hook.

The results however show that the SFRC2 has a slightly higher peak than SFRC1. It can be explained as increase in friction between the fiber and the matrix due to the formation of corrosion products on the surface of the fiber. Corrosion products increase the fiber diameter by 12.5 percent. SFRC3 has lower peak strength compared to SFRC1 and SFRC2 and this is due to the decrease in the fiber diameter. In this group of the specimens, fiber breaks while pull-out test and amount of decrease in fiber diameter is 50 percent.

4. CONCLUSIONS

1. Despite the test period and the exposure condition, no cracking due to corrosion, was detected on the surface of steel fiber-reinforced concrete. However, the color of specimen surface ranged from light orange to dark brown. A Little change in initial modulus of elasticity was also detected after exposure.
2. Observation of fracture surfaces of steel fiber reinforced concrete specimens indicates that the effect of corrosion on fiber diameters gradually changes the type of the failure from typical fiber pull out to fiber fracture. Especially, for the specimens with pre-corroded fiber, 80 percent of fibers were fractured during pull out test.
3. It can be concluded from Fig. 8 that reduction of fiber diameter to 50 percent can decrease toughness almost to 50 percent, and then the specimen becomes more brittle. In other words, after the appearance of the first crack, the specimen will break suddenly.
4. Hot and humid environmental condition increases the chloride activities. Therefore, specimens cured in this exposure condition, corrode faster.
5. According to the pull out tests, at early stages of corrosion, the mechanical properties of the composites are generally improved. It can be the result of the expansion of steel fibers due to corrosion and therefore, their better anchorage in the matrix. However, after reaching a certain degree of corrosion, the mechanical properties are decreased. In fact, the loss of steel in fibers due to the corrosion of this stage causes this deterioration in the mechanical properties.

By increasing the water to cement ratio, effect of corrosion on the reduction fiber diameter was more.

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