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Influence of hybrid fibers on serviceability of RC beams under loading and steel corrosion

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HIGHLIGHTS

- Fibers in concrete changed the profile of corrosion of bars with decreasing the localized corrosion.
- Fibers cannot eliminate the detrimental effect of cracks in accelerating the onset of corrosion.
- Fibers reduced the corrosion-induced deflection of the beams.
- Hybrid fibers has positive effect in controlling corrosion-induced cracking.
- Fibers increased the service life of beams with prolonging their serviceability period in corrosion propagation period.

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ABSTRACT

This paper presents an investigation of the behavior of reinforced concrete (RC) beams containing steel, Polyolefin (PO), Polypropylene (PP), and their combinations under the simultaneous effect of accelerated corrosion and sustained loading. A new setup was designed that made possible the corrosion test of tensile reinforcement and the monitoring of the adjacent concrete cover during loading. During the corrosion test, the parameters of theoretical mass loss, corrosion crack width and cracking area, deflection, and corrosion potential were monitored. After the end of the test, the affected bars were extracted from concrete and gravimetry was done to determine the actual corrosion level. A new method known as "volumetric mass loss" was proposed to determine the profile of corrosion along the corroded bars.

The results show that the presence of fibers decreases the corrosion level of bars, but fibers do not affect the corrosion potential. The assessment of corroded bars by the volumetric mass loss method reveals that the presence of fibers mitigate the severity of localized corrosion. The fibers reduce the corrosion cracking and deflection in comparison to the beam made of plain concrete. The observation indicates that the selection of a proper combination of fibers can significantly improve the service life of beams from structural and aesthetic viewpoints.

1. Introduction

One of the most important factors that lead to the shortening the service life of reinforced concrete structures is reinforcement corrosion. Expansion of concrete cover, the formation of corrosion-induced cracks, and concrete cover spalling are the main types of damages caused by reinforcement corrosion, which threaten the aesthetic integrity of structures. From the structural viewpoint, reducing the bond between corroded bars and concrete and decreasing the confinement of bars due to longitudinal corrosion cracks cause degradation in the stiffness of reinforced concrete (RC) elements. Furthermore, by decreasing the cross-section of corroded bars, the ductility and ultimate strength of RC elements can decrease and even the failure modes can change.

In corrosion-damaged structures, a precise condition assessment is needed to estimate the residual service life and determine the appropriate strategies for repair and rehabilitation. Since the amount of corrosion-induced damage of bars embedded in concrete cannot be measured directly, finding the relationship between apparent indicators of corrosion and the amount of damage can help engineers to estimate the steel corrosion damage. According to literature, the crack width and deflection are probably the most common indicators used by researchers [1,2].

Recently, studies on corrosion of bars in plain concrete have been carried out under sustained loading [1–8], since the structures are normally under service loads and these loads can affect the corrosion process. The stress can affect the corrosion of bars

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and corrosion-induced cracking [1,2]. Also, It is well-established that flexural cracks hasten the initiation of corrosion [4] and increase the rate of corrosion [9]. In most of these studies, accelerated corrosion techniques were employed to shorten the corrosion process.

In recent years, the usage of fibers in concrete has become more prevalent due to their advantages. It is well-established that inclusion of fibers in concrete can control crack propagation and improve the ductility of concrete. Accordingly, it can be expected that the fibers affect the corrosion process and its indicators. A literature review shows that very few studies focus on the corrosion of steel in fiber-reinforced concrete in comparison to that in plain concrete [10–18]. The previous studies show that the presence of fibers in concrete can delay the corrosion initiation of steel [10–12], mitigate the negative effect of corrosion on the bond between corroded steel and concrete [13,14], and prevent the widening of corrosion cracks [15,16]. Furthermore, some researchers [16–18] reported the decrease of steel corrosion in fiber-reinforced concrete. Most of these studies have been conducted on small specimens without considering the simultaneous effect of loading and corrosion. In addition, a few studies [10–12] focus on the initiation of steel corrosion in fiber-reinforced concrete under loading but do not fully discuss the propagation stage of corrosion. Therefore, further studies are needed to better understand the corrosion of reinforcement in fibrous concrete and the performance of concrete structures under the simultaneous effect of corrosion and loading.

In the present study, the corrosion of tensile reinforcement bars of scaled concrete beams made of fiber-reinforced concrete under accelerated corrosion and loading is investigated. The fiber-reinforced concrete mixes were produced using various fibers and their combinations. The beams were also tested in two cases without loading and sustained service loading. Parameters such as corrosion potential, cover cracking, and deflection were investigated during testing. After the end of testing, the corroded reinforcements were extracted from specimens and the amount of corrosion was determined. To measuring the corrosion percentage of steel bars, a new method is suggested which known as “volumetric mass loss”. The results of this study can help engineers in estimating the proper amount of corrosion and determining the appropriate service life of RC beams containing fibers.

2. Experimental work

Two series of concrete beams were prepared to assess the influence of fibers on the corrosion of tensile reinforcement. In each series, the fiber-reinforced concrete mixes were produced by using the steel and polyolefin fibers and combining each of them with polypropylene fibers. The beams were tested under accelerated corrosion method in two cases of without loading and sustained service loading. The amount of sustained load was about 60% of the ultimate flexural load of beams. Parameters such as corrosion potential, cover cracking, and deflection were monitored during testing. After the end of testing, the corroded reinforcements were extracted from specimens and the corrosion levels were determined by theoretical and gravimetric methods. Furthermore, a new method was suggested to measure the corrosion percentage of steel bars, known as the “volumetric mass loss” method. Details of test specimens and methods are presented in following sections.

Table 1
The properties of fibers.

property	Steel	Polyolefin	Polypropylene
Length (mm)	50	48–50	12
Diameter (mm)	0.6	1–1.25	0.02
Density (gr/cm^3)	7.85	0.91	0.91
Tensile strength (MPa)	950	550	400
Elastic modulus (GPa)	200	>8	3.5

2.1. Materials and mix proportions

Ordinary Portland cement was used to produce the mixtures. The fine aggregate was natural river sand with fineness modulus of 2.92. The coarse aggregate was natural crushed gravel with a maximum size of 12.5 mm. To enhance the workability of mixtures, a modified polycarboxylic-ether-based high-range water-reducing admixture (HRWRA) was used. Different fibers such as steel, polyolefin, and polypropylene fiber were used; their properties are given in Table 1. Six mixtures were used; their details are shown in Table 2.

A plain mixture (B1) without fibers was designed to achieve compressive strength of about 40 MPa on 150-mm cube specimens at 28 days. The other mixtures containing fibers (B2–B6) were developed based on the addition of fibers to the plain mixture. For all mixtures, the water-cement ratio was 0.42. In mixtures containing steel and PO fibers individually or in combination with PP fibers, the total fiber volume fraction was limited to 1% to consider the practical concerns about the workability. Moreover, PP fibers were employed at the volume fraction of 0.1%.

2.2. Beam specimen details and preparation

Fig. 1 shows dimensions and reinforcement details of beam specimens. The 12 RC beams—two beams for each mixture, with dimensions of 120 mm in width, 160 mm in depth, and 1240 mm in length—were made. The two deformed steel bars of #12 were used as longitudinal tensile reinforcement with a yield strength of 450 MPa and ultimate strength of 680 MPa. The longitudinal compressive reinforcement included two deformed steel bars of #8 with a yield strength of 360 MPa, and ultimate strength of 530 MPa. In addition, to provide adequate shear reinforcement, a round steel bar of 6-mm diameters spaced at 65 mm was used. Since this study only investigates the corrosion of tensile reinforcement, to prevent the corrosion of stirrups, they were electrically isolated by plastic tape at the junction with the tensile reinforcements. In addition, for facilitating the electrical access to longitudinal reinforcement after casting, small pieces of round steel bars were welded to the end-hooks of longitudinal bars (Fig. 2). For all beams, longitudinal bars had a clear concrete cover of 25 mm on adjacent sides. The beams were cast at three layers and were demolded after 24 h. After this, the beams were wet-cured for 28 days.

2.3. Sustained loading apparatus

To apply sustained load on beam specimens during the corrosion test, the authors designed and built a new apparatus at Guilan University, as shown in Fig. 3. The apparatus was designed so as to produce a third-point loading over an effective span of 1100 mm. A steel beam with the length of 1500 mm was used as the base to provide the adequate support reactions. Regarding the selected span and cross-sections, the ratio of base stiffness to beam specimens' stiffness was approximately 3.5. Two roller supports, spaced 366 mm apart, were located on the base at an equal distance from its center. The beam specimen was placed on these supports so that the tensile reinforcements were positioned at the top and the middle third of loading span, corresponding to the distance between the supports.

The loading was performed using two hydraulic jacks of 50 kN capacity at each end of the beam. The height increment of jacks was limited from above by a steel plate, which linked the threaded rods on each side of the beam. In addition, another steel plate connected the threaded rods under the base. These steel plates were

Table 2
Proportions of mixtures.

Beams	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Fiber volume fractions			HRWR (kg/m3)
					St (%)	PO (%)	PP (%)	
B1	390	164	877	965	–	–	–	1.17
B2	390	164	877	965	–	–	0.1	1.17
B3	390	164	877	965	–	1	–	1.17
B4	390	164	877	965	–	0.9	0.1	1.17
B5	390	164	877	965	1	–	–	1.17
B6	390	164	877	965	0.9	–	0.1	1.17