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Effect of corrosion on flexural strength of reinforced concrete beams with polypropylene fibers

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HIGHLIGHTS

- Effects of polypropylene fibers on uncorroded and corroded reinforced concrete beams were studied.
- Flexural strength of corroded reinforced concrete beams was investigated.
- Shear strength was regained by polypropylene fibers up to a certain corrosion level.
- Displacement ductility of corroded beams was preserved with the aid of increased amount of plastic fibers.

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ABSTRACT

An experimental study was performed to investigate the effects of polypropylene fibers on uncorroded and corroded reinforced concrete beams. Three different volume fractions of polypropylene fibers having 0, 0.5, and 1.5%, were tested at four corrosion levels of 0% and approximately 5, 7, and 9%. A full scale of an accelerated corrosion pool was used for the accelerated corrosion process. Reinforced concrete beams were used for an under monotonic bending test. The contribution of the actual corrosion levels of transverse and longitudinal reinforcement bars to the total corrosion levels were obtained from reinforcement bars fully extracted from concrete. Flexural strength, bond-slip, and moment-curvature relationships were examined for uncorroded and corroded reinforced concrete beams. A new model was developed to predict the flexural strength of corroded reinforced concrete beams. The proposed model for predicting the residual flexural strength of corroded beams was compared with test data published in previous studies. Furthermore, a novel model is presented for improved predictions between the actual and theoretically estimated corrosion mass losses, based on Faraday's law, with the aid of fully extracted reinforcement bars. The model used to predict the flexural strength of corroded reinforced concrete beams with large sizes demonstrated good agreement with current and previously published literature data. In the case of corroded beams comprising differing amounts of polypropylene fibers, the performance of the corroded beams was limited by a fiber volume fraction of 1.5% at low corrosion levels.

1. Introduction

Corrosion of reinforcement in concrete is considered to be one of the most common reasons for the deterioration of reinforced concrete (RC) [1]. Once the corrosion in steel bars initiates it reduces the seismic performance levels of RC structures. Steel depassivation occurs mainly due to concrete carbonation and chlorides contamination [2]. Damaged protective passive film around steel bars under the influence of chloride and carbonation can result loss in cross-sectional area of steel bars. While the cross-sectional area of steel bars is reduced due to corrosion, the corrosion products around the steel bars cause volumetric expansion in concrete zone. Study done by Bazant [3] indicated that the volume of corrosion rust is 2–4 times larger than the volume of uncorroded reinforcement bars which leads to cracking of concrete. As a consequence of changes in the mechanical properties of concrete and steel bars; corrosion may result in loss in ductility ratios, load carrying capacities, bond and shear strength of RC structures. Various materials such as steel and plastic fibers have been extensively applied in the construction industry, in order to increase the shear capacity of RC members. Several studies, including those

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of Song et al. [4], Roesler et al. [5], Michels et al. [6,7], Pujadas et al. [8], Rosidawani et al. [9], Sofi and Phanikumar [10], Park et al. [11], Spadea et al. [12], and Fraternali et al. [13] have investigated the effectiveness of the use of steel, plastic, nylon or polyethylene terephthalate fibers in concrete members. Won et al. [14] tested different sizes and types of synthetic fibers to obtain the optimum sizes and to evaluate the effects of the synthetic fibers on the bond and flexural strength of uncorroded concrete specimens based on pullout tests. Previous studies that used the pullout test to examine the bond strength with the aid of synthetic fibers have not been representative of the actual behavior of concrete members, as both the concrete and reinforcement bars were only under tension during the pullout tests.

Although considerable studies have been performed to take advantage of the use of plastic fibers, to the best of our knowledge, the effect of plastic fibers on full-scaled corroded RC beams has not been studied yet. Moreover, test results of previous studies on uncorroded beams with fibers have been limited based on load–displacement relationships, and the contributions of fibers to bond-slip relationships in full-scaled RC beams have not been investigated. Therefore, in this study, the effects of plastic fibers on both corroded and uncorroded full-scaled RC beams was examined for flexural strength, load deflection, crack patterns, and the contribution of different amounts of plastic fibers on bond-slip relationships at various corrosion levels. Because the present study has already focused on full-scaled corroded RC beams, authors of this paper have expended a significant effort to obtain the actual corrosion levels by extracting reinforcement bars from concrete. Hence, the actual corrosion levels were obtained for each transverse and longitudinal reinforcement bar for improved prediction of the flexural strength of corroded RC beams.

There are two main points that may be considered in the developed models for predicting the flexural strength of corroded RC beams. First, the previously published experimental studies that were performed and applied to corrosion cases generally considered uniform corrosion levels based on Faraday's law, in accordance to the current that flowed through the system. Many other researchers have opted to use steel coupons cut from the corroded bars to calculate the corrosion levels. In simple terms, the assumed or calculated amounts of mass losses in a steel bar return to different corrosion levels for the same amounts of mass losses in different bars owing to the change in the original mass of the bars. This phenomenon was also demonstrated by Malumbela et al. [15] on steel coupons. Very few studies have been performed on calculating the actual corrosion levels by extracting the corroded reinforcement bars from concrete (e.g., [16,17]), where the tested samples had a smaller size than those of the current study. The second important point for the prediction of residual flexural strength may be defined by the calculated moment-resisting capacities of corroded RC beams, considering only corroded tensile reinforcement bars. Although the theoretical calculation of moment-resisting capacities of RC beams does not consider the effects of transverse reinforcement bars, these bars effect the load-carrying and displacement capacities, particularly in the case of corrosion. Theoretical flexural moment capacity which is calculated based on assumptions (i.e., plane section remains plane after bending, tensile strength of concrete and effects of transverse reinforcement bars on moment resisting capacity are neglected) of load carrying capacity is less than the actual capacity since strain hardening of reinforcing steel and confinement effects are neglected. Although transverse reinforcement bars resist the shear forces; they have effects on total displacement in a RC member that can be obtained from displacements due to curvature, slip and shear. Previous studies also indicated this phenomenon (e.g., [18,19]). Moreover, important results were published by Suffern et al. [20]. In their study, the load-carrying capacity of uncorroded stirrups was better compared to beams without stirrups. However, the load-carrying capacity of the beams without stirrups was also greater than that of the corroded beams with stirrups. The results obtained by Suffern et al. [20] indicated how corrosion effectively changes the failure mechanism of concrete members by considering the type of reinforcement bars. Considering the above, a new model was proposed for improved prediction of the flexural strength of full-scaled corroded RC beams by revisiting previous models.

2. Experimental program

2.1. Section configuration and properties

In this study, the plastic fibers that were dispersed in the concrete were used at different levels of corrosion. The test specimens were divided into four main groups: A, B, C, and D. Group A represents a 0% corrosion level, while groups B, C, and D, represent corrosion levels of approximately 5, 7, and 9%, respectively. Each main group was then divided into three subgroups based on the volume fraction (V_f) of polypropylene fibers (P_f) at 0, 0.5, and 1.5%. As shown in Fig. 1, the depth and width of an RC beam were 400 and 250 mm, respectively, while the clear span length of the beam was 2500 mm. The concrete cover from concrete surface to the center of the transverse reinforcement bars was taken as 25 mm. Deformed reinforcement bars were used for each specimen. All RC beams were designed in accordance to the under reinforced beam theory to resist a moment capacity of 118 kN m. The tensile reinforcement bar diameters were 16 mm, and the top compression reinforcement bars were 12 mm. The transverse reinforcement bar intervals were 130 mm at the densifications and 180 mm at the spans. Fig. 2 illustrates the selected and tied RC beams before concrete was poured. In Fig. 2, S indicates the number of the 18 transverse reinforcement bars, while T and C indicate the number of tension and compression reinforcement bars used for the gravimetric test results.

2.2. Material properties and casting concrete

The recorded mechanical properties of the reinforcement bars were as follows: yield strength at 490 MPa, rupture strength at 600 MPa, and strain at yielding and rupture at 0.00245 and 0.0115, respectively. The calculated elastic modulus of the reinforcement bars was 2×10^5 MPa. Ready-mixed concrete was used for all RC beams, and all beams were poured at the same time, and had the same concrete quality. No air-entraining or water-reducing admixtures were used. After three months of curing, the calculated concrete compressive strength was 30 MPa based on cubic tests. The ultimate strain for the concrete was assumed to be as 0.003. The mechanical properties of the plastic fibers were provided by the manufacturer. The tensile strength of the fibers was 650 MPa, the modulus of elasticity was 5400 MPa, and the fiber lengths ranged from 54 to 60 mm, with a density of 0.91 g/cm^3. The diameters of the fibers were ranged between 0.44 and 0.48 mm. Thus, calculated average aspect ratio of polypropylene fibers was 124. Grouped amounts of fibers were gradually added into the concrete mixers before pouring the concrete. In this study, mechanical properties of concrete (i.e., compressive and splitting tests) with fibers as a function of corrosion levels were not tested. Further studies are required by considering the mechanical properties of corroded samples with additive materials to be used for analytical analyses.

2.3. Accelerated corrosion method

Following three months of curing, the specimens were subjected to an accelerated corrosion method. Fig. 3 illustrates the accelerated corrosion method setup. The concrete pool was isolated with a plastic membrane to prevent any loss of current flow, and the copper plates that surrounded the concrete pool acted as a cathode. One of the bending reinforcement bars was extended by 160 mm beyond the concrete top face, and was planned to be used as an anode. The extended bars were surrounded with polyvinyl chloride pipes to prevent pitting corrosion on the concrete's top surface. As shown in Fig. 4, copper tie wires were used in the shear reinforcement bars to provide improved conductivity in the extended bending reinforcement bar. An adjustable, direct current power supply at a rated voltage of 60 V and a rated current within the range of 0–10 A was used. In order to shorten the corrosion process, 3.5% sodium chloride by the mass of water was added to the corrosion pool. Voltmeters were connected to each specimen to record the current at one-minute intervals, in order to monitor and achieve the designed corrosion levels. The time required for achieving the estimated corrosion levels was calculated based on Faraday's law in accordance to the following equation:

$$mass\ loss = \frac{t(s) \times I(A) \times 55.847}{2 \times 96487} \quad (1)$$

where t is the time and I is the current. In this case, Faraday's law was used only to monitor the designed corrosion levels. The actual corrosion level for each specimen was calculated based on Eq. (2):