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Short Communication

High Mechanical Performance of Reinforced Concrete Wrapped with Carbon-Fiber Polymer and Electrochemical Corrosion Behavior of Carbon Steel in the concrete

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One of the solutions proposed by researchers to control the corrosion of reinforced concrete is the use of wrapping technology. Many researchers have investigated carbon-fiber polymer (CFP) for the aim of wrapping reinforced concrete. However, the effect of using CFP on the corrosion resistance of concretes has not been fully studied by researchers. This work focused on the mechanical performance and electrochemical corrosion behavior of carbon steel reinforced concrete wrapped with CFP. The samples were made with one, two, and three CFP layers and tested for corrosion resistance. The orientation of wrapped CFP has also been studied in this work. The results indicated that the compressive strength of the concrete cube samples increased by increasing the CFP layers. Electrochemical impedance spectroscopy tests indicated that the reinforced concrete wrapped with CFP had a higher value of passive film resistance compared to plain concrete, indicating more enhancement of corrosion resistance on the surface of carbon steel rebar.

Keywords: Carbon-fiber polymer; Reinforced concrete, Electrochemical corrosion; Compressive strength

1. INTRODUCTION

Deterioration of concrete substructure components limits the service life of a carbon steel Reinforced Concrete [1, 2]. Generally, concrete structures in harsh environments, such as marine environments and coastal areas, are prone to premature deterioration [3, 4]. In this regard, in reinforced concrete, despite all researches that had been done on this subject, corrosion of carbon steel Reinforced Concrete is still a major problem in construction engineering approach [5, 6]. Hence, various methods of corrosion prevention are still engaging considerable effort among scholars. For example, in transportation infrastructure, a remarkable cost is associated with the repair or replacement of corroded elements. A study revealed that approximately 40% of the highway bridges in the USA are suffering from structural deficiency [7, 8].

The mechanism of corrosion in concrete structures was discussed in different resources [9, 10]. By increasing the reinforcement corrosion, two significant phenomena occur. First, by the expansion of reinforcement, damages in the concrete surrounding the reinforcement are created. Second, the damage frequently caused spalling and cracking which could be easily seen in the concrete surfaces [11, 12]. It should be noted that the loss of rebars section lead to a noticeable damage into structural integrity of steel rebar. The attempts of protecting concrete structures and rehabilitation of corroded elements of concrete structures have led to the development of numerous methods that are used to protect the reinforcement [13-16]. Increasing the volume of rusted reinforcement presses the concrete around the rebars and causes damages. Therefore, the reinforced concrete mainly suffer from cracking (typically parallel to the rebars), delamination, or spalling of the concrete. Obviously, created cracks make the aggressive agents easily ingress toward the steel and consequently increase in the rate of corrosion [17, 18]. Second, due to the progressing of corrosion procedure, the cross-sectional area and load-carrying capacity of a rebar decrease.

One of the methods which had been frequently addressed by different researchers is wrapping the concrete elements with carbon-fiber reinforced polymer [19]. Nowadays, carbon-fiber polymer (CFP) are widely utilized as an alternatives approach for the re-strengthening and rehabilitation of concrete structures [20]. The main advantages of CFP is a high stiffness-to-weight ratio, suitable durability, and remarkable corrosion resistance [21-23]. Incorporating of CFP sheets in wrapping the concrete columns is one of the main applications of CFP, which could increase concrete confinement, strength, and durability [13].

The main goal of wrapping concrete structures with fiber-reinforced polymer is the reduction of reinforcement corrosion since the CFP layer reduces the permeability of concrete and could increase the durability [24]. This technique has continuity, improved fiber orientation, and fewer bonding problems, causing an enhanced ability to develop confinement [7, 25].

Hence, CFP wraps are considered a good long-term solution for the corrosion problems present in civil infrastructures. Since the effects of CFP wraps on the corrosion behavior of carbon steel reinforced concrete have not been previously reported. In this work, mechanical performance and electrochemical corrosion behavior of carbon steel reinforced concrete wrapped with CFP have been evaluated.

2. MATERIALS AND METHOD

In this study, the granite with a unit weight of 1617 kg/m^3, the specific gravity of 2.67, and absorption of 0.66 was used as coarse aggregate. The fine aggregate was natural river sand with a maximum size of 5.0 mm, bulk density of 1547 kg/m^3 and fineness modulus of 2.9. Type I Portland cement was used for this research. Table 1 indicates a mix design of concrete in accordance with ASTM C1567.

Table 1. A mix design of concrete in accordance with ASTM C1567

Mix design	
Water	180 (Kg)
Cement	380 (Kg)
Coarse aggregate	915 (Kg)
Fine aggregate	885 (Kg)
Slump(mm)	65

Table 2. Coating Styles and Sample Surface Treatment

Samples	Number of CFP wraps	Wrap fiber orientation	Number of samples	Coating thickness (mm)
CON	0	N/A	3	0
C1W90	1	90	3	1.5
C1W45	1	45/-45	3	1.5
C2W90	2	90	3	2.3
C2W45	2	45/-45	3	2.3
C3W90	3	90	3	3.4
C3W45	3	45/-45	3	3.4

The different styles of sample, wrap fiber orientation and average coating thickness of each sample are presented in Table 2.

The chemical compositions of carbon steel rebar was C (0.12 wt%), Mn(0.78 wt%), Si(1.5 wt%), Cr(0.08 wt%), Ni(0.11 wt%), Cu(0.32 wt%), Al(0.01 wt%), and Fe is the balance. The concrete mixture was poured into a cylinder mold with a diameter of 10 cm and height of 40 cm, while the steel rebar with 20 cm length and 1.2 cm diameter was placed vertically at the center of the cylinder mold.

For the compressive strength test, 3 replication of cube specimens with a dimensions of 15cm×15cm×15cm were produced. The concrete was poured in the mold and was tempered in order to remove any unwanted holes. Initial curing was 24 hours then molds were removed, and test specimens were put in water for curing.

A three-electrode cell was used for the electrochemical measurements which include the carbon steel reinforced concrete, platinum wires and a saturated calomel electrodes as working, counter and reference electrodes, respectively. The specimens were immersed in a 5% NaCl solution. The schematic of the EIS test configuration is shown in Figure 1. The EIS analysis was done in frequency range of 0.01Hz to 0.1MHz. Value of the water absorption was considered by drying a specimen with constant mass. Then the sample was exposed to water and the mass of the saturated surface-dry was determined. The water absorption is the ratio of the difference between the two-values determined to the dry mass.

A scanning electron microscope (SEM) was used to investigate the surface morphologies of carbon steel rebars.

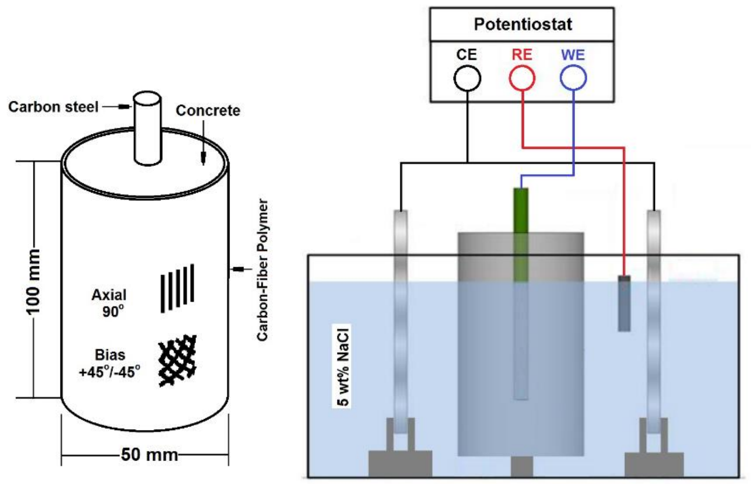

Figure 1. Schematic of EIS test configuration and wrap fiber orientation

3. RESULTS AND DISCUSSION

The compression testing machine was used to evaluate the specimen in 7, 28, and 90 days of curing. The load were applied gradually at the rate of 130 kg/cm^2 per min until the specimens fail. The cube of concrete samples were tested whether in simple or in the condition which was wrapped with CFP.

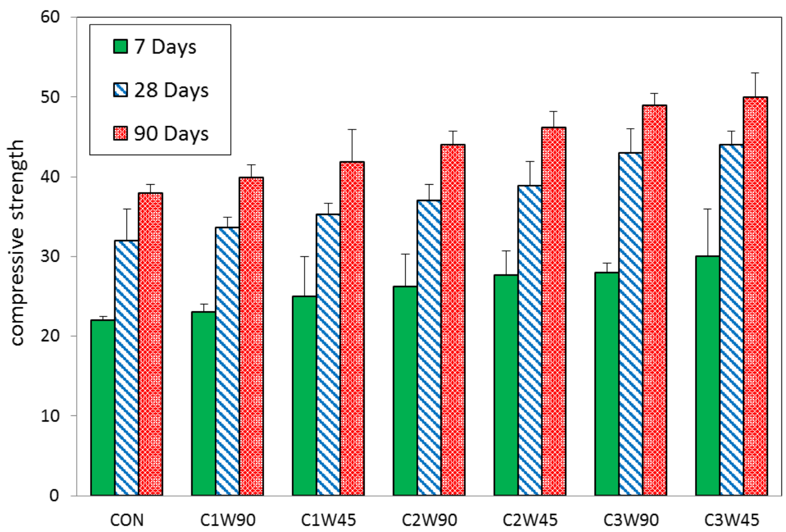

Figure 2. Compressive strength of concrete wrapped with CFP in different wrap fiber orientation at three different ages (7, 28 and 90 days) at room temperature

Figure 2 indicates the compressive strength at three different ages (7, 28 and 90 days). It was observed that the 28-day compressive strength of the control was 32.1 MPa while compressive strength corresponds to the C3W45 and C2W45 were 42.4 and 38.1 MPa. It can be concluded that when the number of CFP layer increase, compressive strength of the concrete subsequently increase [26]. Furthermore, the orientation of CFP wrapping was effective in strengthening the concrete. As shown in figure 2, the specimen with wrap fiber orientation of $45^{o}/-45^{o}$ revealed the higher values for compressive strength.

Figure 3 shows the average days to failure in the different specimens. As shown in Fig. 3, the average lifespan of the wrapped samples were higher than the control sample. These samples with a lower number of the wrapped layer reached the failure significantly sooner. Given the orientation position of CFP, it can be concluded that although the wrap fiber orientation of $45^{o}/-45^{o}$ have a better performance than the 90^{o} one in two layers wrapped, it was not possible to observe a specific trend based on the single-layer and three-layer samples [27].

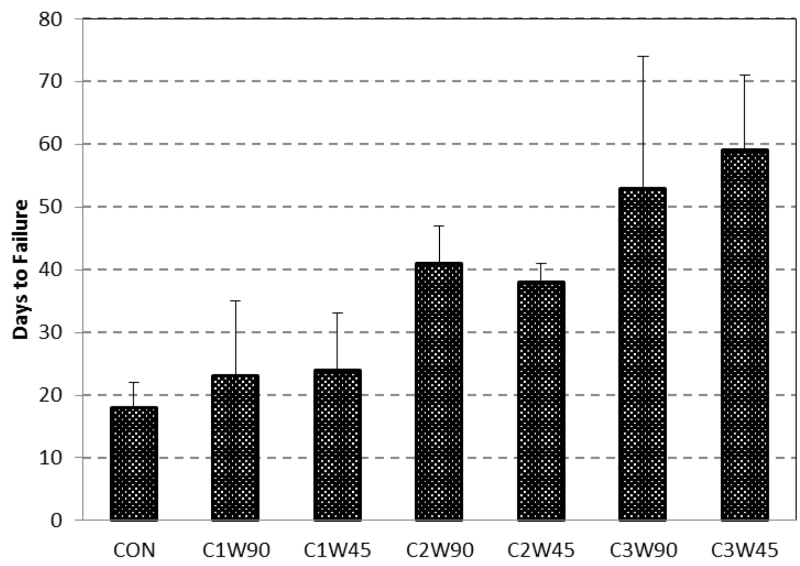

Figure 3. Average day to failure in various samples with CFP in different wrap fiber orientation and different number of CFP layers at room temperature

Figure 4 shows the mass loss data per exposure day. It should be noted that Figure 4 does not provide any information about the rate of corrosion over the sample life. The actual goal of Figure 4 is to normalize the mass loss data because every sample had a varied exposure time. As shown in figure 4, the number of CFP layers had a significant effect on performance of concrete samples. With the increase of CFP layer all samples indicated a smaller amount of mass loss ratio than the control sample, on average.

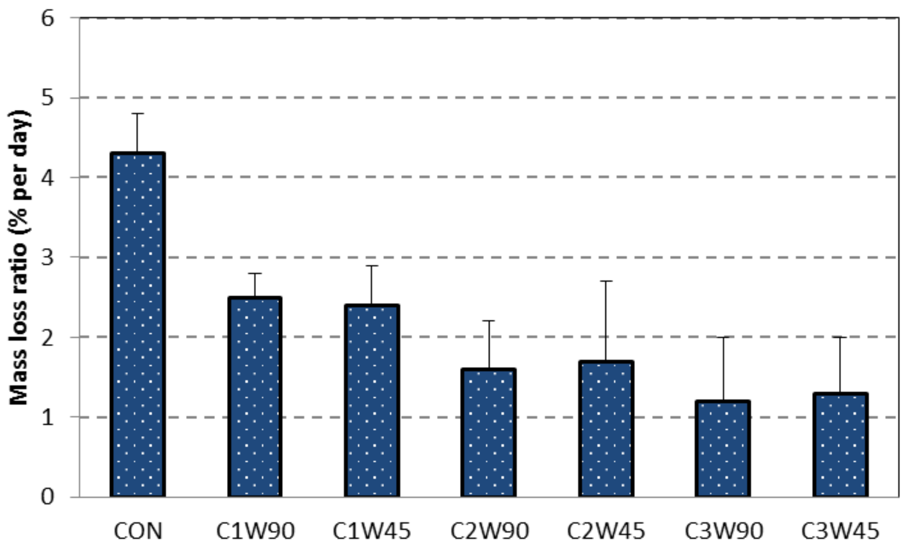

Figure 4. Mass loss ratio (% per day) in various samples with CFP in different wrap fiber orientation and different number of CFP layers at room temperature

Figure 5 indicates the results of chloride ingress measurements. The concentration of chlorides to exposure days (ppm/day) provide a relative measure value to compare samples subjected to different exposure times. As revealed in Fig. 5, when the chloride concentration was divided with the number of days to obtain the data, the concrete chloride content results indicated a remarkable evidence that the number of wraps layers and their orientations influenced the ingress of chlorides. The sample C3W45 revealed lower value than the other samples which can be a good offer as an alternative approach to enhance the corrosion resistance.

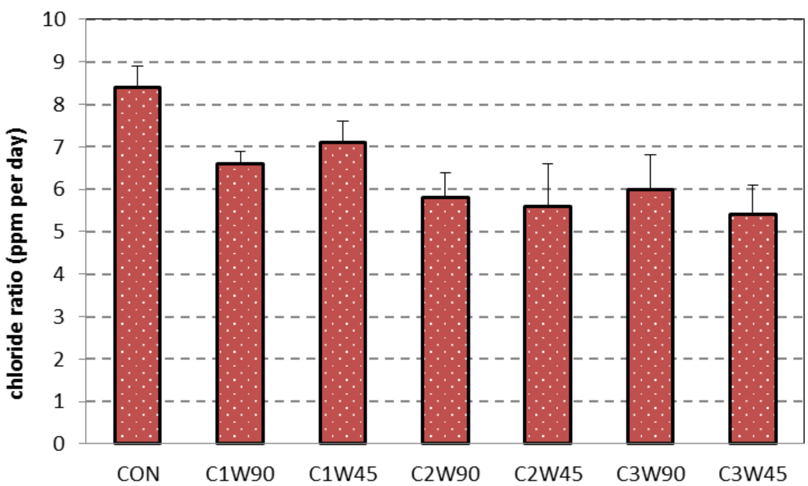

Figure 5. Chloride ratio (ppm per day) in various samples with CFP in different wrap fiber orientation and different number of CFP layers at room temperature

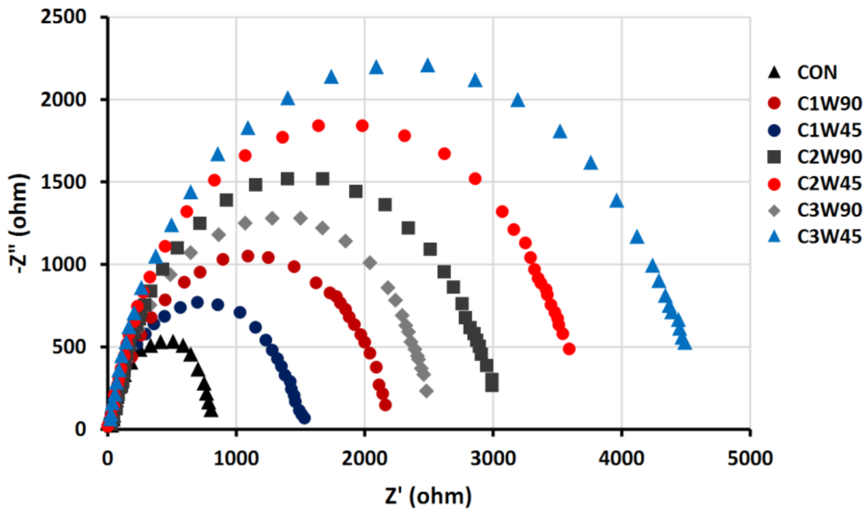

Figure 6. Nyquist plots of carbon steel rebars in concrete with CFP wrapped in different fiber orientation and different number of CFP layers at room temperature in 5% NaCl solution.

An EIS system was used to evaluate the corrosion resistance of carbon steel reinforced concretes wrapped with carbon-fiber polymer in 5% NaCl solution. As shown in figure 6, the increase in CFP layer leads to an increase in the radius of the capacitive loop indicating an enhancement of the corrosion resistance for reinforced concrete. It can be attributed to the formation of protective passive layer [28].

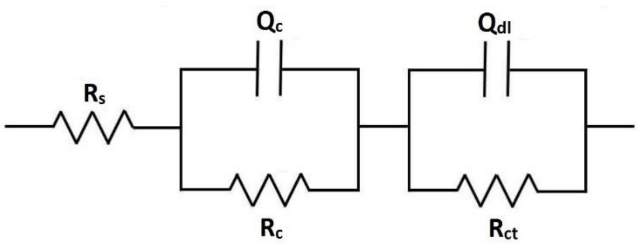

Figure 7. Equivalent circuit model used

The equivalent circuit model used is shown in Fig. 7. It should be noted that R_s, Q_c and R_c is the resistance of solution, capacitance and the resistance element for coated concrete, respectively [29]. Additionally, R_{ct} and Q_{dl} are the charge transfer resistance and the double-layer capacitance of the steel surface [30, 31]. Table 3 indicates the data derived from figure 6. The decrease of Q_C exhibits an enhancement in the corrosion resistance, thickness and stability of the passive layer on the carbon steel rebar. The better performance of corrosion resistance in the wrapped concrete samples with carbon-fiber polymer can be easily concluded from the data in table 3 and Fig.6. In addition, by comparing Q_c and Q_{dl}, it was observed that Q_{dl} was higher than Q_c in all specimens which clarify the formation of the thin passive layer and the double-layer at the interfaces have high capacitive behavior [32]. Furthermore, the higher value of R_{ct} for C3W45 sample (4763 Ω) indicated a higher value of corrosion resistance compared to other samples that can be used as suitable methods to increase the durability of concrete in aggressive environment.

Table 3. The parameter values are derived from figure 5 for carbon steel rebar in concrete wrapped with carbon-fiber polymer in different fiber orientation and different number of CFP layers in 5% NaCl solution at room temperature.

Samples	R_s (Ω)	R_c (Ω)	Q_c (μF cm^{-2})	R_{ct} (Ω)	Q_{dl} (μF cm^{-2})
CON	12.6	506	4.9	825	7.2
C1W90	11.7	1123	3.1	2256	3.6
C1W45	12.8	935	3.8	1642	5.9
C2W90	10.4	1897	1.5	3116	2.7
C2W45	10.9	2349	1.2	3724	2.3
C3W90	9.6	1467	1.7	2631	3.1
C3W45	9.8	2852	0.8	4763	1.8

Due to the confinement of the wrap, the residuals of corrosion were densified and compacted around the reinforcement and formed a barrier layer, which restricted the access of the corrosion causing agents to the carbon steel [14]. The further reduction in the corrosion possibility is evidence of this phenomenon. The phenomenon was first described by Hearn and Aiello, who found a similar experience when evaluating the effect of one-dimensional restraint on corrosion [33].

Figure 8 reveals the water absorption of specimens after four weeks immersing time in 5 wt% NaCl solution. As shown in figure 8, the CFP layers had significant effects on water absorption rates of the samples and by increasing the number of layers the absorption of concrete samples indicated a noticeable decrease. Thus, it can be presumed that the use of CFP wrapped influenced the water absorption of reinforced concrete. Given that the water absorption has a direct relation with the corrosion behavior of steel bars embedded in concrete [34], this result can help to increase the performance of concrete. Moreover, the C3W45 sample shows a more reduction in water absorption compared to the other samples after being exposed to marine environment.

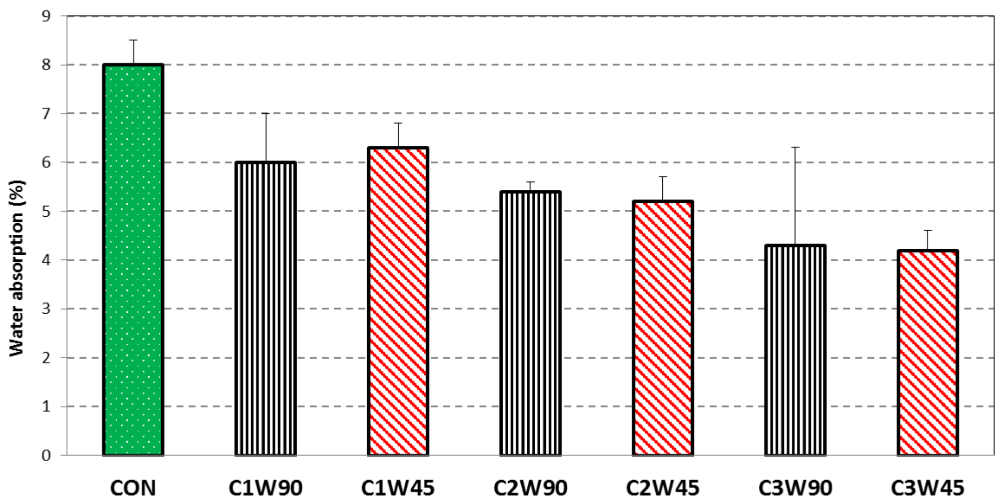

Figure 8. Water absorption of specimens after four weeks immersing time in 5 wt% NaCl solution at room temperature

Figure 9 indicates the surface morphology of carbon steel rebar in CON and C3W45 samples after being exposed to salty environment for 4 weeks. The surface of C3W45 shows low corrosion products, indicating a slight corrosion on the surface of the carbon steel rebar, which is consistent with the results of electrochemical tests. It can be attributed to the decrease of water absorption and chloride ion permeability in the concrete structure [35].

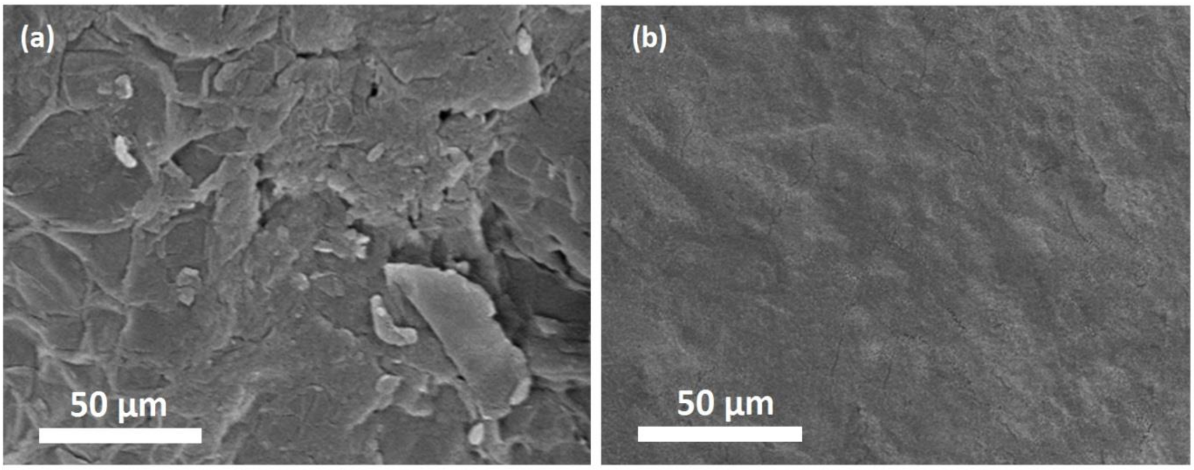

Figure 9. SEM surface morphology of carbon steel rebar in CON and C3W45 samples after exposed to 5 wt% NaCl solution for 4 weeks at room temperature

Increasing the number of CFP wraps from one to two showed to be effective, likely due to the increase of confinement; however, three-wrap layers was not obviously revealed to be more effective than two-wrap layers. This happened because the confining strength of two-wraps was sufficient to limit the rate of the corrosion residual [36, 37]. Furthermore, the orientation of CFP wrap was indicated to affect the corrosion performance by influencing the wrap capacity to advance confining stress. The best results happened when the CFP strong axis was aligned radially, in the trend of maximum possible confinement. This research shows that CFP wrapping is possibly effective in decreasing corrosion in reinforced concrete structures in 5 wt% NaCl solution. This enhanced performance is likely because of the formation of confining stresses in the concrete and the added resistance to the penetration of chlorides and moisture, both provided by the CFP wraps [38, 39].

4. CONCLUSIONS

In this work, the mechanical performance and electrochemical corrosion behavior of carbon steel reinforced concrete wrapped with CFP were investigated. The results show that CFP wrapped reduced concrete chloride content and decreased overall rate of reinforcement mass loss. The number of CFP wraps and their orientations were effective in the performance of the specimen and by increasing the number of layers from one to three, the corrosion resistance of concrete was enhanced. The compressive strength and the corrosion resistance of concrete were affected by changing the orientation of the wrapped fiber. The results indicate that the orientation of +45/-45 had a better performance than longitudinal wrapped fiber. EIS tests indicated that the concrete wrapped with CFP layers had higher value of passive film resistance compared to plain concrete, indicating more enhancement of corrosion resistance on the surface of carbon the steel rebar.

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