

Effect of Sugarcane Bagasse Ash and Ceramic Waste Dust as Partial Replacements of Portland Cement on Corrosion Behavior of HRB400 Low Carbon Steel Reinforcement in 3.5 % NaCl

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Nowadays corrosion protection of reinforced concrete can be increased by improving the concrete structure, particularly the replacement of cement by mineral additives. In this study, the influence of a partial replacement of Portland cement (PC) on the corrosion behavior of HRB400 carbon steel rebar in 3.5% NaCl solution was considered. The PC was replaced by a mixture of bagasse ash (BA) and ceramic waste dust (CWD) admixtures. The mechanical results indicated an increase in compressive strength for BCWD concrete samples containing both BA and CWD additives. The electrochemical findings indicated that the BCWD sample has considerably improved the structure of concrete as well as decreased corrosion resistance due to the decrease of water permeability and chloride ion. Scanning electron microscopy of the steel surface exhibited that the concrete structure including BA and CWD additives was more uniform and denser compared to the PC sample which was in agreement with electrochemical results.

Keywords: Electrochemical corrosion behavior; Partial replacement; HRB400 carbon steel; Compressive strength

1. INTRODUCTION

Concrete is the only widely used material in the world. Nowadays, steel reinforced concrete has been used to enhance durability of concrete structure [1]. However, building materials are typically exposed to corrosive media like carbonization, their coupling effects, freeze thaw cycles and chloride attack which commonly lead to the steel rebar corrosion [2, 3]. Concrete permeability is a negative

feature of concrete durability because it easily transports water or other liquids over the concrete and then carries corrosive materials [4]. Researchers have done a lot of research to develop the durability of concrete structures. Recently, there are many approaches to extend lifespan of the reinforced structures immersed to the corrosive environments, containing the coated materials on steel reinforcement, corrosion inhibitors and non-ferrous reinforcement [5]. A partial replacement of ordinary Portland cement (OPC) through mineral admixtures can be another viable and ecological choice for corrosion resistance [6]. The mineral admixtures reduces the porosity and permeability of concrete due to the creation of cementitious mixtures through a pozzolanic reaction with the calcium hydroxide (Ca(OH)_2) from the hydration of cement [7-9].

Different types of mineral materials, such as metallic based furnace slag, marble waste dust, limestone, silica fume, fly ash and tire rubbers have been commonly used into the concrete structures [10, 11]. Previous research has shown that these compounds can improve the properties of concrete structures, specifically its compressive strength, workability and durability in the concrete structures.

Bagasse ash (BA) is an abundant by-product of bagasse combustion in sugar factories [12, 13]. They are mostly deposited into open dumps which affects disposal and pollution problems. Moreover, many investigations have been done to develop concrete replaced by different kinds of admixtures, which caused the development of its chemical resistance and mechanical properties [14]. A partial replacement of OPC by ceramic waste dust (CWD) makes a substantial modification in chemical and physical properties which makes them suitable for the concrete construction [15, 16].

Because the simultaneous effects of BA and CWD on corrosion resistance of carbon steel reinforced concrete have not been previously reported. In this work, the electrochemical corrosion behavior of HRB500 carbon steel rebar reinforced in concrete containing BA and CWD were considered. Polarization analysis, electrochemical impedance spectroscopy (EIS) measurement, and open-circuit potential (OCP) characterization were used to investigate the corrosion resistance of carbon steel rebar.

2. MATERIALS AND METHODS

HRB400 carbon steel rebar was used to investigate the electrochemical corrosion of reinforced concrete. The chemical composition of HRB400 carbon steel is shown in table 1. The Steel rebars were cleaned and washed with SiC paper and ethanol solution, respectively.

Table 1. Chemical composition of the HRB400 carbon steel (wt%).

Element	Content (%)
Fe	Residual
Mn	1.57
P	0.024
Si	0.57
C	0.196
S	0.017
Cr	0.08

The concrete structures were cast by different content of bagasse ash (BA) and ceramic waste dust (CWD) with replacement of Portland cement (PC). The chemical compositions of CWD and BA are indicated in Table 2. The concrete mix ratios are revealed in Table 3. The PC was blended with sand, gravel, and water to make concrete samples. The mixed cements were prepared by a high-speed mixer system to achieve a heterogeneous dispersion.

Table 2. Chemical compositions of the BA, CWD and PC

Parameters	PC	CWD	BA
SiO ₂ (%)	19.98	54.74	51.74
Al ₂ O ₃ (%)	4.74	14.26	9.52
Fe ₂ O ₃ (%)	3.02	4.98	2.65
CaO (%)	63.53	11.34	9.82
MgO (%)	2.04	3.53	4.36
K ₂ O (%)	0.65	3.13	9.53
Na ₂ O (%)	0.27	1.28	4.45
SO ₃ (%)	2.65	2.78	3.42
LOI (%)	3.12	0.00	4.51

Table 3. Details of the concrete mixtures

Samples	PC	BA	CWD	BCWD
PC (kg/m ³)	600	550	550	500
BA (kg/m ³)	0.0	50	0.0	50
CWD (kg/m ³)	0.0	0.0	50	50
Sand (kg/m ³)	1200	1200	1200	1200
Gravel (kg/m ³)	400	400	400	400
Water (kg/m ³)	300	300	300	300

The compressive strength calculation was done accordance with ASTM C109-16a [17]. The compressive strength can be measured by the following equation:

$$F_{cc}(\text{N/mm}^2) = \text{Ultimate load}(\text{N}) / \text{Sample area}(\text{mm}^2) \quad (1)$$

The EIS analysis was performed by a typical personal computer and a model EA-201 Electrolyte Analyzer. In order to prepare working electrodes, the concrete mixture was poured into the cylindrical mold with 4 cm diameter, while a steel rebar with 1 cm diameter and the 7 cm length was placed vertically at the center of the cylinder. The reinforced concrete samples were cast and subsequently demolded after 24 hours. A three-electrode cell was utilized for the EIS experiments, including steel reinforced concrete as a working electrode, a platinum as counter electrode and a saturated calomel as a reference electrode. The EIS measurements were performed at the frequency range of 0.1 MHz and 0.01 Hz after one month immersion time. All reinforced concrete samples were exposed to 3.5wt% NaCl solution. The half-cell potential measurements are applied to estimate the corrosion potential of each

sample according to ASTM C876-15 standards. The scanning electron microscope (SEM) was used to consider the surface morphologies of the samples. The polarization analysis was done from 250 mV at a scan rate of 1 mV/s. Value of water absorption was considered by drying a specimen with constant mass. Then the sample is exposed to water and determines the mass of saturated surface-dry. The water absorption is the ratio of difference between two-values determined to the dry mass.

3. RESULTS AND DISCUSSION

The obtained compressive strength results of different specimens after two weeks immersion is revealed in figure 1. As shown in Fig. 1, the BCWD mixture had higher compressive strength compared to the other specimens which was 93% greater than the PC samples. The improvement of compressive strength in BCWD samples may be attributed to the use of BA as a micro-filler in modifying concrete structure. Furthermore, the BA is an activator in the pozzolanic reaction that forms a denser and smaller structure, accelerating the hydration process and enhancing the compressive strength [18]. Moreover, the crystal growth of CWD matrix improved the compressive strength of BCWD concrete samples.

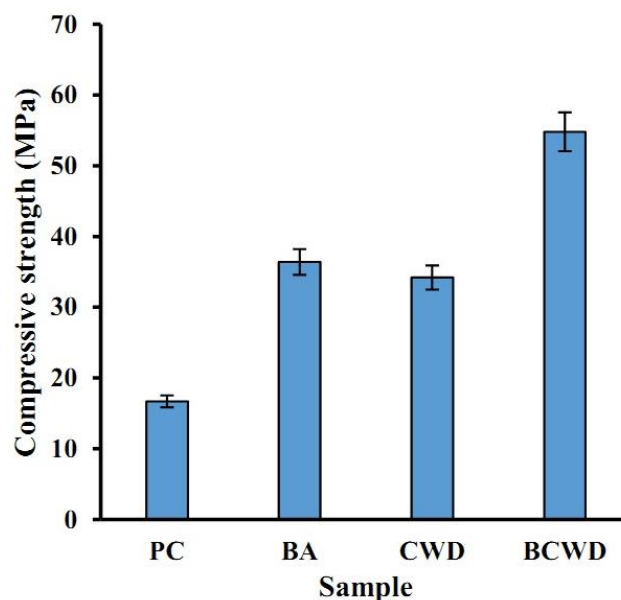


Figure 1. Compressive strength of various concrete samples after two weeks of immersion at room temperature

Figure 2 exhibits polarization curves of HRB400 carbon steel reinforced concrete in different content of admixtures exposed to 3.5% NaCl solution after one month exposure time. As revealed in Fig. 2, the anodic polarization plots are considered through passive zones at all rebars, indicating that the passive films have obviously shaped on the carbon steel surface as the rebars were exposed to the salty environment [19]. Additionally, a major shift was detected in corrosion potential (V_{corr}) to a positive direction that shows the anodic steel dissolution was efficiently retarded by varying the concrete content.

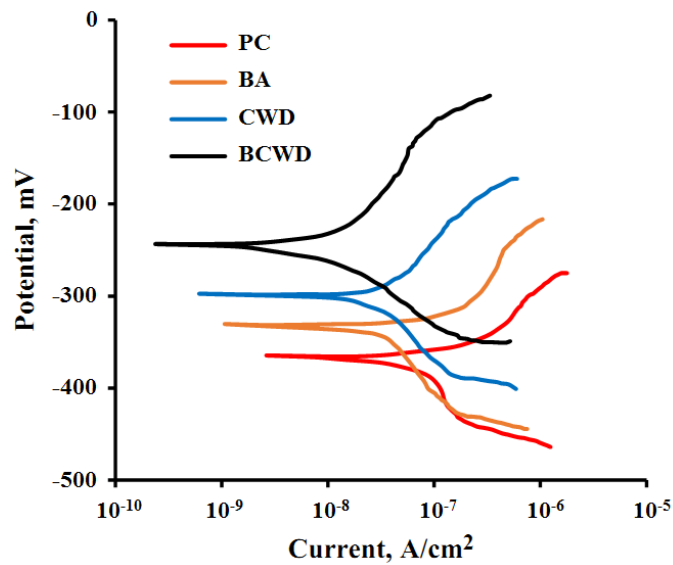


Figure 2. Potentiodynamic polarisation of HRB400 carbon steel embedded in various concrete specimens exposed to 3.5% NaCl solution after one month exposure time at scan rate of 1 mV/s

Table 4. Obtained polarisation data derived from Fig. 2

Sample	I_{corr} ($\mu\text{A}/\text{cm}^2$)	V_{corr} (mV)	β_c (Vdec ⁻¹)	$-\beta_a$ (Vdec ⁻¹)
PC	0.12	-368	54	25
BA	0.08	-334	58	29
CWD	0.06	-295	59	34
BCWD	0.03	-238	55	37

Compared to all specimens, the passive region is much wider at the BCWD sample, as a result the I_{corr} was lower which indicates the corrosion resistance of carbon steel rebar was increased for BCWD concrete containing both BA and CWD mixtures. Increasing corrosion resistance in the BCWD specimen can be related to the BA that can react with calcium hydroxide during PC hydration and produces extra calcium silicate hydrate, which enhances the durability property of the concrete structure. The values of I_{corr} and V_{corr} are shown in table 4 which was obtained from the polarization plots in Figure 2.

The corrosion level could be well-defined in four-levels introduced through the Durrant Network Specification [20, 21]. However, the I_{corr} of BCWD sample in the 3.5% NaCl solution was lower compared to the other samples. Consequently, except the PC specimen, all carbon steel rebars remained at the passive state in the experiment process which indicated their excellent corrosion resistance of carbon steel reinforced concrete in the salty environment.

Furthermore, the anodic and cathodic Tafel slopes were measured from the Tafel extrapolation technique. As revealed in table 4, β_c and β_a values varied in different concrete samples. The variation in

Tafel slope values may be used to find the inhibition behaviour (anodic or cathodic) of carbon steel rebar, the electrolyte concentration, charge transfer coefficient and the working electrode composition. The cathodic Tafel slopes had not changed in different concrete samples, which indicates that its effect on the cathodic reaction does not alter the hydrogen evolution discharge mechanism [22]. However, the slope values of anodic Tafel, changed in different concrete specimens showing a blockage in the anodic reaction sites. Hence, affects the mechanism of anodic reactions. Additionally, the anode Tafel slope enhances in BCWD specimen which means a mixture of BA and CWD in concrete structures can promote corrosion resistance of carbon steel rebars in 3.5% NaCl solution.

Since by addition of CWD, electron conductive paths may be formed, therefore the current density and the electrical resistance of the carbon steel reinforced concrete had reduced. Moreover, the side effects of CWD on corrosion resistance of carbon steel rebar can be compensated by adding BA, which has no significant effect on resistivity of CWD concrete sample but may decrease the porosity and water absorption. Besides, BA can optimize the CWD dispersion in concrete structures. Consequently, the addition of the BA and CWD simultaneously assists to promote concrete structures that decrease the adsorption of chloride ions and water on the steel rebar. It also can be presented as one of the appropriate solutions to decrease negative effects of mineral additives.

Figure 3 indicates corrosion potential for carbon steel embedded in various concrete specimens exposed to 3.5% NaCl. Carbon steel reinforced concrete with PC, BA, CWD and BCWD showed that the BCWD sample indicated a 10% corrosion probability at all exposure times. However, PC sample was shown an uncertain corrosion at most exposure times, showing the slight separation of the passive film or initiation step of pitting corrosion [23].

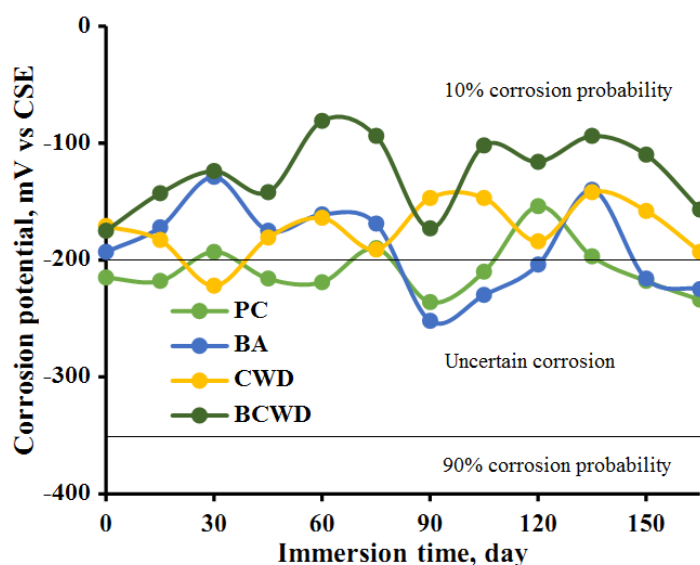


Figure 3. Corrosion potential for carbon steel embedded in various concrete specimens exposed to 3.5% NaCl at different immersion time

One of the significant properties of the BA is its important effect on durability of concrete structure [24, 25], which is due to the reduction of calcium hydroxide, hydration product solubility and pore solution variation. Moreover, more corrosion resistance in BCWD samples may be related to the

CWD that reacted by the calcium hydroxide released in the cement hydration and shaped further calcium silicate hydrate, which developed the concrete durability [26].

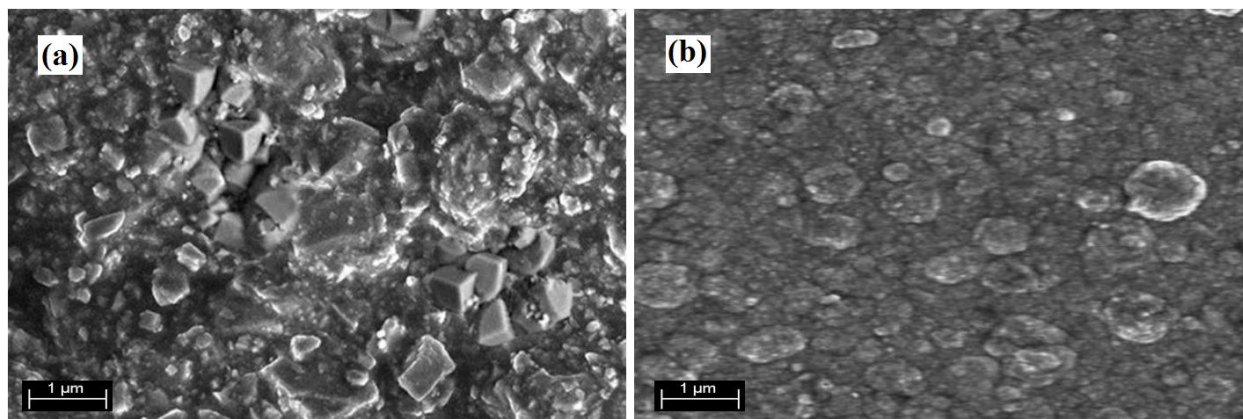


Figure 4. FESEM images of carbon steel reinforced concrete samples. (a) PC concrete, (b) BCWD concrete immersed to 3.5% NaCl solution after one month exposure time at room temperature

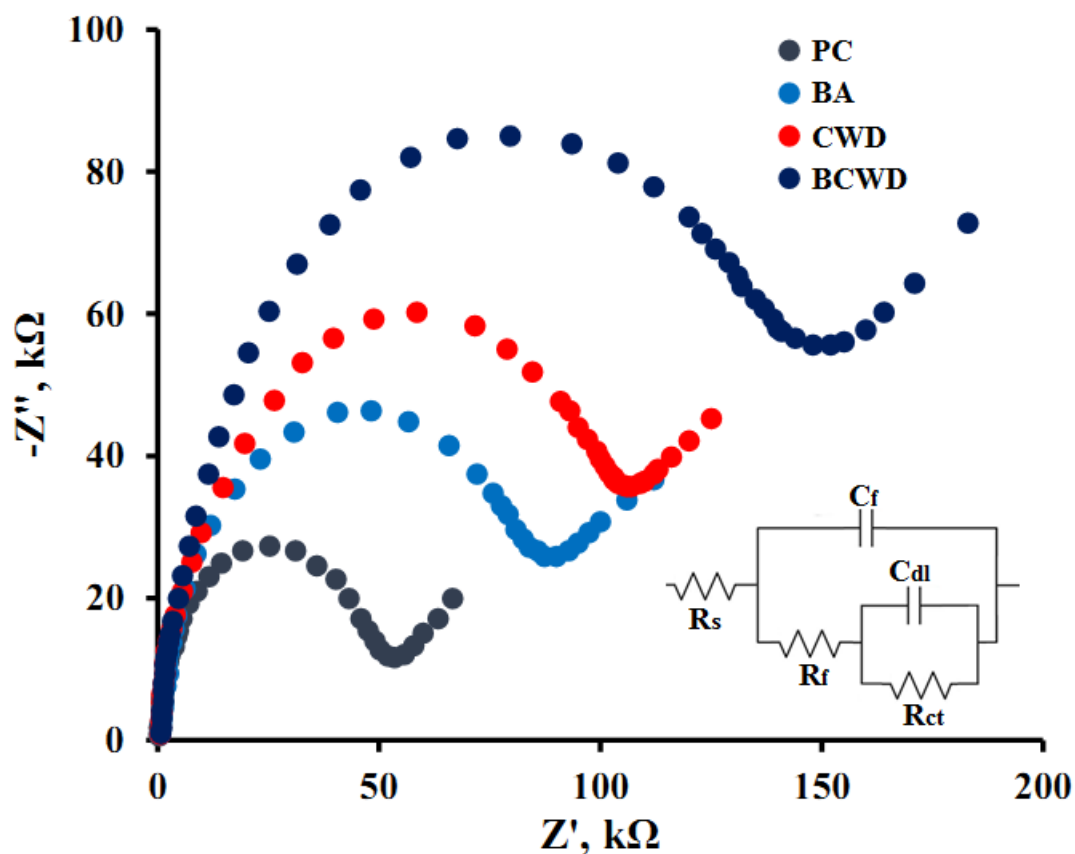


Figure 5. EIS plots achieved from carbon steel reinforced concrete with different admixtures at 3.5% NaCl solution at the frequency range of 0.1 MHz and 0.01 Hz. Inset indicates a used circuit model

Figure 4 indicates the surface morphology of HRB400 carbon steel reinforced concrete with and without CWD and BA admixtures immersed to 3.5% NaCl solution after one month exposure time. The separation gap irregularities for the concrete structures were improved by admixtures. Figure 4b reveals that the carbon steel embedded in concrete with CWD and BA was more uniform compared to the PC specimen which are in accordance with previous studies. The superior result can be attributed to the high concentrations of Al_2O_3 and SiO_2 in BA, which reduce the hydration heat that led to the reaction of water-cement [27, 28]. Moreover, the CWD as a microfiller can reduce concrete permeability and enhance its durability and prevent corrosive ions from reaching the metal surface.

EIS method has been used for investigation of the corrosion resistance of carbon steel reinforced concrete prepared by various admixtures at 3.5% NaCl solution. The Nyquist plots obtained from EIS analysis were revealed in Figure 5. Inset of Fig. 5 indicates an equivalent circuit used in this work. Where R_s presents solution resistance. C_f and R_f show the capacitance and resistance of coated concrete, respectively. R_{ct} and C_{dl} are the charge-transfer resistance and double-layer capacitance of steel surface, respectively [29]. The obtained data are indicated in Table 5.

Table 5. The achieved data for carbon steel reinforced concrete prepared with various admixtures at 3.5% NaCl solution.

Sample	R_s (Ω)	R_f ($k\Omega$)	C_f ($\mu\text{F cm}^{-2}$)	R_{ct} ($k\Omega$)	C_{dl} ($\mu\text{F cm}^{-2}$)
PC	36.7	46.31	11.3	59.68	14.1
BA	38.3	73.22	6.9	99.27	9.8
CWD	41.6	84.94	5.2	127.96	8.1
BCWD	39.4	131.18	4.5	182.17	6.3

As revealed in table 5, with suitable replacement of BA and CWD in PC, C_f decreases and R_f increases, which indicates an enhancement in the stability and corrosion resistance, thickness of passive layer on the carbon steel rebar [30]. The BA makes a pozzolanic reaction through the calcium hydroxides and forms a monolithic, insoluble and dense gel of calcium hydroxides [31]. Additionally, the BA can create a strong adhesion with hydrated cement because of the high surface area which causes a more inhibition of $\text{Ca}(\text{OH})_2$ growth. Both admixtures fill up the small cracks and capillary pores which leads to shrinkage of the cement structure. These agents increase the corrosion resistance of carbon steel rebars in corrosive media.

Figure 6 indicates the water absorption of concrete samples with different admixtures after one week, one month and two months immersed to 3.5% NaCl solution. As shown in Fig. 6, all the samples with admixtures revealed a reduction in water absorption compared to PC samples when exposure time increased. This means that BA and CWD admixtures in PC can reduce the water absorption of the concrete structure after being immersed to a salty environment. Hence, water absorption of the samples decrease when both admixtures are used. However, the presence of water in the early stages of corrosion is required, adsorption and permeability of specimens do not play a major role in the corrosion behavior of carbon steel rebar that is consistent with previous studies [32].

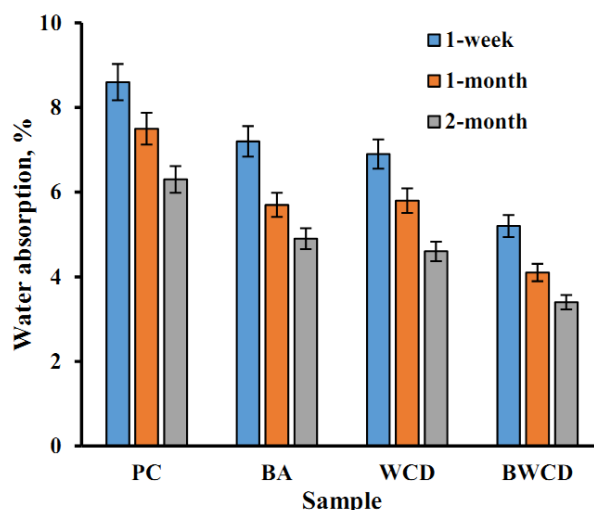


Figure 6. Water absorption of concrete samples with different admixtures at 3.5% NaCl solution after various immersion times.

4. CONCLUSIONS

Here, the influence of a partial replacement of PC on the corrosion behavior of HRB400 carbon steel rebar in 3.5% NaCl solution was studied. The PC was replaced by a mixture of BA and CWD admixtures. The mechanical results indicated an increase in compressive strength for BCWD concrete sample containing both BA and CWD additives. BCWD sample indicated lower water absorption among all concrete samples. The electrochemical findings indicated that the BCWD sample has considerably enhanced the structure of concrete as well as reduced corrosion resistance due to the decrease of water permeability and chloride ion. Scanning electron microscopy of the steel surface exhibited that the concrete structure including BA and CWD additives was more uniform and denser compared to the PC sample which was in agreement with electrochemical results.

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