Chloride-induced corrosion mechanism and rate of enamel- and epoxy-coated deformed steel bars embedded in mortar

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Abstract

The chloride-induced corrosion mechanisms of uncoated, pure enamel (PE)-coated, mixed enamel (ME)-coated, double enamel (DE)-coated, and fusion bonded epoxy (FBE)-coated deformed steel bars embedded in mortar cylinders are investigated in 3.5 wt.% NaCl solution and compared through electrochemical tests and visual inspection. Corrosion initiated after 29 or 61 days of tests in all uncoated and enamel-coated steel bars, and after 244 days of tests in some FBE-coated steel bars. In active stage, DE- and FBE-coated steel bars are subjected to the highest and lowest corrosion rates, respectively. The uncoated and ME-coated steel bars revealed relatively uniform corrosion while the PE-, DE-, and FBE-coated steel bars experienced pitting corrosion around damaged coating areas. Due to the combined effect of ion diffusion and capillary suction, wet-dry cyclic immersion caused more severe corrosion than continuous immersion. Both exposure conditions affected the corrosion rate more significantly than the water-cement ratio in mortar design.

Keywords: Microstructure (B), SEM (B), Corrosion (C), long-term performance (C), Chloride (D)

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1. Introduction

Reinforced concrete (RC) structures are often exposed to a variety of environmental conditions that lead to structural deterioration and service life reduction. For example, corrosion in reinforcing steel bars is one of the most severe forms of deterioration in transportation infrastructure. In general, the life span of corrosion-affected concrete structures with uncoated reinforcing steel bars can be divided into three stages [1]. Stage I represents the healthy state of RC structures from the completion time of new construction to the initiation of corrosion. This stage is controlled by the diffusion of carbon dioxide or aggressive ions such as chloride through the concrete cover, which mainly depends on thickness of the concrete cover, concrete permeability, and the concentration of aggressive ions on the concrete surface [2-4]. Stage II represents the damage state of the structures from the initiation of corrosion to the end of serviceability. The end of serviceability can be defined to correspond to the code-specified critical concrete crack width or delamination or the predetermined deflection design criterion associated with corrosion-induced reduction in stiffness. Stage II is controlled by the corrosion rate of reinforcement steel, which largely depends on environmental factors (temperature, moisture, and oxygen) and the characteristics of concrete materials (thickness and permeability) [5-7]. Stage III represents the safety state of the structures from the end of serviceability to the ultimate failure [8-11]. The ultimate failure due to corrosion can occur in several modes, including losses of flexural and shear strengths as a result of a cross sectional reduction of reinforcing steel. This stage is primarily controlled by environmental factors since the reinforcing steel is directly exposed to the environment through corrosion-induced cracks in the concrete cover.

Despite imperfections due to intrinsic defects and extrinsic damage induced during transportation and handling, protective coating is still one of the most effective and economic techniques to prevent steel from corrosion in RC structures. In our previous study [12], the corrosion mechanisms of deformed steel bars coated with three types of enamel and fusion-bonded epoxy (FBE) were investigated after immersion in 3.5 wt.% NaCl solution. The enamel coatings improved the corrosion resistance of the steel bars to various degrees, depending on their damage and uniformity. Electrochemical tests were also conducted to

study the effect of enamel coatings on the corrosion resistance of smooth steel bars embedded in mortar cylinders [13] and indicated that the corrosion performance of enamel-coated smooth bars was significantly better than that of enamel-coated deformed bars. However, deformed instead of smooth steel bars are widely used in RC structures, and the influence of water-cement (w/c) ratio, exposure condition, the coating damage induced during transportation, and the types of corrosion attack related to different coatings is of great interest to engineering applications. More importantly, the influence of enamel coatings on the service life of RC structures especially in the first and second stages has not yet been investigated.

The aim of this study is to investigate the short- and long-term corrosion performance of uncoated, enamel-coated, and FBE-coated deformed steel bars embedded in mortar specimens immersed in 3.5 wt.% NaCl solution. In particular, the effect of coatings on the initiation of steel corrosion is quantified. Open circuit potential and electrochemical impedance spectroscopy (EIS) were conducted approximately every month up to 244 days to monitor the evolution of corrosion especially during the transition from the passive to active state. At the end of immersion tests, potentiodynamic polarization test and visual inspection were performed to further characterize the type and rate of corrosion attack related to different coatings. Effects of w/c ratio and exposure condition on the chloride penetration in mortar, open circuit potential, and impedance over time were assessed.

2. Material and methods

2.1. Preparation of enamel coatings and cylindrical specimens

Enamel is a silicate-based material that can be deposited on steel bars by firing at high temperature after dipping in enamel slurry. The enamel slurry is made by milling glass frits, clay, and certain electrolytes, and then mixing them with water to provide a stable suspension. In this study, three types of enamel are investigated: pure enamel (PE), mixed enamel (ME), and double enamel (DE). The PE is a

commercially-available alkali borosilicate glass frit from PEMCO (Product No. PO2025), and its chemical composition is given in Table 1. The ME is a mixture of 50% PE and 50% calcium silicate directly taken from the Type I Portland cement by weight, which is designed to enhance its bond strength with surrounding concrete by increased surface roughness and chemical adherence. The DE has an inner PE layer and an outer ME layer, which is designed to increase the corrosion resistance of coated steel bars through the inner PE layer and enhance its bond strength with concrete through the outer ME layer. The PE slurry was prepared by mixing water, alkali borosilicate glass frits, clay and borax in a proportion of 1.00:2.40:0.17:0.01 by weight. Alkali borosilicate glass frits were first added to water and mixed for 20 min. Clay and borax as suspension agents were then added and mixed again for 3.5 hr. The ME slurry was made following the same procedure as the PE slurry except that calcium silicate was added to the glass frits.

In this study, deformed steel bars (12.7 mm in diameter) were used. Their chemical composition was analyzed and presented in Table 2. Before coating, all steel bars were sand-blasted and cleaned with commercially available cleansing solvent. For the PE and ME coatings, the cleaned bars were dipped into their corresponding slurry and heated for 2 min. at 150 °C to drive off moisture, then fired at 810 °C for 10 min., and finally cooled to room temperature. For the DE coating, the steel bar was first dipped into the PE slurry and heated for 2 min. at 150 °C to drive off moisture, then dipped into the ME slurry and heated to 150 °C again to drive off moisture, finally moved into a furnace to fire at 810 °C for 10 min. The firing treatment at high temperature was used to melt the glass frits and chemically bond the enamel to the steel. For comparison, both uncoated (as-received) and commercial FBE-coated steel bars were also prepared and tested.

Mortar was prepared using a mixture of cement, fine aggregate and water. Type I Portland cement as specified in Table 3 and Missouri River sands with a maximum size of 6.35 mm and a fineness modulus of 2.80 were used in this study. Two w/c ratios were considered in the batch design as given in Table 4.

Cylindrical mortar specimens were prepared as shown in Fig. 1. Each specimen was 114.3 mm tall and 38.1 mm in diameter with one concentrically embedded 88.9 mm long steel bar that is uncoated, enamel-coated, or FBE-coated. A copper wire was welded to the top end of the bar to provide an electrical connection. To force the corrosion activity in the middle portion of the steel bar and avoid any potential crevice corrosion at the two ends, each end of the bar was encased in a PVC tube filled with epoxy resins. Therefore, the actual length of steel bar potentially exposed to the corrosive environment was approximately 50.8 mm with a surface area of approximately 20.3 cm². The clear cover of mortar around the exposed portion of the steel bar was 12.7 mm.

To cast each specimen, a PVC pipe with a nominal inside diameter of 38.1 mm was used as a mold. The PVC mold and the steel bar were held in place by pre-cut grooves on a bottom plywood sheet. To ensure a proper consolidation, each mortar specimen was cast in three layers, each compacted 25 times with a 6.35-mm-diameter steel rod and tapped 15 times with a small rubber mallet on the PVC mold to close potential voids generated during each rodding/compaction. All specimens were de-molded after 24 hr., moved to the curing room, and cured at 20 °C and 100% relative humidity for 28 days prior to testing. Three specimens were prepared for each condition to understand the variability of test results.

To investigate chloride penetration through mortar over time, additional mortar cylinders without steel bars were prepared at the same time when the cylinders with one steel bar each were cast. All the cylinder specimens were cured under the same condition.

2.2. Thickness, porosity and surface damage of coatings

The coating microstructure such as thickness, porosity, and surface damage are directly related to the corrosion protection of coating, and thus must be characterized for a better understanding of their effects on the corrosion of steel bars. The coating microstructure was investigated by scanning electron microscopy (SEM, Hitachi S4700). After 28 day curing, one mortar specimen of each type was cross-

sectioned using a diamond saw, and then abraded using a series of silicon carbide papers to 1200 grit. After abrading, the sample was rinsed with de-ionized water and dried for SEM study. The surface damage of coated steel bars induced during transportation was quantified using the image analysis software “ImageJ” prior to mortar casting.

Fig. 2 shows cross-sectional SEM images of the mortar-steel interface of a representative specimen with uncoated steel bar, and the mortar-coating-steel interfaces of specimens with enamel- and FBE-coated steel bars. These images were taken between two ribs on the deformed bars where the enamel coatings are relatively uniform and thick in comparison with those areas over the ribs. Fig. 2a clearly indicates a thin porous oxide layer approximately 30 μm thick between the mortar and the uncoated steel bar, which is the mill scale formed on the steel surface. As shown in Fig. 2b, the PE coating is approximately 150 μm thick and has many small air bubbles (25 μm in diameter) and few large air bubbles (100 μm in diameter), which are generated from the oxidation-reduction reaction of enamel with the steel during the enameling process such as [14, 15]:

These gases such as H_2 , H_2O , CO , and CO_2 increased the porosity of enamel coating, resulting in an increased susceptibility of substrate steel to corrosion. The ME coating (Fig. 2c) is approximately 250 μm thick and possesses an amorphous structure with connected pores through the entire coating thickness. The DE coating (Fig. 2d) has two distinguishable inner and outer layers that are approximately 150 μm and 250 μm thick, respectively. In comparison with the PE coating, the inner layer of the DE coating has fewer but larger air bubbles (over 150 μm in diameter). In comparison with the ME coating, the outer layer of the DE coating has fewer connected pores, which is likely attributed to less chemical reaction

with the steel due to presence of the inner layer. The FBE coating (Fig. 2e) is approximately 300 μm thick and also has air bubbles (50 μm in diameter) near the steel surface. These bubbles can weaken the bond between the FBE coating and its substrate, promoting the well-known under-film corrosion as discussed in [12].

The porosity of enamel and FBE coating was determined and listed in Table 5 based on the SEM images using software “ImageJ”. Among three types of enamel coating, the PE has the lowest porosity of 15% and the ME has the greatest porosity of 39%. Epoxy coating has the lowest coating porosity of 9% among all four coatings. Table 5 also lists the average percentage of damaged area for each coated bar specimen prior to mortar casting. The average surface damage of FBE is 0.68%, which is smaller than all three types of enamel coating. This is probably because FBE coating is basically an organic polymer, which is more flexible and thicker than enamel coating, and can thus bear more external damage during transportation.

2.3. *Electrochemical measurement*

After 28 days of curing, the mortar cylinder specimens were kept in glass beakers filled with 3.5 wt.% NaCl solution, which was made of distilled water and NaCl powder (reagent grade, Fisher Scientific). The specimens were divided into two groups. One group was continuously immersed in the 3.5 wt.% NaCl solution. The other group was subjected to bi-weekly wet-dry cycles, each consisting of one week of continuous immersion (wet) followed by a second week out of solution and exposed to the room ambient (dry) condition. Therefore, four specimen and test conditions were considered for each type of coating case: (1) $w/c=0.40$ and continuously immersed in 3.5 wt.% NaCl solution (40WW); (2) $w/c=0.40$ and subjected to bi-weekly wet-dry cycles (40WD); (3) $w/c=0.55$ and continuously immersed in 3.5 wt.% NaCl solution (55WW); and (4) $w/c=0.55$ and subjected to bi-weekly wet-dry cycles (55WD). For each condition, three specimens were tested to understand the variability of test data, totaling 12 specimens for each of the five types of coating (uncoated, PE, ME, DE, and FBE). In order to keep a constant

concentration of the test solution, a prescribed level of distilled water was added every two days to compensate the evaporation loss.

Both EIS and potentiodynamic polarization tests were conducted in this study. The EIS test was conducted approximately every 30 days up to 244 days after a stable open circuit potential was recorded prior to each measurement. The used NaCl solution was also replaced after each EIS testing. After 244 days of tests, the potentiodynamic polarization test was performed to further characterize the corrosion condition of each steel bar.

Both EIS and potentiodynamic polarization measurements were taken using the typical three-electrode test setup consisted of a 25.4 mm $\times$ 25.4 mm $\times$ 0.254 mm platinum sheet as a counter electrode, a saturated calomel electrode (SCE) as a reference electrode, and a mortar cylinder as a working electrode. These electrodes were connected to a Gamry, Reference 600 potentiostat/galvanostat/ZRA for data acquisition. EIS measurements were taken at 5 points per decade with a sinusoidal potential of 10 mV applied around the open circuit potential with a frequency range of 100 kHz to 5 mHz. The potentiodynamic polarization test was conducted by scanning the mortar cylinder from -300 mV to +1500 mV with respect to the open circuit potential at a scanning rate of 0.166 mV/s.

2.4. Chloride analysis

Chloride ion is the primary aggressive species to break down the passive film and initiate corrosion. Therefore, the chloride penetration through mortar cover was also measured. For each of the four specimen and test conditions (40WW, 40WD, 55WW, and 55WD), four mortar cylinders without steel bars were tested after 61, 124, 182, and 244 days of immersion in 3.5% NaCl solution, respectively. At each time, one cylinder from each of the four conditions was taken out of the solution and wet sectioned into two equal half cylinders with a diamond saw. Mortar powder (equal weight) was collected from three evenly-distributed points around the circumference of the sectioned cross section at depths of 3.2 mm, 7.1 mm, and 11.2 mm, respectively, from the side surface of the cylinder. To avoid the effect of wet cutting

on the surface area, the mortar powder was collected using a 3.175-mm-diameter masonry drill bit to a depth of 25.0 mm from the sectioned cross section. For each depth, the three samples totaling 1.5 g were combined and dissolved in water for a rapid chloride content analysis using the Rapid Chloride Test (RCT) instrument from German Instruments, Inc.

2.5. Visual inspection

After potentiodynamic polarization tests, all mortar specimens were removed from the NaCl solution and dried. The dry mortar was removed from the steel bars using a steel hammer, and the surface condition of the exposed steel bars was examined with an optical microscopy.

To further investigate the corrosion attack (corrosion size/depth) on steel bars with different coatings, two representative steel bars in each case were selected and cast in EpoxyMount (Allied High Tech Products Inc.). The epoxy mounted steel bars were cut using a band saw into approximately 5-mm-thick discs through sites with corrosion products. The discs were abraded with a series of silicon carbide paper up to 1200 grit. After abrading, the discs were examined under an optical microscopy, and the photos were taken at corrosion attacked sites and processed using “ImageJ” to determine the corrosion size.

3. Results and discussion

3.1. Chloride transport

Fig. 3 shows the change of chloride content distribution with mortar cover depth over time. The chloride content represents the water soluble chloride ions only and does not include those ions binding to mortar. In general, chloride transport in concrete is a process that involves ion diffusion, capillary suction, convective flow with flowing water, and physical and chemical binding [16]. Ion diffusion is a primary transport mechanism of chloride in the tested cylinders, largely depending upon the permeability of mortar. Since specimens with $w/c=0.55$ are more permeable than specimens with $w/c=0.40$ [17], by comparing Fig. 3a with Fig. 3c and Fig. 3b with Fig. 3d, it can be clearly observed that the chloride

content in mortar with $w/c=0.40$ is always lower than that with $w/c=0.55$ under the same exposure condition. For mortar specimens subjected to bi-weekly wet-dry cycles, capillary suction plays an important role in water soluble chloride transport in addition to ion diffusion [18]. As a result, by comparing Fig. 3a with Fig. 3b and Fig. 3c with Fig. 3d, it can be seen that the chloride content in mortar subjected to wet-dry cycles is greater than that in the continuously immersed mortar since the capillary suction accelerates the transport of chloride.

3.2. Electrochemical responses

As mentioned before, three specimens in each group were prepared and tested. Results from the same group of specimens are similar. Therefore, only the results of one representative specimen in each group are presented in this paper. The surface damage of each representative specimen is listed in Table 5. To assess the effect of coatings on the initiation of steel corrosion, the threshold values of free chloride content [19], open circuit potential [20], polarization resistance [21], and corrosion current density [22-25] are presented in Table 6. In particular, the threshold values are used to evaluate the transition of steel corrosion from a passive to active state.

3.2.1. Open circuit potential

Fig. 4 shows the evolution of open circuit potentials for mortar specimens with different coated steel bars and under different conditions. For the specimens with uncoated steel bars, the open circuit potentials dropped below -273 mV/SCE after 29 days of test, which means over 90% probability of active corrosion according to Table 6. Similarly, most of the specimens with ME coated steel bars showed a high probability of corrosion after 29 days. However, for the specimens with PE- and DE-coated steel bars, the corrosion potential dropped below -273 mV/SCE after 61 days of test. The specimens with FBE-coated steel bars show different behavior with the potential decreased slowly and remained above -273 mV/SCE throughout the test period. For all specimens, the effects of w/c ratio and exposure condition on the evolution of corrosion potential were quite irregular and appeared insignificant in the evaluation of long-

term corrosion performance. At 244 days of test, the average corrosion potentials of various specimens are -695 mV with uncoated steel bars, -512 mV with PE coated steel bars, -726 mV with ME coated steel bars, -600 mV with DE coated steel bar, and -158 mV with FBE-coated steel bars, respectively.

Similar to the threshold value of free chloride content, 0.07~1.06 wt% of cement, for steel corrosion in concrete as shown in Table 6, American Concrete Institute (ACI) code specifies the maximum water-soluble chloride ion content in concrete, 0.15~1.00 wt.% of cement, for various exposure classes [26]. As shown in Fig. 3, the chloride content at locations close to the steel bar surface (11.2 mm) was measured in the range of 0.06~0.51%, which is close to the threshold value of free chloride. Therefore, it is highly possible that the uncoated steel bars were transitioned from a passive to active state at 61 days, which is consistent with the open circuit potential results. This transition also happened for the specimens with enamel-coated steel bars as indicated in Fig. 4. However, high probability of corrosion was not observed for the specimens with FBE-coated steel bars, indicating a higher chloride threshold compared to the uncoated and enamel-coated steel bars.

3.2.2. EIS results

3.2.2.1. EIS diagrams and equivalent electrical circuit

Fig. 5 shows the evolution of impedance spectra over time for the 55WD specimens with uncoated and enamel-coated steel bars in the format of both Nyquist and Bode plots. The Nyquist plots show the measured data of approximately every month, while Bode plots display results at selected times. The fitting results (Ftd.) using the equivalent electrical circuit (EEC) as shown in Fig. 6 were also presented in the Bode plots in Fig. 5 to demonstrate the goodness of fitting into the measured data (Meas.).

As indicated in Fig. 5a, the uncoated steel bar was in passive state at the beginning of test. Three time constants can be observed from the Bode plots in Fig. 5a-2. The first time constant in the high frequency (> 10 kHz) is related to the mortar cover properties [27-30], the second time constant in the intermediate frequency (10 Hz ~10 kHz) is attributed to the mill scale/passive film layer between the mortar cover and

the steel [31, 32], and the third time constant in the low frequency (<10 Hz) is associated with the steel-electrolyte interface where corrosion occurs [33-35]. The passive film is formed in the high alkaline pore solution of mortar. With the presence of mill scale, the passive film formed on the steel bar surface is less repairable when compared to that formed on the polished steel bar surface [36, 37].

Five EEC models were proposed in this study to fit all impedance spectra of different specimens as summarized in Fig. 6. For specimens with uncoated steel bars in passive state, EEC model (I) was used, in which CPE_m and R_m represent the capacitive and resistive behavior of the mortar cover, CPE_f and R_f represent the dielectric properties of mill scale/passive film layer, and CPE_{dl} and R_{ct} represent the double layer capacitive behavior and charge transfer resistance at the electrolyte-steel interface. Here, a constant phase element (CPE) instead of a pure capacitor was used to describe the dielectric properties of different material layers due to their non-homogeneity [28, 30, 38]. The non-homogeneity of mortar cover is mainly from the random distribution of sand particles, voids and other hydration products in cement paste as well as their different dielectric properties. The non-homogeneity of mill scale mainly comes from its porous structure and non-uniform thickness [39, 40], and the non-homogeneity of electrolyte-steel interface is attributed to irregularities on the exposure steel surface such as non-uniform passive film or certain processes associated with an irregular distribution of the applied potential. Mathematically, the impedance of a general CPE with two parameters Y and n can be expressed into:

$$Z_{CPE} = Y^{-1} \cdot (j\omega)^{-n} \quad (2)$$

where Y is the CPE-constant with unit of $\Omega^{-1} \text{ cm}^{-2} \text{ s}^{-n}$, n is the CPE-power ($0 < n < 1$), j is the imaginary unit ($j^2 = -1$), and ω is the angular frequency of the applied alternating current ($\omega = 2\pi f$, f is the frequency).

After 61 days of test, a dramatic drop of impedance magnitude can be observed in Fig. 5a-2, indicating the breakdown of passive film and the initiation of corrosion. When the test reached 94 days, a diffusion behavior was observed, which is attributed to the oxygen diffusion control due to buildup of the corrosion products [41, 42]. Bi-weekly wet-dry cycles promoted the transportation of more oxygen and

chloride by combined capillary suction and diffusion effects than those continuously in salt solution, increasing the corrosion rate and resulting in the formation of pronounced corrosion products. It is noted that this diffusion behavior was observed for most specimens subjected to bi-weekly wet-dry condition. However, for the specimens continuously immersed in solution, no diffusion appeared throughout the test period. Therefore, EEC model (II) with a diffusion impedance Z_d was used to fit the impedance spectrum. The CPE was also used for the diffusion impedance due to the non-ideal diffusion behavior observed especially for the specimens with coated bars [38, 43]. At the time of 213 days, the time constant corresponding to the mill scale/passive film layer disappeared and EEC model (III) in Fig. 6 was used. The disappearance of the mill scale/passive film layer is ascribed to the continuous penetration of chloride and enlargement of active corrosion area. The evolution of EEC models over time is also shown in the corresponding Nyquist plot.

As shown in Fig. 5b for the 55WD specimen with PE-coated steel bar, the unit of impedance in the Nyquist plot is $M\Omega \text{ cm}^2$ instead of $k\Omega \text{ cm}^2$ as used for the specimen with uncoated steel bar. At the time of 61 days, a significant change of phase angle and a drop of impedance in the low frequencies were observed, which corresponds to a transition from a passive to active state. Prior to 61 days when the specimen in passive state, three time constants in the high, intermediate and low frequency ranges are associated with the properties of combined mortar cover and PE layer, the passive film formed on the exposure steel surface at the damaged coating areas, and the steel-electrolyte interface at the damaged coating areas, respectively. Therefore, EEC model (I) in Fig. 6 was used. After 61 days when the steel bar was in active corrosion, a diffusion behavior appeared and the time constant corresponding to the passive film properties disappeared, and thus EEC model (III) was used. Regardless of w/c ratios and exposure conditions, other specimens with the PE coated steel bars showed similar behavior to the 55WD specimen.

As shown in Fig. 5c for the 55WD mortar specimen with ME-coated steel bar, a sudden reduction of impedance magnitude in the low frequencies could be observed at the time of 61 days, which is attributed to the initiation of corrosion. However, no significant change of phase angle over time was observed

despite a change of surface state from passive to active. Therefore, EEC model (I) with three pairs of resistor and CPE was used to fit all impedance spectra throughout the entire test period. Moreover, there is no diffusion behavior observed for all specimens throughout the test, which is probably because the connected pores in the ME coating are large, and the buildup of corrosion products inside the pores does not significantly affect the diffusion of oxygen to the steel surface.

As shown in Fig. 5d for the specimen with DE-coated steel bar, three time constants can be seen at the beginning of test and a diffusion behavior appeared with an absence of the intermediate time constant at the time of 94 days. These observations are similar to the specimen with PE-coated steel bar in Fig. 5c except for the transition time. Therefore, the corresponding EEC models changed from model (I) to model (III) at the time of 94 days.

Unlike the specimens with uncoated and enamel-coated steel bars, inconsistent behaviors were observed for mortar cylinders with FBE-coated steel bars. For this reason, four representative results are presented in Fig. 7. This inconsistent behavior of the FBE-coated specimens implies that inconsistent corrosion resistances of FBE-coated bars may be expected in field applications [44], which is mainly attributed to various extents of coating surface damage. The coating damages corresponding to the 40WW, 40WD, 55WW, and 55WD specimens are 0.28%, 1.03%, 0.89% and 0.75%, respectively. The 40WW specimen shows capacitive behavior with one big semi-circle appeared in the Nyquist plots. This is because FBE with a small damage area behaves like an insulting layer and suppresses all the contributions from mortar cover and passive film. Therefore, EEC model (IV) in Fig. 6 was used. Here R_{ct} represents the total resistance from mortar cover, FBE coating, passive film, and double layer. With an increase of immersion time, a gradual decrease of impedance in the low frequencies was observed due to the continuous penetration of chloride. For the 55WD specimen, a sudden drop of impedance in the low frequency and a diffusion behavior appeared after 29 days of test, which is attributed to the corrosion initiation at the coating damaged area. Therefore, EEC model (V) was employed.

The 55WW specimen displays similar behavior to those with enamel coatings. The three time constants in the high, immediate and low frequencies as observed in Fig. 7c-2 are associated with the combined mortar and FBE coating, passive film, and double layer at the electrolyte-steel interface. Thus, EEC model (I) in Fig. 6 was used. For the 40WD specimen, a diffusion behavior appeared at the time of 61 days due to the initiation of corrosion and accumulation of corrosion products. Thus, EEC model (II) was used.

3.2.2.2. Parameters evolution of EEC models

The EEC models can be fitted well into the impedance spectra data in the high and intermediate frequency ranges, giving accurate model parameters such as R_m , Y_m , R_f and Y_f . In the low frequency range, however, the extracted parameters such as R_{ct} , Y_{dl} , and Z_D seemed less accurate due to the effect of diffusion [27]. Therefore, the impedance magnitude at 5 mHz ($|Z|_{5\text{mHz}}$) will be directly used as an approximation of polarization resistance to quantify the corrosion condition of steel bars as did by other researchers [45]. In general, the polarization resistance approximately represents the interception of an extended impedance curve with the real axis in Nyquist plot, which is usually greater than the $|Z|_{5\text{mHz}}$. Therefore, the threshold value of $|Z|_{5\text{mHz}}$ for the transition from a passive to active state would be lower than the polarization resistance criterion as shown in Table 6.

Fig. 8 shows the evolution of R_m over time for various specimens under different conditions. Herein, R_m represents the resistance of mortar cover for the specimens with uncoated and ME-coated steel bars or the resistance of the combined mortar cover and coating layer for the specimens with PE-, DE- and FBE-coated steel bars. The R_m for the FBE-coated specimens under the 40WW and 55WD conditions was not available since its represented time constant was suppressed by the time constant representing the steel-electrolyte interface at the damaged coating areas.

For the mortar specimens with uncoated steel bars as shown in Fig. 8a, R_m slightly increased in the first one or two months of test and then fluctuated around its average value over time. The exception to

this trend, though slightly, is the continuous increase for Specimen 40WW. The increase in mortar resistance is probably attributed to further hardening of mortar after 28 days curing. The fluctuation is likely related to the penetration of chloride, resulting in increased conductivity. After 61 days of test, the average $R_m = 5.18 \text{ k}\Omega \text{ cm}^2$ for 40WW, $3.06 \text{ k}\Omega \text{ cm}^2$ for 40WD, $3.55 \text{ k}\Omega \text{ cm}^2$ for 55WW, and $2.31 \text{ k}\Omega \text{ cm}^2$ for 55WD specimen. Since the mortar with higher w/c ratio is more permeable and wet-dry cycles add the capillary suction to the diffusion process, they can absorb more salt solution, increasing conductivity and reducing resistance. The mortar resistances in this study are in good agreement with the reported values from the literature [34, 35, 41]. However, the effects of w/c ratio and exposure condition on the R_m for enamel- and FBE-coated specimens are not as clearly seen as those for the uncoated specimen as observed in Figs. 8b to 8e. For a general comparison, the R_m values for the 55WW condition were averaged over time, resulting in $16.69 \text{ k}\Omega \text{ cm}^2$ for the PE-coated specimen (Fig. 8b), $5.30 \text{ k}\Omega \text{ cm}^2$ for the ME-coated specimen (Fig. 8c), $6.59 \text{ k}\Omega \text{ cm}^2$ for the DE-coated specimen (Fig. 8d), and $68.79 \text{ k}\Omega \text{ cm}^2$ for the FBE-coated specimen (Fig. 8e). The R_m values for the specimens with PE-, DE- and FBE-coated steel bars are significantly higher than the specimens with uncoated and ME-coated steel bars due to the combined action of mortar cover and PE, DE, FBE coatings.

The parameter Y_m is closely related to the capacitance of corresponding materials. For the mortar specimens with uncoated and ME-coated steel bars, Y_m was slightly increased to above $9 \times 10^{-11} \text{ }\Omega^{-1} \text{ cm}^{-2} \text{ s}^{-n}$ since more chloride ions were penetrated into the mortar cover over time. For the specimens with PE-, DE- and FBE-coated steel bars, it fluctuated around a value of $3 \times 10^{-11} \text{ }\Omega^{-1} \text{ cm}^{-2} \text{ s}^{-n}$, which is at least twice lower than that for the specimens with uncoated and ME-coated steel bars. This is because they represent the combined effect of mortar and less permeable PE, DE and FBE coatings. The Y_m values for the specimens with uncoated and ME coated steel bars (closely related to mortar) are in good agreement with the results obtained by others [46, 47].

The parameters R_f and Y_f reflect the resistance and capacitance of mill scale/passive film layer for the specimens with uncoated steel bar, mixed enamel for the specimens with ME coated steel bars, and passive film for the specimens with PE, DE and FBE coated steel bars. The average resistance and capacitance were $2.78 \text{ k}\Omega \text{ cm}^2$ and $1.08 \times 10^{-4} \Omega^{-1} \text{ cm}^{-2} \text{ s}^{-n_f}$ for the mill scale/passive film layer, respectively, and $4.67 \text{ k}\Omega \text{ cm}^2$ and $1.04 \times 10^{-4} \Omega^{-1} \text{ cm}^{-2} \text{ s}^{-n_f}$ for the mixed enamel coating, respectively. The passive film was formed on the exposed steel surface at the locations of damaged PE, DE and FBE coatings. Therefore, their properties were reassessed based on the true areas (coating damaged areas). The average resistances of the passive film were $2.92 \text{ k}\Omega \text{ cm}^2$, $4.45 \text{ k}\Omega \text{ cm}^2$, and $812 \text{ k}\Omega \text{ cm}^2$ for PE-, DE-, and FBE-coated steel bars, respectively. The average capacitances of the passive film were $3.62 \times 10^{-4} \Omega^{-1} \text{ cm}^{-2} \text{ s}^{-n_f}$, $1.46 \times 10^{-4} \Omega^{-1} \text{ cm}^{-2} \text{ s}^{-n_f}$, and $1.30 \times 10^{-6} \Omega^{-1} \text{ cm}^{-2} \text{ s}^{-n_f}$ for PE-, DE-, and FBE-coated steel bars, respectively. The resistance of passive film formed on damaged FBE coating is much higher than those formed on PE and DE coated steel bars, reflecting a relatively dense microstructure. This dense passive film increased the chloride threshold, which is consistent with the open circuit potential results.

Fig. 9 shows the impedance $|Z|_{5\text{mHz}}$ as a function of time for various specimens under different conditions. Since it reflects the impedance at the interface of electrolyte and steel where corrosion occurs, $|Z|_{5\text{mHz}}$ is evaluated based on the actual area of pitting and uniform corrosion. For the specimens with PE, DE and FBE coated steel bars, the corrosion area is basically the coating damage areas where pitting corrosion occurred. For the specimens with uncoated and ME coated steel bars, the corrosion area is the entire surface area that is susceptible to corrosion as discussed in Section 3.3.

As shown in Fig. 9a for the specimens with uncoated steel bars, $|Z|_{5\text{mHz}}$ is rapidly reduced after 29 days of tests from 256 to $130 \text{ k}\Omega \text{ cm}^2$ for 40WW, 147 to $52 \text{ k}\Omega \text{ cm}^2$ for 40WD, 230 to $82 \text{ k}\Omega \text{ cm}^2$ for 55WW, and 38 to $22 \text{ k}\Omega \text{ cm}^2$ for 55WD. As shown in Fig. 9b-9d for the specimens with ME-, PE-, and DE-coated steel bars, a dramatic reduction of $|Z|_{5\text{mHz}}$ is also observed after 61 days of tests. These reductions are an indication of transition from a passive to active state since their values are close to a

threshold value of $0.1\sim1\text{ M}\Omega\text{ cm}^2$ as shown in Table 6. After de-passivation, the $|Z|_{5\text{mHz}}$ continues to decrease gradually towards an asymptotic value. This gradual decrease is attributed to the continuous penetration of chloride and enlargement of active corrosion area, and the stabilization was ascribed to the condition that the majority of the passive film has broken down. For the specimens with FBE-coated steel bars, a sudden or gradual reduction of $|Z|_{5\text{mHz}}$ was also observed over time, indicating an initiation of corrosion. However, the $|Z|_{5\text{mHz}}$ values of all FBE-coated steel bars exceed the threshold values of polarization resistance. Therefore, the corrosion on FBE-coated steel bars is considered to be negligible and all specimens remained passive throughout the entire test period according to Table 6.

At the stabilized active state especially after 150 days, the effect of exposure condition on the $|Z|_{5\text{mHz}}$ is observed from Figs. 9a, 9b, and 9d for the specimens with uncoated, PE and DE coated steel bars. Specimens subjected to weekly wet-dry cycles have lower $|Z|_{5\text{mHz}}$ values than those continuously immersed in solution. This is because wet-dry cycles promote the penetration of chloride and oxygen, resulting in lower corrosion impedance. Effects of w/c ratio on the value of $|Z|_{5\text{mHz}}$ can also be observed for the specimens with uncoated steel bars. However, the effects of both the w/c ratio and exposure condition were not observed for the specimens with ME-coated steel bars as shown in Fig. 9c.

3.2.3. Potentiodynamic polarization

Fig. 10 shows the potentiodynamic polarization curves of mortar specimens with different coated steel bars after 244 days of corrosion test. The current density in Figs. 10a and 10c for the specimens with uncoated and ME-coated steel bars was calculated by dividing the measured current over the total exposed surface area of 20.3 cm^2 . The current density in Figs. 10b, 10d, and 10e for the specimens with PE-, DE-, and FBE-coated steel bars was based on the actual active area or coating damaged area. It can be seen from Figs. 10a, 10c, and 10e that some curves include a passive region in the anodic portion.

The corrosion potential E_c and corrosion current density i_c of each specimen were extracted from the potentiodynamic polarization curves. The corrosion depth of the specimen was estimated based on the

corrosion current density and the time from corrosion initiation to 244 days. The corrosion potential, current density, and corrosion depth are summarized in Table 7. After 244 days of corrosion tests, the corrosion current density of all the uncoated and enamel-coated steel bars as well as two FBE-coated steel bars (40WD and 55WW) exceeded its threshold value of $0.5 \mu\text{A}/\text{cm}^2$ in Table 6, which is an indication of active corrosion. The FBE-coated steel bar (40WW) had a corrosion current density of less than $0.1 \mu\text{A}/\text{cm}^2$ and thus remained in the passive state. In general, the pitting corrosion current density in PE-coated steel bars is in the same order as the uniform corrosion current density in uncoated and ME-coated steel bars. However, the pitting corrosion current density in DE-coated steel bars is significantly higher than that of PE-coated steel bars. The reason is that the larger air bubble trapped in the inner layer of the double layer coating reduces its effective coating thickness while increasing the area for pitting corrosion. For the FBE-coated steel bars, the pitting corrosion current density is small since most of the coating damaged areas are still protected by the passive film in 244 days.

3.3. Visual inspection

At the conclusion of corrosion tests in 244 days, the uncoated, enamel-coated, and FBE-coated steel bars were removed from the tested cylinder specimens and cleaned as illustrated in Fig. 11. Note that the corrosion sites showed in these photos do not necessarily correspond to the overall damage percentages as indicated in Table 5 since they are just a small portion of the total corrosion areas. As indicated in Figs. 11(1-a) to Fig. 11(1-d), relatively uniform corrosion occurred on the surface of uncoated steel bars and it became more severe when the steel bars were subjected to bi-weekly wet-dry cycles rather than continuously immersed in NaCl solution. As indicated in Figs. 11(2-a) to 11(2-d) and 11(4-a) to 11(5-d), pitting corrosion occurred at the damaged coating areas of PE-, DE-, and FBE-coated steel bars. However, significant corrosion products were found outside the damaged coating areas of ME-coated steel bars since chloride penetrated through the connected pores in the ME coating and initiated more active corrosion sites. A layer of mortar was retained on the surface of ME- and DE-coated steel bars

while no mortar was observed on the surface of FBE-coated steel bars. This is because the ME and DE coatings had rough surfaces and were chemically bonded with mortar [48].

Fig. 12 shows the cross-sectional view of corrosion attack on uncoated, PE-, ME-, DE- and FBE-coated steel bars after 244 days of tests. As indicated in Fig. 12a, relatively uniform corrosion occurred on the surface of uncoated steel bars despite the varying corrosion depth along the bar circumference. The average and maximum corrosion depth were respectively 126 μm and 180 μm , respectively, which is consistent with the corrosion depth estimated in Table 7. As indicated in Fig. 12b, typical pitting corrosion revealed on the surface of PE-coated steel bars with average diameter and depth of the corrosion pits being 310 μm and 63 μm , respectively. The pitting corrosion occurred on the damaged coating areas, and no under-film corrosion was observed due to the chemical bonding between the enamel coating and its substrate steel. As indicated in Fig. 12c, the ME-coated steel bars similar to the uncoated steel bars displayed relatively uniform corrosion. The corrosion products accumulated at the ME-steel interface diffused outward and filled the connected pores in the ME coating. The average corrosion depth was estimated to be 71 μm , which is smaller than that on the uncoated steel bars. The relatively uniform corrosion is attributed to the connected pores in the ME, which provides paths for penetration of chloride, water and oxygen. For the DE-coated steel bars, corrosion pits occurred around the large air bubbles in the inner pure enamel layer beneath the damaged areas. Fig. 12d-1 shows three small corrosion pits at the enamel-steel interface, and Fig 12d-2 shows two large corrosion pits with the large air bubbles completely filled with corrosion products. Similar to the PE-coated steel bars, no under-film corrosion was observed on the DE coated steel bars. The corrosion pit depth ranged from 36 μm to 171 μm , and the pit diameter changed from 80 μm to 710 μm . For the FBE-coated steel bars as displayed in Fig. 12(e-1), no corrosion was observed. In other coating damaged area as shown in Fig. 12(e-2), some corrosion can be observed with an average corrosion depth less than 30 μm and under-film corrosion began to appear in the damaged coating area.

3.4. Further discussion

3.4.1. Corrosion mechanism

Based on the evolution of impedance spectroscopy during corrosion tests and visual inspection at the end of the tests in 244 days, the corrosion mechanisms of uncoated, enamel-coated, and FBE-coated steel bars embedded in mortar are schematically illustrated in Fig. 13 together with their corresponding EEC models. For uncoated steel bars as shown in Fig. 13a, three stages of deterioration were observed: (I) penetration of chloride through mortar cover, (II) occurrence of local pitting corrosion at the critical chloride content, and (III) enlargement of active area due to continuous penetration of chloride changing from pitting to uniform corrosion with accumulated corrosion products. In Stage I, corrosion kinetics is controlled by charge transfer across the passive film [31]. In Stage II, the spatial randomness of connected pores and chloride concentration control the rate at which pitting corrosion initiated locally. Diffusion impedance due to the formation of corrosion products appears in this stage. In Stage III, substantial concentrations of chloride ions arrive at the surface of the steel, extending the active corrosion area.

Only two stages of corrosion deterioration were observed for enamel-coated steel bars in mortar, passive state and active corrosion state as shown in Fig. 13b-d. In Stage I, the exposed steel at damaged coating areas is protected by a passive film. In Stage II, the chloride concentrations at the exposed steel area reach their threshold values so that pitting corrosion initiates and corrosion products start to build up. In active stage, corrosion only occurs in the damaged coating areas of PE- and DE-coated steel bars, which is typical of pitting corrosion. More severe corrosion attack occurs on the DE-coated steel bar due to larger air bubbles in the inner enamel layer of the DE coating. ME coated steel bars experience relatively uniform corrosion over the entire surface areas. Corrosion products diffuse outward into the connected pores of the ME coating.

Although most of the FBE-coated steel bars remained in passive state according to the threshold values in Table 6, two stages of corrosion deterioration were observed as illustrated in Fig. 13e. Stage I is

the transportation of chloride in mortar cover when the steel bar is protected by a dense passive film. In Stage II, chloride breaks down the passive film, corrosion initiates and produces corrosion products. Depending upon the damage extent, two EEC models are introduced as demonstrated in Fig. 13e. Due to the weak bond between the FBE coating and its substrate steel, another stage is expected to occur over time if the corrosion test continued [12].

3.4.2. Application to concrete structures

Although mortar instead of concrete was used in this study, the test results would be applicable to reinforced concrete (RC) structures in terms of relative corrosion type (uniform versus pitting), mechanism, and resistances among various coated steel bars (PE, ME, DE and FBE). The difference would be the time of corrosion initiation and the corrosion rate in Stage II. The corrosion initiation largely depends upon the properties of concrete cover such as permeability and thickness. Use of corrosion inhibitors [49], recycled aggregate [50], high performance admixtures [51, 52], and concrete coating [53] also influences the initiation of corrosion. The corrosion rate is affected by the concrete properties, environmental factors such as the presence of moisture, chloride [54], and carbon dioxide [55], and maintenance or repair strategies [56]. These factors would definitely affect the service life of RC structures.

4. Conclusions

The corrosion performances of uncoated, enamel-coated and FBE-coated deformed steel bars embedded in mortar cylinder were investigated and compared in 3.5 wt.% NaCl solution. In particular, the effects of w/c ratio of mortar cover, the exposure condition, the surface damage induced during transportation, the corrosion type related to various coatings, and the transition from the passive to active state were studied. Based on the test results and analysis, the following conclusions can be drawn:

(1) Corrosion type: relatively uniform corrosion occurred on the uncoated and ME-coated steel bars while pitting corrosion occurred in the damaged coating areas of the PE-, DE- and FBE-coated steel bars.

(2) Corrosion initiation: all three enamel coatings did not postpone the corrosion initiation of steel bars. Like the uncoated steel bars, the enamel-coated steel bars experienced corrosion after 29 or 61 days of test. Despite the surface damage, the FBE coating postponed the corrosion initiation of steel bars. Most of FBE-coated steel bars remained passive throughout the test period and some began to show under-film corrosion sign at the end of corrosion test in 244 days.

(3) Corrosion rate: in active state, both the uniform corrosion rate of ME-coated steel bars and the pitting corrosion rate of PE-coated steel bars are in the same order as the uniform corrosion rate of uncoated steel bars. However, the pitting corrosion rate of DE-coated steel bars was significantly higher than that of the PE-coated steel bar due to larger air bubbles trapped in the inner layer of the DE coating. The pitting corrosion rates of some FBE-coated steel bars are very low and considered to be negligible.

(4) Effects of w/c ratio and exposure: the w/c ratio of mortar and the exposure condition clearly influence the corrosion rate of uncoated steel bars. Specimens with higher w/c ratio have a higher corrosion rate than that with lower w/c ratio due to the increased mortar permeability. Bi-weekly wet-dry cyclic immersion accelerated the deterioration rate since oxygen transport was enhanced by capillary suction.

(5) Overall coating performance: the PE coating outperformed both the ME and DE coatings. However, the FBE is the best among all the coatings examined in 244 days; it not only extends the corrosion initiation but also contributes to a low corrosion rate of coated steel bars.

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Fig. 1. Geometry of mortar cylinder specimen (unit: mm).

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Fig. 2. SEM images of steel-mortar interfaces for specimens with (a) uncoated, (b) PE-, (c) ME-, (d) DE-, and (e) FBE-coated steel bars.

Fig. 3. Chloride content evolution over time for mortar and exposure conditions: (a) 40WW, (b) 40WD (c) 55WW, and (d) 55WD.

Fig. 4. Evolution of open circuit potential over time for specimens with (a) uncoated, (b) PE-, (c) ME-, (d) DE-, and (e) FBE-coated steel bars.

Fig.5. Representative EIS results of 55WD mortar and exposure conditions with (a) uncoated, (b) PE-, (c) ME-, and (d) DE-coated steel bars in the format of (1) Nyquist and (2) Bode plots.

Fig. 6. Equivalent electrical circuits.

Fig.7. Representative EIS results of specimens with FBE-coated steel bars for mortar and exposure conditions: (a) 40WW, (b) 40WD, (c) 55WW, and (d) 55WD in the format of (1) Nyquist and (2) Bode plots.

Fig. 8. Evolution of R_m for specimens with (a) uncoated, (b) PE-, (c) ME-, (d) DE-, and (e) FBE-coated steel bars under various conditions.

Fig. 9. Evolution of $|Z|_{5\text{mHz}}$ for specimens with (a) uncoated, (b) PE-, (c) ME-, (d) DE-, and (e) FBE-coated steel bars under various conditions.

Fig. 10. Potentiodynamic polarization curves for specimens with (a) uncoated, (b) PE-, (c) ME-, (d) DE-, and (e) FBE-coated steel bars after 244 days of corrosion tests.

Fig. 11. Surface conditions after 244 days of corrosion tests of representative steel bars extracted from specimens with (1) uncoated, (2) PE-, (3) ME-, (4) DE-, and (5) FBE-coated steel bars under various conditions: (a) 40WW, (b) 40WD, (c) 55WW, and (d) 55WD.

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(a-2)

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(b-1)

(b-2)

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(c-1)

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Fig. 12. Cross-sectional view of corrosion pits on (a) uncoated, (b) PE-, (c) ME-, (d) DE-, and (e) FBE-coated steel bars after 244 days of test.

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(a) EEC: I→II→III

(b) EEC: I→III

(c) EEC: I

(d) EEC: I→III

(e) EEC: I→II/IV→V

Fig. 13. Schematics of corrosion evolution corresponding to EEC models in Fig. 8 for specimens with (a) uncoated, (b) PE-, (c) ME-, (d) DE-, and (e) FBE-coated steel bars.

877 **Table 1**
878 Chemical composition of alkali borosilicate glass frits

Element	SiO ₂	B ₂ O ₃	Na ₂ O	K ₂ O	CaO	CaF ₂	Al ₂ O ₃	ZrO ₂	MnO ₂	NiO	CoO
wt.%	44.0	19.3	15.8	2.8	0.1	4.7	4.6	5.3	1.5	1.0	0.9

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Table 2

Chemical composition of steel bars

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Co	Cu	V	Sn	Fe
wt. %	0.38	0.18	1.00	0.12	0.06	0.10	0.07	0.20	0.01	0.37	0.02	0.03	97.40

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Table 3
Chemical composition of Type-I Portland cement

Loss on ignition	SiO ₂	Al ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	Cl	TiO ₂	Fe ₂ O ₃	P ₂ O ₅	Total
3.98	19.48	6.80	55.35	3.32	4.35	2.39	1.00	0.02	0.20	2.18	0.19	99.27

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Table 4
Mortar mix proportions

Batch	Mix proportions (relative weight)		
	Cement	Sand	Water
w/c=0.40	1	1.83	0.40
w/c=0.55	1	2.81	0.55

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Table 5

Coating porosity and damage (%)

Coating		PE	ME	DE	FBE
Porosity		15	39	26	9
Average Damage		1.13	2.92	2.62	0.68
Representative specimens	40WW	0.75	2.84	2.28	0.28
	40WD	1.60	2.74	3.11	1.03
	55WW	0.90	2.94	1.93	0.89
	55WD	1.10	3.19	3.48	0.75

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Table 6

Threshold values for steel corrosion in concrete

Index	Threshold values from passive to active corrosion	References
Free chloride (wt.% of cement)	0.07~1.06%	[19]
Open circuit potential (vs. SCE)	-273 mV (over 90% probability of corrosion)	[20]
Polarization resistance	0.1~1 MΩ cm ²	[21]
Corrosion current density	0.1~0.5 μA/cm ²	[22-25]

Table 7

Parameters extracted from representative potentiodynamic polarization curves.

Specimen	Corrosion type	E_c (mV)	i_c ($\mu\text{A}/\text{cm}^2$)	Corrosion depth (μm)
Uncoated	Uniform corrosion	40WW	-663	1.04
		40WD	-677	14.1
		55WW	-748	1.36
		55WD	-693	55.0
PE	Pitting corrosion	40WW	-505	3.73
		40WD	-479	10.9
		55WW	-525	2.00
		55WD	-540	7.45
ME	Uniform corrosion	40WW	-773	3.27
		40WD	-732	26.0
		55WW	-691	2.90
		55WD	-708	11.0
DE	Pitting corrosion	40WW	-686	30.3
		40WD	-583	70.4
		55WW	-582	11.4
		55WD	-566	87.9
FBE	Pitting corrosion	40WW	-136	0.03
		40WD	-232	1.65
		55WW	-129	0.67
		55WD	-157	0.27