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Performance Evaluation of Using Electrochemical Deposition as a Repair Method for Reinforced Concrete Beams

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Abstract: In this paper, the corrosion prevention capability and mechanical behavior of a cracked reinforced concrete beam repaired by the electrochemical deposition method were investigated. To evaluate the effects of repair, the crack closure percentage, the water permeability, the corrosion rate of the reinforcing steels and the remaining flexural strength of the repaired RC beams after 48 and 96-hour accelerating corrosion processes were evaluated. Cracks with widths of 0.4, 0.6, 0.8 and 1.0 mm and depths of 3, 7, 11 and 15 mm were artificially made on the RC beams. It was found that the crack closure percentage increased as the polarization time increased. However, the cracks could only be partially sealed within a polarization time of 8 weeks. Among all specimens, the highest crack closure percentage reached about 90%. The water permeability of the repaired RC beam was lower than that of the cracked one, indicating that the mass transportation paths were effectively sealed by the electrochemical deposition method. It was found that the corrosion rates were reduced after repair. In addition, the remaining flexural strengths of the repaired and unrepaired beams after the accelerating corrosion process were compared. Results showed that the repaired ones had much higher remaining flexural strengths than the unrepaired ones. It can be concluded that the electrochemical deposition method is good for repairing RC structures. It was also found that the electrochemical deposition method had a better efficiency of repairing small cracks than the low-pressure epoxy injection. However, in the presence of large cracks, the electrochemical deposition method may not compete with the low-pressure epoxy injection because of its low repairing efficiency.

Keywords: Electrochemical Deposition, Permeability, Crack Closure Percentage, Flexural Strength, Corrosion Rate

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1 Introduction

Durability of structures, especially the infrastructure, is an important issue. To make the structure have longer life, one can select a better design method in the design stage as mentioned in the paper done by [Paik and Thayamballi (2009)] ; or one can place some sensors to monitor the health of the structure [Kuhn and Soni (2009)]; or one can adopt reliability theory to have a better management of structures [Melchers (2009)]; or one can retrofit the structures to enhance its capability [Sung, Chang, Cheng, Chang and Liu (2009)]. The abovementioned strategies are used before the deteriorations of structures happen. Once the structure encounter deteriorations, to repair it become the only way to prolong the service life of structures.

Concrete durability is a very important issue nowadays. How to make durable concretes and protect them from detrimental environments has become a significant task. On the other hand, how to extend the service life of an old, existing reinforced concrete structure is also critical. It is well known that the cracking of concrete may occur when the concrete or rebar deteriorates. If such crack is ignored, the harmful ion species would penetrate into the concrete along the propagating crack. Therefore, in order to stop the deterioration, the repair of crack is necessary.

Depending on the types of the cracks, many repair methods are available, such as epoxy injection, routing and sealing, and grouting [Chong (1989); Moetaz, Husain and Sami (2000); Shannag (2002)]. The epoxy injection and cement grouting techniques have been well established in literatures [Emmmons (1994); Allen and Edwards (1987); Raina (1993)]. The crack sealing can provide an improved water proof, a good mechanical performance and sometimes a high durability. For more details of repairing concrete structures, readers can refer to following books: Chapman (1961), Emmons (1994), US Army Corps of Engineers (1995).

During the end of 1980s, the electrochemical deposition method was developed in Japan and has been used since then to repair concrete cracks in the marine environment or other situations at which traditional repair methods cannot work [Yokoda and Fukute (1992); Sasaki and Yokoda (1992)]. The electrochemical deposition method is briefly stated as follows. The rebar is used as the cathode and connected to the DC power supply and the titanium mesh is used as the anode. Various chemicals can be chosen for the electrolyte [Ryu and Otsuki (1998)]. Otsuki and Ryu (2001) reported that $ZnSO_4$ solution had the best performance, but later they reported that $MgCl_2$ solution was even better [Ryou and Otsuki (2005)]. As the polarization process continues, the electrochemical deposition seals the cracks. This deposition forms a physical barrier against the further penetration of hazard ion species [Ryou and Otsuki (2002)]. Since the applied cathodic current density is so

low that the possibility of the accelerating alkali-silica aggregate reaction due to the cathodic current is very low. The typical chemical reactions of using $ZnSO_4$ solution as the electrolyte are listed as follows [Ryou and Otsuki (2002)].
The anodic reaction is

$$2H_2O \rightarrow O_2 \uparrow + 4H^+ + 4e^- \tag{1}$$

and the cathodic reaction is

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \uparrow \tag{2}$$

The reaction in the electrolyte of $ZnSO_4$ solution is

$$ZnSO_4 \rightarrow Zn^{2+} + SO_4^{2-} \tag{3}$$

The zinc ions move towards the rebar and react with the hydroxyl ions:

$$Zn^{2+} + 2OH^- \rightarrow ZnO \downarrow + H_2O. \tag{4}$$

The electrochemical deposition condenses pores inside the concrete, and the deposition rate is higher at the root of the crack. The typical setup for the electrochemical deposition is illustrated in Figure 1.

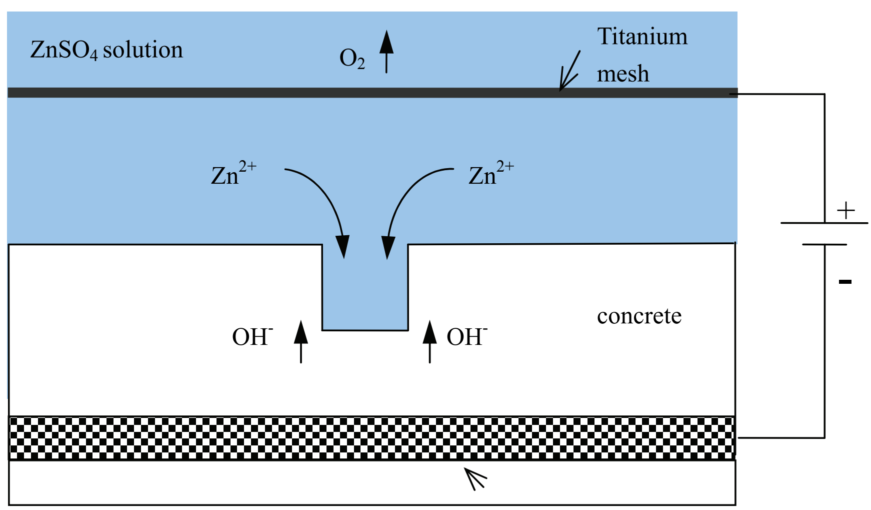


Figure 1: The setup of electrochemical deposition method.

In literature, the crack closure rate and water permeability of concrete specimens repaired by the electrochemical deposition method have been investigated [Ryou and Otsuki (2002)]. In 2005, the flexural behaviors of the repaired RC beams were also reported [Ryou and Otsuki (2005)]. However, comparisons between the effects of the electrochemical deposition and epoxy injection method on the water permeability as well as the flexural behaviors of concrete specimens were not addressed. In addition, it was not clear how well these repair methods worked on corrosion prevention even though water permeability test indirectly gave us the trends. In this paper, we focus on the comparisons between the repair methods of using electrochemical deposition and the low-pressure epoxy injection, especially their effects on the water permeability and the flexural strength. Furthermore, how well the beam was repaired to prevent corrosion is discussed. Both the instantaneous corrosion rate and the remaining flexural strengths are investigated.

2 Experimental

2.1 Specimens

The beam specimens with size of 90 $\times$15 $\times$15 cm were cast, as shown in Figure 2. Four #4 rebars (two on each side) were used as the reinforcement and the concrete cover thickness is 2 cm.

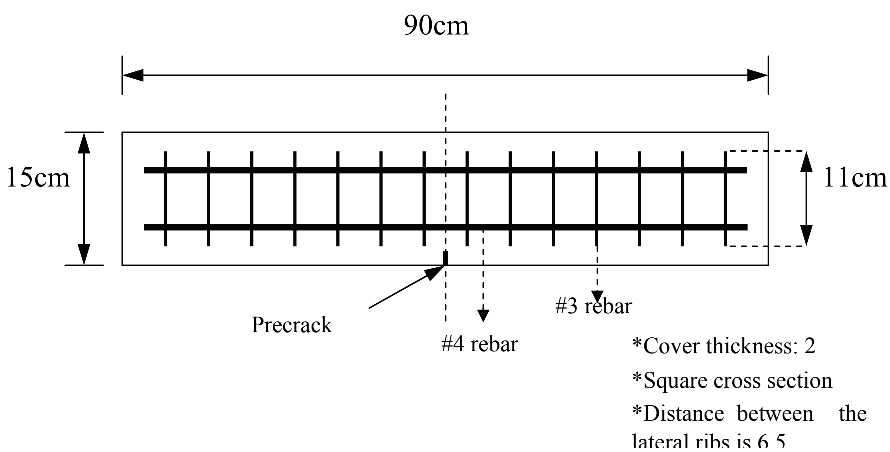


Figure 2: The beam specimen.

The lateral ribs were #3 rebars and the center-to-center distance between the lateral ribs is 6.5 cm. The elastic modulus of the rebar is 203 GPa and the yield strength is 409 MPa. The concrete mix design using water/cement ratio at 0.68 is listed in Table 1. The artificial cracks were made on the bottom of the beam and at the middle position of the beam. Designated crack depths were 3, 7, 11 and 15 mm and the crack widths were 0.4, 0.6, 0.8 and 1.0 mm. The specimens were cast, demolded after 1 day and cured under the standard curing condition for 27 days. After that, we adopted two repairing methods to repair RC beams: low-pressure epoxy injection method and the electrochemical deposition method.

Table 1: Mix proportions of concrete

Water/Cement ratio	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
0.68	223	328	866	892

The epoxy used in the low-pressure epoxy injection method should have low viscosity such that ideally it can fill the cracks fully. In this study, the epoxy with a viscosity of 600 cps is used. Epoxies with viscosities of 100-1000 cps are categorized into the low-viscosity epoxy.

For the electrochemical deposition method, 1 M $ZnSO_4$ solution was used as the electrolyte. The cathodic current density of 0.5 A/m^2 with respect to the cathode area (0.85 A/m^2 with respect to the wet concrete surface) was provided by a power supply between the embedded steel and a titanium mesh anode, which was immersed in the electrolyte solution and located at the bottom of container. After the cathodic current was applied for 2, 4, 6 and 8 weeks, various experiments were conducted for various beam specimens as stated in the followings.

2.2 Experiments conducted

The following experiments were conducted to evaluate the performance of the electrochemical deposition method and/or the low-pressure epoxy injection method.

(1) The crack closure percentage

This experiment is used to evaluate the efficiency of the electrochemical deposition as a repair method. As shown in Figure 3, the deposition starts from the root of the crack and then piles up to the concrete surface. The surface closing length for the crack is then defined as the part of crack length that has been repaired by the piled deposit. By dividing the surface closing length by the initial crack length, one can obtain the crack closure percentage.

(2) The water permeability test

The water permeability test was performed following the regulation in JIS A 6909,

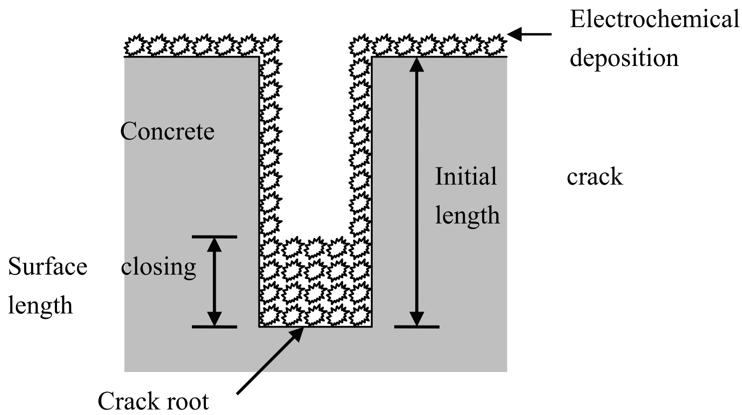


Figure 3: The deposits pile up from the crack root.

as shown in Figure 4. The coefficient of permeability, k, can be calculated by

$$k = \frac{aL}{A(t_1 - t_0)} \ln \frac{h_0}{h_1} \tag{5}$$

where a is the cross sectional area of the upper glass tube, L is the permeation length of the concrete specimen, A is the contacting cross sectional area of the funnel, the elevation of water at the initial time, t_0, is h_0 and the elevation of water at the final time, t_1, is h_1.

(3) Four-point bending test

The purpose of this test is to evaluate the recovery of the mechanical properties of the concrete beam after repair. In addition, the environment of accelerated corrosion for repairing RC beams induced corrosion and deterioration in the RC beams. The residual flexural strength of a repaired RC beam after accelerated corrosion will be used as an index of corrosion prevention capability for each repairing method.

(4) Corrosion rate measurement

The DC polarization is used for calculating the corrosion rate for the reinforcement. Using the Stern-Geary equation [Stern and Geary (1957)], the polarization resistance can be obtained from the Tafel slopes of anodic polarization and cathodic polarization, as expressed by:

$$i_{corr} = \left[\frac{\beta_a \beta_b}{2.303\,(\beta_a + \beta_b)} \right] \times \frac{\Delta E}{\Delta I} = \frac{B}{R_p} \tag{6}$$

where

R_p: polarization resistance (Ohms-cm^2);

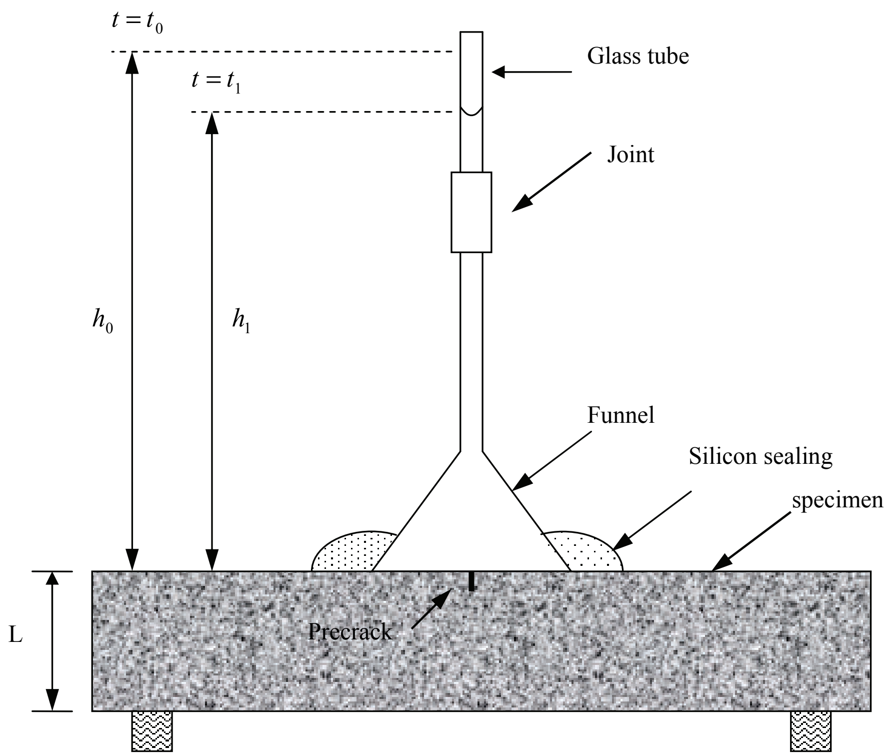
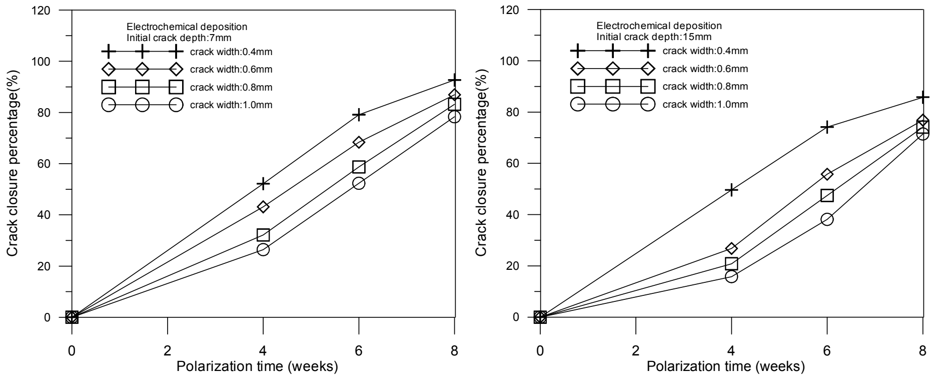


Figure 4: Experiment setup of the permeability test.

i_{corr}: corrosion current density (A/ cm^2);
β_a : Tafel slope of the anode;
β_b : Tafel slope of the cathode;
ΔE : potential difference(Volts);
ΔI : current density difference(A/ cm^2).

The value of B is usually taken as 26 mV for corroded rebar in concrete environment [Berke, Dallaire, Hicks and Hoopes (1993); Dhir, Jouts and McCarthy (1993)]. Substituting the result from Eq.(6) into the Faraday's law, the corrosion rate then can be obtainted.

In the accelerated corrosion process, specimens were immersed in a 3.5% NaCl solution and then corroded by applying an anodic current density of 0.5 A/m^2 (to the cathode area) for 48 and 96 hours. After accelerated corrosion, the corrosion rate measured from the linearized DC polarization and the remaining flexural strength of the beams were summarized to evaluate the corrosion prevention capability of



5(a) **5(b)**

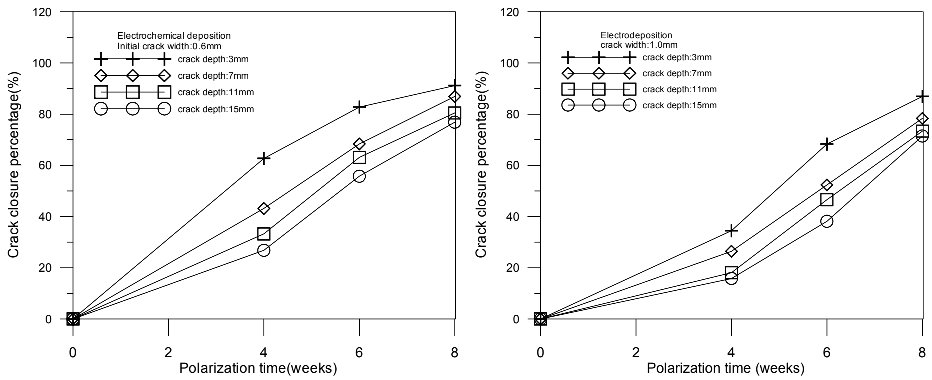
Figure 5: The influence of polarization time on the crack closure percentage of specimens with various initial crack widths: (a) initial crack width of 0.6 mm; (b) initial crack width of 1.0 mm.

each repair method.

3 Results and discussions

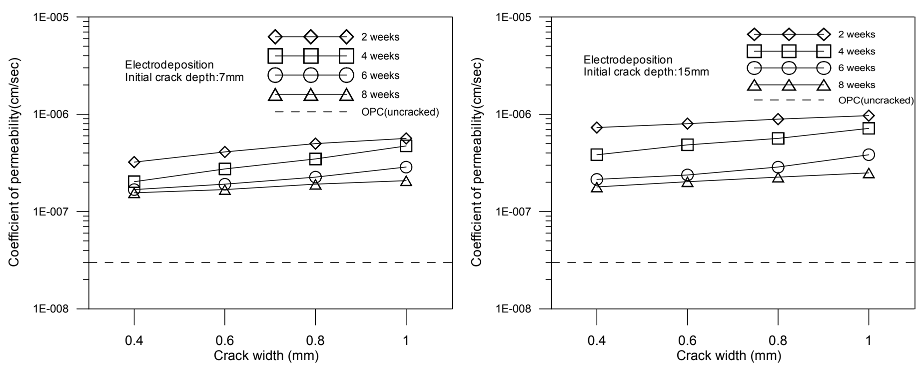
3.1 Crack closure percentage

The influence of the initial crack width on the crack closure percentage is shown in Figures 5(a) and 5(b). It can be said that the crack closure percentage becomes lower when the initial crack width becomes wider. In addition, the crack closure percentage is smaller when the initial crack depth becomes larger, as shown in Figures 6(a) and 6(b). From these figures, it can be concluded that as the crack volume (crack depth $\times$ crack width $\times$ surface crack length) increases the crack closure percentage decreases. The reason is that: it requires more time to yield enough deposits to reduce the crack volume under the same condition. In our experiments, the best crack closure percentage after applying the electrochemical deposition method for 8 weeks reached about 90%. In previous researches [Yokoda and Fukute (1992); Sasaki and Yokoda (1992)], it has been reported that the efficiency of crack closure becomes not economic after a 90% closure percentage is arrived. When the electrochemical deposits seal cracks, the electrical resistance of concrete then is raised up due to the repair, suggesting that it is not easy to have a 100% crack closure.



6(a) **6(b)**

Figure 6: The influence of polarization time on the crack closure percentage of specimens with various initial crack depths: (a) initial crack depth of 7 mm; (b) initial crack depth of 15 mm.



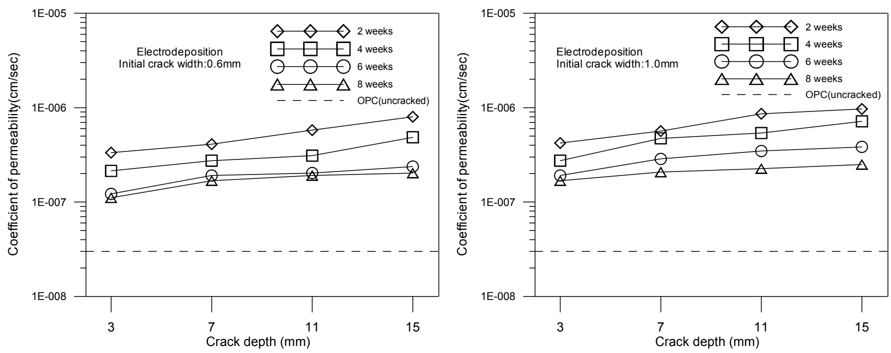
7(a) **7(b)**

Figure 7: The influence of initial crack widths on the permeability of specimens with various initial crack depths: (a) initial crack depth of 7 mm; (b) initial crack depth of 15 mm.

3.2 Water permeability

3.2.1 Water permeability of repaired beams using the electrochemical deposition method

It can be found in Figures 7(a) and 7(b) that, with the same treatment time of electrochemical deposition, when the crack width increases the coefficient of water



8(a) **8(b)**

Figure 8: The influence of initial crack depths on the permeability of specimens with various initial crack widths: (a) initial crack width of 0.6 mm; (b) initial crack width of 1.0 mm.

permeability increases as well. In addition, with the same crack width, when the treatment time increases, the coefficient of water permeability decreases. This reason is that, as the electrochemical deposits increase, they then block the paths for penetrating water. Similarly, it can be found that with the same treatment time, the coefficient of water permeability increases as the initial crack depth increases as shown in Figures 8(a) and 8(b). By summarizing these results, it can be said that as the crack volume increases the repair rate becomes slower and consequently the repair effects on waterproof becomes not so significant. It can be also found that the coefficient of water permeability never recovers to the value of the uncracked beam, indicating that the poor efficiency of the electrochemical deposition method after 90% crack closure percentage is reached may make the full recovery of the crack closure not easy at all.

3.2.2 Permeability of repaired beams using low-pressure epoxy injection method and comparison with the electrochemical deposition method

The water permeability of the repaired beams with a crack depth of 7 mm is illustrated in Figure 9(a). The low-pressure epoxy injection method induces higher water permeability (less waterproof capability) than the electrochemical deposition method despite the crack width. However, the trend changes when the crack depth is 15 mm, as shown in Figure 9(b). From this figure, it can be seen that, the epoxy injection method induces lower permeability than the electrochemical deposition method except for those specimens with a crack width of 0.4 mm. Such controversial results are related to the efficiency of the electrochemical deposition method.

In these two figures, the permeability values taken for the electrochemical deposition method belong to the specimens only with a treatment time of 8 weeks and they show the best repaired results in our experiments (i.e. the longest polarization time in this study is 8 week). Generally speaking, the electrochemical deposition has a better sealing property than the epoxy by assuming that it can seal the crack mostly (the electrochemical deposition method seems to have a better sealing capability on the repairing material-concrete interface). However, if the initial crack volume is large, the electrochemical deposition method cannot compete with the low-pressure epoxy injection method after an 8-week polarization since its crack closure percentage is low. Comparisons between two repair methods for concrete specimens with different initial crack widths are shown in Figures 9(c) and 9(d).

3.3 Flexural strength

3.3.1 The flexural strength of repaired beams using the electrochemical deposition method

The electrochemical deposition method although has been proved to have a good performance on blocking hazard species [Emmons (1994)], the recovery of mechanical property is still not well known.

It can be seen from Figures 10(a) to 10(d) that, under the same treatment, as the initial crack volume increases (either the crack depth or the crack width increases), the recovery of the flexural strengths of the specimens become smaller. Once the electrochemical deposition is applied, the flexural strengths are more or less recovered and better than those of the un-repaired ones. However, it seems that using the electrochemical deposition method to obtain a total recovery of the flexural strength is quite difficult.

3.3.2 The flexural strength of repaired beams using the low-pressure epoxy injection method and comparison with the electrochemical deposition method

The flexural strengths of the repaired beams are illustrated in Figures 11(a) to 11(d). It can be seen that, no matter what initial crack volume is, the low-pressure epoxy injection method can provide a higher flexural strength than the electrochemical deposition method except for two groups (crack width of 0.4 mm and crack depth of 7mm in Fig. 11(a), crack width of 0.6 mm and crack depth of 3 mm in Fig. 11(c)). When the crack closure percentage exceeded 90%, the electrochemical deposition method can provide a better flexural strength recovery than the low-pressure epoxy injection method. Otherwise, the low-pressure epoxy injection method did provide a better flexural strength recovery than the electrochemical deposition method since the crack closure percentage for large initial crack volume was low. It should be no-

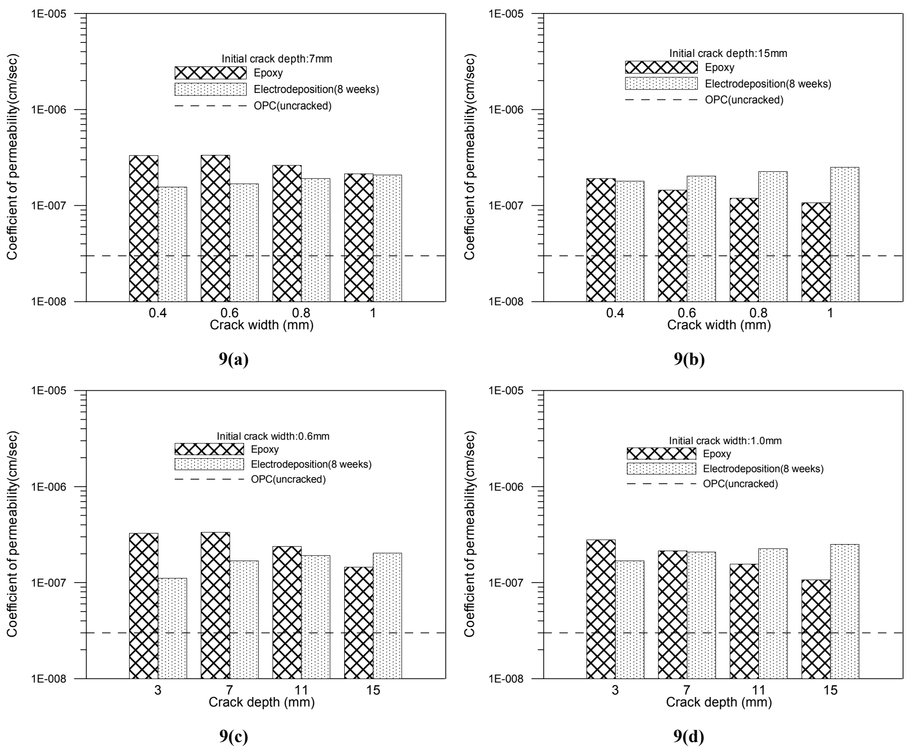
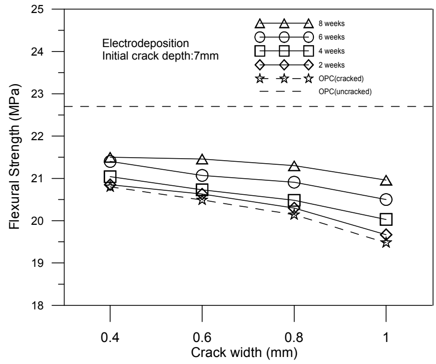


Figure 9: The comparison between permeability values of specimens with different repairing methods: (a) initial crack depth of 7 mm; (b) initial crack depth of 1

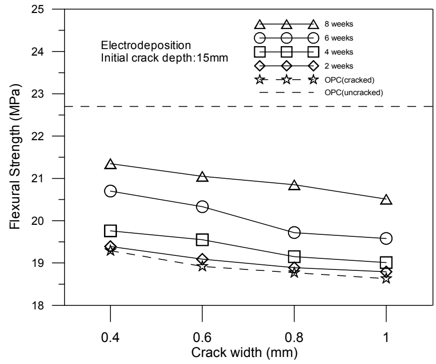
ticed that low-pressure epoxy injection method cannot make the flexural strengths of the repaired beams equal to or higher than those of the uncracked beam. Similar results were reported in Ref. [Thanoon, Jaafar, Kadir and Noorzaei (2005)]. The reason why the low-pressure epoxy injection method cannot fully recover the flexural strength is that it cannot have a good sealing effect along the concrete-epoxy interface due to the low operation pressure. Such reason also explains for high permeability as described above.

3.4 Performance on resisting corrosion

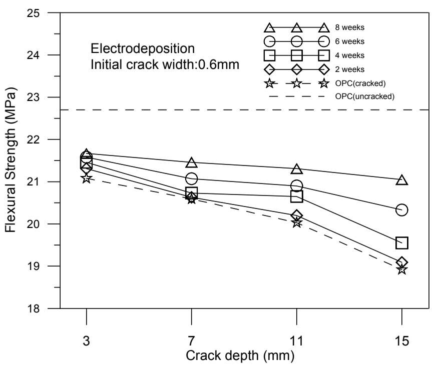
In order to understand the capability of resisting the corrosion in specimens using different repair methods, the accelerated corrosion test is performed as mentioned earlier. After accelerated corrosions of 48 and 96 hours, the instantaneous corrosion rate and remaining flexural strength were then evaluated.



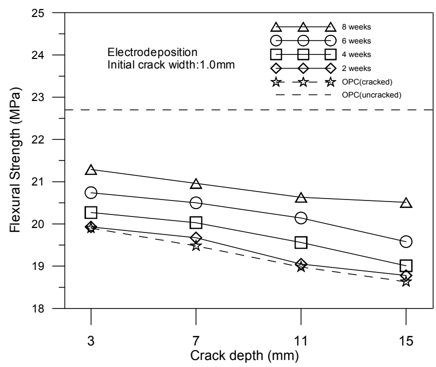
10 (a)



10 (b)



10 (c)



10(d)

Figure 10: The flexural strengths of the repaired beams repaired by the electrochemical deposition method: (a) initial crack depth of 7 mm; (b) initial crack depth of 15 mm; (c) initial crack width of 0.6 mm; (d) initial crack width of 1.0 mm.

3.4.1 Electrochemical deposition method

Corrosion rate

It can be seen from Figures. 12(a) to 12(d) that the beams repaired by the electrochemical deposition method have a lower instantaneous corrosion rate after accelerated corrosions of 48 and 96 hours than the unrepaired cracked beams. In addition, as the initial crack volume increases, the crack closure percentage after an 8-week electrochemical deposition decreases such that the corrosion rate after the accelerated corrosion becomes a little bit higher. The reason why the difference in corrosion rates for concrete with the different initial crack volumes and repaired

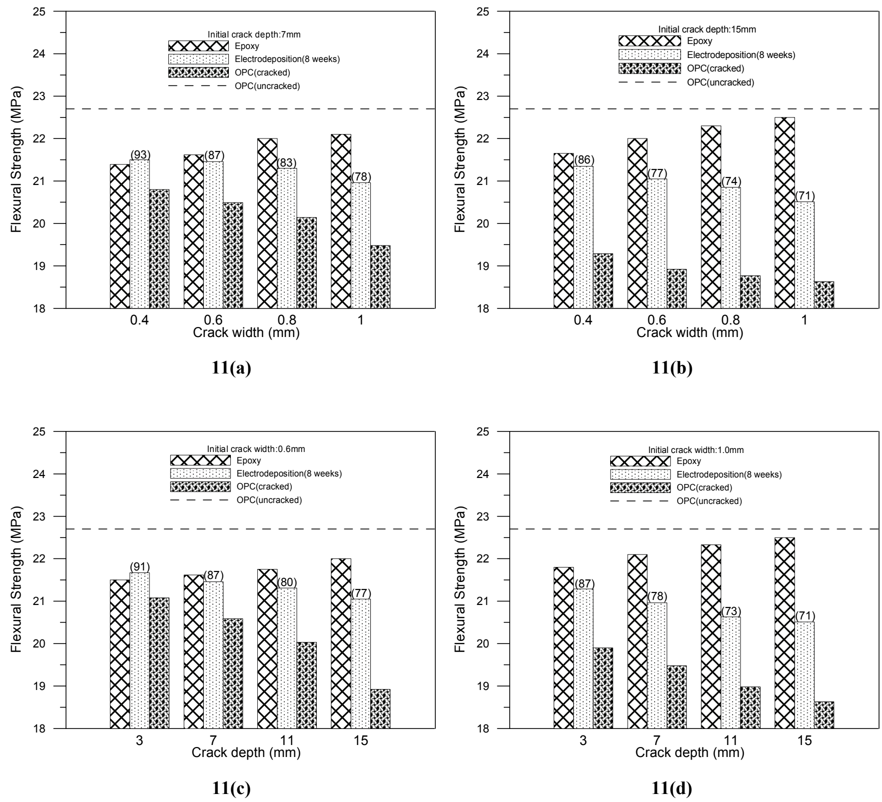


Figure 11: The comparison between flexural strengths of specimens with different repairing methods: (a) initial crack depth of 7 mm; (b) initial crack depth of 15 mm; (c) initial crack width of 0.6 mm; (d) initial crack width of 1.0 mm. (Data in the brackets in the figure means the crack closure percentage)

by the electrochemical deposition method cannot be distinguished is explained as follows. The electrochemical deposition method heals the damaged beams from the location of the rebar to the surface. Therefore, it can be said that although the surface cracks is not been repaired totally, the inner microstructure nearby the rebar has been condensed. Consequently, it is very difficult for hazard species to approach the rebar although the crack paths have not been sealed totally. It then can be said that the electrochemical deposition method can successfully inhibit the approach of the hazard agencies toward the rebar.

Remaining Flexural strength after accelerated corrosion

The flexural strengths of the specimens after accelerated corrosions of 48 and 96

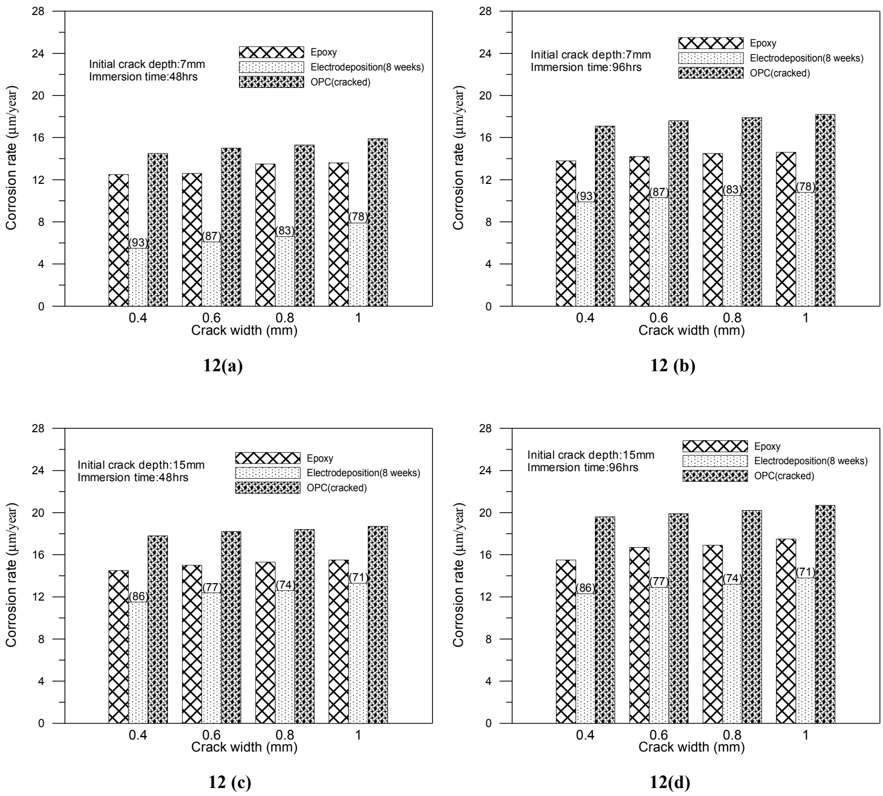
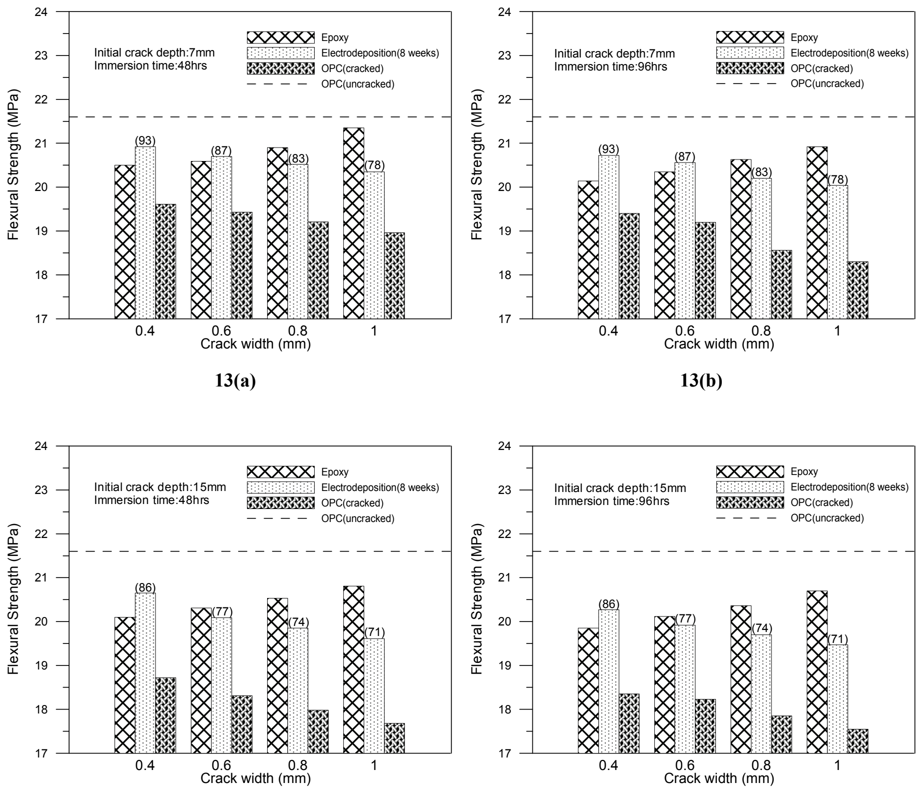


Figure 12: The comparison between corrosion rates of specimens with different repairing methods: (a) initial crack depth of 7 mm subjected to 48-hour accelerating corrosion; (b) initial crack depth of 7 mm subjected to 96-hour accelerating corrosion;; (c) initial crack depth of 15 mm subjected to 96-hour accelerating corrosion; (d) initial crack depth of 15 mm subjected to 96-hour accelerating corrosion. (Data in the brackets in the figure means the crack closure percentage)

hours are illustrated in Figures 13(a) to 13(d). It can be seen that the repaired beams all have higher flexural strength than the cracked beams (un-repaired ones). In addition, the flexural strength loss between the acceleration time of 48 hours and 96 hours shows that the repaired beams has less flexural strength loss than the cracked ones. The reason is that the condensed microstructure reduces the corrosion rate so that the corrosion damage is less.

Furthermore, it can be seen that, as the initial crack volumes increase, the remaining flexural strengths of the specimens after accelerated corrosions become lower. The



13(a) 13(b)

13(c) 13(d)

Figure 13: The comparison between flexural strengths of specimens with different repairing methods: (a) initial crack depth of 7 mm subjected to 48-hour accelerating corrosion; (b) initial crack depth of 7 mm subjected to 96-hour accelerating corrosion;; (c) initial crack depth of 15 mm subjected to 96-hour accelerating corrosion; (d) initial crack depth of 15 mm subjected to 96-hour accelerating corrosion. (Data in the brackets in the figure means the crack closure percentage)

reason has already been explained in the previous paragraphs.

3.4.2 The low-pressure epoxy method and comparison with the electrochemical deposition method

Corrosion rate

It can be seen form Figures 12(a) to 12(d) that the corrosion rates of the repaired beams using the electrochemical deposition method are lower than those using the low-pressure epoxy injection method. It means that the microstructures and the cracks were condensed by the electrochemical deposition method while the low-pressure epoxy injection method could only seal the surface cracks. Consequently, the electrochemical deposition method can block the transport paths for hazard materials more effectively than the low-pressure epoxy injection method so that a lower corrosion rate can be observed.

Remaining flexural strength

Remaining flexural strengths of the specimens after accelerated corrosions are shown in Figures 13(a) to 13(d). It can be found that only for few cases that the electrochemical deposition method already sealed most part of cracks(above 85% crack closure percentage), the remaining flexural strengths after accelerated corrosion process showed that the electrochemical deposition method performed better than low-pressure epoxy injection method. When the crack closure percentage is lower than 85% using the electrochemical deposition method, the repaired beams using the low-pressure epoxy injection method have a higher remaining flexural strength than those using the electrochemical deposition method although they also have higher corrosion rates as discussed in the previous paragraph. However, one cannot say that the electrochemical deposition method induces a lower flexural strength and poorer protection against the corrosion than the low-pressure epoxy injection method. It depends on the crack closure percentage that the electrochemical deposition method can provide. If a crack closure percentage near 85% is reached (for larger initial crack volume it means a longer polarization time is required), the electrochemical deposition method actually can provide a higher flexural strength and better protection against the corrosion than the low-pressure epoxy injection method, as shown in some exceptional cases in these figures.

4 Conclusions

It is found that the electrochemical deposition method can successfully seal the cracks and reduce the water permeability of the concrete specimens. The crack closure percentage is related to the initial crack volume. A larger crack requires more time to heal. Although 100% sealing is quite difficult, the repaired beams have a higher flexural strength in comparison with the cracked one. The repaired beams have a higher resistance to the further corrosion in comparison with the cracked beams. In addition, the beams repaired by the electrochemical deposition method have a lower water permeability values than those repaired by the low-pressure epoxy injection method when the crack closure percentage exceeds certain value. However, the low-pressure epoxy injection method provides a better flexural strength than the electrochemical deposition method. In concern with corrosion prevention, the electrochemical deposition method can provide a better corrosion prevention capability since it can block the paths for hazard materials more effectively than the low-pressure epoxy injection method. If the crack closure percentage of near 90% is achieved by the electrochemical deposition method, it can make repaired beams have higher flexural strength after exposed to the corroded environments.

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