DURABILITY AND SERVICE LIFE OF CONCRETE REPAIRS IN THE PRESENCE OF CRACKS

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Abstract

Engineered Cementitious Composite (ECC) has been proposed to be one of the most promising repair materials due to its unique high ductility and tight crack width control. In concrete repairs, the shrinkage of repair materials is restrained by concrete substrate, and the repair material therefore often cracks. When ECC is used as repair material, the crack width is much smaller compared to normal concrete. The tight crack width of ECC retards the penetration of water and harmful substances and thus enhances the durability of concrete repairs. This paper is aimed to explore the chloride penetration in cracked ECC repairs and to assess the service life of the repair systems. Rapid chloride migration test was conducted to investigate the chloride penetration profile. Based on the experimental results, the service life of repair systems was evaluated.

1. INTRODUCTION

The concrete repair, rehabilitation and retrofitting industry grows rapidly, driven by deterioration of, damage to and defects in concrete structures. In U.S. only, the annual cost for repair, maintenance and strengthening is estimated between \$18 and \$21 billion [1]. However, concrete repairs have been experiencing severe performance problems, and failures of concrete repairs are often manifested by cracking, delamination and spalling. This results in increased economical, social and environmental impact.

One of the main causes to the failure of concrete repairs is the surface cracking induced by differential shrinkage between repair material and concrete substrate [2]. Most repair material shrinks, especially at early age. When the shrinkage is restrained by the concrete substrate, a tensile stress is induced in the repair material. The tensile stress can cause cracking in the repair material, and facilitates the penetration of water, oxygen, chlorides, alkalis or sulphates into the repair system. This causes reinforcement corrosion and concrete deterioration, and eventually the concrete repair fails.

Recently, a high performance cementitious material has been developed by Li et al. [3], called Engineered Cementitious Composite (ECC). This group of materials is characterized by high ductility in the range of 3-7% and tight crack width of around 60 μm. When ECC is used as repair material, the high ductility allows ECC to undergo large deformations, often due to differential shrinkage, while maintaining load capacity [4]. The tight crack width can significantly retard the penetration of water and harmful substances, and thus enhances the durability of concrete repairs in aggressive environments. Therefore, the use of ECC can prolong the service life of concrete repairs and reduce the maintenance and repair costs.

Nowadays, the service life of concrete structures is mainly calculated with the material properties of uncracked concretes. In reality, most structural concretes work with the presence of cracks, particularly in concrete repairs subjected to differential shrinkage. Cracks can adversely affect the durability by facilitating the ingress of aggressive substances, such as chloride ions and cause a decrease in service life. The service life is therefore overestimated when the uncracked material properties are used for the cracked concretes.

In this paper, the durability of cracked ECC repairs is investigated, compared with a widely used repair material. The chloride penetration profile in the cracked repair materials were measured by rapid chloride migration (RCM) test. Based on the experimental data, the chloride migration coefficient was calculated. In order to interpret the chloride penetration profile, the pore structure of these two repair materials was studied by mercury intrusion porosimetry (MIP). The service life of concrete repairs in land and marine environments was predicted using DuraCrete model.

2. MATERIALS AND METHODS

2.1 Concrete substrate

Three-year-old concrete beams were used as substrate specimens, and they had a dimension of 1000 × 200 × 200 mm^3. In this concrete, the binder was blast furnace slag cement CEM III/B 42.5 LH with a cement amount of 350 kg/m^3 and the water-to-cement ratio was 0.48.

2.2 Repair materials

The ECC made of blast furnace slag and limestone powder was used as a repair material [5], and its mix proportion is given in

Table 1. The ECC mixing procedure was as follows: cement, limestone powder and BFS were first mixed with a HOBART® mixer for 1 minute at low speed; then water and superplasticizer were added at low speed mixing; Mixing continued at low speed for 1 minute and then at high speed for 2 minutes; after fibers were added, the sample was mixed at high speed for another 2 minutes.

The other repair material was a fiber-reinforced polymer-modified (FRPM) mortar, which is one of the most widely used repair materials in the Netherlands. The water-to-solid ratio of the FRPM mortar was 0.14.

Table 1: ECC mix proportion (kg/m^3)

CEM I 42.5N	Limestone powder	BFS	Water/powder ratio	Super-plasticizer	PVA fiber
237	790	553	0.26	7.9	25.3 (2% by volume)

2.3 Specimen preparation

Before placing the repair materials, the concrete substrate was grit-blasted and saturated. ECC and FRPM mortar were cast on the concrete substrates, and the thickness of the repair layer was 50 mm. After demolding, the composite beams were moved into a room with ambient conditions of 20°C and 50% RH. The differential shrinkage caused cracking in the repair materials. After 90 days, three cylinders with a diameter of 100 mm were cored out of each composite beam at the locations with cracks. As shown in Figure 1, the specimens consist of a layer of repair material with a thickness of 50 mm and a layer of concrete substrate with a thickness of 20 mm. More than 4 cracks were observed in each ECC specimen and only one crack in each FRPM mortar specimen. The surface crack width was measured using a portable microscope. The specimens were then saturated with $Ca(OH)_2$ solution for 24 hours.

Figure 1: Specimen for RCM tests

2.4 RCM test

The RCM test was carried out according to the Nordic standard NT BUILD 492 [6]. After $Ca(OH)_2$ solution saturation, the specimens were put in a rubber sleeve and fastened with two stainless steel clamps to ensure that no water goes along the edge of the specimens, as shown in Figure 2. The RCM test set-up is illustrated in Figure 3. The substrate surface was immersed in the anolyte solution of 0.3 M NaOH and the cracked repair surface was immersed in the catholyte solution of 10% NaCl. A voltage of 60 V was then applied on the anolyte solution and catholyte solution for 3 days. The room temperature during testing was 24.6 ± 0.2°C.

Figure 2: Specimen sealed with rubber sleeve and stainless steel clamps

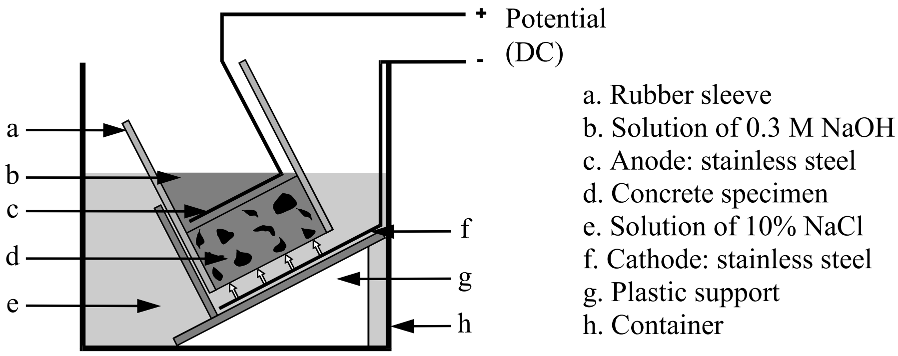


Figure 3: RCM test set-up

After a 3-day exposure to chloride solution, the rubber sleeve and stainless steel clamps were removed and the specimens were split into two pieces perpendicularly to the surface cracks. A 0.1 M $AgNO_3$ solution was sprayed on the freshly split sections. $AgNO_3$ reacts with NaCl and to produce AgCl, which appears white and indicates chloride penetration depth. After around 15 minutes of spraying $AgNO_3$ solution, the penetration depth was measured at 7 locations on every section. The average penetration depth was calculated by averaging the measured values from each specimen. The maximum penetration depth in the specimens was also measured.

2.5 MIP test

In order to interpret chloride transport properties of the repair materials, MIP tests were conducted to investigate the pore structure of the repair materials. At the age of 90 days, the repair materials were sawn into pieces of 0.5 cm^3 and were then dried by freeze-drying method. The samples were quickly frozen by immersing in liquid nitrogen for 5 minutes. Then, they were moved into a freeze-dryer with temperature of -24ºC and vacuum at 0.1 Pa. The sample was considered to be dry, until the water loss was below 0.01%/day. This period lasted for 10-20 days depending on w/c ratio and curing age of the samples. Ye [7] suggested that this method caused less damage on the pore structure of cement paste compared with the other common drying methods, i.e. oven drying and vacuum drying.

The dried samples with a known weight were put into a penertrometer and the penertrometer was closed with a steel cap. After the weight of the penertrometer with the samples was measured, it was placed into a low-pressure chamber. The chamber was evacuated to a pressure of 50 μmHg and mercury then filled the penertrometer. Pressure was gradually increased from 0.004 MPa to 0.15 MPa. The penertrometer was removed from the low-pressure chamber and was then weighted. After the penertrometer was placed in a high-pressure chamber, pressure was gradually increased to the maximum value of 200 MPa. In total, 125 pressure steps in logarithmic distribution were taken. Equilibrating time in every step was 30 seconds.

3. CHLORIDE PENETRATION PROFILE IN REPAIR SYSTEMS

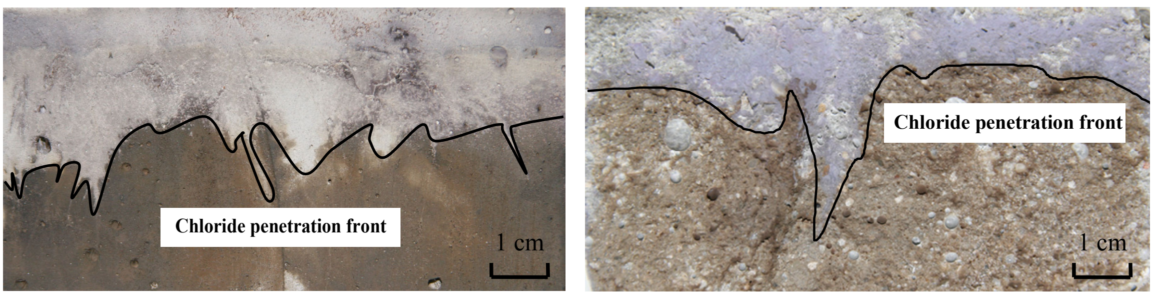
As observed using a portable microscope, the differential shrinkage resulted in averaged crack widths of 39 μm and 112 μm in ECC and FRPM mortar, respectively. As shown in Figure 4, surface cracking facilitates chloride penetration in the repair materials and the cracks are all accompanied by a peak in the chloride penetration front (or all peaks in chloride penetration front were observed in cracks). Due to the presence of more than 4 cracks, the chloride penetration front in ECC shows several peaks. While, there is one major peak in the chloride penetration front in FRPM mortar and this peak is more pronounced than those in ECC. The chloride penetration depth in cracks shows a good linear relationship with its crack width as shown in Figure 5. In both repair materials, as the crack width increases, the chloride penetration depth in this crack increases.

Besides the maximum chloride penetration depth, which is in cracks, the average chloride penetration depths in the two repair materials are calculated by averaging the results at 7 locations in each specimen. The values of the average and maximum chloride penetration depths are given in

Table 2. The average chloride penetration depth in ECC is 57% larger than that in FRPM mortar. However, ECC shows a maximum chloride penetration depth 19% smaller than FRPM mortar.

Table 2: Average and maximum chloride penetration depths in repair materials

Repair material	Average chloride penetration depth (mm)	Maximum chloride penetration depth (mm)
ECC	22.3 ± 0.8	33.0 ± 2.2
FRPM mortar	12.6 ± 1.3	39.2 ± 3.7



(a) (b)

Figure 4: Chloride penetration profile in (a) ECC and (b) FRPM mortar at the age of 90 days

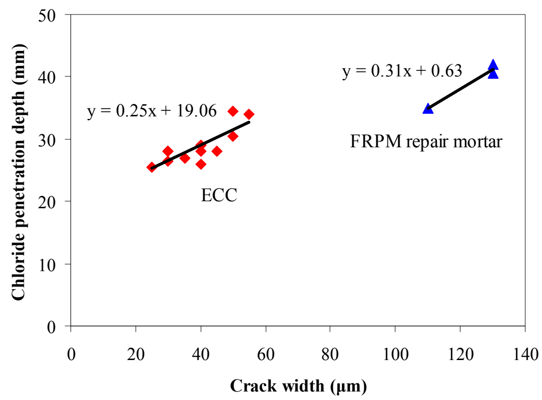


Figure 5: Relationship between the maximum chloride penetration depth in cracks and the crack width

With the chloride penetration depth, the non-steady-state chloride migration coefficients of the repair materials can be calculated with the following equation [6]:

$$D = \frac{0.0239 \times (273+T) \times L}{(U-2) \times t} \times \left(x_d - 0.0238 \times \sqrt{\frac{(273+T) \times L \times x_d}{U-2}} \right) \quad (1)$$

where D is the non-steady-state chloride migration coefficient, T is the temperature in the anolyte solution, L is the thickness of the specimen, x_d is the chloride penetration depth, U is the applied voltage and t is the test duration.

The non-steady-state chloride migration coefficients calculated with the average and maximum penetration depths are given in Table 3. The average chloride migration coefficient of ECC is higher than that of FRPM mortar. However, when calculated with the maximum penetration depth, ECC shows a lower maximum chloride migration coefficient than FRPM mortar.

Table 3: Non-steady-state chloride migration coefficients calculated with the average and maximum penetration depths

Repair material	Chloride migration coefficient calculated with average penetration depth ($\times 10^{-12}$ m^2/s)	Chloride migration coefficient calculated with maximum penetration depth ($\times 10^{-12}$ m^2/s)
ECC	2.4 ± 0.1	3.6 ± 0.2
FRPM mortar	1.3 ± 0.1	4.3 ± 0.4

In order to explain the chloride transport in the repair materials, the pore structures of the repair materials were investigated by MIP. The MIP results of the two repair materials are shown in Figure 6. The experimental results show that ECC is much more porous than FRPM mortar. The total porosities of ECC and FRPM mortar are 26.2% and 12.1%, respectively. The differential curve of ECC shows two major peaks located at the pore diameters of 0.52 μm and 0.04 μm. The differential curve of FRPM mortar shows only one major peak located at the pore diameter of 0.07 μm. Since the addition of fibers induces porous fiber-matrix interface, the porosity is increased. The presence of the peaks corresponding to larger pore diameter might be attributed to the addition of high volume of fibers in ECC.

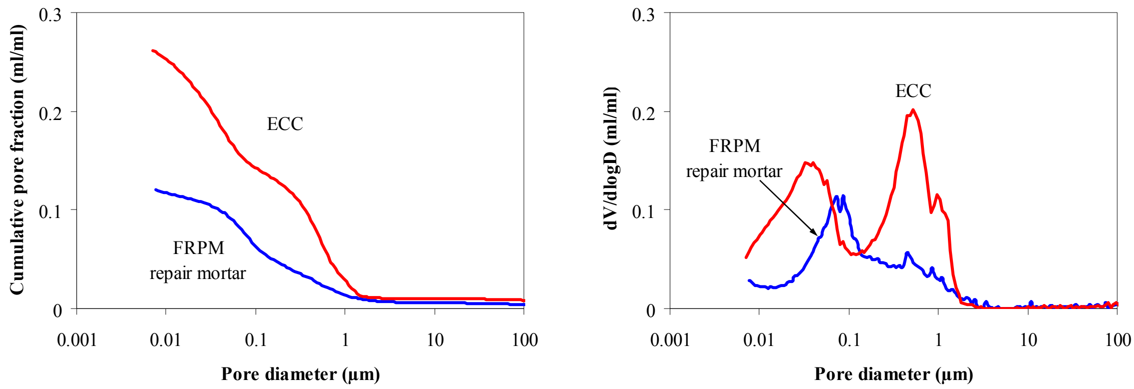


Figure 6: Pore size distributions of the repair materials at the age of 90 days

Chloride ions penetrate into concrete through pore system, when there are no cracks. The pore sizes determine the rate of chloride penetration. The larger the pore sizes are, the faster the chloride penetration is. As a result, ECC shows a larger average chloride penetration depth. Besides pore system, cracks also facilitate chloride ingress in concrete. Usually, chloride penetration in cracks is much faster than that in the pore structure, because the cracks have a larger size than pores. The experimental results also show a larger penetration depth in the cracks. The penetration depth in the cracks has a strength relationship with the crack width. The larger crack width in FRPM mortar results in a larger maximum penetration depth. Consequently, ECC shows a higher average chloride migration coefficient and lower maximum chloride migration coefficient.

4. SERVICE LIFE PREDICTION OF CONCRETE REPAIRS

Chloride-induced reinforcement corrosion is the major cause of deterioration of reinforced concrete structures [8]. The chloride penetration profile in concrete is therefore often used as an index to predict the service life of concrete structures.

The chloride migration coefficients are used to predict the service life of concrete repairs. The service life in this case is defined as the duration from placing repair materials until the initiation of chloride-induced reinforcement corrosion. Once the chloride content at the surface of the rebar has exceeded the critical value, the service life of the structure is considered to end. The DuraCrete model is used to calculate the service life of the concrete repairs. The DuraCrete model is a transport property-based model, adopting the semi-probabilistic approach. The concept of this model, its validation and application has been presented and discussed in details in [9,10]. In the DuraCrete model, the chloride penetration process is calculated as:

$$C(x,t) = C_s - \left(C_s - C_i\right) \times erf\left(\frac{x}{\sqrt{4ktD(t)}}\right) \qquad (2)$$

where $C(x,t)$ is the chloride content at depth x at time t, C_s is the surface chloride content, C_i is the initial chloride content in the concrete, k is a correction factor and $D(t)$ is the chloride migration coefficient at time t.

The critical chloride content is set to be 0.6% by mass of the repair material [11]. The surface chloride content is often taken equal to 3.0% for marine structures [9] and 1.5% for land structures [11]. The initial chloride content in the repair material is assumed to be 0.1% [10]. The correction factor k depends on the type of binder, the environmental factors and curing conditions. According to [8], the k-values of ECC and FRPM mortar are taken equal to 2.97 because of high slag content in the two repair materials. The chloride migration coefficient is a time-dependent factor, and it decreases along time. This phenomenon can be described with an aging coefficient as follows:

$$D(t) = D_0 \left(\frac{t_0}{t} \right)^n \tag{3}$$

where, D_0 is the chloride migration coefficient at the reference time t_0 (90 days in this study) and n is the aging coefficient. The value of the aging coefficient depends on the type of binder, the rate of cement hydration and environmental factors. In moderately wet environment, the n-values of ECC and FRPM mortar are taken to be 0.85 [8].

The minimum cover depth required for the service life of 100 years, exposed to marine and land environments is determined using Eq. 2 and summarized in Table 4. Because of the high chloride content in seawater, the repair materials in the marine environment need a thicker cover compared to those in the land environment. No matter in land or marine environment, ECC needs smaller cover depth compared to the FRPM mortar due to its tiny crack width and low chloride penetration coefficient.

Table 4: The minimum cover depth (mm) required for the service life of 100 years. Exposure classes XD1, XD2 and XD3 represent land environment, and XS2, XS3 represent marine environment.

Repair materials	Exposure class	
	XD1, XD2, XD3	XS2, XS3
ECC	18.6	26.7
FRPM mortar	20.4	30.2

5. CONCLUSION

The durability of cracked ECC repairs was experimentally investigated by RCM test. The experimental results were then used to predict the service life of the repair systems. Based on the experimental results, the following conclusion can be drawn:

- The surface cracking facilitates chloride penetration in repair materials. The maximum chloride penetration depths are all located along cracks.
- Due to the tight crack width, ECC has a relatively smaller maximum chloride penetration depth compared to FRPM mortar.
- To achieve the same service life, ECC needs smaller cover depth than FRPM mortar.

6. ACKNOWLEDGEMENTS

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