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Research Paper

EXPERIMENTAL STUDY ON CHLORIDE PENETRATION DEPTH IN CRACKED REINFORCED CONCRETE

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The durability of reinforced concrete structures in marine environment has been investigated as a serious problem in concrete construction technology where the chloride attack was an interested topic. Chloride attacking the reinforced concrete structure through the crack is complicate and more dangerous than uncracked concrete. In this paper, the chloride diffusion into cracked reinforced concrete was studied by a basic of migration tests. The crack is a cause for increasing chloride penetration depth, there the crack depth plays an important role. Besides crack depth, the crack width is also investigated to obtain its influence on the chloride penetration depth. Kind of crack investigated is natural crack (V-shape crack) and it is generated by bending moment of reinforced concrete beam.

Keywords: Chloride penetration depth, Natural crack, V-shape crack, Crack depth, Reinforced concrete

INTRODUCTION

Up to now, the chloride penetration into concrete is one of the best topics and very exciting in the field of concrete durability (Sugiyama *et al.*, 2008). Especially, when the cracks occur in the concrete cover, the rate of chloride ion is accelerated to diffuse into concrete structure in which durability, as a result, will be reduced quickly. That is why many researchers have tried to take into account, the influence of crack on the chloride penetration into concrete structure because the cracks cause a damage for the durability of concrete under marine environment (Ismail *et al.*, 2008; Mien *et al.*, 2009; Mien *et al.,* 2011; Vu *et al.*, 2011; Vu *et al.*, 2012).

Normally, the crack width was focused to investigate the chloride penetration into cracked concrete (Djerbi *et al.*, 2008). Gowripalan *et al.* (2000) pointed out a relationship between corrosion of embedded steel and ratio of crack width to concrete cover thickness. As a result, the depth of concrete cover is very important for

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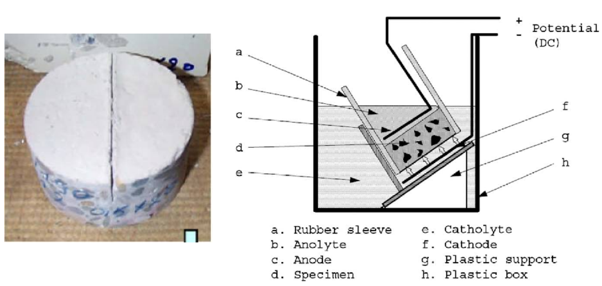
the resistance of the reinforcement corrosion by reducing depth of chloride penetration and protecting reinforcements. However, with a pathway created by the depth of crack, the chloride ions will penetrate deeper into concrete structure, so that the crack depth is also very important to consider for reinforcement corrosion in addition to crack width (Vu *et al*., 2013). Marsavina *et al*. (2009) studied on the chloride penetration depth with a notch instead of a crack (Figure 1). He used a steel sheet pressed on a fresh concrete specimen to create an artificial crack. The depth of this artificial crack is varied by varying depth of the steel sheet submerged into fresh concrete.

However, the studies about crack depth affecting on the chloride penetration have not been clear and complete. In the field, the cracks of reinforced concrete member often present under natural cracks due to service load. Contrary to the notch, the shape of natural crack plane is tortuous and rough. For this reason, it is necessary to conduct an influence of natural crack on the chloride penetration depth. This paper is carrying out the experimental effects of natural crack characteristics, such as crack width and crack depth, on the chloride penetration depth in cracked reinforced concrete structure.

Figure 1: The Chloride Migration Test with a Notch Specimen



Source: Marsavina et al. (2009)

EXPERIMENTAL INVESTIGATION

Materials

The materials used were 20 mm maximum size crushed gravel, river sand, Ordinary Portland Cement (OPC). The concrete proportion and physical properties of concrete used in this research are shown in Table 1. The sand and coarse aggregate were washed before casting to remove the initial chloride content in fresh concrete.

TEST DETAILS

Experiment program determines a correlation of crack characteristics on the chloride penetration depth. In this research, these characteristics of a crack are crack width and crack depth. This experiment will be based on the short-term diffusion test, a basis of chloride migration test (Sugiyama *et al.,* 2001), which is modified by combination of ASTM C1202 and Nordtest NT build 492. However, the shape of applied voltage

Table 1: Mix Proportion and Physical Properties of Concrete

Mix	W/C	Cement (kg)	Water (kg)	Sand (kg)	Crushed gravel (kg)	Av. Comp. Str. (MPa)	Av. Slump (cm)
1	0.4	513	205	664.14	1,024	48.1	7.5
2	0.5	410	205	748.62	1,024	39.3	8.5
3	0.6	342	205	804.93	1,024	32.8	8

cell was modified to change from cylinder-shape specimen to cubic-shape specimen, shown in Figure 2.

A single natural crack was generated by bending a reinforced concrete beam. Then, the cubic specimens (Figure 3) containing the single

Figure 2: Set up of Short-term Diffusion Test Modified by ASTM C1202 and Nordtest NT Build 492 for Cubic Specimen

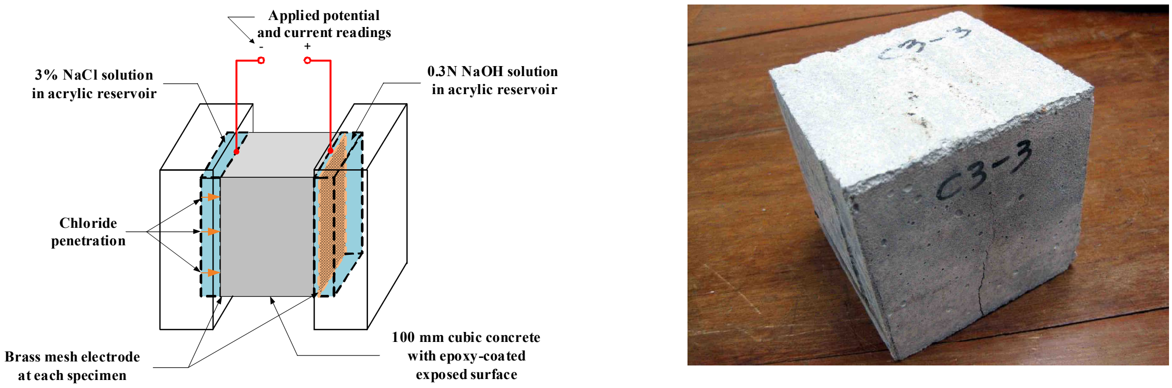


Figure 3: Cubic Specimens for Testing with W/C = 0.4 (a), 0.5 (b) and 0.6 (c)

Figure 4: The Short-term Chloride Diffusion Test (A) and Chloride Penetration Depth At Cracked Concrete (B)

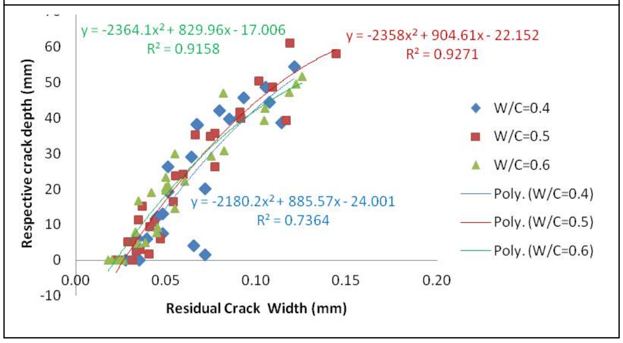
crack were sawed from the pre-cracked beams. Before conducting chloride short-term diffusion test, a correlation of the crack depth to crack width along crack plane of the cubic specimen is measured on both crack sides of the cubic specimen by digital microscope. Due to the complicated torturous crack plane, it is very difficult to determine where crack tip by eye. So, in this research, crack depth of cracked concrete for chloride migration test is defined as a straight length from the crack mouth along crack plane to where having a crack width of 30 μm, because when crack width is less than 30 μm there is insignificant for chloride diffusion (Djerbi *et al.*, 2008; Ismail *et al.*, 2008). Therefore, in this study, it is termed as respective crack depth. The crack width (crack mouth on the tensile surface) of cubic specimen was measured at 9 points of interval distance of 1 cm. The applied volt for testing was 60 V. The duration time of testing was 10 h. After chloride migration test, the cubic specimens were split into two parts. The silver nitrate 0.1 M was then sprayed on the split surface of the concrete. After 15 min, the chloride penetration depth was measured as visible white precipitation of silver chloride at crack tip, shown in Figure 4.

RESULTS AND DISCUSSION

Correlation Between Crack Depth and Crack Width

Regarding experimental results, shown in Figure 5, it is not difficult to recognize the trends of influence of respective crack depth on the residual crack width are similar with varying W/C ratio. Because mix proportions of concrete beams are similar without W/C ratio, it causes the differences of compressive strength. However, its influence on the opening crack width is not much; because varying crack width is primarily affected by the bond strength, as well as the slip value is a main parameter. As this study, the round reinforcement steel was used, so the compressive strength did not promote ability for the bond strength so much, compared with the bond strength between deformed steel bar and concrete. Moreover, the results of measurement for residual crack width and crack depth and are measured as the applied load retired.

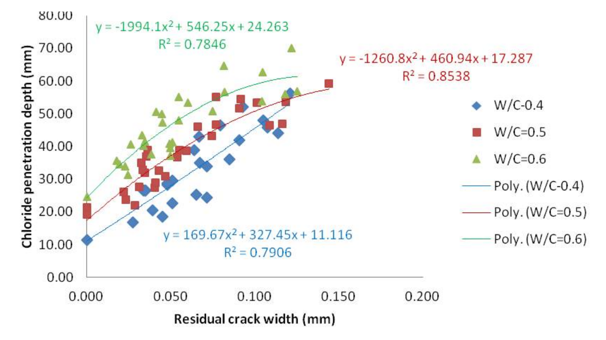
Figure 5: The Correlation Between Respective Crack Depth and Residual Crack Width



Influence of Crack Width on the Chloride Penetration Depth

The experimental results, plotted in Figure 6, show that the chloride penetration depth increased in increase of residual crack width. However, it seems that the rate of the increasing chloride penetration depth will reduce when the crack width increasing. It can be explained by the influence of limitation of crack depth on that. Viewing back the correlation between crack width and crack depth in Figure 5; the rate of increasing crack depth correlating to residual crack width also reduce. It means that the influence of crack depth on the chloride penetration depth is more significant than the crack width. It is easy to understand that the chloride penetration depth of a deeper crack depth is larger than that of a shallow crack depth, although they have the same crack width.

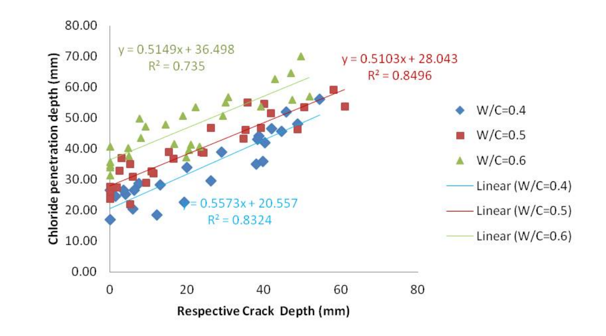
Figure 6: The Correlation Between the Residual Crack Width and Chloride Penetration Depth



Influence of Crack Depth on the Chloride Penetration Depth

A crack caused the strong influence on the chloride concentration depth. Generally, the chloride ions penetrate through crack path into concrete causing the increasing depth of chloride concentration at the crack location, shown in Figure 7.

Figure 7: The Chloride Penetration Depth at Cracked Concrete Versus Respective Crack Depth



The experimental results for an influence of respective crack depth on the chloride penetration depth are shown in Figure 7. The chloride penetration depth increased linear with respective crack depth, which varied from zero to 60 mm. The results also showed that the chloride penetration depths of W/C of 0.6 were higher than W/C of 0.5 and 0.4 at the same depths of cracks. It is explained by the influence of the density of concrete on the chloride penetration depth. Normally, the density of concrete with W/C of 0.6 is less than that of concrete with W/C of 0.5 and 0.4.

Furthermore, the trends of increasing chloride penetration depth in the increase of crack depth are similar when the water to cement ratios varied. It can be concluded that the trend of increasing the penetration depth of chloride, when the crack depth varies, is independent with the proportion of concrete (W/C) but dependent on the geometry of crack.

The chloride penetration depth at crack location (x_{cr}) could be expressed by a function of respective crack depth (L) and the chloride penetration depth at uncrack location of concrete (x_{uncr}). In the same condition of environment and the concrete properties, the x_{cr} would be considered the linear relation to respective crack depth (L). Moreover, if crack depth equals zero (no crack) as the boundary condition, the x_{cr} will equal x_{uncr}. Consequently, by the linear regression of experimental results, the correlation between penetration depths at crack location (x_{cr}) and uncrack location (x_{uncr}) is expressed by following equation:

$$x_{cr} = 0.53 * L + x_{uncr} \quad ...(1)$$

where

L: is the respective crack depth (mm).

x_{cr}: is the chloride penetration depth at crack location (mm).

x_{uncr}: is the chloride penetration depth at uncrack location of concrete (mm).

CONCLUSION

- Characteristics of a crack, such as crack width and crack depth, were investigated on the chloride penetration into the cracked reinforced concrete structure. The results of research showed the strong influence of crack depth, in addition to crack width, on the rate of chloride penetration into cracked reinforced concrete.
- The depth of chloride concentration increased in increase of the crack depth and their rate trends were independent to the proportion of concrete, it is dependent on the geometry of crack. The study also indicated that the service load had a significant role for increasing the chloride penetration due to varying crack characteristics.
- In the reinforced concrete structure where the crack width could be limited, the influence of crack depth on the chloride penetration depth is more significant than the influence of crack width on that.

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