DISTRIBUTION OF CHLORIDE ION IN CRACKED REINFORCED CONCRETE PRISM TRANSPORTED BY CYCLIC RAIN WITH CHLORIDE ION

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ABSTRACT

Experimental study was performed to investigate the effect of crack on chloride content due to penetration of salty water through the crack under exposure test that consists of cycles of rain of salty water and dry (40°C in temperature and 60% in relative humidity). Twelve reinforced concrete specimens that were made of concrete of 0.40 water-cement ratio and reinforced with a steel bar of D19 in the center are prepared. Water content was detected by measuring the electrical resistance between stainless steel rods installed in the specimens. These specimens were cracked in a direction normal to their longitudinal axis at the center of their span. Various coating conditions were applied to the specimens to distinguish the rate of chloride ion penetration through crack.

The results show that chloride content on the surface of the crack under cyclic rain is not homogenous and affected by the diffusion process from the upper surface and wet-dry cyclic condition. Moreover, chloride ion content in concrete adjacent to the reinforcing bar at cracks is remarkably larger than that in concrete at the same depth of the steel bar.

Keywords: Water content, Electrical resistance, Chloride ion, Crack, Wet-dry cyclic condition

INTRODUCTION

Cracks in concrete accelerate the deterioration of reinforced concrete structures, since they facilitate ingress of chloride ion carried by rain and wind into concrete. Consequently, chloride ion content increases, and it leads to corrosion of reinforcing steel bar. Most researches, related to chloride ingress in concrete, assumed that concrete is perfect and free from cracks, besides under certain conditions. In Former
researches, Takeda (1999) performed two accelerating tests for damage due to salt attack on reinforced concrete, which cycles were salt spray and dry, and soaked into salt water and dry respectively. Comparison with result of 1-year exposure tests in marine environment indicates that proposed accelerating tests for chloride attack is comparable and suitable for the process of corrosion in RC members. Uomoto (1998) investigated permeating chloride on cracks in concrete experimentally that was exposed under submerged condition (3 ± 0.3% NaCl). Such experiments are also conducted by Hooton (2003). In the case of submerged test, the chloride ingress from the crack was under almost steady state condition. Although, this exposure condition is not realistic in the most of reinforced concrete structures in practice, but it is valid only for comparison purposes.

In this study, the effects of cracks on penetration of salty water as well as chloride ion were experimentally investigated and discussed, considering water and chloride ion content distribution along the depth of reinforced concrete specimens subjected to cycles of wetting (salty rains) and drying, in large corrosive environmental chamber.

**OUTLINE OF EXPERIMENT**

**Materials**

In this study, ordinary Portland cement was used to cast concrete mix of 0.40 water-cement ratio. Proportions of concrete mix are illustrated in Table 1. Coarse aggregate was a crushed stone with maximum nominal size of 40 mm, density of 2.62 g/cm³ and fineness of 7.20. The fine aggregate was crushed sand with density of 2.58 g/cm³ and fineness modulus of 2.94. The concrete compressive, splitting tensile strength and Young’s modulus at age of 28 days were 57.7, 6.3 N/mm² and 45.7 kN/mm², respectively. Deformed steel bar D19 of 19 mm in nominal diameter and 345 N/mm² in nominal yield strength was used as reinforcement.

<table>
<thead>
<tr>
<th>W/C</th>
<th>Unit</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Kg/m³</td>
<td>168</td>
<td></td>
</tr>
<tr>
<td>Cement Kg/m³</td>
<td>420</td>
<td></td>
</tr>
<tr>
<td>Sand Kg/m³</td>
<td>676</td>
<td></td>
</tr>
<tr>
<td>Gravel Kg/m³</td>
<td>1030</td>
<td></td>
</tr>
<tr>
<td>S.P. Kg/m³</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Air %</td>
<td>4.50%</td>
<td></td>
</tr>
<tr>
<td>Slump mm</td>
<td>65</td>
<td></td>
</tr>
</tbody>
</table>

**Specimens’ configurations**

The experimental work consists of twelve reinforced concrete specimens of dimensions of 150x200x900 mm³ that reinforced with deformed steel bar of D19 coincided with longitudinal axis of the specimen, as shown in Fig. 1. In the centre of span, the cross section of the specimen was reduced to 130x200 mm by the making two grooves (5x10 mm²) resulted from especial preparation in the mould before casting. The reduction in the cross section directed crack

![Fig. 1 Specimens’ specifications](image-url)
Table 2 Final crack widths

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>Series 1</th>
<th>Series 2</th>
<th>Series 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N1-1</td>
<td>N2-1</td>
<td>N3-1</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.22</td>
<td>0.29</td>
<td>0.26</td>
</tr>
<tr>
<td>180</td>
<td>0.16</td>
<td>0.34</td>
<td>0.26</td>
</tr>
<tr>
<td>Average</td>
<td>0.24</td>
<td>0.31</td>
<td>0.28</td>
</tr>
</tbody>
</table>

location to be in the centre of the span in each specimen. For specimens specified for measuring water content, stainless steel rods of 2.00 mm in diameter were installed, before casting, crossing horizontally the specimen cross section. The stainless steel rods were arranged vertically in three zones; at crack, near-crack zone and non-cracked zone at horizontal distances of 0, 40 and 225mm from the span centre of specimen. The number of stainless steel rods and vertical spacing in-between are shown in Figure 1(b). The top surface during casting is the same top surface exposed to salty rain.

After 28 days, the specimens were loaded for getting targeting crack widths at depths of 20, 100 ,180 mm from top surface. The targeting crack widths is between 0.25 and 0.30 mm. During injection of non-shrinkage mortar into the grooves, which are produced for inducing crack, and its hardening process, the displacement was kept constant. And after motor getting hardening degree that was sufficient to keep the crack width almost constant, the load was released. The final crack widths are illustrated in Table 2.

Coating conditions

Fig. 2 shows the four sealing patterns used in this study as well as the assigned specimens for each pattern. In order to model the case of wide concrete area like slab and concrete pavement, all the vertical sides of the specimens were coated using waterproof materials (three layers of primer and three layers of epoxy). In order to distinguish cracking effect on water and chloride penetrations, the top surface was coated in two patterns (N2 and N4 series), except at the crack to allow penetrations through crack surface only. Bottom surface was coated to prevent evaporating of water through this surface. Coating the bottom surface would simulate the case of concrete pavement over asphalt layer and/or some indoor coating. However, at the bottom of the crack, drainage could exist in some circumstances, such as cracking the indoor coating and concrete pavement over substrata of rocks.

Measuring electrical resistance

Concrete conductivity increase with increasing water content. Therefore, in the specimens related to water content measurements, electrical resistance was
measured between every two consequent stainless steel rods in a direction normal to the axis of the specimen, as shown in Figure 3. The depths of stainless steel rods were 5, 45, 85, 115, 155 and 195 mm that represent measuring zones at the averages depths of 25, 65, 100, 135 and 175 mm, respectively.

LCR Hi-tester (1.0 kHz and 1.0 volt of AC) connected to a computer system was used to measure and record the electrical resistance with time during the experiment period at pre-set intervals. As shown in Figure 3, the 30 and 40 mm were used as spacing between the rods. Therefore the electrical resistance was divided over the distance in-between the measured rods to eliminate the effect of the different rods spacing. Stainless steel rods as well as the wires were perfectly isolated from water using epoxy, to ensure that the measured electrical resistance is that measured through the concrete.

**Adjusting initial moisture condition**

After 55 days, all the specimens were moved to the environmental room in which exposure test will be carried out, under totally controlled environmental conditions of 40°C in temperature, and 60% in relative humidity. In order to get an initial saturation condition before starting exposure test, all the specimens were submerged in a tank containing water without adding NaCl. The electrical resistance was monitored during this period, where it was decreasing with time. After about four days the decreasing rate became negligible, and the electric resistance became almost constant for about three days. Therefore, it could be assumed that after a total submerging period of about seven days, the specimens became fully saturated of water, where the increase in water content became almost negligible.

After reaching full saturation condition, specimens were kept to dry in the environmental room for six days, before starting exposure test. The exposure test, as shown in **Fig. 4**, consists of cycles of salty rain (3.0% NaCl) for one day followed by drying for six days with a total period of seven days per cycle. Temperature was adjusted to be 40°C. Meanwhile, humidity was controlled to be 60% RH during drying period only, where it increased to almost 95% due to rain. Electrical resistances for the...
all the specimens were automatically recorded. This exposure test simulates an extremely aggressive environment with respect to corrosion, where, this study is a part of a project, which also covers investigating the resultant corrosion of reinforcing steel bar.

**Chloride concentration in cracked section**

After 45-cycles (392 days), 95-cycle (742 days), and 144-cycle (1085 days) in exposure test, chloride ion contents were measured by means of colorimeter. Fig. 5 shows sampling locations. At crack, samples were collected by drilling holes in the concrete to a distance of 10mm from the crack surface, in the direction of the longitudinal axis of the specimen. In non cracked area, samples were collected from 10, 25, 55 and 100mm in depth measured from the top concrete surface.

**RESULTS AND DISCUSSIONS**

**Electrical resistance before beginning exposure test**

Distribution of electrical resistance after submerging in water for 8 days is presented in Fig. 6. Therefore the electrical resistance is divided over the distance in-between the measured rods to eliminate the effect of the different rods spacing. As shown in figure, despite the difference in coating condition, electrical resistance tends to increase with increasing the distance from the top concrete surface. This may indicate decreasing water content with depth, which implies smaller pore size along casting direction due to segregation.

Distribution of electrical resistance during drying for 7 days after above-mentioned submerging is also illustrated. During drying, water content decreased due to evaporation of water and the electrical resistance increased. From this figure, electrical resistances at near- and non-cracked zone for all specimens were almost similar. In case of un-drainage (N1 and N2), upside electrical resistance is larger than the other lowers. Meanwhile, in the case of drainage (N3 and N4), upside and downside electrical resistance is larger than middle one; in particular, downside one is the same or larger than un-drainage. This reflects that rain-dry repetition is run remarkably on downside of drainage specimen.

**Fig. 6 Electrical resistance before exposure test**
Variation of electrical resistance during cycle of rain of salty water and dry

A calibration curve was obtained for converting electrical resistant to relative water content. Temperature effect on the resistance is calibrated according to the experiment by Tanaka (Tanaka et al. 2000); inverse number of resistance changes 2.5 % per 1 °C. Specific resistance $\rho$ can be obtained with shape coefficient $C$ according to the equation (1).

$$\rho = \frac{R}{C}$$  \hspace{1cm} (1)

where $R$ is electrical resistance.

And relative specific resistance $\rho_r$ is defined as:

$$\rho_r = \frac{\rho}{\rho_{100}}$$  \hspace{1cm} (2)

where $\rho_{100}$ is the specific resistance at saturated condition.

0% and 100% free water content is defined by the state of concrete which is dried in 105 °C and submerged into water for 8-days respectively. And using the mass of those concrete, relative water content $W_r$ (%) is defined by equation (3):

$$W_r = \frac{(w - w_d)}{(w - w_s)} \times 100$$  \hspace{1cm} (3)

where $w$ is mass of concrete, $w_d$ is mass of concrete dried in 105 °C condition, and $w_s$ is mass of concrete submerged into water.

Several relative water contents were artificially made and electrical resistance were measured. The relationship between relative water content and relative specific resistance can be observed as is shown in Fig. 7.

![Fig. 7 Relationship between relative specific resistance and relative water contents.](image)

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![Fig. 8 Relative water contents along the crack during raining period at 2-cycle and 131-cycle.](image)

Fig. 8 Relative water contents along the crack during raining period at 2-cycle and 131-cycle.
In Fig. 8, it is shown that relative water contents in concrete at 2-cycle and those at 131-cycle are different. Relative water contents at 10 mm from upper surface at 131-cycle of N1-3 and N2-3 are about 40% and about 20% smaller than the relative water contents at 2-cycle. Meanwhile, the relative water contents of N3-3 and N4-3 at 131-cycle are about 50% and those are 10% smaller than those at 2-cycle.

These values indicate that the concrete is getting dried under this cyclic condition. It should be noted that the concrete below 65 mm from the upper surface, little water is supplied during raining in the case of N1-3 and N2-3 at 131-cycle, though the concrete at 131-cycle is more dried than those at 2-cycle.

In the case of N3-3 and N4-3, supply of water is detected between 200mm to 135mm from the upper surface. The area that are supplied water is corresponding to the area which has larger amount chloride content shown in the Fig. 9. The theoretical explanation of this phenomenon remains to be further research.

Chloride ion content due to chloride diffusion through crack

Fig. 9 shows chloride ion content profile for samples at 10 mm depth from crack surface and non-cracked surface at 45th, 95th and 144th cycle, in addition to, samples adjacent to the steel bar at the same time. As shown in figure, it was found that chloride content increased in all measured points at crack zone as cycle was progressed, especially downside case of N3 and N4. In this case of drainage, electrical resistance increased due to humid regardless of whether surface is sealed or not. Consequently it could be explained that rain-dry cyclic condition concentrated the salt which should be induced by the water penetration through crack.

Chloride contents adjacent to steel bar were remarkably larger than chloride contents in concrete at the same depth not adjacent to steel bar. This can be explained by the presence of conical cracks that exist near the crack surface around the steel bar (Goto, et al. 1980), as well as, gaps under the reinforcing bars due to bleeding (Otsuki, et al. 2000), as illustrated in Fig.10.

![Fig. 9 Profile of chloride content at 45, 95, and 144-cycle](image-url)
Chloride content in non-cracked zone at the 10 mm from the upper surface is larger than those in cracked zone at more than 75 mm from the upper surface. This tendency indicates that the chloride profile of cracked concrete under cyclic salty rain and dry condition is different from that submerged in salty water.

And chloride contents in the cracked zone at the depth between 50 and 175 mm are almost constant in the case of N2, N3 and N4. From the distribution of chloride ion in the section of these RC members, the cover depth more than 50 mm is effective for the case of this experiment.

CONCLUSIONS

- Chloride distribution along the crack surface was uneven under salty-rain and dry cyclic condition. And, it was indicated, by the result of slight variations of electrical resistances at the middle-level zone, that middle level zone is rather humid than those of others just before raining.
- The variations of upside electrical resistance were affected by raining and those of downside electrical resistance may be affected by humid in the case of specimen that has drainage.
- Wet-dry cyclic condition might concentrated the chloride. This phenomenon can be seen in the specimen that has drainage.
- Chloride contents adjacent to steel bar were remarkably larger than chloride contents in concrete at the same depth but not adjacent to steel bar. This resulted from the presence of conical cracks that exist near the crack surface around the steel bar, in addition to, gaps under the horizontally oriented steel bars due to bleeding.

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![Fig. 10 Concrete conditions in cracked zone](image-url)
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