Effect of cyclic exposure of carbonation and chloride on corrosion of reinforcing steel in concrete

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INTRODUCTION

Corrosion of reinforcing steel is one of major mechanisms deteriorating the reinforced concrete (RC) structure. Although reinforcing steel is depassivated by the high alkalinity of concrete, ingress of chloride or carbonation from surrounding are widely known as a source of the steel passivation. Due to reinforcing steel corrosion, high internal pressure is generated; as a result covering concrete is cracked and spalled.

In order to prevent corrosion of reinforcing steel, durability design standard is proposed. This standard is based on the defined critical level of the structure after deteriorated by individual chloride or carbonation at the specific service life. Many methods are used to reduce the deterioration rate. Ground granular blast furnace slag (GGBS) is widely used in Japan as a mineral admixture in concrete to increase resistance against chloride penetration of concrete because pore structure of GGBS concrete is finer than that of normal concrete. In contrast, resistance of GGBS concrete against carbonation is lower than normal concrete due to lower amount of produced calcium hydroxide.

As explained, durability design standard tends to independently consider corrosion due to chloride or carbonation. However, properties of GGBS concrete against corrosion of reinforcing steel due to chloride or carbonation are contrast. Therefore the main objective of this study is to investigate the most suitable cementitious material for RC structure, if it has to be exposed to both of chloride and carbonation at the same time.

EXPERIMENTAL

Materials

Ordinary Portland Cement (OPC) Type I was used in this study. GGBS, which is classified as slag4000, was used to replace OPC as replacement ratios of 0%, 45%, and 70%. Three concrete mix proportions are shown in Table 1 with slump values, air contents, and compressive strengths. Plain round steel bar with diameter of 10 mm was drilled and tapped at the middle of the one end in order to be connected by lead wire. Steel’s surface was then polished by sandpaper No. 200 and degreased by acetone before being used.

Specimen preparations

Two steel bars with length of 400 mm, were centrally placed at depth 20 mm and 10 mm from the top and bottom surface as shown in Figure 1 and 2, respectively. Size of specimen is 100 × 100 × 380 mm. Specimens were de-molded 24 hrs after casting and were cured afterward in 20°C water for 7 days and air-cured for other 7 days under controlled temperature at 20°C and 60% relative humidity. Lead wire was connected to drilled end of steel by connector and bolt. All surfaces, excepting the top and bottom surfaces that were left to be exposed surfaces, were coated with epoxy.

Exposure conditions

Exposure conditions were started 3 weeks after casting of specimen. One cycle of exposure is 2 weeks. Detail information is shown in Table 2. Temperature of solution was controlled at 20°C. Conditions of carbonation chamber are 40°C and 50% relative humidity (RH).

Figure 1 Locations of measurement and cross section of specimen

Figure 2 Locations of measurement and cross section of specimen

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Measurements

Specimen, exposed for 13 cycles, was sliced as 0-1, 1-2, 2-3, and 3-5 cm from the exposed surface and measured total chloride content as specified in the standard method\(^3\). Total chloride content is reported as % of chloride by weight of ground sample. Carbonation depth is measured by spraying Phenolphthalein solution on freshly broken surface of specimens after exposed for 1, 2, 4, 7, and 13 cycles. Average value of 3 points measuring is reported. Corrosion of reinforcing steel was investigated by half-cell potential measurement using saturated silver-silver chloride (Ag-AgCl) reference electrode on both top and bottom surfaces. Measurements of half-cell potential were conducted every completed cycle for first 5 cycles, and every 2 completed cycles thereafter. Specimens were air-dried for 3 days before being measured in order to avoid effect of polarization phenomenon, which is due to limited oxygen concentration around steel surface after being submerged\(^4\). Refer to Figure 1; the measurements were made at totally 16 points with 2-cm spacing.

**RESULTS AND DISCUSSIONS**

**Carbonation depth**

Carbonation depth of specimens exposed to only carbonation, shown in Figure 3, are larger than that of specimens cyclically exposed between carbonation and solution as shown in Figure 4. This is mainly due to saturated pore structure of specimen cyclically submerged retards the process of carbonation. More detailed study\(^5\) showed that there is no significant effect of concentration of NaCl solution on the rate of carbonation in case of cyclic exposure. Moreover, as GGBS replacement ratio is increased, carbonation depth is also increased.

**Total chloride content**

Total chloride content is maximum at the surface part in case of specimens exposed to only NaCl solution as shown in Figure 5. However, the peak of total chloride content is found inside the specimens that cyclically exposed to carbonation and NaCl solution as shown in Figure 6. Releasing of fixed chloride due to carbonation is believed to be the main explanation\(^4,5,7\). As fixed chloride is released, concentration of free chloride in pore solution increases. Then, there is a larger concentration gradient forcing chloride to penetrate deeper into the inside of specimen. Larger carbonation depth of GGBS concrete causes larger chloride content diffused into the inside of specimen.

**Half-cell potential**

If half-cell potential value measured against Ag/AgCl electrode is lower than -236 mV, steel are high possibility to be corroded according to ASTM C876\(^8\). As shown in Figure 7, steel in M00 group’s specimen cyclically exposed was corroded fastest when

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### Table 1 Mix proportions and properties of concrete

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>W/B, %</th>
<th>S/A, %</th>
<th>Replacement Ratio, %</th>
<th>Mixture Proportion, kg/m³</th>
<th>Slump, cm</th>
<th>Air Content, %</th>
<th>Strength, ksc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>W  C  GGBS  S  G  Admixtures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M00</td>
<td>0</td>
<td>160</td>
<td>291</td>
<td>0  826 1032</td>
<td>304</td>
<td>317</td>
<td></td>
</tr>
<tr>
<td>M45</td>
<td>55</td>
<td>45</td>
<td>45</td>
<td>160 160 131 821 1026 (C+GGBS) * 2%</td>
<td>12±2 5.5±1</td>
<td>269 378</td>
<td></td>
</tr>
<tr>
<td>M70</td>
<td>70</td>
<td>160</td>
<td>87</td>
<td>204 818 1023</td>
<td>272</td>
<td>370</td>
<td></td>
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</tbody>
</table>

### Table 2 Exposure conditions

<table>
<thead>
<tr>
<th>Name</th>
<th>Duration in 1 cycle (1 cycle = 2 weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1st-4th</td>
</tr>
<tr>
<td>C5</td>
<td>CO₂ 5%</td>
</tr>
<tr>
<td>Sol3</td>
<td>NaCl 3%</td>
</tr>
<tr>
<td>Sol3-C5</td>
<td>NaCl 3%</td>
</tr>
</tbody>
</table>

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**Figure 3 Carbonation depth of specimens exposed to only carbonation (C5)**

**Figure 4 Carbonation depth of specimens cyclically exposed (Sol3-C5)**
Accelerated steel corrosion is a result of faster diffusion of chloride due to carbonation as explained in last section. However, the fastest corroded steel in M70 group’s specimen is exposed to only carbonation as shown in Figure 8. This is mainly due to weak resistance of M70 against carbonation. It is valuable to be noted that very aggressive carbonation was used in this study compared to the actual environmental condition. Further study is required to validate result of accelerated test to simulate the actual condition.

Numerical modeling is performed to simulate carbonation depth and profile of total chloride content\(^5\). Only the examples of simulation of carbonation depth and total chloride content in case of cyclic exposure were shown in Figure 9 and 10. As shown, effects of cyclic exposure on carbonation depth and total chloride content can be fairly well simulated.

Finally, in order to clearly express the effect of cyclic exposure on corrosion initiation time, comparison the service life of structure based on JSCE\(^1\) from simulated results of individual exposure and cyclic exposure was conducted. Figure 11 and 12 shows the comparison. Please be noted that exceeding the critical chloride limitation determine the service life of structure in all sim-
ulated scenario. As shown, GGBS concrete shows the longest expected service life of structure, if only individual chloride exposure is considered as shown in Figure 11. However, significant decreasing of service life of GGBS concrete can be realized after cyclic exposure is considered in the simulation as shown in Figure 12.

**CONCLUSIONS**

Current durability design for concrete structure against steel corrosion may be suitable for individual aggressive chloride or carbonation environment. However, combined environment between carbonation and chloride accelerated the penetration of chloride. As a result, steel corrosion is accelerated. Structure that has a chance to be exposed to both of chloride and carbonation should be carefully concerned about its service life. Further research should be conducted to clarify the validity of acceleration test to simulate the actual environmental condition.

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**REFERENCES**

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