Moisture Behavior in Concrete Repaired by Patching Observed with Neutron Imaging

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The cross sectional repair of concrete structures is carried out for the purpose of restoring or improving durability. However, some re-deterioration, such as corrosion of reinforcing bars, floating of repair materials, or peeling, has been observed. Such re-deterioration is considered to be due to deterioration factors such as water that has permeated the repair area. In this paper, we report the result of non-destructive visualization of the moisture behavior of the repair area using a neutron beam tester.

Key words: concrete, cross-section repair, moisture penetration, corrosion of reinforcing bar (rebar corrosion), interface

1. Introduction

To repair a deteriorated concrete structure, cross-section repair is widely used, which repairs deteriorated portions by chipping. Cross-section repair is carried out to restore or improve durability, but may partially cause some re-deterioration, including lifting, peeling, and peeled falling of cross-section repair materials (CRMs) in addition to steel material corrosion. These re-deterioration phenomena are considered to be due to deterioration factors such as water and chloride ions that have permeated portions which have undergone cross-section repair. In particular, water acts as a carrier for carrying harmful substances such as chloride ions, and can also be a physical deterioration factor of frost damage, etc., as well as facilitating reinforcing bar corrosion (rebar corrosion): therefore, it is important to know the behavior of water.

Although there have been many studies on moisture penetration into concrete structures in recent years [1], these addressed single concrete units; there are few studies that have focused on the periphery of the cross-section repair portions. To clarify the effect of the method for treating the interface between the base concrete and the CRM on the moisture behavior in the cross-section repair portion, we conducted a permeability test applying a water pressure of 1 MPa for 48 hours and demonstrated that the hydraulic conductivity decreases by primer treatment or water wetting treatment [2]. We also examined a method of detecting the depth of moisture penetration into concrete by destroying the test piece and spraying a chemical on it [1]. However, it is not yet known how the moisture action in normal pressure (e.g. water splashing) affects the moisture behavior around the cross-section repair portion. Therefore, we examined the moisture behavior in the cross-section repair section using a visualization technique with a neutron beam tester that makes it possible to non-destructively visualize the behavior with the same test piece [3]. This paper describes this process.

Depending on the water content of the base concrete or the chloride ion content, a poor reaction of the primer may occur and the moisture behavior at the interface of the cross-section repair portion may change, which may promote rebar corrosion. Therefore, we examined the following fundamental items: (i) the substrate treatment method at the interface between the concrete and CRM regarding various CRMs, and (ii) the relationship between moisture behavior and rebar corrosion at the interface from mass change and rebar potential (by conducting a salt spray test on rebar-embedded test pieces with different chloride ion contents in the base concrete).

2. Outline of the test

The following test pieces were made. TP-A was a rebar-embedded test piece with a simulated cross-section repair portion, which was for examining the effect of moisture behavior at the interface on rebar corrosion. TP-B was a test piece in which a part of the cross-section repair portion was cut out, which was for visualizing the moisture behavior at the interface of the cross-section repair portion by neutrons.

2.1 Outline of the TP-A test (rebar-embedded test piece)

2.1.1 Making of TP-A

Figure 1 shows a conceptual diagram of TP-A, which we made. Table 1 lists the materials used. Table 2 summarizes the composition of concrete. Table 3 lists the materials used for the CRMs. The dimensions and shape of each test piece was a cube of side 100 mm, and the rebar was placed at a depth of 30 mm.

To simulate cross-section repair, about 50 mm of base concrete was cast in the lower layer, then the CRM was added (Fig. 2). Then, to clarify the effect of the state of the interface between the CRM and concrete on the rebar corrosion, sodium chloride (NaCl) was mixed at the outer percentage to make it a high-salt state so that the following conditions were met for the base concrete with φ100 mm embedded round steel: with/without primer construction, water wetting treatment of 2.0 g for every 10,000 mm², and chloride ion 10 kg/m² (Fig. 3). In addition, a test piece consisting of only concrete and one consisting of only CRM were made for comparison. Three test pieces were used for the salt spray test for each condition, and one test piece was left in the atmosphere.

2.1.2 CRM construction

Each test piece was roughened on the base material surface at a material age of 1 day after the base concrete was cast. After cleaning, the interfacial treatments in Fig. 3 were performed. Then, the
CRM was constructed and was left at 20°C and 60% RH for 14 days. After demolding, the test surface and the surface on the opposite side were opened, and the remaining four surfaces were covered with a covering material. This state was left in the same environment until the material age of 28 days. For the convenience of making the test piece, the test direction was rotated 90° relative to the driving direction.

2.1.3 TP-A rebar corrosion test by salt spray

The rebar-embedded test piece, the single concrete unit for comparison, and the single CRM unit made above were subjected to the salt spray test, which measured the mass and the rebar potential. The test piece was exposed to a 3% concentration of sprayed salt water at a rate of approx. 0.6 g/cm²/h for one day. Then, it was left in a dry environment for six days. This period of a total of seven days was defined as one cycle. The test piece mass and the rebar potential were measured before the start of spraying and again after 7, 14, and 28 days. The rebar potential was measured by pressing the reference electrode against the 60 mm surface with an uncoated cover placed on the other side of the salt spray, and forming a corrosion circuit to the rebar (Fig. 4). Some test pieces were left at 20°C and 60% RH for comparison.

2.2 Outline of the TP-B test

2.2.1 Making, curing, and strength test of TP-B

The specifications of concrete are the same as Section 2.1 and as summarized in Tables 1 to 3. The dimensions of the test pieces were 100 × 100 × 100 mm. After the base concrete was cast up to 5 cm, it was cured at 20°C and 60% RH until the material age of 7 days. Then, the organic (VF) and inorganic (NDK) CRMs in Table 3 were added for the remaining 5 cm. After the material had aged 28
The six faces of the cubic test piece were cut to a size of 70 × 70 × 25 mm for the neutron imaging test. Then, the material was left at a constant temperature and humidity (20°C and 60% RH) until the material age of 6 weeks. Then, it was dried at 40°C until the age of 9 weeks, then left at a constant temperature and humidity (20°C and 60% RH) until the age of 11 weeks. In addition, three cylindrical test pieces (φ100 × 200 mm) were made for the strength test of a single concrete unit, and the compression strength and static elasticity test were conducted as per JIS A 1108 at an age of 28 days.

2.2.2 TP-B test

To clarify the moisture behavior in the base concrete, CRMs, and near their interface, a one-sided immersion test was conducted that immersed the test piece surfaces with the interface into the water by 5 mm (Fig. 5), followed by the neutron beam imaging test. This paragraph outlines the neutron beam imaging test. While neutrons have a high penetrating power for calcium and silicon, which are abundant in concrete, they are strongly scattered by hydrogen. Therefore, the obtained transmission image shows a shadow in places that contain moisture originally contained in the test piece or a permeated moisture. The darkness of the shadow changes along with the amount of hydrogen distributed in the permeation direction because the rate of permeability is output as an integrated value in the neutron beam permeation direction. From this principle, the distribution of the rate of permeability corresponds to the distribution of water absorption.

The test piece was taken out of water 24, 48, and 72 hours after the start of the one-sided immersion test, and the water on its surface was wiped off with a waste cloth, etc. before the mass was measured. Then, with the test piece set on the measurement stage, neutron beam imaging was conducted. A neutron beam output from the neutron source was irradiated to it for 3 minutes, and a neutral transmission image (which corresponds to an X-ray photo by neutron beams) was output by a detector consisting of a neutron converter and a CCD camera (a neutron image intensifier is used in this evaluation).

Open source software ImageJ was used for image analysis. For the immersion surface, the side surface for making the test piece was used to reduce the effect of bleeding on the upper surface of the test piece and the effect of consolidation of the lower surface.

3. Test results and discussion

3.1 Basic characteristics of concrete

Table 4 lists the fresh properties, compression strength, and static modulus of elasticity of concrete.

3.2 TP-A mass change

Figure 6 shows the results of the concrete and the single unit of CRM regarding TP-A mass change. Figure 7 shows the measured mass of the test pieces simulating cross-section repair. For all the specimens, the mass increased in one cycle and the subsequent mass change was small. Figure 6 shows that the mass increase of the concrete and the single CRM unit with NaCl added were smaller than that of the single concrete unit and in particular, the mass change of every type of CRM was as small as approx. 1/8 that of the concrete. In addition, Figure 7 shows no clear differences resulting from the “with/without primer construction” condition regarding any of the CRMs. This can be because the interfacial area was very small.
pared to the surface of moisture action on the base concrete and the CRM, and the mass change was greatly affected by the amount of water that has permeated from the entire surface of the single concrete unit or the single CRM unit.

3.3 TP-A Potential of rebar

Table 5 summarizes the potential and rebar corrosion likelihood according to the Japan Society of Civil Engineers criteria [4]. This study used a silver-silver chloride electrode (SSE) as the reference electrode. Therefore, the values of the copper-copper sulfate electrode (CSE) in Table 5 were corrected according to Equation (1) [5]. If the potential was nobler than −90 mV vs SSE, it was considered to be not corroded with a probability of 90% or more; if it was more base than −240 mV vs SSE, it was considered to be corroded with a probability of 90% or more.

Table 5  Relationship between potential and rebar corrosion characteristics

| Potential (E) | Possibility of rebar corrosion |
|---------------|-------------------------------|
| -200 < E      | Not corroded ≥ probability 90% |
| -350 < E ≤ -200 | Undeterminable                |
| E ≤ -350      | Corroded ≥ probability 90%    |

\[ E_{\text{CSE}}^{Fe} = E_{\text{SSE}}^{Fe} - 120.1 - 2.00 \cdot (t - 25) \]  

where  
\[ E_{\text{CSE}}^{Fe} \] (mV): Potential measurement of rebar for saturated copper sulfate electrode at temperature t (℃) and  
\[ E_{\text{SSE}}^{Fe} \] (mV): Potential measurement of rebar for saturated silver-silver chloride electrode at temperature t (℃).

Figures 8 to 12 show the measurement results of the rebar potential. Figure 8 shows for the test pieces left at 20℃ and 60% RH without being subjected to the salt spray test, the change in potential was small and constant regardless of the “with/without NaCl addition” condition or the CRM type. Figure 9 shows that the potential of the single concrete unit was base in the one-cycle test and the change in the potential was small thereafter. On the other hand, the concrete with NaCl added exhibited a base value even before being subjected to the salt spray test, and the value did not change significantly even after the start of the test, with the effect of salt spray being small. Also for the single CRM unit, the salt spray caused the potential value to be a base in 14 days up to the same level as the single concrete unit.

Figures 10 to 12 show that the potential of the rebar in the test pieces simulating the cross-section repair was almost the same as that of the single concrete unit in each test piece subjected to normal construction, which means adding the CRM after constructing the primer on the base concrete. By contrast, when the CRM was added without primer construction, the value varied widely. However, it was more base than in the normal construction and showed a value indicating a zone deemed to be corroded with a probability of 90% or more. For the test piece subjected to normal construction after water wetting treatment of the base concrete interface, like normal construction with primer construction, it showed that the value tended to be on the noble side compared to the case where the primer was not yet constructed. For the test piece cross-sectionally repaired to the base concrete containing NaCl, like the result of potential in a single concrete unit containing NaCl, the base value appeared before the salt spray, and it did not exhibit a clear effect of the difference in the chloride ion content at the interface on rebar corrosion.

The above suggests that, by performing primer treatment or primer and water wetting treatment at the interface between the base...
concrete and CRM, the water transfer at the interface can be suppressed and the progress of rebar corrosion can be suppressed in the cross-section repair portion.

3.4 Mass change of TP-B for neutron beam imaging test during one-sided immersion

Figure 13 shows the measurement results of the TP-B mass changes for one-sided immersion. The mass change rate of the single CRM unit was smaller than that of the single concrete unit. No clear difference was seen between “with/without primer construction” like the results in Section 3.2.

![Fig. 13 TP-B mass change rate](image)

3.5 TP-B neutron beam imaging

Figure 14 contains the images showing the differences between before and after the one-sided immersion, where the portions containing water permeated are represented by shading. A comparison of the single concrete unit (1) and single NDK (organic CRM) unit (2), shows that, for the single concrete unit, the water gradually permeated with the passage of the immersion time, and after 72 hours, permeated the whole, whereas moisture penetration in the single NDK unit was more suppressed than that in the single concrete unit.

These results match those of the mass changes from moisture penetration in Fig. 13. Considering the moisture penetration into cross-section repair portions, polymer cement mortar, widely used as a CRM, contains organic materials such as polymers as its constituent materials; therefore, it has a larger hydrogen content in the base metal itself than that of concrete. In this test, for example, as a polymer component, the mortar contains acrylic resin, which is said to have a hydrogen density equivalent to that of water.

For this reason, since the CRM has more hydrogen content than that of the concrete, we expected that the difference in moisture penetration could not be clearly captured. However, from the results of mass change and neutron beam imaging in this test, we found that even a CRM containing a large polymer content can be neutron imaged by obtaining the difference before and after immersion. From the results of NDK (organic CRM) construction (3) and VF (inorganic CRM) construction (4), which simulated cross-section repair, moisture penetrates into concrete but has difficulty penetrating the CRM; both exhibited this tendency. Moisture penetration into inorganic CRM was larger than that of organic CRM, but it was smaller than that of a single concrete unit. Water diffusion from the interface was not found in both organic and inorganic ones. In addition, unlike the results inferred from the rebar corrosion data, the comparison between (3) and (5) in Fig. 14 showed that there was no significant difference in the moisture penetration status near the interface depending on the “with/without primer construction” condition. One of the possible reasons for this is that the CRM construction on the base concrete was vertically downward and the construction conditions were relatively good. The other is that, because the concrete side of the base material was at an early age and contained a large amount of water, the interface was densely filled without drying out at the interface. As for the test pieces in (5), the base concrete entered the CRM side in the shallow part, and the black discolored part was only on the base material side.

As detailed above, we attempted to visualize the behavior of moisture in cross-section repair portions over time with neutron beam imaging. As a result, we found that the moisture penetration rate differs greatly between concrete and CRM, it differs depending also on the CRM type, and if the CRM construction conditions for the base concrete are relatively good, no significant moisture penetration occurs near the interface.
4. Conclusion

The findings from this study are summarized below.
(1) The amount of mass change associated with moisture penetration was as small as approximately 1/8 of the single concrete unit in CRM, and the moisture penetration test by neutron beam imaging showed that the spread of moisture to CRM was small, which revealed that CRM has a high mass transfer resistance to water.

(2) It was suggested that, by treating the interface between the base concrete and the CRM with primer or water wetting, (i) the effect of the construction situation would be reduced, (ii) the movement of water at the interface would be suppressed, and (iii) as a result, the progress of rebar corrosion in the cross-section repair portion could be suppressed.

(3) We attempted to visualize the behavior of moisture at cross-section repair portions over time by neutron beam imaging. As a result, we found that the moisture penetration rate differs greatly between concrete and CRM, it differs depending also on the CRM type, and if the CRM construction conditions for the base concrete are relatively good, no significant moisture penetration occurs near the interface.

References

[1] H. Suzuki, H. Ueda, “The effect of concrete quality on the time dependence of moisture penetration depth,” Proceedings of the Japan Concrete Institute, Vol. 36, No. 1, pp. 676-681, 2014 (in Japanese).
[2] H. Suzuki, H. Ueda et al., “Base treatment of concrete at the time of repair,” 67th Annual Academic Lecture, V-157, pp. 313-314, 2013 (in Japanese).
[3] Y. Yoshimura, M. Mizuta et al., “Evaluation of Water Flux of Concrete by Neutron Imaging,” Proceedings of the Concrete Structure Scenarios, JSMS, Vol. 19, pp. 379-384, 2019 (in Japanese).
[4] Second Term Corrosion Protection Subcommittee of JSCE Concrete Committee, “Test method for half-cell potential of uncoated rebars in concrete structures (JSCE-E601-2000),” Concrete engineering series , Vol. 30, pp. 248-256, December 2000 (in Japanese).
[5] Y. Shinoda, N. Mochizuki, “Base treatment of concrete at the time of repair,” 66th Annual Academic Lecture, IV-224, pp. 447-448, 2011 (in Japanese).

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