Fracture Mechanics of Concrete and Concrete Structures -
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A study on re-deterioration of surface-coated sluice structures due to frost damage

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ABSTRACT: The purpose of this study is to present an appropriate application method for surface coating repair to prevent the early re-deterioration of surface-coated concrete structures. External Visual Inspection, Ultrasonic Propagation Velocity Measurement, Adhesive Strength Test Method and other investigations were conducted for sluice structures in cold, snowy regions to clarify the nature of frost deterioration depending on differences in such environments and the causes of re-deterioration. The results revealed that the degree of concrete deterioration was higher in sections that were exposed to a direct water supply, and that it varied in line with temperature and other regional conditions. A major cause of early re-deterioration was the presence of deteriorated parts remaining on Surface coating material or patching material, which led to the progress of deterioration inside the concrete due to freeze-thaw action. It was therefore found that the durability of concrete structures repaired using the surface coating method in cold, snowy regions depended greatly on pre-repair surface preparation.

1 INTRODUCTION

Concrete river structures in cold, snowy regions are exposed to severe environments and constantly affected by frost damage. While surface coating repair to block moisture from the outside is considered effective as a measure to repair concrete deteriorated by frost damage, early re-deterioration after coating has been observed in some cases. This is due to a lack of knowledge regarding the durability of existing repair methods in cold, snowy environments and a lack of manuals outlining techniques for precise assessment of deterioration status and identification of areas of concrete for repair. A sluice is a type of concrete river structure consisting of an underdrainage channel and a facility to open and close it. Its main roles include drainage of water from inside a levee to the river and intake of water from the river. It also prevents water from flowing into residential and farming areas within the levee by closing the channel at times of flooding. In Hokkaido, which is a cold, snowy region, numerous sluice structures have been built as part of river improvements on rivers under the direct control of the national government since around 1965. Approximately 1,500 such structures currently exist, and there is concern about a dramatic increase in repair and reconstruction expenses in the future due to their deterioration and aging with the passage of time (Naitoh et al, 2009). Since public works spending tends to be reduced yearly, the importance of life prolongation by repair has now been revalued, and it is necessary to reduce life-cycle costs through more efficient and effective maintenance/management methods.

Accordingly, degrees of frost deterioration depending on differences in the conditions of cold, snowy environments were identified, and field investigations of re-deteriorated surface-coated sluice concrete were conducted in this study to enable estimation of the causes of re-deterioration and examine deterioration diagnosis methods. The ultimate aim was to present an appropriate repair method and an effective inspection method as measures against frost-related deterioration of sluice concrete.

2 STUDY METHODS

Meteorological investigation and External Visual Inspection of sluice structures were conducted to assess structural deterioration due to frost damage in different environments. To examine re-deteriorated surface-coated concrete, Ultrasonic Propagation Velocity Measurement (Uomoto et al. 1990), Adhesive Strength Test Method and Visual observation of internal status were performed. The effectiveness of the deterioration diagnosis method using ultrasonic propagation velocity measurement was also examined to improve the efficiency of investigations and to avoid a decline in the coating effect of surface-coated concrete and the infiltration of detrimental factors as much as possible.

The study is outlined in detail below.

2.1 *Study of frost deterioration in sluice structures under different environments*

As shown in Figure 1, the study was conducted on the Teshio River in the Kamikawa area and the Mukawa and Saru rivers in the Hidaka area, which are two typical regions of Hokkaido with differing cold, snowy environments. Table 1 shows the number of sluice structures involved in the study.

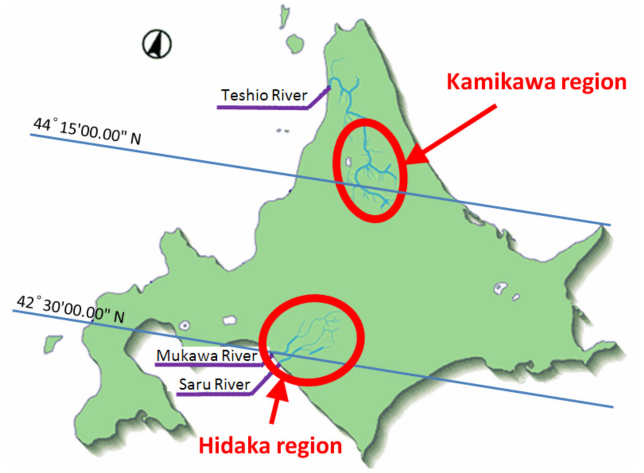

Figure 1. Locational map of the study sites.

Table 1. No. of sluices studied.

Years	Teshio	Mukawa	Saru	Total
1950s	0	0	0	0
1960s	18	6	6	30
1970s	17	13	4	34
1980s	17	5	4	26
1990s	7	4	0	11
2000s	6	5	9	20
Total	65	33	23	121

2.1.1 *Meteorological investigation*

In the meteorological investigation, AMeDAS (Automated Meteorological Data Acquisition System by Japan Meteorological Agency) data from between October 1998 and May 2008 (Japan Meteorological Agency, 1998.October-2008.May) were used to find the annual lowest temperature, maximum snow depth, number of freeze-thaw days and number of freezing days in each area in winter (between October and May). The annual lowest temperature and maximum snow depth are the average values for this ten-year period, freeze-thaw days are those on which the daily highest temperature was 0°C or higher and the lowest temperature was -1°C or lower, and freezing days are those on which the daily highest temperature was -1°C or lower (Hama et al, 1999).

2.1.2 *External visual inspection*

Photo 1 shows the sluice parts examined (i.e., the control platform, gatepost and retaining wall). Two parts of the retaining wall (top and underwater) were examined. The degree of frost deterioration in sluice concrete was evaluated using an appearance rating method as shown in Table 2. The appearance of scaling deterioration was rated through external visual inspection for macroscopic evaluation in accordance with the ASTM C 672 (ASTM International, 2004) visual inspection method for laboratory testing. The highest rating for each part was adopted as that part's overall rating.

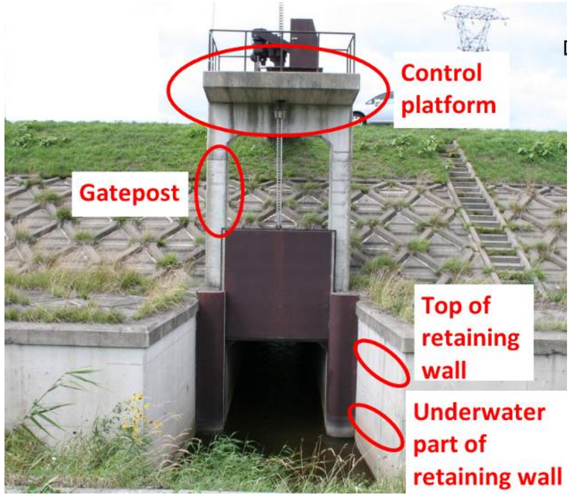

Photo 1. Sluice parts examined.

Table 2. Visual rating of surface scaling.

Rating	Deterioration ref. photo	Rating	Deterioration ref. photo
0	 No scaling	1	 Very slight scaling (3 mm deep at max; no coarse aggregate visible)
2	 Slight to moderate scaling	3	 Moderate scaling (some coarse aggregate visible)
4	 Moderate to severe scaling	5	 Severe scaling (coarse aggregate visible over entire surface)

2.2 *Study of re-deteriorated sluices*

The sluice structure for which the study on re-deterioration was conducted was constructed in 1961 in Shibetsu City in the Kamikawa region. It was repaired in 2003, 42 years after its construction, using a combination of acrylic resin Patching material and Surface coating material, but cracking was observed 18 months after the repair as shown in Photo 2.

Photo 2. Re-deterioration status.

2.2.1 *Ultrasonic propagation velocity measurement*

The conditions of Patching material under Surface coating material and matrix concrete (referred to here as M*atrix*) were examined by conducting Ultrasonic Propagation Velocity Measurement and analysis using the tomography (Kimura, 2008) and penetration method (Public Works Research Institute et al, 2006). Figure 2 shows the tomography measurement and core drilling sections. In the tomography method, the number of survey lines on each section was 62 (Section 1), 106 (2), 158 (3), 218 (4) and 286 (5). Cores were collected from two areas on the west side of the sections where deterioration was found in the analysis results using the tomography method, and Ultrasonic Propagation Velocity Measurement was conducted using the penetration method at intervals of 2 cm in the depth direction from the core ends. Ultrasonic Propagation Velocities measured using these two methods at the Patching material, Matrix and deteriorated parts were compared.

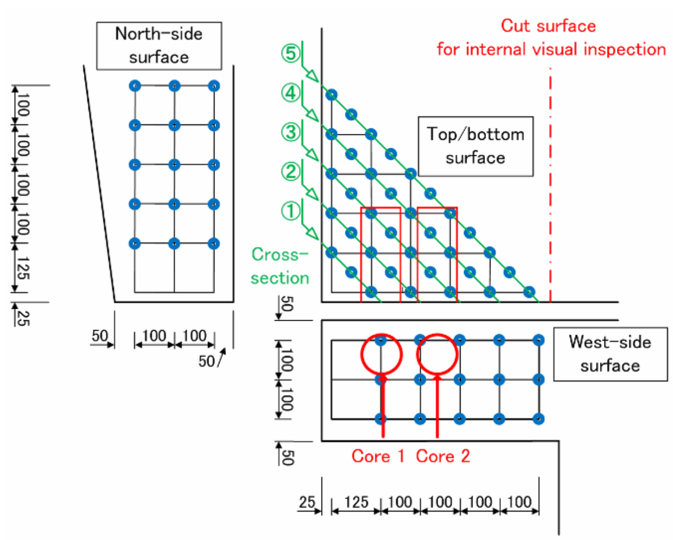

Figure 2. Tomography measurement sections and core positions.

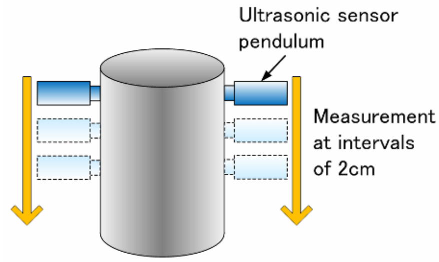

Figure 3. Core measurement using the penetration method.

2.2.2 *Adhesive strength test method*

To assess the Adhesive Strength of the Patching material and Surface coating material, Adhesive Strength Test Method was conducted at the sections shown in Figure 4 using a Building Research Institute-type adhesion tester. An epoxy resin adhesive was used to adhesive metal jigs with concrete and other materials. In the testing, Adhesive Strength between Surface coating material and Patching material, Patching material and Matrix and Surface coating material and Matrix were measured in accordance with the JSCE-K 561-2003 (Japan Society of Civil Engineers, 2007b) and JSCE-K 531-1999 (Japan Society of Civil Engineers, 2007a) standards of the Japan Society of Civil Engineers.

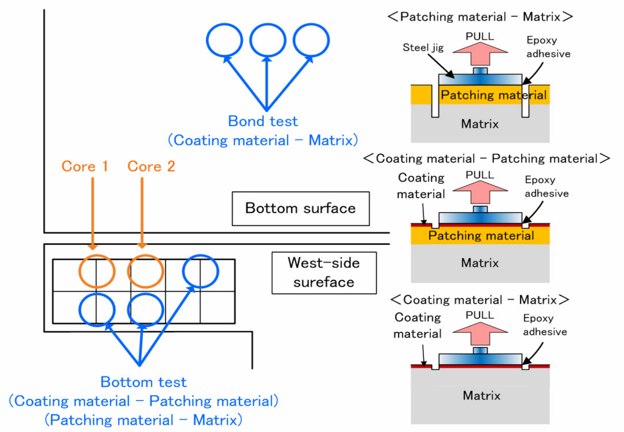

Figure 4. Adhesive Strength Test Method positions and test patterns.

2.2.3 *Visual observation of internal state*

After Ultrasonic Propagation Velocity Measurement, a part near the measurement sections was cut off (Fig. 2) and the repair and deterioration conditions under Surface coating material were visually observed from the cut surface for comparison with the results of analysis based on Ultrasonic Propagation Velocity Measurement and Adhesive Strength Test Method.

3 TEST RESULTS AND DISCUSSION

3.1 *Evaluation of frost deterioration under different environments*

3.1.1 *Weather conditions*

Table 3 shows the annual mean lowest temperature, annual maximum snow depth, number of freeze-thaw days and number of freezing days in each region. A comparison of weather conditions in the two regions indicates that the Kamikawa area has a severe cold, snowy environment, as the annual mean lowest temperature is lower and the annual maximum snow depth is greater. While the number of freezing days is higher in Kamikawa, the number of freeze-thaw days is higher in Hidaka. It can be seen from these results that the influences on sluice concrete in these two areas are different in winter.

3.1.2 *Appearance rating*

Figure 5 shows the results of appearance rating by section based on external visual inspection, and Figure 6 shows the results of control platform appearance rating by the number of in-service years. By part, the control platform rating was generally the highest, followed by the underwater part of the retaining wall, the top part of the retaining wall and the gatepost. Control platform frost deterioration was especially severe, with a rating of up to 5 in some cases. Since control platforms have a shape on which snow is likely to accumulate and their structure is relatively thin, they are more susceptible to the influence of freeze-thaw action caused by the retention of snowmelt and other factors. Conversely, gateposts are not susceptible to freeze-thaw action as they stand behind control platforms and are minimally exposed to snow accumulation and sunlight. It was found from this that parts directly affected by water supply are also affected significantly by freeze-thaw action, and that the degree of deterioration found in them increases.

Table 3. Weather conditions of different areas.

Region		Annual lowest temperature (°C)	Annual max. snow depth (cm)	No. of freezing days	No. of freeze-thaw days
Kamikawa	Otoineppu	-29.0	201.0	93.6	61.7
	Bifuka	-29.0	147.3	91.4	64.1
	Nayoro	-27.5	114.4	92.8	66.4
	Shimokawa	-30.0	131.0	93.6	73.2
	Shibetsu	-28.5	119.3	94.8	58.7
	Asahi	-24.1	No data	95.3	63.2
Hidaka	Mukawa	-21.9	37.7	56.8	91.5
	Hobetsu	-25.3	54.6	60.7	102.9
	Hidaka Monbetsu	-17.7	20.2	46.9	91.0

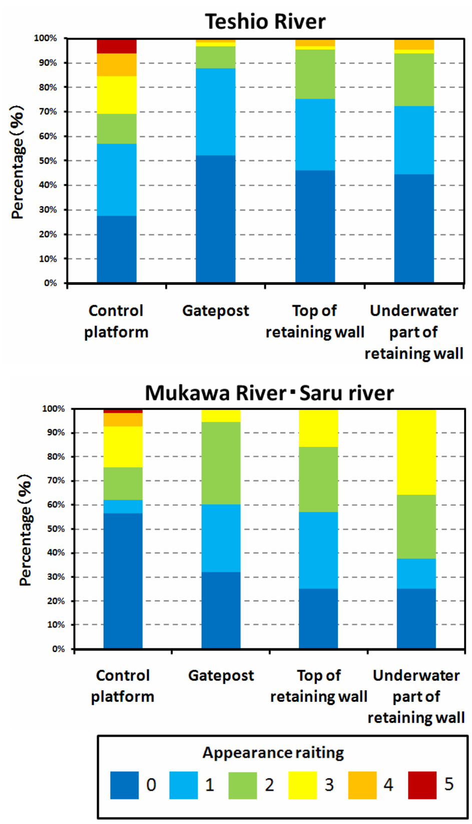

Figure 5. Appearance rating of river sluices by part.

By region, the ratio of parts rated three or higher was generally greater on the Mukawa and Saru rivers than on the Teshio River, although no ratings of four or higher were observed except for control platforms. Conversely, while some gateposts and retaining walls were rated four on the Teshio River, the ratio of lower ratings was generally higher compared with those of the Mukawa and Saru rivers. Looking at the number of in-service years, ratings tended to be higher for structures that had been used for 20 years or more on the Teshio River and for 30 years or more on the Mukawa and Saru rivers. It can therefore be said that frost deterioration progressed faster and its degree tended to be greater in the Kamikawa region, while the phenomenon tended to

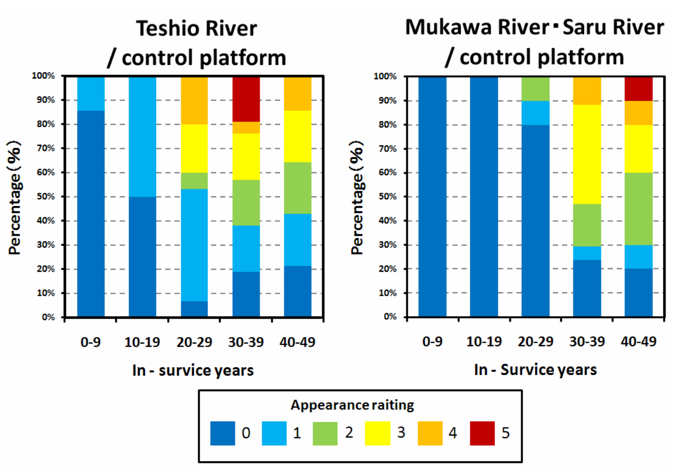

Figure 6. Appearance ratio of each sluice control platform by the number of in-service years.

occur regardless of part types in the Hidaka region, although the progress of deterioration there was slower and no significant deterioration was observed. Figure 7 shows the repair and re-deterioration rates in the two regions. While the repair rate was around 20% in both, re-deterioration occurred in more than half of the sluices after repair. It also occurred in all surface-coated sluices in both regions.

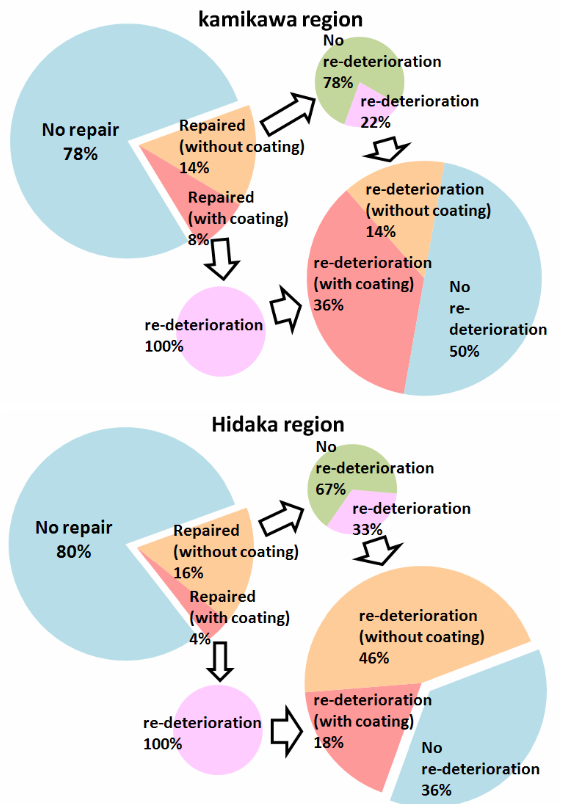

Figure 7. Repair and re-deterioration rates.

These results indicate problems regarding the durability of existing repairs in cold, snowy environments.

The above results reveal that appropriate measures against frost damage depending on differing regional environments must be taken to prevent re-deterioration, since the degree of frost deterioration in sluice concrete varies with differences in cold, snowy environments and the durability of existing repair methods is unclear.

3.2 *Estimation of the causes of re-deterioration, and deterioration diagnosis*

3.2.1 *Ultrasonic Propagation Velocity Measurement*

Figure 8 shows Ultrasonic Propagation Velocity distribution in Sections 1 to 5 as found using the tomography method. Since the velocity was generally lower on the outside than on the inside and the distribution is round at the corners of each cross-section, it was presumed that Patching was conducted for defective corners. As such defects represent a type of deterioration peculiar to frost damage, it can be assumed that frost deterioration had occurred in Matrix

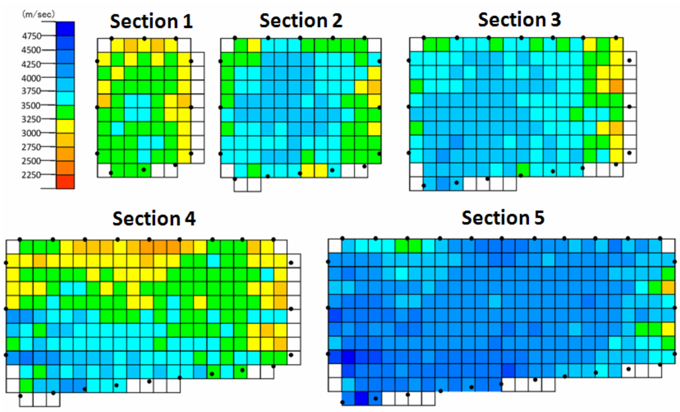

Figure 8. Velocity distribution on each cross-section as found using the tomography method.

before repair. It can also be seen that the defect on the west side was slightly deeper and larger in area than that on the north side. This was probably because of the greater influence of freeze-thaw action due to the more abundant sunlight on the west side. In addition, the velocity became very low in a V-shaped part on the topside of Section (4), indicating an internal defect in the vicinity. However, there were generally no clear differences in velocity between the repair material and the deteriorated parts of the matrix.

Figure 9 shows the velocity results for collected cores as assessed using the penetration method. Patching material thickness was around 10 cm and Patching material velocity was around 3,500 m/sec for both cores 1 and 2. While the velocity of concrete is generally 3,500 m/sec or higher, the value was a little higher than 2,000/sec in some parts of Matrixes of both cores, indicating partial deterioration. Since these sections are positioned similarly to the deteriorated part on the topside of Section (4)

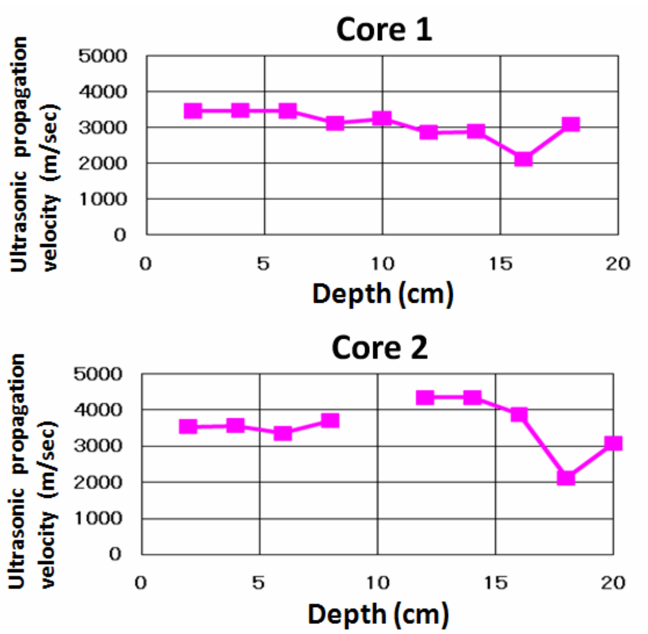

Figure 9. Ultrasonic Propagation Velocity of cores as found using the penetration method.

where the velocity was low, it was found that the position of internal deterioration can be identified to a certain degree using the tomography method. These results indicate that the internal state and degree of deterioration under Surface coating material can be roughly determined by Ultrasonic Propagation Velocity Measurement, and the technique's validity as a frost deterioration diagnosis method was confirmed.

3.2.2 *Adhesive strength*
Figure 10 shows Adhesive Strength test Method results. Adhesive Strength between Surface coating material and Patching material was 1.630 N/mm^2. The catalog standard value is 1.5 N/mm^2 or larger. Since NEXCO's (Nippon expressway Company) quality standard (JHS-416) (NEXCO.2004) for Patching materials (known as the common reference values for Adhesive Strength in Japan) specifies Adhesive Strength between Surface coating material and Patching material as 1.0 N/mm^2 or higher and that between Patching material and concrete as 1.5 N/mm^2 or higher, Adhesive Strength assessed in this study can be considered sufficient. However, Adhesive Strength values between Surface coating material and Matrix and between Patching material and Matrix were very low (0.507 and 0.404 N/mm^2). In these sections, fracturing occurred in the deteriorated Matrix but not in the adhesive surface with Matrix, as shown in Photo 3. Since external influences had been blocked until cracking in Surface coating material occurred 18 months after the repair, deterioration in sound Matrixes was unlikely at the post-repair stage. Accordingly, it was highly likely that the deteriorated parts of Matrix remained at the time of repair.

3.2.3 *Internal state*
Photo 4 shows a cross section created by cutting part of a control platform. Cross-sectional repair using a Patching material had been conducted for the inside of the defective Matrix, and Surface coating material had been applied to the surface. This corresponded roughly with the internal state found in the above-mentioned analysis using the tomography method.

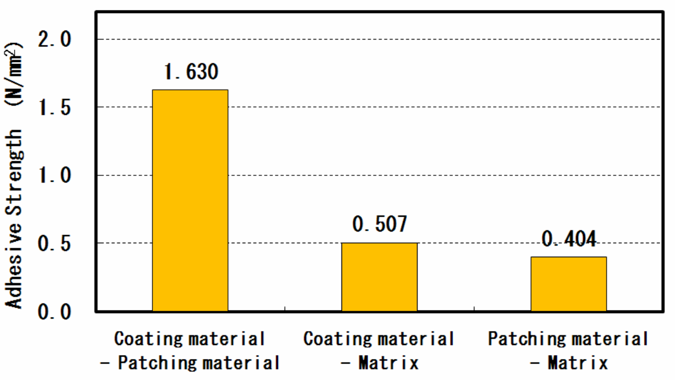

Figure 10. Adhesive Strength.

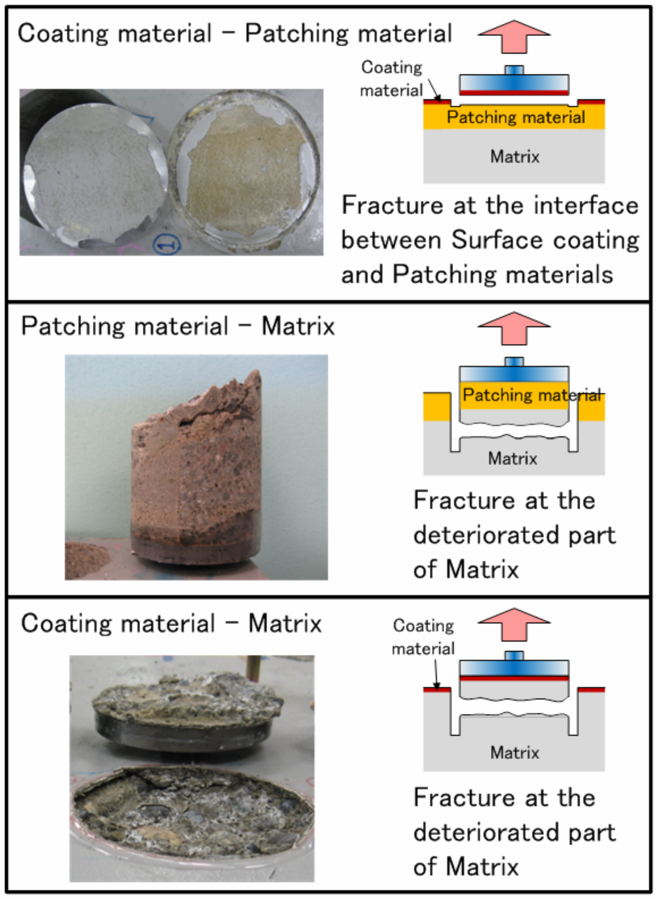

Photo 3. Fracture conditions.

Since voids were observed near the interface between Matrix and Patching material, it was also presumed that deterioration in Matrix near the interface progressed and cracking occurred in Surface coating material at the bottom. This result also supported the outcomes of Adhesive Strength Test Method. Since the repair of this sluice structure was conducted in winter, it is highly likely that removal of the deteriorated part of Matrix was incomplete in the surface preparation before the repair, and that Patching material and Surface coating material were applied while moisture from snow accretion and other sources was still present

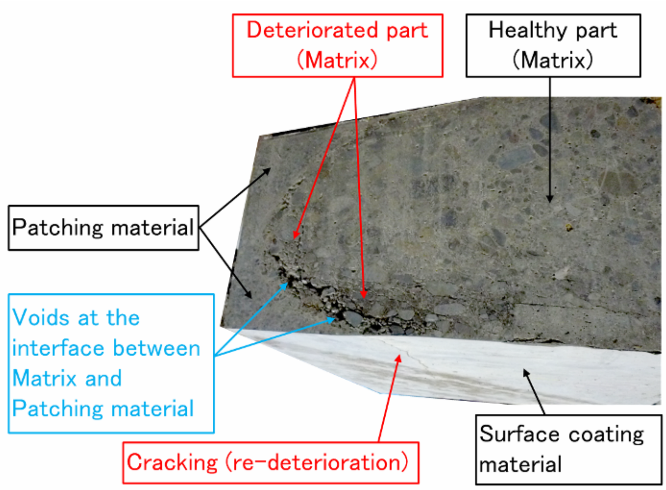

Photo 4. Cross section of the control platform.

inside the voids of the remaining deteriorated part. Accordingly, it is presumed that the progress of frost damage due to moisture retention in the deteriorated part of Matrix caused early re-deterioration, and that the cracks in Surface coating material caused by such deterioration let in more water, thereby accelerating frost deterioration.

4 CONCLUSION

The findings of this study are as follows:

(1) Since the degree of frost deterioration in sluice concrete varies by differences in cold, snowy environments and re-deterioration occurred in more than half of repaired sluices, it is necessary to take appropriate measures against frost damage depending on regional environments to prevent re-deterioration.

(2) Since Ultrasonic Propagation Velocity Measurement can determine the internal state and degree of deterioration under Surface coating material, its validity as a method for frost deterioration diagnosis is confirmed.

(3) Early re-deterioration of Surface-coated concrete was presumed to be caused by the progress of frost deterioration as a result of insufficient removal of deteriorated parts of Matrix at the time of repair and the confinement of water remaining in deteriorated parts by the surface coating material.

These results indicate the necessity of establishing accurate frost damage diagnosis and appropriate repair methods depending on deterioration conditions, since the durability of surface-coated concrete in cold, snowy environments greatly affects not only material properties but also the environment at the time of repair and the need for surface preparation of concrete before repair. The authors plan further studies and investigations to contribute to the extension of sluice concrete's service life and the reduction of maintenance/management costs.

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