Maintenance of Concrete Bridges Deteriorated by Chloride Attack in Japan

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Abstract

Chloride attack is a major deterioration factor for concrete structures in Japan. Chloride initiates the corrosion of embedded reinforcements, which not only produces signs of deterioration on the concrete surface, such as rusting, cracking and spalling, but also reduces the load-carrying capacity. This paper presents the current status of chloride-deteriorated concrete structures in Japan, and provides an overview of the maintenance manual for concrete bridges deteriorated by chloride attack. Research work conducted at PWRI and future research programs are also discussed.

Introduction

Corrosion of embedded reinforcements is a global problem for concrete structures. In Japan, many concrete bridges along the coastline have suffered corrosion due to the ingress of chloride from seawater, as shown in Fig. 1. When reinforcements corrode, signs of deterioration, such as rusting, cracking and spalling, usually appear on the concrete surface. Once these signs appear, it may be too late to prevent further deterioration through repair work. Moreover, corroded reinforcements significantly reduce the load-carrying capacity of concrete bridges.

Research institutes including PWRI continually conduct research to clarify the deterioration mechanism of concrete bridges due to chloride attack. Based on the findings, some specifications for countermeasures have been proposed. However, more information and research are required to develop an improved maintenance strategy for concrete bridges deteriorated by chloride attack.

This paper presents current status of concrete structures deteriorated by chloride attack in Japan, and provides an overview of the maintenance manual for concrete bridges deteriorated by chloride attack. Research work conducted at PWRI, such as nondestructive testing and load tests on prestressed concrete beams, and future programs are also discussed.

Fig. 1 Corrosion of reinforcements

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Concrete structures deteriorated by chloride attack in Japan

This chapter introduces the current status of concrete structures deteriorated by chloride attack in Japan. Previous research work involved calculating the life cycle cost (LCC) of a prestressed concrete bridge (PWRI, 2001) and conducting a questionnaire survey on deteriorated concrete structures and their repair (Watanabe, 1995).

Fig. 2 shows the cost for maintenance of a prestressed bridge located in a severe chloride environment. The bridge was completed in 1965 and was demolished after 35 years of service. The vertical axis represents the total cost for initial construction, maintenance and removal of the bridge. Additionally, the initial construction cost is normalized to 100 and other costs have been converted and summed. Expenses during the first 16 years of service were nil even though rusting due to reinforcement corrosion was observed after approximately 10 years. Maintenance costs started with the detailed inspection, surface coating of concrete, patch repair and strengthening by external cables and temporary pier bents. However, this rehabilitation work did not prevent further deterioration and the bridge was demolished after 35 years of service due to reduced load-carrying capacity. Total LCC was increased by 1.5 times due to the delay in repair work.

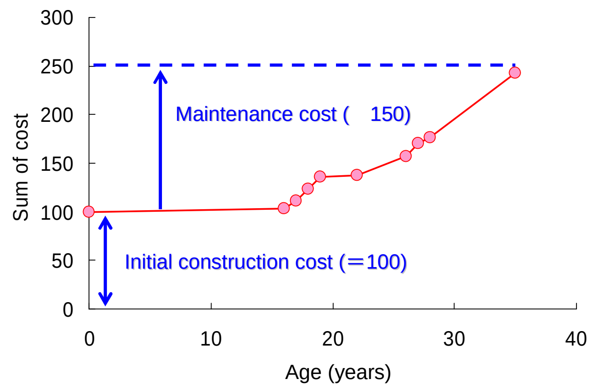


Fig. 2 LCC of prestressed concrete bridge

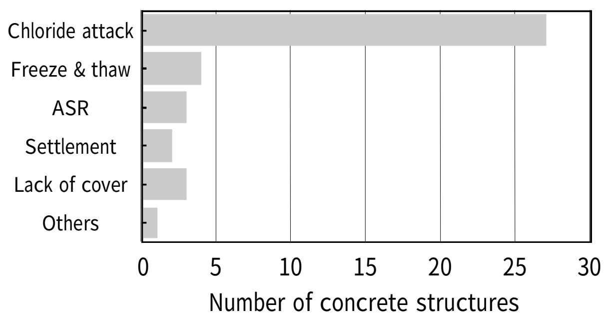


Fig. 3 Deterioration factors of concrete structures

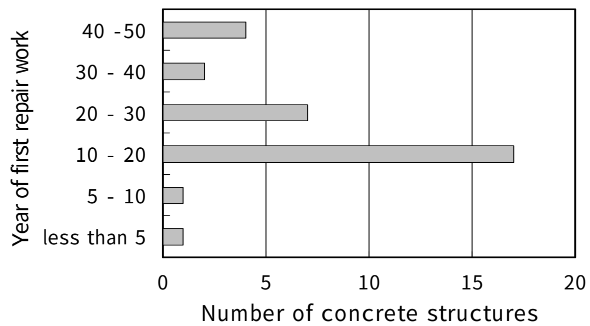


Fig. 4 Year of first repair work

In addition to calculating the LCC, a questionnaire survey was conducted at local branch offices of the Ministry of Land, Infrastructure and Transport (MILIT). The total number of concrete structures targeted in the survey was 40. Fig. 3 shows the deterioration factors for existing concrete structures. It is reasonable to conclude that the most severe deterioration is caused by chloride attack. Other deterioration factors, such as freeze and thaw, ASR, etc., were also observed, yet the number of affected structures is negligible. Additionally, Fig. 4 shows the year of the first repair work after completion. Most of the existing concrete structures were repaired within 10 to 20 years after completion. The repair of a few structures within the first 10 years is assumed to be due to poor workmanship. Moreover, Fig. 5 shows the results of visual inspections conducted 5 to 10 years after repair work. For repaired concrete structures located less than 100 m from the coastline, 42% showed signs of redeterioration. Meanwhile, 15% of the concrete structures located more than 100 m from the coastline demonstrated the same tendency. These facts reveal that repair work should be launched before any signs of reinforcement corrosion appear on the concrete surface. Moreover, the corrosion condition of reinforcements should be checked at regular intervals.

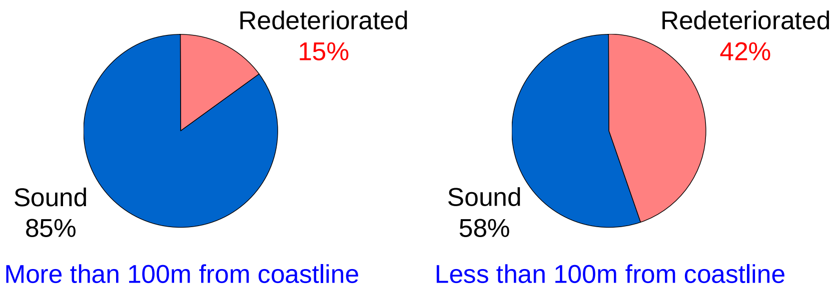


Fig. 5 Results of visual inspection after repair work

Maintenance manual for concrete bridges deteriorated by chloride attack

Based on existing research findings, MLIT proposed a maintenance manual for concrete bridges deteriorated by chloride attack. PWRI participated in compiling the manual and its research findings were applied in the countermeasures to chloride attack.

The scope of the manual covers the maintenance for the superstructure of concrete bridges deteriorated by chloride attack. It consists of six chapters: General Rules, Detailed Inspection, Deterioration Prediction, Diagnosis, Countermeasures and Record of Inspection Data, as shown in Table 1. Additionally, some technical recommendations, such as the mechanism of redeterioration, electrochemical techniques, etc., are attached as reference documents.

In the chapter on detailed inspections, tests such as the detailed visual inspection of the concrete surface and reinforcements, the chloride content and carbonation depth, are employed for assessing the condition of concrete bridges. The detailed visual inspection is indispensable for evaluating whether or not concrete bridges are deteriorated by chloride attack. However, the visual observation of embedded reinforcements must be limited to the minimum area in order to avoid deterioration due to the removal of the concrete cover. Additionally, the chloride content is used not only for assessing the corrosion risk for reinforcements but also for deterioration prediction. A small-size core and the concrete powder taken with a drill are recommended to avoid damaging the concrete cover and adversely affecting the structural performance. Inspection of the reinforcements and measurement of the chloride content are conducted where the most severe signs of deterioration appear on the concrete surface. The carbonation depth is also checked by spraying with phenolphthalein solution to evaluate the condition of the concrete cover.

Additionally, in the chapter on diagnosis, the condition of concrete bridges is evaluated based on the results of the detailed inspection. For diagnosis, concrete bridges are divided into 2 classes depending on their in-service period: over or within 30 years after completion. This criterion was established based on existing research findings that indicate the deterioration of concrete bridges progresses rapidly within 30 years if exposed to severe chloride attack. The criteria for diagnosis based on visual inspection and reinforcement corrosion are provided as shown in Tables 2 and 3. All data is rated using those criteria and the condition of concrete bridges is evaluated.

In the chapter on countermeasures, a number of techniques are introduced for repair, strengthening and renewal. For instance, patch repair, surface coating, cathodic protection and desalination are described for repair, while FRP sheets, external cables and temporary pier bents are for strengthening. These techniques are employed based on the condition of the bridge, such as bridge conditions, LCC, traffic conditions, budget and future planning.

The manual is expected to be useful in the maintenance of concrete bridges deteriorated by chloride attack. However, further research works should be carried out in future programs, such as the use of nondestructive testing for reinforcement corrosion and the estimation method for the load-carrying capacity of deteriorated concrete bridges. PWRI has conducted research focusing on these topics. The results are presented in the following chapters.

Table 1 Contents of manual

Chapter	Contents
1	General Rules
2	Detailed Inspection
3	Deterioration Prediction
4	Diagnosis
5	Countermeasures
6	Record of Inspection Data
Reference documents	Technical Recommendations

Table 2 Diagnosis criteria based on visual inspection

<table>
<tr><td colspan="2" rowspan="2">Condition</td><td colspan="2">Condition of appearance</td></tr>
<tr><td>Not repaired</td><td>Repaired</td></tr>
<tr><td>1</td><td>Deteriorated by factors other than chloride attack</td><td colspan="2">Chloride content is less than 1.2 kg/m^3 and will not be more than 1.2 kg/m^3 within 20 years.</td></tr>
<tr><td>2</td><td>Deteriorated in near future by chloride attack</td><td colspan="2">Chloride content is less than 1.2 kg/m^3 but will be more than 1.2 kg/m^3 within 20 years.</td></tr>
<tr><td rowspan="4">3</td><td rowspan="5">Already deteriorated due to chloride attack</td><td>Minor rusting and cracking</td><td>-</td></tr>
<tr><td>Rusting, cracking and partial spalling</td><td>More than 5 years after repair work; deterioration area is limited</td></tr>
<tr><td>Rusting, cracking and consecutive spalling</td><td>Less than 5 years after repair work; deterioration area is limited.
More than 5 years after repair work; deterioration area is widespread.</td></tr>
<tr><td>Damage to concrete and exposure of reinforcement</td><td>Less than 5 years after repair work; deterioration area is widespread.</td></tr>
<tr><td>4</td><td>Damage to concrete and fracture of reinforcement</td><td>Fracture of reinforcement</td></tr>
</table>

Table 3 Diagnosis criteria based on reinforcement condition

<table>
<tr><td colspan="2">Conditon</td><td>Condition of reinforcement</td></tr>
<tr><td>1</td><td>Deteriorated by factors other than chloride attack</td><td>Sound or superficial corrosion</td></tr>
<tr><td>2</td><td>Deteriorated in near future by chloride attack</td><td>Sound or superficial corrosion</td></tr>
<tr><td rowspan="2">3</td><td rowspan="3">Already deteriorated by chloride attack</td><td>Minor loss of cross section</td></tr>
<tr><td>Severe loss of cross section</td></tr>
<tr><td>4</td><td>Fracture</td></tr>
</table>

Nondestructive testing for reinforcement corrosion of concrete structures

Half-cell potential measurement is a simple, inexpensive and virtually nondestructive technique for assessing the corrosion risk for reinforcements embedded in concrete. The measurements can be used to estimate the corrosion risk even if there are no signs of corrosion on the concrete surface, which is a significant advantage for inspecting existing concrete structures. This chapter presents an example of practical application of half-cell potential measurement on an existing prestressed concrete bridge located near the coastline of Japan (Nakamura, 2008).

The prestressed concrete bridge was built in 1975 and has a span length of 25 m. Considerable airborne salt must have been present during the in-service period because the bridge is located within 200 m of the coastline. The second beam from the sea side was selected for the experiment. No signs of corrosion, such as rust, cracking or spalling, appeared on the concrete surface. Corrosion was highly likely to have started behind the concrete cover since the bridge existed in a severe chloride environment for over 30 years, yet a visual inspection cannot provide adequate information on the corrosion risk for reinforcements embedded in concrete. Half-cell potential was measured according to ASTM C 876. The measurement points were spaced 300 mm apart in the direction of the bridge axis, which corresponded with the spacing of the web reinforcement. Hence, the measurement points were located immediately above the web reinforcements. This was because the risk of corrosion due to airborne salt was likely to be higher for the web reinforcement located nearest to the concrete surface than for other steels. Fig. 6 shows the measurement points on the beam.

Fig. 7 shows the results of half-cell potential measurement and chloride analysis. The measurement results are represented as an equipotential contour map using different colors for each 50 mV. Carbonation depth, obtained by spraying phenolphthalein solution, was approximately 9 mm and concrete cover thickness at the web reinforcement was 40 mm. Thus, it is reasonable to assume that carbonation was not related to the corrosion. The most negative potential was obtained around a measurement point of 73 on the D measurement line. This area was located on the sea side of the beam, where considerable airborne salt was present. Comparing the results of the chloride analysis, the chloride content at PC5 was highest among the five points PC1 to PC5. Fig. 8 shows the relationship between the half-cell potential in summer and winter and the chloride content at the web reinforcement. The half-cell potential shifted depending on the season, but it was obvious that the negative potential was measured where the chloride content at the web reinforcement was high. Fig. 9 shows the state of the web reinforcement at four points: PC1, PC2, PC3 and PC5. Corrosion was found only at PC5, where the most negative potential was measured. Hence, the negative potential area on the equipotential contour map could be a good indicator for detecting points with high chloride content and localized corrosion even if there are no signs of corrosion on the concrete surface.

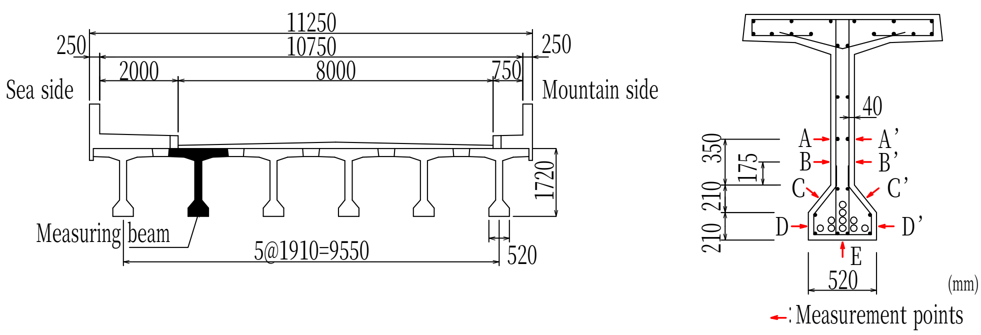


Fig. 6 Measurement points of half-cell potential on the beam

Based on the current research work, the most negative potential area on the equipotential contour map corresponds to the point with high chloride content and localized corrosion. The potential gradient is a good indicator for selecting the position for further destructive tests when there are no signs of corrosion on the concrete surface.

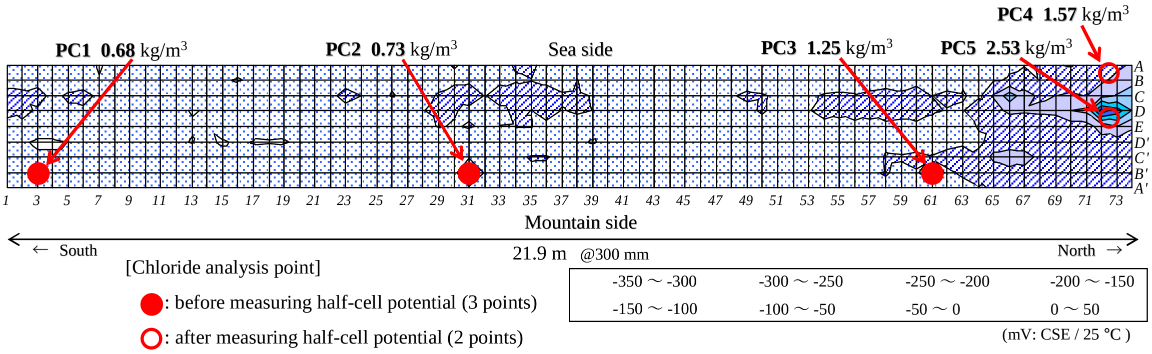


Fig. 7 Equipotential contour maps of prestressed concrete bridge in summer and winter

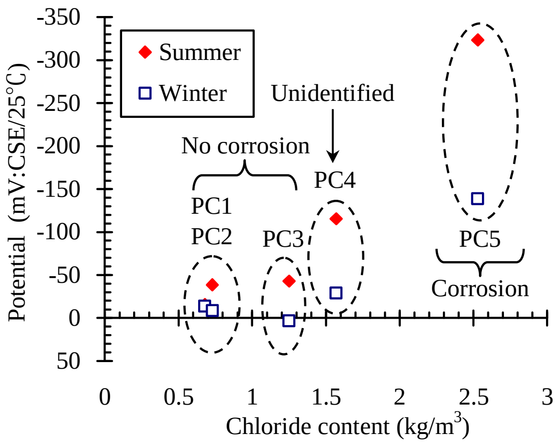
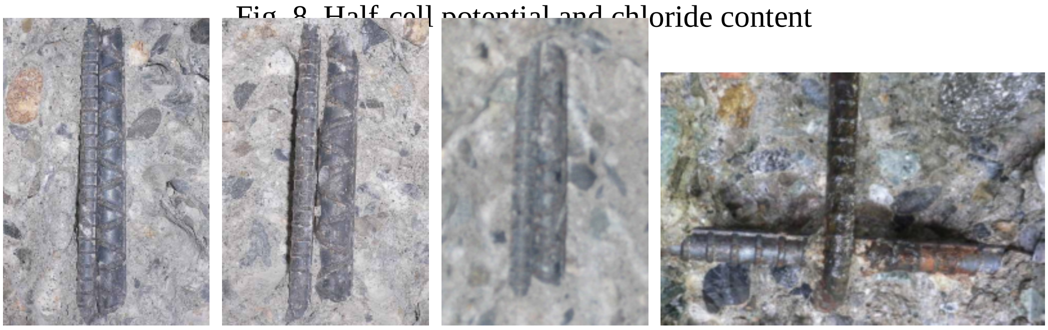


Fig. 8 Half-cell potential and chloride content



(a) PC1 (b) PC2 (c) PC3 (d) PC5

* PC1, PC2, PC3: No corrosion, ** PC5: Corrosion

Fig. 9 Corrosion state of web reinforcements

<u>Load-carrying capacity of prestressed concrete beams deteriorated by chloride attack</u>

This chapter presents an example of the loading tests on prestressed concrete beams deteriorated by chloride attack (Tanaka, 2001). The prestressed concrete bridge showed severe loss of tendon cross-sectional area due to corrosion under a severe chloride environment. The bridge had undergone some repair and strengthening work after 15 years from the completion, and was removed after 34 years of service. In order to discuss the effects of corrosion on the load-carrying capacity of prestressed concrete beams, loading tests were carried out.

Fig. 10 and Table 4 show the details of prestressed concrete beams S3 and S5. Both beams are post-tensioned prestressed concrete beams taken from the bridge that was demolished due to severely corroded tendons. S3 is the third beam of six beams in the third span, 39.34 m long. S5 is the third beam of five beams in the fifth span, 21.15 m long. Severe corrosion of reinforcements and tendons around the failed cross section of S3 was confirmed after the loading tests.

The average compressive strength of the concrete cores taken from S3 and S5 was 42 and 46 MPa, respectively. The average elastic modulus was 25 and 26 GPa, respectively. Average ultimate strength and elastic modulus of tendons was 1,750 MPa and 203 GPa, respectively. Average elongation of tendons in 100 mm was 6.7%. All tendon test pieces were carefully taken from the web near the support points in the fourth beams, which have a low concentration of chloride because of the deep concrete cover. As a result, no rust was found on these test pieces.

The loading scheme of S3

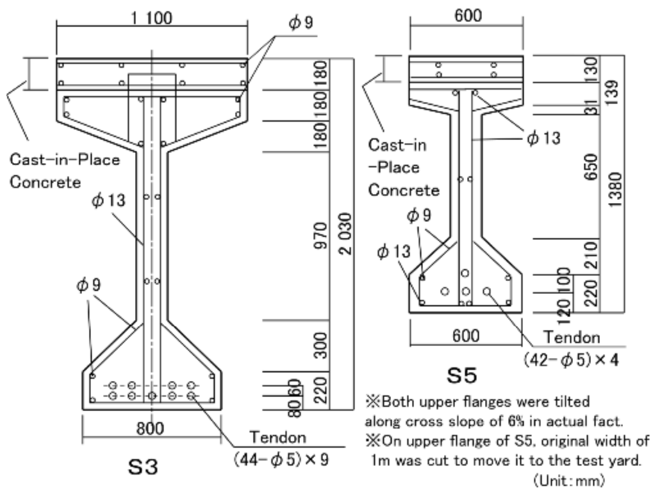


Fig. 10 Details of prestressed concrete beams

Table 4 Design specification and service term

Specimen	S3	S5
Beam No.	Third Span, Third Beam	Fifth Span, Third beam
Bridge Type	Post-tentioned Concrete Bridge	
	I-Shaped Composite	T-Shaped Non-composite
	6 beams	5 beams
Design Strength of Concrete	Main Beams 39MPa Deck 29MPa	
Tendon	BBRV 9-44ϕ5	BBRV 4-42ϕ5
Spec. of Wire	SWPR1 5mm	
Design Ultimate Strength of Tendon	1620MPa	
Introduced Prestress	1130MPa	
Effective Prestress	773MPa	843MPa
Completion of Bridge	March-65	
Removed Month	August-99	June-99

was planned as shown in Fig. 11. After removing the external cables for strengthening and temporary pier bents, S3 was suspended by a wire at one third of the span. Two point loads were tried to be applied at the center of S3. However, while the suspension wire was being released, fracture of the tendons occurred. As a result, the actual loading test was not executed since S3 was unable to carry its own weight due to severely corroded tendons. In the meantime, two point loads were applied to S5. The distance between loading points was 1.5 m. The crushing of concrete in the extreme compressive fiber caused the failure of S5.

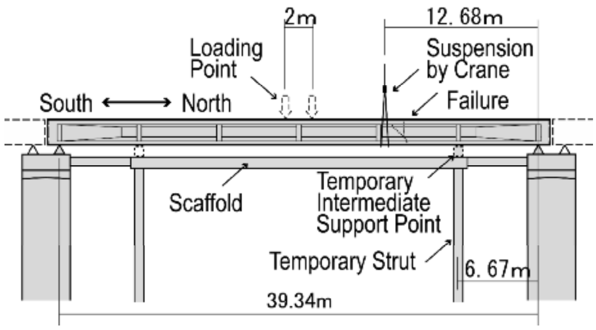


Fig. 11 In-situ loading scheme for S3

Fig. 12 shows the relationship between the remaining ratio of cross section of tendons (RRCT) and Mu/Muo. Mu means the experimental ultimate moment of the corroded prestressed concrete beam, while Muo denotes the calculated ultimate moment of the sound prestressed beam. Previous test results for two corroded precast prestressed concrete beams are also plotted in the same figure. The failure of sound prestressed concrete beams is usually caused by the crushing of concrete, unless the tendons and reinforcements are extremely corroded. However, prestressed concrete beams with an RRCT less than 80% failed with the fracture of tendons. This was because the heavy corrosion could have decreased the strength of tendons as well as their elongation. Additionally, RRCT is proportional to Mu/Muo. This means that the load-carrying capacity of corroded prestressed concrete beams can be predicted using the corrosion condition of the tendons. Based on this finding, the calculated Mu/Muo, Calc., was in good agreement with the experimental Mu/Muo, Ex.

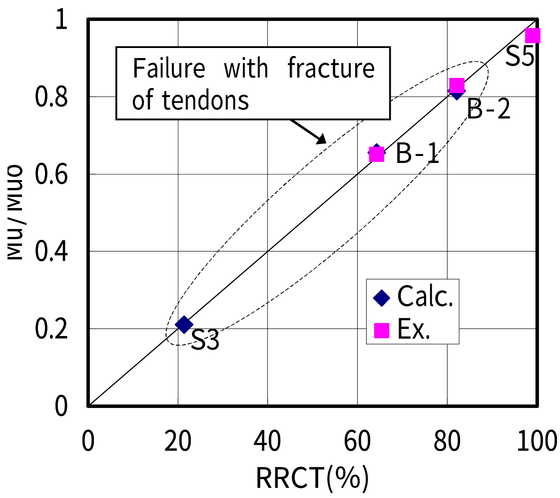


Fig. 12 Relationship between RRCT and Mu/Muo

Future programs

As mentioned earlier, PWRI has already conducted research works on chloride-deteriorated concrete structures. Additionally, the proposed maintenance manual for concrete bridges will be a helpful tool for road administrators. However, several problems must be resolved in future programs.

First, the reliability of nondestructive testing must be improved and its applicable scope should be widened. In the previous section, half-cell potential measurement was found to be a useful tool for assessing the risk of reinforcement corrosion. However, it cannot provide other important information about reinforcements, such as their corrosion rate, weight loss and fracture. These several new techniques have already been developed, yet their reliability and applicable scope are not adequate for practical application.

Second, the estimation method for load-carrying capacity of existing concrete bridges should be developed for assessment of structural performance. The previous section revealed that the load-carrying capacity of corroded prestressed concrete beams is proportional to the remaining ratio of tendons. However, the brief method for checking the remaining ratio of tendons has not been developed. Additionally, the adverse effects of other deterioration factors, such as corrosion of stirrups, loss of prestress and bond strength between concrete and reinforcements, are not clarified. These problems should be resolved for assessing the remaining load-carrying capacity of existing concrete bridges.

Third, the effect of de-icing salt on the performance of concrete bridges should be clarified based on field survey and experiment. The amount of de-icing salt sprayed on national highways is increasing from year to year. As a result, reinforcement corrosion due to de-icing salt has been reported in Japan. Thus, the adverse effects of de-icing salt and the appropriate countermeasure should be discussed in future programs.

Conclusions

This paper presents current issues on the maintenance of concrete bridges deteriorated by chloride attack in Japan. The following conclusions can be drawn based on the current research work.

1. Regular inspection is required to manage the many concrete bridges existing in a severe chloride environment. Additionally, delay of repair work should be avoided so as not to induce redeterioration and increase in LCC.
2. The maintenance manual for concrete bridges deteriorated by chloride attack was proposed by MLIT based on existing research findings. The manual evaluates the condition of concrete bridges using the results of the detailed inspection and introduces several countermeasures to chloride attack. This manual could be a useful tool for road administrators.
3. Half-cell potential measurement was found to be a useful tool for detecting the high chloride content area and reinforcement corrosion. Additionally, the load-carrying capacity of corroded prestressed concrete beams was proportional to the remaining ratio of tendons according to the loading tests on prestressed concrete beams. The next step involves improving the nondestructive techniques and the estimation method of the load-carrying capacity. Applying them to the detailed inspection of existing concrete bridges is also required in future programs.

Acknowledgement

Maintenance Manual for concrete bridges deteriorated by chloride attack was proposed by MLIT with the cooperation of the members in the technical committees.

References

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