- Technical Paper -

INVESTIGATION OF THE STEEL CORROSION IN CONCRETE STRUCTURES DETERIORATED BY ASR AND INFLUENCED BY DE-ICING SALTS

Hong Sao HO[*1], Yoshimori KUBO[*2], Sota KIKUCHI[*3]and Michio TAKENOUCHI [*4]

ABSTRACT

Many concrete structures are currently affected by the alkali-silica reaction (ASR). In addition, the de-icing salts have sprayed in the winter to ensure the safety of vehicles. The in-situ survey was conducted to comprehend the steel corrosion in the abutments affected by the combined deterioration of ASR and de-icing salts. The result indicated the influence of water leakage included de-icing salts become a considerable cause of corrosion in ASR deteriorated structures. Furthermore, the evaluation of corrosion risk can carry out based on the surface moisture of concrete and chloride ions contents.

Keywords: ASR, De-icing salts, Combined deterioration, Chloride ions, Corrosion risk

1. INTRODUCTION

Recently, many concrete structures have deteriorated by Alkali-silica reaction (ASR) in the Hokuriku region during the serving period. Some countermeasures have been implemented, however, the reliable repair techniques for long-term have not established. On the other hand, the de-icing salts have sprayed to ensure the safety of transport vehicles during the winter in this region. On the highway, at the joint positions between the bridge decks and abutments, these concrete parts affected significantly by water leakage and the degradation of concrete structures may be promoted in a relatively short time [1, 2]. It has been reported that the steel corrosion in concrete affected by ASR was not more significant than that of concrete not affected by ASR. The existence of ASR gel surrounds on steel bar is considered to be a factor to reduce the risk of steel corrosion (the assimilation of chloride ion and the reduction of water/oxygen supply due to the presence of this gel) [2, 3, 4]. However, in recent years, it is reported that the steel corrosion in ASR affected concrete occurs similar to the concrete not affected by ASR when the amount of chloride ion penetration reaches or exceeds certain limits. The previous study was carried out in abutments affected by ASR to investigate steel corrosion. The result showed that cracks caused by ASR promote the chloride ion penetration and accelerate the steel corrosion [5].

In this study, further investigation was conducted to measure the moisture content and chloride content on the concrete surface, analyse the chloride ion content penetrate into concrete, and comprehend the corrosion rate of steel bars by electrochemical method (half-cell potential and polarization resistance).

2. RESEARCH METHOD

2.1 Overview of abutments

In the winter, many bridges on the Hokuriku Expressway have affected by ASR deterioration and de-icing salts spaying. Six bridges were chosen as the target of the in-situ survey. In these bridges, the un-repaired parts of 9 abutments were selected and the front wall of an abutment was divided into two sides: the up line side and the down line side. The in-situ survey was conducted on the front walls and wing walls. It was reported in the previous study [5] that these abutment were affected by ASR and de-icing salts and these abutments were deteriorated by combined deterioration. Table 1 shows the overview of survey abutments. In addition, all bridges have affected by the spraying of de-icing salts.

2.2 Outline of in-situ survey

The in-situ survey was conducted to investigate the influence of ASR and de-icing salts on chloride penetration and the occurrence of steel corrosion. Regarding the effect of the de-icing salts, the amount of water leakage from the joints was comprehended through the moisture content on the concrete surface. On the ASR progression, the crack density on the surface was used as an evaluation index. From the results of surface moisture content and crack density measurements, 12 positions were selected for detailed investigation (chipping investigation and chloride ion analysis). Additionally, the connection wire was attached to the steel bar to measure the steel corrosion by electrochemical method. Table 2 shows all contents of the investigation. Based on the measured data, the relationship between water leakage (de-icing salts) and

*1 Graduate School of Science and Technology, Kanazawa University, JCI Student Member
*2 Associate Prof., Dept. of Environmental Design, Kanazawa University, Dr.E., JCI Member.
*3 Graduate School of Science and Technology, Kanazawa University, JCI Student Member
*4 Kanazawa Branch, Road Engineering Department, Central Nippon Highway Engineering Nagoya Co. Ltd

the corrosion occurrences of steel bars were investigated. The method used to determine the influence of de-icing salts based on the chloride ion content of concrete surface referred to the previous study [6] in order to evaluate the steel corrosion risk in the ASR deteriorated abutments affected by the de-icing salts spraying. The in-situ survey was executed in sunny or cloudy days.

2.3 Survey contents

(1) Surface moisture measurement

The surface moisture content of concrete was measured at intervals of 0.1m along the horizontal straight line of the front wall by using a high-frequency concrete moisture tester. The average value of the surface moisture content of concrete was calculated on each side of the front wall. The surface moisture content of concrete was used as an index to evaluate indirectly the influence of water leakage or the influence of de-icing salts.

(2) Chipping investigation

In order to determine the steel corrosion grade in the abutment affected by ASR and de-icing salts, 12 positions were selected to conduct the chipping investigation. These positions were chosen based on the results of the surface moisture content of concrete and the crack density survey, and it was covered in a wide range (from small to large of crack density, from high to low of moisture content of concrete). By using the concrete hammer drill, the concrete cover was removed in small areas (about 0.2m x 0.2m) to identify the corrosion grade of steel bars and measure the chloride ion penetration content. Table 3 shows the corrosion grade of steel bars, based on criterion 8 in "Concrete cracks analysis, repairing and reinforcement guidelines 2003: Japan Concrete Engineering Association".

(3) Chloride ion analysis

Samples for chloride ion analysis were collected by drill method of measuring positions. The samples were taken every 20 mm from the surface upon 120 mm and stored in the zip-plastic bags before the chloride ion analysis. These samples were analysed by the potentiometric titration method (JCI-SC5) to obtain the distribution of chloride ion penetration. The surface chloride ion content of concrete was measured by portable X-ray fluorescence meter.

(4) Corrosion measurement by electrochemical method

Half-cell potential and polarization resistance were measured by a portable corrosion meter (reference electrode: silver/saturated silver chloride electrode) to investigate the steel corrosion rate in the abutments. Before measurement, the concrete surface at the measured position was wetted by water spraying. The criteria of ASTM C-876 used to evaluate the steel corrosion by the half-cell potential. Table 4 shows the criteria for corrosion evaluation of half-cell potential. The AC impedance method was selected to measure the polarization resistance. The AC voltage (ACV) applied at 10 mV, the frequencies were 10 Hz and 20 Hz, and the integral number was set to 1 as the integration condition. Table 5 shows the criteria used for judging the corrosion rate, according to CEB recommendation.

Table 1 Survey abutments

Abutment	Investigated Objects	Serving life (years)	Number of chipping
A (Up line)	Front wall	40	1
A (Down line)	Front wall	40	1
B (Down line)	Front wall	40	1
C (Down line)	Front wall	40	1
C (Up line)	Front wall	40	1
D (Up line)	Front wall	35	4
E (Down line -wing)	Down line -wing wall	32	1
F (Up line)	Front wall	32	1
F (Up line -wing)	Up line -wing wall	32	1

Table 2 In-situ survey summary

Content	Outline understanding
Surface moisture content	Evaluate the amount of water leakage.
Chipping investigation	Determine the corrosion grade of steel bars, wire setting for corrosion measurement.
Electrochemical corrosion measurement	Measure the half-cell potential and polarization resistance of steel bars.
Chloride ion analysis	Collect samples by the drill method at chipping positions. Analyse the chloride ion content in different depths.

Table 3 Steel corrosion grade

Corrosion grade	State of reinforcing bar
I	Surface with mill scale or rust is not occurring as a whole. It has thin and slight rust, and rust does not adhere to the concrete surface.
II	Partially floating rust and small spotted state is observed.
III	Sectional defects are not observed by visual observation, but floating rust occurs around the reinforcing bars or the entire length.
IV	Remarkable corrosion and cross-section defects occurred.

Table 4 Corrosion evaluation of half-cell potential

Half-cell potential (mV vs. SSE)	Corrosion evaluation
$E > -80$	No corrosion (more than 90%)
$-80 \geq E \geq -230$	Uncertain
$E < -230$	Corrosion (more than 90%)

Table 5 Corrosion rate by polarization resistance

Polarization resistance ($k\Omega.cm^2$)	Corrosion rate
$R_p > 130$	No corrosion
$130 \geq R_p > 52$	Low ~ Moderate
$52 \geq R_p > 26$	Moderate ~ High
$R_p \leq 26$	High

3. RESULTS AND DISCUSSION

3.1 The effect of water leakage

Fig. 1 shows the average values of the surface moisture content of all abutments (up line side and down line side of each wall) and these values range from 5% to 9%. In the previous study [7], it was reported that the abutment of around 4% of the surface moisture content of concrete was not significantly influenced by water leakage and de-icing salts. In this study, the influence of de-icing salts is considered relatively small when the surface moisture content remains approximately 4%. Therefore, the influence of water leakage on these abutments of around 4% of the average surface moisture content of concrete was evaluated to be relatively small. On the other hand, it is considered that the influence of de-icing salts is relatively large in the case of exceeding 6% of the surface moisture content of concrete.

In the previous studies [5, 7], it was reported that the abutment of around 4% of the surface moisture content of concrete was not influenced significantly by water leakage and de-icing salts. Furthermore, in the case of exceeding 6% of the surface moisture content of concrete, the influence of water leakage and de-icing salts was relatively high [5, 7].

3.2 Influence of moisture content on corrosion

Fig. 2 shows the relationship between the half-cell potential/the polarization resistance and the surface moisture content of concrete. The surface moisture values were calculated by the average value of the same measuring sections (1m x 1m) in 2014 and 2015, respectively. Although the results showed some variations, abutment of the higher surface moisture content had the lower half-cell potential values that make easy to corrode steel bars. Additionally, when the surface moisture content of concrete exceeded 8%, most half-cell potential value was plotted in the corrosion zone. On the other hand, when the value was lower than 4%, most half-cell potential value was plotted in the no corrosion zone. The position of high surface moisture content is considered to be affected by water leakage (de-icing salts). Thus, the steel corrosion rate may be increased in these areas of high moisture content of concrete.

The similar tendency was also found in the relationship between surface moisture content and polarization resistance. When the surface moisture content is higher, the polarization resistance is the lower value that has the larger of steel corrosion rate. When the surface moisture content of concrete exceeded 6%, polarization resistance value was significantly decreased and most polarization resistance value was plotted in the steel corrosion zone.

3.3 The influence of de-icing salts on corrosion (surface chloride ion content)

Fig. 3 shows the relationship between half-cell potential/polarization resistance and surface chloride ion content. On the half-cell potential, although the values show some variations, half-cell potential tends to

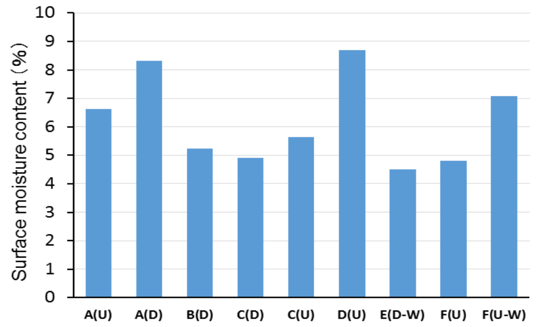
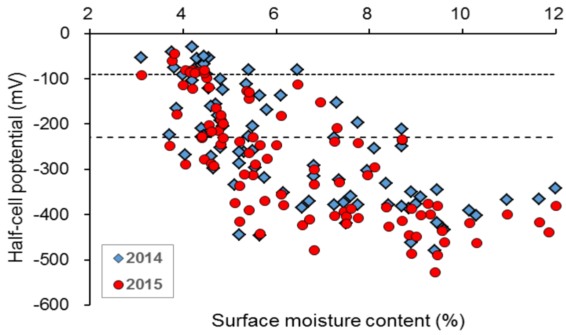
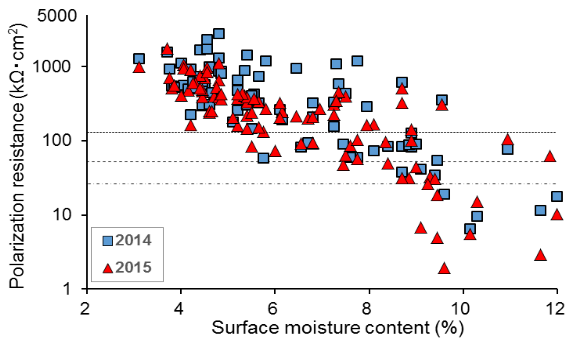


Fig.1 Surface moisture content of all abutments



(a) Surface moisture content of concrete and half-cell potential relationship



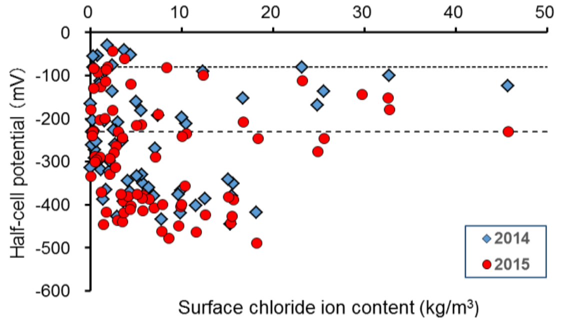
(b) Surface moisture content of concrete and polarization resistance relationship

Fig. 2 Surface moisture content and corrosion relationship (by electrochemical measurements)

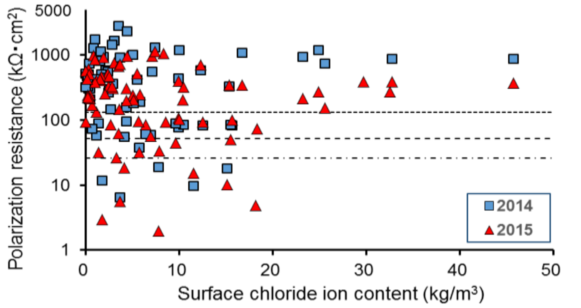
decrease in accordance with the increase of the surface chloride content. It is considered that these areas with high surface chloride ion content has a large penetration of chloride ion into concrete and the steel bar in the concrete becomes to be corroded easily.

On the polarization resistance, although the value showed some variations, the polarization resistance tended to decrease with the increasing of the surface moisture content. There were only a few areas where both polarization resistance and half-cell potential values plotted in no corrosion zone beyond 20 kg/m^3 of the surface chloride content. These values were obtained on the abutment C where the moisture content of concrete was low. On the abutment C, steel corrosion is considered to be suppressed due to the low moisture content of concrete.

Although there were some variations, the results showed that in case of the surface chloride ion content was larger than approximately 5 kg/m^3, many values of



(a) Half-cell potential and surface chloride relationship



(b) Polarization resistance and surface chloride relationship

Fig. 3 Surface chloride ion content and corrosion relationship (by electrochemical measurement)

polarization resistance and half-cell potential were plotted on the corrosion zone. It is considered that the larger of surface chloride ion corresponds to the possibility of higher corrosion rate and the value 5kg/m^3 of surface chloride ion was used as the index for the evaluation of steel corrosion.

3.4 Evaluation and verification of corrosion

(1) Evaluate corrosion risk of steel bars

From the above discussion, it is considered that the surface moisture content of concrete corresponds to the degree of water leakage and surface chloride ion content correlates to the degree of de-icing salt supply. However, the paths of water leakage in in-situ structures may change greatly during the service periods. Thereby, the degree of water leakage at the present time of measurement can differ with the degree of the leakage in the past time. On the other hand, it is considered that the surface chloride ion content approximately corresponds to the degree of de-icing salt supply even if the supply of water leakage becomes small at the present and the accumulation of the de-icing salt supply is large. Therefore, the degree of de-icing salt supply can be evaluated from the surface chloride ion content.

Fig. 4 shows the relationship between the surface moisture content (average value of each measured point of 2 years) and surface chloride ion content of concrete. Surface chloride ion content increased with the increasing of the surface moisture content, although the variation was large. There were some areas where the surface moisture content was less than 6% and the surface chloride ion content was high. There were other exceptions where the surface moisture content was high and the surface chloride ion content was smaller than 5 kg/m^3. It is considered that the remarkable change of water leakage in the past and the present occurs in above exception areas.

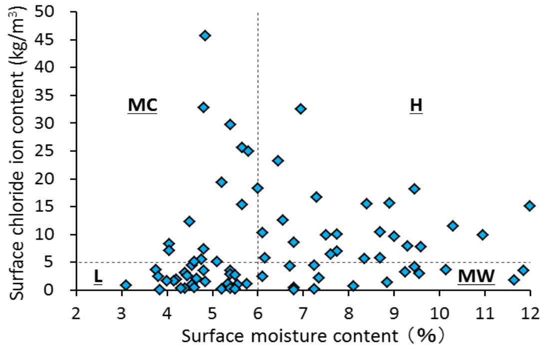


Fig. 4 Corrosion risk classification based on surface moisture and surface chloride ion contents

Table 6 Corrosion risk classification

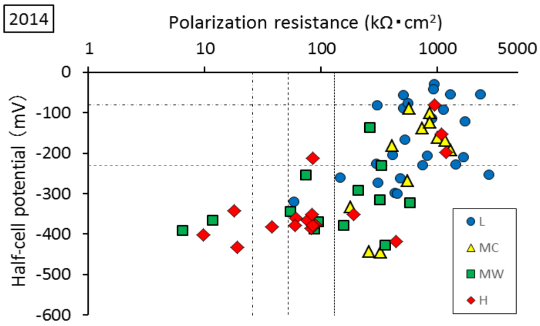
Risk	Surface moisture	Surface chloride ion	2014	2015	Total
L	< 6%	< 5kg/m^3	25	26	51
MW	≥ 6%	< 5kg/m^3	13	15	28
MC	< 6%	≥ 5kg/m^3	12	14	26
H	≥ 6%	≥ 5kg/m^3	17	24	41

On the other hand, in the case of both values of surface moisture content and surface chloride ion content is large, the degree of chloride penetration and water leakage are large, it is considered that the risk of corrosion is relative high. Conversely, the corrosion risk is considered to be small when both values are small. Thus, the evaluation of corrosion risk can be examined based on the relationship between surface moisture content and the surface chloride ion content in in-situ structures. From the results mentioned in sections 3.2 and 3.3, the threshold values of surface moisture content and the surface chloride ion content were set at 6% and 5 kg/m^3 for the evaluation, respectively. Corrosion risks were classified as L, MW, MC, H. The classification of each corrosion risk is shown in the Fig. 4. Furthermore, the number of measuring area corresponds to the corrosion risk classification is shown in the Table 6.

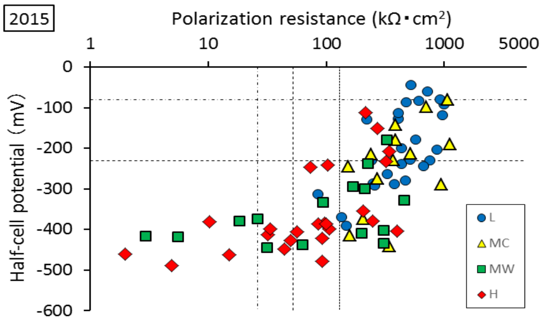
(2) Verification of the corrosion risk based on the steel corrosion rate

In order to verify the evaluation of corrosion risk, the relationship between half-cell potential/polarization resistance and the corrosion risk were discussed. The correlation between corrosion rate and polarization resistance/half-cell potential for each measured year correspond to the classification of corrosion risk is shown in the Fig.5. The number of occurrences and the percentage for each corrosion rate correspond to the corrosion risk is shown in the Fig. 6.

In corrosion risk L, the corrosion rate in almost areas showed no corrosion zone and corrosion rate in a few areas showed low to moderate zones in both 2014 and 2015. On the other hand, in corrosion risk H, the corrosion in almost areas (more than 70%) showed in corrosion zone. It inferred that the higher corrosion rate



(a) Corrosion measurements in 2014



(b) Corrosion measurements in 2015

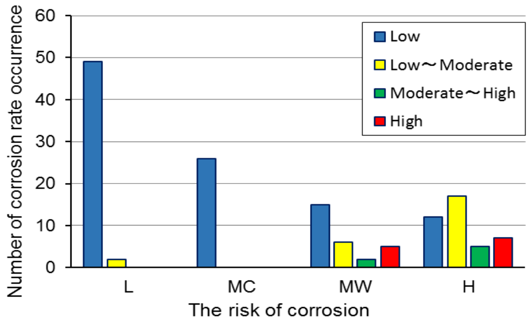
Fig. 5 Corrosion risk classification based on electrochemical measurement

is likely to occur in the high corrosion risk H, whereas the low and/or no corrosion rate is likely to occur in the low corrosion risk L.

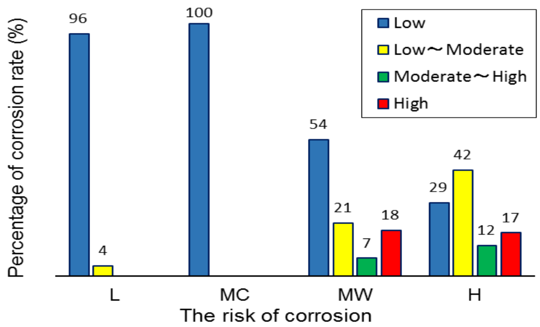
On the corrosion risk MC where the surface chloride ion content was high and the moisture content was relatively low, the corrosion rate in all areas showed no corrosion zone in both years. On the corrosion risk MW where surface chloride ion was low and the moisture content was relatively high, the corrosion rate of around a half of areas (more than 40%) showed the corrosion zone. In other words, the high moisture content indicates that the degree of the current water leakage is large and the moisture content of concrete near steel bar is kept in high moisture content. It is considered that this results in the occurrence and the progress of steel corrosion in the corrosion risk MW.

On the contrary, in the corrosion risk MC, it is inferred that the corrosion rate is suppressed due to lower moisture content of concrete near the steel bars although high surface chloride ion content.

The relationship between corrosion risk and corrosion grade of steel bar judged from the visual observation of steel bar after chipping survey was investigated. In addition to above relating, the chloride ion content at the concrete cover depth (from 80 to 100mm) was discussed in order to verify the evaluation of the corrosion risk. The other corrosion risk was evaluated from the chloride ion content at concrete cover depth. Corrosion risk evaluated from surface moisture and surface chloride ion content information was compared to the corrosion risk (L', MC', MW', H') that evaluated from the surface moisture and chloride ion content at cover depth. The information to verify the evaluation of corrosion risk is shown in Table 7.



(a) Corrosion risk classification based on the number of corrosion rate occurrence



(b) Corrosion risk classification based on the percentage of corrosion rate occurrence

Fig. 6 Verification of corrosion rate corresponds to the risk of corrosion

Table 7 Verification of corrosion risk

Abutment	Corrosion risk (Cl- on surface)	Corrosion grade	Chloride ion content at cover depth (kg/m^3)	Corrosion risk (Cl- at cover depth)	Evalu-ation
A(U)	MW	I	0.63	MW'	O
A(D)	H	I	1.60	MW'	Δ
B(D)	MC	II	0.86	L'	O
C(D)	L	II	1.67	L'	O
C(U)	MC	III	2.03	MC'	O
D1(D)	L	I	0.34	L'	O
D2(D)	MW	II	3.38	H'	O
D3(D)	MC	I	0.25	L'	X
D4(D)	H	II	0.63	MW'	O
E(D-W)	L	I	0.16	L'	O
E(U)	L	I	0.32	L'	O
F(U-W)	MW	I	0.29	MW'	O

O: True X: False Δ: unclear

In the corrosion risk MC, the corrosion rate was negligible (no corrosion). However, corrosion grade of steel bar was grade II or III in 2 of 3 measured areas. It is considered that the corrosion progress in the past was large and the current progress is suppressed due to lower moisture content caused by the change of water leakage degree.

In the corrosion risk MW, the corrosion rate around a half of measured areas was equal or lower than "low to moderate". However, it is noticeable that corrosion grade II occurred in the front wall of abutment D. Many cracks occurred in concrete structures affected by ASR expansion. Accordingly, these cracks can make water and chloride ion easy to penetrate into the concrete. Thus, it is considered that water and oxygen supply to near steel bar increase with the increasing of the crack density. This results in the promotion of occurrence of steel corrosion and corrosion rate in concrete even in the low chloride ion content. Although it is inferred that the current corrosion rate in the corrosion risk MW is small, it is noted that the potential of steel corrosion may be high.

On the wing wall of corrosion risk MW, it showed the corrosion grade I. The influence of de-icing salt on steel corrosion in concrete may differ between the front wall and the wing wall since the de-icing salt supply on the wing wall is relatively smaller than that on the front wall and the wing wall is affected directly by rainwater and the surface chloride ion wash away due to rain water. From the results of chipping investigations on 2 wing walls, it may be recognized, as the above evidence that both the corrosion grade and the chloride ion content at cover depth is small. This difference between the front wall and the wing wall is should be cleared in the future.

In the corrosion risk L, the corrosion rate at almost of measured areas was low. All abutment showed corrosion grade I and the chloride ion content was lower than 0.5 kg/m^3 except for abutment C(D). The evaluation of corrosion risk was corresponded to the result of corrosion grade and chloride ion content at cover depth.

In the corrosion risk H, the corrosion rate around a half of measured areas was larger than “low to moderate”. On the other hand, at 30% of measured areas the corrosion rate was low. In Table 7, there were only 2 abutments of corrosion risk H (Abutment A(D) and D4(D)). Abutment A(D) showed corrosion grade I but the chloride ion was 1.6 kg/m^3. Abutment D4(D) showed corrosion grade II but chloride ion content was 0.63kg/m^3. Both abutments had the possibility of steel corrosion. It is considered that the evaluation of corrosion risk based on the surface moisture content and the surface chloride ion content has high validity.

Generally, the degree of water leakage varies considerably because it depends on some factors such as the condition of joint and drainage device, the addition of the bridge preventing device, etc. The influence of de-icing salts on the structure may be changed largely in the past and present. Therefore, it is noted that the evaluation of corrosion risk based on only surface moisture content and surface chloride ion contents entails some uncertainty. However, it was considered that surface chloride ion content reflected the situation in the past to some extent and it provided the wealth of information in the corrosion risk evaluation. In this study, the surface moisture content was also used in order to evaluate the corrosion risk with the surface chloride ion. It is considered that the surface moisture content is useful to recognize the degree of water leakage in the present. It is concluded that this evaluation method of corrosion risk is effective when the concrete structures are affected by both ASR and de-icing salts.

4. CONCLUSIONS

(1) From electrochemical corrosion measurement, the half-cell potential and polarization resistance trended to decrease with the increasing the surface moisture content. On the surface chloride ion content, the same tendency was observed.
(2) The evaluation of corrosion risk can be determined based on the relationship between surface moisture content and the surface chloride ion contents in in-situ structures.
(3) The influence of de-icing salts on the structure may be changed largely in the past and present. Therefore, it is noted that the evaluation of corrosion risk based on only surface moisture content and surface chloride ion contents entails some uncertainty.
(4) The surface moisture content was also used in order to evaluate the corrosion risk with the surface chloride ion. It is considered that the surface moisture content is useful to recognize the degree of water leakage in the present.
(5) It is concluded that this evaluation method of corrosion risk is effective when concrete structures are affected by both ASR and de-icing salts.

REFERENCES

[1] Kiyoshi Honjo, Masahiro Nakano, Norio Fujiwara, Kazuhiro Kuzume, Hironori Maki, “Detailed investigation of steel bar in RC slab degraded by de-icing salts,” Repairing of concrete structure, Reinforcement, Upgrade paper report, Vol.10, Oct. 2010, pp. 51-56. *(in Japanese)*

[2] Kazuaki Yokoyama, Kiyoshi Honjo, Katsuhiro Kuzume, Norio Fujiwara, “Study on elucidation of deterioration mechanism accompanied with the steel corrosion of RC deck on the road bridge,” Concrete Engineering Annual Proceedings, Vol.30, No.3, Jul. 2008, pp. 1687-1692. *(in Japanese)*

[3] M. Kawamura, D. Shinghal, and Y. Tsuji, “Effects of ASR on corrosion of reinforcement in concrete under saline environment,” Proceedings of East Asia Alkali-Aggregate Reaction, Tottori, 1997, pp. 179-190.

[4] Yuki Fujimura, Takashi Habuchi, Kazuyuki Torii, “Steel corrosion behaviour of concrete structures influenced by ASR and sea water,” Concrete Engineering Annual Proceedings, Vol.31, No.1, 2009, pp. 1285-1290. *(in Japanese)*

[5] Yoshimori Kubo, Toshiki Yano, Toru Kikuchi, Yuichi Ishikawa, “Study on the corrosion of reinforcing bars in ASR deteriorated structures affected by de-icing salts,” Repairing of Concrete Structures, Upgrade paper report, Vol.15, Oct. 2015. *(in Japanese)*

[6] Sota Kikuchi, Yoshimori Kubo, Hisato Kimura, Yoshihiro Yanai, Yoshiyuki Momiyama, “A Study of Surface Chloride Ion and Chloride Penetration Distribution of Concrete Structure under Sprinkling with De-icing Salts,” Upgrade Paper Report, Volume 16, Oct. 2016. *(in Japanese)*

[7] Shiho Ibata, Toshiki Yano, Yoshimori Kubo, Yasunori Hashizume, “Estimate the influence of de-icing salts based on the monitoring results of structures affected by de-icing salts spraying,” Annual Concrete Engineering Proceedings, Vol.1, No.36, Jul. 2014, pp. 934 - 939. *(in Japanese)*