

Committee Report: JCI- TC222A

## **Technical Committee on Unified Treatment of Reinforcement Corrosion in Concrete**

Satoshi TAKAYA\*<sup>1</sup>, Shinichi SATO\*<sup>2</sup> and Hiroshi UEDA\*<sup>3</sup>

### **Abstract**

The purpose of this research committee was to collate information on the influence of water on concrete corrosion and to propose a scenario for the uniform treatment of rebar corrosion. To this end, we conducted a survey study on the influence, form, and supply routes of water contributing to rebar corrosion. In addition, we conducted a survey of actual structures with steel bar corrosion, and analyzed the factors influencing wetting and drying processes at such sites. The results revealed that the rate of drying is slow and chloride ions influence the migration rate. In addition, hardly any corrosion of rebar was observed in sections of actual structures with no water migration, irrespective of the presence of chloride ions or neutralization.

Keywords: Rebar corrosion, salt damage, neutralization, water, oxygen

### **1. Introduction**

In recent years, the aging of social infrastructure and the importance of its maintenance have become social issues. Now that many structures constructed during the 1960s and 1970s are entering a period requiring maintenance management, their mechanisms of deterioration must be understood accurately to maintain and manage the vast infrastructure efficiently on a limited budget. Especially in Japan, which is surrounded by the sea on all sides and features mountainous regions where anti-freezing agents are sprayed, corrosion of rebar is a serious problem facing concrete structures. Thus, its modality must be better understood.

In the past, chloride ions and neutralization have been considered with regard to rebar corrosion, with the general consensus being that higher chloride ion content is correlated to greater neutralization depth and faster corrosion progress<sup>[1]</sup>. Recently, however, it has become clear that although chloride ion penetration and pH reduction due to neutralization may be initiate corrosion, its subsequent progress is likely to be determined by the interaction of water and oxygen. Survey results of corrosion products in various structures indicate that corrosive

environments can be classified into four types based on this factor<sup>[2]</sup>. Further, surveys of actual structures reveal the main cause of rebar corrosion to be dry-wet cycles.

Therefore, data collation on the interaction between water and oxygen would enable unified corrosion treatment, instead of one restricted to a framework comprising salt damage and neutralization.

In this context, the purpose of this research committee was to collate the form, supply routes, and other influencing factors that affect corrosion, and to propose a scenario for treating rebar corrosion in a unified manner based on our analysis of the corrosion mechanism.

**Table 1** lists the members of the committee. The Literature Review Working Group (WG1) performed a literature review and basic experiments, and investigated the significant influence of water on the corrosion process in the presence of oxygen. Their results revealed that the rate of wetting to drying is slow and chloride ions affect the migration rate. In addition, we studied the critical current density of oxygen diffusion in concrete, and concluded that it is highly likely to be basically oxygen diffusion controlled except in the case of dry-wet cycles. The Structural

**Table 1 Committee members**

Chair : Satoshi TAKAYA (Kyoto Univ.)	
Secretary : Shinichi SATOH (ORIST)	
Hiroshi UEDA (RTRI) Koichi MATSUZAWA (Meiji Univ.)	
Tomoko FUKUYAMA (Ritsumeikan Univ.) Nozomi SOMEYA (Nakabohtec)	
<b>【WG1 : Literature Review WG】</b>	
◎Shinichi SATOH (ORIST)	○Yuya SAKAI (Univ. of Tokyo)
○Kotaro DOI (NIMS)	○Koichi MATSUZAWA (Meiji Univ.)
Go IGARASHI (Nagoya Univ.)	Ryosuke SAITO (Shimizu Corpotation)
Kohei SAKIHARA (Ryukyu Univ.)	Nozomu SOMEYA (Nakabohtec)
Kiyoshi NAKATA (BRI)	
<b>【WG2 : Structural Investigation WG】</b>	
◎Hiroshi UEDA (RTRI)	Toshinori KANEMITSU (CRIEPI)
Hiroshi KUROKAWA (JR West)	◎Nozomi SOMEYA (Nakabohtec)
Masayuki TSUKAGOSHI (Fukuoka Univ.)	Tomoko FUKUYAMA (Ritsumeikan Univ.)
Makoto MURANAKA (NEXCO Central)	Shinya WATANABE (CMI)
<b>【WG3 : Uniform Treatment of Corrosion WG】</b>	
◎Satoshi TAKAYA (Kyoto Univ.)	
All Members	◎WG Chief ○SWG Chief

\*1 PhD (Engineering), Department of Civil and Earth Resources Engineering, Graduate School of Engineering, Kyoto University (Regular Member)

\*2 PhD (Engineering), Metal Surface Treatment Research Department, Osaka Research Institute of Industrial Science and Technology (Regular Member)

\*3 PhD (Engineering), Accounting Department, Railway Technical Research Institute (Regular Member)

Investigation Working Group (WG2) recorded various measurements on full-scale specimens and structures with rebar corrosion to survey the condition of concrete, the degree of corrosion, and water supply routes. Their results confirmed that even in the presence of chloride ions or in environments with reduced pH owing to neutralization, rebar hardly corrodes in the absence of water migration, i.e., when the concrete is kept in a dry or wet environment consistently. Based on the results of the two aforementioned WGs, the Systematization of Corrosion Handling WG (WG3) proposed a scenario for treating corrosion of rebar in a unified manner and developed a flow to assess corrosion risk based on water and oxygen supply conditions.

## **2. Activities of Literature Survey WG (WG1)**

WG1 was divided into three sub-working groups (SWGs), which were integrated to enhance each other's activities. Overviews of the activities of the three SWGs are presented below.

### **2.1 Corrosion Principal Survey SWG (SWG1-1)**

The Corrosion Principal Survey SWG (SWG1-1) conducted a survey and experiments on corrosion principles, with a focus on concrete environments but not limited to them.

#### **(1) Destruction of passive film**

Corrosion of iron in an alkaline environment is believed to require the destruction of the passive film. Several studies have been conducted on this topic from the perspective of salt damage and neutralization. However, rebar embedded in concrete is covered with mill scale from the outset. In this context, this SWG started their survey noting the point with no passive film on the iron base surface. Defects were observed in the mill scale, including some crevices between the mill scale and iron matrix. Passive film was assumed to exist in these crevices, and corrosion was assumed to be initiated when the passive film is destroyed by the action of chloride ions in addition to neutralization. The possibility of crevice corrosion within the crevices was also considered, leading to localized reduction in pH even when the concrete maintained overall alkalinity. This was confirmed by the Structural Survey WG (WG2). This indicated that even in non-neutralized concrete environments, acidic corrosion is possible.

Iron covered by passive film with no mill scale induced by immersion in an aqueous solution with chloride ions in an overall alkaline environment is known to suffer general iron corrosion [2], rather than pitting corrosion. However, anodic polarization by electrochemical measurement

revealed measurable pitting potentials<sup>[3]</sup>. Thus, the characteristics of passive films on iron in alkaline environments were observed to be significantly different from those of passive films on stainless steel, which is often studied in the field of corrosion.

## (2) Corrosion process

Once the destruction of the passive film is completed, two important stages remain in the process of corrosion. First, a cathodic reaction occurs, which is paired with the anodic reaction of iron corrosion. Second, a corrosion cell is formed in which the anodic and cathodic reactions occur in pairs on the iron surface. The presence of liquid water on the iron surface is essential for the formation of this corrosion cell as it helps close the circuit of the corrosion cell, and the ions generated at each reaction site diffuse and migrate to generate current.

After identifying the two subsequent stages of corrosion progress, the WG investigated corrosion progress of iron in concrete. Their results indicated that in the presence of an external supply of water, such as rainwater, the interior of concrete becomes wet. In such a situation, the presence or absence of oxygen is an important factor. On the other hand, when the interior of concrete is dry, which is often the case in the construction field, there is sufficient oxygen inside the concrete; in this case, the presence or absence of liquid water is an important factor. Although the corrosion stresses on concrete depend on the external environment to which it is exposed, corrosion was observed to progress when both of the two aforementioned conditions were satisfied.

## (3) Cathodic reaction in concrete

SWG1-1 surveyed and studied cathodic reaction in wet concrete. They performed experiments on the oxygen reduction reaction and the reduction reaction of ferric ions as cathodic reactions paired with the anodic reaction of iron in an alkaline environment. In the oxygen reduction reaction, concrete was observed to be a major resistance to oxygen diffusion, and diffusion-controlled phenomena in electrochemical measurements, which are often observed in cathodic reactions in aqueous solution, was captured. In the reduction reaction of ferric ions, in contrast to large cathodic current densities reported in surveys in acidic and neutral environments, our experiments revealed small cathodic current density in alkaline environments owing to the low solubility of ferric ions in aqueous solutions. In the case of the oxygen reduction reaction, drying inside concrete was inferred to increase the current density of the cathodic reaction. Thus, the balance between dryness and wetness was indicative of

whether the oxygen reduction reaction or the ferric ion reduction reaction was more likely to occur. Thus, the dry-wet cycle environment, which is important for corrosion progress in concrete, can be categorized in terms of the cathodic reaction.

## **2.2 Application of Corrosion Principles to Concrete SWG (SWG1-2)**

The Application of Corrosion Principles to Concrete SWG (SWG1-2) conducted a survey and experiments on the connection between the external environment of exposure of concrete on the corrosive environment of rebar embedded in concrete.

### **(1) Cycle test**

The results of other SWGs indicated that the drying of wet concrete is difficult. Therefore, once wet, rebar environments are likely to continue to be wet due to the influence of concrete covers, even in the presence of an external dry-wet stress with a cycle of one week (e.g., the conditions in JCI-SC3, “Accelerated Corrosion Test Method for Reinforced Steel Bars in Concrete Containing Salinity-Dry Wet Repeat Method”). SWG1-2 conducted experiments on dry and wet conditions inside concrete when the cover was as thin as 10 mm, confirming that wet conditions are more easily maintained when the cover thickness exceeds 30 mm. In addition, experiments also confirmed that although the presence of intrinsic salt content in concrete inhibits the evaporation of water outside concrete, the rate of water migration inside concrete is faster due to the osmotic pressure of salinity between the dry concrete surface and the interior of the concrete. In addition, when concrete was subjected to cyclic testing with higher intrinsic salt content, the osmotic pressure generated between the dry concrete surface and its interior was not very large. Further, corrosion of rebar was observed to be less likely in wet concrete due to oxygen depletion, even in the presence of intrinsic salt content.

### **(2) External environment and corrosive environment inside concrete**

WG2 members also participated in SWG1-2 and classified the external environment into five categories: constantly dry, relatively dry, dry-wet cyclic, relatively wet, and constantly wet, and classified concrete conditions into three categories: thin cover, cracking, and presence of salt. They analyzed the risk of corrosion progress in rebar with respect to the presence of oxygen.

## **2.3 Water Behavior in Concrete Survey SWG (SWG1-3)**

The Water Behavior in Concrete Survey SWG (SWG1-3) investigated the absorption of water in dry concrete based on theoretical equations (Lucas-Washburn equation assuming liquid water

penetration and Fick's diffusion equation assuming water vapor penetration). Since no theoretical equation is available for the drying of wet concrete, they investigated this case based on existing experimental data. The results demonstrated that concrete dries slowly. In addition, the WG collated previous studies on this topic in cases involving salt content and other tidal salts. Their results confirmed that the relative humidity within concrete increases with temperature, similar to how the increase in humidity within concrete follows the adsorption isotherm, as confirmed in SWG1-2 experiments. Principles and precautions were also formulated for humidity sensors embedded in concrete used in the experiments.

### 3. Activities of Structural Survey WG (WG2)

The Structural Survey WG (WG2) identified various situations of rebar corrosion occurring in the field, and aimed to assist the development of theories on rebar corrosion to benefit future design, construction, and maintenance. The structures surveyed and the results obtained are summarized below.

#### 3.1 Surveyed structures

WG2 conducted surveys of structures at six locations: five actual structures and one full-scale specimen. **Table 2** presents a summary of the structures surveyed and the number of surveys.

**Table 2 List of structures surveyed**

Surveyed structures		Outline of structures	Year of construction	Number of survey
①	Full-scale specimen	Full-scale specimen simulating actual slab partially influenced by chloride ion	2013	3
②	Highway bridge A	Abutment of highway bridge influenced by water flow	1967	2
③	Railway viaduct	Slab of railway bridge under dry environment	1970	2
④	Highway bridge B	Abutment of highway bridge influenced by water flow and deicing salt	1981	1
⑤	Highway bridge C	Slab of highway bridge constructed over sea	1983	1
⑥	Experimental housing complex	Outside of wall and slab of RC housing complex	1974	1

### 3.2 Survey method

WG2 made selections using the survey method described below, taking into account the condition of the structures and restrictions at the time of surveying, in order to examine the effects of water, oxygen, chloride ions, and neutralization on rebar corrosion in concrete structures. Further, since the survey was conducted as a research activity, many methods were used to the extent that they could be implemented by the committee members, even though some did not directly contribute to elucidating the subject of investigation.

The main survey methods applied were as follows.

- Overall condition: Visual observation
- Environmental action: Temperature and humidity in air and on concrete surfaces
- Cover: Electromagnetic wave radar method, visual observation after chipping
- Moisture conditions: Surface moisture content, electrical resistivity, internal moisture content
- Internal environment of concrete: Temperature and humidity inside concrete
- Concrete quality: Simple permeability test, moisture penetration rate coefficient test
- Neutralization depth: Phenolphthalein solution sprayed on sampled core and drilling powder
- Chloride ion content: Potentiometric titration using sampled core and drilling powder
- Concrete strength: Mechanical impedance method, compressive strength test
- Corrosion status of rebar: Natural potential method, polarization resistance method (3-pole, 4-pole), visual observation after chipping, analysis of corrosion products, measurement of reduction in rebar area, measurement of pH on rebar surface

### 3.3 Summary of results obtained

#### (1) Full-scale test body

The test specimen simulated a full-scale slab. To simulate localized salt damage induced by the application of anti-freeze, a calcium chloride solution was periodically applied to a limited area of the upper surface of the test specimen. In addition, the floor slab was exposed to the

outdoor environment. Neutralization depth was observed to be lesser than the cover width.

The survey was conducted in three parts. First, concrete properties and rebar corrosion on a portion of the upper surface of the slab were measured. In addition, one rebar was extracted and observed for corrosion, and a new rebar was embedded in the same location after creating a simulated crack. In the second survey, similar measurements were recorded at a different location and the corrosion state was observed by extracting rebars in an area of approximately 1 m x 2.7 m. We intend to survey the rebar embedded at the time of the first survey in a third survey.

The main results obtained from the first survey are summarized below.

- Corrosion was observed around the entire circumference of the extracted rebar in regions where salt water was sprayed. Corrosion was also observed on the sides and underside of the rebar near the sprayed area, with corrosion on the sides extending to a distance of 500 mm from the rebar.
- The corrosion status of rebar suggested that water penetration had occurred along the rebar. A cylindrical specimen with embedded rebar was prepared and a water flow test was conducted by focusing on the interface with the rebar. The results indicated that water flow was generated along rebar with both a round steel bar and deformed steel bar, with the flow being more discernible for the round steel bar.
- These results suggest that water penetration through cracks can affect a wider area, e.g., the sides and underside of rebar, causing more extensive corrosion of steel. In addition, extensive corrosion was observed not only on the top surface of steel, but the sides and underside as well, rendering top side surveys of concrete ineffectual. Additionally, our results indicated the possibility of rebar corrosion being missed via visual inspection performed during a chipping survey.
- In some cases, e.g., if the area to be repaired by patching was narrowed, re-deterioration was observed outside the repaired area. Macro-cell corrosion, which occurs between patching materials and existing concrete, was actually believed to have occurred in a small number of cases because the corrosion factor could not be removed completely.

The main results of the second survey conducted on the basis of the first survey are listed



below.

- Electrochemical measurements revealed variations in natural potential and concrete resistance even within the range of salt water application. In addition, a range of low natural potentials outside the spreading range, -300 to -400 mV vs. SSE, was observed.
- Visual inspection of the corrosion status of steel revealed that corrosion was more pronounced on the bottom side of the steel compared to its top surface. In addition, since chloride was present in the corroded areas and the surface of the rebar was acidic with a pH of 2–3, crevice corrosion occurred, as predicted in 2.1(1).
- Chloride ions on the concrete surface in contact with the bottom side of the steel were observed not only in the regions where salt water was sprayed, but also at other locations with reduced natural potential. This was attributed to the penetration of salt water into the bottom surface of steel through the crevices induced by bleeding and other factors.
- The maximum extent of water penetration through the crevice on the bottom surface of steel was approximately 1200 mm within the scope of this test, and a penetration exceeding 1 m was estimated.
- Green rust, which is considered to be a preliminary corrosion product, was observed in concrete in contact with steel. This suggests that steel in concrete, which has a secure cover and is subject to rain exposure, experiences a limited supply of oxygen from the external environment.

## (2) Highway bridges A and B

Highway bridge A is located in an urban area, which is not affected by airborne salts and features reduced application of anti-freeze. On the other hand, highway bridge B is located in a mountainous area, and although it is not affected by airborne salt, its environment includes salt damage owing to the application of a large amount of anti-freeze in winters.

A survey was conducted on abutments of both bridges, on the parapet and wall of highway bridge A and on the parapet of highway bridge B. Each surveyed area included regions with high and low water exposure of the superstructure, and the effects of these differences on rebar corrosion were investigated.

The main results are presented below.

- The rate of rebar corrosion was observed to be affected by differences in the process and frequency of dry-set cycles occurring near the location of rebar in concrete, depending on environmental conditions and cover.
- The effect of cover on corrosion of rebar in concrete was observed to be more significant than environmental conditions. Even when the cover was large, cracks and the condition of scaling in the concrete surface layer reduce the actual cover, potentially increasing the corrosion rate of rebar in concrete.
- Even in environments with water exposure, the frequency of dry-wet cycles near rebar locations depend on cover and chloride ion content, the aforementioned factors should be considered, besides environmental conditions, while assessing the corrosion risk of rebar in concrete.

### (3) Railway viaducts

A survey was conducted on a standard 3-span railway rigid-frame viaduct, located in an area surrounded by fields and private houses. The survey was conducted in two parts, one on the bottom surface of the slab and another on the side of the transverse beam with no water exposure. In the first survey, micro-destructive measurements were recorded mainly using nondestructive methods or small-hole drilling.

Since concrete was subsequently removed from a portion of the bottom surface of the slab for repair by patching, a second survey was conducted as well. The amount of chloride ions in the surface layer of concrete was approximately  $0.3\text{--}1.6 \text{ kgm}^3$  owing to the effects of enrichment by neutralization.

The main results obtained from the survey are summarized below.

- In rebars at different locations with 15-mm and 27-mm cover, corrosion progressed below horizontally installed joints in both cases, but not above, despite a difference of 12 mm between the cover widths. In addition, even though the entirety of the rebar with a 15-mm cover was present in the neutralized zone, only its lower surface was corroded.
- In the raised rebar adjacent to the aforementioned one, corrosion progressed below the joints regardless of the cover width, even in the raised sections with variable cover.
- These phenomena cannot be explained based solely on the depth of cover or the progress of

neutralization. Although neutralization is a factor in corrosion, it does not explain rebar corrosion by itself. Additionally, corrosion progress below the rebar joints was attributed to the supply of water (vapor) from underneath the concrete structure in relatively dry environments with no water exposure, which created a corrosive environment, resulting in the formation of red rust with  $\gamma$ -FeOOH and  $\beta$ -FeOOH as the main components.

- Corrosion occurred not only on the lower surface, but also on the upper surface of rebar in the vicinity of the aforementioned rebars with joints installed at an angle. This suggests that the corrosion status of rebar depends on the location of the rebar joints.
- The pH of the rebar surface was measured at rebar corrosion sites, with some exhibiting pH3-level acidity.

#### (4) Highway bridge C

Highway bridge C is an elevated sheet-girder highway bridge at sea with reinforced concrete slabs. Due to the corrosion of steel members in the plate girders and deterioration of the floor slabs induced by the severe environmental salt damage, titanium protection panels were installed in 2018 to cover the steel members and the bottom surface of the floor slabs entirely. The survey was conducted on the bottom surface of the slab.

The main results of the survey are summarized below.

- The visual survey and corrosion environment survey indicated that the environments both inside and outside the concrete structure were dry, with moisture penetration through cracks running from the top to the bottom surface of the slab. Corrosion induced by dry-wet cycles was inferred based on rust observation.
- At a distance of approximately 120 mm from the cover surface, the chloride ion content tended to be larger in deteriorated areas than in healthy areas, and it exceeded the limit concentration for corrosion occurrence. In addition, its presence extended from both the bottom and top surfaces of the slab, implicating cracks as a likely supply route.
- When the external environment was considered to be a severe salt-damage environment, the chloride ion concentration was not very high, despite the supply of chloride ions through cracks.
- The threshold for corrosion determination measured without water spraying in a dry

environment. It shifted by about 200 mV to the noble side, but it should be assessed in detail to serve as a relative comparison.

- Careful examination of the area to be measured was considered to be essential while measuring the polarization resistance of rebar in concrete that is dry or exhibits high electrical resistance. It also influences the corrosion rate.
- Although the structures surveyed in this study were placed in a salt-damage environment, neutralization was assumed to only initiate corrosion, and subsequent corrosion was considered to have progressed via dry-wet cycles. However, the presence of chloride ions may also have been a factor in the increased corrosion rate.

#### (5) Experimental housing complex

The experimental housing complex was a reinforced concrete housing complex constructed to perform experiments on sound insulation and heat insulation of floors. The subjects of the survey comprised the outside surface of the exterior wall exposed to rain, the inside surface of the exterior wall not exposed to rain, and the floor slab between the second and third floors. Notably, the building was not affected by salt damage.

The survey yielded interesting results regarding water penetration through cracks in the exterior wall and its effect on rebar corrosion. In addition, neutralization was observed to have progressed only in the vicinity of the cracks. Neutralization and water penetration at the cracks were considered to be the cause of rebar corrosion, but the results are currently being collated.

### 3.4 Investigation of survey location selection and survey method

#### (1) Investigation of survey location selection

While surveying the structures, the survey locations were selected judiciously. Measurement results are known to vary significantly due to differences in water exposure, sunlight, and chloride ion supply. In the present survey as well, measurement results are observed to depend on the survey location significantly.

Since the same principle applies to practical surveys, we advocated for survey locations to be selected judiciously, e.g., by presenting and examining examples of common mistakes in the selection of survey locations.

#### (2) Investigation of survey method

Based on the results of the survey of each structure, we are in the process of compiling a

summary of the main survey methods used, their features, and comments regarding their application.

For example, while recording measurements using the nondestructive polarization resistance method, a frequency range was observed where higher noise was generated when a generator or commercial power source was used. This noise can be reduced by using a lithium-ion battery. Another point to note is that corrosion of rebar only on the surface opposite to the measurement surface cannot be detected; and it is sometimes difficult to calculate polarization resistance in dry concrete.

In the survey of structures reported here, nondestructive measurement, micro-destructive measurement with small hole drilling, and destructive measurement with excavation and core sampling were used based on site conditions and restrictions.

#### **4. Activities of Systematization of Corrosion Handling WG (WG3)**

As described above, pH reduction due to chloride ion penetration and neutralization may be considered to initiate corrosion, but the subsequent corrosion rate is determined by the interaction between water and oxygen. Even in the presence of chloride ions, the corrosion rate remains slow if the concrete interior is kept wet or dry consistently. However, the corrosion rate is believed to increase when ferric ions are reduced in a cathodic reaction during transition periods of dry-wet cycles. On the other hand, once the interior of concrete becomes wet, it is difficult to dry, and dry-wet cycles are unlikely to occur in the presence of a secure cover. However, a gradient in chloride ion concentration extending from the surface to the interior of concrete was confirmed (with the surface corresponding to higher concentration), with water migration to the surface due to osmotic pressure, resulting in faster drying of the concrete interior. In addition, the possibility of cracking precursor dry-wet cycles was recognized because cracking facilitates the migration of water and oxygen. Therefore, in addition to the external corrosion environment, the corrosion risk of the rebar was assessed based on parameters such as cover, presence of cracks, and presence of chloride ions.

Our results demonstrated that the corrosion rate is determined by the interaction between water and oxygen, irrespective of the presence of chloride ions or pH reduction due to neutralization. We also presented a scenario for uniform treatment of rebar corrosion in future works, instead of remaining constrained within the framework of salt damage or neutralization.

## 5. Conclusions

The WG1 of this research committee identified the corrosion mechanism of rebar in concrete based on theoretical principles of corrosion and the results of basic experiments, and conducted a literature survey and experiments to collate data on the migration of water in concrete. The results revealed that cathodic reaction is insignificant in concrete, that water migration is unlikely to occur if the cover is sufficiently secured, and that osmotic pressure-induced water migration occurs in the presence of chloride ions. WG2 conducted a survey of full-scale specimens and actual structures, and investigated the causes of corrosion progress, including environmental conditions. The results revealed that the process and frequency of dry-wet cycles significantly affect the progress of corrosion, that water migration occurs through crevices due to bleeding, and that the pH of rebar surfaces may become acidic due to crevice corrosion even if they are not neutralized. Based on the results of WG1 and WG2, WG3 presented a scenario to treat rebar corrosion in a unified manner, transcending the framework of salt damage or neutralization.

Some of the results of this research committee have been published in the 2024 Proceedings of the Japan Concrete Institute.

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