

Committee Report : JCI- TC162A

Technical Committee on establishing effective operation and management techniques using electrochemical techniques

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Abstract

The purpose of this technical committee is to organize the technical information required to use various electrochemical techniques for effective and sustainable operation and management. In this report, the committee has conducted round-robin tests of methods to evaluate chloride penetration resistance of concrete, specifically nonsteady-state electrophoresis tests, and has summarized future outlooks based on the results. Key points and expert know-how on measuring rebar corrosion have been gathered, utilizing examples of real structures. Furthermore, the committee has proposed a performance verification-based design method that may serve as a form of cathodic protection in the future, and has compiled the techniques required for inspection, construction, operation and maintenance, as well as the issues thereof.

Keywords: Electrochemical measurement, chloride penetration resistance, nonsteady-state electrophoresis, electrical resistivity, performance specifications, cathodic protection method

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1. Introduction

In the operation and maintenance of existing concrete structures, there has been an increase in adopting settings and using techniques developed in other fields. Electrochemical techniques are among those that have been used for a relatively long time. The “Technical committee on the systematization of electrochemical measurement techniques based on physicochemical interpretation,” which is an antecedent to this technical committee, systematically organized the physicochemical theories that ought to be considered when applying various electrochemical techniques to concrete structures, and compiled know-how and other information on implementing highly reliable measurements and their interpretation¹⁾. Through this lecture series, the committee recognized the high need for electrochemical techniques in the concrete engineering field, but also simultaneously ascertained the high need for organizing technical issues and compiling measures to more practically and effectively utilize electrochemical techniques in operation and maintenance settings involving real structures.

Considering these needs, the technical committee engaged in activities for two years starting in 2016, for the purpose of organizing the technical information required to use new electrochemical techniques as effective and sustainable operation and management techniques. Specifically, the committee set up a performance diagnosis working group and deterioration measures working group, and mainly studied the design of evaluation techniques for chloride penetration resistance of concrete, key points of electrochemical techniques, and performance specification-type cathodic protection methods. This report presents a summary of a larger report compiling the activity results, which should be referred to for the details.

2. Techniques for evaluating chloride penetration resistance of concrete

2.1 Introduction

There is already a technique available for evaluating chloride penetration resistance of concrete using electrochemical techniques standardized by the Japan Society of Civil Engineers (JSCE) in JSCE-G 571: Electrophoresis-based test method for effective diffusion of chloride ions in concrete. JSCE-G 571 is a test method classified as a steady-state electrophoresis test. Looking overseas, there are methods for simply evaluating chloride penetration resistance using the amount of charge passing through a cross-section of concrete, such as the nonsteady-state electrophoresis test in NT BUILD 492: Concrete, Mortar and Cement-based Repair Materials:

Table 1: Examples of test methods to evaluate chloride penetration resistance of concrete

Test method	Description	Standard test period*
Immersion-based test method for apparent diffusion of chloride ions in concrete (draft) (JSCE-G 572)	Immerse test pieces in sodium chloride solution for a fixed period, measure chloride ion concentration distribution within test pieces after immersion, and then use this concentration distribution to determine the apparent diffusion coefficient of chloride ions and evaluate chloride penetration resistance of concrete.	Approximately 3 months or longer
Electrophoresis-based test method for effective diffusion of chloride ions in concrete (draft) (JSCE-G 571)	While regarding the point at which chloride ion transfer flux is constant as a steady state, charge saturated test pieces, determine the effective diffusion coefficient of chloride ions at steady state, and evaluate chloride penetration resistance of concrete.	Approximately 1 to 3 months
Nonsteady-state electrophoresis test	Charge saturated test pieces for a fixed period, spray aqueous silver nitrate on cleaved test piece surfaces after charging, and measure chloride ion penetration depth. Then use the measurement values to determine the chloride ion diffusion coefficient, and evaluate chloride penetration resistance of concrete.	Several days
Electrical resistivity test (JSCE-G 581)	Measure the electrical resistivity of concrete prepared such that the water-containing state is saturated or uniform, and then use measurement values to indirectly evaluate chloride penetration resistance of concrete.	Several minutes

*This time period assumes concrete superior in salt blocking

Chloride Migration Coefficient from Non-steady-state Migration Experiments, Nordtest, 1999R, and the AASHTO T 277-89 and ASTM C 1202-91: Rapid Chloride Permeability Test (RCPT). Furthermore, there are also methods of evaluating chloride penetration resistance of concrete based on its electrical resistivity, such as AASHTO T358: Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration. Here, the committee has collected examples of using the above methods, reviewed up to the decision-making process for grading blocking set forth in AASHTO T358, for example, and systematically compiled the relevant information.

In addition, the committee conducted round-robin tests of nonsteady-state electrophoresis tests that have long been studied in Japan, and enumerated the issues facing the reliability and standardization of those tests. Moreover, the committee also verified the validity of the newly enacted JSCE standard JSCE-G 581: Four-electrode method-based test method for electrical

resistivity of concrete (draft).

Finally, the committee showed the outlook for methods of using evaluation tests for chloride penetration resistance of concrete using electrochemical techniques.

2.2 Example of quality verification using electrochemical techniques

(1) Types of test methods and applicable overseas examples

Here, the committee summarizes indoor experiments for chloride penetration resistance of concrete, and introduces examples of using nonsteady-state electrophoresis tests and electrical resistivity tests as examples of quality verification using electrochemical techniques.

Table 1 shows examples of test methods for evaluating chloride penetration resistance of concrete. This report organizes the features of these test methods, the key points of applying them to concrete superior in chloride penetration resistance, and their relationship to test methods that have already been standardized overseas. Electrophoresis tests and electrical resistivity tests are used overseas with concrete structures deployed in salt damage environments in cases of rapidly evaluating the chloride penetration resistance of concrete when selecting concrete mixtures, and simply confirming the chloride penetration resistance of concrete after placement. The report also introduces examples of use in North America, Northern Europe, Singapore, and China.

(2) U.S. examples (AASHTO T358)

In the U.S., the Rapid Chloride Permeability Test (RCPT) in AASHTO T 277-89 and ASTM C 1202-91 has been enacted as a method of estimating the resistance to chloride penetration in concrete. The report introduces the concept, development background, and applicability of the above methods of using the electrophoresis of ions in pore water to rapidly measure the chloride ion penetration of concrete. These methods evaluate chloride penetration resistance of concrete from the amount of charge passing through concrete during electrophoresis testing (electric charge) on a five-point scale corresponding to the amount of charge.

On the contrary, in AASHTO T358, chloride penetration resistance of concrete is evaluated in terms of five levels according to the electrical resistivity of concrete specimens. The report explains the background behind the setting of threshold values and the problems involved. In simple terms, the threshold values for AASHTO T358 are essentially set to meet the standard values used in AASHTO T 277-89 in an attempt to achieve consistency between the two methods.

However, it is difficult to say whether the AASHTO T277-89 grading itself has been sufficiently verified. Reasons for this include the fact that it is based on cut-off coulomb quantities, there are some 10 types of core material for specimen types (one test body per mixture) used for grading chloride penetration resistance picked from flat slabs provided by the U.S. Federal Highway Administration (FHWA), mixture types consist only of three water-to-cement ratios (0.4, 0.5, 0.6), the concrete graded consists of latex and polymers, and each grade of chloride penetration resistance of concrete is verified only with data from one to four cases. Consequently, the committee indicates in the report that it is essential to establish a connection between electrical resistivity and indexes indicating chloride penetration resistance of concrete in order to correctly use these standard values.

(3) Trends in Japan

As described above, although there are problems with the grading for chloride penetration resistance of concrete in AASHTO T358, evaluating it according to electrical resistivity is still useful in and of itself. This is because electrical resistivity is overwhelmingly simple and immediate in the evaluation results it provides compared to other evaluation tests. However, when measuring the electrical resistivity of specimens, evaluation results differ depending upon the way the electrodes are installed. This may be resolved by properly applying a cell constant k defined by the following formula.

$$k = R/\rho \quad (1)$$

Here, k : cell constant (m^{-1}), R : measured electrical resistance (Ω), and ρ : electrical resistivity (Ωm).

With such a viewpoint in mind, JSCE combined the previously standardized four-electrode method (JSCE-K 562) and the widespread nondestructive Wenner's method (four-probe method) into a single test standard, and standardized the test methods providing stipulations such as proper individual cell constants for each as JSCE-G 581: Four-electrode method-based test method for electrical resistivity of concrete (draft). The committee verified the validity of this test method through round-robin tests, and furthermore converted the standard values for chloride penetration resistance of concrete in AASHTO T358 into the electrical resistivity obtained by this test method.

2.3 Round-robin tests of techniques for evaluating the diffusion coefficient of chloride ions using nonsteady-state electrophoresis tests

(1) Nonsteady-state electrophoresis test characteristics and test methods in round-robin tests

Electrophoresis tests standardized by JSCE-G571 are classified as steady-state methods, which calculate the chloride ion diffusion coefficient based upon the flow rate of Cl^- when the time change of Cl^- penetrating concrete is constant. On the contrary, nonsteady-state methods stop charging prior to Cl^- penetrating concrete, and calculate the chloride ion diffusion coefficient from the Cl^- penetration depth at that time. Consequently, nonsteady-state methods tend to achieve test results within a short time. A typical nonsteady-state electrophoresis test method is that in NT BUILD 492. However, NT BUILD 492 needs to confer a chloride ion concentration that serves as a boundary condition when calculating the diffusion coefficient, which has proven to be a major problem. A method has been studied²⁾ in Japan to resolve this issue. Aqueous silver nitrate is sprayed on specimens subjected to tests (**Fig. 1**) at multiple charging times to measure the chloride ion penetration depth within the specimens after charging (**Fig. 2**). Assuming the measurement values for chloride ion penetration depth and charging depth are linearly related, K is determined by regression analysis (**Fig. 3**) and then used in Formula (2) to calculate the chloride ion diffusion coefficient D_{nssm} .

$$D_{\text{nssm}} = \frac{RT}{zFE} K \quad (2)$$

With this method, the boundary problem in NT BUILD 492 is avoided, and the generality is enhanced.

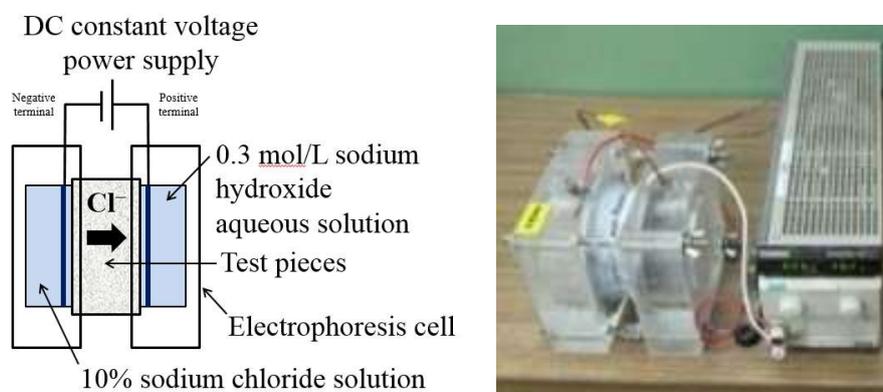


Fig. 1: Example of electrophoresis cell and charging conditions

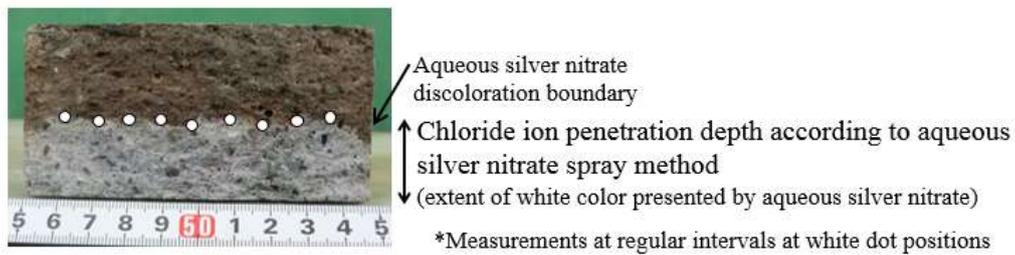


Fig. 2: Example of chloride ion penetration depth measurement

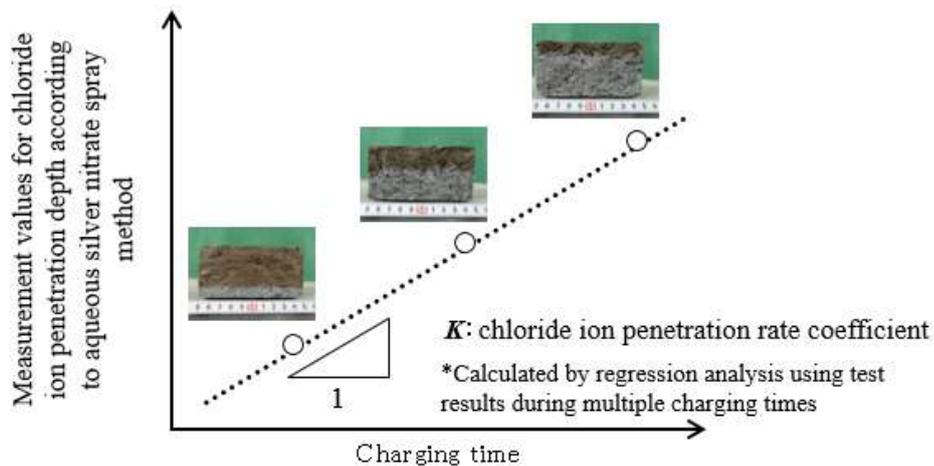


Fig. 3: Determination of chloride ion penetration rate coefficient

(2) Round-robin test results

In order to verify the reliability of nonsteady-state electrophoresis cell tests, the committee allotted multiple specimens prepared on the same day in the same batch at one to six facilities, and conducted round-robin tests. Furthermore, the committee analyzed the test results submitted by the participating facilities, extracted key points when evaluating the chloride ion diffusion coefficients according to these tests, and organized the information that had to be defined for standardization.

Table 2: Summary of round-robin test specimens

Binder	Fine aggregate	Coarse aggregate	W/B (%)
OPC	Crushed sand	Macadam	35
OPC	BFS	Macadam	35
OPC+GGBS	BFS	Macadam	35
OPC	Mountain sand	Macadam	40
OPC	Mountain sand	Macadam	50
OPC	Mountain sand	Macadam	60

OPC: ordinary Portland cement, GGBS: ground granulated blast slag, BFS: blast furnace slag fine aggregate

The six concrete mixtures shown in **Table 2** were supplied for the round-robin tests. When the committee determined the coefficient of variation from the round-robin test results excluding data with definite errors in the test procedures, the smallest coefficient of variation with these mixtures was 4% and the largest was 27%, with a mean of 14%. According to past studies³⁾⁴⁾, the errors resulting from individual differences in the slump are 3 to 16% when evaluated by the coefficient of variation, and similarly, the coefficient of variation for air volume is approximately 7 to 22% (mean value of air volume). In addition, the committee sampled ready-mix concrete with the same mixture (preparation) 15 times by a proportion of once every 15 to 20 m³ per day, and performed accelerated carbonation tests on these samples. The samples for evaluating the coefficient of variation of the mean value of each test⁵⁾ indicate that the coefficient of variation of the test results is 4.1 to 7.7%. As a result, it is possible to verify that the reliability of the nonsteady-state electrophoresis cell tests evaluated from the viewpoint of the coefficient of variation is the same as in these tests. Furthermore, cases have been found in which the coefficient of variation for the chloride ion diffusion coefficient in the present round-robin tests is larger than the coefficient of variation for the carbonation depth (mean value 11 to 29 mm) obtained from a previous study⁵⁾, particularly in mixtures with high chloride penetration resistance. The higher the chloride penetration resistance, the smaller the chloride penetration depth (several millimeters to approximately 10 mm), and the more irregularities appear in

chloride penetration depth measurement results. Hence, it is felt that coefficient of variation is larger with mixtures that are high in chloride penetration resistance. Consequently, it was recognized that it is important to ensure test method reliability by setting charging conditions capable of ensuring a chloride penetration depth of approximately 10 mm or more when standardizing the same test methods.

2.4 Connection between nonsteady-state electrophoresis tests and evaluation tests for chloride penetration resistance

The nonsteady-state electrophoresis tests evaluated here are capable of shortening test periods and quantitatively calculating the chloride ion diffusion coefficient, and furthermore verifying consistent reliability. Thus, it would be desirable for future steps to be taken toward standardization. However, conformity with other test methods must be verified for standardization. Although there are few records for nonsteady-state electrophoresis tests and very little compiled data, the committee collected and organized as much existing data as possible, and included it in this report. A general tendency that was found is that the diffusion coefficients obtained from nonsteady-state electrophoresis tests tend to be larger than the diffusion coefficients obtained from salt water immersion tests such as in JSCE standard JSCE-G 572.

2.5 Outlook for methods of using evaluation tests for chloride penetration resistance using electrochemical techniques

The nonsteady-state electrophoresis tests whose reliability was evaluated in the present round-robin tests are capable of significantly shortening the test periods for obtaining the diffusion coefficient. The test period shortening effects when evaluating highly chloride penetration resistance concrete are particularly high, shortening the test period from several years in the case of immersion tests, and several weeks to several months in the case of steady-state electrophoresis tests, to several days. More durable concrete is certainly desirable when upgrading existing structures, in which case it would be desirable for them to acquire certain physical properties for efficient design. It is believed that nonsteady-state electrophoresis tests are test methods that meet such needs.

The operating costs of using nonsteady-state electrophoresis tests for daily quality control of chloride penetration resistance are undeniably high. However, in such cases, methods that use

electrical resistivity, which are capable of immediate and very simple measurements, are believed to be useful. Such methods are considered using evaluation results for operation and maintenance. These make careful use of measurement results for electrical resistivity: screening and continuously monitoring concrete that may deteriorate in quality, or increasing the inspection frequency for structures. In addition, because they can quickly detect the possibility of quality deterioration, they make it possible to quickly review the material, manufacturing, and construction used, thus making them a highly reliable tool for construction.

3. Organization of key points when applying electrochemical techniques to concrete structures

3.1 General points when performing electrochemical measurements

Electrochemical indexes such as self-potential, polarization resistance, and concrete resistance are widely used for concrete structures, but expert know-how in measurement and data interpretation is often left undocumented. In addition, with electrochemical measurement, data are still obtained when tentative measurements are made with improper application, and thus there is a risk of incorrect diagnosis during use without an understanding of the principles. The report takes such contemporary issues into account to explain the key points of measurement and diagnosing the soundness of structures from practical and academic viewpoints, including the scatter of actual measurement results.

The committee introduced considerations when selecting measurement positions and preliminary preparations for instruments and other factors, dividing work procedures for real structures into stages: 1) preliminary preparations, 2) measurements, and 3) data sorting. It is believed that the calibration of measurement instruments, the composition and length adjustment of cables, terminal selection criteria, and other information unfamiliar to persons working in the concrete engineering field may be of particular benefit to persons working with concrete. In addition, it is believed that explaining the setup of reference electrodes and electrode reactions, and pointing out the importance, methods, and principles of constituent part maintenance will improve the data reliability.

As for data fluctuation factors during measurements, major effects, such as from watering or applying voltage to concrete, are considered, while environmental conditions (temperature, humidity, solar radiation, etc.) fluctuate during measurements. Techniques are available in which

the presence of fluctuation is checked by measuring self-potential at the start and end of the measurement. This involves applying extreme voltage to measurement subjects, which also verifies whether there are any major changes in the state of the rebar.

The effects of seasonal changes and temperature need to be considered during the data sorting, and because cell constants are also determined by the geometry of probes and rebar (diameter of cover and rebar), it is necessary to keep in mind that they cannot be uniform.

3.2 Key points when using electrochemical techniques on ordinary concrete structures

The “ordinary concrete structures” referred to here point to “unrepaired structures (uniformly made of concrete),” and the electrochemical indexes are self-potential, rebar polarization resistance, and concrete electrical resistance. The report broadly divided concrete structures by constituent material into “concrete” and ‘rebar,” considered the effects of changes in chemical composition due to water content, cement type, and deterioration, and the effects of cracks and other geometric changes, and thereby explained key points for persons working with concrete.

In addition, the committee dealt with special rebar in the form of epoxy resin-coated rebar, stainless-steel rebar, and hot dip galvanized rebar, collected and organized examples of measuring their self-potential and polarization resistance, and presented opinions on the applicability of electrochemical measurement from a theoretical viewpoint.

3.3 Examples of electrochemical measurement of ordinary concrete structures

Based upon previously organized points, the report used RC slabs cut from pier superstructures, and then explained methods of selecting positions for performing electrochemical measurement, and the effects of concrete watering times on measurement results for self-potential and polarization resistance. Furthermore, regarding the handling of very high concrete resistance and measurement data thought to be low in reliability, the report additionally explained methods of data sorting according to threshold values provided by considering the presence of measurement errors and conduction.

In addition, the report also indicated key points for organizing self-potential measurement results, based upon examples of applying the self-potential method to pre-stressed concrete bridges. Examples of self-potential measurements made with concrete directly above shear reinforcements at two temperatures—summer (approximately 30 °C) and winter (approximately

6 °C)—suggest that it is important to ascertain the form of self-potential distribution when organizing self-potential measurement results.

3.4 Key points when applying electrochemical techniques to repaired concrete structures

Repaired concrete structures often have original and repair materials differing in electrochemical properties, and thus may be considered to be made of multi-layered or composite material. The report first introduced examples in the electrochemical field of electrochemical measurements of multi-layered/complex materials, followed by an explanation of key points for per each type of repair material (per differences in charge migration pathway).

First, the report dealt with binary alloy composite materials, introducing quantitative analysis techniques for dissolved metal ions using inductively coupled plasma mass spectrometry (ICP-MS). In addition, it focused upon depth direction profile analysis of semiconductor material using glow discharge optical emission spectrometry (GD-OES) to evaluate multi-layer material. Furthermore, the report presented examples of analyzing the dissolution and repair rate of high-resistance chromate film formed on the surface of iron and steel material using a 3D impedance method (regular alternating current impedance method with time axis information added) as examples of measuring high-resistance materials.

The main cause of difficulties in electrochemical measurement of repair material in concrete structures is the fact that nonconductive materials such as resin, and admixtures such as lithium nitrite, which reduce the electrical resistivity of hardened concrete bodies, are used as repair materials. The report classified repair materials into two types: composite materials (surface impregnation materials, fibers, rust inhibitors, etc.) and multi-layer/multi-phase materials (cross-section repair materials, crack grouting materials, etc.). While offering practical examples, it presented key points when taking measurements, while broadly explaining the effects of these repair materials on the charge behavior during measurements.

4. Electrochemical repair methods

4.1 Introduction

It is believed that there will be increased application of electrochemical repair methods in the future, resulting from concerns over the increasing number of deteriorating concrete structures. Presently, design and construction guidelines⁶⁾ for electrochemical repair methods have been established to some degree, but because they are specification-type guidelines, proper

management may not be possible depending on the facilities or environment involved. Furthermore, there are still many civil engineers who do not fully understand electrochemical repair methods, and there is concern over improper construction, operation, and maintenance as these methods are increasingly used. Therefore, the technical committee focused upon cathodic protection methods, which have the most cases of actual application of all the electrochemical repair methods, and are highly likely to increase in future cases of construction. It organized the characteristics of structures in different fields (roads, railways, ports, overseas plants) and key points when applying cathodic protection methods, and then highlighted prominent issues. This paper includes a summary of the general and port-related results. Furthermore, based on these issues, the committee has proposed a performance verification-based design technique that may serve as a form of cathodic protection in the future, and has compiled the techniques required for inspection, construction, operation, and maintenance, as well as the issues thereof.

4.2 Differences in thinking about cathodic protection methods in each field and examples to consider

(1) General

Cathodic protection methods essentially involve continuously supplying protection current during corrosion protection periods. Furthermore, the assessment of corrosion protection effects basically involves “changing rebar by potential 100 mV or more in the negative direction (100 mV shift standard)” as the standard for corrosion prevention⁶⁾. This was determined out of consideration of overseas standards and past results, as well as safety. However, in past study reports^{7),8)}, the opinion was that structures in severely corrosive environments require a change in potential of 150 to 200 mV or more.

The protection current density required to satisfy a 100 mV shift standard has often been approximately 10 to 20 mA/m² per concrete surface area in past results, but proper protection current density essentially needs to be determined according to the rebar corrosion status and the amount of rebar. Specifically, a method is considered involving a charging test (cathodic polarization test) prior to the start of corrosion, and then setting a current density satisfying the 100-mV shift standard. However, the obtained values can only be verified at the positions of reference electrodes embedded in the vicinity of rebar, such that the method does not really verify the corrosion state of an entire structure. Thus, the results need to be generalized in order



Fig. 4: Anode product generated on line

to verify the corrosion state by accounting for irregularities in the current distribution due to differences in member shape and environmental conditions, and, for example, installing reference electrodes at multiple positions. In addition, it is important to properly design the cathodic protection circuits, such as the arrangement of anodes and distributors, the circuit area, and the arrangement of charging points and distribution points, in order to uniformly supply protection current to rebar within the target range. Furthermore, adding protection current density requires proper current management owing to concerns of significant performance loss in anode systems, such as loads upon direct current power supply or anodes, and the generation of anode product, as shown in **Fig. 4**.

(2) Ports

Port structures are placed in extremely severe salt damage environments, and thus it is extremely important to prevent corrosion of rebar in order to ensure long-term safety. In general, if a cathodic protection method is applied to offshore concrete structures, the standard is to apply an impressed current system to structures that are always in the open air, and apply a galvanic anode system to structures that are always in seawater⁹⁾. Actual applications of cathodic protection methods to port structures mostly involve bridges and piers; because these are structures built at sea, their operation and maintenance usually has little effect upon third parties, and the methods are used as measures to prevent loss of structural performance due to rebar corrosion. Consequently, there are often cases in which cathodic protection methods are applied as final measures against salt damage for structures with deterioration that has advanced to a certain degree.

Here, regarding the peculiar problems facing port structures, the technical committee has organized matters when applying cathodic protection methods, and key points and issues concerning design, operation, and maintenance. The peculiar conditions are direct effects from

seawater (including waves), as well as cases when concrete structures are placed in tidal zones affected by sea level variation.

a) Selection of anode systems with high durability

Because these structures are affected by seawater, charging occurs under highly corrosive environments, and thus measures are required for pipes or wiring dropping off due to wave impacts and flotsam collisions; therefore, high-durability durable anode systems accounting for these factors must be selected and constructed.

b) Circuit dividing of cathodic protection systems according to environmental differences

When the applicable scope of cathodic protection straddles the splash zone to the tidal zone, and protection current is supplied with the same circuit, the protection current is concentrated in a range with high concrete water content (low resistance range) and corrosion effects decrease in a range with low concrete water content (high resistance range). Hence, methods are adopted to divide circuits by splash zones and tidal zones, and supply protection current with respective independent direct current power supply devices.

c) Effects of lower steel structures

Because galvanic anode system cathodic protection using an aluminum alloy anode is applied to substructures (steel pipe pile, sheet piling, etc.), protection current flows into rebar in concrete within tidal zones from a sacrificial anode during immersion. Although it has been experimentally verified that corrosion protection effects are improved by this inflowing current¹⁰⁾, caution is required because there are cases in which the amount of depolarization cannot be accurately measured by current flowing in from the aluminum alloy anode in inspections of concrete structures with applied cathodic protection methods.

d) Corrosion protection standards in wet environments (including tidal zone)

Because the supply of oxygen required for depolarization when concrete is in a wet state is slow, a long time is required for depolarization. Hence, depolarization often does not reach self-potential with 24-hour potential after stopping the charging ordinarily performed during inspection, in which case the corrosion protection effects cannot be properly evaluated with 24-hour measurement results. Methods are thus considered to ensure complete depolarization, though the necessary charging interruption time sometimes reaches several months, which is quite difficult in reality. Consequently, in such cases, several indexes other than the degree of depolarization must be used to evaluate the corrosion protection effects. Reports on indexes other

than the degree of depolarization include the following. Yamamoto et al.¹¹⁾ report verifying that corrosion protection effects may be achieved with “rebar potential lower than -850 mV vs CSE,” and that corrosion protection effects were achieved with real structures by combining this standard with “depolarization of -100 mV or more.” In addition, Kobayashi et al.¹²⁾ indicate that the evaluation standard of “instant-off potential is -650 mV vs SSE (approximately -770 mV vs CSE) or less” is effective. Furthermore, in the ISO standards¹³⁾, “ -790 mV vs CSE or less” is provided as a corrosion assessment standard for wet environments.

In any case, when using measurement values for rebar potential to evaluate corrosion protection effects, the reliability of reference electrodes to measure potential is important, and thus methods of inspecting reference electrodes are important. Although the future collection and verification of examples of studying corrosion protection standards in wet environments is considered necessary, the establishment of inspection techniques for reference electrodes would be desirable for effective operation and maintenance.

4.3 Proposal for performance verification-type design

(1) Performance verification-type design technique using corrosion rate theory

It is possible to explain the corrosion of rebar in concrete and cathodic protection using the relationship (Evans diagram) between the current density (i) and potential (e) of rebar in concrete shown in **Fig. 5**. In a natural corrosion state, the anode and cathode current densities (i_{corr}) are in a balanced state with the self-potential (E_{corr}), and in an Evans diagram, this is the intersection point of the anodic polarization curve and cathodic polarization curve. This current is referred to

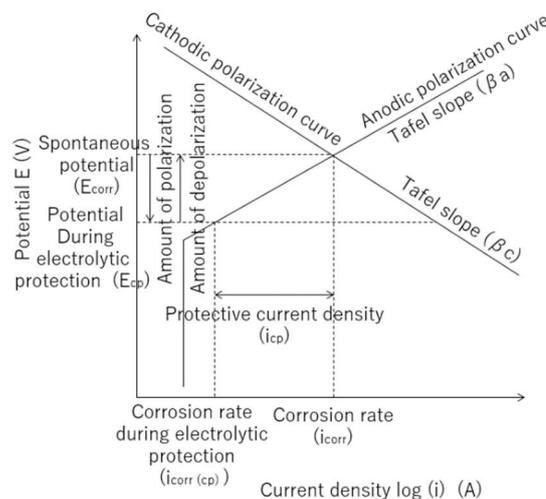


Fig. 5: Relationship of current density and potential

as the internal current, and is exchanged on the rebar surface. Consequently, it is possible to determine the self-potential (E_{corr}) and corrosion rate (current density (i_{corr})) according to this point of intersection. However, this is polarized to the cathode side during cathodic protection (cathode corrosion protection). In the present cathodic protection methods, the current magnitudes satisfying the 100-mV shift standard are set from a cathodic protection curve obtained from charging tests, but the corrosion rate during cathodic protection may be determined according to the intersection point of the anodic polarization curve shown in the figure with the potential during cathodic protection.

Present cathodic protection methods are designed such that they satisfy the specification of a 100-mV change in potential as described above, but this is for reducing the corrosion rate using the corrosion rate of rebar when applying a cathodic protection method for reference. Concrete structures are essentially operated and maintained such that they satisfy the required performance throughout their design lifetime, which includes safety and usability. This is an idea based upon performance specifications, which means that structures are operated and maintained such that when there is salt damage, the amount of corrosion in the rebar does not exceed preset corrosion limits during the design lifetime, considering the importance, operation, and maintenance categories of the structure. Consequently, when designs for cathodic protection methods are turned into performance specifications, the rebar corrosion rate may be properly controlled such that the amount of rebar corrosion does not exceed the corrosion limits during the design lifetime by supplying protection current. If performance verification-type design were realized, then it would be possible to adopt various cathodic protection design techniques without being bound to the current specification for a 100-mV change in potential. Furthermore, the amount of rebar corrosion at the end of the design lifetime is the cumulative amount of rebar corrosion during the service period of a structure, and may be determined by Faraday's law as shown in Formula (3).

$$\Delta W = \frac{i \cdot S \cdot \Delta t \cdot M}{n \cdot F} \quad (3)$$

Table 3: Comparison of specification-type design method and performance verification-type design method for cathodic protection

Specification-type design method	Performance verification-type design method
<p>[Advantages]</p> <ul style="list-style-type: none"> • No difficulties because it determines pros and cons of corrosion protection according to 100-mV change in potential. 	<p>[Advantages]</p> <ul style="list-style-type: none"> • Can control the corrosion rate of rebar during charging periods with cathodic protection. • Can build a cathodic protection system corresponding to required performance.
<p>[Issues]</p> <ul style="list-style-type: none"> • Supplies corrosion protection current for obtaining 100-mV potential change regardless of corrosion state of rebar. • Cannot quantitatively evaluate corrosion rate during charging. 	<p>[Issues]</p> <ul style="list-style-type: none"> • Must properly set corrosion rate of structures. • Requires greater expertise, and design and management is more complicated. • Corrosion protection management is required at the proper positions (positions with severe corrosion).

Here, ΔW : amount of corrosion reduction (g), i : current density (A/cm^2), S : rebar surface area (cm^2), Δt : time period (s), M : atomic weight of iron (55.85 g/mol), n : valence (2 eq/mol), F : Faraday constant (96500 A-s/eq). This amount of corrosion reduction is expressed as the constant of the current density and service period in reaction to corrosion, wherein the current density is equal in value to the corrosion rate. Hence, the corrosion rate of rebar may be kept at the design value or less over the service period such that the amount of rebar corrosion is the corrosion limit or less at the end of the design lifetime.

In the design process, it is possible to determine the amount of electric current and amount of polarization necessary for corrosion by setting the design value for the corrosion rate during cathodic protection ($i_{corr(cp)}$) and the anode Tafel slope for rebar in concrete (β_a), together with the corrosion rate of structures obtained, for example, from surveys (i_{corr}). Furthermore, the amount of polarization or depolarization during cathodic protection may be determined with Formula (4).

$$\Delta E = \beta_a \cdot \log_{10} (i_{corr}/i_{corr(cp)}) \quad (4)$$

Here, ΔE : amount of required polarization (V), β_a : anode Tafel slope (V/decade), i_{corr} : rebar

corrosion rate (A/m^2), $i_{\text{corr (cp)}}$: design value of corrosion rate when applying cathodic protection (A/m^2).

Table 3 shows an example of the advantages and issues when transitioning the cathodic protection method from the current specification-type design method to a performance verification-type design method. By transitioning the cathodic protection method to one based on performance specifications, cathodic protection system deterioration is inhibited, and more economic and efficient long-term operation of cathodic protection may be possible. However, the corrosion of rebar in concrete advances differently depending upon environmental factors, including temperature, humidity, moisture, and the supply of chloride ions, which are not constant even if the structures are the same. Hence, it is difficult to realize a design (for example, circuit dividing, anode area (intervals), protection current density, monitoring positions) that reduces the load on cathodic protection systems in consideration of economic factors, in addition to ensuring that the amount of rebar corrosion does not exceed the specified limit over the design lifetime of a concrete structure. In addition, knowledge of and experience in advance electrochemistry is naturally required, and thus there will presumably be occasions when management by making acceptance judgments based on the amount of depolarization as in the past will prove inadequate.

(2) Technical issues facing performance verification-type design

The rate of rebar corrosion in concrete structures is not uniform. Hence, design values for the corrosion rate during cathodic protection need to be set based upon the highest corrosion rate in the range where cathodic protection is applicable. Consequently, it is important to ascertain the distribution of rebar corrosion rates within the applicable scope of cathodic protection methods, and proper preliminary examination methods need to be stipulated.

The anode Tafel slope β_a is required in order to set the “required amount of polarization” ΔE according to Formula (4), but based on past study results⁸⁾, β_a is within a range of 100 to 250 mV/decade. When considered in terms of the present 100 mV shift standard, if β_a is 100 mV/decade, then relatively high corrosion protection effects are achieved with a 90% corrosion protection rate, but if β_a is 250 mV/decade, then the corrosion protection rate drops to 60%. Consequently, the methods of determining the anode Tafel slope of rebar in concrete structures, which greatly affect the setting of the required polarization, need to be standardized for performance verification-type design.

There are many technical issues facing performance verification-type design, but cathodic protection is the only repair method that can control rebar corrosion, and it would be desirable for a performance specification-type design technique such as that proposed here to be established in order to implement effective operation and management techniques for extensive infrastructure stock. Hence, not only do individual techniques need to be carefully investigated, but the thinking behind the characteristic values, limit values, and safety factors used in design needs to be clarified.

(3) Operation and maintenance during charging

Ordinary corrosion protection management is performed based upon the potential of rebar monitored with reference electrodes installed within concrete. However, in many cases, reference electrodes are fixed to internal rebar after chipping into the back of the rebar, and thus the corrosion protection management of overall structures is accomplished through passivation by cross-section repair, and monitoring the state of rebar with greatly improved corrosion environments. Naturally, rebar that is subject to monitoring demonstrates behavior different from rebar within existing concrete in a corrosive environment, and it is possible that the degree of rebar polarization is greater, and the instant-off potential may be evaluated on the noble side. Monitoring under conditions that do not disturb the environment surrounding the rebar is ideal for avoiding this problem, but in cases in which reference electrodes must be installed in a cross-section repair area, they must be installed as close as possible to boundaries with existing concrete, and thus corrosion protection management by monitoring existing rebar within concrete is considered important.

Operation and maintenance after applying cathodic protection methods demands the formulation of dedicated plans such that concrete structures maintain their required performance, and regular checking of structure exteriors, rebar corrosion protection effects, and cathodic protection equipment, the results of which must be recorded for safe-keeping. Inspections of cathodic protection are often performed by costly experts, and sometimes cannot be done per the recommended frequency in Reference⁶⁾ (four times per year or per season the first year, once every two to three years), depending on the availability of structure managers. In terms of practical work, it is felt that stipulating a uniform inspection frequency would be an effective method. However, it is important that concrete structures satisfy their performance requirements throughout their design lifetime. One strategy would be to set a proper inspection frequency for

structure managers that takes into account the importance of structures, as well as their operation, maintenance, environmental impact, and durability. However, another possible idea would be to set an inspection frequency according to the state of the internal rebar. For example, it is known that when proper cathodic protection management is performed, there is a tendency for the rebar off-potential to be enobled over time compared to during the initial application of cathodic protection as a result of rebar re-passivation. Re-passivation of rebar due to cathodic protection in an aerial environment (an environment in which dissolved oxygen is supplied to rebar) is thought to be due to an elevated pH from the generation of hydroxide ions by cathodic reactions on the rebar surface, as well as the effects of improving the environment near the rebar from reduced rebar surface concentration of chloride ions as they pass to the anode side. The result is that a lower required protection current density is possible, and deterioration of the cathodic protection system (anodes and mortar around anodes, etc.) may be inhibited. In such cases, it is felt that the inspection frequency may be changed depending on the situation. In any case, operation and maintenance with proper regular inspection after operation is important when adopting cathodic protection methods.

In cases in which cathodic protection is performed based upon performance specifications, the rebar corrosion rate during cathodic protection must be measured at inspection, and checked to see if it is at or below the rebar corrosion limit at the end of design lifetime. However, measuring the corrosion rate of rebar during cathodic protection requires the proper instruments and specialized knowledge, which means relying on experts for measurement. Therefore, operation and maintenance methods that, in order to construct a reasonable inspection and diagnosis system, determine the amount of electrical change satisfying the corrosion rate during corrosion protection set at the design stage, evaluate the corrosion protection performance according to assessments based upon the current degree of depolarization, and measure the corrosion rate of rebar during cathodic protection only when evaluation by the depolarization degree is not possible, are considered realistic. Although no evaluation methods for corrosion rate during charging have yet been established, there are reports of estimating the corrosion rate of rebar during cathodic protection by using direct current power supply devices to measure the polarization curve of rebar, as in Reference¹⁵⁾. This method obtains a depolarization curve by scanning the potential from the cathode side to the anode side, and then estimating the corrosion rate during application of cathodic protection from the intersection point of the anode Tafel line

and the instant-off potential.

In any case, if such new techniques were established, then operation and maintenance combining management according to the degree of change in potential and management according to the corrosion rate of rebar during cathodic protection would be possible.

5. Conclusion

This technical committee, as indicated by the committee name, focused on electrical techniques with the aim of establishing effective operation and management techniques for concrete structures. The committee believes that it has shown the future direction that should be taken with respect to evaluating chloride penetration resistance and performance specification-type cathodic protection methods, and the attendant technical issues that must be addressed. In addition, the committee has used examples of measurements and other information from real structures to summarize key points and expert know-how on electrochemical techniques, such as those typified by the self-potential method utilized in current operation and maintenance, which are expected to be used soon in actual practical situations, drawing from scenarios prior to, during, and using the results of measurements. However, it is not always possible at present to obtain sufficient necessary information with the generally used techniques, and thus this problem is not easy to solve. Taking all of this into consideration, the committee has compiled the electrochemical techniques used in other fields into a report, and would appreciate it if this were used as a reference for future technical development.

Furthermore, a briefing by this technical committee is scheduled in tandem with a symposium for related papers on Friday, September 21, 2018 at Chiyoda Ward Uchisaiwai-Cho Hall.

Finally, the committee would like to express its sincere thanks to everyone who cooperated in compiling this report.

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