DESIGN SYSTEM FOR ELECTROCHEMICAL CORROSION CONTROL TECHNIQUES CONSIDERING THEIR EFFECTS ON ALKALI–SILICA REACTION

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Abstract

It is a concern that electrochemical corrosion control techniques, such as cathodic protection, chloride removal method and realkalization, may accelerate expansion of concrete due to alkali–silica reaction (ASR), which leads to production of hydroxyl ions and accumulation of alkali ions around steel in concrete. It is difficult to apply these electrochemical techniques to concrete structures, which probably contain reactive aggregates.

In this paper, a design system for electrochemical corrosion control techniques is proposed considering their effects on ASR. To develop this system, in addition to referring to past research papers and reports, an experimental investigation was conducted. In this system, the applicability of electrochemical corrosion control techniques is evaluated on the basis of residual expansion capacity. Moreover, a procedure to design the conditions for electrifying treatment is proposed. This system will expand the application of such electrochemical techniques to complex deterioration cases involving steel corrosion and ASR.

Keywords: electrochemical corrosion control technique, ASR, conditions for electric treatment

1 INTRODUCTION

Recently, a large number of concrete structures have been deteriorated as a result of corrosion of reinforcing steel. The corrosion of steel in concrete occurs by chloride attack or carbonation of concrete. In order to repair such deteriorated structures or to protect against steel corrosion, electrochemical corrosion control techniques have been developed and applied to many existing structures in Japan. These techniques include cathodic protection, electrochemical chloride removal (desalination), and electrochemical realkalization. The corrosion control effect of these techniques has been confirmed by many researchers using data obtained in the inspection of actual structures.

However, it is a concern that these techniques may accelerate concrete expansion due to alkali–silica reaction (ASR), which leads to production of hydroxyl ions and accumulation of alkali ions around steel in concrete [1], [2], [3]. Therefore, it is difficult to apply these techniques to concrete structures, which probably contain reactive aggregates.

In this paper, a design system for electrochemical corrosion control techniques is proposed considering their effect on ASR. To develop this system, in addition to referring to past research papers and reports, an experimental investigation was conducted. In this system, the applicability of these techniques is evaluated on the basis of residual expansion capacity. Moreover, a procedure to design the conditions for electrifying treatment is proposed. This system will expand the application of such electrochemical techniques to complex deterioration cases involving steel corrosion and ASR.

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This paper introduces an outline of the guidelines for application of these techniques considering ASR, which was prepared by the Technical Committee on Application of Electrochemical Corrosion Control Techniques to Concrete Structures organized by the Japan Society of Materials Science (JSMS).

2 INFLUENCE OF ELECTROCHEMICAL CORROSION CONTROL TECHNIQUES ON ASR IN CONCRETE

An outline of an electrochemical corrosion control technique is shown in Figure 1. In this treatment, an anode is placed on the concrete surface and direct current is supplied between this anode and steel in the concrete, which acts as a cathode. Using this procedure, steel corrosion in the concrete is suppressed electrochemically, with the migration of chloride anions (Cl^-) toward the anode and of sodium cations (Na^+) toward steel in the concrete.

The mechanism of ASR acceleration due to the applied electrochemical method is considered as follows.

Step 1: Electrochemical migration of Na^+ and K^+ toward steel in the concrete

Step 2: Accumulation of Na^+ and K^+ around steel and production of OH^- by cathodic reaction at steel can form high alkalinity environment mainly around steel

Step 3: The high alkalinity environment accelerates the progress of ASR and concrete expansion, especially around steel

A few reports have indicated the effect of the electrifying conditions on concrete expansion. Kuroda et al. suggested that the pessimum current density that results in maximum concrete expansion is 25~50 mA/m^2 [4]. The mechanism is considered that alkali silica gel formed by ASR becomes fluid under the high alkalinity environment around steel. Shayan also reported such pessimum behavior but he suggested that the effect of the current density on concrete expansion depended on the type of aggregate and the alkali content of the concrete [5]. Page et al. showed that the pessimum integrated current density is $1\sim2 \times 10^7$ C/m^2, which is supposed to be a result of the balance between the amount of SiO_2 supplied from the reactive aggregates and R_2O supplied from the concrete [6]. However, the detailed mechanism has not been clarified yet.

3 OUTLINE OF GUIDELINES FOR APPLICATION OF ELECTROCHEMICAL CORROSION CONTROL METHODS CONSIDERING ASR

An outline of the guidelines proposed by the Technical Committee is shown in Figure 2. Concrete structures are classified into four maintenance categories by "JSCE Standard Specifications for Concrete Structures 'Maintenance'" in Japan. Category A includes structures for preventive maintenance and Category B includes structures for corrective maintenance. As Category C is for observational maintenance and Category D is for non-inspection maintenance, only Categories A and B are discussed in this paper. If these structures do not satisfy their category requirements, adequate countermeasures should be selected. For selecting an electrochemical corrosion control method as a protection or repair measure, "JSCE Recommendation for Design and Construction of Electrochemical Corrosion Control Methods" is available in Japan. This guideline shows how to consider the effect of ASR as a complement to the JSCE Recommendation.

As shown in Figure 2, the procedure is divided into three stages. As a first stage, data on the degree of deterioration and the structural performance of the deteriorated structure are collected in order to grasp the condition of the structure and predict the deterioration progress and performance degradation. Then, the applicability of electrochemical methods is evaluated and decided on the basis of residual expansion capacity of a sample core (evaluation and judgment (1)). The second stage is for design and construction. After the selection of adequate remedial methods including an electrochemical corrosion control method and, if necessary, a countermeasure for ASR, strengthening method, etc., electrifying conditions considering ASR are selected to reduce the risk of ASR acceleration. From this, applicability is evaluated and decided considering the electrified concrete expansion (evaluation and judgment (2)). The third stage is for maintenance after construction. The effects of corrosion control and change in concrete expansion rate after construction are monitored by inspections. Then, the required corrosion control effect and accelerated ASR expansion should be evaluated and decided (evaluation and judgment (3)).

4 EVALUATION OF APPLICABILITY OF ELECTROCHEMICAL METHODS

In the guidelines, the applicability of an electrochemical corrosion control method is evaluated on the basis of the residual expansion capacity of the concrete core at the first stage (evaluation and judgment (1)), as shown in Figure 2. The residual expansion capacity criterion for determining applicability is shown in Table 1.

As shown in Table 1, residual expansion capacity of the concrete core should be less than 0.1% for the application of electrochemical methods to structures in Category A. On the other hand, for structures in Category B, the criterion is not as stringent as in Category A because some deterioration due to ASR is permitted. In such cases, the residual expansion capacity should be less than 0.4% for the requirement of maintaining mechanical performance. Moreover, it is preferable to monitor the progress of ASR and to select repair of cracks or surface treatment with the electrochemical corrosion control method, according to the condition of the structures. In Table 1, the criteria values, 0.1% and 0.4%, were determined with reference to the data obtained by Strunge et al. [6].

On the other hand, if corrosion control is top priority, as shown in the bottom row of Table 1, it is possible that there is no upper limit of residual expansion capacity. In such cases, it is necessary to consider selecting another method that might include a strengthening treatment such as use of external cables. Owners of structures should select the best option considering the life-cycle design of their structures.

5 DESIGN OF ELECTRIFYING CONDITIONS

In the guideline procedure, if an electrochemical corrosion control method is determined as applicable in “evaluation and judgment (1)” as already mentioned above, suitable electrifying conditions considering the effect of ASR should be decided. The committee proposed a design procedure for selecting electrifying conditions, as shown in Figure 3. Referring to the residual expansion capacity of the concrete core of the target structure, the permissible residual expansion capacity of electrified concrete is determined. Then, for selecting the electrifying conditions, the residual expansion capacity of electrified concrete should be evaluated. As shown in Figure 3, there are three ways to evaluate the residual expansion capacity of electrified concrete, i.e., process A, B, and C. Finally, electrifying conditions are chosen by confirming that the residual expansion capacity of electrified concrete evaluated through process A, B, or C is less than the permissible residual expansion capacity of electrified concrete in “evaluation and judgment (2).”

The technical committee conducted an experimental investigation in order to obtain feedback about the guidelines for evaluation of the expansion behavior of electrified concrete. The following section 5.1 presents the experimental program, and sections 5.2–5.4 explain detailed procedures for process A, B, and C referring to the results of this experiment.

5.1 Experimental program

Mix proportions of concrete used in the experiment are shown in Table 2. Water/cement (W/C) ratios of concrete were 45% and 60%. Ordinary Portland cement and non-reactive fine aggregates were used, and as the coarse aggregate, reactive aggregate (G1) and non-reactive aggregate (G2) were mixed in the pessimum weight ratio of 6:4. In order to adjust the total alkali content as R_2O (Na_2O + 0.658 K_2O) = 8.0 kg/m^3 for acceleration of ASR in each concrete specimen, NaCl was premixed into the mixing water. Specimens prepared for this study were 100 × 100 × 300 mm concrete prisms. Each specimen had a rounded steel bar (□ = 13mm) SR235 (JIS) at the center of the square section (Figure 4). All specimens were cured for 28 days in a wet condition, and after curing, electrochemical treatment was applied to these specimens. As the anode material, titanium mesh was placed on one surface (100 × 300 mm) and covered by a mortar layer to maintain electrical contact with the concrete surface.

Electrochemical treatment was applied to the concrete specimens after curing the anode mortar layer. As the electric current density, 0 (non-treated), 5, 30, and 100 mA/m^2 of the concrete surface were selected, and the specimens were maintained in the condition favorable for ASR acceleration (40°C, 95% RH) during the electrochemical treatment. Concrete expansion rates of the specimens were measured by the contact gage method at three points on each specimen as shown in Figure 4, i.e., near the anode surface, above the steel, and on the opposite side to the anode surface. Moreover, the distributions of alkali content (amount of R_2O) in concrete were measured.

5.2 Evaluation of electrified concrete expansion using non-electrified concrete expansion (Process A)

As a part of the experimental results, Figure 5 shows the relationship between expansion ratio at the steel position (above the steel in Figure 4) and the electrification period. Expansion ratio is the ratio of the electrified concrete expansion to the non-electrified concrete expansion. From this figure, the ratio varies with current density and W/C of concrete, but all ratios are less than 1.5.

In process A, the residual expansion capacity of electrified concrete is supposed to be, at most, 1.5 times the residual expansion capacity of non-electrified concrete referring to the results of the experiment. If the maximum residual expansion capacity of electrified concrete is determined to be less than the permissible residual expansion capacity of electrified concrete in "evaluation and judgment (2)," the electrifying conditions can be determined considering only the corrosion control effect.

5.3 Evaluation of electrified concrete expansion by simulation test (Process B)

In this process, the residual expansion capacity of electrified concrete is evaluated by simulation test of electrochemical treatment with concrete cores from the subject structures. The technical committee proposed a simulation test. The outline of this test is shown in Figure 6. As shown, a steel bar, which is inserted into a drill hole in the concrete core, acts as a cathode. Then, anodes are placed in electrolyte at both ends of the core, and direct current is supplied between these electrodes. During the electrochemical treatment, concrete expansion rates are measured using brass chips bonded to the core surface.

It is impossible to completely reproduce actual conditions in the simulation test. For example, in the case of cathodic protection, the actual treatment period is generally from several years to several decades. However, application of such a long treatment in a laboratory test is impractical. Then, in this proposed test, a relatively large current density is applied in a short period and by establishing the relationship between integrated current density and concrete expansion rate, the current density for the actual structure is decided considering the actual treatment period.

The equation for evaluating the relationship between integrated current density and concrete expansion rate is based on the results of experiments performed by the Technical Committee as follows.

Relationships between the concrete expansion rate at the steel position and the integrated current density are shown in Figure 7 for different current densities. As shown, the relationship can be expressed as the following general equation regardless of current density.

$$y = \mathrm{a} \ln x + \mathrm{b}$$

Moreover, there are relationships between current density and coefficients 'a' and 'b', as shown in Figure 8. From this, if concrete expansion data for three or more different current densities is available, the relationships between current density and coefficients 'a' and 'b' can be given. The relationship between measured concrete expansion rates and calculated values is shown in Figure 9. From this figure, it can be concluded that the proposed method can predict the electrified concrete expansion. Then, the relationship between integrated current density and concrete expansion rate for every current density can be found. Finally, the appropriate electrifying condition (current density) is decided considering the actual treatment period.

5.4 Evaluation of electrified concrete expansion from the prediction of alkali accumulation around steel (Process C)

In this process, the residual expansion capacity of electrified concrete is evaluated without a simulation test. The amount of R_2O accumulating around steel in concrete is calculated by the supposed integrated current density and then the concrete expansion ratio (expansion rate of electrified concrete/expansion rate of non-electrified concrete) corresponding to the accumulated R_2O is predicted. From this, the residual expansion capacity of electrified concrete is determined and finally, the appropriate electrifying condition (integrated current density) is determined as a result of "evaluation and judgment (2)."

When discussing the R_2O content value, the area subjected to chemical analysis and the method of measuring ion content affect the data. In this paper, the analyzed area around steel is shown in Figure 10. Concrete in this part was crushed into a fine powder, and Na^+ and K^+ were extracted with nitric acid. Atomic absorption spectrometry was adopted as the method of measuring ion content. The relationship between (accumulated/initial) R_2O and integrated current density is shown in Figure 11. The left part of Figure 10 shows all plots including the results of experiments conducted by the Technical Committee and in previous reports on electrochemical techniques. The right part of Figure 11 shows plots of the upper limit of (accumulated/initial) R_2O. From this figure, the upper limit line is approximated by a second-order curve. The relationship between expansion ratio and amount of R_2O in steel is shown in Figure 12. In this system, the expansion ratio, not the expansion rate itself, is adopted as the concrete expansion index, because the expansion ratio can show the essential effects of the electrochemical treatment while separating the natural expansion due to non-electrified concrete expansion. From this figure, although more data are necessary to make a precise judgment, it can be seen that there is a pessimum amount of R_2O that will maximize concrete expansion. As the pessimum value is about 12 kg/m^3, the integrated current density should be selected to avoid such a level of accumulated R_2O. However, at present, it seems risky to avoid the pessimum R_2O by exceeding the pessimum R_2O.

The square symbols in Figure 12 correspond to chloride removal treatment. From Figure 12, LiOH solution is a more effective electrolyte solution than $Ca(OH)_2$ solution in suppressing the expansion rate of electrified concrete due to ASR.

6 CONCLUSIONS

In Japan, many concrete structures are deteriorating as a result of a combined effect of steel corrosion and ASR. In such cases, the deterioration rate is larger than in cases of deterioration due to just one of these factors. However, application of countermeasures against complex deterioration has been difficult because electrochemical corrosion control methods may accelerate ASR and concrete expansion. In this situation, it seems important to propose guidelines and a design system for electrochemical corrosion control techniques considering their effects on ASR.

In this paper, residual expansion capacity criteria have been proposed as shown in Table 1 to determine the applicability of electrochemical corrosion control methods. Moreover, for the decision on appropriate electrifying conditions, three ways have been proposed to provide the residual expansion capacity of electrified concrete, considering experimental results regarding the acceleration effect of electrochemical treatment on concrete expansion occurring by ASR.

However, to improve the reliability of this system, it is necessary to promote further research on the mechanism of concrete expansion accelerated by electrochemical treatment and to accumulate related data from the inspection records of actual structures.

7 ACKNOWLEDGMENT

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8 REFERENCES

[1] Sergi, G., Page, C.L. and Thompson, D.M. (1991): Electrochemical Induction of Alkali-Silica Reaction in Concrete. Materials and Structures (24): 359-361.

[2] Ali, M.G. and Rasheeduzzafar (1993): Cathodic Protection Current Accelerates Alkali-Silica Reaction. ACI Materials Journal: 247-252.

[3] Ishii, K., Torii, K., Kawamura, M. and Matsumoto, K. (1996): Influence of Cathodic Protection on Alkali-Silica Reaction of Concrete Structure. Annual Proc. of JCI (18): 861-866 (in Japanese).

[4] Kuroda, T., Nishibayashi, S. and Bian, Q. (1996): Study of Alkali-Aggregate Reactions in Electrical Fields, Proc. of the 10th International Conference on Alkali-Aggregate Reaction in Concrete: 645-652.

[5] Shayan, A. (2000): Combined Effects of Alkali-Aggregate Reaction and Cathodic Protection Currents in Reinforced Concrete, Proc. of the 11th International Conference on Alkali-Aggregate Reaction in Concrete: 229-238.

[6] Page, C.L. and Yu, S.W. (1995): Potential Effects of Electrochemical Desalination of Concrete on Alkali-silica Reaction, Magazine of Concrete Research (47): 23-31.

[7] Strunge, H., Chatterji, S. and Jensen A.D. (1991): Estimation of Residual Expansion Capacity of Concrete Structures due to Alkali-Silica Reaction. il cemento: 158-162.

[8] Japan Concrete Institute (1986): JCI-DD2 Method for testing expansion rate by using concrete core from concrete structures suffered from alkali-aggregate reaction -draft-, report of technical committee on diagnosis of durability.

Table 1: Criteria of residual expansion capacity for determining the applicability of electrochemical corrosion control methods

Maintenance category	Required performance	Residual expansion capacity*
A (Preventive maintenance)	Prevention of deterioration like concrete cracking	Less than 0.1%
B (Corrective maintenance for structures in severe corrosion environment and corrosion control is prior to countermeasure against ASR)	#Prevention of progress of steel corrosion #Prevention of decrease of mechanical performances due to ASR	Less than 0.4%
	#Prevention of progress of steel corrosion	0.4% and more

*Residual expansion capacity should be measured by an accelerated expansion test. As the accelerated expansion test, the method proposed by Danish Technological Institute (Denmark) [7] is applicable in the case that the target structure is subject to chloride penetration, and JCI-DD2 method [8] is applicable for other cases.

Table 2: Mix proportions of concrete

R_2O (kg/m^3)	W/C (%)	s/a (%)	Gmax (mm)	Content (kg/m^3)							
				C	W	S	G1	G2	WRA*	AEA**	NaCl
8.0	60	45	15	300	180	781	579	386	0.6	0.02	11.9
8.0	45	45	15	400	180	743	552	368	0.8	0.03	10.9

*WRA: Water reducing agent **AEA: Air entraining agent

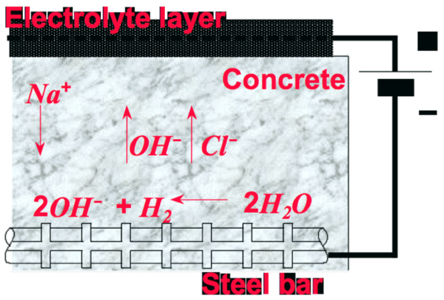

Figure 1: Schematic of an electrochemical corrosion control technique.

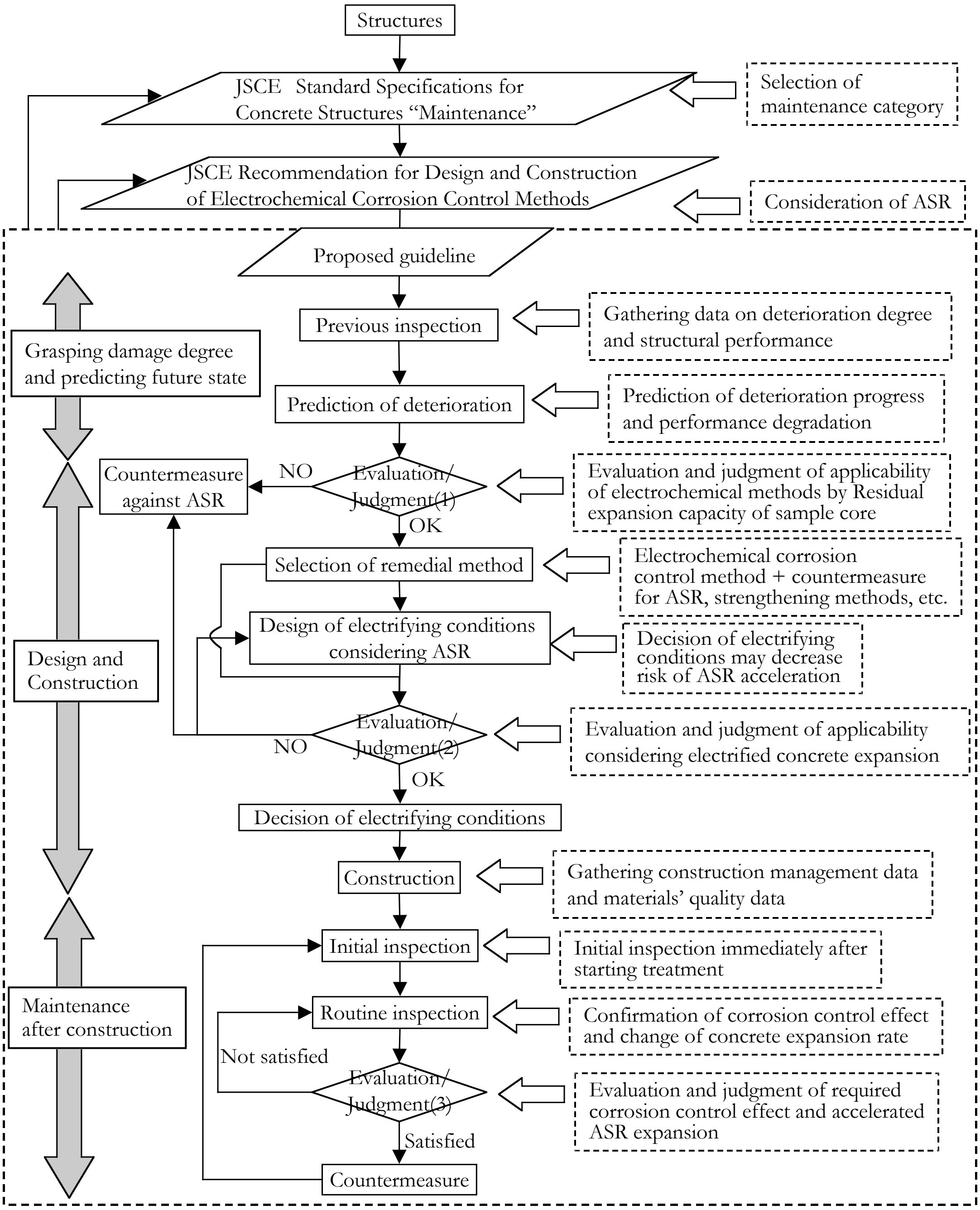

Figure 2: Outline of guidelines.

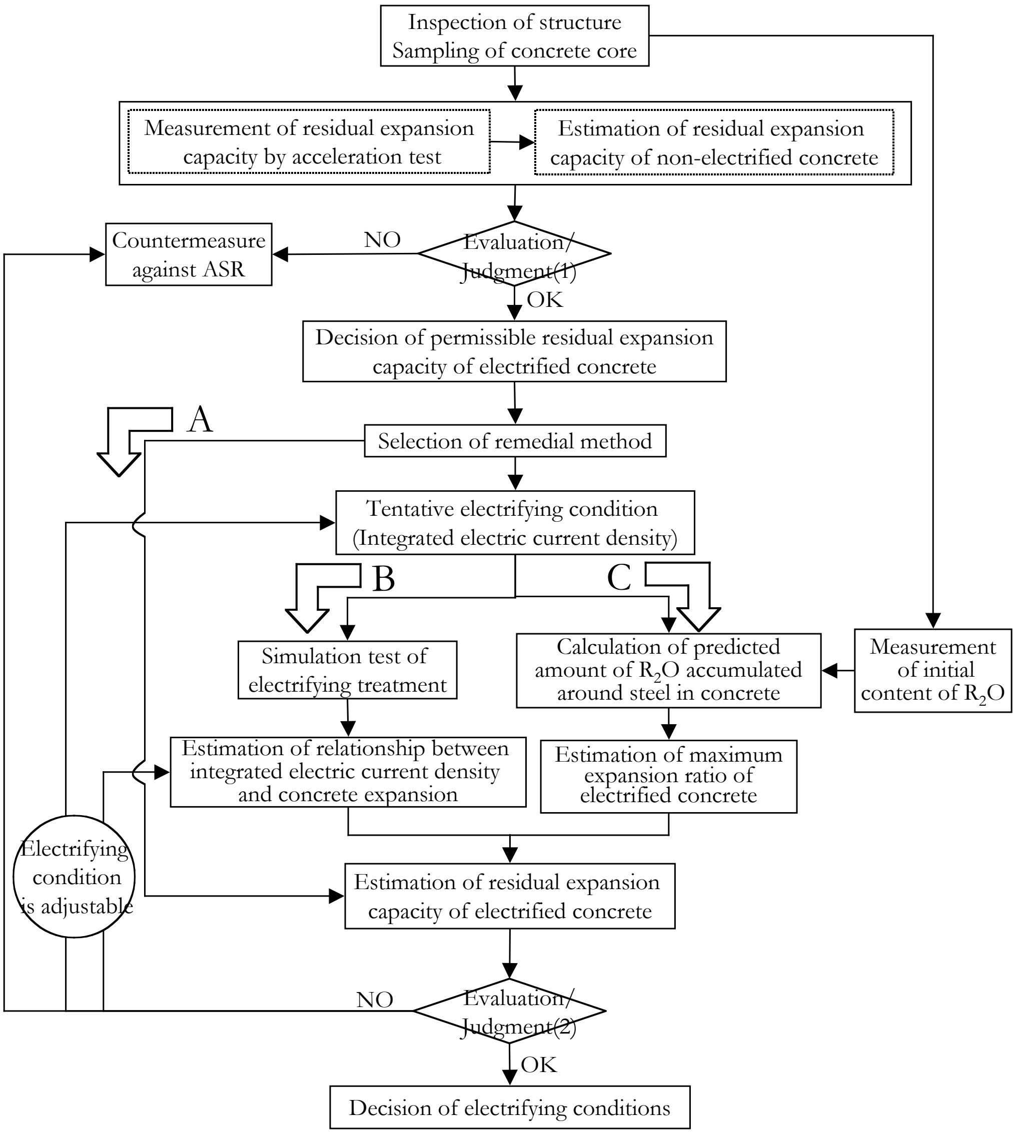

Figure 3: Design procedure for electrifying conditions.

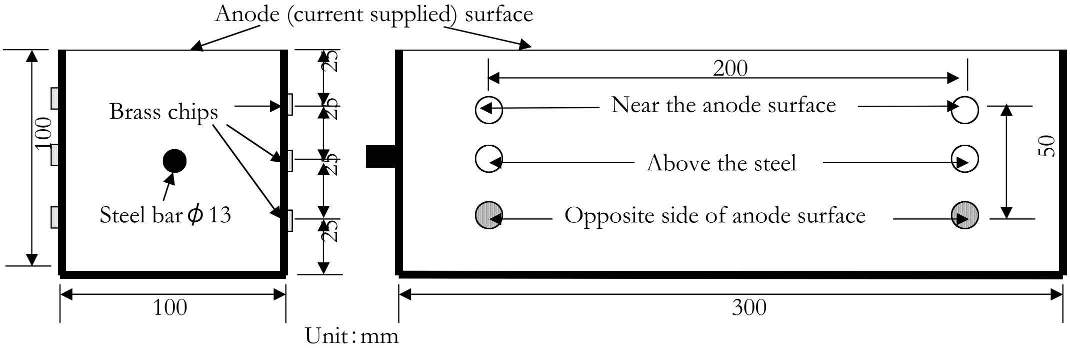

Figure 4: Schematic diagram of concrete specimen.

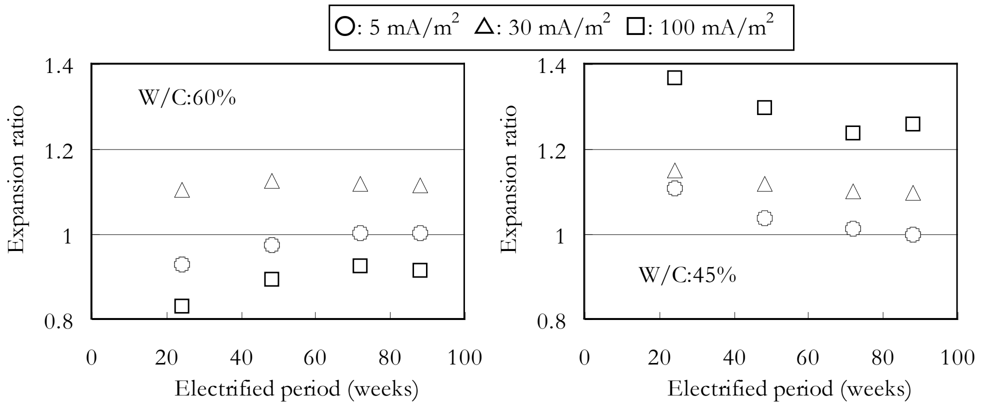

Figure 5: Relationship between expansion ratio at the steel position and electrified period.

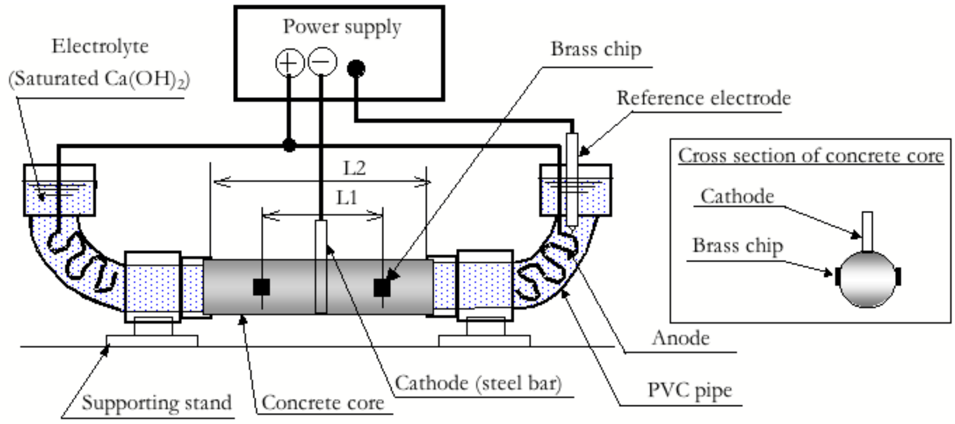

Figure 6: Outline of simulation test of electrochemical treatment.

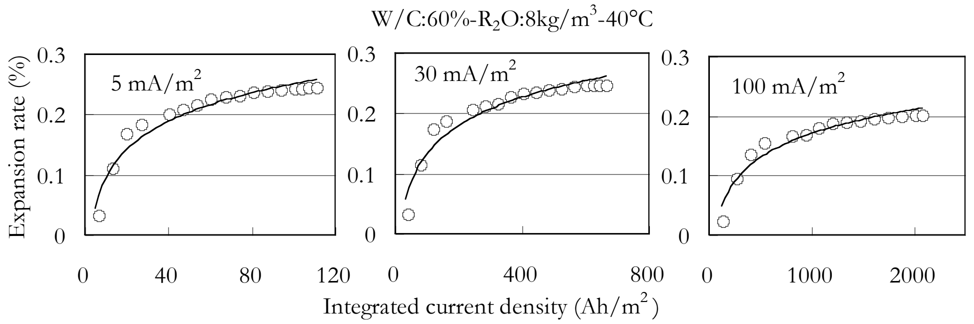

Figure 7: Relationships between expansion rate at steel location and integrated current density.

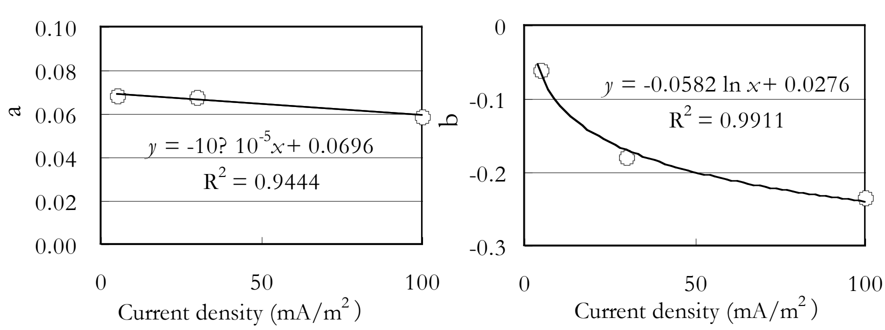

Figure 8: Relationships between coefficient ‘a’ or ‘b’ and current density.

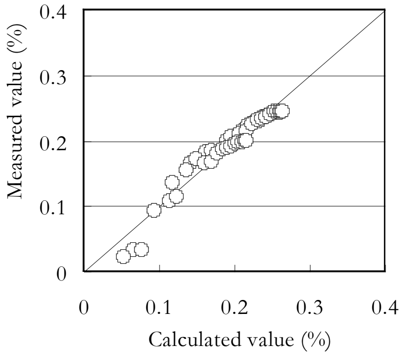

Figure 9: Relationship between measured concrete expansion rates and calculated values.

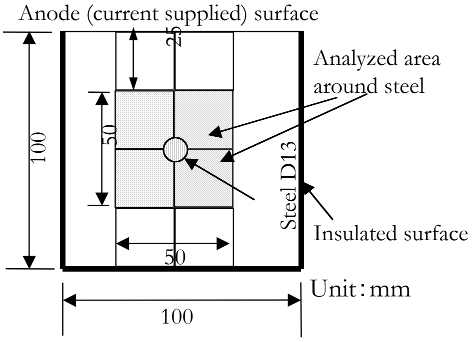

Figure 10: Area around steel subjected to chemical analysis for measuring R_2O content.

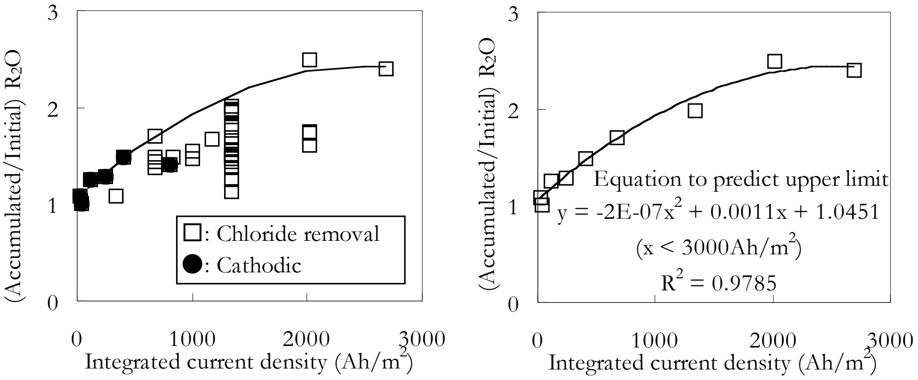

Figure 11: Relationship between (accumulated/initial) R_2O and integrated current density.

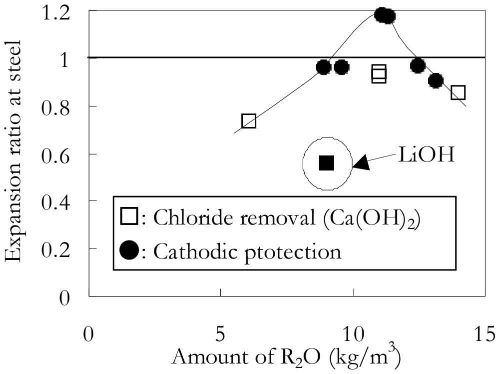

Figure 12: Relationship between expansion ratio and amount of R_2O at steel.