Committee Report: JCI-TC182A

Technical Committee on the Inspection, Diagnosis, and Repair Method of the Existing Concrete Structure Aiming at Preventive Maintenance

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Abstract

The preventive maintenance of concrete structures, which considers appropriate measures before any apparent deformation, is realized from the viewpoint of longevity and life-cycle cost (LCC). However, these measures are rarely implemented, owing to the lack of concrete procedures and systematization of inspection, diagnosis, and repair methods in the early stages of deterioration. For dissemination of preventive maintenance, the technical committee targeted conventional concrete structures, without apparent visible deformation, in their early stages of deterioration. They conducted inspections, diagnosis, and repair methods, and also analyzed case studies and proposed procedures associated with it.

Keywords: Maintenance, preventive maintenance, deterioration, inspection, diagnosis, repair, life-cycle cost

1. Introduction

In the maintenance of concrete structures, several studies and applications have been conducted on corrective maintenance strategies, primarily in the "acceleration" or "deterioration” stage, considering the urgency of taking measures against deteriorating structures. In contrast, when considering maintenance from the viewpoint of longevity and life-cycle cost (LCC), the significance and effectiveness of preventive maintenance, which implements taking actions before the occurrence of deformation, is becoming widely recognized.

However, presently, it cannot be stated that preventive maintenance, which conducted repairs before the actual deformation becomes apparent, is often implemented. One of the reasons is because the information and evaluation methods of inspection, diagnosis, and repair methods, in the early stages of deterioration, have not been systematized, and concrete procedures for carrying out preventive maintenance have not been outlined. In recent years, inspection and repair methods that focus on preventive maintenance have been developed, and is considered extremely important to understand their applicability and problems of performing preventive maintenance.

Under such circumstances, a “Technical Committee on the inspection, diagnosis, and repair methods of conventional concrete structures targeting preventive maintenance” was established in FY2018 and has been carrying out activities for two years. This committee focuses on the maintenance of conventional concrete structures in their early stages of deterioration process and have no visible deformation in their appearance. They systematize inspection, diagnosis, and repair methods related to preventive maintenance and collect specific cases. This committee has proposed procedures for preventive maintenance. Also, they conducted a questionnaire survey on the case studies and awareness of preventive maintenance for engineers and identified problems in the current state of preventive maintenance and its dissemination. Recently, the committee organized inspection techniques using drones, which have been widely utilized in the inspection of structures.

The technical committee established the following three working groups (WG), structure shown in **Table 1**, to carry out activities.

[WG1 (Systematization WG)] Collects, organizes, and classifies information on inspection/diagnosis/repair techniques applicable for preventive maintenance and examines the scope of application, accuracy, reliability, points to note, etc.

[WG2 (Applicability evaluation WG)] Examines environmental extrinsic force evaluation methods necessary for preventive maintenance, performance evaluation method for inspection and diagnosis techniques, confirmation methods for effective repair and sustainability, etc.

[WG3 (Procedure manual WG)] Examines the concept of preventive maintenance for each deterioration factor, case studies, and life-cycle cost estimation, and the procedures for preventive maintenance.

Table 1: Committee Structure and Members

Chairman：Nobufumi TAKEDA（Hiroshima Institute of Technology）
Secretary-General：Kazunori ERA（Kyokuto Kowa Corporation）
Advisor：Shigeyuki SOGO（Near Future Concrete Association）
【WG1：Systematization WG】
Chief examiner：Hitoshi HAMASAKI（Shibaura Institute of Technology）
Hiromichi IIZUKA（Asahi Kasei Advance Corp.）
Kenji HANAFUSA（BASF Japan）
Makoto YAMAMOTO（Sumitomo Osaka Cement Co., Ltd）
【WG２：Applicability WG】
Chief examiner：Toshinobu YAMAGUCHI（Kagoshima University）
Hiroyuki MIYAUCHI（Building Research Institute）
Masanori TSUZUKI（Obayashi Corporation）
Masumi INOUE（Kitami Institute of Technology）
Yoshikazu AKIRA（Kagoshima University）
Hiroshi MINAGAWA（Tohoku University）
Koichi MATSUZAWA（Building Research Institute）
【WG３：Procedure manual WG】
Chief examiner：Hirokazu TANAKA（Shimizu Corporation）
Shoji NOJIMA（Central-NEXCO Technical Marketing Co., Ltd）
Hiroshi UEDA（Railway Technical Research Institute）
Hirotake ENDOH（Civil Engineering Research Institute for Cold Region）
Hikaru YUJI（Toyo Construction Co., Ltd）
Tatsuya INDEN（Kokushikan University）
Tomoaki TSUTSUMI（International Research Institute for Nuclear Decommissioning）

2. Facts and issues of preventive maintenance

2.1 Concept of preventive maintenance at institutions and academic societies

To understand the current state and facts of preventive maintenance, the concept of preventive maintenance at individual institutions and academic societies were initially organized. In civil engineering, the term "preventive maintenance" in the "Standard Specification for Concrete Structures [Maintenance]"[1)] is defined as "the maintenance that systematically implements preventive measures to prevent the occurrence or manifestation of deterioration in either structures or performance." In the field of construction, the term related to maintenance is defined in the "Principal Guide for Service Life Planning of Buildings," [2)] and the term "preventive maintenance" is defined as "a maintenance performed to check, test, readjust, repair, etc., the object systematically and to prevent breakdown during use, before it occurs.” It is positioned as a comparison with corrective maintenance.

Although the Ministry of Land, Infrastructure, Transport and Tourism has no objection in the functioning of a structure, preventive maintenance of carrying out early detection and early measures in desirable situations is considered owing to the concept of minimizing LCC and extending life of the structure. The concept of conventional "corrective maintenance" to "preventive maintenance" is being expanded in the construction of roads and bridges, nationwide. Taking a highway structure managed by the East, Central, and West Nippon Expressways (NEXCO) as a reference, deterioration prediction is performed on the bridge structure based on the results of periodic maintenance check and detailed inspection. Then, based on the evaluation and soundness of judgment, the frequency and methods of preventive maintenance are standardized.

Additionally, the concept of preventive maintenance in railway structures, harbor structures, agricultural irrigation facilities, and electric power facilities was also investigated The usage and variations of the term "preventive maintenance" in technical fields besides construction is also summarized.

2.2 The technical committee's preventive maintenance target

As described above, the concept and target of preventive maintenance at academic societies and institutions are not always unified. It is difficult to clearly define "preventive maintenance of conventional concrete structures" at this point. Therefore, the technical committee considered the contents of preventive maintenance to be examined as general maintenance, comprising inspection, diagnosis, countermeasures, etc., to prevent any further noticeable deformation. The concrete structure to be examined was in a deteriorated environment, at a stage where no deformation had occurred yet, or a slight deformation had occurred locally and deterioration would be apparent in the future.

2.3 Awareness survey on preventive maintenance

In carrying out the activities of this technical committee, a nationwide questionnaire survey for engineers was conducted, on the awareness of preventive maintenance and its efforts; 1055 responses were received.

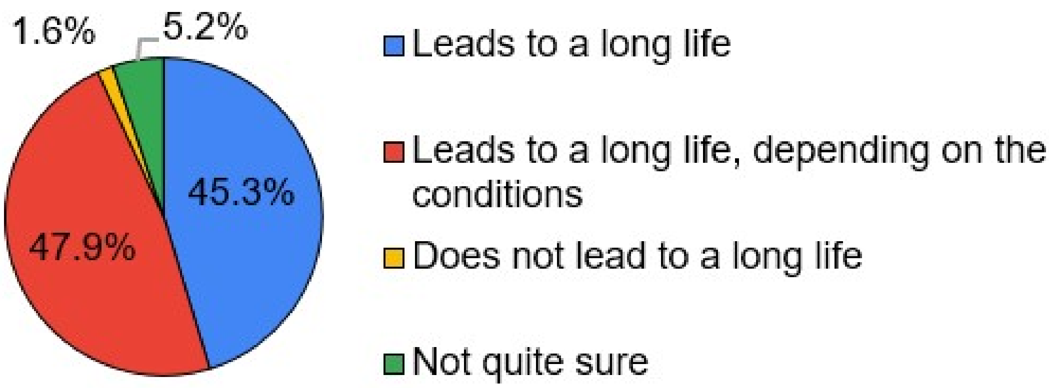

Fig. 1: Question. "Does preventive maintenance lead to long life?"

First, in the survey, about 70~80% of the respondents had a high level of understanding of the concrete deterioration process and the concepts of corrective and preventive maintenance, and it was observed that these are widely recognized. More than 90% of the respondents, including a majority of engineers, were completely aware of the effectiveness of preventive maintenance with respect to the viewpoint of reducing maintenance cost, LCC, and extending the life of structures (**Figure 1**). For queries about the items necessary for the dissemination of preventive maintenance, there were several opinions that necessitated "Budget," "Orderers' awareness," "Guidelines, manuals and procedures for preventive maintenance," and "Manpower resources", and there were also many voices such as "Effectiveness evaluation method of preventive maintenance" and "Systematization of preventive maintenance technology" (**Figure 2**).

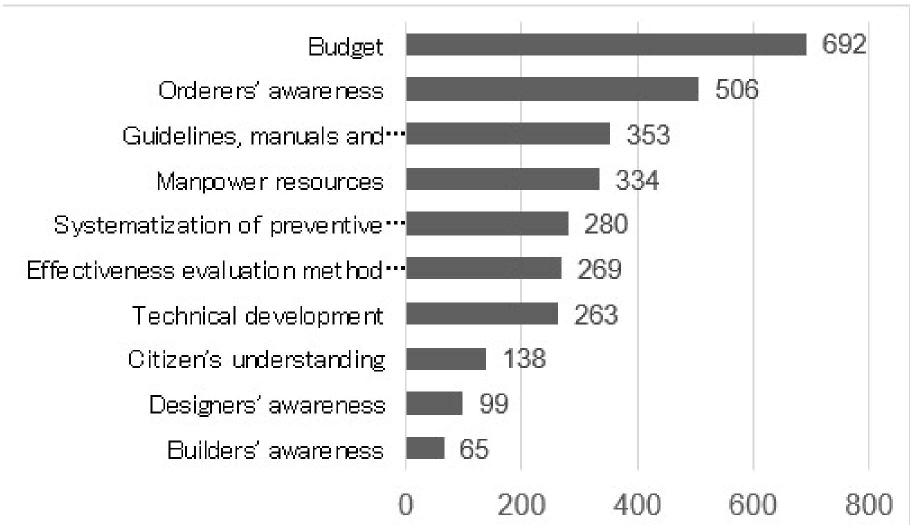

Fig. 2: Question. "What is needed for the dissemination of preventive maintenance?"

Next, in the case study of preventive maintenance, more than half of the respondents had experience of engaging in the business corresponding to preventive maintenance, and the number of cases showed a rapid increasing trend after 2011. Only about 60% responded that preventive maintenance could reduce the maintenance cost (LCC) and about 30% said "not quite sure." This is primarily caused by the short elapsed period after construction, the challenging evaluation for LCC, and the unclear method of evaluation. The positive response that the preventive maintenance carried out led to long life of the structure was about 70%. Even among the respondents with no experience of engaging in the business corresponding to preventive maintenance, more than 80% of them were positive about the approach to preventive maintenance, which demonstrated their high interest in preventive maintenance.

The aforementioned reasons indicate that awareness about preventive maintenance has penetrated to a certain extent, and that although many engineers have a high level of interest in preventive maintenance, the preventive maintenance guidelines and systemization of evaluation methods have not advanced, and thus becomes a hindrance for the spread of preventive maintenance along with the shortage of budget and manpower. From this fact, it is considered that organization and systematization of information are vital in spreading and expanding awareness regarding preventive maintenance. It is considered that the proactive dissemination of this organized information leads to a change in the awareness of the orderers and the builders.

3. Current inspection status and diagnosis techniques for preventive maintenance

3.1 Overview of inspection

For preventive maintenance of a structure, after assuming in advance the deterioration mechanism that has occurred or may occur in the structure, it is extremely important to precisely comprehend the situation of performance deterioration of the structure before the deformation of the structure becomes apparent such as "initiation stage" or "propagation stage" or at the stage with a small degree of deformation, and to predict future deterioration and implement necessary measures. Specifically, after selecting a deterioration mechanism that can occur in the target structure, the "acting force" of the environmental extrinsic force against the deterioration mechanism and the "resisting force" of the structure or its parts/members are each evaluated appropriately. By comparing and examining them, prediction of future deterioration progress and evaluations on the requirement of measurements are conducted.

Regarding the concept of inspecting and diagnosing concrete structures from the viewpoint of preventive maintenance and corresponding current technologies, an examination was conducted for each item of "Selection of deterioration mechanism to consider," "Evaluation of environmental extrinsic force," and "Evaluation of condition of structure."

3.2 Selection of deterioration mechanism to be considered

This committee deals with six deterioration mechanisms that are set as targets for preventive maintenance: carbonation, salt damage, frost damage, chemical erosion, alkali–silica reaction (ASR), and fatigue. **Table 2** shows the major deterioration factors and characteristics of each deterioration mechanism, and examples of their deterioration indexes.

Table 2: Deterioration mechanisms, factors, characteristics and examples of indexes [1)]

Deterioration mechanism	Deterioration factors	Characteristics	Examples of deterioration index
Carbonation	Carbon dioxide Water spill	Carbon dioxide reacts with hydrated cement and undergoes carbonation, and the steel material rusts by lowering the pH of the pore solution. On further exposure to moisture, cracking and peeling of concrete and reduction in the cross section of steel occur.	Carbonation depth Steel corrosion amount Corrosion cracking
Salt damage	Chloride ion	Corrosion of steel in concrete is accelerated by chloride ions, leading to the cracking and peeling of concrete, and reduction of the steel cross section.	Chloride ion concentration Steel corrosion amount Corrosion cracking
Frost damage	Freezing and thawing action	Repeated freezing and thawing of moisture in the concrete leads to deterioration in the form of scaling, minute cracks, popouts, etc., on the concrete surface.	Scaling depth Steel corrosion amount
Chemical erosion	Acidic substance Sulfate ion	The hardened concrete decomposes on contact with the acidic substance and sulfate ions, and the concrete is deteriorated by expanding pressure during compound formation.	Penetration depth of deterioration factor Carbonation depth Steel corrosion amount
Alkali–silica reaction (ASR)	Reactive aggregates	Reactive silica minerals contained in the aggregate react with the alkaline aqueous solution in the concrete, causing abnormal expansion and cracking in the concrete.	Expansion amount (crack)
Fatigue (Road/bridge deck)	Heavy vehicle traffic	Reinforced concrete slabs of roads/bridges cause cracking or sinking due to repeated loading of vehicles.	Crack density Deflection

Figure 3 shows the basic concept of deterioration mechanism estimation shown in the JSCE Concrete Standard Specification. In preventive maintenance, since the primary focuses are diagnosis and measures before the manifestation of a deformation or at a stage with a small degree of deformation, it is important to select a deterioration mechanism to consider, from diagnosis based on the inspection results, from the action on the structure determined by the environment and operating conditions during design and service, etc., or from the deterioration factors that the structure potentially holds. And, it is important to conduct appropriate inspection and diagnosis accordingly. For example, when the environment and the action can be identified and grasped during design or by actual field inspection, the deterioration mechanism to be considered can be selected from **Table 3**. In addition, as information on the state of design and construction of the structure, the presence or absence of various regulations and standards such as use of reactive aggregates and desalination of sea sand at the time of construction, and the confirmation of whether appropriate construction was carried out, etc. are also important.

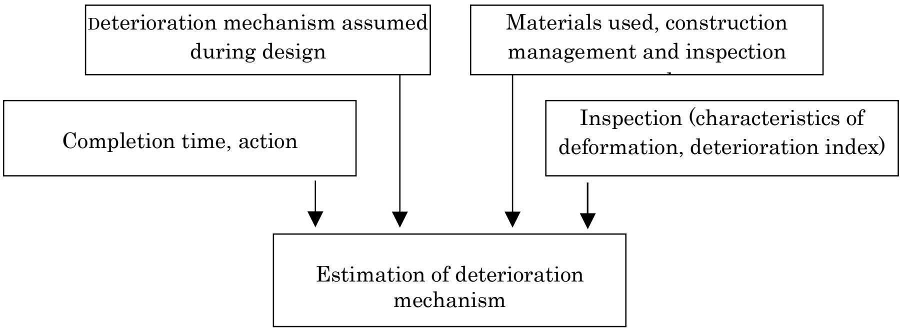

Fig. 3: Concept of deterioration mechanism estimation [1)]

Table 3: Deterioration mechanisms inferred from environmental and usage conditions

		Estimated deterioration mechanism
Environment	Coastal regions	Salt damage
	Cold regions	Frost damage, salt damage
	Hot springs	Chemical erosion
Other actions	Wet and dry cycle	Alkali-silica reaction, salt damage, frost damage
	Use of de-icing salt	Salt damage, alkali-silica reaction
	Cyclic loading	Fatigue, abrasion
	Carbon dioxide	Carbonation
	Acidic water	Chemical erosion
	Flowing water, vehicles, etc.	Abrasion

If a local deformation is discovered by inspection, it is necessary to initially examine whether the deformation is caused by an initial defect, damage, or deterioration. When deformation due to deterioration is suspected, the deterioration mechanism will be estimated as a primary factor, by first screening the expected deterioration mechanism by an action that is determined by the environmental and operating conditions, and then by comparing the characteristics of the deformation observed in the inspection based on factors such as materials used and workability with the characteristics of each deterioration mechanism shown in **Table 2**. **Table 4** shows the characteristics of appearance of deformation caused by the primary deterioration mechanism.

Table 4: Characteristics of defects due to deterioration mechanism

Deterioration mechanism	Deformation characteristics
Carbonation	Axial cracking in steel, concrete peeling
Salt damage	Axial cracking in steel, rust exudation, cross-sectional defects of concrete and steel
Frost damage	Fine cracks, scaling, pop-out, deformation
Chemical erosion	Discoloration, concrete peeling
alkali–silica reaction (ASR)	Expansion of cracks (restraint direction, alligator crack), gelling, discoloration
Fatigue（slabs）	Lattice cracking, falling corners, efflorescence
Abrasion	Mortar defect, coarse aggregate exposure, cross-sectional defects of concrete

3.3 Evaluation of environmental extrinsic force

Environmental extrinsic force evaluation on salt damage and on frost damage, and impact assessment of water spills were examined for the target. This article introduces examples of environmental extrinsic forces related to salt damage.

As environmental extrinsic force on salt damage, the supply quantity of water and oxygen which affects the corrosion reaction mechanism of steel materials and detailed information such as temperature and concrete resistance are also included. The supply quantity of chloride ion due to airborne salt, de-icing salt, etc. serves as a significant factor.

According to the Japan Society of Civil Engineers Specification for Concrete Structures-2018 “Maintenance”, the reference values are shown according to the region and distance from the coast for the surface chloride ion concentration, which is necessary when estimating the amount of chloride ion around the steel material in concrete as an apparent diffusion phenomenon. However, the transportation quantity of air-borne salt varies depending on the coastal and wind conditions, the land topography and presence or absence of obstacles, the altitude, and even for the same structure; the shape of the structure causes a difference between the part where the influence of airborne salt is large or small. Therefore, to understand the environmental extrinsic force on salt damage at the preventive maintenance stage, it is extremely important to evaluate the content of air-borne salt reaching each part of the structure in advance. Based on this background, recently, many experimental or analytical studies have been conducted on environmental extrinsic force evaluation focusing on the airborne salt content. The current major evaluation methods of airborne salt and their characteristics are described below.

3.3.1 Method for direct measurement of airborne salt

1) Doken-type airborne salt collector

A typical method for measuring the airborne salt content from the ocean is via a Doken-type collector. In this measuring method, salt adhering to a stainless-steel plate of 10 cm×10 cm is stored in a tank. The airborne salt content is measured by measuring the salt concentration. The measured airborne salt content is arranged in unit of mg/dm / day (or mdd). Here, dm=100 cm^2, implying the area of the stainless-steel plate in the collecting part. Airborne salt measurement was carried out in coastal areas nationwide from 1984 to 1986 using a Doken-type collector. Using those results, the following equation has been proposed to predict the airborne salt content at each point.

$$C_{air} = C_1 \cdot d^{-0.6} \qquad \text{Eq.(1)}$$

C_{air} : Airborne salt content, C_1 : 1km equivalent airborne salt content

2) Dry gauze method

This is a method of collecting airborne salt in dried gauze. The salt adhered to the gauze is dissolved in purified water, etc. and the amount of salt is measured to evaluate the airborne salt content. Since the collection area of salt is the same as that of the Doken-type, the unit of the airborne salt content is the same as that of the Doken-type.

3.3.2 Method for indirect measurement of airborne salt

1) Collection method using thin plate mortar

Considering the actual permeation of salt into the concrete structure, by the effect of the washing away and adsorption to concrete porous structure, a part of the salt adhered to the surface of the structure permeates into the interior of the structure. Therefore, to evaluate the airborne salt content in the structure, it is considered that using a material close to concrete will lead to the grasp of appropriate airborne salt content. Saeki et al. are evaluating the local environmental action in the structure by gluing mortar disk specimen and small thin plate mortar to various positions of the same structure.

2) Gauze wiping method

Based on the Japan Road Association's "Gauze Wiping Chlorine Ion Detector Tube Method", this is an evaluation method of wiping the concrete surface within a certain range (about 20 cm x 20 cm) with gauze, immersing the wiped gauze in deionized water, and detecting chlorine ions using a chlorine ion detector tube. Since no special equipment is required, the inspection cost is inexpensive, and can be applied easily.

3.3.3 X-ray Fluorescence evaluation method

This method performs qualitative or quantitative analysis of elements by measuring secondary X-rays (fluorescent X-rays) generated when the sample to be analyzed is irradiated with X-rays. Although this method has high measurement accuracy, owing to the low measurement range, the local difference in salt concentration due to the arrangement of aggregates becomes large when measuring concrete surfaces. In the case of using portable type, it is also considered effective to use it as a primary evaluation tool for the purpose of understanding the environmental extrinsic forces including difference in location conditions and difference between parts, change over time, etc. by utilizing its simplicity rather than precise analysis of the concentration of the contained chloride ion.

3.3.4 Numerical simulation method

A method using three-dimensional random walk method, which is a kind of particle diffusion method, has been proposed as an advection-diffusion model of airborne salt. This method prepares a virtual wind velocity field calculated from the topography and wind speed at the location of the structure as well as from the shape of the structure in advance, releases a large amount of salt particle model in the virtual wind velocity field, and evaluates the motion of salt particles carried by mean and turbulent flows by three-dimensional numerical simulation. By combining the total amount of airborne salt particles reaching the structure with the advection-diffusion model of airborne salt, it is possible to perform a more detailed environmental extrinsic force evaluation.

3.4 Structure state evaluation

As for the method for evaluating the state of structures, the current technology for each deterioration mechanism shown in Table 2 is summarized. As in the previous section, we will introduce an overview of the case for salt damage.

In general, deterioration due to salt damage is observed at the time after the acceleration stage after the crack caused by steel corrosion occurs. Therefore, the state of members at the point of time when deterioration is expected to become apparent in the future is shown in **Table 5**.

Regardless of the state of the structure, most of the inspected objects do not show deterioration when trying to judge the necessity of measures in a state where deterioration is expected to become apparent in the future. Therefore, the necessity of measures cannot be judged only by visual inspection of the appearance. Therefore, to evaluate the state of the structure, it is necessary to inspect the distribution of chloride ion concentration inside the concrete, the corrosion state and the corrosion risk of the steel material. The report shows the following contents as inspection method and evaluation method of each. In addition, the information for reference has been organized even in previous reports.

Table 5: State of members subject to preventive maintenance

Initiation stage	・Total chloride ion concentration at the steel material location is less than the corrosion threshold chloride ion concentration. ・Steel corrosion has occurred
Propagation stage	・Total chloride ion concentration at the steel material location is higher than the corrosion threshold chloride ion concentration. ・Although steel corrosion has occurred, the expansion pressure due to the generation of corrosion products is at a minor stage, and no corrosion cracking has occurred.
Former acceleration stage (i)	・Total chloride ion concentration at the steel material position is higher than the corrosion threshold chloride ion concentration ・Corrosion cracking, floating, peeling and flaking occur in some parts, due to the expansion pressure of the corrosion products generated by steel corrosion.

Note (i) Even if a crack occurs, it remains localized

3.4.1 Evaluation based on chloride ion concentration distribution

A widely method in practice, is to quantify the chloride ion concentration distribution by chemical analysis of core samples and drilling powder collected from members, and JIS A 1154 (test method of chloride ion contained in the hardened concrete), JSCE-G 573 (measurement method of total chloride ion distribution in the concrete in the actual structure), etc. are used. There is also JSCE-G574 (a surface analysis method for elements in the concrete by EPMA method), which is applied to core samples but has extremely high resolution of analysis results. Once the concentration distribution is obtained, the surface chloride ion concentration and apparent chloride ion diffusion coefficient are obtained by fitting the solution of Fick's diffusion equation, and accordingly, it is possible to evaluate the state of the members from the future prediction of chloride ion concentration at the reinforcing bar position.

3.4.2 Inspection based on corrosion state of steel materials

To evaluate the corrosion state of steel materials, there is a method of directly visually inspecting the reinforcing bar by chipping, or an electrochemical measurement method such as natural potential method and polarization resistance method. Both these methods evaluate the corrosion state of the steel material inside the concrete, and the latter is a method that can quantify the corrosion rate.

3.4.3 Corrosion risk assessment of steel materials

As an additional method for evaluating the corrosion risk of steel materials due to salt damage, there is a method of indirectly nondestructively evaluating the amount of chloride ions and liquid water, which are substances related to steel corrosion. If these quantities can be measured nondestructively and in a short period, it is possible to obtain information on the surface steel material risk, and can be used as a judgment of necessity of measures or an auxiliary information thereof. Specific measurement methods include electrical resistivity method, near infrared spectroscopy, etc.

4. Systematization of repair technology in preventive maintenance

4.1 Overview of examination

4.1.1 Policy of examination

In the conventional maintenance of concrete structures, countermeasures are examined when deterioration becomes apparent, and since budget measures are also taken based on the results of the inspection, it was a system of maintenance that assumed corrective maintenance. Therefore, the inspection/diagnosis technology and repair technology conducted there assume the state where the deformation is actualized, and are not systematized to apply the concept of preventive maintenance. The FS Committee held in 2017 investigated the current state of development and dissemination of the technologies required for inspection/diagnosis and repair in the initiation stage and the propagation stage. This technical committee has summarized the current state of repair methods, further detailed classification, state of applicable deterioration, points to consider when applying, etc. Also, this committee has organized selection and evaluation of repair technology for subsequent maintenance, and has carried out analysis of current situation and extraction of issues.

4.1.2 State of target structure and repair technology

In this committee, the examination target of preventive maintenance is considered as “general maintenance activities to prevent the deformation from becoming noticeable,” and the target structure to be examined is positioned as "a structure wherein the concrete structure is in a deteriorated environment, and is in a state (1) where no deformation has occurred yet, (2) where a slight deformation has already occurred locally, and (3) where deterioration is expected to become apparent in the future. **Table 6** shows the deterioration to be examined and the state of deterioration. No deformation in appearance is observed in any of the factors during the initiation stage. During the progress stage, ASR and frost damage are in a state in which deformation such as fine cracks occurred.

Therefore, this technical committee preceded the examination for "Surface impregnation method," "Surface coating method," "Crack repair method," "Electrochemical repair method" as repair techniques applicable to preventive maintenance. This committee also examined repair materials and construction methods for sewerage structures, which are being maintained based on the concept of preventive maintenance.

4.1.3 How to proceed with examination

We have summarized the current state of repair methods, systematic classification, state of applicable deterioration, and points to consider when applying. The summary was carried out in the format shown in **Table 7**. We also examined the evaluation technology for the selection of repair materials and construction methods. The purpose and timing of evaluation include selection of materials and construction methods (during design), evaluation of construction quality (construction management), evaluation of performance continuity (maintenance management), etc., and the evaluation items and methods of repair technology are summarized in the format shown in **Table 8**.

Table 6: Deterioration process and state of deterioration (carbonation, salt damage, ASR, frost damage)

Deterioration process	State of deterioration			
	Carbonation	Salt damage	ASR	Frost damage
Initiation stage	No visible deformation, carbonation residue is above the rust limit.	No visible deformation, below the corrosion threshold of chloride ion concentration.	Expansion due to ASR and accompanying crack have not yet occurred, and no visible deformation is observed.	Period of time before scaling under freeze-thaw action, fine cracking, and burst-out occurs.
Propagation stage	No visible deformation, carbonation residue is below the rust limit, and corrosion begins.	No visible deformation, above corrosion threshold chloride ion concentration, corrosion begins.	Expansion continues to progress due to the supply of moisture and alkali and cracking occurs; discoloration and leaching of alkali-silica gel are observed. However, no rust fluid due to steel corrosion is observed.	Period of time until scaling, fine cracks, popouts occur; and the aggregate is exposed.

Table 7: Inspection format for repair technology

Large classification	Middle classification	Small classification	Overview	Scope of application *										Upon application	
				Salt damage		Carbonation		ASR		Frost damage		Chemical erosion			
				Initiation stage	Propagation stage	Initiation stage	Propagation stage	Initiation stage	Propagation stage	Initiation stage	Propagation stage	Initiation stage	Propagation stage	Disadvantages /points to note	Advantages/ superiority
Construction method	Classification of construction methods according to principles, materials used, etc.	Sub-classification by method, application method, etc.	Overview of classified construction methods	○/ △/ ×/ ―											

Table 8: Inspection format for evaluation method of repair technology

Repair method		Evaluation method				Application		
Large classification	Middle classification	Evaluation item	Test method	Test period	Standard value, etc.	①Selection of materials and construction methods (design)	②Confirmation of construction quality (construction management)	③ Confirmation of performance continuity (monitoring)
Classification of repair methods		Organized overview of evaluation methods				○ ／ －		

4.2 Inspection results on systematization of repair technology

Regarding the inspection results and their summary, we would like to introduce primarily the surface impregnation method.

Even with a surface impregnation method, it is distinguished by the type of material and reaction mechanism, and the scope of application, application conditions, etc., also differs. And, materials and construction methods that are expected to have anticorrosive effects have also been proposed recently. In the committee report, these are systematically classified, and an overview of each material and construction method is summarized.

Table 9 shows the scope of application according to the factors and degree of deterioration. It organizes and shows that the scope of application differs for each construction method and material. For example, when considering a countermeasure for carbonation, the silane-type surface penetrants is an ineffective countermeasure from the viewpoint of suppressing carbonation because it makes the surface layer of concrete to be in a dry state. However, from the viewpoint of suppressing steel corrosion, it can be an effective countermeasure depending on the state of other deterioration factors and the combined use with other construction methods since being in a dry state works effectively. When fine cracks, etc., are occurring in the propagation stage like ASR, the silane-type and silicate-type surface penetrants are ineffective and can be converted to be an effective countermeasure by a combined construction method in which components such as lithium nitrite that have ASR inhibitory effects are impregnated from cracks. The scope of applicable was examined based on such technical knowledge.

Table 9: Scope of application of surface impregnation method

Middle classification	Small classification	Sub classification	Scope of application: Salt damage – Initiation stage	Salt damage – Propagation stage	Carbonation – Initiation stage	Carbonation – Propagation stage	ASR – Initiation stage	ASR – Propagation stage	Frost damage – Initiation stage	Frost damage – Propagation stage	Chemical erosion – Initiation stage	Chemical erosion – Propagation stage
silane-type surface penetrants method	Silane type	—	○	△	△	△	○	—	○	△	—	—
	Silane/Siloxane type	—										
	Reinforcement corrosion inhibition silane type	Protective layer forming type	○	○	△	△	○	—	○	△	—	—
		Anti-rust compounding type	○	○	△	△	○	—	○	△	—	—
Silicate-type surface penetrants method	Solidified silicate type	Lithium silicate type	△	—	△	△	○	—	△	—	△	—
	Reactive silicate type	Sodium silicate type	○	△	○	○	△	—	○	△	— or △	—
		Potassium silicate type										
		Silicate mixed type										
		Subcomponent complex type										
		others										
Silicate-type + silane-type surface penetrants method	—	—	○	△	○	○	○	—	○	△	— or△	—
Others	Coating type anti-corrosion material combination	Lithium-based	○	○	○	○	○	○	—	—	—	—
		Other salt-based	○	○	○	○	○	○	—	—	—	—

※explanatory notes for scope of application ○ : Applicable, △ : Need to consider for application, × : If applied, it will cause problems, — : Not applicable

Notably, advantages and superiority when applying each material/construction method are summarized as in the example in **Table 10**. Here, although only examples for silicate-based surface impregnation method are introduced, technical information is summarized for each material and method. In this way, by organizing cautionary points, significant points, etc. related to materials selection and construction, it is expected to be useful information for engineers, who perform maintenance through preventive maintenance, when planning, designing, ordering, and managing.

Table 10: Points to note when applying surface impregnation method (excerpt only for silicate-based surface impregnation materials)

<table>
<tr><th>Middle classification</th><th>Small classification</th><th>Sub classification</th><th>Disadvantages/Points to note</th><th>Advantages/Superiority</th></tr>
<tr><td rowspan="7">Silicate-based surface impregnation method</td><td rowspan="2">Solidified silicate type</td><td>Lithium silicate type</td><td rowspan="2">・When a substance inhibits the surface impregnation of a material onto the concrete surface, it is removed by appropriate method.
・The concrete surface should be as dry as possible after curing for a specified period when applied to newly constructed structures, and also to existing structures. (Moisture content about 6% or less)
・In order to demonstrate the effect with drying after construction, it is necessary to have a predetermined period of curing, such as by preventing the construction site from being exposed to rain.
・Impregnation depth is affected by the mixing and drying state of the underlying concrete</td><td rowspan="2">・It can be relatively easy to construct without damaging the appearance of concrete structures.
・Gives alkalinity to the neutralized concrete surface layer and solidifies the fragile concrete surface layer.</td></tr>
<tr><td>Subcomponent complex type</td></tr>
<tr><td rowspan="5">Reactive silicate type</td><td>Sodium silicate type</td><td rowspan="5">・When a substance inhibits the surface impregnation of a material onto the concrete surface, it is removed by an appropriate method.
・The concrete surface should be as wet as possible after curing for a specified period when applying to newly constructed structures, and also to existing structures.
・For waterproofing purposes, the wet condition is retained for more than 2 weeks after construction.
・For solidification purposes, it is cured so that it will not be washed away by rainfall, until the construction surface is dried and hardened. (Approximately 4-8 hours)
・When rainfall is expected, the construction should be ended early or measures should be taken such that rain does not affect the construction site.</td><td rowspan="5">・It can be relatively easy to construct without damaging the appearance of concrete structures.
・Gives alkalinity to the neutralized concrete surface layer and solidifies the fragile concrete surface layer.
・Densification of construction</td></tr>
<tr><td>Potassium silicate type</td></tr>
<tr><td>Silicate mixed type</td></tr>
<tr><td>Subcomponent complex type</td></tr>
<tr><td>Others</td></tr>
</table>

4.3 Evaluation of repair materials and construction methods and future challenges

Evaluation method for materials and construction methods is indispensable for selecting appropriate materials and construction methods. This technical committee examined the current evaluation items and methods, and their application purposes, and carried out extraction of current state and issues.

Regarding the surface impregnation method, JSCE-K-571 "Test method for surface impregnated materials (draft)" and NSKS-04 "Permeable water-absorption preventing materials" are specified for silane-type materials and are used as a reference for material selection. For construction quality confirmation and performance continuity, a method using a surface resistance type moisture meter after water sprinkling can be referred to in the structural construction management guidelines of East/Central/West Nippon Expressway Co., Ltd. However, regarding the actual confirmation of the impregnation depth, there is no standardized method that is non-destructive and relatively easy to implement, although there are some examples in which the confirmation by pull-off method, etc., and the confirmation by EPMA and gas chromatography by collecting sample are being carried out.

For silicate-based materials, JSCE-K-572 “Test method for silicate-based surface-impregnated materials (draft)” and JIS abrasion resistance test are effective as evaluation for material selection. For construction quality confirmation and performance continuity, a method of analyzing alkali impartiality of surface layer by reagents and fluorescent X-ray analysis, a method of analyzing ion distribution by sampling, etc. are being implemented. There are also examples where the modification of the surface layer is evaluated by the rebound hardness and permeability. However, there is no simple and standardized method as with the silane-type materials.

For the surface coating method, crack repair method, etc., although there are evaluation methods and quality standards for material selection, the nondestructive and simple evaluation method for construction state and performance sustainability has not been standardized.

In contrast, for the electrochemical repair method, it is possible to evaluate the anticorrosion effect by repair and its sustainability depending on the potential shift amount by depolarization test, and there are cases where long-term monitoring is a prerequisite for ordering. Since preventive maintenance is not necessarily a maintenance method that completely eliminates deterioration factors, it is important that performance and re-deterioration can be monitored as needed.

As future challenges, several test methods have been proposed for evaluation method for selecting materials and construction methods, and it is fundamental to confirm their consistency and to develop a system to utilize them for design, by accumulating knowledge on whether the test results obtained by the evaluation is in relation with the actual required performance. Also, regarding the evaluation of construction quality and performance sustainability, the development of a method that can evaluate the required performance in a non-destructive and simple manner and the standardization of these methods can be challenging.

5. Current state of maintenance and proposal of maintenance procedures for preventive maintenance

5.1 Current state of maintenance system for preventive maintenance at each organization

5.1.1 Preventive maintenance in expressway structures (NEXCO)

For the maintenance of existing bridges maintained by NEXCO, preventive maintenance is standardized in Design Guidelines Vol. 2 Bridge Maintenance. [3] Furthermore, in the selection of repair and reinforcement methods for concrete structures, preventive maintenance measures are systematically planned after considering the life cycle cost (LCC).

In the flow of deformation measures of concrete bridges, future performance deterioration is predicted for concrete structures in which deformation is not confirmed as a result of inspection, and the preventive maintenance measures are carried out at the appropriate time, if necessary. Specific preventive maintenance measures include pretreatment, patching repair, concrete surface protection work, scrap prevention measures, salt damage measures, and cathodic protection method.

5.1.2 Preventive maintenance in railway structures

For railway structures, the systematization of maintenance for entire railway structures was advanced in Maintenance Standards for Railway Structures and Commentary [4] published in 2007 (hereinafter referred to as Maintenance standards).

The classification of inspection of structures in the Maintenance standards is defined as initial inspection, general inspection, individual inspection, and occasional inspection. As a result of each inspection, soundness is evaluated according to the degree of structure deformation, and it is fundamental to take necessary measures. Therefore, when defining preventive maintenance as maintenance carried out prior to the occurrence of deformation, it has become a system based on so-called corrective maintenance. Thus, the definition of preventive maintenance in the maintenance standards is generally unclear; however, taking measures to prevent future deformation generation and progression is treated as preventive maintenance, at a zero deformation or minor stage so that the structure does not threaten driving security, safety for passengers and the public, etc.

5.1.3 Preventive maintenance in road structures (Hokkaido Development Bureau)

At the Hokkaido Development Bureau, extending the life span of bridges by switching from "corrective maintenance type" to "preventive maintenance type" management is expected to level the reconstruction time of road bridges and maintenance/repair budgets, and reduce life cycle cost, so life-extending measures are implemented before large-scale repair or replacement. Road bridge inspections are carried out on all bridges under management. The inspection results are organized into 9-level judgment classification according to the deformation of the structure. Periodic checks are performed to detect damage early, and the degree of damage, the possibility of third party damage, the magnitude of impact on vehicle traffic, the degree of impact on the road network function such as the presence or absence of a detour, etc. are comprehensively judged, and repairs are carried out from places of high importance.

5.1.4 Preventive maintenance in electric power structures

There are numerous types of concrete structures in the electric power field, such as dams and waterways in the hydropower field, intake-discharge channels and ports in the thermal power/nuclear power field, steel tower foundations and service tunnels in the distribution field. Among the wide range of deterioration factors of concrete structures, the primary deterioration factors are salt damage in thermal/nuclear power generation facility, and abrasion and frost damage in hydropower generation facility.

Unacceptable performance degradation in electric power facility is "performance degradation that may cause a public disaster during service period or cause power supply disruption," and as a general rule, maintenance is performed to ensure appropriate measures are taken at an appropriate time in accordance with the maintenance flow and criteria so as not to reach that point. Furthermore, depending on the degree of structural importance and degree of deformation, it is categorized into those that require immediate measures, those that are inspected thoroughly, etc., and the judgment of the necessity of repair and the execution time are set under the principle of not causing unacceptable deformation, and the leveling of maintenance cost is aimed so that repairs do not concentrate at one time. Although this is a corrective maintenance in that it allows the deformation to some extent, this system assumes preventive maintenance that does not lead to unacceptable performance degradation.

5.1.5 Preventive maintenance in buildings

Among the buildings, especially for maintenance of condominium buildings, the Ministry of Land, Infrastructure, Transport and Tourism has formulated the "Standard Condominium Management Bylaws," which is the format for condominium management regulations. Among the repair plans to be carried out in the maintenance process of this regulation, large-scale repairs to be carried out every 10 to 15 years are painting work for iron parts, exterior wall painting work, roof waterproofing work, water supply pipe work, drainage pipe work, etc. In this way, it can be said that most of the buildings consequently carry out preventive maintenance activities regardless of the deformation of the concrete body, since the exterior wall painting renovation is carried out periodically by systematically carrying out routine inspection diagnosis, and large-scale repairs.

5.2 Considerations for implementing preventive maintenance in accordance with deterioration mechanism

5.2.1 Salt damage

Regarding the concept of preventive maintenance, it can be said that the initiation stage, the propagation stage, and the former acceleration stage are the timings for performing preventive maintenance when the purpose is to "not make the deformation noticeable in the future."

The necessary inspection items for preventive maintenance include deformation of appearance, chloride ion concentration, corrosion of steel, environmental conditions, etc., and it is necessary to select them according to the deterioration process.

Prediction and performance evaluation include prediction of chloride ion diffusion to estimate the period of initiation stage, and prediction of reinforcement corrosion progress to estimate the period from propagation stage when reinforcement corrosion begins to former acceleration stage when corrosion cracking occurs.

5.2.2 Carbonation

Regarding the concept of preventive maintenance, the targets of preventive maintenance are the initiation stage, the propagation stage, and the early stage of acceleration stage when the purpose is to "not make the deformation noticeable in the future".

Regarding necessary inspection items for preventive maintenance, the items necessary to confirm the degree of deterioration due to carbonation include depth of carbonation, position of the steel material, deformation of appearance, etc., and the items necessary to predict deterioration progress include environmental conditions such as temperature, humidity, and water spill, etc.

Prediction and performance evaluation include prediction of progress of carbonation performed to estimate the period of initiation stage, and prediction of reinforcement corrosion progress to estimate the period from propagation stage when reinforcement corrosion begins to former acceleration stage when corrosion cracking occurs.

5.2.3 Alkali-silica reaction

Regarding the concept of preventive maintenance, in the alkali-silica reaction, effective preventive maintenance is often difficult because the degree of progress of deterioration varies greatly, due to the action of natural environment during service, the action of other deteriorated extrinsic forces (water leakage, spraying of de-icing salt, etc.), etc. However, in regions where deteriorations have been reported in large numbers, it may be effective to formulate maintenance plan that assumes preventive maintenance in the initiation stage and propagation stage.

Regarding necessary inspection items for preventive maintenance, it is considered that initial inspection which is carried out to clarify the presence or absence of possibility of alkali-silica reaction and to determine the necessity of measures is important.

Regarding prediction and performance evaluation, it is difficult to predict this quantitatively since various factors such as type and amount of reactive minerals in the aggregate, reinforcement state of members, environmental conditions (temperature and water supply condition) have a complex effect on the progress of expansion due to the alkali-silica reaction. In the Concrete Standard Specification, the prediction of progress of expansion may use either method of inspection-based method or method combining test results and analysis.

5.2.4 Frost damage

Regarding the concept of preventive maintenance, it is fundamental to suppress contact and intrusion of water and chloride ions in frost damage. During the initiation stage, application of surface coating and surface impregnation, and proper wastewater treatment are listed as the main countermeasures, and after the initiation stage, it is common to take measures to stop water and conduct water treatment after recovering the performance by presence or absence of fine cracks, width and depth, crack injection/filling according to scaling depth, etc., and patching repair.

As necessary inspection items for preventive maintenance, the following are considered: supply of water and chloride ions, solar radiation action and outside temperature (minimum temperature), number of freeze-thaw cycles that have acted so far (years elapsed), etc.

For prediction and performance evaluation, method that use a frost damage risk map and method that predict the progress of frost damage are there.

5.2.5 Chemical erosion

Regarding the concept of preventive maintenance, it is important to know the design concept for chemical erosion of the concrete structure. Chemical erosion is taken into consideration at the time of design such as concrete for sewerage and structures constructed on sulfate soil and concrete in an environment that comes into contact with acids and sulfates, and when some measures are taken, it is necessary to confirm specific methods of classification and measures such as whether or not to allow concrete deterioration to some extent, estimated deterioration mechanism, etc.

Regarding necessary inspection items for preventive maintenance, according to Concrete

Standard Specification [Maintenance Edition], it is stated that monitoring should be considered for structures that perform preventive maintenance, for the purpose of continuously grasping generation status of hydrogen sulfide (H_2S) gas, concentration of deterioration factors, temperature, humidity, carbon dioxide (CO_2) concentration, presence or absence of rusting of steel materials in concrete, etc.

Regarding prediction and performance evaluation, it is not always easy to predict the progress of chemical erosion, and various methods are taken according to the situation. The Concrete Standard Specification [Maintenance Edition] shows method using inspection results, method by accelerated tests, and method by numerical analysis considering migration and reaction of environmental conditions and deterioration factors.

5.3 Proposal of maintenance procedures for preventive maintenance

5.3.1 Flow of preventive maintenance type maintenance procedures

The flow of preventive maintenance procedures proposed by this technical committee is shown in **Figure 4**. First, as a result of standard inspection (periodic check), it is judged whether the condition of the target structure is "not yet deformed" or "a slight deformation has occurred." If a non-minor deformation has occurred, move to corrective maintenance type maintenance. If it falls within the scope of preventive maintenance, the manager who carries out the maintenance next judges whether to perform preventive maintenance. When it is judged that preventive maintenance is to be performed, evaluation of environmental extrinsic force, estimation of deterioration mechanism, implementation of deterioration prediction are carried out, and the manager who carries out the maintenance judges the necessity of preventive maintenance measures. In judging whether or not preventive maintenance measures are needed, it is important to ascertain whether deterioration will become apparent in the future though the present state is a state where "no deformation has occurred yet" or "a slight deformation has occurred". In addition, evaluation of environmental extrinsic force, estimation of deterioration mechanism, implementation of deterioration prediction are basically carried out quantitatively in detail, but if reliable evaluation can be performed under similar environmental conditions and deterioration conditions until now, it may be implemented simply based on actual results. When it is judged that preventive maintenance measures are necessary, candidates for preventive maintenance measures are selected, a comparative examination of the measures is conducted based on actual results, LCC evaluation, degree of structural importance evaluation, etc., and the type of measures is selected. At this time, it is also possible to select the corrective maintenance measures by comparing preventive and corrective maintenance measures based on the evaluation of the manager who conducts the maintenance. When preventive maintenance measures are selected, specific preventive maintenance measures are selected from the comparison results and implemented.

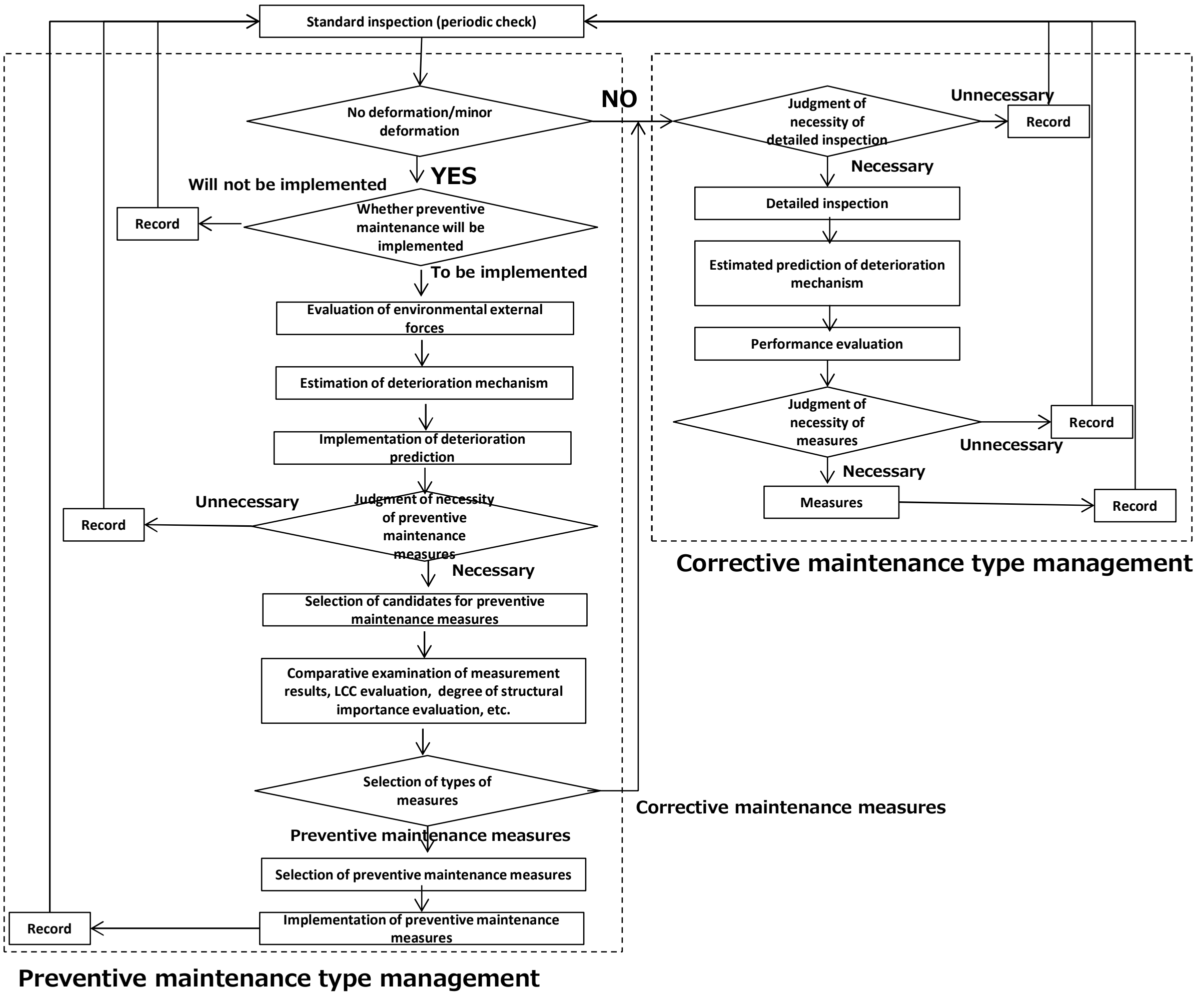

Fig. 4: Flow of preventive maintenance procedures

5.3.2 Preliminary calculation example of LCC for preventive maintenance

For road bridge superstructures constructed in the coastal part of the Sea of Japan, LCC for preventive maintenance was calculated for the case when deterioration due to salt damage occurs. In order to examine the effect of deterioration rate, the deterioration rate is set to three levels, large, medium, and small, and when the time to start preventive maintenance is set to the initiation stage, the propagation stage, or the former acceleration stage, the conditions under which LCC becomes advantageous by performing preventive maintenance compared with corrective maintenance are summarized.

6. Conclusion

It seems effective to carry out preventive maintenance from the viewpoint of preventing accidents in concrete structures, extending their life span, and reducing LCC. According to the questionnaire survey conducted for engineers, it was observed that there were several opinions such as budget, manpower resources, awareness for ordering side, maintenance of guidelines, and systematization of technology, to disseminate preventive maintenance in the future. From these results, it is important to organize and systematize the technologies applicable for preventive maintenance, and it is considered that transmitting such information will raise the awareness of the orderers and the builders. In recent years, a number of techniques have been developed to evaluate environmental extrinsic forces, to inspect/diagnose and repair structures that can be applied to preventive maintenance, and it is considered that effective preventive maintenance can be conducted by appropriately using these technologies. In addition, although this committee proposed maintenance procedures for preventive maintenance, it is considered that selection of preventive maintenance measures technology and LCC evaluation are important when implementing it.

In the future, it is expected that procedures for preventive maintenance will be established by enhancing inspection/diagnosis techniques, establishing a test method for selecting repair techniques, and accumulating and verifying LCC evaluations, and that the transition from corrective maintenance type to preventive maintenance type will advance.

Acknowledgment

We have received a great deal of cooperation from many associations, organizations, companies, and engineers for the questionnaire survey conducted by this committee. We would like to express our gratitude by mentioning it at the end.

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