Committee Report: JCI- TC201A

Technical Committee on the Role and Application of Academic Research in Predicting the Deterioration of Concrete Structures

Yoshitaka KATO[*1], Manabu KANEMATSU[*2], Takeshi IYODA[*3], Takahiro NISHIDA[*4], Koichi MATUZAWA[*5]

Abstract

This technical committee conducted its activities to link engineering models used in deterioration prediction in maintenance management and the results of environmental and phenomenological evaluations with the survey results of actual structures. We summarized earlier academic results (theoretical and phenomenological results) and survey methods related to structural deterioration and investigated approaches to utilize these results for the deterioration prediction of actual structures. Further, we focused on water as an action, summarized concrete deterioration and rebar corrosion, and we summarized the current status of research and issues, which includes those on structural performance evaluation.

Keywords: Deterioration prediction, academic research, water and concrete deterioration, water and rebar corrosion, performance evaluation

1. Introduction

In concrete structures, the extent of deterioration varies depending on the materials used, construction conditions, environmental conditions of the structures in service, and other factors. Therefore, it is important to determine the causes of deterioration accurately, predict the deterioration progress with the necessary accuracy, and perform structural maintenance to ensure that these structures can satisfy the predetermined performance over the planned service period. Complex environmental actions and physicochemical phenomena need to be considered to predict the deterioration progress of actual structures for maintenance management accurately. The prediction method is very complicated even if these effects can be considered in deterioration prediction. Meanwhile, the use of engineering prediction methods is considered desirable for practical maintenance management. Information obtained from structures impacted by the actual environment over time can fill the gap between the above two aspects.

Table 1: Member composition of JCI-TC-201A "Technical Committee on the Role and Application of Academic Research in Predicting the Deterioration of Concrete Structures"

Chair	Yoshitaka Kato	Tokyo University of Science
Vice-chair	Manabu Kanematsu	Tokyo University of Science
Secretary-general	Takeshi Iyoda	Shibaura Institute of Technology
[Water and concrete deterioration WG]		
Chiefs	Koichi Matsuzawa	Building Research Institute
	Yuko Ogawa	Hiroshima University
	Kentaro Koike	Kagoshima University
	Yoshinori Gondai	National Institute of Technology Sendai College
	Yuya Sakai	The university of Tokyo
	Kennosuke Sato	Yamanashi University
	Madoka Taniguchi	Hokkaido Research Organization
	Atsushi Teramoto	Hiroshima University
	Atsushi Tomoyose	The university of Tokyo
	Takeshi Iyoda	Shibaura Institute of Technology
[Water and reinforcing bar corrosion WG]		
Chiefs	Takahiro Nishida	Shizuoka Institute of Science and Technology
	Keiyu Kawaai	Ehime University
	Masaki Sakai	Obayashi Corporation
	Kohei Sakihara	University of the Ryukyus
	Akio Tanaka	Nippon Institute of Technology
	Katsufumi Hashimoto	Hokkaido University
	Yoshinao Hoshi	Nagoya Institute of Technology
	Manabu Kanematsu	Tokyo University of Science

This committee summarized earlier academic research results (theoretical and phenomenological) and survey methods related to the deterioration of structures, and they investigated their use in the deterioration prediction of actual structures.

The committee members are listed in Table 1. The committee held all meetings online because of the impacts of the COVID-19 pandemic. During the first year, we discussed academic research on the titles presented in Table 2. The research was introduced in a wide variety of ways; information such as the investigation of the deterioration mechanism, evaluation of deterioration scenarios, and measurement methods were collected. These discussions indicated that water plays a major role in concrete deterioration and steel corrosion. In concrete, water was added as a unit water volume and used for hydration reactions in cement. Further, water needs to be retained during curing. Meanwhile, moisture often intervenes in the physical characteristics and deterioration of concrete and corrosion of reinforcing bars when considering the progressive deterioration over long periods of time. Thus, we established the two WGs of "water and concrete deterioration" and "water and reinforcing bar corrosion," and we focused our discussions on water.

Fig. 1 shows each correlation diagram. Substances that move in concrete were divided into gas, liquid, and ions; we discussed the characteristics of each mass transfer. Then, we focused on the water, and we summarized the effects of water supply by curing and internal curing on concrete strength as the physical characteristics of concrete. In addition, we summarized the effects of the presence of water on concrete strength and material permeation tests. We focused on topics that committee members are actively researching in terms of water and concrete deterioration; we also summarized their involvement with water. Moreover, we summarized the existence of water and the cases where water is used as a medium with topics focusing on the effects of water on drying shrinkage, neutralization shrinkage, and frost damage, and on the sulfate attack and ASR.

Table 2: Introduce for latest research from the members of committee

Date	Lecturer	Title
First session: 6/25	(1) Kohei Sakihara	Proposal of salt-damage environmental assessment method using machine learning
	(2) Madoka Taniguchi	Recent efforts in Hokkaido
	(3) Katsufumi Hashimoto	Detection of cracks in concrete using laser-excited elastic waves
Second session: 8/5	(1) Kentaro Koike	Moisture movement characteristics and corrosion characteristics in bridges parts where water is applied
	(2) Atsushi Teramoto	Soundness evaluation of ASR-deteriorated structures
	(3) Yoshinao Hoshi	Corrosion evaluation and monitoring of reinforced concrete by electrochemical impedance method
Third session: 9/14	(1) Takahiro Nishida	Impressions of concrete mixed with seawater and its reality
	(2) Keiyu Kawaai	Measurement techniques for water permeation and oxygen permeation
	(3) Masaki Sakai	Research on the prediction of neutralization and reinforcing bar corrosion in construction fields and countermeasures
Fourth session 11/30	(1) Atsushi Tomoyose	Role of academic research on volcanic glass powder and utilization of its results
	(2) Yuya Sakai	New utilization of mercury porosimetry method and investigation of moisture movement in concrete
	(3) Kennosuke Sato	Investigation on secondary ettringite formation behavior using synthetic hydrates
	(4) Takeshi Iyoda	Meaning of neutralization progression and acceleration tests using mixed cement
Fifth session: 12/10	(1) Manabu Kanematsu	Rethinking the limit state of reinforced concrete buildings
	(2) Yuko Ogawa	Internal curing effect of waste tile aggregates on material permeability of blast furnace cement concrete
	(3) Akio Tanaka	Calibration of surface air permeability tests and measurement of bubble structure
Sixth session: 3/11	(1) Yoshinori Gondai	Basic study on scaling characteristics of concrete in stress fields
	(2) Koichi Matsuzawa	Effects of finishing materials on concrete neutralization and rebar corrosion over a 30-year exposure period
	(3) Yoshitaka Kato	Major realizations through research relating to the understanding of phenomena: using salt damage as an example

---

*1 Tokyo University of Science Faculty of Science and Technology Department of Civil Engineering, D.Eng. (Regular member)

*2 Tokyo University of Science Faculty of Science and Technology Department of Architecture Professor, D.Eng. (Regular member)

*3 Shibaura Institute of Technology Faculty of Engineering Innovative Global Program Professor, D.Eng. (Regular member)

*4 Shizuoka Institute of Science and Technology Faculty of Science and Engineering Department of Civil Engineering Professor, D.Eng. (Regular member)

*5 Building Research Institute Department of Building Materials and Components, D.Eng. (Regular member)

In addition, we summarized items that can be measured, and we discussed the possibility of the applications to deterioration prediction.

We focused on the destruction of the passive film caused by neutralization and salt permeation by considering the action and mass transfer for water and rebar corrosion. To this end, we summarized information on the corrosion environment and its rate-determining conditions and the measurement items to determine the progress of deterioration for each rate-determining condition; further, we attempted to investigate the deterioration prediction.

In Fig.1, the action and mass transfers are expressed as arbitrary time T and changes in concrete physical properties, progress of concrete deterioration, and progress of reinforcing bar corrosion expressed as T+ΔT based on the results. These phenomena progress continuously with time at every moment. In contrast, the measurements conducted during maintenance management are conducted discontinuously with respect to time such as appearance surveys conducted once every five years, nondestructive measurements implemented as required, and measurements that use cores. Further, we will investigate methods that evaluate the deterioration prediction and performance based on measurement results at a given time X while repeated permeation and deterioration of substances occur over time as shown here. We investigated the results of academic research and its utilization in maintenance management.

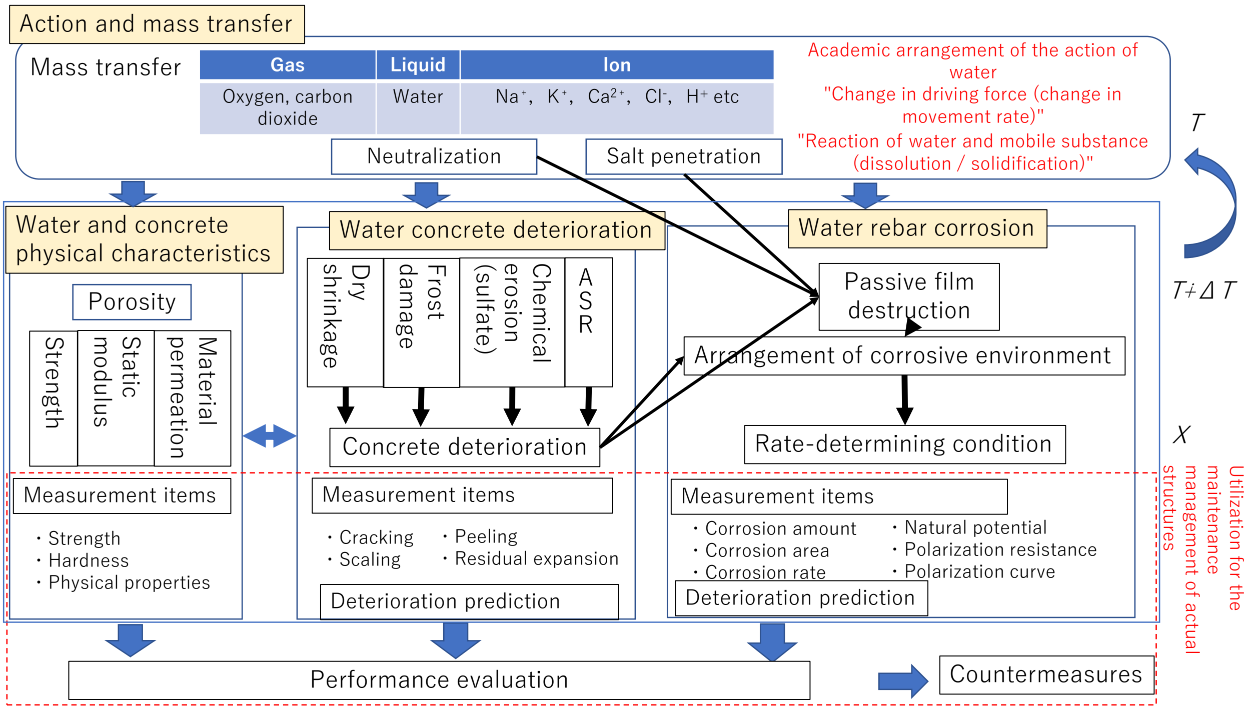

Fig.1: Relationship water concrete deterioration and water rebar corrosion

2. Actions and mass transfer

2.1 Gas movement

Substances in concrete are assumed to move through voids that exist in concrete. There are several voids in concrete, and it is believed that they are connected in a complicated manner. Gas movement needs to be considered separately because nitrogen and oxygen do not react with cement hydrate and carbon dioxide react with the hydrate. The gases that do not react with hydrates move in the voids, and the oxygen is believed to affect the rate of corrosion. It is believed that the movement depends largely on the connectivity of voids when only the gas movement is considered; the connectivity of voids can be determined by pressure air permeability tests and others. Meanwhile, the movement of carbon dioxide is affected by diffusion and chemical reactions when there are chemical reactions with hydrate such as carbon dioxide. Furthermore, carbonation causes a decrease in pH, and this can promote rebar corrosion. Further, the reaction between carbon dioxide and hydrates such as calcium hydroxide and C-S-H causes the voids to become denser and coarser, which also affects subsequent mass transfer characteristics.

Regardless of the presence or absence of reactions with the hydrate, the movement of gas depends on the water content of the hardened product. The water content has been known to also affect the chemical reaction rate if the reaction with a hydrate occurs; it is important to consider the water content of concrete when discussing the movement of gas in concrete.

2.2 Moisture movement

Water that infiltrates concrete structures has a dominant effect on various deterioration events such as rebar corrosion, frost damage, and alkali-silica reactions, and therefore, it is important to understand its infiltration behavior. Water that infiltrates into concrete takes the form of liquid water and water vapor. However, during the infiltration, the liquid water evaporates into water vapor; the water vapor condenses into liquid water, and thus, it is difficult to measure and evaluate these separately.

Thus, we divided water into “water vapor” and “liquid vapor,” We conducted trial calculations of water vapor infiltration with the assumption that diffusion was involved for water vapor. Liquid water infiltration uses capillary tension as a driving force for liquid water, and we compared the movement rates for each.

2.3 Ion movement

Ion movement in concrete involves many ions such as Na^+ and Ca^{2+} as indicated in Fig. 1. We focused on the movement of Cl^- (chloride ion), which is a factor that causes salt damage. We investigated the effect on the movement of chloride ions and summarized the driving force (boundary conditions) and mass transfer (diffusion coefficient, etc.). In addition, ion permeation mechanisms involve not only concentration diffusion but also the influence of water movement caused by repeated dry and wet conditions and the adsorption and immobilization of chloride ions when considering the permeation of chloride ions in an actual environment. Thus, we summarized the effects of concentration diffusion, water transfer, and chloride ion adsorption/immobilization. Further, we summarized issues with the current concentration diffusion model, which is treated as a macroscopic diffusion phenomenon of chloride ions into concrete, and the phenomenon of the stagnation of chloride ion permeation into concrete.

3. Water and concrete physical characteristics/deterioration

3.1 Water and concrete physical characteristics

Wet curing during the hardening process of concrete is important for developing its strength. We summarize the relationship between the strength characteristics of concrete and each curing aspect and the effect of each curing aspect on the strength characteristics of concrete.

The self-drying concrete may hinder strength development. A proposed method for alleviating this self-drying is an internal curing method in which an internal curing material in a highly moisturized state is kneaded into the concrete; the internal curing material supplies curing water to a dried-cement hardened body. Therefore, we summarized the relationship between internal curing and the strength characteristics of concrete.

The moisture condition of the concrete surface layer has an effect when measuring the strength of concrete. Therefore, we showed the effect of water content on the test.

3.2 Water and concrete deterioration

3.2.1 Volume change (shrinkage)

Concrete expands because of water absorption and shrinks when dried (dry shrinkage). Further, hydration reduces volume after the onset of condensation (self-shrinkage). The self-shrinkage increases with an increase in unit cement amount, and therefore, this needs to be considered for high-fluidity concrete, high-strength concrete, and mass concrete. The length and volume changes with variations in temperature (i.e., volume change due to temperature change) based on the environment in which the concrete is placed. Here, we summarized mechanisms related to this volume change (shrinkage). In addition, we focused on shrinkage cracks that occur because of these volume changes, and we summarized how to conceptualize measures taken before and after their occurrence.

In addition to the above-mentioned studies on volume change, other studies have investigated carbonation shrinkage, wherein concrete shrinks with carbonation. We summarized the mechanism of carbonation shrinkage in concrete based on research examples.

3.2.2 Frost damage

The frost damage to concrete can be divided into internal deterioration, scaling, and pop-out. Internal deterioration causes expansion and shrinkage deformation under freeze–thaw actions; the deteriorated concrete undergoes residual deformation after thawing. In actual structures, hexagonal cracks occur initially; however, the concrete peels and collapses with progress in deterioration. Scaling is the gradual peeling of the surface layer of concrete, and thus, it is promoted significantly by the action of chloride ions in addition to freezing and thawing. Pop-out is a phenomenon in which coarse aggregates, which is porous and has a high-water absorption rate, and it expands and breaks because of freezing and results in the peeling of the surface mortar layer.

These factors that affect these types of frost damage can depend on the material and composition (adjustment); however, they are affected greatly by environmental factors such as temperature, water content, and the number of freeze–thaw cycles, and by water. We summarize the effects of water on frost damage and the countermeasures.

3.2.3 Sulfate attack

Chemical erosion refers to the deterioration phenomenon where the cement hydrate in concrete causes a chemical reaction and changes the quality of the hydrate because of erosive substances such as acids, inorganic salts, and corrosive gases supplied from the external environment. Various types of corrosive substances have been targeted; however, according to the JSCE Standard Specifications for Concrete Structures [Maintenance Edition]1). Even among inorganic salts, the sulfate is classified as having an action of reacting with cement hydrate in concrete to form an expansive compound and deteriorate the concrete by the expansion pressure. We classified and organized the mechanism of sulfate attack, which includes the forms of deterioration that have been clarified in recent years.

An external sulfate attack (ESA) involves sulfate being supplied from the surrounding environment (e.g., soil, groundwater around the concrete structure) and resulting in the progression of the deterioration of concrete. The sulfate ions that infiltrated the concrete chemically reacted with minerals that compose the hardened material to form secondary minerals; this produces an expansive force. This expansive force results in the manifestation of defects such as cracks; however, the types of secondary minerals produced by the chemical reaction with sulfate ions change in the deterioration process of ESA and the form of deterioration caused by differences in the concentrate saturation state and pressure gradient. Thus, we investigated the effect of water on ESA. Then, we summarized the prediction model of ESA, its problems, and the suppression measures.

3.2.4 ASR

Among the alkaline aggregate reactions, the alkali-silica reaction (ASR) is a harmful long-term deterioration process that progresses at various levels. This is caused by silica ions in the aggregate and alkaline ions that coexist with water in the pore solution (reaction product level). The generated alkaline silica gel swells when exposed to moisture and increases the internal pressure, which results in the formation of cracks in the aggregate and cement paste (aggregate level). This causes the concrete to expand and reduce its mechanical properties (concrete level). The decreased material performance results in the decreased performance of the member both in terms of structural yield strength and durability (structural level).

We summarize models based on the concrete expansion strain, internal pressure, gel formation, and ion diffusion reaction, which are prediction methods for ASR, in addition to the roles of water from the ASR expansion model.

4. Water and rebar corrosion

4.1 Investigation policy

Water affects the corrosion reaction rate of reinforcing bars in concrete by changing the corrosion reaction field and supply of corrosion-causing substances and the rate-determining conditions of the corrosion reaction caused by fluctuations in the water amount. A corrosion reaction is a general reaction that comprises several elementary reactions (processes); the overall rate is determined by the balance of these elementary reactions. Thus, changes in the rate-determining condition of a corrosion reaction signifies a change in the corrosion rate; this is a crucial factor in the accurate evaluation of the corrosion rate, future prediction, and selection of countermeasures. Considering rate-determining conditions allows the application of appropriate measurement techniques, prediction of future corrosion rates, and clarification of targets to be suppressed. Therefore, , e focused our discussions on how moisture conditions change the rate-determining conditions, and what evaluations should be conducted based on utilizing them for maintenance management.

Rate-determining conditions include (1) oxygen diffusion, (2) charge transfer (near the reinforcing bar), (3) concrete resistance rate-determination, and (4) mixing rate-determining factor because oxygen has a large impact on the corrosion rate despite not being a rate-determining factor. We assumed that the passive film of the reinforcing bar was destroyed (after the development stage) to focus our discussion here; the phenomenon of moisture permeation into concrete was not the main topic of discussion.

4.2 Classification of the environment for rebar corrosion

Environments in which reinforced concrete can be exposed includes underwater, constant wetting, repeated drying and wetting, dew condensation, and drying. The amount of water and oxygen supplied to the surface of the reinforcing bars needs to be determined to understand the rate-determining conditions in the progress of corrosion of reinforcing bars. However, we focus on the effect of water on rebar corrosion; we summarized the corrosive environment of reinforcing bars as listed in Table 3 with reference to guidelines such as those from the Japan Society of Civil Engineers1), Architectural Institute of Japan2), and ISO3). In each environment, we set the condition of reinforced concrete (visual surveys, etc.) as the input for summarizing changes in the state of water around the reinforcing bar and impact on the corrosion of the reinforcing bar in the concrete and the product type and rate magnitude. Furthermore, we considered the combinations of each environment to consider anode and cathode reactions.

4.3 Rate-determining conditions for rebar corrosion reaction

The metal generates a potential difference at the interface in contact with the aqueous solution when a metal is immersed in an aqueous solution (ion conductor) as an electrode (electron conductor). This potential difference (internal potential difference) is called the electrode potential; when the electrode potential is determined by the corrosion reaction of the metal, it is called the corrosion potential. Unlike the electrode potential determined by an equilibrium system in which the anode and cathode reactions are opposite to each other (i.e., equilibrium potential); the corrosion potential is determined by a mixed system in which the anode and cathode reactions are a completely different combination of reactions. Simplifying the rate-determining conditions after considering the electrode reaction process and summarizing them yields the following:

a) Supply of reactive species in the solution to electrode surface (diffusion process).

b) Reduction of reactive species by receiving the electrons from the electrode (charge transfer process).

c) Diffusion process from the electrode surface of the product to bulk (position away from electrode surface)

In reinforced concrete, the electrochemical reaction progresses through the generation of a potential difference at the interface between the reinforced concrete and water infiltrated from inside the concrete (electrolyte). Meanwhile, the region surrounding the reinforcing bar in the concrete is an alkaline environment, and therefore, a high corrosion resistance is present because of the formation of a stable passive film on the surface of the reinforcing bar. Further, the cover thickness of the reinforced concrete can be a factor attributed to water infiltration and reaction resistance.

Thus, we focused on the three rate-determining factors of (1) oxygen diffusion, (2) charge transfer (iron dissolution), and (3) concrete resistance; we considered recent research examples and summarized the rate-determining conditions for corrosion reactions of reinforcing bars in concrete.

4.4 Various factors and corrosion rate

The rate-determining condition determines the corrosion rate, and therefore, it is important to identify it to deal with the corrosion of reinforcing bars in concrete. Meanwhile, this can be beneficial in practice to evaluate the corrosion rate using other factors as indices. Thus, we summarized examples that present the relationship between the general composition, environmental indices, and corrosion rate. We focused on water content, temperature, humidity, water application, neutralization, chloride ion concentration, water-cement ratio, and rebar cover. Yamamoto et al.4) investigated the corrosion of reinforcing bars in concrete with a cover of 100 m. They reported that the relationship between the relative humidity and corrosion rate/corrosion area ratio4) and this indicates that the corrosive properties differed greatly depending on the relative humidity.

Table 3: Environmental classification for the corrosion of reinforcing bars in concrete

Environmental classification (Major classification)	Environmental classification (Minor classification)	Example of environment
Noncorrosive environment	Dry environment (Noncorrosive)	・ Parts where drains function under bridges and viaducts, and where there is no water supply from above.
Corrosion environment	Constantly wet environment (Low corrosion)	・ Parts constantly underwater ・ Parts constantly underground.
	Humid environment (Moderate corrosion)	・ Environment where raindrops directly hit concrete surface when raining ・ Exteriors, balconies, rain-exposed interior corridors, staircases, rooftops, etc.
	Repeatedly drying and wetting environment (High corrosion)	・ Parts where water leaks from the top ・ Parts where water is retained and is difficult to dry such as cracks or joints, etc.

4.5 Evaluation of rebar corrosion considering rate-determining conditions

The corrosion reaction in concrete includes an anode reaction where the iron dissolves, and cathode reaction, where oxygen and water are consumed. The previously mentioned rate-determining conditions control these reactions for determining a corrosion rate. The relationship between the rate-determining condition and corrosion reaction is summarized as shown in Table 4. In addition, the relationship between each elementary reaction (anode reaction or cathode reaction) with the overall corrosion reaction rate is considered for clarifying what should be used as a measurement index. Further, this table summarizes the relationship with the measurement method. In this report, we mentioned countermeasures for rebar corrosion in concrete that consider these elementary reactions.

Table 4: Relationship between rate-determining condition and anode/cathode reaction and evaluation method

Rate-determining condition	Type of elementary reaction		Corrosion-rate evaluation method			
	Anode reaction	Cathode reaction	Natural potential	Polarization resistance	Polarization curve	Electrical resistivity
Oxygen diffusion	×	○	—	△	○	—
Charge transfer	○	○	—	○	○	—
Resistance (Macro-cell)	— (Concrete resistance between two)		—	○	○	○
Mixing	×	○	—	△	○	—

5. Performance Evaluation

It is appropriate for evaluating and predicting the decreased performance of a structure caused by deterioration based on the change over time in the material property values of the reinforcing bar and concrete. Deterioration indices show that reinforcing bar damage (corrosion) include the physical damage of the reinforcing bars and adhesion characteristics between the reinforcing bars and concrete. The deterioration indices that show concrete damage include the mechanical properties of the concrete itself, cracks, adhesion, and fixing characteristics between the reinforcing bars and concrete and cross-sectional defects. There is a decreased performance attributed to material properties of concrete and reinforcing bars shown as a single problem; the decreased performance is shown as an environmental problem of concrete and reinforcing bars. The performance of concrete structures should be evaluated in combination with the various decreases in performance.

We can see a deterministic evaluation method and probabilistic classification evaluation method when arranging the performance evaluation methods. For example, the former may deterministically confirm the desired possessed performance using finite element analysis; the latter may obtain the possessed performance as a probability distribution on the premise of a phenomenon of substance penetration or material-specific variation. Further, there are cases where the measured values that indicate deterioration are directly evaluated, and cases where they are indirectly evaluated. For example, the former may include cases where the corrosion rate is directly determined, and the latter may include cases where the state is evaluated using natural potential.

We classified these deterministic/probabilistic performance evaluation methods that used direct/indirect indices into four quadrants, and we summarized them as shown in Fig. 2. Furthermore, based on the conceptualization of these performance evaluation methods, we clarified the measurement techniques in need of development and sophistication in the future by summarizing findings related to the latest measurement techniques and discussed their utilization methods.

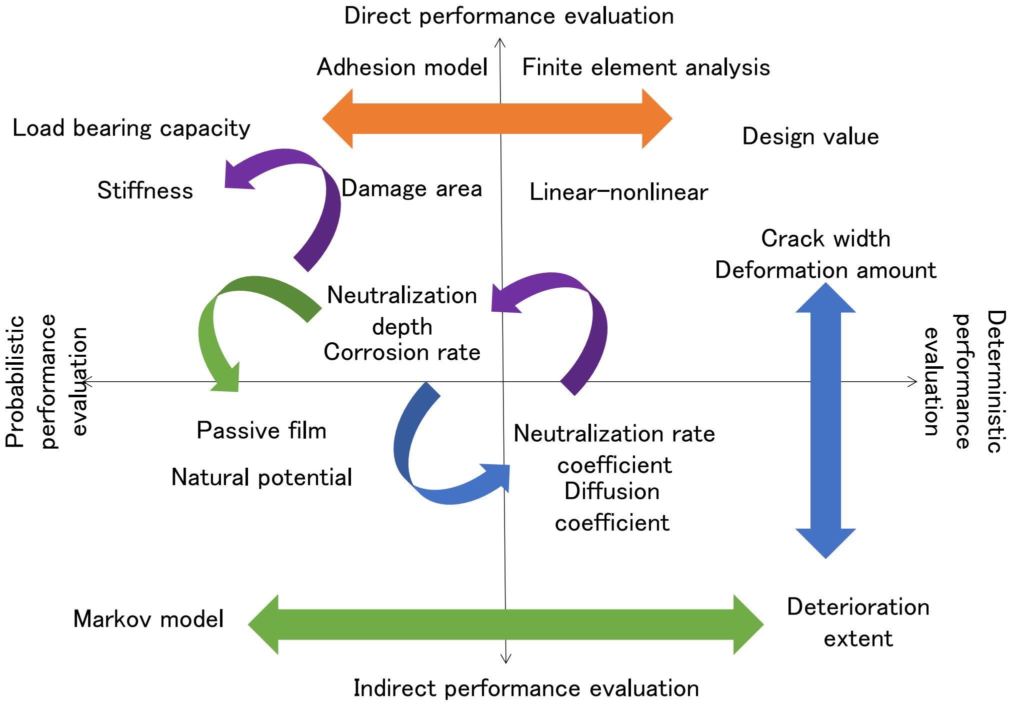

Fig. 2: Summary of the performance evaluation methods

6. Conclusion

In this committee, we discussed the possibility that the results of the academic research will lead to the deterioration prediction of actual reinforced concrete structures by identifying the relationship between water and concrete deterioration and with rebar corrosion. Thus, we re-affirmed the importance of predicting deterioration that can occur by sufficiently evaluating environmental actions; we propose a series of flow processes to deterioration prediction and performance evaluation that use measurable items.

References

1) Japan Society of Civil Engineers, Standard Specifications for Concrete Structures, 2018 [Maintenance Edition]

2) Architectural Institute of Japan, Recommendations for Durability Design and Construction Practice of

Reinforced Concrete Buildings, 2016

3) ISO 22965-1 Concrete — Part 1: Methods of Specifying and Guidance for the Specifier, 2007

4) Yamamoto, K., et al.: Basic experiment on the effect of moisture content of concrete on rebar corrosion, Proceedings of the Japan Concrete Institute, Vol. 23, No. 2, pp. 535-540, 200