Committee Report: JCI-TC172A

Technical Committee on Clarification of Mechanism and Countermeasure for Combined Deterioration of RC structure

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Abstract

The rate of damage propagation within reinforced concrete structures exhibiting combined deterioration is sometimes higher than that within structures exhibiting single deterioration. However, there has been no systematic organization of information in this regard since that performed by the "Technical Committee on Evaluation, Operation and Management Planning of Concrete Structures with Combined Deterioration" by the Japan Concrete Institute from 2000 to 2001. Therefore, this study has sought to organize the research and survey results regarding combined deterioration caused by chloride attack and carbonation, chloride attack and frost damage, chloride attack and alkali–silica reaction (ASR), frost damage and ASR, and delayed ettringite formation (DEF) and ASR, which have been identified since 2002. Thereafter, the propagation mechanism of combined deterioration in actual structures has been closely examined, and measures for repair and reinforcement of these structures are discussed.

Keywords: combined deterioration, propagation mechanism, fact-finding investigation, results of measures, preventive maintenance, corrective maintenance

1. Introduction

Reinforced concrete with combined deterioration sometimes experiences damage that propagates faster than that in concrete with single deterioration. Such deterioration is on the rise in actual structures in Japan, which presently faces the growing social problem of an aging population. Therefore, the Japan Society of Civil Engineers Standard Specifications for Concrete Structures and the Architectural Institute of Japan Architectural Standard Specifications and

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Commentaries for Reinforced Concrete Work JASS5 stated that “attention should be paid to combined deterioration.” However, there has been no systematic organization of findings in this regard since the “Technical Committee on Evaluation, Operation and Management Planning of Concrete Structures with Combined deterioration” reported its results in 2001.

Consequently, this committee has identified mechanisms of combined deterioration in actual structures and buildings, collated the results of the latest research while considering the aspects of material science, and proposed effective methods for maintenance of the structures and prevention of such deterioration.

In order to achieve the above-mentioned objectives, we first collected findings on combined deterioration reported since 2002, and then organized them into a consistent format. Thereafter, two working groups (WG) were set up as shown in **Table 1**. In this paper, as shown in **Figure 1**, we present the results of a material science WG in Section 2, and the results of a measures WG in Section 3. Furthermore, in Section 4, we organize points of disagreement and agreement between the WGs, and then discuss measures based on the mechanisms uncovered.

Table 1: Membership of each WG

Chairman: Shinichi Miyazato (Kanazawa Institute of Technology)
[Material Science WG] ◎Tsuyoshi Saito (Niigata University), ○Shintaro Miyamoto (Tohoku University), Yuya Suda (University of the Ryukyus), Yuya Takahashi (The University of Tokyo), Natsuki Yoshida (General Building Research Corporation of Japan), Madoka Taniguchi (Hokkaido Research Organization), Kenzo Watanabe (Kajima Corporation) [Measures WG] ◎Hajime Ito (Toyama Prefectural University), ○Akihisa Kamihirako (Hirosaki University), ○Koichi Matsuzawa (Building Research Institute), Hiroyuki Kobayashi (Nakabohtec), Yoshinori Gondai (National Institute of Technology, Sendai College), Takuya Kondo (National Institute of Technology, Kochi College), Kohei Sakihara (University of the Ryukyus), Tetsuro Matsushita (Takenaka Corporation), Hiroki Sakuraba (Public Works Research Institute), Masahiro Nomura (Nomura Concrete Laboratory), Takashi Matsubayashi (Maeda Corporation), Keiki Yamamoto (Taisei Corporation) ◎Chief Examiner, ○Sub Examiner

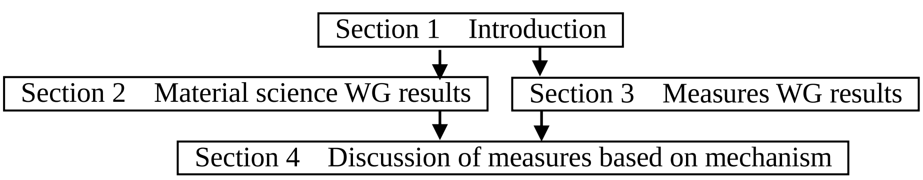

Fig. 1: Chapter flow

2. Mechanism of combined deterioration

2.1 Placement of this chapter

Combined deterioration is the process wherein several deterioration phenomena occur in an overlapping manner. The deterioration observed in actual structures is often actually of this type. Combined deterioration propagates via several processes. It may occur additively, wherein several deterioration phenomena act simultaneously but in isolation; otherwise, several forms of deterioration may occur which mutually influence each other, resulting in the propagation of synergistic deterioration. In this section, we address five kinds of combined deterioration: i) chloride attack and carbonation, ii) chloride attack and frost damage, iii) chloride attack and alkali–silica reaction (ASR), iv) frost damage and ASR, and v) delayed ettringite formation (DEF) and ASR. We then collate and present the effects of each pair of influences on the process by which combined deterioration is propagated.

2.2 Combined deterioration due to chloride attack and carbonation

Regarding the effects of carbonation on chloride attack, a quantitative evaluation is applied to changes in the phase composition of hardened cement and the accompanying changes to fixed amounts. Changes in the monocarbonate in Friedel's salt are present in the pH of the liquid phase, and Cl^- and CO_3^{2-} concentrations. Furthermore, based on the thermodynamic phase equilibrium calculation, carbonation even affects the fixation of Cl^- in C–S–H, and an increased Cl^- concentration in the liquid phase attributed to pH changes has been shown in the thermodynamic phase equilibrium calculations.

On one hand, chloride attack present in concrete affects carbonation by causing change in the strength of the liquid phase Cl^- and other ions and also the cement hydrate, owing to the influence of alkalis. These affect factors such as the carbonation rate and pore structures after carbonation. In addition, if combined deterioration is caused due to chloride attack from external chloride and carbonation, the carbonation rate greatly differs depending on the effect of moisture infiltration into the concrete, along with Cl^-. This moisture effect greatly influences carbonation, so it is difficult to conclude that the carbonation is caused by external chloride alone.

2.3 Combined deterioration due to chloride attack and frost damage

Combined deterioration due to frost damage and chloride attack is expected to propagate simultaneously. This makes it difficult to examine their individual effects and identify the main cause.

Regarding this present situation, we examined how chloride attack affects frost damage. We recreated the mechanism by which the presence of chloride ions influences the propagation of frost damage. Reinforced cement that undergoes repeated freezing and thawing while having absorbed a solution containing chloride ions experiences severe scaling deterioration. This is caused by stress generated due to osmotic pressure, elevated water saturation, thermal shock, and interlayer freezing. Furthermore, it has also been indicated that the behavior of a frozen solution greatly differs from that of fresh water. It has also been pointed out that when the amount of chloride present in endogenous form in concrete becomes large, there is a possibility that internal deterioration and surface deterioration will be promoted.

Next, to observe the effects of frost damage on chloride attack, we first recreated the conditions wherein frost damage encourages chloride attack. It has been reported that when an apparent relationship with a diffusion coefficient is observed while evaluating specimen damage due to frost damage and the degree of damage per decreased relative dynamic modulus of elasticity, the diffusion coefficient increases as the damage becomes more extensive.

However, in actual environments, frost damage and chloride attack do not repeatedly occur in an orderly manner, and antifreezing agents are sprayed while the effects of freezing and thawing occur. It is proposed that the freezing and thawing processes cause the chloride content to concentrate within concrete, and chloride ions accumulate owing to freezing, which means that complexities must be considered.

2.4 Combined deterioration due to chloride attack and ASR

As for the effect of chloride attack on ASR, the deterioration mechanism of ASR is caused due to not only the alkalis in seawater and antifreezing agents but also chloride ions in those. These factors reportedly affect the pore solution pH by virtue of ion exchange with hydration products, and the ionic strength of pore solution that increases the solubility of Si. In addition, it has been indicated that the composition of ASR gel differs depending on the presence of NaCl supplied from the outside, and it is presumed that the action of Cl^- also affects processes from ASR generation to the expansion characteristics of ASR gel. Therefore, as a measure for percolation control of external factors, admixtures are very effective in densifying concrete internal structure, and many researchers have reported such ASR inhibition effects.

Regarding how ASR affects chloride attack, chloride penetration resistance is reduced by cracking due to ASR, which then encourages steel corrosion. On the other hand, reportedly prior cracking due to ASR, compositional densification, and rebar immobilization due to filling by ASR gel contributes to inhibition of steel corrosion. However, it is predicted that the propagation rate of corrosion increases when cracks form due to ASR propagation, so it is important to conduct evaluations as ASR propagates. In addition, ASR and chloride attack deterioration often propagate simultaneously in actual environments, and the mechanism of combined deterioration from ASR and chloride attack is assumed to promote single deterioration. Therefore, it is presumed that in environments in which both forms of deterioration act in combination, attention needs to be paid to the propagation of each individual entity.

2.5 Combined deterioration due to frost damage and ASR

If frost damage occurs after ASR, the propagation rate of frost damage tends to increase. The main causes of this are thought to be penetration of moisture and other deterioration factors promoted by cracking due to ASR, and infiltration of pores and air bubbles by the ASR product, which decreases expansion pressure relief functions. On the other hand, it is thought that, if ASR occurs after frost damage, no major changes in the ASR expansion rate are seen, and the effects of frost damage on ASR are limited.

When we consider actual environments in cold regions in which antifreezing agents are sprayed, ASR proceeds in the summer season, and frost damage proceeds in the winter season, so environments in which ASR and frost damage alternately proceed are considered realistic. When we consider how deterioration proceeds in such places, it seems that because ASR promotes frost damage, combined deterioration from ASR and frost damage greatly increases the deterioration rate compared to when the processes occur separately and on an individual basis. Actually, multiple experiments have shown that alternate freezing and thawing promotes ASR. It has been observed that expansion and deterioration are promoted by the adding up of separate forms of deterioration. For example, Deshenes, et al.[1)] reports measuring the expansion behavior of separate prismatic specimens on which he applied only ASR promotion, only freezing and thawing, and combined ASR promotion and freezing and thawing for 21 cycles. Compared to single deterioration, combined deterioration resulted in a greater amount of expansion.

2.6 Combined deterioration due to DEF and ASR

Prior to the concept of deterioration due to DEF being recognized, cases were reported in which concrete cracking with ASR and ettringite in pores was found. While there have been such cases, others have reported the simultaneous occurrence of DEF and ASR in concrete, with ASR as the main cause of deterioration and DEF having a limited influence. However, it has been shown that, when the results of recent research on DEF are highlighted, combined deterioration with DEF cannot necessarily be ruled out.

It has been suggested that DEF is a trigger for ASR. It is hypothesized that when liquid phase calcium ions due to ettringite generation are consumed, portlandite is dissolved, the pH of the pore solution rises, and ASR is promoted.

On one hand, there is the theory that ASR is a trigger for DEF. Studies have reported, for example, that ettringite generation becomes likely when OH^- is consumed by the generation of ASR gel and when silicate ion concentration is lowered by ASR gel generation.

In addition, when we focus on the expansion rate, it of concrete specimens assumed to experience combined deterioration from ASR and DEF is reportedly the same as the expansion rate of specimens assumed to have only ASR. In addition, it is reported that the expansion rate is lower than that in specimens assumed to experience only DEF.

However, it is likely that there will be pending issues that need to be addressed in the future. These include resolving a lack of consensus regarding the mechanism of combined deterioration due to DEF and ASR, and the fact that there is insufficient experimental data on the relationship between combined deterioration from DEF and ASR, and physical changes. Relevant research will hopefully be conducted in the future.

3. Measures for actual combined deterioration

3.1 Summary

In surveys regarding deterioration in reinforced concrete structures, it is presumed that deterioration factors other than those specified are lurking, and that if parallel occurrence could not be identified, then mistakes were made in observing the deterioration progress and overall health, and deterioration occurred again after repair. By recognizing that deterioration factors may be working in combination and determining that a possible measure may be to handle them in the same way as single deterioration, it is possible to control the deterioration rate and symptoms, and prevent further deterioration after repair. In the previously mentioned 2001 combined deterioration report, all the relationships among combined chloride attack, carbonation, frost damage, and ASR were categorized into synergistic combined deterioration and causal combined deterioration. Specifying a synergistic relationship or causal relationship is rational and economical and leads to the selection of effective deterioration measures.

Hence, the subjects in Section 3 are "Chloride attack and carbonation (3.2)," "Chloride attack and frost damage (3.3)," "Chloride attack and ASR (3.4)," and "Frost damage and ASR (3.5)." As shown in **Figure 2**, these have a strong connection to combined deterioration. We analyzed examples of combined deterioration occurring in actual structures and exploratory research examples in each survey of combined deterioration since the issuing of the 2001 combined deterioration report, and organized them in order of "Summary", "Examples of deterioration in actual structures", "Measures for actual structures and their results", "Researched measures", and "Outlook". Additionally, we organized some types of combined deterioration into "Effects on structural function" and "Predicted deterioration".

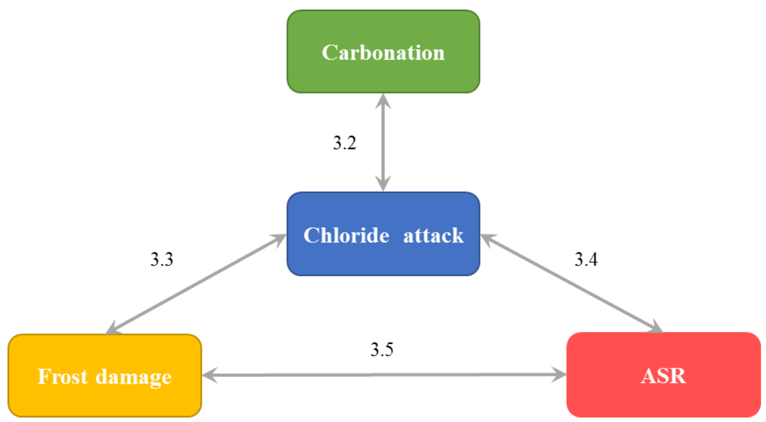

Fig. 2 Types of combined deterioration and sections composition highlighted in Section 3

We organize the 61 examples of deterioration and measures addressed in this section into a single list, as shown in **Table 2**, for final reporting. This table correlates types of structures with types of combined deterioration, and indicates regions, environmental conditions, inspection and survey items, measures, and whether there was a follow-up survey. Based on this, we organized points of disagreement with single deterioration, long-term results of measures, the suitability of measures, and any issues. We also discussed ways to resolve issues and develop corrective maintenance methods aimed at reducing propagation of combined deterioration. Additionally, we addressed ways of increasing longevity for cases of new construction or updating in regions where combined deterioration is a concern.

Table 2: A list of examples of deterioration and measures (excerpt)

No	Combined deterioration types	Structural member	Category				
			Region	Environmental conditions	Inspection and survey items	Corrective measure	Moni-toring
1	Chloride attack + Carbonation	Railroad bridge	Kinki, Chugoku region	Sea sand use	Cover depth, Carbonation depth, Chloride ion content, Rebar corrosion rate, Rebar yield strength, Nominal safety factor	Electrolytic protection	Yes
2	Chloride attack + Carbonation	Bridge pier	Kanto region	Partial seawater contact	Appearance, Chloride ion concentration, Cover depth, Rebar corrosion grade, Spontaneous potential	RC lining, Patch repair	No
3	Chloride attack + Carbonation	Pier	Chugoku region	At sea	Carbonation depth, Chloride ion concentration, Rebar corrosion grade		No
4	Chloride attack + Frost damage	Highway bridge	Hokkaido	Coastal, Inland	Scaling deterioration, Chloride ion concentration, Antifreezing agent spray rate	Predict deterioration	No
5	Chloride attack + Frost damage	Floor slab	Tohoku region	Inland, Fatigue	Crack density, chloride ion concentration, compressive strength, rebar corrosion rate	Ultra rapid hardening cement mortar (test)	No
6	Chloride attack + ASR	Abutment	Hokuriku region	Several km from coast	Crack density, Chloride ion concentration, Rebar corrosion, Amount of moisture		No
7	Chloride attack + ASR	Bridge, Wheel guard	Hokuriku region	Middle of peninsula	Crack width, Chloride ion concentration, Rebar corrosion	Surface coating, Patch repair	Yes
8	Chloride attack + ASR	Bridge pier	Okinawa region	At sea	Rebar corrosion, Chloride ion concentration, Rock analysis	Epoxy-coated rebar + Flyash	Yes
9	Frost damage + ASR	Tunnel	Hokuriku region	Mountainous region	Carbonation depth, Fluorescence microscopy, Polarization microscopy		No
10	Frost damage + ASR	Electric power facility	Hokuriku region	Mountainous region	Uranyl acetate fluorescence, X-ray diffraction, Core residual expansion test, Compressive strength, Modulus of static elasticity		No

Next, we organized the 13 example measures with investigative results addressed in this section into a list. Here, we present the categories of measures, test environments and specimens, main test items, and effects, while matching them to the methods of measures and types of combined deterioration. Based on this information, we organized the characteristics and scope of the methods of measures that had been researched. These results were used to discuss effects contributing to reduced propagation of combined deterioration, and the possibility of applying them to actual structures.

Finally, in the outlook for the various forms of combined deterioration, we focused our analysis on survey results for annual construction, annual measures, regional characteristics, and measures to combat future problems, with the objective of showing how to use them in future survey diagnoses and selecting methods for repair work. Furthermore, we discovered some points for increasing longevity during new construction of concrete structures. A summary of survey results for the four types of combined deterioration is found in sections 3.2 to 3.5.

3.2 Combined deterioration due to chloride attack and carbonation

Combined deterioration due to chloride attack and carbonation in reinforced concrete structures involves the freeing of chloride ions in the pore solution fixed to the cement hydrates as Friedel's salt, for example, by carbonation. The chloride ion concentration in the pore solution thus rises, and chloride ions are concentrated at the back of the carbonized area; if this occurs around a rebar, then greater rebar corrosion is promoted compared to single deterioration from chloride attack. In addition, decreased pore solution pH due to carbonation may hasten the start of rebar corrosion. **Figure 3** shows a summary of combined deterioration due to chloride attack and carbonation.

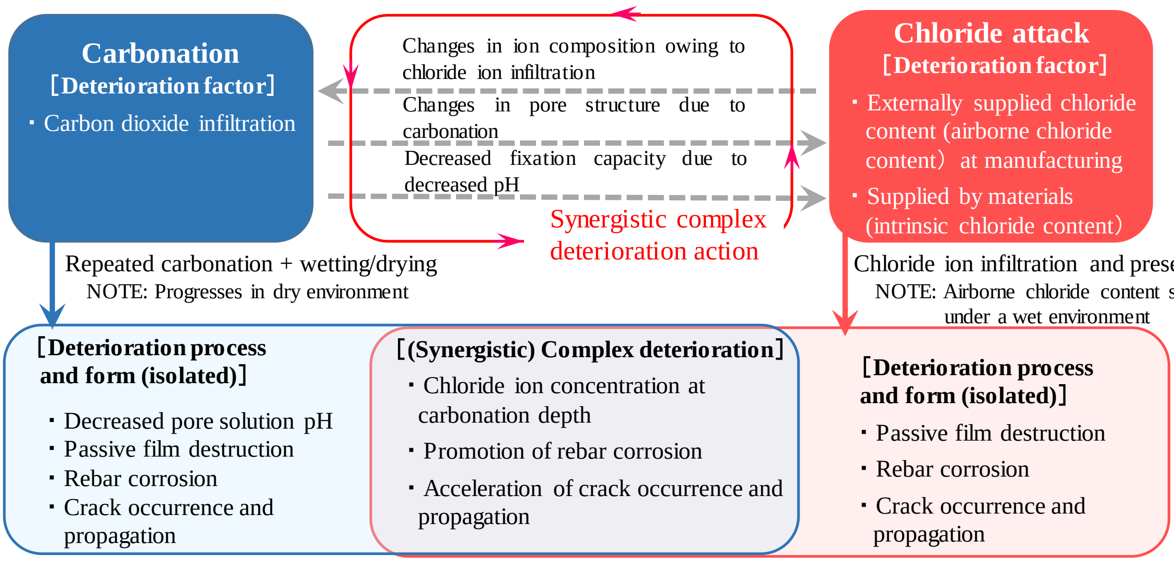

Fig. 3: Summary of combined deterioration due to chloride attack and carbonation

In this section, regarding combined deterioration from chloride attack and carbonation in actual structures, we describe practically applied measures and the results of subsequent follow-up surveys for rail structures with chloride ions present within concrete from the start of construction, examples of deterioration in harbor structures with chloride ions supplied to concrete after construction, and combined deterioration that developed in rail structures. In addition, regarding deterioration measures studied at the laboratory level, we describe measures for preventive maintenance using mixing materials and mixed cement when mixing concrete, measures for corrective maintenance using combinations of realkalization and desalination with electrodeposition, and techniques for evaluating the remaining life of structures with deterioration due to chloride attack and carbonation. Then, we give a final summary, and describe the future outlook of combined deterioration due to chloride attack and carbonation.

3.3 Combined deterioration due to chloride attack and frost damage

Combined deterioration due to chloride attack and frost damage in reinforced concrete structures is characterized by greater acceleration than single deterioration due to mutual deterioration actions acting synergistically. **Figure 4** shows a summary of combined deterioration due to chloride attack and frost damage. Deterioration propagation occurs primarily as a result of chloride ions infiltrating concrete in freezing and thawing environments. Osmotic pressure rises owing to the freezing and thawing action because of the presence of chloride ions, and accelerated scaling (a peeling phenomenon) propagation. Propagation of scaling reduces the protective function of the concrete surface layer (cover) through partial loss of area and systematic loosening.

In this section, based on findings from a literature survey, we describe examples of deterioration in actual structures, measures for actual structures and their results, measures being researched, and evaluation of structural functions. As for examples of deterioration in actual structures, we explain the regional risks of combined deterioration due to chloride attack and frost damage. Furthermore, we introduce examples of deterioration in the Chugoku and Kyushu regions, which are relatively low in frost damage risk. As for measures adopted in actual structures and their results, we touch upon actual examples of the effects of applying measures to test construction with surface impregnation, and early re-deterioration of patch repairs. In addition, we explain measures being researched and evaluation of structural functions.

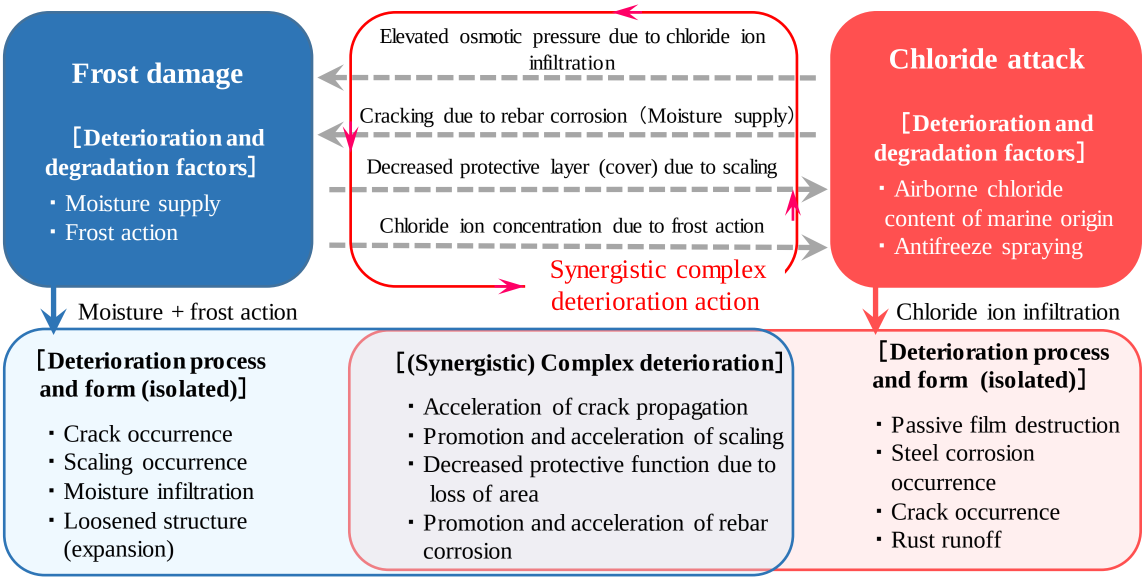

Fig. 4: Summary of combined deterioration due to chloride attack and frost damage

3.4 Combined deterioration due to chloride attack and ASR

The propagation of combined deterioration due to chloride attack and ASR in reinforced concrete structures accelerates more than that of single deterioration due to mutual deterioration actions acting synergistically. **Figure 5** shows a summary of combined deterioration due to chloride attack and ASR. Rebar corrosion due to chloride ion penetration of the interior of concrete during chloride attack, gel generation due to the reaction of reactive aggregate and alkaline aqueous solutions in concrete during ASR, and cracking in concrete from some form of single deterioration are generated. When cracking is generated, it originates from the promotion of an ASR reaction by the infiltration of moisture and alkali, and the promotion of rebar corrosion due to the moisture, chliride, and oxygen being supplied by cracking. These synergistic actions occur in a chain and appear as early phenomena of deterioration in concrete structures.

In this section, regarding combined deterioration from chloride attack and ASR in actual structures, we provide examples of surveying the degree of damage due to ASR in bridges affected by antifreezing agents, examples of surveying the actual state of deterioration in abutments affected by antifreezing agents, and examples of bridge curbs in which surface protection has been applied by the spraying of antifreezing agents. In addition, we provide examples of surface protection of bridge curbs by spraying antifreezing agents, examples of repair and reinforcement design for bridges spanning maritime canals, and examples of deterioration in long and massive remote island bridges. Then, we describe examples of research on preventive maintenance measures, patch repair methods, and electrochemical repair methods, as researched measures. Then, we give a final summary and describe the outlook from the viewpoint of construction years and repair methods.

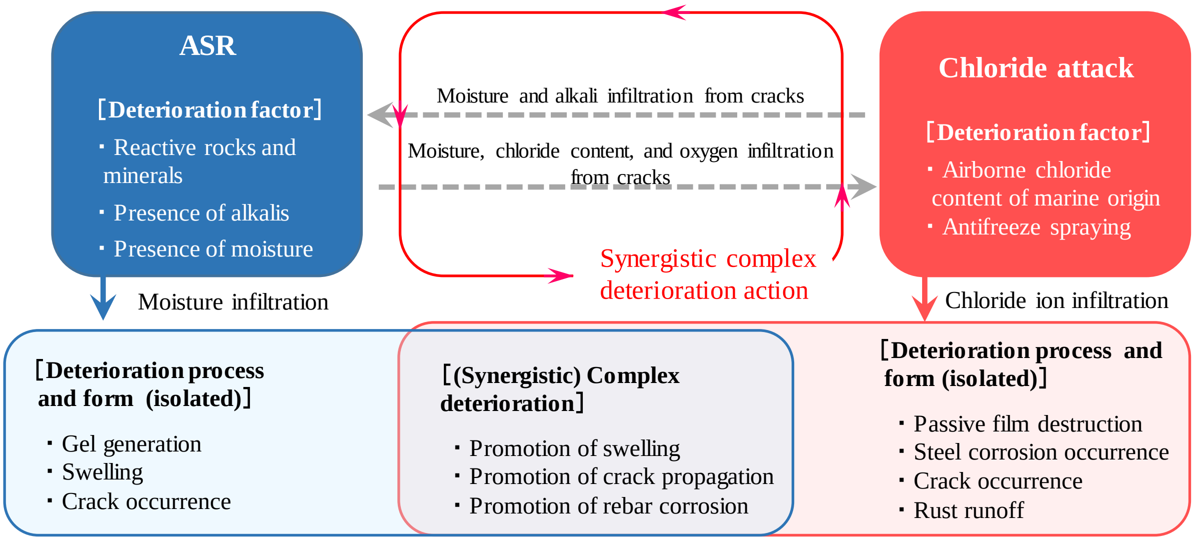

Fig. 5: Summary combined deterioration due to chloride attack and ASR

3.5 Combined deterioration due to frost damage and ASR

Combined deterioration due to frost damage and ASR in concrete structures is positioned as synergistic combined deterioration. Propagation is accelerated more than with single deterioration by a mutual deterioration action acting synergistically. **Figure 6** shows a summary of combined deterioration due to frost damage and ASR. The dominant route of deterioration propagation originates from water infiltrating concrete in freezing and thawing environments. Osmotic pressure due to the action of freezing and thawing rises with the generation of cracking due to ASR from the presence of water, and scaling propagates in an accelerating manner. In addition, rebar corroding and expanding due to decreased protective functions induces cracking and encourages the supply of moisture deep within concrete.

In this section, based on findings obtained from a literature survey, we describe examples of deterioration in actual structures, and measures for actual structures and their results. Regarding deterioration in actual structures, we introduce tunnels and road structures, for example, in cold snowy regions. As for measures adopted in actual structures and their results, we touch upon actual examples of methods for surface covering and bonding of continuous fiber sheets, for example, in environments in which antifreezing agents are sprayed. Furthermore, as for measures being researched, we introduce the effects of silane-based surface impregnated in chloride attack environments.

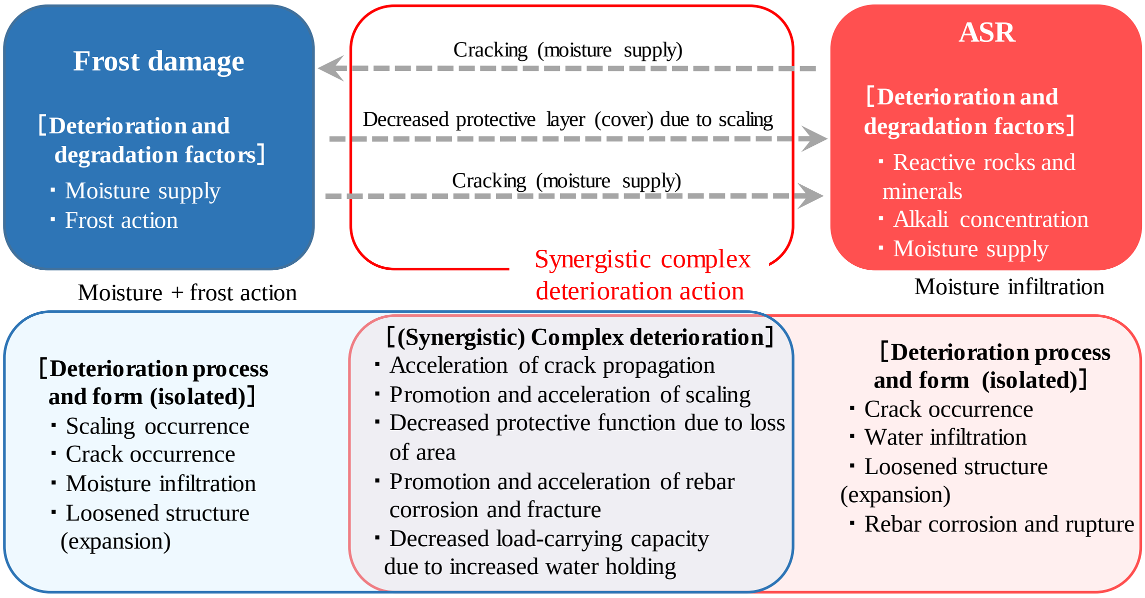

Fig. 6: Summary of combined deterioration due to frost damage and ASR

4. Mechanism-based measures for combined deterioration

4.1 Combined deterioration due to chloride attack and carbonation

As shown in **Figure 7**, we compare the mechanisms identified in Section 2 with the survey results for actual structures verified in Section 3. According to this, we confirmed that combined deterioration proceeds in actual structures according to certain mechanisms.

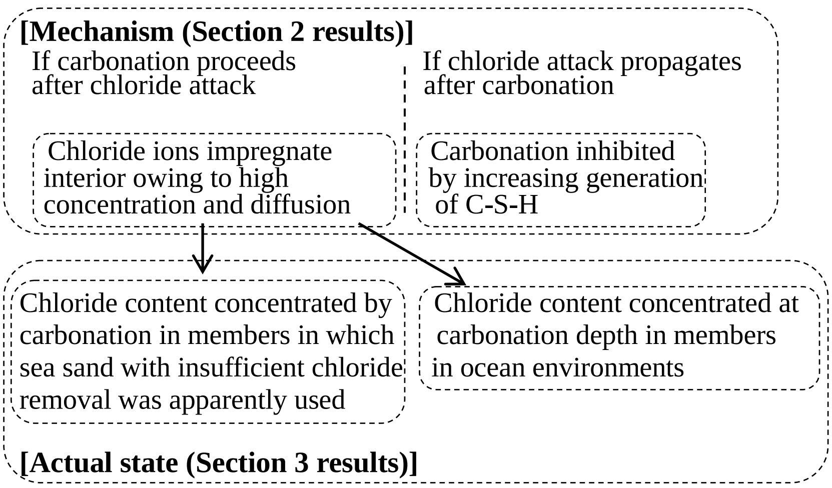

Fig. 7: Relationship of mechanism and actual state of combined deterioration due to chloride attack and carbonation

Table 3 shows effective maintenance methods for combined deterioration due to chloride attack and carbonation based upon the above. In the table here, A is a method with results in actual settings, B is a method that was investigated in studies, and C is a method newly proposed in this technical committee.

Table 3: Maintenance methods for combined deterioration due to chloride attack and carbonation

No	Category	Method	A	B	C
1)	Preventive	Use concrete mixing CaO・2Al_2O_3 (CA2), a type of calcium aluminate.		✓	
2)		Use three component system concrete (FA about 15 to 20%).		✓	
3)		Build members that are highly waterproof in terms of material and construction.			✓
4)	Corrective	Combine multiple electrochemical repair methods.	✓	✓	
5)		Patch repair with material low in permeability, including nitrite ions. However, prevent formation of macrocells.			✓

According to this table, there are five effective maintenance methods. However, in the method in 1), there is a possibility that captured chloride ions will be released by carbonation; therefore monitoring is important. In addition, in method 2), it is possible that carbonation is promoted when the amount of flyash (FA) mixture is high.

4.2 Combined deterioration due to chloride attack and frost damage

As shown in **Figure 8**, we confirmed that combined deterioration in actual structures proceeds according to certain mechanisms.

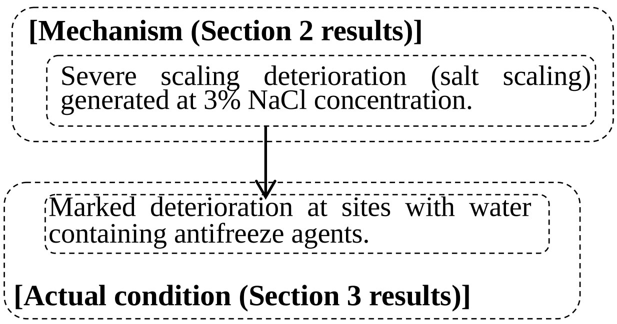

Fig. 8: Relationship of mechanism and actual state of combined deterioration due to chloride attack and frost damage

Table 4 shows effective maintenance methods for combined deterioration due to chloride attack and frost damage. Furthermore, in patch repair methods using cement mortar, penetration by chloride ions and relatively rapid re-deterioration have likely been confirmed in follow-up surveys of the sites of results and research-based studies. It is presumed that this happens because entrained air does not get into sprayed patch repairs. Because of this, in method 4), polymers are expected to play the role of entrained air.

Table 4: Maintenance method for combined deterioration due to chloride attack and frost damage

No	Category	Method	A	B	C
1)	Preventive	Coated with silane-based surface penetrant.	✓	✓	
2)		Build members that are highly waterproof in terms of material and construction.			✓
3)	Corrective	Mechanical performance recovery by using high-toughness material.		✓	
4)		Waterproof after patch repair with polymer-impregnated material having freezing and thawing resistance.			✓

4.3 Combined deterioration due to chloride attack and ASR

As in **Figure 9**, we confirmed that combined deterioration in actual structures proceeds according to certain mechanisms. In other words, although the possibility that deterioration is inhibited by complex actions was indicated, we confirmed that it is always promoted in actual structures.

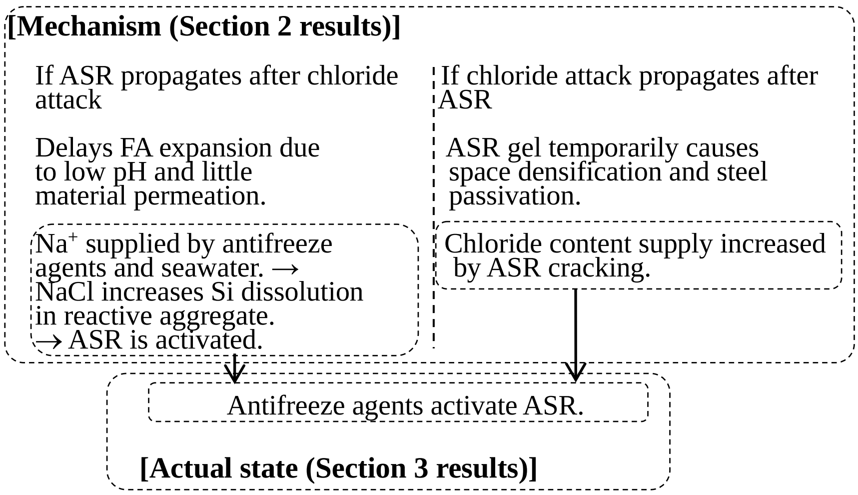

Fig. 9: Relationship of mechanism and actual state of combined deterioration due to chloride attack and ASR

Table 5 shows effective maintenance methods for combined deterioration due to chloride attack and ASR based upon this.

Table 5: Maintenance methods for combined deterioration due to chloride attack and ASR

No	Category	Method	A	B	C
1)	Preventive	Mix effective FA as a control measure against chloride attack in ASR.		✓	
		Increase cover (thickness), use epoxy-coated rebar, and mix FA.	✓		
2)		Build members that are highly waterproof in terms of material and construction.			✓
3)	Corrective	Impregnate effective $LiNO_2$ as a control measure for chloride attack in ASR.		✓	

4.4 Combined deterioration due to frost damage and ASR

As shown in **Figure 10**, we confirmed that combined deterioration in actual structures proceeds according to certain mechanisms.

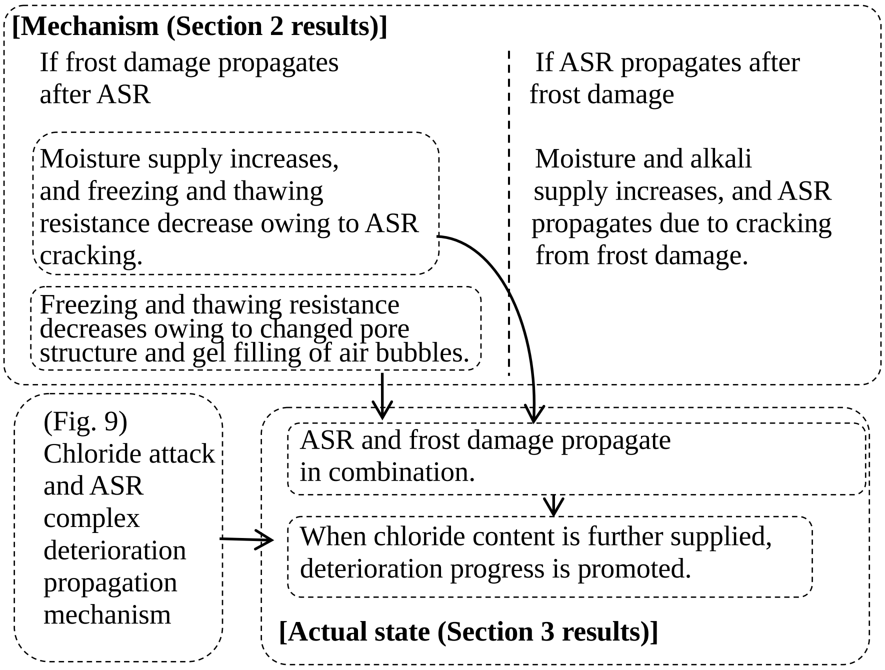

Fig. 10: Relationship between mechanism and actual state of combined deterioration due to ASR and frost damage

Table 6 shows the effective maintenance methods for combined deterioration due to frost damage and ASR based upon this. According to this table, there are five effective maintenance methods. Furthermore, as for method 5), it is thought possible that frost damage is promoted as nitrous acid has water-holding properties. Furthermore, onsite surveys indicating re-deterioration have been reported for sodium silicate surface impregnation methods and continuous fiber sheet bonding methods.

Table 6: Maintenance methods for combined deterioration due to frost damage and ASR

No	Category	Method	A	B	C
1)	Preventive	Build members that are highly waterproof in terms of material and construction.			✓
2)	Corrective	Use surface covering methods that thicken undercoat.	✓		
3)		Perform silane-based surface impregnation and pipe drainage from the interior, after polyurethane flexible sealing material injection.	✓		
4)		Apply additional cover concrete removal + reinforcing steel, and concrete jacketing.	✓		
5)		Impregnate $LiNO_2$; measure similar to that for carbonation of chloride attack and ASR.			✓

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