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Deterioration Control of Concrete Structures by Surface Coating Methods

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ABSTRACT

From the “high economic growth period” to the “stable-growth period” (Nov.1954 - Feb.1991) in Japan, vast social and civilian-infrastructures had been constructed. In present society, concrete structures have become essential and important social infrastructure stocks for our life and economical activities. To protect and to gain longer operation life for concrete structures from severe environment, author mentions about required performance against each deteriorate factor for the surface coating methods, and then presents some application cases in Japan.

Keywords. Surface coating methods, Chemical & Physical deterioration, Maintenance planning, Maintenance operation technology

INTRODUCTION

Japanese domain is surrounded and enclosed by sea, latitudinally long islands from north to south and located in circum-Pacific volcanic zone. For this reason, concrete structures frequently exposed to severe environment. Many chemical deterioration and physical damage cases has been reported such as by salts, freezing, wet and dry alternate, volcanic gas derived acid rain, acid soil derived neutralization, earthquake, tsunami and so forth.

To protect and to gain longer operation life for concrete structures from these severe environment, maintenance planning and maintenance operation technology by repair works has been well-developed in Japan. In these technologies, surface coating materials area has many field experiences for the good reasons that the surface coating materials have a feature its would be easily controlled with the required performance criteria in barrier effect from substances account for deterioration, weatherability and flexibility, because main ingredients, resin materials, can be formulated in broad range with its components and molecular weight.

In this report, firstly author mentions about the history of deterioration control of concrete structures by surface coating methods and required performance against each deteriorate factor for the surface coating methods, and then present some application case in Japan.

HISTORY OF CONCRETE SURFACE COATING METHOD

Beginning of concrete surface coating method (former 1980's). The first standard in Japan to implement preventive maintenance for deterioration of concrete structures was

"Tentative guidance for chloride contamination of highway bridges and explanation" (Japan Road Association, 1984) which was published by the Japan Road Association in 1984. Before then, the measures against deterioration of concrete structures were not standardized and various methods have been proposed. Establishment of this guideline has built the base of ideas that specify the performance on the concrete surface coating method. For example, a flexible type surface coating method is used for reinforced concrete which allows for generation of crack to some extent. A fundamental concept in design of the current surface coating method is described.

Development of repair material and method for deteriorated concrete structures (latter 1980's to 1990's). The purpose of the guidance (Japan Road Association, 1984) above was to implement preventive maintenance on new construction structures. It was also found that there were a number of structures in Japan of which deterioration has been in progress. Development and research on evaluation technique of repair materials and repair performance have been active. In these activities, "Concrete protection work" (Nihon Doro Kodan Research Institute, 1994) was published by current Nippon Expressway Research Institute Company Limited in 1994 classified the quality standard of the surface coating material under a general environment and an environment exposed to salt damage. As for chloride ion permeability and crack adherability, higher performance level is required under an environment exposed to salt damage. In addition, in 1989, the result of the general engineering development project by the Ministry of Construction was announced as "Development of concrete durability improvement technology" (Public Works Research Center, 1989). In addition to measures against salt damage, the quality standard of the surface coating material to prevent alkali aggregate reaction was determined.

Determination of guideline and criteria on concrete surface coating method (latter 1990's to present day). The Japan Society of Civil Engineers published "Recommendation for Concrete Repair and Surface Protection of Concrete Structure" (Japan Society of Civil Engineers, 2005) in 2005. The book showed the basic concept to maintain the concrete structures so that LCC (Life Cycle Cost) may be the minimum, and showed the performance requirement of the surface coating method for each deterioration cause of structures. In addition, in 2007, the test method to standardize the surface coating was published as "Standard specification for concrete structures - Criteria" (Japan Society of Civil Engineers, 2007). This has standardized the test methods which were owned by each structure control entity. Not only the time and effort required for the test were simplified, but also the performance of each surface coating method was able to be compared.

CURRENT STATUS OF CONCRETE STRUCTURE DETERIORATION IN JAPAN AND REQUIRED PERFOMANCE OF SURFACE COATING METHOD

Current status of concrete structure deterioration. Figure 1 shows the relation between the deterioration causes and the construction year from the nationwide investigation of concrete structures by the Civil Work Concrete Structure Durability Study Committee performed by three old ministries of Ministry of Construction, Ministry of Transportation and Ministry of Agriculture, Forestry and Fisheries (Ministry of Construction, Ministry of Transportation and Ministry of Agriculture, Forestry and Fisheries, 2000). (The investigations targets are 2344 structures such as bridges, retaining wall, culvert, etc., excluding tunnels.) This investigation result shows that deterioration of reinforced concrete structures excluding tunnels is often caused by "defective construction" such as "poor concrete quality" and "Improper rebar arrangement". The rate of deterioration arising from salt damage, Alkali Aggregate Reaction (hereinafter referred to as AAR), frost damage, etc. is not high at all in the total investigation items. However, (although it is not shown on the figure), when only items with progressed deterioration are picked, the rate of salt damage, AAR and frost damage is high. When only items which require immediate repair due to deterioration are picked, the cause is only salt damage.

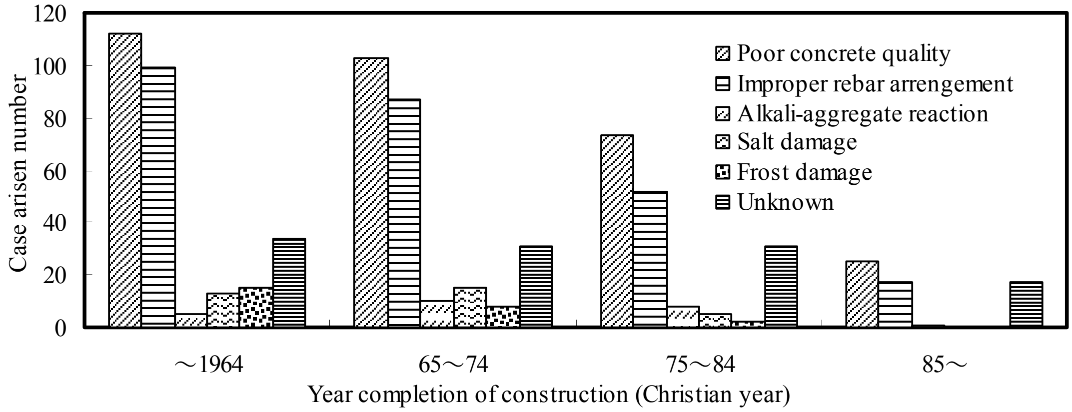

Figure 1. Deterioration factor number in decennial year completion of construction

Deteriorated structures do not concentrate on specific period. In general, the older the structures are, the more the deterioration rate is increased. As shown in **Figure 2**, the rate of structures with some repairs has been increased along with the years of service. It was found that when the years of service are 50 years or more, about 40% structures have been repaired.

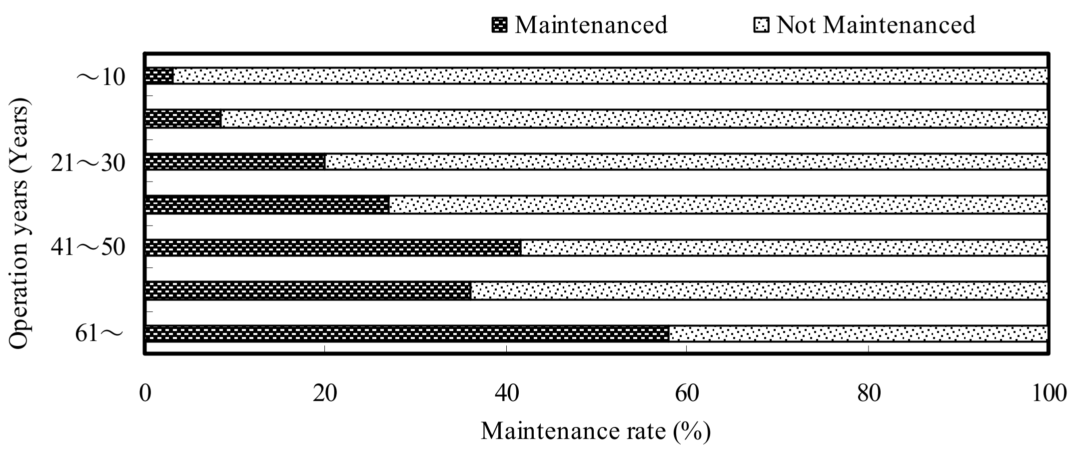

Figure 2. Maintenance rate of concrete structures in decennial operation year

Requirement performance of concrete surface coating method. To economically maintain and control concrete structures, it is necessary to study the life cycle plan considering the repair period for each structure as well. In above " Recommendation for Concrete Repair and Surface Protection of Concrete Structures" (Japan Society of Civil Engineers, 2005), the requirement performance of the surface coating method for each deterioration mechanism is described as shown in **Table 1**. The largest factor which governs the deterioration mechanism is entry of deteriorating substance into concrete. The main requirement performance is to shield these substances. To prevent crack on the surface coating material and not to lose the function of the surface coating method, it is necessary to have crack adherability. In addition, if measures to prevent spalling of concrete pieces are required, it is necessary to have the anti-spalling performance.

Table. 1 Major performance requirements for concrete surface coating method

Requirements for surface coating method \ Deterioration mode	Neutralization	Salt damage	Frost damage	Chemical erosion	Alkali-aggregate reaction
	◎				
Chloride ion blocking property (Salt blocking property)	○	◎	○		○
Oxygen blocking property	○	○			
Freeze-thaw resistance			◎		
Acid resistance, Sulfuric acid resistance				◎	
Alkaline resistance				◎	
Water proofing property (Water blocking property)		○	◎	○	◎
Water vapor permeability (Moisture permeability)					◎
Crack adherability (flexibility)	△	△	△	△	△
Spalling resistance	△	△	△	△	△

◎: Major requirement
○: Subordinate requirement
△: Requirement as the case

SURFACE COATING METHODS WHICH HAVE BEEN FREQUENTLY USED IN JAPAN, AND THEIR APPLICATION EXAMPLES

Table 2. Coating specification example of organic base surface coating method

Process		General Name	Dilution ratio (wt.%)	Coating Method	Coverage (kg/m^2)	Target DFT (μm)	Coating Interval (20°C)
1	Surface preparation	To treat water leakage and cracking prior to this process. Remove brittle layer, dust and foreign matter completely. Flatten raised and tiered portion by power and hand tool. Clean sufficiently by brush, bloom and air blow. To confirm below 5% of surface moisture content by using surface moisture content meter (HI-500, Kett Electric Laboratory).					
2	Putty	Epoxy resin polymer cement putty	1 ~ 5	Roller Trowel Spatula	1.00	-	12 hours ~ 10 days
3	1st. layer of intermediate coat	High-build flexible type epoxy resin paint	0 ~ 5	Brush Roller	0.30	260	12 hours ~ 10 days
4	2nd. layer of intermediate coat				0.30		12 hours ~ 10 days
5	Top coat	Flexible type fluoro resin paint	0 ~ 8	Brush Roller	0.12	30	-

Organic based surface coating method. Table 2 shows a specification example of the organic based surface coating method which has been frequently used in Japan. **Table 3** shows its performance. This method is a thick film flexible coat, using the epoxy resin based polymer cement mortar as putty. The coating finish is fluoro resin which is durable for a long time. This method has been applied to harsh salt damage environment as in **Figure 3**. Long-time durability has been proven.

Table 3. Performance of organic base surface coating method

Required Performances	Test items		Quality requirement	Test results	
Durability	Soundness of coating	After standard drying time	Coating film shall be uniformity, no flow, even, no blistering, no cracking and no peeling.	Coating film was uniformity, no flow, even, no blistering, no cracking and no peeling.	
		After accelerated weatherability test	Coating film shall be no chalking, no blistering, no cracking and no peeling.	Coating film was no chalking, no blistering, no cracking and no peeling.	
		After hot-wet cycle test	Coating film shall be no blistering, no cracking and no peeling.	Coating film was no blistering, no cracking and no peeling.	
		After alkaline resistance test	Coating film shall be no blistering, no cracking and no peeling.	Coating film was no blistering, no cracking and no peeling.	
		After humidity test	Coating film shall be no blistering, no cracking and no peeling in 7(10) days*1.	Coating film has no blistering, no cracking and no peeling in 10 days.	
	Adhesive property to concrete			Adhesive strength (N/mm^2)	Major failure mode
		After standard drying time	Adhesive strength between coated film and concrete shall be 1.0 N/mm^2 and more.	3.22	Adhesive failure from substrate
		After accelerated weatherability test		2.23	Adhesive failure from substrate
		After hot-wet cycle test		3.24	Cohesive failure in coating
		After alkaline resistance test		2.77	Cohesive failure in coating
Salt blocking property	Salt blocking property		Chloride ion permeation amount of coating film shall be 5.0×10^{-3} mg/cm^2•day and less.	Below minimum measurable value ($< 0.34\times10^{-3}$)	
Oxygen blocking property	Oxygen permeation blocking property		Oxygen permeation amount of coating film shall be 5.0×10^{-2} mg/cm^2•day and less.	3.3×10^{-2}	
Water vapor blocking property	Water vapor permeation blocking property		Water vapor permeation amount of coating film shall be 5.0 mg/cm^2•day and less.	0.9	
Neutralization blocking property	Neutralization blocking property		Neutralization depth shall be 1 mm and less.	0.0	
Flexibility	Crack adherability			Elongation (mm)	Determination
		After standard drying time (at ambient temp.)	Elongation of coating film shall be 0.4 (0.8) mm and more*2.	1.36	at maximum elongation
		After standard drying time (at low temp.)	Elongation of coating film shall be 0.2 (0.4) mm and more*3.	0.55	at maximum elongation
		After accelerated weatherability test (ambient temp.)		1.04	at maximum elongation

*1: !0 days for using under high temperature and high humidity environment.
*2: 0.8 mm and more for especially required crack adherability.
*3: 0.4 mm and more for especially required crack adherability.

Figure 3. Applied case to a harsh salt damage environment

Anti-spalling method. Table 4 shows a specification example of the method for anti-spalling of concrete pieces. **Table 5** shows the performance. **Figure 4** shows the push-out loading test condition. In this method, a continuous fiber sheet is affixed to the concrete surface with epoxy resin adhesive to form the FRP layer so that spalling of the concrete pieces may be prevented. In the past, workability on the continuous fiber sheet has not been satisfactory. Therefore, the finish appearance and the anti-spalling performance were varying. The specification shown in **Table 5** is using the nylon 2-axis mesh sheet which is excellent in workability. It has succeeded in elimination of work defect and in achieving stable quality of the anti-spalling performance. Recently, the construction records have been increasing.

Table 4. Coating specification example of anti-spalling method for concrete

<table>
<tr><th colspan="2">Process</th><th>General Name</th><th>Dilution ratio (wt.%)</th><th>Coating Method</th><th>Coverage (kg/m²)</th><th>Target DFT (μm)</th><th>Coating Interval (20°C)</th></tr>
<tr><td>1</td><td>Surface preparation</td><td colspan="6">To treat water leakage and cracking prior to this process. Remove brittle layer, dust and foreign matter completely. Flatten raised and tiered portion by power and hand tool. Clean sufficiently by brush, bloom and air blow. To confirm below 5% of surface moisture content by using surface moisture content meter (HI-500, Kett Electric Laboratory).</td></tr>
<tr><td>2</td><td>Primer</td><td>Epoxy resin primer</td><td>0</td><td>Brush
Roller</td><td>0.15</td><td>-</td><td>Immediately
~
7 days</td></tr>
<tr><td>3</td><td>Putty, Impregnate adhesion, Impregnate weather strip</td><td>Epoxy resin adhesive</td><td>0</td><td>Roller
Trowel
Spatula</td><td>1.00</td><td rowspan="2">over 500</td><td>Immediately</td></tr>
<tr><td>4</td><td>Affix</td><td>Nylon 2-axis mesh sheet</td><td>0 ~ 5</td><td>Roller
Trowel</td><td>1.1
(m²/m²)</td><td>16 hours
~
10 days</td></tr>
<tr><td>5</td><td>Top Coat</td><td>Polyurethane resin paint</td><td>5 ~ 10</td><td>Brush
Roller</td><td>0.15</td><td>50</td><td>-</td></tr>
</table>

Table 5. Performances of anti-spalling method for concrete

Items	Test methods	Testing conditions	Check results
Anti-spalling performance	JHS424*2	-30°C(test temp.)*1 23°C(test temp.) 50°C(test temp.) After recoated After maintenanced	Passed Passed Passed Passed Passed
Primer, crack impregnation performance	JHS426*4	—	Passed
Durability	JHS425*3	Adhesive strength Crack resistance Chloride ion permeability	Passed Passed Passed

*1: Preparation of test specimens were conducted at 10, 23 and 40°C.
*2: Push-out loading test
*3: Each performance has checked by comparing between before and after loading.
*4: Impregnation performance from surface into crack was assessed by flexural strength of concrete.

Figure 4. Push-out loading test

Surface impregnation method. Table 6 shows a specification example of the surface impregnation method. This specification has given the results in **Table 7** in the test in accordance with "Test methods of surface penetrants for concrete structures (JSCE-K 571-2005)" (Japan Society of Civil Engineers, 2005). The characteristic point is forming of a protection layer in 4 mm thick which prevents entry of corrosive factors such as oxygen, carbon dioxide, water, etc. into the concrete layer. **Figure 5** shows the water repellent condition (cross-section) by splitting the mortar with surface impregnated material and immersing it in water. **Figure 6** shows the wet condition when water drips are applied to the mortar surface, comparing with the case without an impregnation material. Based on these results, it is obvious that application of the surface impregnation material can form a water repellent protection layer on the concrete surface and that it controls penetration of corrosive substances. This method shows good performance when it is used on the tight concrete structure. In this way, it is suitable for preventive maintenance of new construction concrete structures.

Table 6. Coating specification example of surface impregnation method

Process		General Name	Dilution ratio (wt.%)	Coating Method	Coverage (kg/m^2)	Target DFT (μm)	Coating Interval (20°C)
1	Surface preparation	To treat water leakage and cracking prior to this process. Remove brittle layer, dust and foreign matter completely. Flatten raised and tiered portion by power and hand tool. Clean sufficiently by brush, bloom and air blow. To confirm below 5% of surface moisture content by using surface moisture content meter (HI-500, Kett Electric Laboratory).					
2	Impregnator application	Silicone resin impregnator	0	Brush Roller	0.19	-	-

Table 7. Performance of surface impregnation method

Test items	Performance results	Test methods
Appearance observation test	No appearances change	According to the "Standard Specifications for Concrete Structures - 2007, Test methods and Specifications", Japan Society of Civil Engineers (JSCE). 15. Test methods of surface penetrants for concrete structures（JSCE-K 571-2005）
Impregnate depth measurement test	4.4 mm	
Water penetration amount test Water penetration ratio	4 %	
Water absorption rate test（7 days） Water absorption ratio	7 % (Water absorption rate 0.1 %)	
Water absorption rate test（10 days） Water absorption ratio	10 % (Water absorption rate 0.2 %)	
Water vapor permeability test Water vapor permeability ratio	100 %	
Neutralization resistance test Neutralization depth ratio	0 %	
Chloride ion penetration resistance test Chloride ion penetration depth ratio	0 %	
UV-light deterioration resistance UV-light deterioration inhibition ratio	96 %	According to the "Design Construction Guidelines for Concrete Surface
Notes; Time from spraying a test solution to the penetration depth measurement: - Neutralization depth measurement: Immediately - Chloride ion penetration depth measurement: after 2 hours		

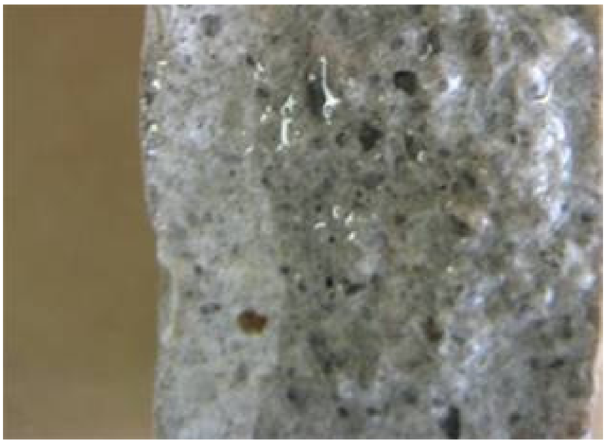

Figure 5. Cross section appearance after coated the surface impregnator (Wet condition)

Figure 6. Surface of with or without the surface impregnator (Water drip applied condition)

Application examples of surface coating methods. Figure 7 to Figure 10 show application examples of the concrete surface coating methods. In Japan, the history and performance described above are well understood. There are many application records for maintenance and appearance.

Figure 7. Sea bridge at Tokyo

Figure 8. Sea bridge at Tohoku district

Figure 9. River bridge at Tokyo

Figure 10. Passenger vessel terminal at Yokohama

CONCLUSION

From the great earthquake in 2011, Japanese people are conscious of safety, security, energy-saving, cost-saving, etc. more than ever. In modern society, concrete structures are important social capital stock which is essential to life and business activities. We would like to contribute to safe and economical maintenance and control of concrete structures through development of the surface coating method with better functions and higher durability.

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