Long-term Study on Properties of High-strength Mass Concrete in PCCV (Prestressed Concrete Containment Vessel) (Monitoring Test Results and Durability of Concrete over 22 years)

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ABSTRACT

This paper describes the strength gain properties of mass concrete specimens cast in wintertime and summertime. Subsequently we discussed the verification data for the effect of increasing durability of coating for protective finish and durability assessment for the coating itself.

At first, the long-term properties of concrete is summerized. The compressive strength increases gradually from one year to 20 years. The strength of core sample is almost same as that of standard curing specimen at the 22nd year. It was confirmed that the compressive strength is sufficiently larger than the specified design strength.

Secondly, the effect of protective finish of coating is described. The protective finish of coating is expected to have chloride resistivity and restraint effect of neutralization. The performance and those effects are maintained judging from the results of follow-up surveys over 20 years The chloride resistivity of coated film is confirmed since the specimens with coating does not increase the chloride content even if at near the surface.

Finally, the durability performance of coated film over 20 years is summerized. All of the specimens do not show marked deterioration such as blistering, stripping and cracking, do not show dirt and maintain favorable conditions over 20 years.

It is concluded that the durability of mass concrete and finishing material is verified through monitoring tests described here over the long term. These tests are quite useful in case direct destructive tests for important buildings such as nuclear reactor buildings are restricted since the tests could be conducted under the same circumstances as actual buildings. This clearly demonstrates that the monitoring tests will make a substantial contribution to verify the integrity of the building and make the maintenace plan for the buildings.

INTRODUCTION

Most important buildings in nuclear power plants are required to have higher performance for earthquake-resistance and radiation shielding other than generic performance for ordinary buildings. The buildings are characterized by composing of massive reinforced concrete. The total amount of concrete used for a nuclear power plant is 250 to 300 thousands m^3. Considering those reliability to the general public, the safety and the integrity of the buildings are ensured for the quality of concrete through in-depth preliminary study for planning, intensive quality control for construction and both durability survey and property assessment during in-service period.

The design and the construction for nuclear power plant facilities in Japan shall be conducted based on Japanese Architectural Standard Specification for Reinforced Concrete Work (JASS 5) and Japanese Architectural Standard Specification for Reinforced Concrete Work at Nuclear Power Plants (JASS 5N). At the beginning of this study actual examples achieving required performance and reliable data needed for design had not been accumulated, and there were very few data observing physical properties of concrete continuously for a long time after construction.

Nuclear power plants in operation in Japan have been located in coastal areas since they need a large amount of water for electric power generation. Since chloride contents have an impact on the reinforced concrete buildings covering most of nuclear facilities, durability performance against chloride contents in sea breeze needs to be adequately considered from the standpoint of both construction planning in coastal areas and maintenance management in operation.

Coating for protective finish on exterior walls is one of the effective methods for increasing durability. The coating is expected largely to have an effect on preventing neutralization and blocking chloride contents from sea breeze.

However, there is insufficient knowledge of the effect on increasing durability of coating for protective finish and durability assessment of the coating itself by long-term monitoring study.

With these background, Kyushu Electric Power Co. has launched the durability monitoring study using mass concrete specimens. We presented a paper based on the monitoring data for five years in SMiRT11[1]. The strength of the structural concrete indicates different increase properties according to the timing of placement (i.e. wintertime and summertime). The strength of concrete in the structure was found to be approximately equal to that with standard curing in water for 5 years irrespective of the timing of placement. Wide range of valuable data were continuously accumulated over twenty years. In this paper, at first we discuss the strength properties of mass concrete specimens cast in wintertime and summertime. Subsequently we discuss the verification data for the effect of increasing durability of coating for protective finish and durability assessment for the coating itself.

MONITORING TESTS ON CONCRETE STRENGTH

Outline of Tests

Full-size test specimens simulating general portion of a PCCV cylinder and a buttress were manufactured ,and the strength gain properties (hereafter called SGP) of structural concrete were investigated. Strength tests using strength control cylinders cast at the same time were investigated on the relationship with the actual concrete strength. Configuration of concrete specimens is shown in Fig. 1 with 3 different types for each placing time. Type 1 simulates the thick wall, such as a buttress portion of a reactor building. Type 2 and Type 3 simulates the ordinary cylinder portion and each wall thickness is 1.3m. Heat insulation was installed in each model simulating the actual structure. Simulating the actual structure, liner plate is embedded on one surface and plywood is used on the other surface as formwork. Coring location in each test specimen is also shown in Fig. 1. Table 1 summarizes the concrete specimens (size, water-cement ratio and placing temperature) In wintertime test, the SGP are investigated due to the effect of the size of the specimen and water-cement ratio. On the other hand, in summertime test, the effects of placing temperature and the size of the specimen on the SGP are to be examined. Structural concrete strength is evaluated as the mean value of each core specimen. The test was performed nine times at the concrete age of 4, 8, 13 and 26 weeks and 1, 2, 5, 12 and 22 years. Mix proportioning conditions of concrete are shown in Table 2 , and the details are summarized in Table 3.

Mass concrete Specimen Cast in Wintertime

Fig. 2 shows the comparison of the long-time SGP in the winter test between core samples and specimens under standard curing condition. The effects on long-time SGP due to the water-cement ratio were investigated. The following results were derived from this study.

- The strength of concrete under standard curing condition and that of core specimen shows almost gradual increase in its long time characteristics.
- The strength of concrete under standard curing condition and that of core specimen shows almost the same at the age of 5 years (260 weeks), and after that up to 22years (1144 weeks) , both trends show the similar way.
- With respect to the water-cement ratio, around the age of 22years SGP becomes a larger in its trend as the water –cement ratio becomes less.
- Average strength of core specimens regardless of the water-cement ratios shows fully margin to its specified design strength at the age of 22 years.

Mass concrete Specimen Cast in Summertime

Fig. 3 indicates the summertime test results. The temperature history at the center of each specimen by wintertime test results is shown in Fig. 4, and one by summertime test results is also shown in Fig.5. The effects on long-time strength gain properties(SGP) due to the placing temperature were investigated.
The following results were derived from this study.

- The strength of core specimens shows a remarkable SGP due to its initial high temperature history, and gradually increases from 1 through 22years in its age.
- On the contrary to the wintertime result, long-time strength under standard curing condition shows a steady increase as the age of concrete.
- Placing temperature was selected as a key parameter here, and it is obvious that placing temperature becomes lower, the SGP show larger at the age of 22 years.
- The average strength of core specimens from all the test specimen at the age of 22 years shows a sufficient margin to each specified design strength due to its gain property just as that from the wintertime tests.

Comparisons of SGP between Cast in Wintertime and those in Summertime

The SGP of core specimens cast in wintertime is different from those in summertime with view to the properties in early stage and those in extra-long time stage. In summary, in wintertime test core specimen shows the clear SGP subject to its age up to about one year (52 weeks), and after that it shows almost the same or gradual increase in the SGP. On the other hand, in summertime test it shows almost the same strength gain properties up to one year ,and after that it shows larger strength gain properties compared to those in wintertime test and further shows a steady increase up to 22 years.

The structural strength of concrete derived from the wintertime and summertime tests shows sufficient margin of 1.72~1.89 for the former and 1.57~1.77 for latter compared with each specified compressive design strength at the age of 22 years.

DURABILITY MONITORING TEST OVER TWENTY YAERS

The study of monitoring test using full-size simulated models related to durability of coating and the effect of surface coating of concrete for preventing penetration of the salts containing in sea breeze is described. First we investigate the effects of coating which influences the durability against the concrete. Next, we examine the restraint effect of neutralization. Finally we conduct the durability tests on coated film.

Test Specimens

The concrete specimens are shown in Table 1 and the total number of specimens is ten. Nine out of ten specimens are simulated for mass concrete in actual nuclear power plant buildings and the specified design strength is 41 N/mm^2. Type WA- and type WB- show specimens cast in wintertime, type SA- and type SB- in summertime. Nc specimen is a reference for ordinary buildings and the specified design strength is 29 N/mm^2. WB1, WB2 and SB1 are painted with protective finish coating. There are three types in finish coating. Type A and type U were used for actual buildings. Type C was chosen as a reference. The protective coating is multi-layer finish coating and is composed of first, base and finish coatings. The five combinations with primer coating are shown in Table 5. Fig. 4 also shows the partitioning of coating for three specimens.

The coated film specimens were made in order to study aging of protective finish coating. The protective finish coating was painted on packaging tapes put on cement slates and was sampled by removing from the tapes with each testing. These specimens are shown in Photo 2.

Tests on Chloride Resistivity by Coating

The chloride contents of horizontal core samples from vertical planes with coating or without coating were analyzed in order to confirm chloride resistivity of coating. The diameter of a core sample is 100 mm, the length is 250 mm and three samples per one plane were cored. The samples were sliced with every 15mm length from the surface for preparing chemical analysis samples. The method of analysis for chloride content was subjected to “The method of analysis for salt content in hardened concrete” of Japan Concrete Institute and the total amount of chloride quantity was determined.

The chloride resistivity by protective finish coating is shown in Figs. 5 and 6. Fig. 5 shows the chloride content distribution compared to that in the depth of 135 to 150 mm (hereafter called Reference Zone). The chloride content at the depth of 15 mm without coating increases with age. This resulted in the penetrated accumulation of chloride content from the sea breeze. On the other hand, there is little change of the chloride content in the coated specimens and it is confirmed that the protective finish of coating has sufficient chloride resistivity. Fig. 6 shows the increment over exposure duration. Three specimens without coating vary in the chloride quantity with age. It depends on the concrete material, water-cement ratio and the surface conditions. The increment of chloride content per unit area without coating is about 400 to 900 mg Nacl/(m^2・yr). The chloride resistivity of coated film is confirmed since the specimens with coating does not increase the chloride content even if at near the surface.

Tests on Restraint Effect of Neutralization by Coating

The depth of neutralization was measured by spraying phenolphthalein alcohol solution on the splitting surfaces of the samples. Fig. 7 shows the relationship between the square root of exposure duration and the depth of neutralization. The average depth of neutralization over twenty years for Nc specimen without coating is 5.5 mm. However the average depth over ten years of the specimens that have 41 N/mm^2 of specified design strength and have no coating is less than 0.5 mm. The reason why the depth of neutralization for those specimens is very short is due to low water-cement ratio. The specimens with low water-cement ratio are thought to have higher resistance to neutralization. The average depth of the specimens that have 41 N/mm^2 of specified design strength and have coating is also less than 0.5 mm and longer exposure duration is needed for quantitative evaluation of restraint effect of neutralization by coating.

Tests on Durability of Coated Film

Visual observation, adhesion measurement, glossiness measurement, chalking observation, electron microscope observation and measurement of tensile strain and tensile strength of coated film were made as durability test. The methods for these items and the results are as follows.

Degradation phenomenon such as blistering, stripping and cracking on the surface of concrete specimen was checked by visual observation. All of the specimens do not show marked deterioration such as blistering, stripping and cracking, do not show dirt and maintain favorable conditions over 20 years.

Adhesion between coated film and 40 mm square attachment on the coated film was measured by pull-off method. The adhesion has varied through twenty years and the fluctuation does not have a constant tendency. Most of the values are more than 0.49 N/mm^2 which is set up as the administered value of the surface treatment. The adhesion does not show marked degradation over twenty years and the bond between the coated film and the primer coating of concrete maintains favorable conditions over 20 years.

The glossiness was measured by the method for brilliance test based on “Testing Method for Paints (Japanese Industrial Standard),” after washing the surface of coated film piece removed from the coating plate specimen. The glossiness is converted into the gloss retention by setting the initial value up as 100 %. Fig. 8 shows the relationship between the exposure duration and the gloss retention. The gloss retention of “CR” drops down to less than 50 % in one year. The gloss retention of “A” and “CR” drops below to 50 % in five years. The drop of the glossiness is related closely to the deterioration of the surface of finish coating and is highly relevant with the chalking.

Chalking was evaluated by observing the weathered material of the coated film through the low power of the optical microscope. The weathering material was obtained from the sticky tape that was taped on the coated film of the concrete specimens and was slowly peeled. Degree of chalking was quantified from zero to nine. The maximum value of the degree of chalking is nine and the degree was evaluated in increments of 0.5. Fig. 9 shows the relationship the exposure duration and the degree of chalking. All of the coated films clearly show chalking in five years and show the deterioration of the surface of the finish coating. In particular, “CR” is vulnerable to the development of chalking compared with other two finish coating specimens. After five years each degree of chalking remains at approximately the same level.

The surface of the coated film obtained from the coated plate specimens was observed using scanning electron microscope (SEM). Photo. 3 shows the surface of the coated film by SEM. Fig. 10 shows the pattern diagrams of the criteria on the deterioration of the surface. The degradation of the finish coating spreads within the coating at the level 4. The repair work of coating is thought to be required at the level 4. “CR” reached the level 4 in about five years, and “A” and “U” reached in 10 years.

The tensile strain and the tensile strength of coated film specimen were measured based on the method for “Liquid-applied compounds for waterproofing membrane coating of buildings.” Fig. 11 shows the relationship between the elongation and the exposure duration. This elongation is governed by the properties of the base coating. The difference of the initial values depends on the material of the base coating. The initial elongation of “U” is about 600 % and this shows that the cracking following capability is extremely high. The initial elongation of “A” is about 250 % and that of “CR” is 55 %. The elongation of “A” and “U” drops down to 40 % of the initial values in one year. This drop causes not the deterioration but the perfect separation of solvent component and the development of the bridging reaction. After one year the elongation of “A” is about 150 % and shows stable. It does not appear the decrease of properties by the deterioration. The elongation of “U” has a tendency of decreasing gradually, but the value at the year ten is almost same as the initial elongation of “A.” The elongation of “CR” keeps nearly the initial value over 20 years.

CONCLUSIONS

We discussed the strength gain properties (SGP) of mass concrete specimens cast in wintertime and summertime. Subsequently we discussed the verification data for the effect of increasing durability of coating for protective finish and durability assessment for the coating itself.

At first, the long-term properties of concrete is summerized. The compressive strength increases gradually from one year to 20 years. The strength of core sample is almost same as that of standard curing specimen at the 22nd year. It was confirmed that the compressive strength is sufficiently larger than the specified design strength.

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Finally, the durability performance of coated film over 20 years is summerized. All of the specimens do not show marked deterioration such as blistering, stripping and cracking, do not show dirt and maintain favorable conditions over 20 years.

It is concluded that the durability of mass concrete and finishing material is verified through monitoring tests described here over the long term. These tests are quite useful in case direct destructive tests for important buildings such as nuclear reactor buildings are restricted since the tests could be conducted under the same circumstances as actual buildings. This clearly demonstrates that the monitoring tests will make a substantial contribution to verify the integrity of the building and make the maintenace plan for the buildings.

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1. Mitarai, Y., Shigenobu, M., Hiramine, K., Inoue, K., Nakane, S., and Ohike, T., “Strength Gain Properties up to Five-Year Age of High-Strength Mass Concrete,” Transactions of the 11th Structural Mechanics in Reactor Technology, pp.299-298, Tokyo, Japan, August 1991.
2. Mitarai, Y., Inatomi, T., Ohike, T., Moriya, M. and Koyama, T, “Study on Quality Control of High Strength Mass Concrete in Important Structures - Results of Monitoring Tests Related to Durability and Effect of Coatings up to 20 Years -,” AIJ Journal of Technology and Design (in submitting).

Table 1. Full-scale Concrete Specimens

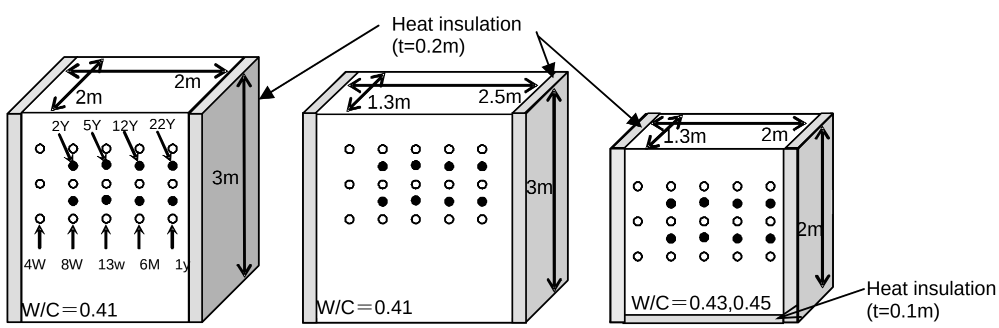
	Size(m) D×B×H	Water-cement ratio, W/C			Placing temperature, T(℃)			
		0.41	0.43	0.45	20	25	30	35
Type 1	2.0×2.0×3.0	WA1	-	-	-	-	SA1	-
Type 2	1.3×2.5×3.0	WA2	-	-	-	-	SA2	-
Type 3	1.3×2.0×2.0	-	WB1	WB2	SB3	SB2	-	SB1
Total Number		4			5			

Table 2. Mix Proportioning Conditions and Materials

Specified concrete strength	41.2 N/mm^2
Control age	13 Weeks
Slump	10 cm
Air content	4±1%
Cement	Moderate heat cement + fly ash (20% replacement)
Fine aggregate	Marine sand (70%) + basalt sand (30%)
Coarse aggregate	Basaltic crushed stone, 5-20mm
Admixture	Retarding type air-entrained water-reducing agent, supplementary air-entrained agent

Table 3. Mix Proportions of Concrete

Placing Time	W/C	s/a	Weight (kg/m^3)				
			Water	Cement	Fine aggregate	Coarse aggregate	Admixture
Wintertime	0.41	0.43	164	400	735	1056	1
	0.43	0.436	162	377	754	1062	0.942
	0.45	0.43	158	352	759	1082	0.88
Summertime	0.41	0.43	163	398	740	1059	0.995
Nc*	0.29	0.54	166	308	832	1076	0.77



Type1 Type2 Type3

Fig. 1 Configuration of Concrete Specimens and Coring Locations

Table 4. Concrete Specimen

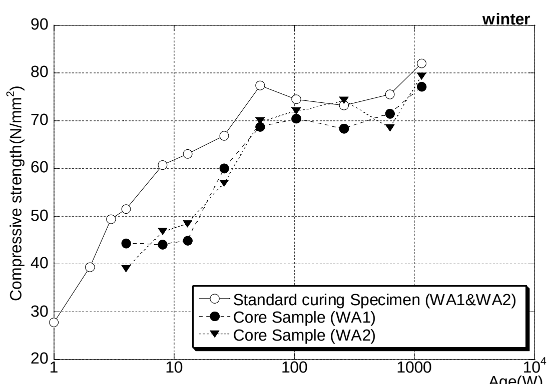
Specified concrete strength	Cast Season	Name of Specimen	Coating	Research of Neutralization & Chloride
41N/mm^2	Winter time	WA1	-	○
		WA2	-	○
		WB1	R+A, R+U	○
		WB2	K+A, M+U	○
	Summer time	SA1	-	-
		SA2	-	○
		SB1	H+C	○
		SB2	-	-
		SB3	-	-
29N/mm^2		Nc	-	○

Table 5. Contents of Coating

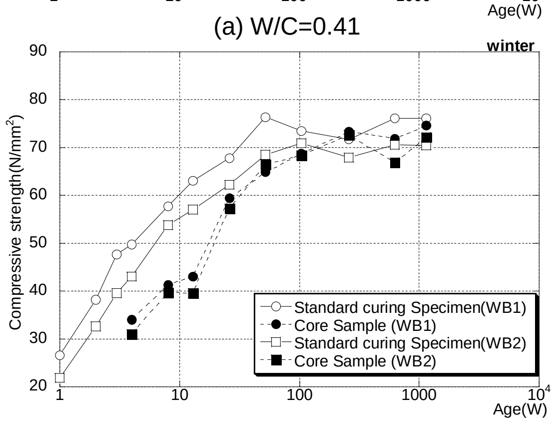
Item	Symbol	Contents of Coating
Primer Coating	R	Styrene Butadiene Rubber PCM
	K	Acrylic resin PCM
	M	Acrylic resin PCM
	H	Acrylic Rubber PCM
Protective Finish Coating	A	First: Chlorinated resin Base: Acrylic rubber emulsion Finish: Flexible acrylic urethane resin
	U	First: Epoxy resin Base: Polyurethane rubber Finish: Flexible acrylic urethane resin
	C	Base: Urethane resin + Cement Finish: Acrylic urethane resin
Combinations		R+A, R+U, K+A, M+U, H+C

Photo 1. Concrete Specimens

Photo 2. Coated Film Specimens

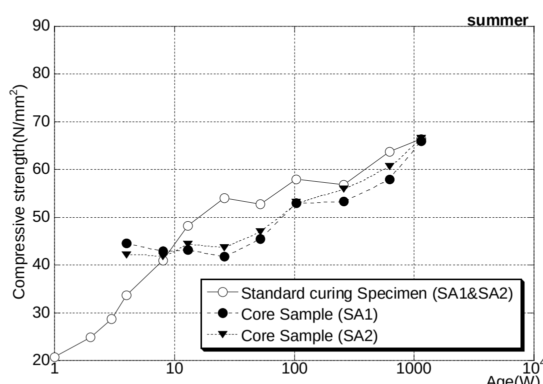


(a) W/C=0.41

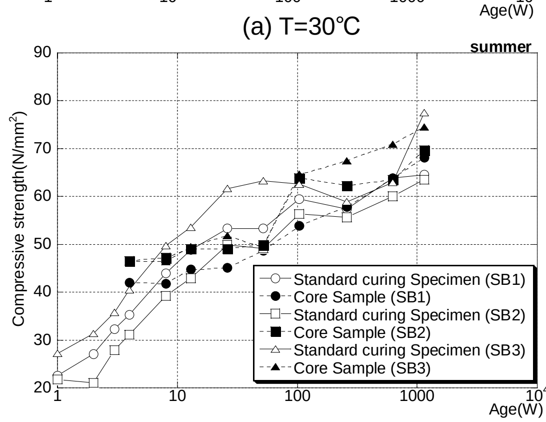


(b) W/C=0.43(WB1)&0.45(WB2)

Fig. 2 Relationship between Compressive Strength and Age (Wintertime test)



(a) T=30℃



(b) T=35℃(SB1), 25℃(SB2) & 20℃(SB3)

Fig. 3 Relationship between Compressive Strength and Age (Summertime test)

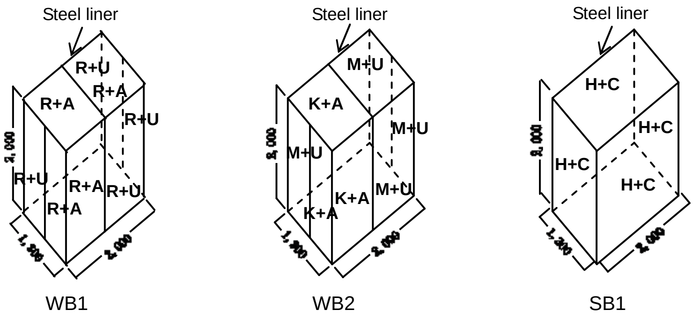


Fig. 4 Partitioning of Coating

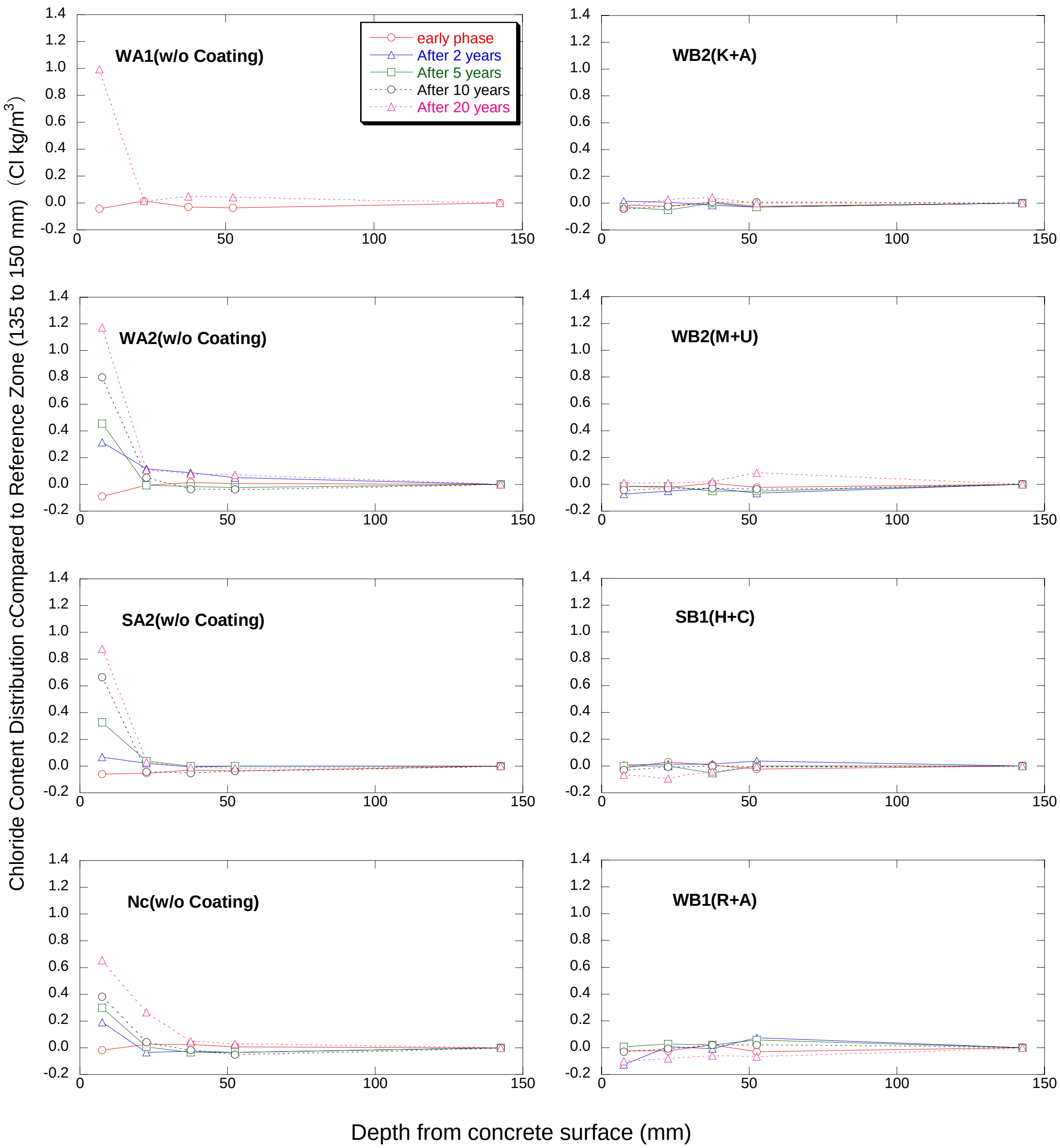


Fig. 5 Comparisons of chloride content Distribution between Specimens without Coating and Coated Specimens

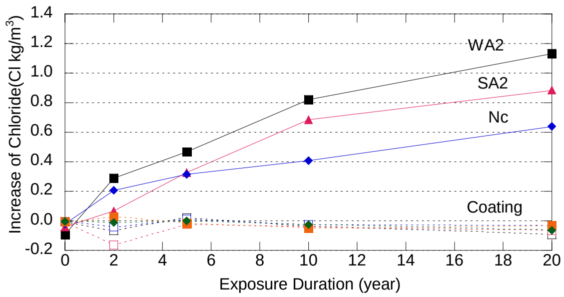


Fig. 6 Relationship between Increase of Chloride and Exposure Duration

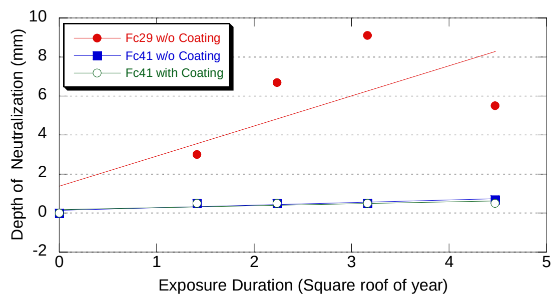


Fig. 7 Relationship between Depth of Neutralization and Exposure Duration

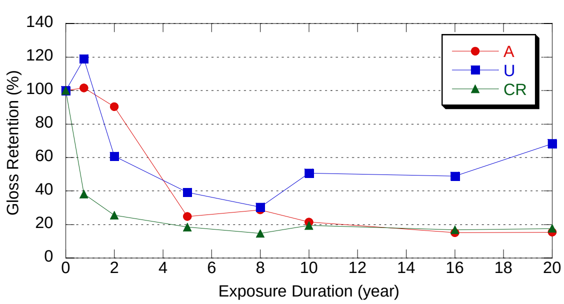


Fig. 8 Relationship between Gloss Retention and Exposure Duration

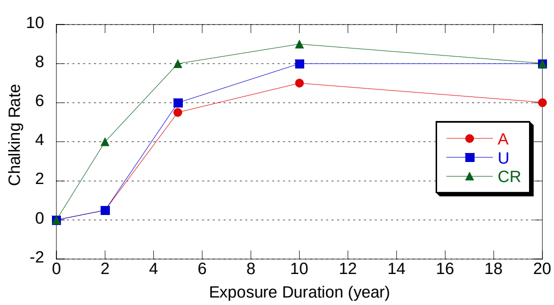


Fig. 9 Relationship between Degree of Chalking and Exposure Duration

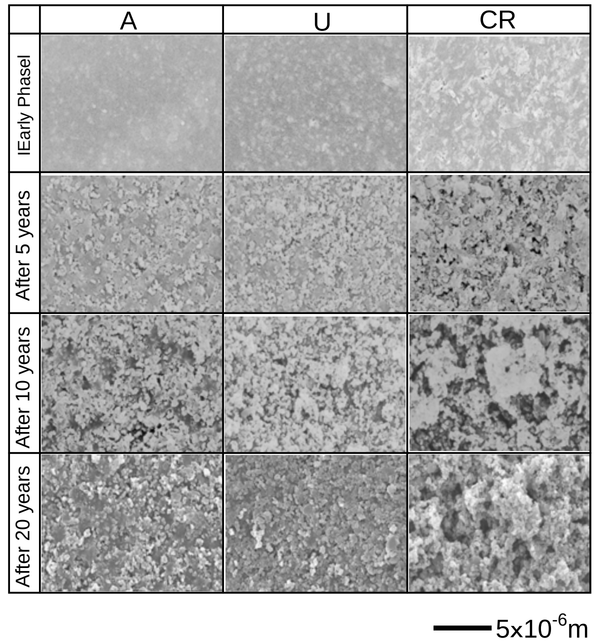


Photo. 3. Coating Surface Observation by SEM

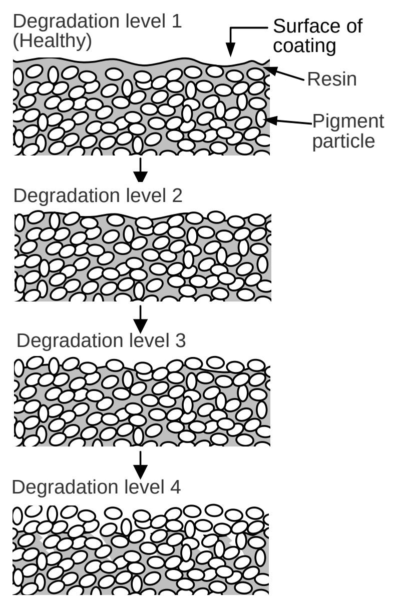


Fig. 10 Schematic Drawings of Degradation by SEM

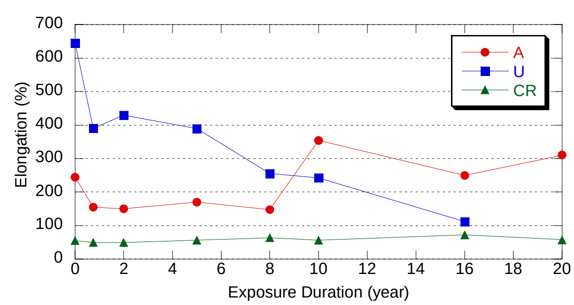


Fig. 11 Relationship between Elongation and Exposure Duration