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Effect of Concrete Surface Treatment on Expansion due to Alkali-Silica Reaction

By Toyoaki MIYAGAWA [*1], Makoto HISADA [*2], Susumu INOUE [*3] and Manabu FUJII [*4]

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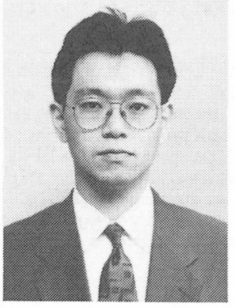

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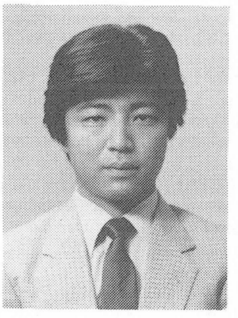

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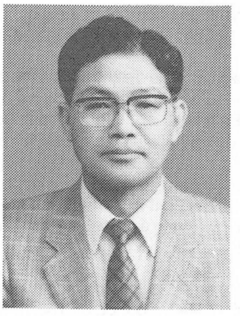

Manabu FUJII

Synopsis

Recently, a number of examples of premature deterioration caused by alkali-silica reaction have been reported. This paper deals with concrete surface treatment adopted in maintenance work. The long-term performance of typical surface treatments is examined and the effect of surface treatment on expansion of concrete due to alkali-silica reaction is investigated experimentally. The fundamental concept to determine the effect of surface treatment for alkali-silica reaction is discussed.

Keywords: Surface treatment, Expansion due to alkali-silica reaction, Waterproof, Water repellent, Ratio of surface and volume, Ratio of surface treated area, Water permeability, Water vapor transmission rate

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1. INTRODUCTION

It has been well known that the deterioration of concrete structures due to alkali-silica reaction (ASR) is generated when a sufficient quantity of alkali, reactive silica as well as water exist altogether[1]. It is considered that the control of deterioration due to ASR expansion, can be done by excluding at least one of these three factors. Existence and accumulation of the three factors within concrete is supposed to be attributed to two supply sources as shown in Table 1. Therefore, in order to control the deterioration, it is necessary to take precautions in two aspects: namely, to control intrusion of deteriorating factors from outside to prevent their contents from exceeding the critical value beyond which ASR expansion is generated and to dissipate deteriorating factors that have existed in concrete to keep their contents below the critical values beyond which ASR expansion is generated.

Under today's level of technology, the following methods are considered to be taken as the measures for controlling or dissipating deteriorating factors. First, in case of new construction, ASR expansion can be controlled by using low alkali cement or a non-reactive aggregate. But, in case of repair of the existing structures, it is difficult to eliminate alkali and reactive silica in concrete and controlling of water content is an important and feasible technique. Moreover, even in case of new construction, if attempts for control of the quantity of alkali or exclusion of reactive aggregate failed, control of water content becomes important in repair measure as preventive maintenance.

When ASR takes place, the progress of damage in concrete structures is composed of the following 4 phases[2),3)].

① Migration of reactants to aggregate (process of physical transfer)

② Production of alkali silica gel (process of chemical reaction)

③ Gel absorbs water causing expansion. (physio-chemical process of water absorption)

④ Concrete expands, cracks are generated and various damages occur (Process of generation of deterioration)

As shown in the above, expansion is caused directly by absorption of water by gel from which the significant influence of water on the expansion is made clear.

Recently, repair by concrete surface treatment has been applied to the damaged structures due to ASR expansion. Such surface treatment is used mainly for the purpose of controlling water content among the deteriorating factors. However, applying surface treatment simply will not always bring the expected effect, but there may be even possibility of resulting in an adverse effect. Investigations must be made fully on the environmental conditions of the concrete structure and the conditions of concrete at the time of application of surface treatment such as the moisture content of concrete.

In this study, under the various environmental conditions, the authors tried to make a comparison on the long-term base among the typical surface treatment systems generally used for controlling ASR expansion, and to make clear the characteristics of various systems. Then, several factors in the stage of surface treatment practice are picked up and their influences on the effectiveness of surface treatment are investigated.

Table 1. Principal Supply Sources of Deteriorating Factors

Factor of deterioration	Including in concrete materials	Intrusion from outside
Alkali	Cement, admixture, mixing water, aggregate	Seawater, etc.
Silica	Aggregate	Aggregate
Water	Unhydrated water	Weathering action, etc.

2. OUTLINE OF EXPERIMENT

This study is composed of the following three series. The systems of surface treatment are shown in Table 2. Surface treatment is to be applied before the expansion test when concrete has both the very large potential of expansion due to ASR and the sufficient residual potential of expansion. The expansion test is started at around the age of 2 months in consideration of the curing period of surface treatment. As the reactive concrete to which surface treatment is to be applied, those that have the past records of large expansion are chosen and the mix proportion of reactive concrete is shown in Table 3. The ratio of reactive aggregate and non-reactive is determined to reach pessimum and the equivalent alkali content in reactive concrete is adjusted to 8.0 kg/m^3 by adding NaCl. In addition, for the purpose of comparison, non-reactive concrete is also provided. The mix proportions are summarized in Table 3. The specimens are prism of 10 x 10 x 40 cm, except a part of the Series 2.

When discussing ASR the environmental conditions are very important factors. Generally speaking, the accelerated exposure conditions that are employed most often would be 38 C (or 40 C), RH 100% in accordance with ASTM C 227 (mortar bar method). However, for the cases in which dissipation of moisture from the inside to the outside of concrete should be taken into consideration, 100% of ambient humidity is not proper since no dissipation will occur. Therefore, in this study the following two exposure conditions are taken which are as close to the real ones as possible with opportunities to meet both wet and dry periods:

① Outdoor: The specimens are placed in Kyoto City area (on the roof of the school of Civil Engineering, Kyoto University) so as to receive the influence of the natural environment such as sunshine, wind, rain and so forth. The annual average temperature is about 15 C and the annual average humidity is about RH 75%.

② Dry and wet: In consideration of the fact that the maximum values of the annual average temperature and humidity in various districts in Japan are at around 25 C and RH 80% respectively, it is planned to obtain the conditions of the average temperature of 30 C and the average humidity of 80% by repeating the condition of 40 C, RH 100% and that of 20 C, RH 60% alternately for 12 hours each. While this is an accelerated test, the authors intended to reproduce the temperature and humidity very close to the most severe condition that could be expected in Japan.

Table 2. Properties and Composition of Surface Treatment System

System	Type	Properties	Series	Specified quantity	
Urethane	Lining	Fairly high waterproof, relatively large elongation (400%)	1, 3	Modified MDI prepolymer · Polybuthadien urethane Polybuthadien urethane Acrylic urethane	30 μm 120 μm 150 μm 60 μm
Epoxy	Lining	Highly waterproof, but small elongation (130%)	1, 3	Epoxy Epoxy putty Epoxy Acrylic urethane	0.1 kg/m² - 240 μm 30 μm
MMA	Impregnation	Waterproof due to filling pore in concrete	1	MMA Acrylic polymer	0.21 kg/m² 0.14 kg/m²
Sodium Silicate	Impregnation	Low water repellant, but poorly waterproof	1	Sodium silicate	370 cc/m²
Silan	Impregnation	In view of weather proofing and prevention of carbonation, apply polymer cement mortar or methylmethacrylate respectively after impregnation with silan	1, 2, 3	Silan	400 cc/m²
Silan + PCM	Composite		2, 3	Silan Acrylic PCM	400 cc/m² 1.2 mm
Silan + MMA	Composite		3	Silan MMA Acrylic polymer	0.30 kg/m² 0.15 kg/m² 0.15 kg/m²
Sheet 5000	Bonded to concrete surface Bonded to mold	Water vapor transmission rate: 4790g/m²/day	3	Polyethylene foam sheet Nylon mat	50 μm 250 μm
Sheet 1000	Bonded to concrete surface	Water vapor transmission rate 930g/m²/day	3	Polyethylene foam sheet Nylon mat	50 μm 250 μm

Table 3. Mix Proportion of Concrete

Series	Type	M.S. (mm)	Slump (cm)	Air (%)	W/C (%)	s/a	Weight (kg/m³)					
							Water	Cement	Fine	Coarse	Coarse	Vinsol
1	Reactive	0	9 1	4 0.5	50	44	176	352	754	468	493	88
	Non-reactive	20	-	4 0.5	50	44	176	352	754	-	1010	106
2, 3	Reactive	20	9 1	4 0.5	50	44	176	352	783	468	493	35.2
	Non-reactive	20	-	4 0.5	50	(%) 44	176	352	783	-	1010	35.2

Note)	Specific gravity	Water absorption ratio	Chemical method (Sc/Rc)	Mortar bar method ($\times 10^{-6}$)	
Reactive coarse aggregate:	2.55	1.89%	789/181=4.36	3 months = 2650,	6 months = 2819
Non-reactive coarse aggregate:	2.69	0.88%	43/152=0.28	3 months = 17,	6 months = 47

2.1 Series 1 - Effect of various surface treatment systems on ASR expansion -

In Series 1, the concrete specimens to which typical surface treatment systems now being used for controlling ASR expansion are applied are exposed under the environmental conditions of two kinds and the effects are compared and investigated among the various systems on a long-term basis. When surface treatment is applied to concrete in this series, the moisture content of the surface of concrete is made at 10% in the reading of the high frequency moisture meter (equivalent to about 5% of the water content of the absolute dry concrete). The moisture content of 10% is a dry condition that could be achieved rather easily even in the case of repairing of existing structures. The factors of the specimens are listed in Table 4.

Table 4. Specimens - Series 1 -

System of surface treatment	Number of specimens	
	Outdoor environment	Dry environment
Reactive without treatment	2	2
Urethane	2	2
Epoxy	2	2
MMA	2	2
Sodium silicate	2	2
Silan	2	2
Non-reactive	2	2

2.2 Series 2 - Effect of surface treatment system of water repellant type on ASR expansion -

It is made clear in the tests of Series 1 that the water repellant type (silan) is effective as the system for controlling ASR expansion. In Series 2, for the purpose of improving the weather proofing and preventing carbonation of concrete the water repellant type in which polymer cement mortar of the acrylic type is used as top coat in combination with silan impregnation are applied. The influence of following two factors on the effect of surface treatment of the water repellant type are investigated. The moisture content of surface concrete used in this series is also 10%, the same value as in Series 1.

2.2.1 Ratio of surface and volume

Concrete structures are abundant of varieties in their shapes and dimensions. In this study, the ratio of the surface(S) and volume (V) (S/V) is used as the index to represent its influence. The influences of S/V on the expansion are investigated under conducted outdoor conditions.

2.2.2 Ratio of surface treated area

Since concrete structures are used in various places and purposes, some portions of their surface can not be treated. Anticipating such cases, surface treated specimens with different ratios of surface treated area are provided and the influences of the ratio of surface treated area are investigated under dry and wet condition. The ratios of surface treated area of the specimens are illustrated schematically in Fig. 1.

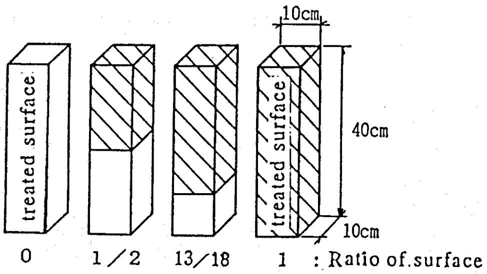

Fig. 1. Ratio of surface treated area ratio

Table 5. Specimens - Series 2 -

<table>
<tr><td>S/V (cm⁻¹)</td><td colspan="2">0.25</td><td colspan="2">0.32</td><td colspan="2">0.45</td></tr>
<tr><td>Dimensions</td><td colspan="2">20 x 20 x 40</td><td colspan="2">15 x 15 x 40</td><td colspan="2">10 x 10 x 40</td></tr>
<tr><td>Number</td><td colspan="2">2</td><td colspan="2">2</td><td colspan="2">2</td></tr>
<tr><td>Ratio of surface treated area</td><td>1</td><td colspan="2">13/18</td><td colspan="2">1/2</td><td>0</td></tr>
<tr><td>Number of specimens</td><td>2</td><td colspan="2">2</td><td colspan="2">2</td><td>2</td></tr>
</table>

2.3 Series 3 - Influence of moisture content of concrete and composite water repellant treatment -

In Series 3, picking up the following two factors as well as the permeability to water in a liquid and vapor phases of various systems, their relation with the effect on ASR expansion is investigated.

2.3.1 Moisture content of concrete

In case of applying surface treatment to the concrete structures, the factors such as the ratio of surface and volume, the ratio of surface treated area, etc., should be taken into consideration and the moisture content of existing concrete at the time of application is also important. In Series 1 and 2, from the viewpoint of actual practice, measurement of the moisture content is made on the surface and its volume is deemed to represent that of interior and fixed at 10%. In the Series 3, the values of initial moisture content are fixed at two points, namely the one is 10% and the other is 8% which can be reached only after concrete has been dried fully in the field(equivalent to about 4% of the water content to the absolute dry concrete), and their influence on the effect of ASR expansion is investigated.

2.3.2 Composite water repellant system

The composite water repellant systems including those of the sheet types are provided and their influence on the effect on expansion is investigated. With regard to the systems of the sheet type, in addition to the method of applying it after concrete has been hardened in the similar way to the cases of other systems, a system in which the sheet is bonded to the mold prior to placing of concrete is adopted. The factors of these specimens are listed in Table 6.

Table 6. Specimens - Series 3 -

Specimen	Expansion			Water Permeability	Moisture Permeability
Surface treatment system	Initial moisture content (%)	Number of specimens		Number of specimens	
		Outdoor	Dry and Wet		
Silan + PCM	10	2	2	1	2
	8	2	2		
Silan + MMA	10	2	2	1	2
	8	2	-		
Silan	10	2	2	1	2
	8	2	-		
Urethane	10	2	2	1	2
	8	2	2		
Epoxy	10	2	2	1	2
	8	2	-		
Sheet 5000	10	2	2	1	2
	8	2	-		
	Under placing of concrete	3	-		
Sheet 1000	10	2	2	1	2
	8	2	-		
Reactive, without treatment	-	2	2	1	2
Non-reactive	-	2	2	1	2

2.4 Items to be measured and discussed

In this study, the following nine items are picked up as those to be measured and discussed. Measurement and discussion are conducted on the subjects provided by properly combining them. The outline of every item is described below. In principle, these results of measurement are presented by the average value with respect to the specimens having the same factors in principle.

2.4.1 Concrete specimens

(1) Observation of appearance: Cracks in every specimen, cracks of surface treatment, blisters, and color change, etc. are observed.

(2) Expansion (strain): The distance between two plugs that were buried longitudinally about 20cm apart into two opposite sides (10x40cm) is measured and its change rate with time is taken as the amount of expansion (strain).

(3) Weight change: By measuring the weight of the specimen and the ratio of its change is calculated.

(4) Relative dynamic modulus of elasticity: From the resonant frequency of the longitudinal vibration of the first order of the specimen, the relative dynamic modulus of elasticity is evaluated.

(5) Pulse velocity: The time of transmission of the ultrasonic wave is measured along the direction of the longer side (40cm) from which the pulse velocity is evaluated.

2.4.2 Controlling effect

(1) Expansion reducing effect (E_e): Taking the amount of expansion of the specimen with no surface treatment as the basis, this is calculated as an index with which the degree of the effect on ASR expansion by various surface treatment systems are compared. The smaller the volume of E_e is as compared with 1.0, its effect on expansion is judged to be greater.

$$E_e = \varepsilon_r / \varepsilon_{rr}$$

where, $\varepsilon_{rr} = \varepsilon - \varepsilon_{nn}$: Expansion due to ASR

ε : Expansion of each specimen (+ means expansion)

ε_{nn} : Expansion of the non-reactive specimen under the same exposure condition

ε_{rr} : Expansion of the reactiver specimens without treatment under the same exposure condition

(2) Weight control effect (E_ω): Taking the weight change of the reactive specimen without surface treatment as the basis, this is calculated as the index for comparing the degree of the controlling effect on weight increase due to water absorption among various surface treatment systems. The smaller the value of E_ω is, the controlling effect is evaluated greater.

$$E_\omega = \omega - \omega_\gamma$$

Where,

ω: Weight change of each specimen (+ means increase)

ω_γ: Weight change of the reactive specimen without surface treatment under the same exposure condition.

2.4.3 Properties of surface treatment

(1) Water permeation performance: Referring to the water permeability test of JIS A 6910 "Multi-layer Wall Coatings for Glossy Textured Finishes", the water permeability is calculated as the capacity of permeation of liquid phase water based upon the change of the water head in the apparatus as shown in Fig. 2 under the condition of 20 C, and RH 80%.

(2) Moisture permeation performance: Referring to JIS Z 0208 "Testing Method of Moisture Permeability of Moisture-proof Wrapping Materials" and the study by Kobayashi et al.[4] the weight change of the specimen as illustrated in Fig. 3 is measured under the condition of 20 C, RH 80% and the water vapor transmission rate is calculated as the dissipating capacity of water vapor. By the way, wet-screened reactive concrete is used as mortar.

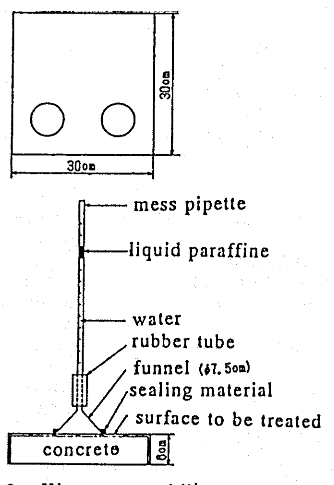

Fig. 2. Water permeability test

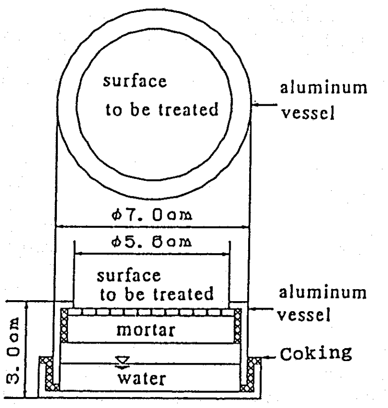

Fig. 3. Water vapor transmission test.

3. RESULTS AND DISCUSSION

3.1 Series 1

From Series 1, the results for longer periods as compared with other series are gained which involve important information. However, in Series 1, the temperature-humidity controller often went wrong. Therefore, while the results of Series 1 was discussed, re-examination is to be made in other series with regard to its principal item.

(1) Appearance

At the 216th week after the beginning of the tests, only the silan which is the typical water repellent system except non-reactive one has kept sound appearance in the outdoor tests, but in the dry and wet condition, in all the cases cracks are generated including silan except the cases of non-reactive ones. In the cases of the lining system of epoxy and urethane, surface deterioration such as blisters and eduction of gel are confirmed.

Particularly, the epoxy lining, is cracked heavily and it is known that it is inferior to urethane with respect to its crack bridging performance. Also in the cases where MMA or sodium silicate is used, heavy damages in appearance are observed with a lot of cracks and gel under the both environmental conditions.

(2) Expansion

Expansions with elapsed time are shown in Figs. 4 and 5. With regard to the reactive specimen without treatment, the rate of expansion is faster in the dry and wet condition as compared with the outdoor condition and the expansion saturated a bit earlier. However, the final amounts of expansion look to be almost in the same order. By the way, according to the accelerated test[5] conducted at 40 C and RH 100% as an extra case, while the final amount of expansion is nearly the same, the rate of expansion is so larger that the time until the expansion saturate is about 40 weeks. Therefore, the degree of acceleration of ASR expansion by the dry and wet conditions adopted in this experiment is to be situated at between the outdoor environment in Kyoto and ASTM C277 "Mortar bar method".

In the outdoor tests, the controlling effect of silan on expansion is very high. When epoxy or MMA is applied, concrete tends to expand after around the 60th week gradually and little effect is seen in a long-term basis. In these specimens, it is supposed that the lining films were cracked by expansion due to the initial interior water in a relatively early stage, then the effect has been reduced due to intrusion of water through the cracks. Therefore, for the purpose of controlling ASR expansion, the system with high crack bridging performance is supposed to be favorable. Though urethane shows higher effect at the stage of 216 weeks, concrete itself is cracked and the trace of cracks are observed on the coated film. Sodium silicate has been considered to be a water repellant and weather proofing agent, but in this experiment, it has the same trend toward expansion as those with no treatment and its effect looks to be considerably smaller than that of silan which belongs to the same water repellant type.

In the dry and wet condition, expansion took place in all of the specimens that have reactivity but those treated with silan showed smaller expansion as compared with other surface treatment systems. This means nothing other than the fact that silan is the most effective in controlling ASR expansion, and further investigation is supposed to be necessary for raising its effectiveness. With regard to epoxy and urethane, their final amounts of expansion are nearly equal and it is supposed that the effects of both of them are not large under severe conditions and the expansion is rather larger than that of the specimen without treatment. As epoxy and urethane linings are waterproof systems, they does not allow dissipation of interior moisture and accelerate ASR expansion on the contrary.

The final expansion reducing effect, E_e, measured at the stage when expansion has almost saturated are shown in Fig. 6. The effectiveness of silan and urethane in the outdoor and that of silan under the dry and wet, though much smaller as compared with the outdoor test, can be confirmed.

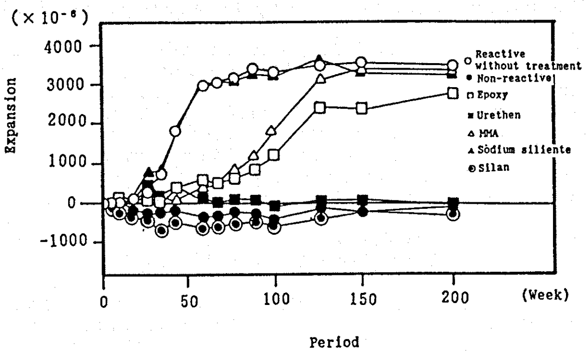

Fig.4. Expansion - Series 1: outdoor -

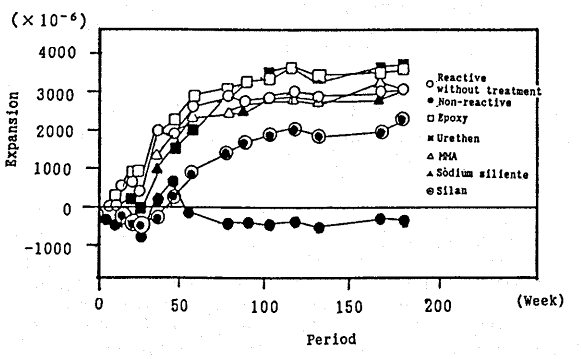

Fig.5. Expansion - Series 1: dry and wet -

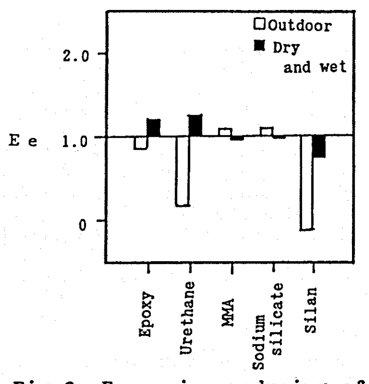

Fig.6. Expansion reducing effect (Ee). - Series 1 -

(3) Weight change

The correlations between the expansion and the weight change at every measurement are shown in Figs. 7 and 8. They show the tendency that the expansion increases with increase in weight and suggest that increase of water absorption of concrete has a great influence on the expansion due to ASR directly. Though there is scatter of data, in the majority of the specimens that showed increase in weight by more than 0.4%, expansion exceeding 0.05%[6] that has been considered to be the critical strain at which hair cracks are generated from reactive coarse aggregate was observed. Therefore, with regard to the aggregate used in this experiment, if the degree of progress of expansion is to be judged by the weight change, it may be allowed to deal with the ratio of weight increase at around 0.4% as the critical value. These numerical values will be discussed in Series 3, too. In this series weight increase less than 0.4% could be observed in spite of expansion exceeding 0.05% are found. These phenomena are shown in the specimens that have been left for a long period after expansion exceeding 0.05% or in those that were in a constant dry condition due to disorder of the temperature-humidity controller for a long period (a few days - one week). Particularly in the cases of the dry and wet for silan and urethane, even considerable decrease in weight was recorded.. This is supposed to be caused by the dissipation of water from concrete after its expansion has taken place due to the water repellant performance. With regard to urethane, too, it may be considered to have the water repellant property to a certain extent, though it is usually classified as lining type.

The weight control effects, E_w, of various surface treatment systems at the final measurement are shown in Fig. 9. The effect of silan and urethane can be confirmed.

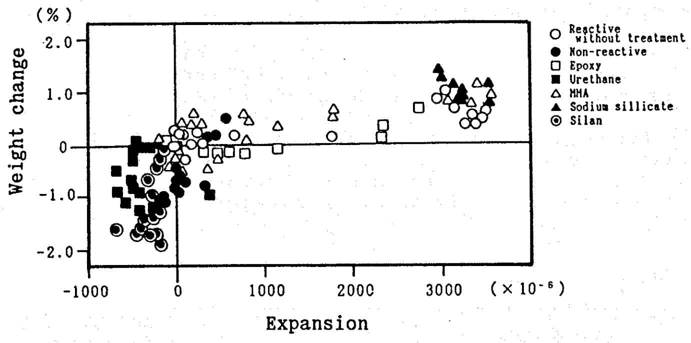

Fig. 7. Relation between expansion and weight change.

- Series 1: outdoor -

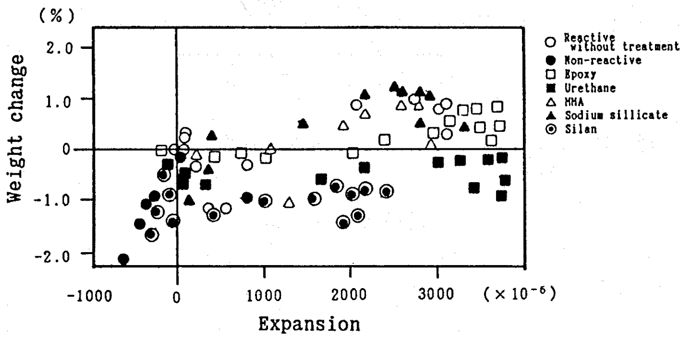

Fig. 8. Relation between expansion and weight change

- Series 1: dry and wet -

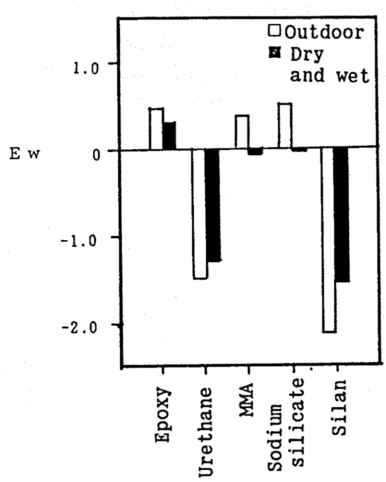

Fig. 9. Weight control effect (Ew).

- Series 1 -

(4) Relative dynamic modulus of elasticity

The correlation between the strain and the relative dynamic modulus of elasticity is shown in Figs. 10 and 11. In the outdoor tests, remarkable reduction in the relative dynamic modulus of elasticity is observed following the rapid expansion. It is generally accepted that the first visible crack of the specimen is found in the stage of expansion of 0.05 - 0.10[7] and in the stage of expansion above 0.10%, the modulus of elasticity drops to about 60% of the initial value. In the tests under the dry and wet, almost similar results are gained. Such tendency of decrease is also reported by Nishibayshi <u>et al</u>.[8]

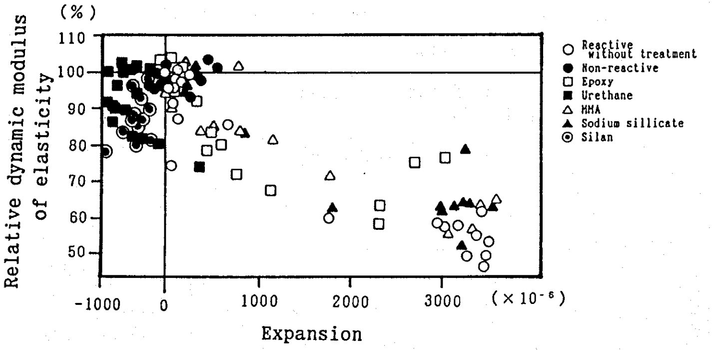

Fig. 10. Relaton between expansion and relative dynamic modulus of elasticity.

- Series 1: Outdoor -

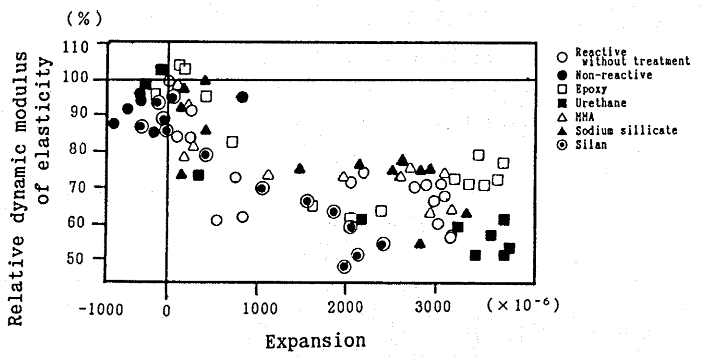

Fig. 11. Relation between expansion and relative dynamic mokulus of elasticity.

-Series 1: dry and wet -

(5) Pulse velocity

The correlation between the expansion and the pulse velocity is shown in Figs. 12 and 13. In every specimen, reduction of the pulse velocity is observed as ASR expansion takes place and in the stage of expansion above 0.10%, its values comes down below about 90% of the initially measured one. According to Amasaki et al.[9], in the case of plain concrete, reduction of the pulse velocity is reported to be about 10 - 20% for the cube of 20 - 3-cm, though the reduction depend upon the dimensions of the specimen, which is similar to the result gained in this study.

3.2 Series 2

3.2.1 Ratio of surface and volume

The ratio of surface and volume means the surface area per unit volume which is supposed to be far larger in actual structures than the values used in this experiment. While the results gained in this study can not be simply applied to the evaluation of actual structures as they are, the following tendency have been known:

(1) Appearance

The appearance of the specimens is shown in Table 7. Cracks are generated in all specimens with no surface treatment. While no cracks are. observed in the specimens with surface treatment, eduction of gel is confirmed at the part of PCM in these specimens.

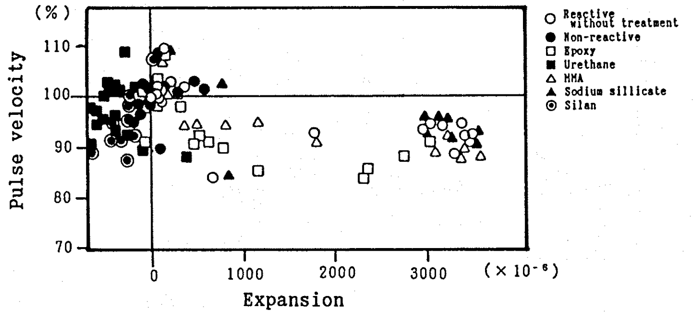

Fig. 12. Relation between expantion and pause verocity
- Series 1: outdoor -

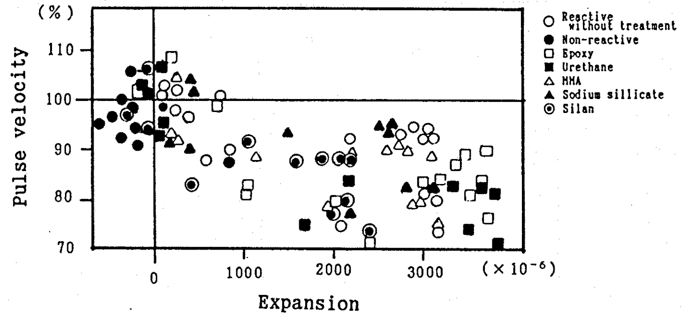

Fig. 13. Reltion between expansion and pulse velocity.
- Series 1: dry and wet -

Table 7. Appearance of Specimens
- Series 2: Influence of S/V -

S/V (cm^{-1})	0.25	0.32	0.45
With treatment	Gel	Gel	No change
Without treatment	Many wide cracks	Many wide cracks	Many cracks

(2) Expansion

The expansion of every specimen with time is presented in Fig. 14 and the expansion reduction effect, E_e, and the weight control effect, E_ω, after 165 weeks of testing are shown in Fig. 15. The specimens without treatment show remarkable expansion, and as S/V becomes smaller, the expansion increases. Particularly, in the specimen whose S/V is 0.25, the amount of expansion exceeds 5,000μ after around 120 weeks of testing, thus the more massive concrete is, the more remarkable ASR expansion is supposed to take place. Among the specimens with surface treatment, also, some of them are showing expansion due to ASR after around the 50th weeks of testing and increasing tendency of the amount of expansion as S/V is 0.45, almost no expansion is generated at present. Therefore, the larger the ratio of surface treated area to the volume of concrete in a structure, the higher controlling effect on ASR expansion could be expected.

Since the period of testing is not long enough and expansion has not saturated yet, quantitative evaluation by E_e will be necessary in the future.

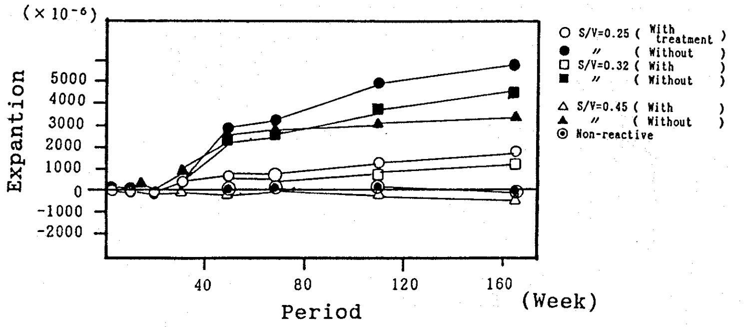

Fig. 14. Expansion
- Series 2: influence of S/V -

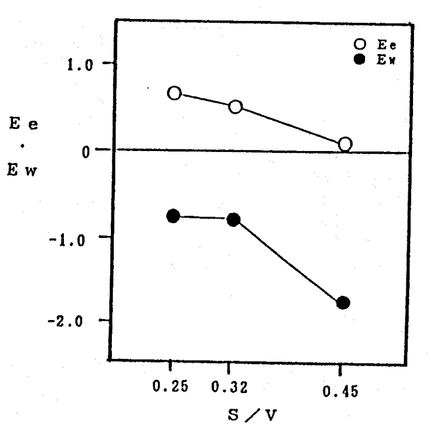

Fig. 15. Influence of S/V on E_e and E_ω.

3.2.2 *Ratio of surface treated area*

(1) Appearance

The appearance of the specimens after 60 weeks of testing is listed in Table 8. Cracks are seen on all untreated portions of the surface, but not on the treated surface. Since cracks is observed along the border zone between the treated surface and untreated one, these results does not mean that no cracks are generated at all on the treated surface of concrete but means that PCM has so large capability of crack bridging that it covers up cracks.

Table 8. Appearance of Specimen
- Series 2: Influence of the ratio of surface treated area -

Ratio of surface treated area	0	1/2	13/18	1
Appearance	Many cracks, gel	Concrete cracks, color change of lining	Concrete cracks, color change of lining	Color change of lining

(2) Expansion

The expansion with time is shown in Fig. 16 and the expansion reducing effect, E_e, and the weight control effect in Fig. 17. It is clearly that the larger the ratio of surface treated area becomes, ASR expansion is controlled to be smaller. However, in the experiment conducted this time, there was a period in which the humidity was very low as the temperature-humidity controller went wrong after about 20 weeks of testing. Therefore, in order to make clearer the influence of the ratio of surface treated area on the controlling effect with respect to the systems adopted in this experiment, it is supposed to be necessary to continue measurement.

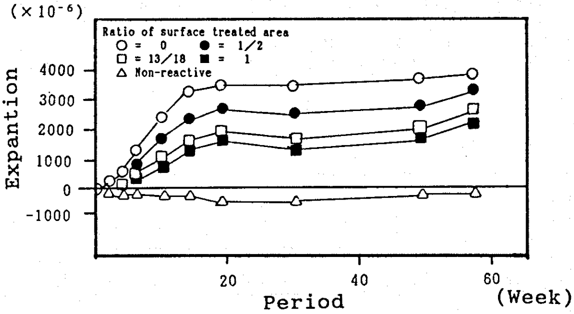

Fig. 16. Expansion
- Series 2: influence of the ratio of surface treated area -

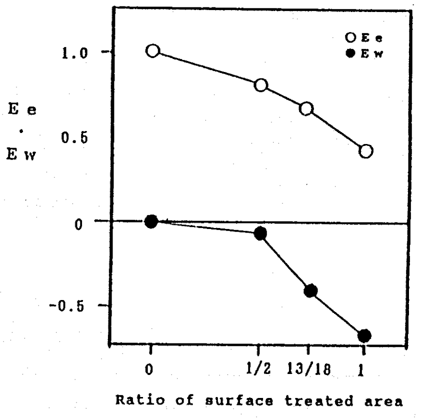

Fig. 17. Influence of the ratio of surface treated area on E_e and E_w.

3.3 Series 3

(1) Appearance

The appearance of every specimen after 80 weeks of testing is listed in Table 9. In the outdoor, no change is observed in the specimens to which urethane, epoxy and silan were applied. Beginning from about 50th week of testing, Sheet 5000 and Sheet 1000 have become damaged and after 80 weeks of testing, rips are found in the sheet and eduction of gel is confirmed partially. On the other hand, in the dry and wet, regardless of initial interior moisture content, blisters of lining and eduction of gel that are generated on the urethane and epoxy specimens are remarkable, and in particular, the lining film is cracked in the epoxy specimen. By the way, in the specimens to which silan is applied, the color of PCM turned milky is observed. In the dry and wet environment, no damage of the sheet can be seen, though there is eduction of gel on Sheet 5000 and Sheet 1000.

Table 9. Appearance of Specimens - Series 3 -

System	Environment	Appearance
Urethane	Outdoor	In the 79th week, small blisters are confirmed on the surface of lining.
	Dry and wet	In the 27th week, blisters, eduction of gel and concrete cracks are confirmed, but lining is not cracked.
Epoxy	Outdoor	No change
	Dry and wet	In the 20th week, blisters, eduction of gel and concrete cracks are confirmed, and lining film is cracked.
Silan + PCM	Outdoor	In the 79th week, weathering of lining surface (hardening) is confirmed.
	Dry and wet	In the 2nd week, the top coat peels off and in the 20th week, it turned white.
Silan + MMA	-	No change is observed in either environment.
Silan	Outdoor	No change
	Dry and wet	In some specimens, small cracks are found.
Sheet 5000	Outdoor	In the concrete-bound type specimens, rips are generated in around the 50th week, and in the mold-bond type specimens, rips are generated in the 20th week in the sheet on the surface of concrete as it was placed.
	Dry and wet	Gel is confirmed in the 32nd week.
Sheet 1000	Outdoor	In the 50th week, rips are found in the sheet and gel is confirmed.
	Dry and wet	Gel is confirmed in the 79th week.
Reactive	-	In both environments, cracks are confirmed in the 4th week.
Non-reactive	-	No change

(2) Expansion

The expansion with time is shown in Figs. 18 - 21 and the expansion reducing effect, E_e, calculated from the final measurement in Fig. 22 respectively. In the outdoor, almost no expansion is seen in the urethane coated specimens similarly to Series 1. As for epoxy, too, expansion is not observed until around the 80th week. This is a bit later as compared with the result in Series 1, but this presumably owes to the fact that the waterproof nature of epoxy is maintained since no crack damages are confirmed on the treated surface. With regard to these specimens, no remarkable influence of the initial interior moisture content is recognized so far. As for Sheet 5000, both specimens of 8% and 10% moisture content started expansion in around the 40th week, but little influence of initial interior moisture content is observed. In the specimens of Sheet 5000, damage to the sheet have been generated in around the 40th week, and influence of moisture intrusion from outside is greater, thus it is presumed that influence of the difference in the initial interior moisture content did not reflect on the strain. Regarding Sheet 1000, it can be recognized that the strain of the specimen of 10% moisture content show a larger strain than that of 8%.

In the dry and wet, controlling effect to a certain extent is observed with respect to urethane, but no remarkable difference is observed as the influence of moisture content that changes over the range in the order of 8 - 10%. In the case of epoxy, cracks and blisters are generated on the coated film, eduction of gel is recognized on the surface and the amount of expansion is greater than that of the reactive specimen without treatment. As for sheets, when the sheet in order of Sheet 5000 is used under the highly humid environment that would provide RH 100%, the influence of water that intrudes from outside looks to exceed the influence of water dissipation, almost no effect on ASR expansion is observed. However, in the order of Sheet 1000, controlling effect equivalent to that of silan is gained. But, in the both of Sheet 5000 and Sheet 1000, no damages are observed in their appearance. If these results are considered together with those gained in the outdoor tests, in applying the surface treatment system with the sheet, consideration for its weather proof performance is supposed to be necessary. By the way, the test period of Series 3 is shorter than that of Series 1, it will need some more time until the conclusion is finally reached.

In the specimens of the silan type, almost no expansion is generated in any system of treatment in the outdoor, but in the dry and wet, the specimen to which PCM is applied together with silan presents the expansion similar to that of the reactive without treatment specimen at about the 80th week of testing, its expansion develops farther than that of the specimen to which silan was applied alone. Combined application of silan and MMA shows the controlling effect on ASR expansion almost to the same degree as that given by application of silan alone, thus any significant improvement in the effect is not observed so far.

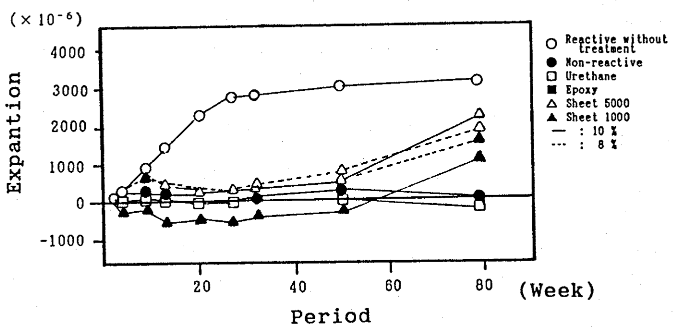

Fig. 18. Expantion
- Series 3:lining and sheet types, outdoor -

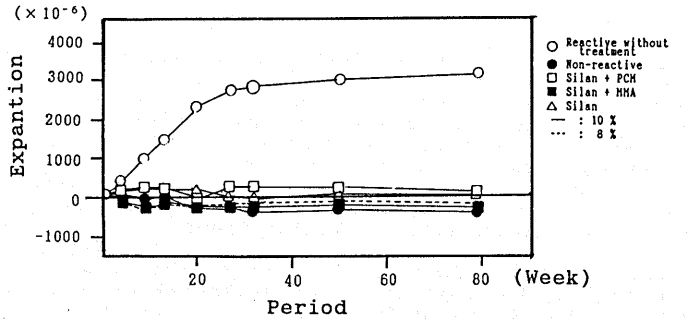

Fig. 19. Expantion
- Series 3: silan type, outdoor -

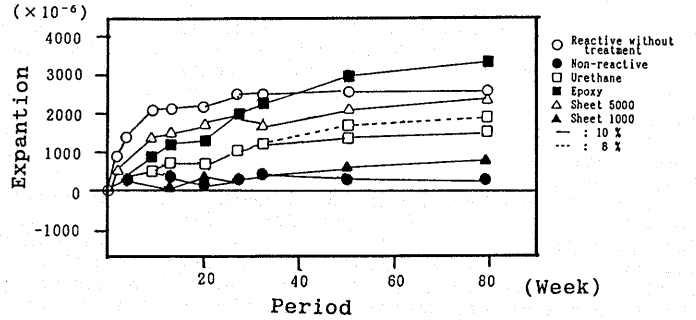

Fig. 20. Expantion
- Series 3: lining and sheet types, dry and wet -

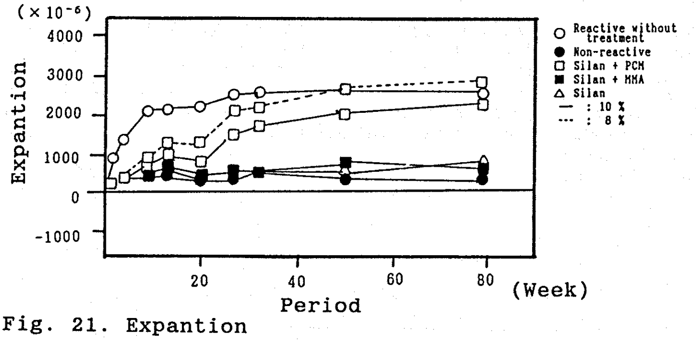

Fig. 21. Expantion
- Series 3: silan type, dry and wet -

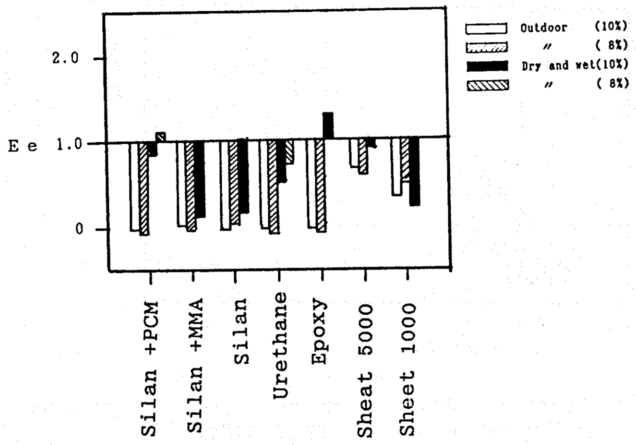

Fig. 22. Expantion reducing effect (Ee)
- Series 3 -

(3) Weight change

The correlation between the expansion and the weight change at the time of every measurement is shown in Figs. 23 - 26 and the weight control effect, E_{ω}, is presented in Fig. 27. According to these data, no remarkable expansion take place in the outdoor except the reactive specimens without treatment from which correlation with the weight change can not be made clear. In the tests under the dry and wet conditions, however, the tendency that the weight increase following the expansion of the specimen is clearly recognized. Such trend is the same as that gained in Series 1, but, unlike the test in Series 1, the testing period after expansion beginning place is rather short and troubles happened to the apparatus were not so often, therefore, few specimens loose their weight after they experienced expansion exceeding 0.05%. Evaluating the change of tendency due to the difference in the initial interior moisture content is difficult at this moment. By the way, the cases of remarkable increase in weight without accompanying expansion are seen in the test under the dry and wet condition. But, they are the specimens with surface treatment of the sheet type and the weight increase is not caused by the water absorption of concrete proper but of the sheet itself.

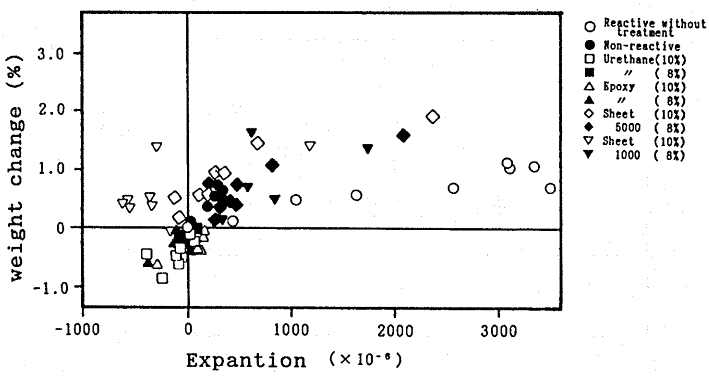

Fig. 23. Relation between expantion and weight change
- Series 3: lining and sheet types, outdoor

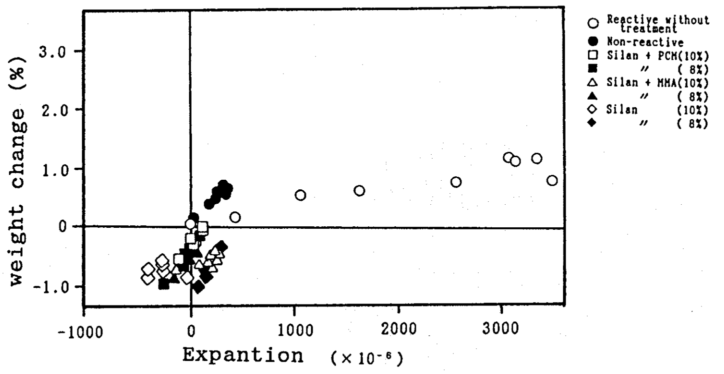

Fig. 24. Relation between expantion and weight change
- Series 3: silan type, outdoor -

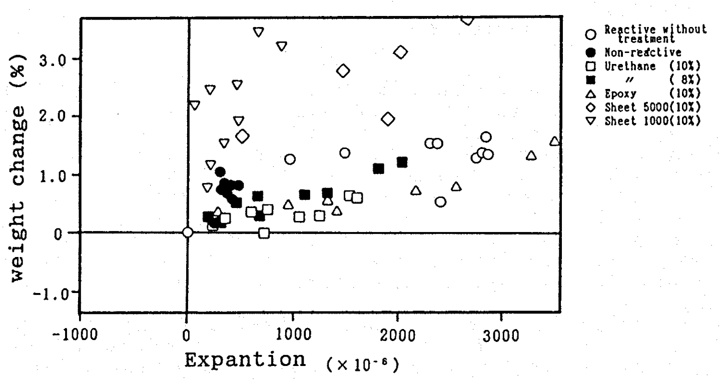

Fig. 25. Relation between expantion and weight change
- Series 3: lining and sheet types, dry and wet -

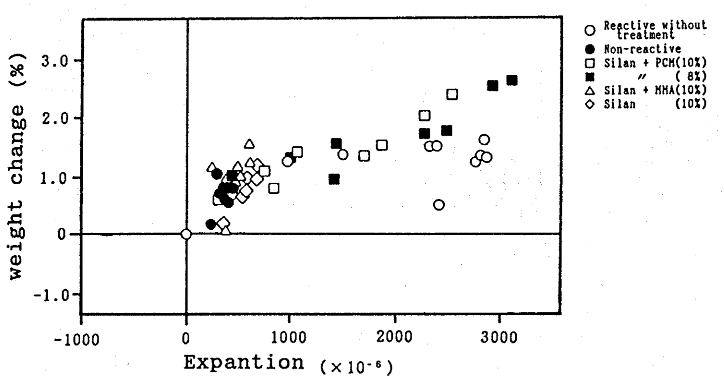

Fig. 26. Relation between expantion and weight change
- Series 3: silan type, dry and wet -

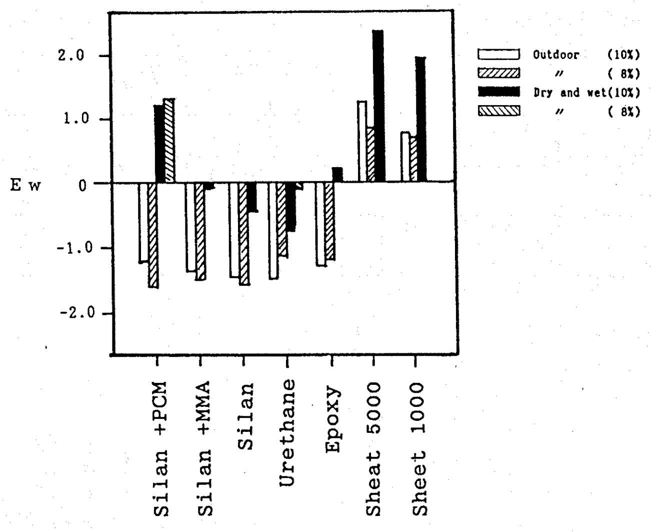

Fig. 27. Weight control effect (Ew) - Series 3. -

(4) Water permeability in liquid and vapor phases

The test results of water permeability and water vapor transmission rate are shown in Table 10. Among the specimens with no surface treatment, reactive concrete shows higher water permeability than non-reactive one which may be caused by some changes happened in the properties of reactive concrete such as generation of gel and cracks, thus making permeation of water easier.

The capability of surface treatment for controlling moisture content is the most important factor in controlling ASR expansion. From the viewpoint of controlling the intrusion of water into concrete from outside, smaller permeability is desirable, but from the viewpoint of dissipating water from concrete it is required that it has the capability to allow the movement of water to a certain extent. The former is supposed to be mainly related to the permeability of water in the liquid phase and the latter is to be related to the permeability of water in the vapor phase. Therefore, as the surface treatment of concrete to be applied for the purpose of controlling ASR expansion, those that have small water permeability for water together with large water vapor transmission rate are desirable. This means that having a smaller value of water permeability to a certaIn extent, the larger the value represented by (Water vapor transmission rate)/(water permeability), the surface treatment with the higher capacity of controlling moisture content is given. According to Table 10, among the surface treatment systems used in Series 3, those of urethane, composite use of silan and MMA and silan alone are considered to be excellent in the controlling capability of moisture content. As previously mentioned, with respect to controlling effect on expansion they yielded good results as well.

The relation among water permeability, water vapor transmission rate and the expansion reducing effect, E_{e}, in Series 3 is presented in Fig. 28. Though there are slight differences among their tendency due to the differences in the environmental conditions, it is recognized that the systems that have water permeability not so high and a high value of (water vapor transmission rate)/(water permeability) clearly tend to have high controlling effect on expansion. Therefore, approximate evaluation of the controlling effect of the surface treatment is supposed to be made possible by combining water permeability and water vapor transmission rate properly.

Table 10. Water Permeability and Water Vapor Transmission Rate

(g/m²/day)

Surface treatment system	Silan + PCM	Silan + MMA	Silan	Urethane	Epoxy	Sheet 5000	Sheet 1000	Reactive	Non-reactive
Water permeability	4.45	6.74	8.05	1.67	1.78	33.79	10.6	56.72	17.87
Water vapor transmission rate	2.41	21.01	16.64	4.10	2.20	48.07	17.48	31.18	-
Water vapor trans./water perm.	0.54	3.12	2.07	2.46	1.24	1.42	1.65	0.55	-

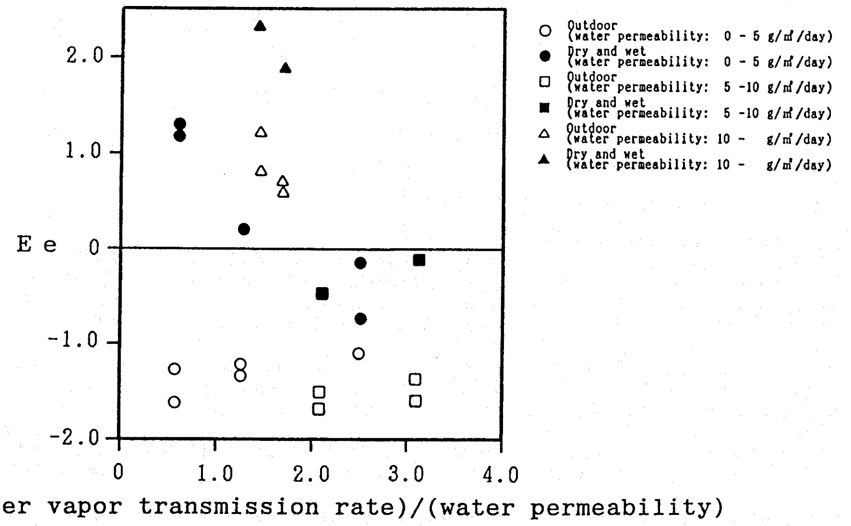

Fig. 28. Influence of water permeability and water vapor transmission rate on expantion reducing efect (Ee)

3.4 Effect of surface treatment on ASR expansion of concrete structures from the viewpoint of controlling moisture content

In investigating control of ASR expansion by means of the surface treatment of concrete, ① if no expansion takes place or ② if generation of excessive expansion is avoided, it may be considered to be effective. Among the systems of surface treatment applied in this study, there were those that made it possible to allow little expansion (silan type and urethane) in the outdoor during the period of tests conducted this time. However, in the dry and wet, no systems could be found that prohibited expansion entirely and only some systems (part of silan type) could control expansion. Therefore, depending upon the environmental conditions, the systems applicable are supposed to be different.

Now, if the problem is viewed in the aspect that the expansion is controlled by controlling moisture content, it has been known that the critical humidity below which no expansion takes place in concrete even if surface treatment is not applied to it. For instance, Morinaga[10] reported that RH 90% or so is the critical humidity and according to Jones et al., below RH 85% at 38 C and below RH 75% at 20 C, no ASR expansion takes place. In other words,if the case of 20 C is taken as example and there is dissipation of water exceeding the water vapor transmission rate at 75%, it is presumed that no ASR expansion will take place. This water vapor transmission rate may be considered to be the critical value at which whether ASR expansion takes place or not. if the situation remains the same with aggregate used this time, the following presumption may be possible. While the water vapor transmission rate 31.18g/m^2/day was recorded at 20 C, the humidity at that time was RH 80%. Now, by means of interpolation between this and the water vapor transmission rate 39.14g/m^2/day[12] at 20 C and RH 60% obtained in a separate study[12], the water vapor transmission rate is found to be 37.35g/m^2/day at RH 75%. In the actual environment, the humidity rarely keeps any constant value and changes every moment, and dissipation corresponding to these values is supposed to take place. It could be assumed that if average dissipation of water content exceeds 37.35g/m^2/day, no expansion would take place, without any major error.

Besides, as is made clear in Series 1 and 3, it is the case that concrete has absorbed water equivalent to 0.4% of its own weight, when excessive expansion takes place. Therefore, the critical value above which excessive expansion is generated in the reinforced concrete structure is considered to be the content of water absorbed equivalent to 0.4% of the weight of covered concrete at which ASR expansion is said to be apt to happen. This water absorption content could be estimated from the difference between the quantity of absorbed water which can be calculated mainly from the water permeability and the probability of existence of water on the concrete surface that involves the probability of raining and the quantity of dissipated water that is calculated from the water vapor transmission rate and humidity.

From the critical values for generation of expansion and that of excessive one as mentioned in the above, the flow diagram for judgment on the expansion damage caused by the alkali aggregate reaction of the concrete structure is presented as in Fig. 29. In evaluating the effect of the of surface treatment systems, it should be so made at least that generation of excessive expansion is avoided.

In the discussion in above, of course, only the tentative way of thinking is proposed.

Those values in the flow diagram are not precise ones, but only an example. In the future, however, quantitative investigations on the control of moisture content such as these will be needed as well as on the crack bridging performance.

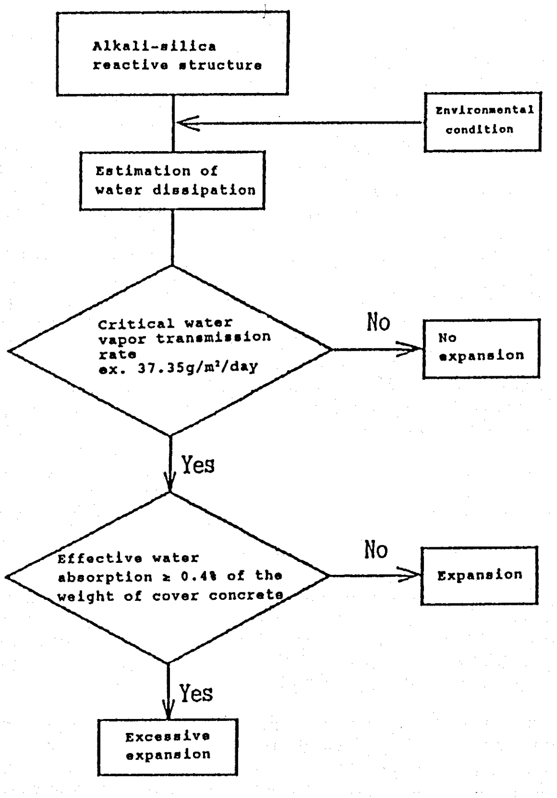

Fig. 29. Flow diagram for evaluating the ASR expantion

4. CONCLUSION

In this study, the authors conducted the experimental investigations in various aspect by using the surface treatment of various systems. Every system of surface treatment that is found in the market does not always show the same performance, even if it bears the same name and its water permeability and water vapor transmission rate is often different from each other. If the water permeability and the water vapor transmission rate are different, the controlling effect of surface treatment on ASR expansion will be different similarly to the cases under different environmental conditions. The principal conclusions that are gained within the reach of the investigations made in this study are stated hereunder.

(1) The surface treatment of the lining type such as urethane, epoxy shows the visible damage such as cracks, blisters of lining film and eduction of gel when ASR expansion takes place. Therefore, in bringing them into practice, those that are excellent in the crack bridging performance are preferable.

(2) Among the systems of surface treatment used in this study, those of the water repellant type in which silan is used are recognized for their relatively high effectiveness in controlling ASR expansion. Further investigations on the quantity of silan to be used and its combined use with other materials are needed.

(3) When the weight of concrete has increased beyond a certain critical value

(about 0.4%) due to water absorption, ASR expansion occurs.

(4) The ratio of surface and volume and the ratio of surface treated area of concrete are the factors that affect the controlling effect on ASR expansion. They must be taken into consideration as factors of treatment. The interior moisture content at treatment is also considered to be one of the factors that affect the effect on ASR expansion, but its influence is not so large if range over which the moisture content 8 - 10%.

(5) In the case of controlling of ASR expansion is intended by controlling the moisture content by means of surface treatment, both of the water permeability toward the supply of water and the moisture permeability toward the dissipation of water should be taken into consideration.

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