

LONG TERM EFFECT OF SILANE TREATMENTS ON EXPANSION DUE TO ALKALI-SILICA REACTION BY WATER CONTROL

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ABSTRACT

The long term effect of silane treatments to repair concrete structures was investigated in the quasi-actual condition to evaluate the effective depth and water control properties of silane treatments. Quasi-actual size concrete specimens and small specimens were placed outdoors and the relative humidity of concrete at various depth from surface were measured. Furthermore, the effect of silane treatments to reduce alkali-silica expansion by water control was discussed. Water control properties and the effect of silane treatments were simulated on the basis of moisture transfer analysis. The results were compared with experimental data. The analytical models of silane treatment and environment for simulation were reliable enough to evaluate the effect of silane treatment.

Keyword: Silane treatment, water control, hydrophobic effect, reduction of alkali-silica expansion, relative humidity in concrete

INTRODUCTION

In the deterioration mechanism of alkali-silica reaction (ASR), water is one of the most important factor. Expansion due to ASR was caused by water absorption from outside and inside of concrete. Therefore, it is a very effective mitigation method against ASR to control water content of concrete. Silane treatments which are typical hydrophobic treatments have been focused to have better performance as appropriate repair method of concrete structures deteriorated by ASR.

In previous studies, the effect of silane treatments have mainly been investigated by use of small specimens. In this study, quasi-actual size specimens were placed outdoors to take account of moisture transfer of concrete in the state of quasi-actual condition and the relative humidity of concrete at various depths from surface were measured. The effective depth and water control properties of silane treatments were evaluated. Furthermore, the effect of silane treatments to reduce alkali-silica expansion by water control was investigated. Water control properties and the effect of silane treatments were simulated on the basis of moisture transfer analysis. The results were compared with experiment data.

EXPERIMENTAL EVALUATION OF SILANE SYSTEM

Outline of Experiment

Concrete Mixes—Non-reactive fine aggregate, non-reactive and reactive coarse aggregate were used. Reactive concrete had the pessimum volume ratio with respect to reactive and non-reactive aggregates. The properties of aggregates are shown in Table 1. Mixture proportions of concrete are shown in Table 2. Total amount of Na₂O equivalent alkali of reactive concrete was 8 kg/m³.

Silane Systems—In this study, two types of silane systems (silane impregnation, silane impregnation with mortar top lining) were used. Silane of molecular weight 262 which had shown better hydrophobic performance was used. In Japan, water vapour permeable mortar top lining has been commonly used for protection against carbonation of concrete and durability of surface treatment. Silane was used as 1 mol/kg alcohol solution. Polymer modified mortar was used as the mortar top lining. The amount of application of silane solution and mortar top lining was 300 g/m² and 2.0 kg/m², respectively. The properties of silane systems are shown in Table 3.

TABLE 1 : Properties of Aggregate (ASTM C289 and C 227)

Aggregate	Chemical method			Expansion of mortar bar		
	Sc (mmol/l)	Rc (mmol/l)	Sc/Rc	2weeks (%)	4weeks (%)	8weeks (%)
Reactive	725	190	3.82	0.011	0.025	0.039
Non-reactive	33	36	0.92	0.009	0.016	0.021
Mix (volume 1:1)	616	133	4.63	0.0298	0.101	0.156

TABLE 2 : Mixture Proportions of Concrete

W/C (%)	s/a (%)	Unit (kg/m ³)						W.R.A. *3 (ml/m ³)
		W	C	S	Gn*1	Gr*2	NaCl	
51	44.8	192	377	766	944	-	-	3740
51	44.8	192	377	755	479	465	10.55	3740

*1: Non-reactive, *2: Reactive, *3: Water reducing agent

Specimens and

Experimental

method—The quasi-actual specimens (reactive and non-reactive concretes) were placed outdoors (non-reactive :100×100×15 cm, reactive 50×50×15 cm, Fig.1). The prism specimens (10×10×40 cm) were also placed outdoor. The effect of two types of silane systems were evaluated. The mass changes of prism specimens

TABLE 3 : Properties of Silane Systems

Silane system	Water vapour permeability	Water liquid permeability	Flexibility
Silane	31g/m ² /day	2.8g/m ² /day	-
Silane with PCM	25g/m ² /day	2.1g/m ² /day	75%

*Silane with water vapour permeable polymer modified mortar top lining

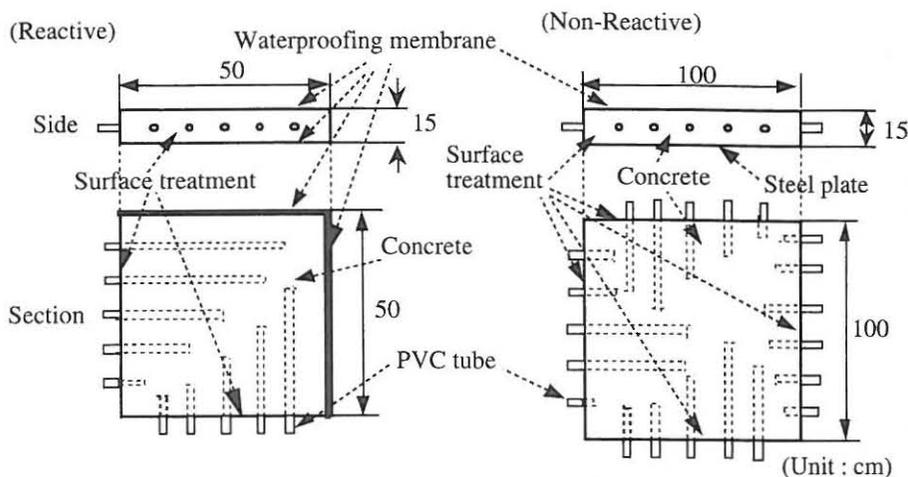


Fig. 1 : Quasi-actual specimens

TABLE 4 : Types and Number of Specimens

	No-treatment	Silane	Silane +PCM
Reactive	1(3)	1(3)	1(3)
Non-reactive	1(3)	1(3)	1(3)

(): number of prism specimens

and reactive quasi-actual specimens were measured. The expansion of reactive specimens were measured. Three types of treatments were used: 1), silane impregnation (Silane) 2), silane impregnation with water vapour permeable polymer modified mortar top lining (Silane+PCM) and 3), no treatment (No-treatment). Types and number of specimens are shown in Table 4.

The specimens were demolded 3 days after being cured in wet condition. The non-reactive quasi-actual specimens were cast on a steel plate to allow no movement of water through the lower surface of concrete. Reactive quasi-actual specimens were applied with waterproofing membrane on the lower surface and two side surfaces so that movement of water in reactive quasi-actual specimens were the same as non-reactive ones. Then, both quasi-actual specimens were cured in wet condition for 2 weeks and were dried for 1 week. Quasi-actual specimens were then applied with waterproofing membrane on the upper surfaces of concrete. Consequently, the movement of water into or out of specimens took place on four (non-reactive) and two (reactive) side surfaces, i.e., moisture transfer in the specimens were two dimensional phenomenon. After being dried for additional 3 days, specimens were applied with silane systems and specimens were cured for 5 days. PVC (polyvinyl chloride) tubes of various length were embedded in both quasi-actual specimens to measure the relative humidity in concrete at various depth from surface. The profiles and the changes of relative humidity in concrete were measured. The prism specimens were made similarly to the quasi-actual specimens without waterproofing membrane.

Results and Discussions

Prism specimens—The mass reductions of prism specimens are shown in Fig. 2. In the non-reactive series, Silane-treated prism showed rapid mass reduction up to 3.2% after 1 year of exposure. Silane+PCM-treated prism showed slow mass reduction up to 2% after 2 years of exposure. In the reactive series, Non-treated prism showed significant mass gains after first summer. It was considered that mass gains were caused by ASR. Although the mass changes of reactive treated specimen showed a similar trend to the non-reactive one, the mass reductions of reactive treated specimens were smaller than that of non-reactive treated ones.

The expansions of reactive prism specimens are shown in Fig. 3. Silane and Silane+PCM treatments were effective in controlling alkali-silica expansion of test specimens. On the other hand, expansion of Non-treated prisms were accelerated due to high temperature and high humidity summer condition. Silane and Silane+PCM had good performance to reduce alkali-silica expansion.

Quasi-actual Specimen—The mass reductions of reactive quasi-actual specimens are shown in Fig. 4. Non-treated specimen showed mass gains after first summer. Silane-treated specimen showed rapid mass reduction in short term when influence of ASR was not significant. However, it showed little mass reduction after first summer. On the other hand, Silane+PCM-treated specimens showed slow mass reduction regardless of cracks caused by expansion after first summer.

The expansion of reactive quasi-actual specimens is shown in Fig. 5. The expansion of specimens was significantly accelerated due to high temperature and high humidity in summer. Silane-treated specimen had the smallest expansion of all specimen after 1 year of exposure since Silane made surface

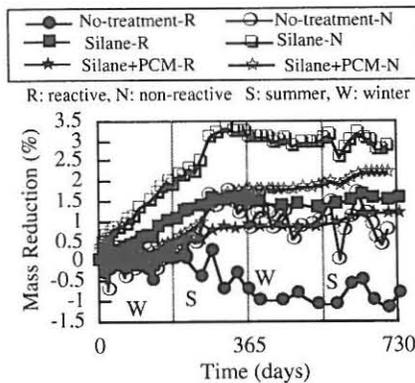


Fig. 2 : Mass reduction (prism specimen)

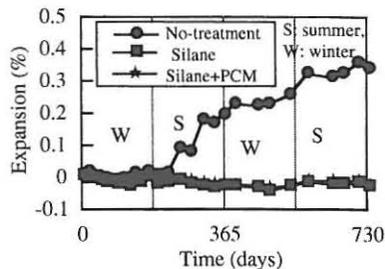


Fig. 3 : Expansion (reactive prism specimen)

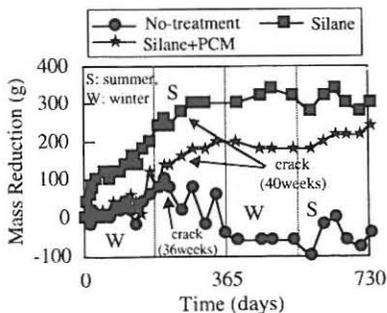


Fig. 4 : Mass reduction (reactive quasi-actual specimen)

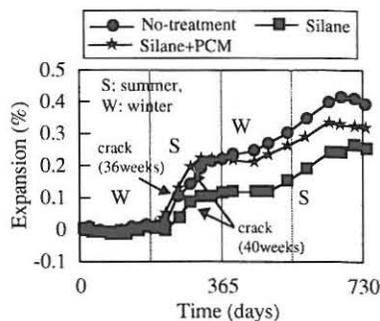


Fig. 5 : Expansion (reactive quasi-actual specimen)

layer of concrete dry in a short term. However, expansion of Silane-treated specimen during the 2nd year was larger than the 1st year. This result suggests that hydrophobic effect of Silane is offset by the development of cracks caused by alkali-silica expansion. Although the expansion of Silane+PCM was larger than that of Silane, the expansion changes after cracks was small. The reduction of hydrophobic effect of Silane+PCM due to the development of cracks was limited. On the other hand, expansion rate of treated specimens was similar to non-treated ones at summer condition. The expansion of treated specimens was smaller than that of non-treated ones, since the expansion of treated specimens was delayed and was reduced except during summer condition by water control of silane treatments.

The profiles of relative humidity in concrete of quasi-actual specimens after 160 days and 2 years of exposure are shown in Fig. 6 and Fig. 7, respectively. The expansions of specimens were still not significant after 160 days. The relative humidities of treated specimens in the surface layer were lower than that of non-treated specimens after 160 days of exposure. The reduction of relative humidity of Silane was observed up to about 20cm.

The differences in the effects of silane systems between both concretes were significant after 2 years of exposure. In the non-reactive series, the effective depth of Silane was increased and was up to 40 cm after 2 years of exposure. The effective depth of Silane+PCM was up to 10 cm. On the other hand, in the reactive series, the relative humidities of treated specimens after 2 years of exposure were not lower than that of non-treated one. It was considered that the high relative humidities of reactive specimens were caused by cracks and water absorption of alkali-silica gel.

The relative humidities in concrete of specimens at 5 cm and 20 cm from surface are shown in Fig. 8. The relative humidities in concrete of all specimens showed seasonal variations; i.e., they were high in summer and low in winter. The relative humidities in concrete of reactive non-treated specimen ranged from 85% to 95% in summer, when the alkali-silica expansion was significant. The relative humidity in concrete had a close relationship with alkali-silica expansion. The expansion was reduced when the relative humidity in concrete

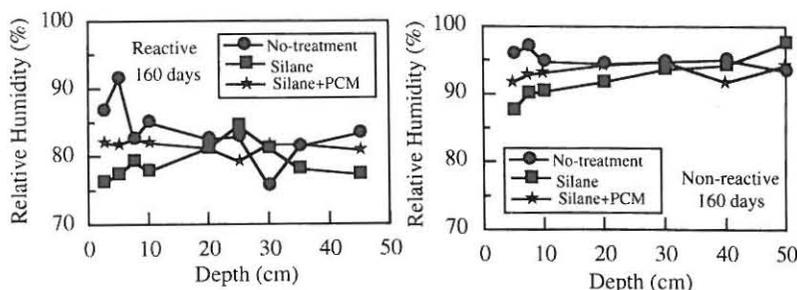


Fig. 6 : Profiles of relative humidity (160 days)

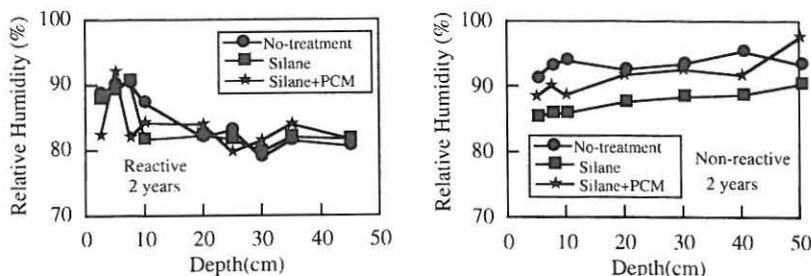


Fig. 7 : Profiles of relative humidity (2 years)

was reduced by the surface treatment.

The reduction of relative humidity in concrete of Silane was much larger than that of Silane+PCM in a short term (Fig.8 A and B). Silane had good hydrophobic effect when influence of ASR was not significant. However, although in the non-reactive series the beneficial effect of silane systems was observed to some extent even after 2 years of exposures (Fig. 8 D), in the reactive series the beneficial effect of silane systems was insignificant after 2 years of exposure.

Evaluation of Silane Systems—Silane, which makes surface layer of concrete dry in a short term by good hydrophobicity, is effective in reducing alkali-silica expansion. However, the effect of Silane is reduced due to development of cracks caused by alkali-silica expansion. On the other hand, the expansion of silane+PCM by water remaining in concrete is larger than that of silane. However, the reduction of the effect of Silane+PCM is small.

The difference in reducing alkali-silica expansion by silane treatments between quasi-actual specimen and prism was observed. The effectiveness of silane treatments was very high on the prism. On the other hand, the effectiveness of silane treatments was insignificant on quasi-actual specimen. The expansion of quasi-actual specimen was not perfectly controlled by silane treatments, since it needed more times than prism specimen to make inside concrete of quasi-actual specimen dry by silane treatments.

Concrete structures deteriorated by ASR are generally high water content. It is most important to make concrete dry in a short term to reduce alkali-silica expansion. Therefore, Silane has better effect to reduce alkali-silica expansion. Judging from these results, it is noted that the maintenance of silane systems after applying is very important. For example, the effect of silane system may be enlarged by re-applying silane or mortar top lining after drying concrete using Silane only.

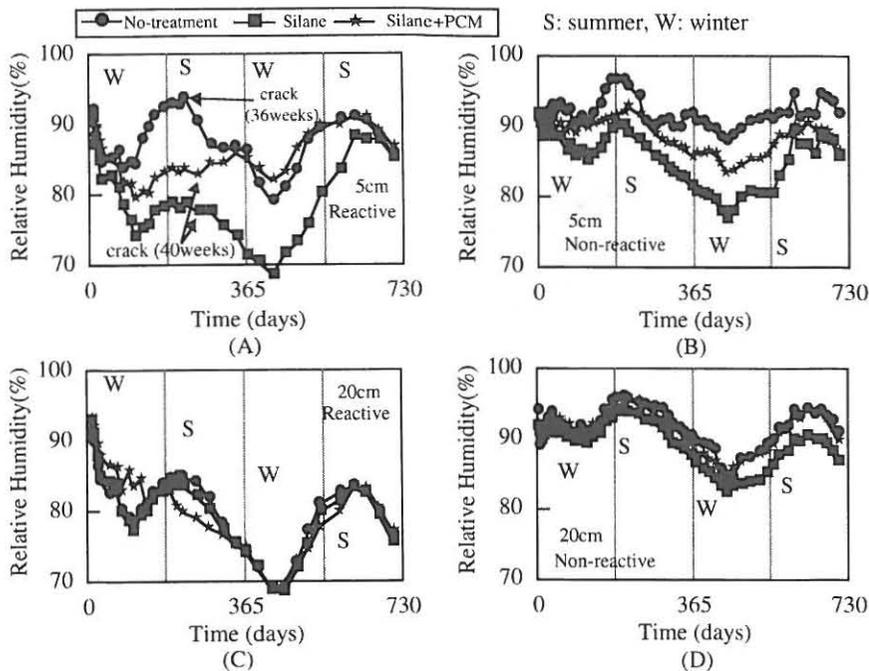


Fig. 8 : Relative humidity changes (5 cm, 20 cm)

ANALYTICAL EVALUATION OF SILANE SYSTEMS

Moisture Transfer of Concrete

Generally, Fick's second law of diffusion has been applied for moisture transfer analysis of concrete. The governing equation of moisture transfer in concrete is expressed as eq. 1. Eq. 2 is obtained by applying finite element method using Galerkin's method to eq. 1.

$$\frac{\partial C}{\partial t} = \text{div}(k(C)\text{grad}C) \quad [1]$$

$$[A]\{\dot{C}(t)\} + [K(C)]\{C(t)\} = \{Q(t)\} \quad [2]$$

where

[A] : water capacity matrix

{C(t)} : vector of water content of concrete at t (t = time)

[K(C)] : diffusion matrix depending on water content of concrete

{Q(t)} : vector of water flux into/out of concrete at t

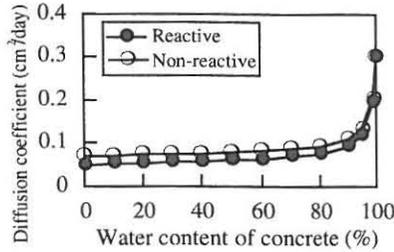


Fig. 9 : Relationships between water content of concrete and diffusion coefficient

Boundary condition is shown as eq. 3. Water flux through concrete surface is proportional to differences of water content between concrete and atmosphere.

$$k(C)\left(\frac{\partial C}{\partial x}\right)_s = f(C_e - C_s) \quad [3]$$

TABLE 5 : Surface Factor (cm/day)

	Non-reactive	Reactive
No-treatment	1.0	1.0
Silane	1.0	0.1
Silane+PCM	0.02	0.03

where

C_e: water content of atmosphere (%)

C_s: water content of concrete at surface (%)

f: surface factor (cm/day)

k(C): diffusion coefficient of concrete (cm²/day)

These analytical parameters (k(C),f) were decided after another experiment of water loss of specimens through drying process. Water control properties and the effect of silane systems were simulated on the basis of moisture transfer analysis using these parameters.

Decision of Analytical Parameters

Concrete specimens with various axial length (Section:10×10 cm, Length:8,16,24,32,40cm), in which moisture transfer phenomenon is one dimensional, were used. Materials and mixture proportions of concrete were the same as above concrete "Experimental evaluation of silane system". Diffusion coefficient of concrete, which is based on water content of concrete, was experimentally decided from results of water content changes of specimen in drying process. The relationship between water content of concrete and diffusion coefficient of both concrete are shown in Fig. 9. The surface factors of specimens in drying process were decided so that the water loss of specimens gave good agreements with calculated ones. The surface factors of specimens are shown in Table 5.

Relationship between Relative Humidity and Water content

Water content of concrete was used as an index of moisture content of concrete in the analysis. To compare with experimental profiles of relative humidity in concrete of quasi-actual specimens, the relationship between water content of concrete and relative humidity in con-

crete was required. Relationship obtained by another experiment for both concretes are shown in Fig. 10.

Analytical Model

The analytical models of environment and silane systems were decided so that mass reduction of prism specimen gave good agreement with calculated mass reduction by trials. The analytical models were also applied for simulation of quasi-actual specimens.

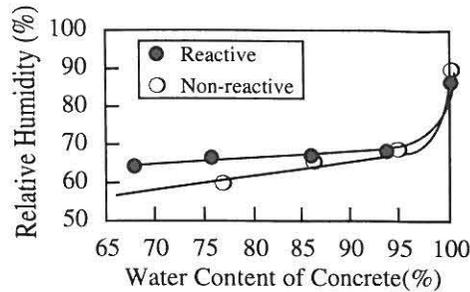


Fig. 10 : Relationship between relative humidity and water content of concrete

Initial Water Content of Concrete—It was assumed on the basis of curing condition and size of specimen that initial water content of concrete in quasi-actual and prism specimen were constant 90% and 100% respectively after being cured in wet condition. The drying period of both specimens before exposure was 15 days.

Analytical Models of Environment and Silane Systems—It was assumed that dry and rainfall period were 15 days and 1day respectively from rainfall probability (Fig. 11). Taking into account the average relative humidity of the atmosphere and rainfall probability, estimated water content of atmosphere during dry periods was 50%. Water absorption due to rainfall was modeled as follows. Water capillary absorption depth at which concrete was saturated with water during rainfall was 10mm from rainfall probability. That is, the water content of concrete in 10mm layer concrete of non-treatment was 100% during rainfall period. On the other hand, since water absorption of treated specimens was small, water capillary absorption depth of treated specimen was 0mm. The surface factors of treated specimen during rainfall were decided 0.1cm/day for Silane and 0.02cm/day for Silane+PCM respectively, so that mass changes of prism specimens gave good agreement with calculated mass changes.

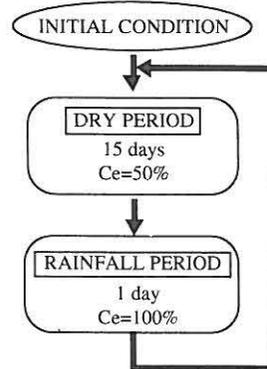


Fig. 11 : Flowchart of simulation

Influences of Alkali-Silica Reaction—Properties of water absorption and water retaining capacity of reactive concrete were influenced by cracks due to ASR and alkali-silica gel. The surface factors of specimens obtained by indoors experiment in only drying process were different from that of exposed specimens affected significantly by ASR. Therefore, the influence of ASR was considered as follows. The surface factors of specimen affected by ASR were enlarged during rainfall period since water permeation into concrete was increased by alkali-silica gel, and the hydrophobic effects of treated specimens were reduced. The surface factors of the specimens were reduced during dry period since water retaining capacities of specimens were enlarged by ASR. Furthermore, retaining and absorbing water by alkali-silica gels was enlarged after propagation of cracks caused by alkali-silica expansion. The surface factors of specimens are summarized in Table 6.

Simulation of Effect of Silane Systems

The calculated mass changes of prism specimens are shown in Fig. 12. The calculations gave good agreement with experiment data. The analytical models for simulation were appropriate with enough accuracy.

TABLE 6 : Surface Factors of Specimens as Analytical Model (cm/day)

outdoors condition	Non-reactive		Reactive			
	Dry	Rain	Stage 1 ¹		Stage 2 ²	
			Dry	Rain	Dry	Rain
No-treatment	1.0	-	0.1	-	0.01	-
Silane	1.0	0.1	0.1	0.1	0.04	1.0
Silane +PCM	0.02	0.02	0.01	0.02	0.01	0.1

*1:Influence of ASR is not significant. *2:Influence of ASR is significant.

The calculated profiles of water content of concrete of the quasi-actual specimens were translated to profiles of relative humidity by using relationships between water content of concrete and relative humidity in concrete (Fig. 10). The calculated profiles of relative humidity in concrete after 160 days of exposure when influence of ASR was not significant are shown in Fig. 13. The relative humidity of treated specimens in 10cm surface layer was lower than that of non-treated one. The relative humidity of Silane was much lower than that of Silane+PCM even in a short term.

The calculated profiles of relative humidity in concrete after 2 years of exposure when influence of ASR was significant are shown in Fig. 14. In the non-reactive series, the beneficial effect of silane systems was maintained and the effective depth of silane systems was increased. On the other hand, in the reactive series the effective depth of silane systems were

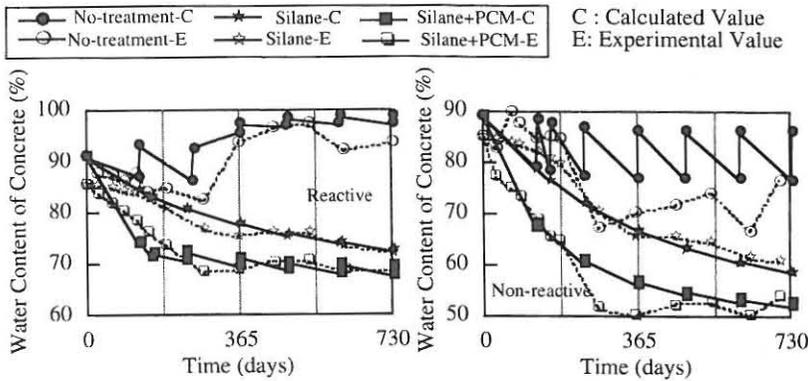


Fig. 12 : Calculated mass changes (prism specimen)

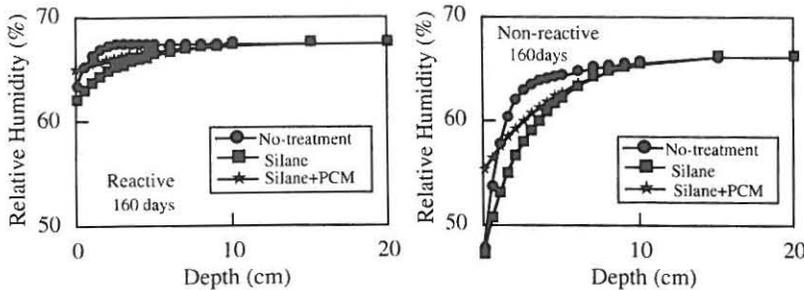


Fig. 13 : Calculated profiles of relative humidity (160 days)

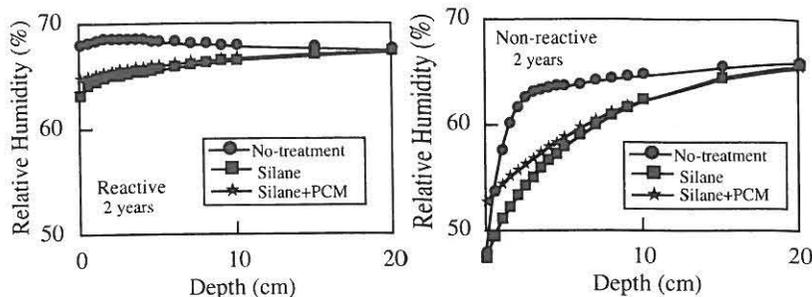


Fig. 14 : Calculated profiles of relative humidity (2 years)

only slightly increased. The profiles of relative humidity in concrete of Silane were similar to that of Silane+PCM. However, the expansion of Silane was smaller than that of Silane+PCM after 2 years of exposure. These results suggest that the expansion of specimens due to water remaining in concrete were reduced significantly by drying the surface layer of concrete in a short term. Therefore, drying concrete in a short term is most important to reduce alkali-silica expansion. Judging from the simulation, silane has better effect in reducing alkali-silica expansion.

CONCLUSION

The main results obtained in this study are summarized as follows.

- (1) Silane, which make surface layer of concrete dry in a short term by good hydrophobicity, is effective in reducing alkali-silica expansion, although the beneficial effect of Silane is reduced due to development of cracks caused by alkali-silica expansion. The expansion of Silane+PCM by water remaining in concrete is larger than that of Silane, although the reduction of beneficial effect of Silane+PCM is smaller than that of silane.
- (2) Concrete structures deteriorated by ASR are generally be high water content. It is most important to make concrete dry in a short term to reduce alkali-silica expansion. Therefore, Silane has better effect to reduce alkali-silica expansion.
- (3) The expansion is reduced when the relative humidity in concrete is reduced through surface treatment. The reduction of relative humidity of concrete by surface treatments is very effective to reduce alkali-silica expansion.
- (4) The environment and silane systems were modeled to evaluate the effect of silane systems in simulation. Water control property and the effect of silane systems to reduce alkali-silica expansion were simulated with enough accuracy.

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