

THE EFFECT OF SILANE-TYPE SURFACE PENETRANTS TO CONTROL SCALING AND SALT DAMAGE OF HIGHWAY BRIDGE WHEEL GUARD CONCRETE IN COLD REGION

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ABSTRACT

In cold regions, there is concern about the deterioration of concrete structures caused by freeze-thaw action and deicing salt. In particular, scaling (concrete peeling the results from frost damage) and reinforcing bar corrosion due to chloride ion penetration. On the other hand, budgets for maintenance of concrete structures are very low. For that reason, a deterioration control technique that is economical and easy to adopt is required. As one such method, application of silane-type surface penetrants had gained attention. However, there is little data on deterioration control in cold regions. In this study, to evaluate the effectiveness of silane-type surface penetrants application, such penetrants were applied on to the concrete of highway bridge wheel guards in Hokkaido. Although the test period was only six years, the persistence of the effects was confirmed.

1. INTRODUCTION

To ensure the safety of winter roads, road administrators apply chloride-based deicers to the road surface (Photo 1). However, such application exposes many highway bridges in cold regions to the freezing and thawing as well as to deicing salt, leading to severe deterioration of concrete (Photo 2). The combination of freeze-thaw action and deicing salt is known to accelerate scaling (local peeling) of the concrete surface and reinforcing bar corrosion (Photo 3), which raises the concern about the durability decrease of concrete materials. Given that the budgets necessary for maintaining such highway bridges are expected to increase, effective measures to ensure the structures' durability are essential. One potential method for control frost and salt damage is to prevent the external supply of water and chloride ions. Effective agents for this are silane-type surface penetrants [1].



Photo 1 - Deicing salt spraying



Photo 2 - Deicing salt supplied to a concrete structure



Photo 3 - Scaling deterioration and reinforcing bar corrosion



Photo 4 – A coating of silane surface penetrants is applied.

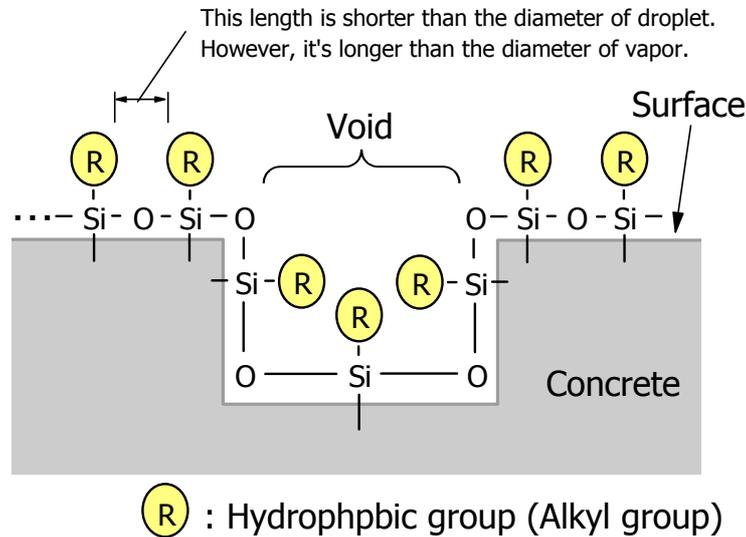


Figure 1 – Structure of water repellence

Silane-type surface penetrants are permeating surface-coating materials that are used to control the water absorbability of concrete surfaces. When coated on the concrete surface (Photo 4), water repellence function is shown when the hydrophobic (Alkyl) groups stick to the surface and void walls (Figure 1), and the permeated area turns into hydrophobic area ("water repellent layer").

Silane-type surface penetrants have several advantages.

- (1) They are easy to use and relatively reasonable in price.
- (2) They coat the surface colorlessly, so as not to affect the structure's appearance, which makes daily visual check and maintenance easier.
- (3) Unlike covering materials, this is a material penetration method, so that the permeated areas are not degraded by ultraviolet rays.

In the United States and Europe, silane-type surface penetrants have long been a popular coating material for outer walls of structures [2, 3] and stone sculptures [4]. More recently, research has been underway toward using the penetrants to improve the durability of civil-engineering structures [5, 6]. Nevertheless, few case studies have addressed the penetrants' effect on highway bridges in cold regions. Therefore, we tested silane-type surface penetrants on wheel guard concrete and observed how much the effect of control

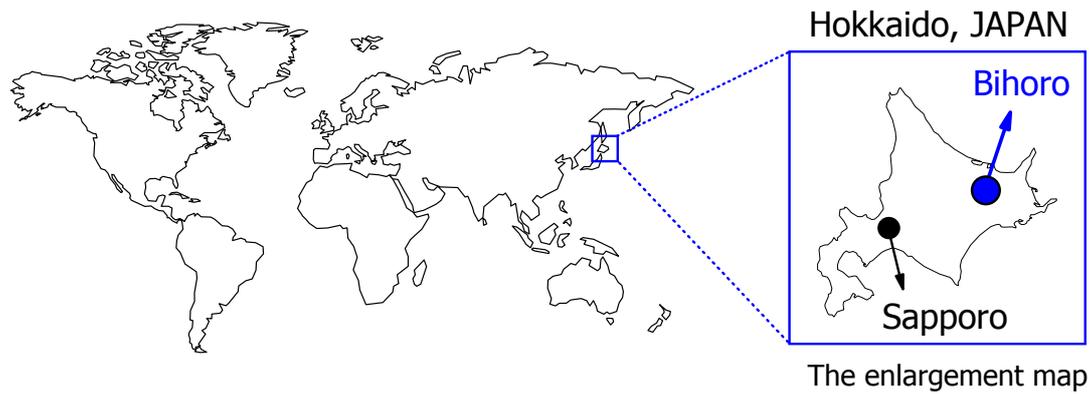


Figure 2 - The location of Bihoro, Hokkaido (Japan)

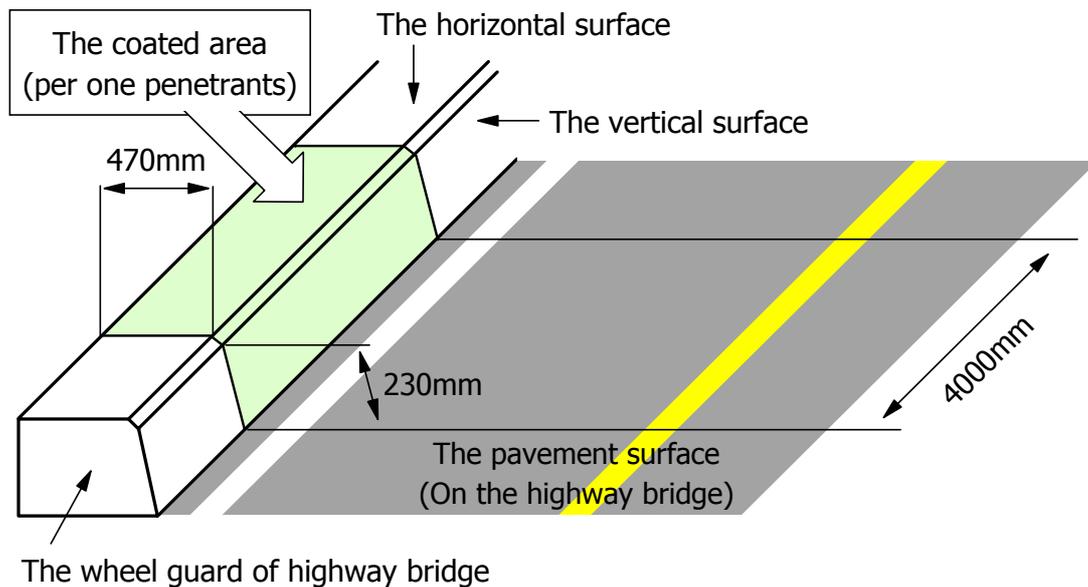


Figure 3 - The size of the wheel guard and the coated area

the concrete deterioration progress. We reported in a previous paper the findings from a 4-year observation of concrete deterioration (scaling) [7]. In this paper, we report our subsequent observation in its 5th and 6th years. The paper will also report the findings about concrete scaling and chloride ion permeability.

2. SUMMARY

2.1. Location of the Highway Bridge, and the Coating Work

Figure 2 shows the location of the highway bridge where the test coating was performed. The bridge, in Bihoro, Hokkaido (Japan), has 3-span steel beams and a length of 73 m. In Bihoro, the temperature drops to minus 25 degrees Celsius in winter, when deicing salt spraying to roads. For testing purposes, the coated area was limited to the wheel guard concrete, which is the bridge member that is most prone to scaling damage.

Figure 3 shows the shape and coated area of the wheel guard, Table 1 shows the mix proportion of the wheel guard concrete and Table 2 shows the outline of the five commercial silane-type surface penetrants used for the test (No.1, No.2, No.3, No.4 and No.5). The highway bridge is designed with a 4% cross-slope from the center-line to the

Table 1 – Mix proportion of wheel guard concrete

W/C (%)	Unit quantity (kg/m ³)					Slump (cm)	Air (%)
	W	C	E	S	G		
57	145	252	30	713	1144	8	4.5

Remarks ; W/C : Water cement ratio
W : Water
C : Cement
- Ordinary Portland cement used
E : Expansive additive
S : Fine aggregate (sand)
G : Coarse aggregate (gravel)
- Max. diameter of coarse aggregate: 40mm

Table 2 - The silane surface penetrants used for test construction

Name	No.1	No.2	No.3	No.4	No.5
% content of active ingredient	42	43	80	10.5	90
Type	Aqueous			Solvent	Non-solvent
Application quantity (g/m ²)	200	300	200	300	400

Application quantity was in accordance with the requirements of individual penetrants.



Photo 5 – Coating work (28 October 2004)

wheel guard. Coating work was performed in October 2004 using penetrants Nos.1 through 5. On site, concrete was placed two months before the coating work so that it was never affected by freeze-thaw action. A 20-meter-long wheel guard was divided into five areas (four meters per area). Each area was coated with one penetrants. One representative from each penetrants manufacturer participated and coated the assigned area in accordance with their original specifications. Photo 5 shows how the coating work was performed. Rollers or paintbrushes were used. Some manufacturers made prior surface treatment.



Photo 6 - Measurement of the water permeation ratio

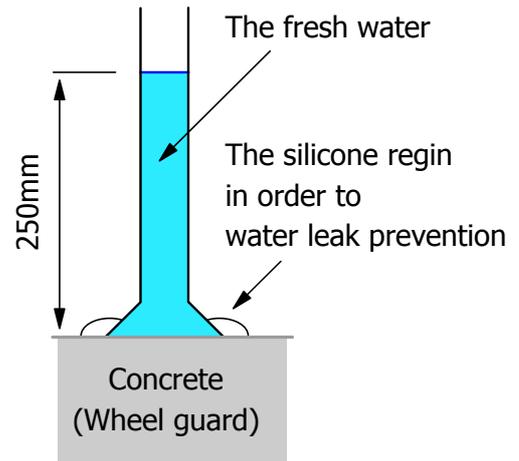


Figure 4 – Method for measuring the water permeation ratio

2.2. Follow-up Investigation

In our follow-up investigation of surface penetrants, the water permeation ratio was calculated to assess the sustainability of the water repellency, and the scaling area ratio was calculated to assess their effectiveness in control scaling. For some areas, the thickness of the water-repellent layer and the chloride ion penetration content that assesses the water repellency of chloride ion were observed.

Photo 6 shows measurement of water permeation ratio. In measuring, water was poured into plastic funnels of 75 mm in diameter and then placed on the horizontal surface of the wheel guard until the water reached 250 mm in height (Figure 4). Twenty-four hours later, the heights of water in the funnels were measured individually to determine water absorption, and water permeation ratios were calculated for each by using Equation (1):

$$W_r = I_s / I_n \quad (1)$$

where

W_r is water permeation ratio

I_s is water absorption of the coated face (ml)

I_n is water absorption of the uncoated face (ml)

Photo 7 shows measurement prior to calculation of the scaling area ratios. In the measurement, spots on which scaling developed were marked and then photographed digitally. Sketches of the scaling based on the photos were processed on the computer to calculate the scaled area. Finally, scaling area ratios of each area were calculated by Equation (2):

$$R_{sc} = (A_{sc} / A_{coat}) \times 100 \quad (2)$$

where

R_{sc} is scaling area ratio (%)

A_{sc} is area of scaling within the tested area (cm²)

A_{coat} is total tested area (cm²)



Photo 7 - Investigation of scaling area:
chalk sketch



Photo 8 - Core sampling

The thickness of the water-repellent layers and chloride ion penetration content were examined at the spots that had presented relatively favorable results from the previous two calculations (i.e., ratios of water permeation and of scale area). For assessment of the thickness of the water repellent layers, concrete cores were extracted from the vertical surface of the wheel guard (Photo 8). Individual cores cut, and water was sprayed on the chopped areas. The area that immediately dried was considered to be the water repellent layer. Measurement was made using a vernier caliper. A final value for each core was presented as the average of five measurements.

By using similarly extracted concrete cores, the chloride ion content was measured with two methods. Initially, the chloride ion concentration distribution between the surface and 4 cm in depth was visualized by using an electron-probe-micro-analyzer (EPMA), which is equipped with an X-ray analyzer. Also, Mohr's Method was applied to measure the chloride ion content in the concrete. In this method, each core was cut at 1, 2, 3 and 4 cm from the surface, and the pieces were separately crushed. The crushed powders were added to nitric acid solution to reduce their pH to 3 or lower, and then they were boiled. Silver nitrate was added to the solution to precipitate insoluble silver chloride. Using Mohr's method, which is employed to determine the concentration of chloride ion based on the quantity of nitric acid required to complete the precipitation, the concentration of chloride ion in the concrete was determined.

3. RESULTS AND DISCUSSION

3.1. Water Permeation Ratio

Figure 5 shows the water permeation ratios of tested penetrants over six years. The permeation ratios for all penetrants are 1 or lower in the first year of coating, but greater than 1 for Nos.1 and 2 after a winter had elapsed, which means that the ability of control water absorbability was lost. Values for Nos.3, 4 and 5 remained 1 or lower in general, except minor fluctuations. Thus, it was confirmed that the persistence of control water absorbability varies by penetrants type.

Photo 9 shows a wheel guard photographed on a rainy day between an uncoated area and the No.5-coated area. In the uncoated area, the concrete surface looks darkly wet; in the No.5-coated area, the concrete surface looks wet but does not look as apparently water-absorbing as the uncoated area.

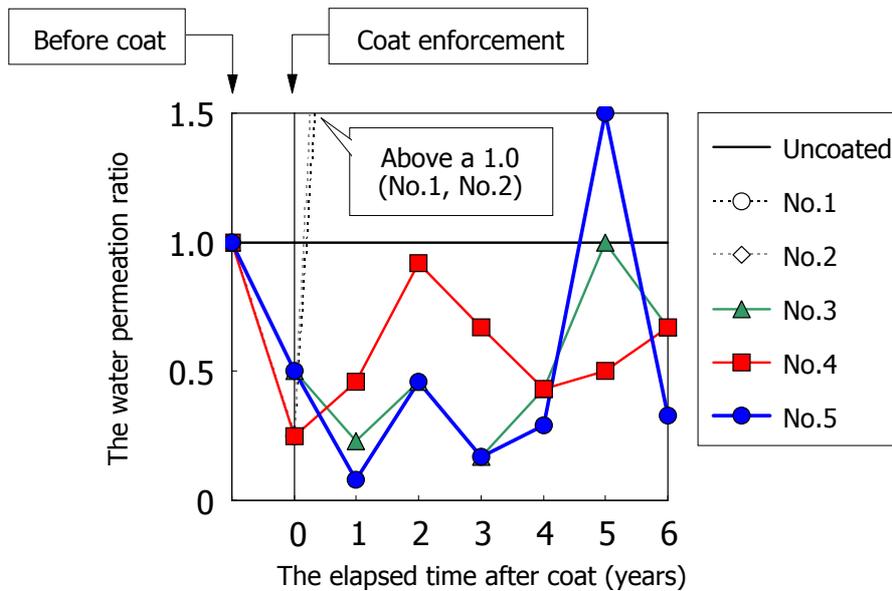


Figure 5 - Change in the water permeation ratio with time

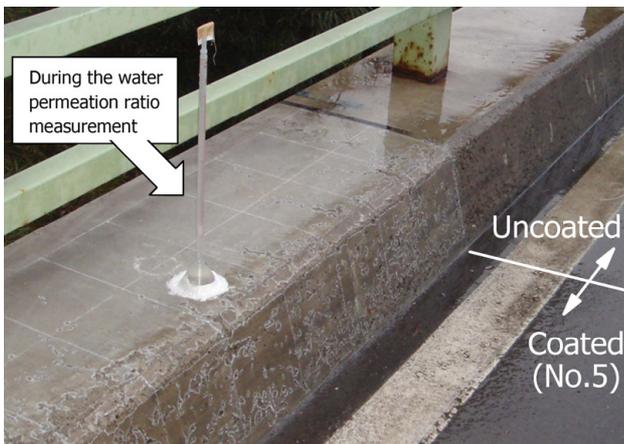


Photo 9 - The condition at the time of rainy weather (6 years elapsed)

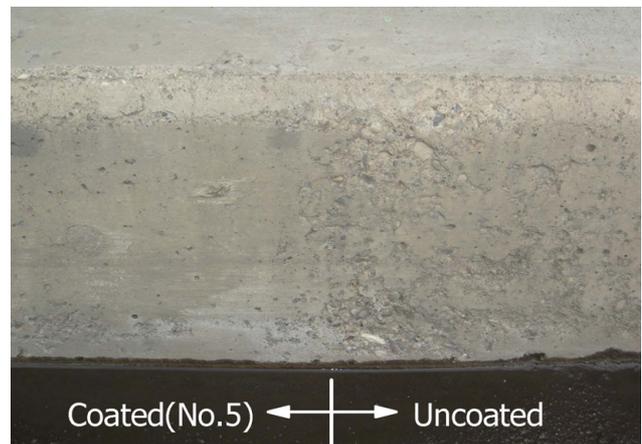


Photo 10 – Condition of the wheel guard (4 years elapsed)

3.2. Scaling

Photo 10 shows scaling of the wheel guard in the fourth year after coating, and Figure 6 shows sketches of the scaling area of the wheel guard in the third and sixth years. From the sketches of the third year, it can be seen that the coating effect was significant given that less scaling was recognized in the coated area than in the uncoated area, and given that the scaling was more recognizable on the vertical surface than on the horizontal surface. This may be because the horizontal surface is highly likely to be covered with grit and snow, which may prevent freeze-thaw action (Photo 11).

From the sketches of the sixth year, it can be seen that local scaling developed relatively intensively in the coated area. As Photo 12 shows, the scaling on the horizontal surface was especially clearly at the site near the passing-through cracks which had developed when the concrete was placed. Such cracks are generally known to absorb snowmelt water, and, in concrete matrix, non-freeze water moves to around ice crystal due to osmotic pressure when cooled [8]. In the concrete coated with silane-type surface penetrants, however, movement of non-freeze water was blocked by a hydrophobic group;

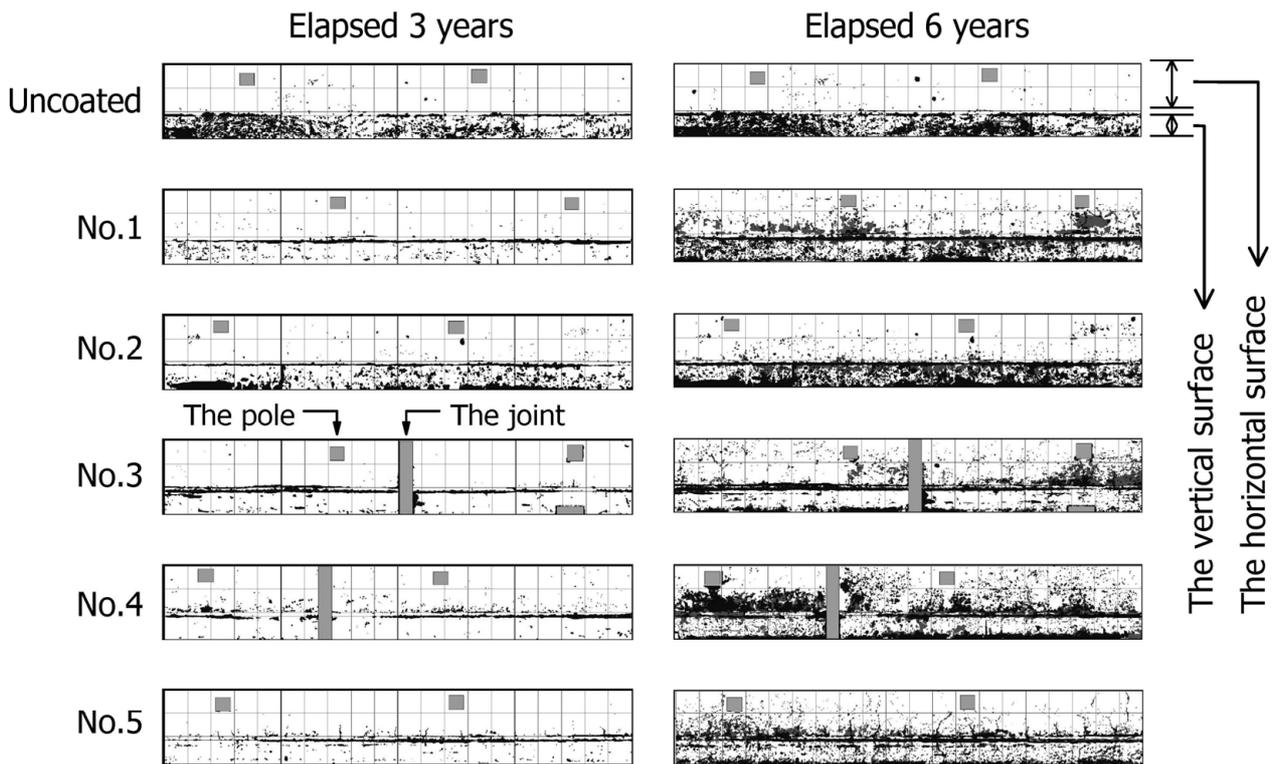


Figure 6 - The scaling area (black)



Photo 11 – The wheel guard in spring

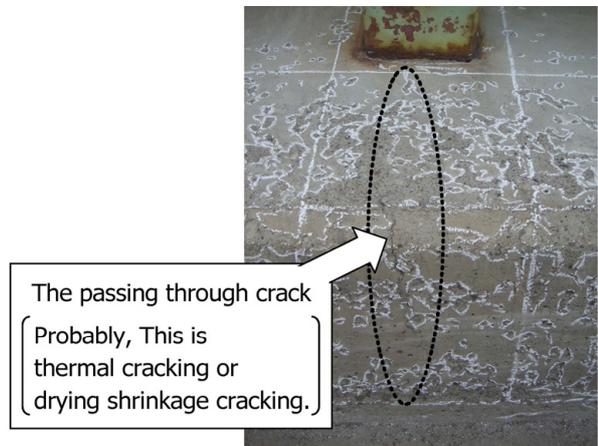


Photo 12 – The condition of wheel guard surface adjacent to passing-through cracks (area No.5)

thus, high water pressure occurred locally, which led to tangible scaling. This suggests that it is essential to repair such cracks prior to applying silane-type surface penetrants as coatings.

Figure 7 shows the yearly changes in scaling area ratios on the vertical surface. In the sixth year after coating, scaling developed more significantly for the areas coated with No.1 and No.2 than for the uncoated area, but scaling was 10% to 50% lower for the areas coated with No.3, No.4 and No.5. This shows that penetrants No.3, No.4 and No.5 have the ability to delay scaling progress, and these findings agree overall with the results of Figure 5. Sketches of the vertical surfaces in the sixth year after coating (Figure 6) show

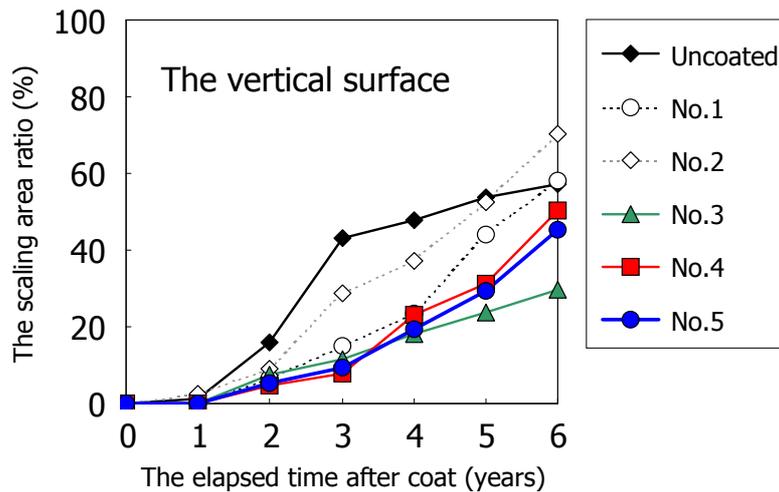


Figure 7 – Secular change in scaling area ratio for the vertical surface

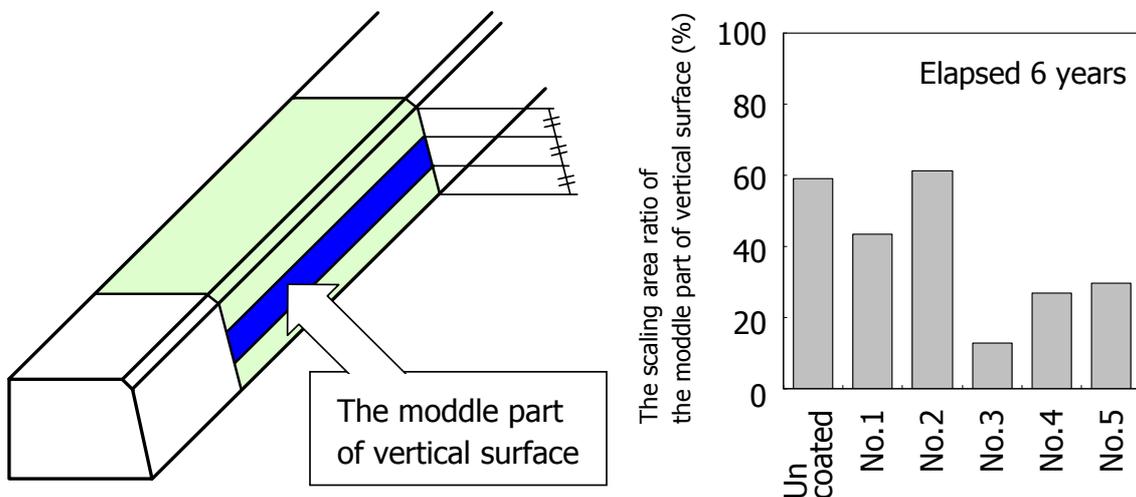


Figure 8 - Scaling area ratio of the middle part of the vertical surface at 6 years elapsed

that the scaling develops overall at the uncoated area but is uneven at areas coated with No.3, No.4 and No.5. On those areas, scaling develops more intensively at the bottom of the vertical surface, near the pavement, than at the middle part. This seems to be because the highway cross-slope causes water to converge at the bottom of the vertical surface. We examined scaling area ratios for the middle part of the vertical surface in particular, since this part looked the most affected by water splashed by cars. Scaling area ratios of No.3, No.4 and No.5 in the sixth year after coating (Figure 8) indicate that the scaled areas were 50% to 80% smaller than that of the uncoated area. From this point, it is reasonable to conclude that a selection of appropriate silane-type surface penetrants will delays scaling progress for more than six years after coating. It is noted, however, that the penetrants ability may vary by concrete condition and road drainability.

3.3. The Condition of the Water Repellent Layer

Areas coated with Nos.3, 4 and 5 showed favorable results with respect to water permeation ratio (3.1) and scaling control (3.2). Cores were extracted from the vertical surfaces coated with those penetrants (Photo 13) to further examine their water repellent layers. Figure 9 shows the water repellent layer thicknesses of the cores coated with



Photo 13 – The wetted core (The layer near the upper surface that is not wet is the water-repellent layer.)

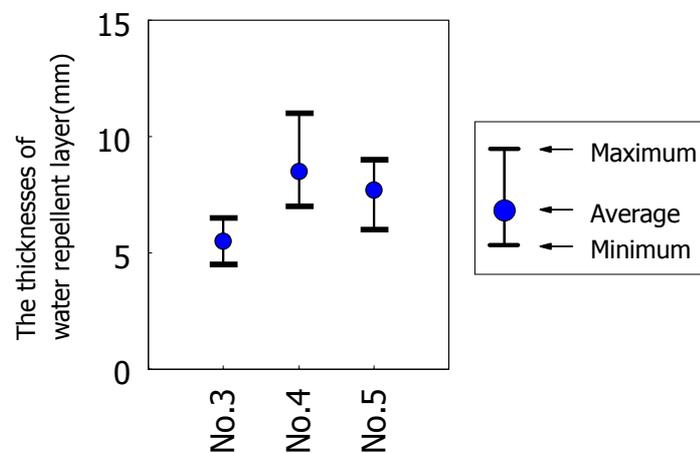


Figure 9 - Measured thicknesses of the water repellent layer at 6 years elapsed

Nos.3, 4 and 5, indicating that 5- to 10-mm-thick water repellent layers formed at the wheel guard of the tested highway bridge. The layers were confirmed to exist even in the sixth year after coating.

3.4. Chloride Ion

Photo 14 shows the distribution of chloride ion concentrations of the 4-cm concrete cores at the sixth year after coating. Measurement was performed by using an EMPA. The photo legends are the weight ratios of chloride ion masses to concrete masses (expressed as percents). Analyses were conducted on cores coated with Nos.3, 4 and 5. For comparison, a core from the uncoated area was also analyzed.

In the uncoated area, chloride ion concentrations were the greatest on the surface, and chloride ion penetrated well from the surface through the inner part of the concrete. In the areas coated with Nos. 3 and 5, chloride ion concentrations were lower than that of the uncoated area. It confirms that silane-type surface penetrants are effective in controlling chloride ion supply to concrete. The area coated with No.4, however, showed a slightly different result: Chloride ion concentrations were low on the water repellent-layered surface, immediately below which chloride ion was recognized. The thickness of chloride ion penetration was shown to be smaller than that of the uncoated area.

Our previous study reported that: (1) in structures coated with silane-type surface

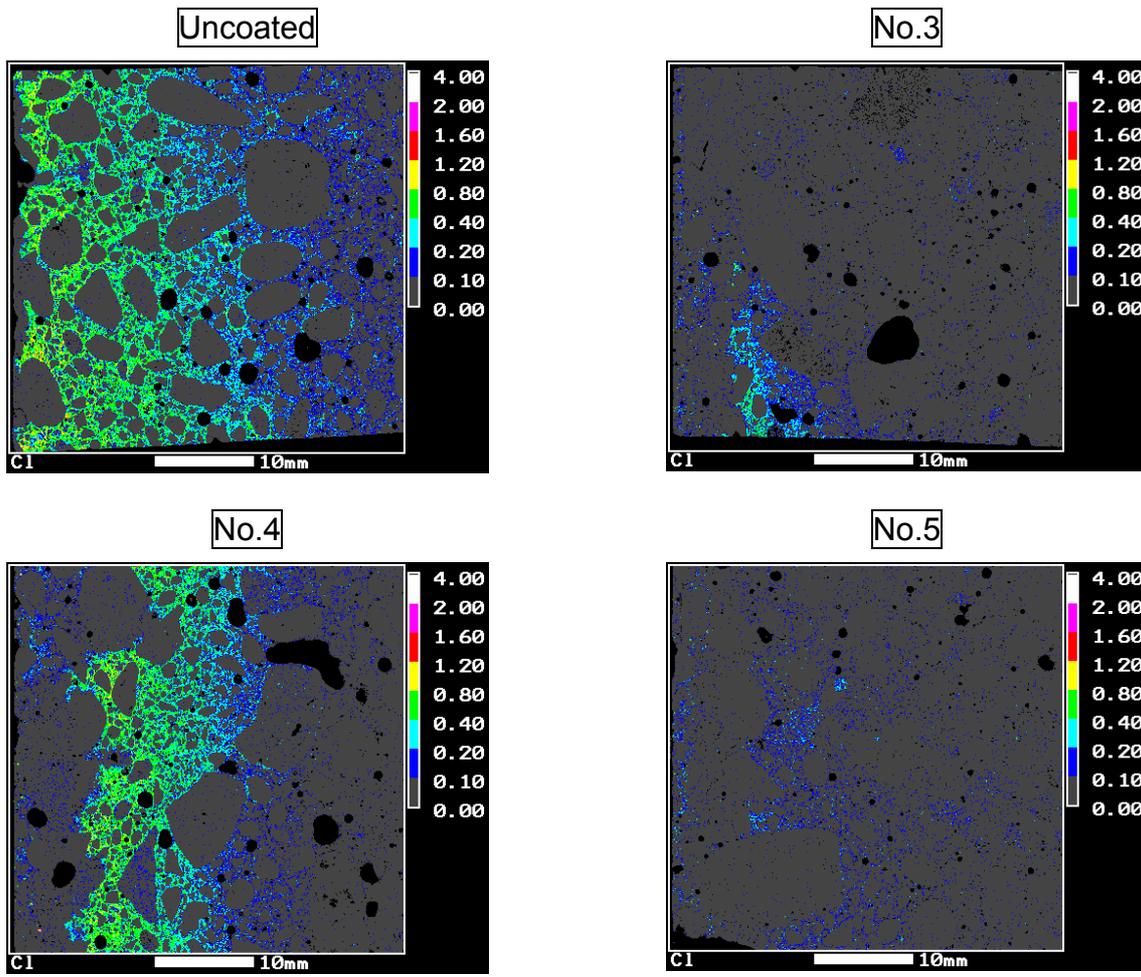


Photo 14 - EPMA analysis of chloride ion concentration distribution at 6 years elapsed. The left side of the image is the surface. Legend: weight ratio (%)

penetrants, the carbonation (a phenomenon whereby carbon dioxide in the air lowers the concrete's pH) of the concrete surface is easy to be promoted due to decrease water content (from high quantity to middle quantity) [9]; and (2) this carbonation may cause chloride crystals to re-dissolve, thus making chloride ion move further inward through a concentration diffusion process [10]. In light of our previous report, we assume that chloride ion penetrates the water repellent layer on the surface of No.4-coated concrete and forms chloride crystals that then dissolve through carbonation to further permeate inward. No.4 is likely to lose its ability to delay chloride ion supply faster than Nos.3 and 5.

3.5. Trial Calculation of Wheel Guard Maintenance Costs

Figure 10 shows the total content of chloride ion in the extracted concrete cores (for 4 cm from the surface) per cubic meter, calculated by using Mohr's method. No.5 shows the greatest ability to delay chloride ion supply of any penetrants. Accordingly, we looked closely at No.5 to estimate the chloride ion penetrations both at No.5-coated and uncoated areas. For estimation, we used the Fick's second law of diffusion, expressed in Equations (3) and (4):

$$\text{Uncoated) } C(x,t) = C_0 \left(1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_c \cdot t}} \right) \right) \quad (3)$$

$$\text{Coated) } C(x,t) = C_0 \left(1 - \text{erf} \left(\frac{1}{2\sqrt{t}} \left(\frac{t_h}{\sqrt{D_h}} + \frac{(x - t_h)}{\sqrt{D_c}} \right) \right) \right) \quad (4)$$

where

$C(x, t)$ is the chloride ion content at the depth x cm in the t^{th} years (kg/m^3)

C_0 is the chloride ion content on the concrete surface (kg/m^3)

erf is an error function

D_c is the chloride ion diffusion coefficient in the concrete (cm^2/yr)

D_h is the chloride ion diffusion coefficient in the water repellent layer (cm^2/yr)

t is years elapsed (yr)

x is the depth from the concrete surface (cm)

t_h is the thickness of the water repellent layer (cm)

Figure 11 compares measured and estimated values of chloride ion content in the sixth year after coating. The two values roughly agree. The Standard Specification for Concrete Structures, published by the Japan Society of Civil Engineers, specifies that “the limit chloride ion content for the occurrence of corrosion of reinforcing bar” is $1.2 \text{ kg}/\text{m}^3$ [11]. By using Equations (3) and (4), we estimated the number of years it would take for the chloride ion content to reach $1.2 \text{ kg}/\text{m}^3$ at reinforcing bar of the wheel guard (with 5cm concrete cover). Our calculation found that chloride ion content would outperform the threshold for corrosion in 50 years at the uncoated area, while remaining below $1.2 \text{ kg}/\text{m}^3$ at the No.5-coated area in 100 years.

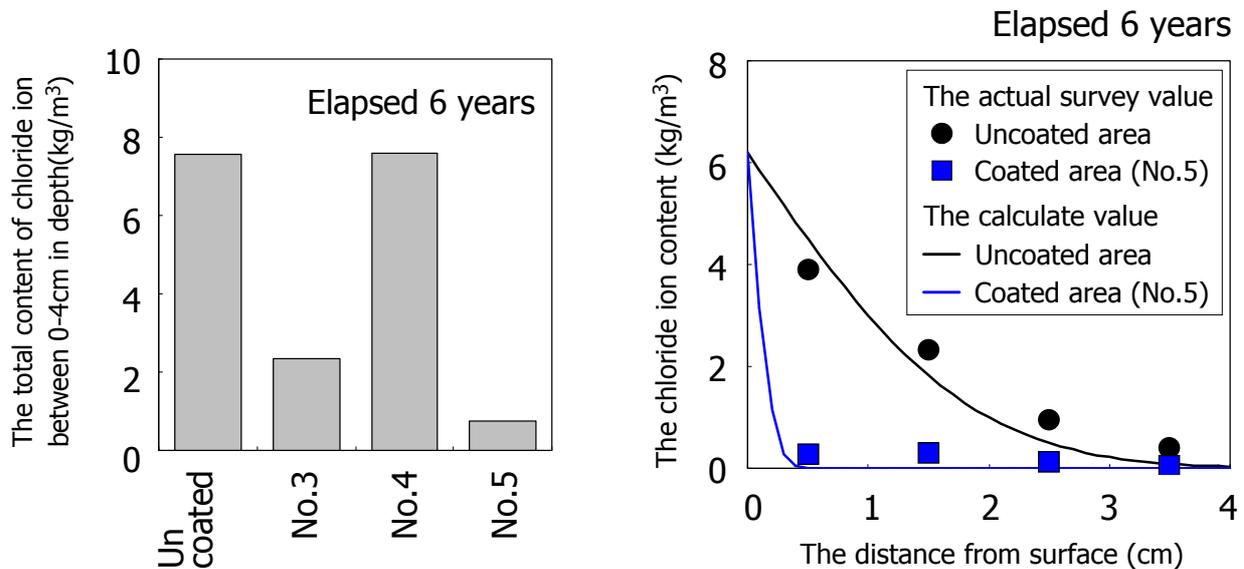


Figure 10 – The total content of chloride ion between 0-4cm in depth at 6 years elapsed

Figure 11 - Chloride ion content distribution of uncoated and No.5 at 6 years elapsed

Furthermore, we estimated the wheel guard maintenance costs at the No.5-coated and the uncoated areas under the following conditions:

- (1) The service period of the highway bridge is 100 years.
- (2) At the uncoated area, the wheel guard is replaced at the 50th year after placing. This is based on remarks by a road administrator that the work is normally performed every 50 years at wheel guards with measures against deterioration.

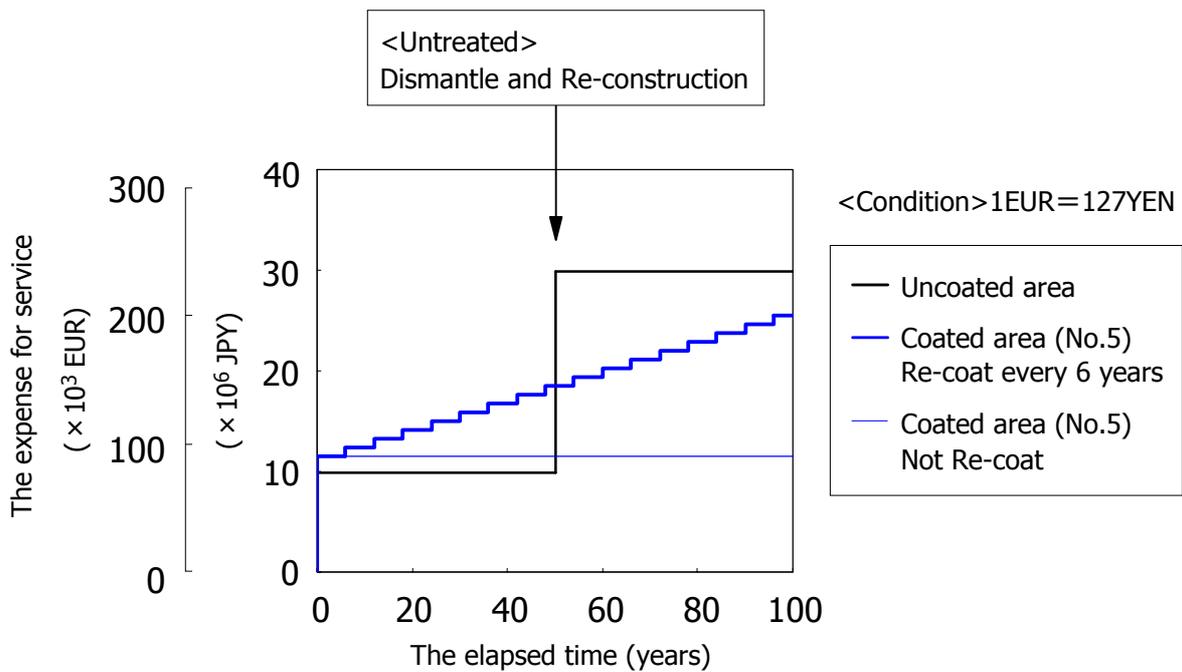


Figure 12 - Trial calculations of wheel guard maintenance costs

(3) Expenses for replacing wheel guards are based on construction fees estimated by road maintenance offices that manage bridges.

(4) Based on a manufacturer's estimate, the total expenses to apply silane-type surface penetrants are 3,500 JPY (27.6 EUR) per square meter.

(5) The area with silane-type surface penetrants is recoated every six years. This is based on our assumption that six years is the maximum period that a silane-type surface penetrants may ensure its delay of scaling progress, though that scaling control may continue to be effective for more than six years. For comparison, we estimated the expense for the case of no recoating.

(6) The coating area is the all surface of the wheel guard for the initial coating and only the vertical and horizontal surfaces for recoating.

(7) Scaffold building is included in a total cost.

Figure 12 shows our expense calculations, which indicate that applying a coat of silane-type surface penetrants reduces the expense for 100-year service of the wheel guard by 15 percent versus no coating (with one replacement). If no re-coating is performed, the expense will be 60% percent.

Actual expenses required for maintaining the wheel guards for 100 years may vary by various factors of road shape (such as alignments, slope gradients, drainability, and so on) and concrete conditions of highway bridges. Based on the findings, we conclude that silane-type surface penetrants may help cut such expenses by between 15% and 60%.

4. CONCLUSIONS

In view of social demands for the longevity of highway bridges through effective and reasonable maintenance methods, we have conducted field tests on the effectiveness of silane-type surface penetrants and we have tracked the progress in deterioration of the wheel guard for six years. Though the trend may vary by penetrants type, we conclude the following:

(1) Water absorption was less at the coated areas than the uncoated area.

- (2) Appropriate penetrants help delay of scaling progress, although the trends vary by concrete condition and road drainability.
- (3) A 5- to 10-mm-thick water repellent layer formed on the surface of the wheel guard. The water repellency persisted in the sixth year after coating.
- (4) Appropriate silane-type surface penetrants have the ability to greatly retard chloride ion supply.
- (5) Expenses required for maintaining wheel guards for 100 years vary by various factors, but the appropriate selection of a silane-type surface penetrants can help lower the cost by 15% to 60%.

REFERENCES

1. Hayashi, D., Sakata, N., Mimura, T. and Kanzawa, H., (2000). Development of High-performance Water Repellent Agent of Concrete, 22nd Annual Journal of Japan Concrete Institute, Vol.22, No.1, pp 301-306
2. Roth, M., (1982). Silicon - Bautenschutzmittel Fuer die Oberflaechenimpraegnung von Mineralischen Baustoffen, Kunststoffe im Bau, Vol.19, No.2, pp71-74
3. Weber, H., (1983). Untersuchung an Hydrophobierten und Nichthydrophobierten Weissbetonteilen im Olympischen Dorf Munchen, Elements+Fertigbau
4. WACKER-CHEMIE GMBH, (1980). Silicones for Protection of Monuments
5. Johansson-Selander, A., Tragardh, J., Silfwerbrand, J. and Janz, M., (2010). Preventing Chloride Ingress in Concrete with Water Repellent Treatments, The 6th International Conference on Concrete Under Severe Conditions, Vol.2, pp1189-1194
6. Liu, G., Gjorv, O.E. and Arskog, V., (2010). Effect of Concrete Surface Hydrophobation Against Chloride Penetration, The 6th International Conference on Concrete Under Severe Conditions, Vol.2, pp1157-1163
7. Endoh, H. and Taguchi, F., (2010). The Effect of Using Surface Penetrate Materials (Silane Type) to Control the Scaling of Wheel-Guard Concrete on Highway Bridges, The 6th International Conference on Concrete Under Severe Conditions, Vol.2, pp1149-1156
8. Powers, T. C. and Helmuth, R. A., (1953). Theory of Volume Change in Hardened Portland Cement Paste During Freezing, Highway Research Board, Vol.32, pp285-297
9. Hayashi, D., Sakata, N., Taguchi, F. and Endoh, H., (2008). Study on Durability of Concrete using Water Repellent Agent in Marine Environment and Cold Region, 30th Annual Journal of Japan Concrete Institute, Vol.30, No.2, pp649-654
10. Tanaka, H., Takimoto, K. and Kurita, M., (2008). Durability of Concrete using Surface Improvement Materials, 30th Annual Journal of Japan Concrete Institute, Vol.30, No.2, pp667-672
11. Japan Society of Civil Engineers, (2007). Standard Specifications for Concrete Structures-2007, Design, p120