

Research Article

Evaluation of Concrete Durability Performance with Sodium Silicate Impregnants

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This paper presents an enhanced performance in concrete impregnated with silicate compound. Two different types of impregnant materials (inorganic and combined type) are applied to concrete samples with different strength grade (21 MPa and 34 MPa). Through lab-scale test, improved performances in impregnated concrete are evaluated regarding porosity, strength, chloride diffusion coefficient, permeability of air/water, and absorption. Long-term exposure tests including strength, chloride penetration depth and contents, and electrical potential for steel corrosion are performed for different marine conditions. While the surface-impregnated concrete shows marginal increase in strength, significant improvements of porosity, absorption, and permeability are evaluated. The resistance to chloride attack reasonably improved through simply spraying the inorganic silicate in atmospheric-salt spraying condition.

1. Introduction

Reinforced concrete (RC) structures usually undergo deteriorations and the damages due to deteriorations eventually cause the structural safety problems although they have been used showing good structural and durability performance. Recently, repair techniques using surface-impregnation are proposed for improvement of concrete properties [1–4]. The research significance of surface-impregnated concrete can be explained in two viewpoints. One is a development of reactive repair material using silicate compound. In 1980–90, impregnation with sulfate compound was used for improvement of strength and elasticity of concrete. However, the repair technique using additional formation of ettringite due to sulfate compound had a limited application to concrete structures because another hydration procedure or high temperature was required for the impregnation [4]. Afterwards, liquid organic or inorganic/organic surface impregnants using silicate compound were developed and applied to existing RC structures as repair techniques [5–8]. Impregnated silicate compound such as colloidal silicate and Na-silicate through

capillary suction reacts with the calcium hydroxide- $\text{Ca}(\text{OH})_2$ in concrete and produces additional CSH gel [9]. Through the reaction with SiO_2 and $\text{Ca}(\text{OH})_2$, the pore structure in concrete is modified to be more denser and invisible micro cracks can be closed. The other is a development of repair system using silicate compound and the related equipment. The organic surface impregnant is mainly used for waterproofing and surface protection since it has several advantages like low price and easy coating process. However, most of them are basically constituted of volatile organic compound and they have the decisive shortcoming of being air-polluting during manufacturing process as well as coating works [8]. Besides the environmental problem, delamination of impregnation layer easily occurs since organic coating cannot distribute the evaporation from inner concrete to outside. In addition, the material behaviors like shrinkage and thermal expansion in organic coating are significantly different from those in concrete [2]. These disharmonious characteristics of surface layer cause cracks, delamination, and coming-off from the concrete surface [2, 8, 10]. The pores and cracks in concrete become such main routes

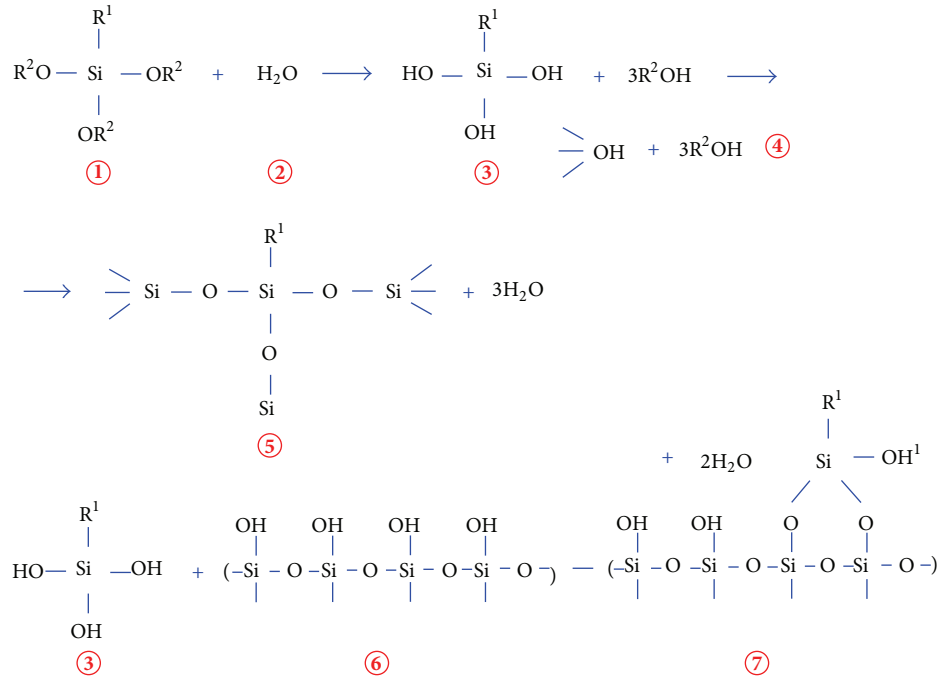


FIGURE 1: Chemical chain in inorganic impregnant.

for deteriorating agents that durability improvement can be obtained through reducing porosity and permeability [11–14], Long-term exposure tests for surface-impregnated concrete are limitedly performed while accelerated deterioration tests in laboratorial scale are widely carried out.

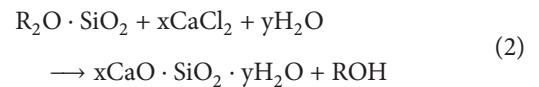
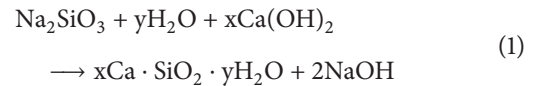
This paper presents an enhanced performance of concrete with impregnation of organic and combined type. For the purpose, two types of surface impregnants which are inorganic type and combined type are applied to two different concrete levels. Properties evaluation tests including porosity, chloride diffusion coefficient, compressive strength, permeation of water and air, and moisture absorption are performed. Through long-term exposure tests, chloride behaviors and electrical potential for steel corrosion are evaluated for the surface-impregnated concrete. Quantitative improvement of material properties and resistance to chloride attack in concrete with surface impregnation are evaluated and discussed in this paper.

2. Mechanism of Engineering Properties Enhancement through Surface Impregnation

2.1. Denser Pore Structure with Intrusion of Silicate Compound. Among the silicate components such as calcium silicate, potassium silicate, and colloid silica which make pore structure denser through reaction of rehydration, sodium silicate ($\text{Na}_2\text{O}-\text{SiO}_2$) is recently utilized for repair technique. Through capillary suction into concrete, this silicate compound reacts with calcium hydroxide and eventually forms insoluble CSH gel ($\text{Ca}-\text{SiO}_2$) which makes concrete denser [6–8, 15]. Namely, the porosity in concrete is reduced through

the reaction with intruded silicate compound and residual $\text{Ca}(\text{OH})_2$, which generally occupies 25–30% of amount of CSH in concrete [16]. In the conventional repair system with plate-bonding technique, organic adhesive such as epoxy resin is usually used but it cannot guarantee the durability performance under severe condition because of delamination of protection layer [2, 17, 18]. The material property of reproduced CSH gel in impregnation layer has the same material property as concrete, which enables perfect bond without delamination of impregnation layer. The delamination and peeling-off of coating layer frequently occur in organic coating on concrete surface [8].

The reactions of inorganic and combined type of impregnation applied in this study are written in (1) and (2), respectively [6, 7]:



In Figure 1, chemical compound in inorganic impregnant is shown.

2.2. Reduced Chloride Penetration through Surface-Impregnation. In hardened concrete, chloride ion can be divided into free chloride ion affecting steel corrosion directly and bound chloride ion, chemically stable without exposure to severe environmental condition like carbonation [19, 20]. Formation of bound chloride can be expressed as (3) through the reaction with soluble CaCl_2 and monosulfate. Similar

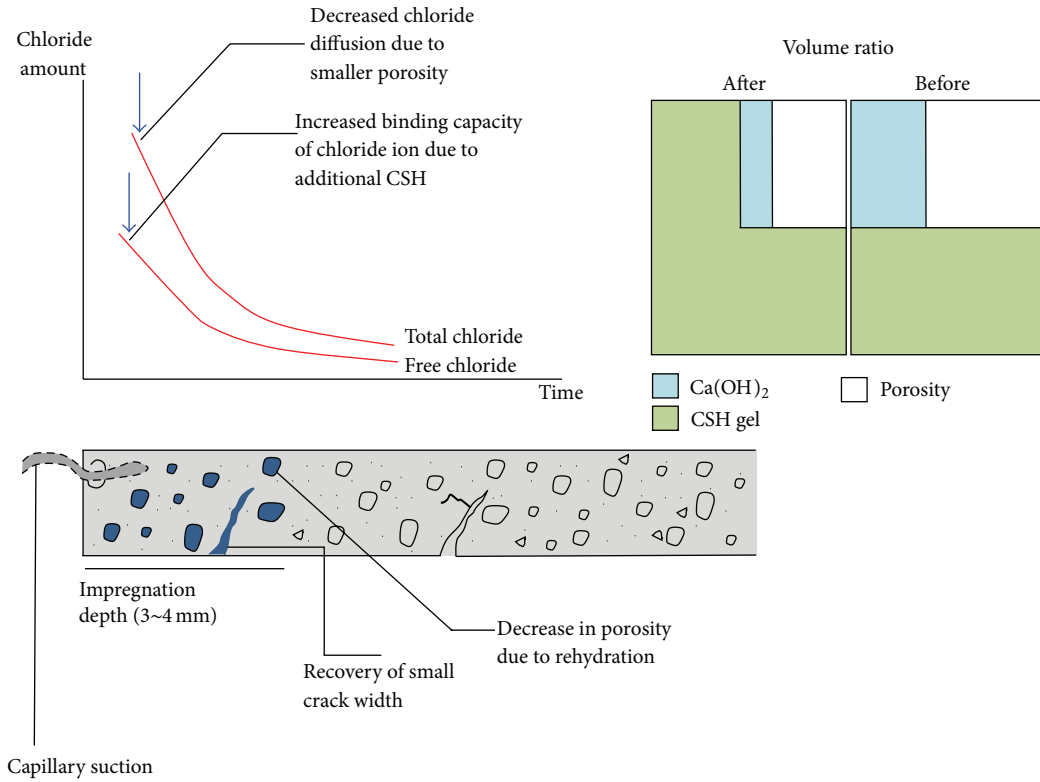
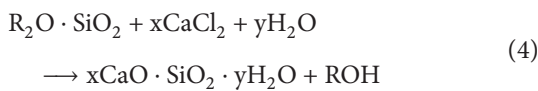
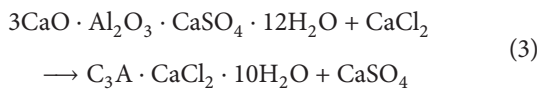


FIGURE 2: Durability improvement in surface-impregnated concrete.

TABLE 1: Characteristics of applied surface impregnants.

Type	Main ingredient	Color	Viscosity (cp)	Surface tension (dyne/cm)	Solvent
I Inorganic	Sodium silicate	No color	3.72	26.0	Alcohol
C Combined inorganic/organic	Sodium silicate + polymer	Sky blue	4.13	38.0	Water

as (3), soluble CaCl₂ can be changed into insoluble silicate compound through intrusion of silicate compound as shown in (4):



According to the previous researches [21], chloride ion in pore water can be changed into bound chloride ion through absorption to CSH gel and it is related with the amount of CSH gel. The resistance to chloride attack can be obtained through both increase in bound chloride ion due to reproduced CSH and decrease in diffusion of chloride ion due to reduced pore structure in surface-impregnated layer. If the property of concrete surface is improved, it can provide an effective resistant barrier to chloride attack. These durability characteristics using improved skin properties are verified by both experiments [5] and analytical solution [22]. The enhancing resistance to chloride attack by surface-impregnated concrete can be summarized as Figure 2.

3. Experimental Program

3.1. *Materials Used.* In this paper, two surface impregnants are applied to concrete samples with two different mix proportions. One is the inorganic type (I) and the other is the combined inorganic and organic type (C). The properties of applied impregnants are listed in Table 1. The mix proportions of concrete and the physical properties of aggregates are listed in Tables 2 and 3, respectively.

3.2. *Experiment Procedures.* The experiment program in this paper has two parts; one is for evaluation of enhancing properties after impregnation and the other is for durability evaluation under chloride attack for 2 years in exposure test.

3.2.1. Enhancing of Engineering Properties through Surface-Impregnation

(1) *Curing and Impregnation.* The tests for enhancement of engineering properties include porosity measurement, chloride diffusion coefficient, compressive strength, permeability of air/water, and water absorption ratio. Concrete samples are mixed based on Table 2 and threefold samples are

TABLE 2: Mixture proportions of concrete.

MPa	Slump (cm)	w/c (%)	S/a	W (kg/m ³)	C (kg/m ³)	S (kg/m ³)	G (kg/m ³)
21	15	55.4	45.8	166	267	810	979
34	15	48.7	43.0	185	380	731	994

S/a: ratio of sand to total aggregate; W: water; C: cement; S: Sand; G: gravel.

TABLE 3: Physical properties of aggregates.

Type	G _{max} (mm)	Density (g/cm ³)	Absorption (%)	Fineness modulus
Fine aggregate	—	2.60	0.95	2.64
Coarse aggregate	25	2.65	0.85	6.80

TABLE 4: Specimens and curing procedures.

Test	Specimens (mm)	Curing and impregnation
Porosity	50 × 50 × 50 (cubic)	(1) Mixing based on Table 2
Chloride diffusion coefficient	100 × 50 (cylinder)	(2) Curing in air for 1 day
Compressive strength	100 × 200 (cylinder)	(3) Curing in water for 4 weeks
Permeability of water and air	200 × 200 × 100 (rectangular)	(4) Drying in air for 2 weeks
Absorption	100 × 100 × 100 (cubic)	(5) Spraying impregnant
		(6) Curing in air for 2 weeks

manufactured for each test. Each sample is demolded after 1 day and cured in submerged condition (20°C of temperature) for 4 weeks. After curing for 4 weeks, they are exposed to air for 2 weeks and then surface impregnation was performed through spraying. The test items, size of sample, and curing procedures are summarized in Table 4.

(2) *Tests for Impregnated Concrete.* For the control concrete (21 MPa and 34 MPa) and impregnated concrete (I and C type), porosity is measured through mercury intrusion porosimetry (MIP). The porosity in impregnated concrete is reduced through additionally reproduced CSH so that durability performance can be improved. They are measured based on the related guideline [23]. For design of durability, chloride diffusion coefficient is essential parameter. In this test, accelerated test in nonstationary condition is performed based on the previous research [24]. Chloride diffusion coefficient can be obtained as follows:

$$D_{cpd} = \frac{RTL}{zFU} \cdot \frac{x_d - \alpha \sqrt{x_d}}{t}, \quad (5)$$

$$\alpha = 2 \sqrt{\frac{RTL}{zFU}} \cdot \operatorname{erf}^{-1} \left[1 - \frac{2C_d}{C_0} \right],$$

where D_{cpd} is diffusion coefficient in nonsteady state condition from rapid chloride penetration test (m²/sec), R is universal gas constant (8.314 J/mol·K), T is absolute temperature (K), L is thickness of specimen (m), z is ionic valence (=1.0), F is Faraday constant (=96,500 J/V mol), U is applied potential (V), x_d is the penetration depth of chloride ion (m), t is test duration time (sec), C_0 is chloride concentration in the upstream solution (mol/L), C_d is chloride concentration at the chloride penetration front (mol/L), and erf^{-1} is the inverse of the error function.

Compressive strength is considered as basic parameter for property evaluation so that compressive strength test is

also performed referring KS F 2405 [25]. Permeabilities of water and air have important roles of durability performance since they are directly related to moisture transport. Because concrete in partially saturated condition always has moisture gradient, evaporation occurs on the surface. When the inorganic material without moisture evaporation to outer surface is coated, it causes delamination and peeling-off of coating material [8]. The permeability of water and air can be calculated through (6) and (7), respectively [6, 7]:

$$C_{CP} = \frac{q}{P/L} \quad (6)$$

$$K = 4 \left[\frac{V_c (dP_I/dt)^2}{A (P_a^2 - P_I^2)} \right] \frac{\mu P_a}{\varepsilon} \int_{t_0}^t \left[1 - \left(\frac{P_I}{P_a} \right)^2 \right] dt, \quad (7)$$

where C_{CP} is permeability of water (m²/sec), q is velocity (m/sec), P is pressure (BAR), L is depth of gasket (15 mm), K is permeability of air (m²), ε is porosity in concrete (1/m³), A is area of chamber, μ is dynamic viscosity of air (Ns/m²), P_I and P_a are pressure in chamber and air, respectively (N/m²), and V_c is volume of chamber (m³).

In order to obtain absorption ratios for the different concrete samples, the impregnated specimens kept in submerged condition for 72 hours after curing shown in Table 4 based on KS F 2459 [26]. The absorption ratio can be obtained through

$$A = \frac{W_2 - W_1}{W_1} \times 100, \quad (8)$$

where A is absorption ratio (%) and W_1 (g) and W_2 (g) are weight of specimens before and after the submerged condition, respectively.

3.2.2. Enhancing Durability through Surface-Impregnation

(1) *Compressive Strength.* Test method and mix design for concrete are same as those for compressive strength test



FIGURE 3: Photos for long-term chloride exposure test.

described in Section 3.2.1. The concrete specimens are cured for 2 weeks in submerged condition and impregnation is performed after 2 weeks of exposure to air. After impregnation, they are exposed to tidal zone of sea water. The compressive strength is evaluated at the age of 28 days, 90 days, 360 days, and 720 days. Three concrete samples are prepared for average value in the each measuring time.

(2) *Chloride Penetration Depth.* The cylindrical samples (100 mm × 200 mm) with same curing and impregnation procedures are prepared and exposed to chloride conditions. The samples with 21 MPa are exposed to atmospheric (salt-sprayed), tidal, and sea water submerged conditions. Those with 34 MPa are exposed to only tidal condition. For the measurement of chloride penetration depth, splitting test is performed and AgNO_3 solution (0.1N) as an indicator is sprayed on the split section based on the previous research [27]. For measurement of chloride penetration depth, the colored depths are measured 10 times with 10 mm interval and the averages are used. It is reported that color in split layer changes when free chloride concentration reaches 0.15% (cement weight) through 0.1N AgNO_3 indicator. For the sake of convenience, colorimetric method of 0.1N AgNO_2 is adopted in this paper. The optimum indicator and procedures vary with test methods and chloride concentration. The reactive indicators with various colorimetric methods are well summarized in the reference [28].

(3) *Electrical Potential for Steel Corrosion.* For evaluation of steel corrosion, electrical potentials (Half Cell Potential) are measured for RC samples (50 × 50 × 400 mm) based on ASTM C 876-80 [29]. The conditions of curing and exposure for this test are same as those for chloride penetration depth. Steel reinforcement of 10 mm diameter is embedded in RC specimen which has 20 mm cover depth. The exposed rebar from concrete surface is coated with epoxy for preventing corrosion. In Figure 3, photos for long-term chloride exposure tests are shown.

(4) *Chloride Content Evaluation (Acid-Soluble).* In order to evaluate the chloride content exposed to chloride attack, cylindrical samples (100 × 200 mm) are exposed to tidal and submerged conditions. For 1-dimensional intrusion, side and bottom are coated with epoxy and only top surface is directly exposed to sea water. Based on AASHTO T 260, standard

solution of AgNO_3 is used for determining the chloride content. After grinding concrete cover with 10 mm depth, the particles are tested with adding HNO_3 .

4. Results and Discussion

4.1. *Improved Properties of Surface-Impregnated Concrete.* Porosity in the case of 21 MPa decreases to 62.8~74.4% compared with control results. Results in the case of 34 MPa show reduction to 45.4~91.7% and they are reduced significantly since they have more $\text{Ca}(\text{OH})_2$ which can react with silicate compound. Pores in concrete are much related with diffusion mechanism so that reduced chloride diffusion coefficient can be obtained through impregnation. Chloride diffusion coefficient decreases to 85% (21 MPa) and 71.6~74.8% (34 MPa). When we assume 100 mm of cover depth and critical chloride content of 1.2 kg/m^3 , service life is evaluated to increase from 37.8 years to 50.5 year through simply spraying I type impregnant to 34 MPa concrete based on Fick's 2nd Law [30]. For compressive strength, it is measured that results in both impregnated concrete samples slightly increase because material properties are improved only within the impregnated depth (below 10 mm). No significant development in strength is measured in the test. The strength gaining ratios are evaluated to be 112.4~121.2% (for 21 MPa concrete) and 114.1~116.1% (for 34 MPa concrete). Permeability of water/air is the unique characteristics of porous media like concrete. It is strongly related with transport of external agents so that it can be used as durability index [31]. In water permeability test, reduction ratios to control samples are measured to be 45.4~50.0% in surface-impregnated concrete with 21 MPa and 25.6~27.3% in that with 34 MPa. In air permeability test, reduction ratios are also measured to be 86.7% in surface-impregnated concrete with 21 MPa and 85.0~90.0% in that with 34 MPa, respectively. Similarly as the results of compressive strength, there is no significant difference from the impregnant types. While the surface-impregnated concrete shows significantly reduced water permeability, the effect of impregnation on air permeability seems to be marginal. As previously explained, delamination between concrete and surface coating easily occur in organic impregnated concrete since coating on surface cannot permit evaporation to outer surface [2, 6–8, 10]. The improved property with lowering water permeability but maintaining air permeability is

TABLE 5: Summary of modified properties tests.

Test items	Concrete-21 MPa (% to control of 21 MPa)			Concrete-34 MPa (% to control of 34 MPa)		
	Control	C type	I type	Control	C type	I type
Porosity (%)	25.8 (100.0)	19.2 (74.4)	16.2 (62.8)	20.2 (100.0)	18.5 (91.7)	9.2 (45.4)
Chloride diffusion coefficient (m^2/sec)	2.61 (100.0)	2.23 (85.4)	2.23 (85.4)	1.55 (100.0)	1.11 (71.6)	1.16 (74.8)
Compressive strength (MPa)	25.0 (100.0)	28.1 (112.4)	30.3 (121.2)	29.8 (100.0)	34.0 (114.1)	34.6 (116.1)
Water permeability (10^{-14} m/sec)	170.7 (100.0)	85.4 (50.0)	77.6 (45.4)	153.8 (100.0)	42.0 (27.3)	39.4 (25.6)
Air permeability (10^{-16} m^2)	2.3 (100.0)	2.0 (86.9)	2.0 (86.9)	2.0 (100.0)	1.8 (90.0)	1.7 (85.0)
Absorption (%)	2.7 (100.0)	0.7 (25.7)	0.5 (16.9)	2.1 (100.0)	0.5 (25.9)	0.4 (18.5)

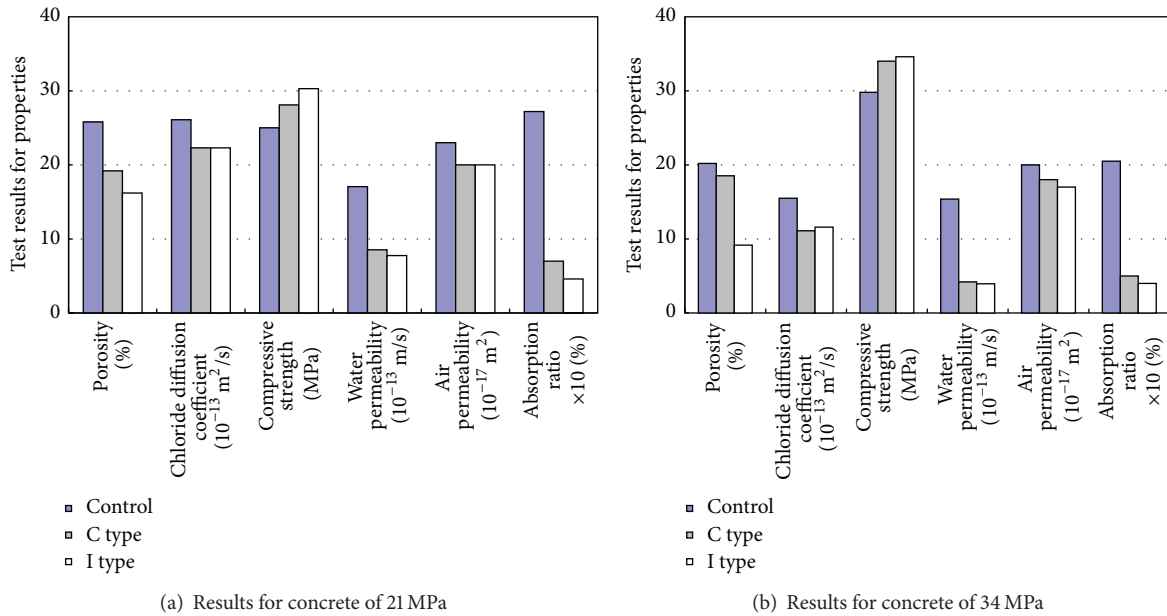


FIGURE 4: Results for modified properties test.

a notable engineering advantage and this can prevent the delamination of impregnated layer. The surface-impregnated concrete has hydrophobic characteristics so that it can reduce the intrusion of water. Reduction ratios in absorption test are measured to be 16.9–25.7% in surface-impregnated concrete with 21 MPa and 18.5–25.9% in that with 34 MPa. For overall test results, the concrete with inorganic coating (I type) shows slightly better enhanced performances both in concrete of 21 MPa and 34 MPa. The results for improved properties are summarized in Table 5 and Figure 4. Figures 4(a) and 4(b) show the results of impregnated concrete of 21 MPa and 34 MPa, respectively.

The effect of surface impregnation on engineering properties is evaluated to be remarkable in reducing porosity, water permeability, and absorption ratio among the others.

4.2. Durability Evaluation for Surface-Impregnated Concrete

4.2.1. Compressive Strength in Long-Term Exposure to Chloride Attack. As shown in Figure 5, compressive strength in impregnated concrete shows increase with exposure period but no clear strength gaining. The impregnated depth is usually 5–6 mm when it is sprayed. In the results in Table 5,

strength increasing ratios are 112.4–121.2%, however the results in this section are different from those in Table 5 because of their different curing conditions and period. It is recommended to take a conservative repair strategy through disregarding an increase in strength. Slight increase in compressive strength is measured in surface-impregnated concrete with 21 MPa, while it goes down to 92.6–94.5% in 34 MPa concrete. Considering the harsh environmental condition like tidal zone where physical and chemical attacks act simultaneously, the difference of measured strength seems to be small.

4.2.2. Chloride Penetration Depth in Long-Term Exposure to Chloride Attack. The measurements of the chloride penetration depth with different exposure conditions are shown in Figure 6. As described in Section 3.2.2, samples with 21 MPa are located in 3 different conditions like atmospheric, tidal, and submerged condition. Those with 34 MPa are located only in tidal condition.

In durability design, the chloride penetration depth with critical chloride amount (i.e., 1.2 kg/m^3) should be smaller than the cover depth within the intended service period since

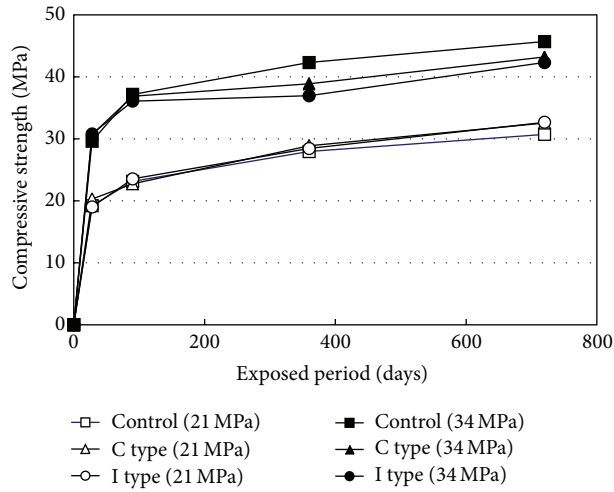


FIGURE 5: Change in compressive strength in surface-impregnated concrete under long-term exposure condition.

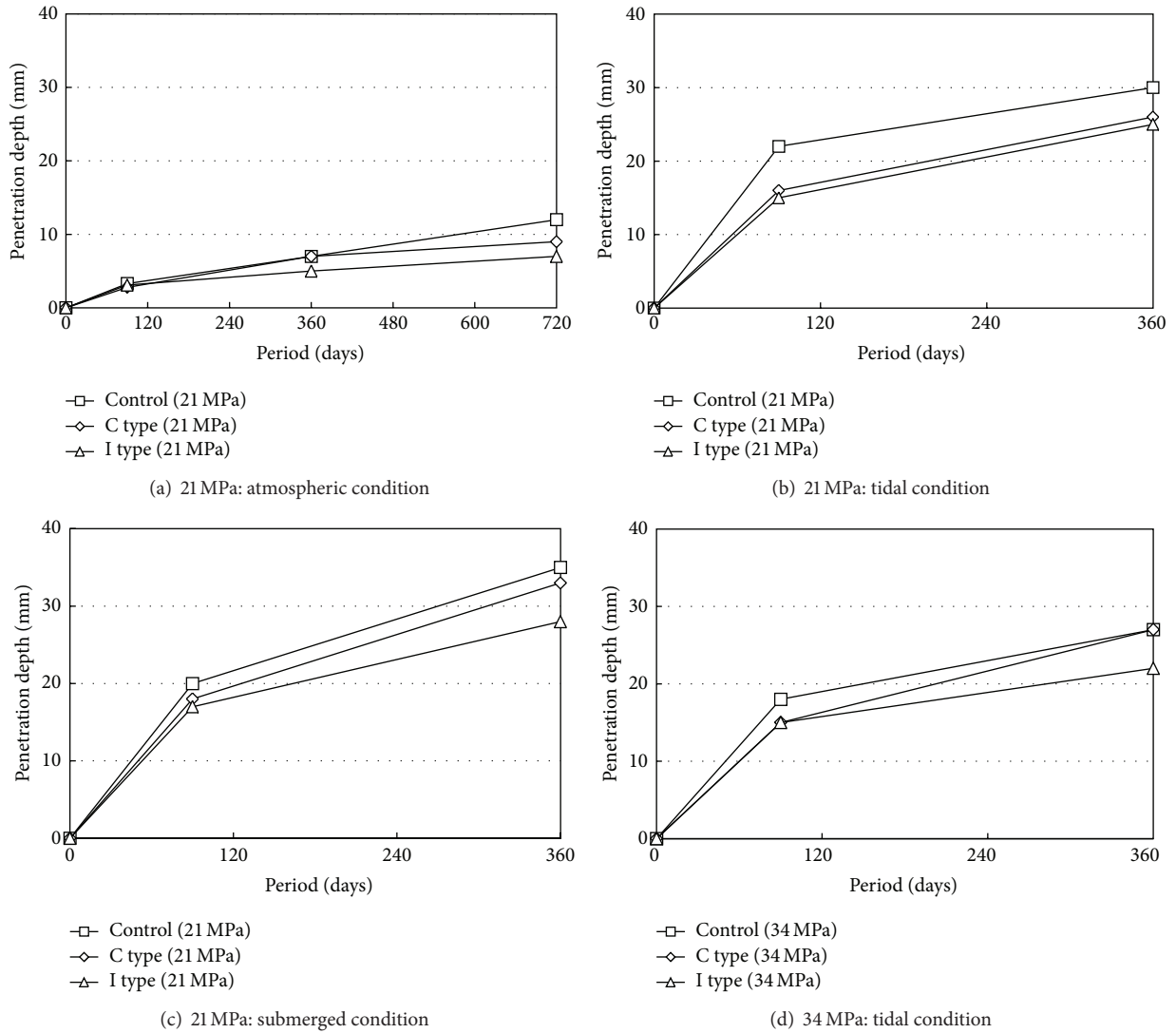


FIGURE 6: Chloride penetration depth in surface-impregnated concrete.

TABLE 6: Decrease ratio of chloride penetration depth.

Period (days)	Condition	Control	C type	I type
Ratio of chloride penetration depth (21 MPa: %)				
360	Tidal	100.0	94.3	80.0
360	Submerged	100.0	86.7	83.3
720	Salt-sprayed	100.0	75.0	58.3
Ratio of chloride penetration depth (34 MPa: %)				
360	Tidal	100.0	100.0	81

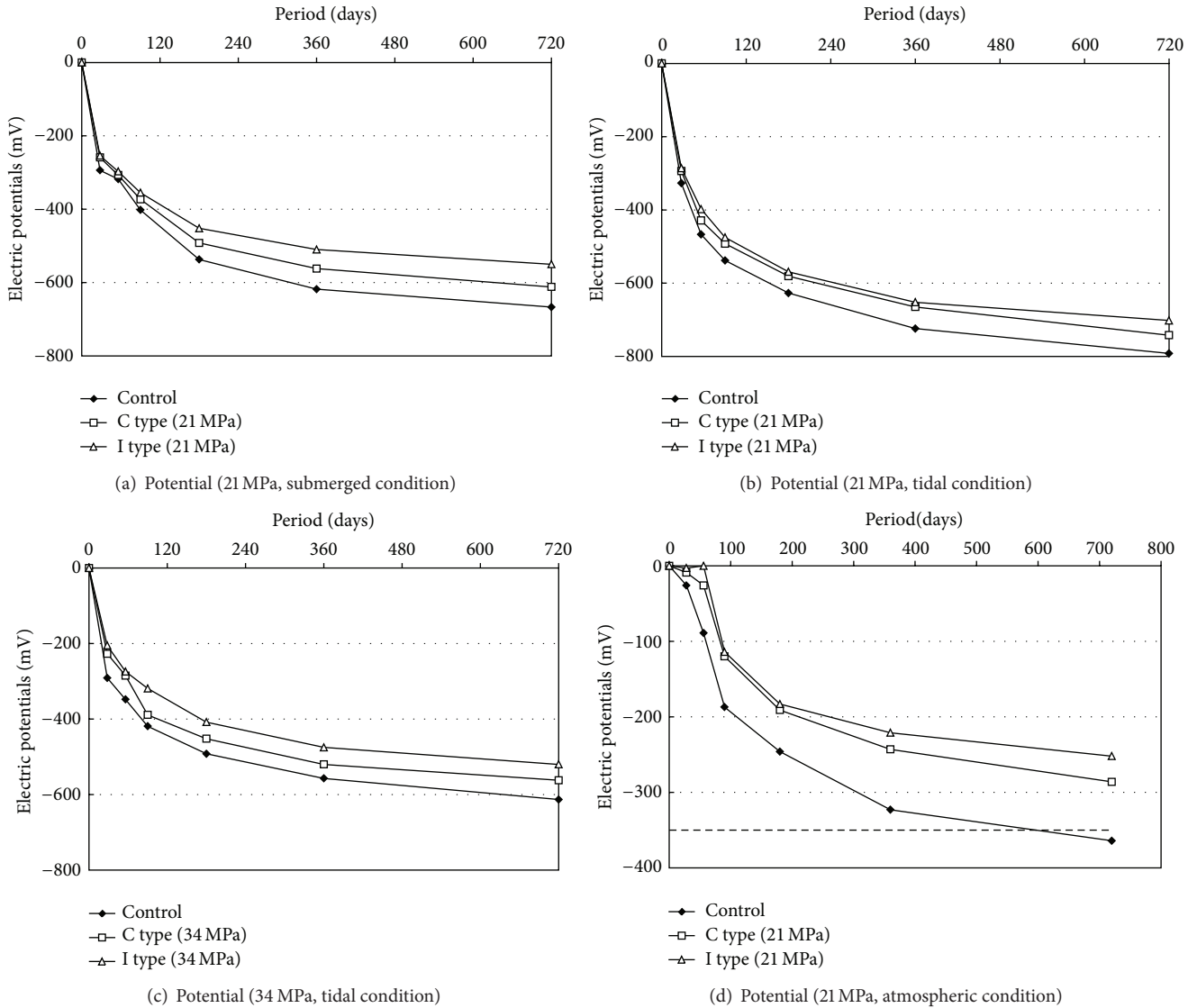


FIGURE 7: Result of measured potential in surface-impregnated concrete.

chloride ion is one of the most critical deteriorating agent for its rapid propagation and its direct effect on steel corrosion [1, 12, 27, 29]. As shown in Figure 6, chloride penetration depth is reduced in both I and C type impregnated concrete through enhancement of surface impregnation. The concrete samples with inorganic impregnation show better resistance to chloride penetration and this trend is clear with the longer

exposure period. The resistance to chloride attack is closely related to impregnation depth of silicate. The impregnation depth increases with activated capillary suction, which is caused by lower viscosity and surface tension of impregnant type [5–7]. The ratio of chloride penetration depth is listed in Table 6. Unlike strength evaluation, it shows reasonable resistance to chloride penetration.

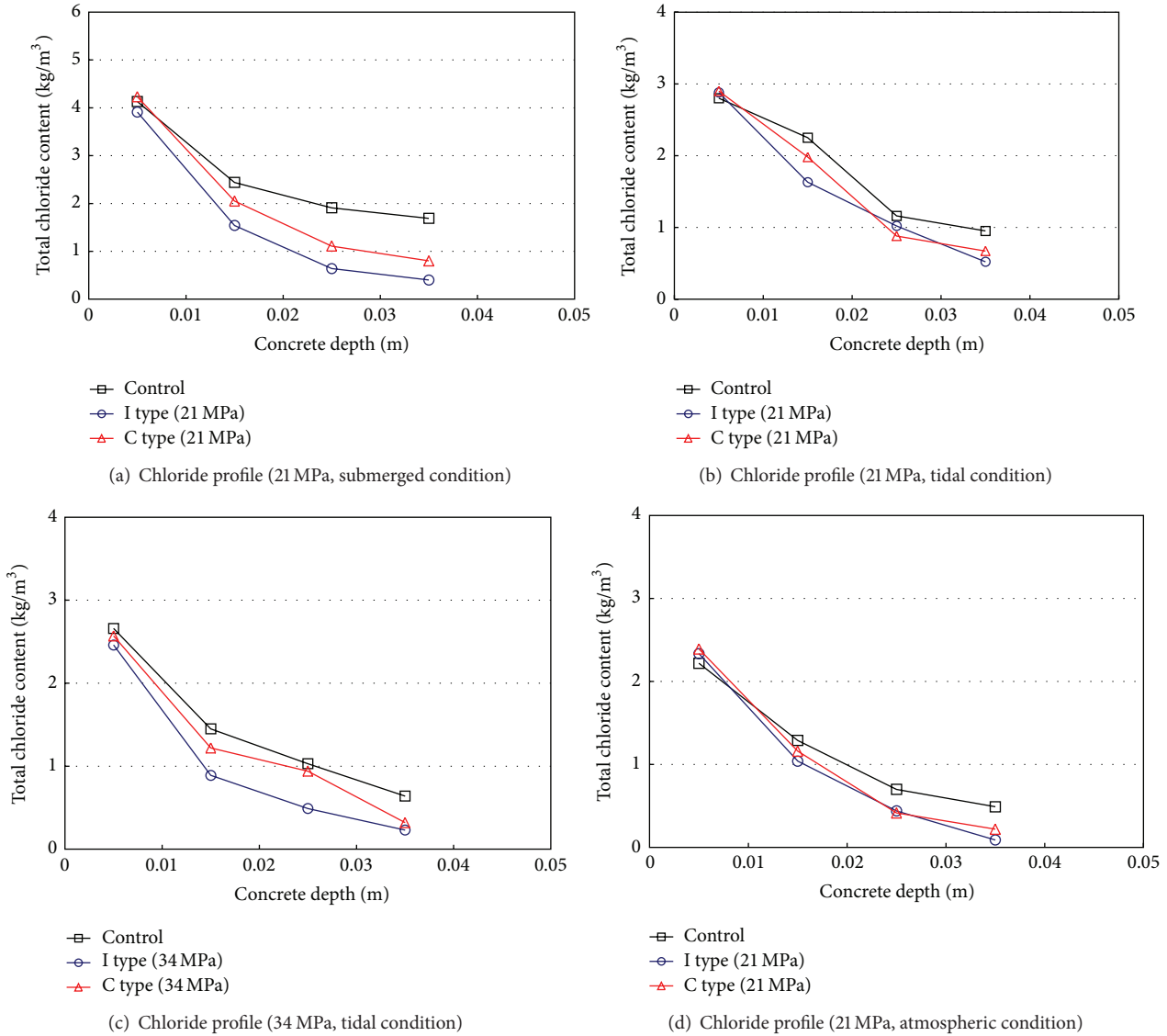


FIGURE 8: Total chloride profile in concrete with/without impregnation after 2 years.

4.2.3. *Electric Potential for Steel Corrosion (Copper-Copper Sulfate Half Cell: CSE).* It is reported that steel corrosion easily occurs at the location where lower electrical potential is measured since possibility of corrosion is governed by electrical potential and resistivity around steel location [29, 32]. The results of electronic potential indicate an improved resistance to steel corrosion as shown in Figure 7.

Potential in surface-impregnated concrete with 21 MPa in Figure (b) is evaluated to be similar as that in nonsurface-impregnated concrete with 34 MPa in Figure (c). It shows that concrete with low strength can obtain reasonable resistance to chloride attack like concrete with high strength by simple spraying of surface impregnation. In every condition, concrete with I type impregnation has better resistance to steel corrosion than that with C type impregnation. Previously described, lower viscosity and surface tension of I type are more effective to impregnation. According to the pervious researches [31, 32], probability of steel corrosion is higher

than 90% in the concrete area under -350 mV of HCP. While the electric potential in control decreases to the level of critical value (-350 mV) after 1.8 years, the others with impregnation show higher potential than -350 mV after 2 years as shown in Figure 7(d). The decrease ratios of measured electrical potential after 2 years are listed in Table 7. The effect of impregnation is shown to be most effective in atmospheric condition since the intruded silicate compound is not distilled and impeded by water intrusion and leaching out.

4.2.4. *Profiles of Total Chloride Contents.* In Figure 8 chloride profiles are shown for concrete in tidal and salt-sprayed conditions. Chloride profiles in the results show impregnated concrete have improved resistance to chloride penetration. Similarly as durability test results, I type impregnation with lower viscosity and surface tension shows better resistance than C type impregnation. With simplified regression

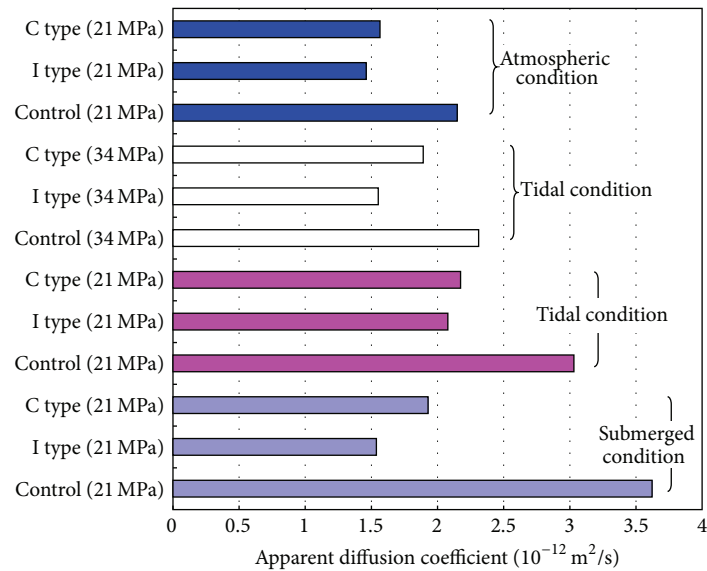


FIGURE 9: Derived apparent diffusion coefficient and surface chloride contents.

TABLE 7: Decrease ratio of electrical potential after 2 years.

Period (days)	Condition	Control	C type	I type
Decrease ratio of potential (21 MPa: %)				
720	Tidal	100.0	93.6	88.6
	Submerged	100.0	91.8	82.4
	Salt-sprayed	100.0	78.5	69.2
Decrease ratio of potential (34 MPa: %)				
720	Tidal	100.0	91.6	84.8

analysis, apparent diffusion coefficients are obtained and plotted in Figure 9. The effects of reduction ratio regarding apparent diffusion coefficient are 42.5–68.6% for I type impregnation and 53.2–72.9 for C type impregnation.

5. Concluding Remarks

The conclusions on evaluation of concrete durability performance with sodium silicate impregnants are as follows.

- (1) The surface-impregnated concrete shows marginal increase in compressive strength. For conservative repair design, it is reasonable not to consider the strength gaining in surface-impregnated concrete. The enhancement effects of surface impregnation are remarkably observed in reducing water permeability, absorption, and porosity.
- (2) I type (inorganic) impregnated concrete has slightly better resistance to chloride penetration than the C type (combined inorganic/organic) impregnated concrete due to lower viscosity and surface tension, which cause deeper impregnation depth. After 360 days, it is measured that the chloride penetration depths in impregnated concrete of 21 MPa decrease to 80.0~94.3% of those in control concrete under tidal

condition, 83.3~86.7% under submerged condition, and 58.3~75.0% under salt-sprayed condition, respectively.

- (3) After impregnation, the results of the electrical potential in concrete with 21 MPa and 34 MPa decrease to 69.2~91.8% and 84.8~91.6% of those in control concrete, respectively. The surface-impregnated concrete with 21 MPa shows similar durability performance as nonsurface-impregnated concrete with 34 MPa in electrical potentials for corrosion.
- (4) Through analysis on chloride profiles, apparent diffusion coefficients are reduced to 42.5~68.6% for I type impregnation and 53.2~72.9% for C type impregnation. The effect is smaller than reduction of permeability and porosity; however reasonable resistance to chloride attack can be obtained by simply spraying sodium silicate compound.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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