- Technical paper -

CORROSION PROPERTIES OF REINFORCED CONCRETE WITH TYPES OF SURFACE COATING UNDER THE COMBINED DETERIORATION ENVIRONMENTS

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ABSTRACT: This study is carried out to investigate corrosion properties of reinforced concrete due to permeation of deterioration factors such as CO_2 and chloride ion with covering depth and types of surface coating under the combined deterioration environments. In this study, combined deterioration environments including various factors such as carbonation, salt damage, and the repetition of drying-wetting and low-high temperatures were set up.
KEYWORDS: combined deterioration, carbonation velocity coefficients, chloride ion diffusion coefficients, corrosion velocity

1. INTRODUCTION

Durability evaluations to assess the deterioration of reinforced concrete structures in the present have been considered only individual deterioration factors such as salt damage and carbonation. Also, indoor accelerated experiments have not been able to realize the combined deterioration factors that actually affect real concrete structures [1, 2]. So, to establish the proper maintenance and rehabilitation methods of reinforced concrete structures that are subject to combined deterioration, a systematic study on combined deterioration is necessary [3].

Therefore, it is the aim of this study to compare individual deterioration test with combined deterioration test and to investigate the effect of the permeation of deterioration factors such as CO_2 and chloride ion on the corrosion properties of steel bars under the combined deterioration environments. After setting up various deterioration factors and levels such as carbonation, salt damage, and the repetition of drying-wetting and low-high temperatures, items such as carbonation velocity coefficients, chloride ion diffusion coefficients, corrosion velocity were measured and evaluated under the combined deterioration environments.

Consequently, the results of this study will be useful to provide fundamental data for the appropriate selection of repair and maintenance materials and the establishment of performance evaluation systems of reinforced concrete structures.

2. EXPERIMENTAL PROGRAM AND METHODS

2.1 EXPERIMENTAL PROGRAM

In this study, permeation of deterioration factors and corrosion properties with covering depth and types of surface coating were examined under the combined deterioration environments as shown in **Table 1.** experimental program consisted of series Ⅰ, Ⅱ and Ⅲ.

In series I, carbonation depth and chloride ion penetration depth in individual deterioration and combined deterioration environments were investigated respectively and their results were compared and evaluated. Under the individual deterioration environments, carbonation depth was measured by accelerated carbonation test recommended by A I J [4], and the chloride ion penetration depth was measured by the immersion test in 3% NaCl solution. Under the combined deterioration environments, the accelerated conditions and cycles including various factors such as carbonation, salt damage, and a repetition of drying-wetting and low-high temperature

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Table 1. Experimental program

Series	Types of surface coating	Deterioration environments	Covering depth (mm)	Measurement items	Measurement age (days)
I	▪ Non-treatment	▪ Individual deterioration ▪ Combined deterioration	-	▪ Carbonation depth (mm)	7, 28, 56
				▪ Chloride ion Penetration depth (mm)	56, 91
II	▪ Organic based A ▪ Organic based B ▪ Inorganic based A	▪ Combined deterioration	-	▪ Carbonation depth (mm) and Velocity coefficients (mm/√day) ▪ Chloride ion Penetration depth (mm) and Diffusion coefficients (cm²/sec)	10[1] 20 30
III	▪ Inorganic based B ▪ Non-treatment		10, 20	▪ Corrosion area ratio (%) ▪ Weight reduction ratio (%) ▪ Corrosion velocity (mg/cm²year)	40 50

1) Accelerated cycles in the combined deterioration environments (1cycle=2days)

Table 2. Factors and levels of the deterioration environments

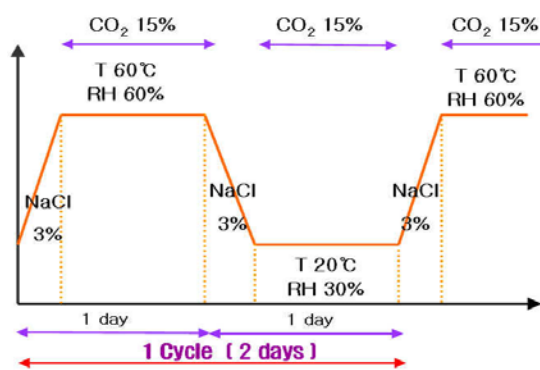| Series	Factors	Levels
I	▪ Carbonation	▪ Acceleration by CO_2 5% ▪ Humidity 50% ▪ Temperature 20℃
	▪ Salt damage	▪ Immersion in 3% NaCl solution ▪ Immersion - drying repetition in 3% NaCl solution
II III	▪ Carbonation	▪ Acceleration by CO_2 15%
	▪ Salt damage	▪ Spray by 3% NaCl solution
	▪ Humidity	▪ Setting up from 30% to 60%
	▪ Temperature	▪ Setting up from 20℃ to 60℃

Fig. 1 Accelerated conditions and cycles for combined deterioration environments
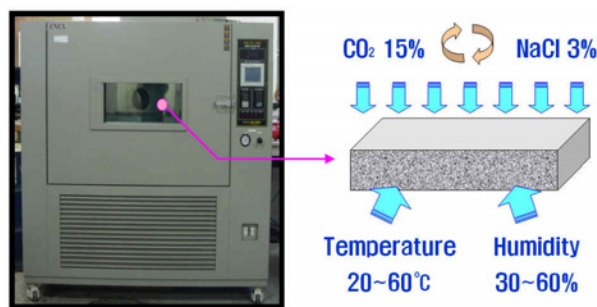

Photo 1. Combined deterioration chamber

were set up **(Table 2 and Fig.1)**. Then, the carbonation depth and the chloride ion penetration depth were measured using a combined deterioration chamber as shown in Photo 1.

In series II, permeation of deterioration factors such as CO_2 and chloride ion into the interior of concrete was measured and analyzed under the combined deterioration environments.

In series III, corrosion properties of steel bar such as corrosion area ratio, weight reduction ratio and corrosion velocity of steel bar at each cycle were measured and analyzed under the combined deterioration environments. And the correlation between permeation of deterioration factors of concrete and corrosion of steel bar was analyzed.

2.2 MIX PROPORTION OF CONCRETE AND MATERIALS

The mix proportion of concrete is shown in **Table 3** and physical properties of using materials, chemical properties of surface coating materials and method of coating are shown in **Table 4, 5.** The Ø19mm round steel bar was cleaned with No. 800 sandpaper, and then inserted into the concrete specimens.

2.3 MANUFACTURE OF SPECIMENS AND TEST METHODS

Non-treatment specimen with size of 75×100×400 mm was manufactured and subjected to the following tests: the accelerated carbonation test, the immersion test and the immersion-drying repetition test in 3% NaCl solution under the individual deterioration environments.

Table 3. Mix proportion of concrete

W/C (%)	S/a (%)	Unit Weight (kg/m³)			
		Water	Cement	Sand	Gravel
60	43	185	308	778	1048

Table 4. Physical properties of materials

Materials	Physical properties
▪ Sand	▪ Sea sand, Specific gravity 2.6
▪ Gravel	▪ Crushed stone, Specific gravity 2.6
▪ Cement	▪ O.P.C., Specific gravity 3.1

Table 5. Chemical properties of surface Coating materials and method of coating

| Kinds of surface coating materials	Chemical properties	Thickness and method of coating
▪ Organic based A	▪ Acrylic emulsion type-1, water-soluble paint	▪ Two times by 0.5 mm
▪ Organic based B	▪ Acrylic emulsion type-2, water-soluble paint	▪ Two times by 0.5 mm
▪ Inorganic based A	▪ Acrylic copolymer redispersion type powder resin	▪ A time by 2 mm
▪ Inorganic based B	▪ Siliceous based, Coating material	▪ Two times by 0.5 mm
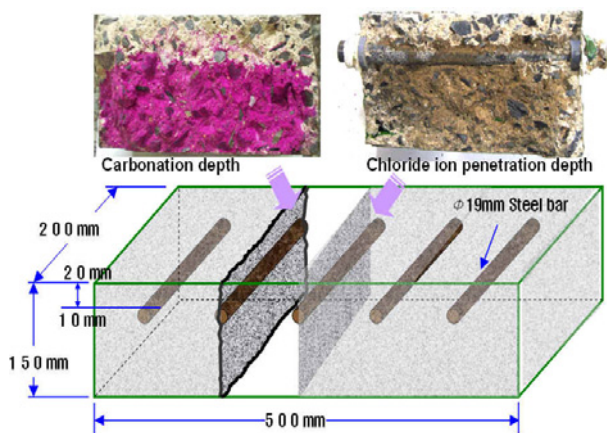
Fig. 2   Specimen for measuring corrosion velocity

$$C = A\sqrt{t} \qquad \text{------------------------} \quad \textbf{Eq.(1)}$$

where, C : Carbonation depth (mm)
   A : Velocity coefficient (mm/√day)
   t : Time (days)

$$C_{(x,t)} = C_i + (C_0 - C_i) \cdot erf\left(\frac{x}{2\sqrt{D_e t}}\right) \text{----} \quad \textbf{Eq.(2)}$$

Initial condition : 0, x > 0, t=0
Boundary condition : C_0, x=0, t > 0

where, C_0 : Concentration at the surface (%)
   $C_{(x,t)}$: Concentration at depth X after time t (%)
   C_i : Initial concentration in concrete (%)

$$Wrs(\%) = \frac{Iws - Aws}{Iws} \times 100 \qquad \text{---------} \quad \textbf{Eq.(3)}$$

where, Wrs : Weight reduction ratio (%)
   Iws : Intial weight of steel bar (mg)
   Aws : Weight of steel bar after corrosion removal (mg)

$$Cv = \frac{Wr}{As \times Tp} \qquad \text{--------------------} \quad \textbf{Eq.(4)}$$

where, Cv : Corrosion velocity (mg/cm²year)
   Wr : Weight reduction (mg)
   As : Area of steel bar (cm²)
   Tp : Testing period (year)

Fig.2 shows the 150×200×500 mm concrete specimen with a Ø19 mm steel bar manufactured for the measurement of carbonation depth, carbonation velocity coefficients, chloride ion penetration depth, chloride ion diffusion coefficients, corrosion area ratio, weight reduction ratio, and corrosion velocity of steel bar under the combined deterioration environments. The remaining surface besides measuring surface of specimens were coated with epoxy resin to ensure that the chloride ion and CO_2 could only diffuse into measuring surface.

The carbonation velocity coefficients were calculated using **Eq.(1)**. And chloride ion diffusion coefficients were calculated using **Eq.(2)** recommended by Browne, Crank and Laylor [5]. In the present case, the chloride ion penetration depth was evaluated by 0.1N $AgNO_3$ indicator on the split surface of the concrete specimen. It is assumed that C_0 corresponds to the amount of acid-soluble chlorides at the 0 to 3 mm depth interval determined by JCI-SC 4 method.

The corrosion area was estimated by sketching the corrosive region using tracing paper. The weight reduction ratio of steel bar was calculated using **Eq.(3)**. And the corrosion velocity was calculated using **Eq.(4)**.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 CARBONATION DEPTH AND CHLORIDE ION PENETRATION DEPTH IN SERIES I

Fig.3 and **Fig.4** show the variation of the carbonation depth and chloride ion penetration depth by the progression of individual and combined deterioration. Carbonation depth of the combined deterioration condition was greater by 3.8 mm than that of the individual
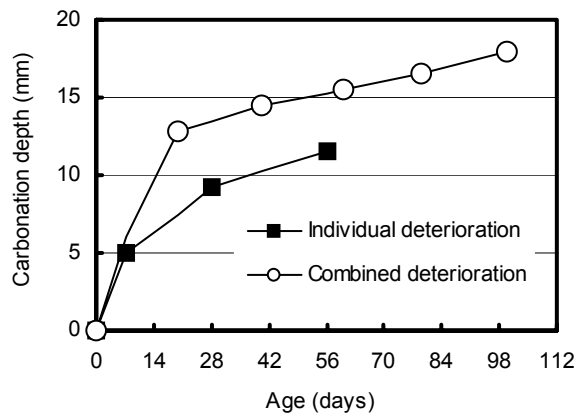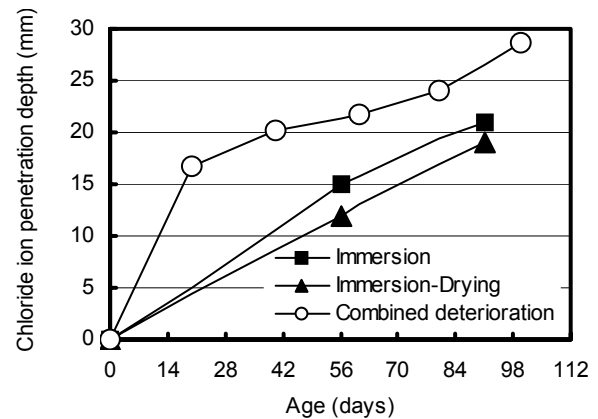
Fig.3 Carbonation depth with age

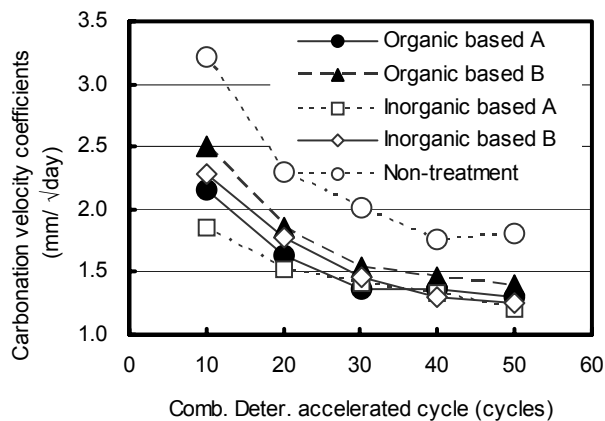**Fig.4 Chloride ion penetration depth with age**

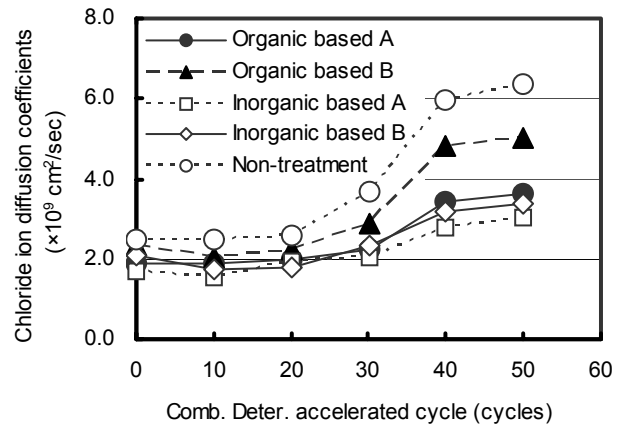**Fig.5 Carbonation velocity coefficients with combined deterioration accelerated cycle**

Fig.6 Chloride ion diffusion coefficients with combined deterioration accelerated cycle

deterioration condition at 56days. And the chloride ion penetration depth of the combined deterioration condition was greater by 5.5 mm and 7.5 mm than that of the immersion and immersion-drying test at 91 days, respectively.

3.2 PERMEATION OF DETERIORATION FACTORS IN SERIES Ⅱ

Fig.5 shows the variation of the carbonation velocity coefficients with the combined deterioration cycles, for different types of surface coating. As shown in the **Fig.5**, the carbonation velocity coefficients decrease as the deterioration cycle elapses. It is assumed that this behavior is due to calculating method of carbonation velocity coefficients being directly proportional to carbonation depth **C**, and inversely proportional to time $\sqrt{t}$.

For different types of surface coating, the variation of the chloride ion diffusion coefficients with respect to the combined deterioration cycles is shown in **Fig.6**. It shows that permeation of deterioration factors increases as the deterioration cycle elapses. The behavior can be attributed to the fact that surface coating materials are deteriorated by combined deterioration making it easier for deterioration factors to penetrate into the interior of concrete. The magnitudes of the chloride ion diffusion coefficients in the same cycle were in the following order: Non-treatment > Organic based B > Organic based A > Inorganic based B > Inorganic based A. The results indicate that permeation of deterioration factors can be reduced by the surface coating comparing with Non-treatment.

3.3 CORROSION PROPERTIES OF STEEL BAR IN SERIES Ⅲ
(1) Corrosion area ratio, weight reduction ratio and corrosion velocity of steel bar

Fig.7 and **Fig.8** show that the corrosion area ratio and weight reduction ratio increase as the cycle progresses. At the same cycles, the observed order was: Non-treatment > Organic based B
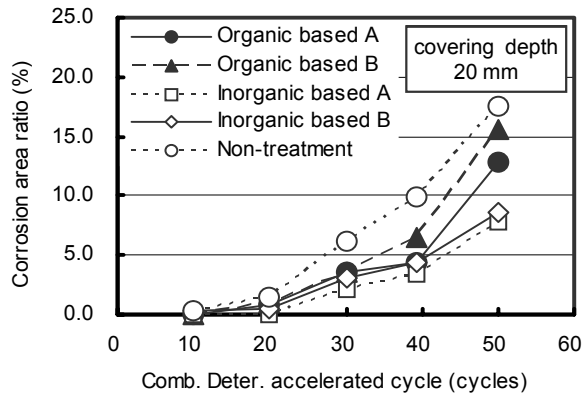
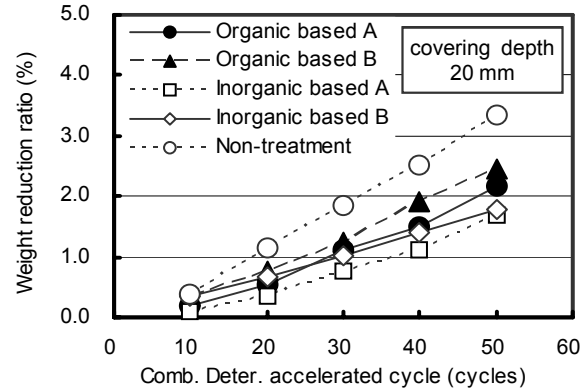**Fig.7 Corrosion area ratio with combined deterioration accelerated cycle**

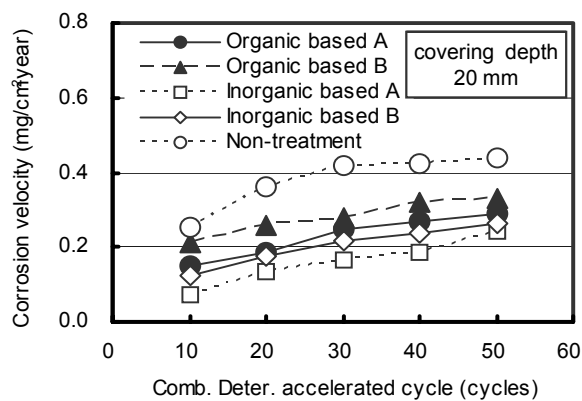**Fig.8 Weight reduction ratio with combined deterioration accelerated cycle**

Fig.9 Corrosion velocity with combined deterioration accelerated cycle
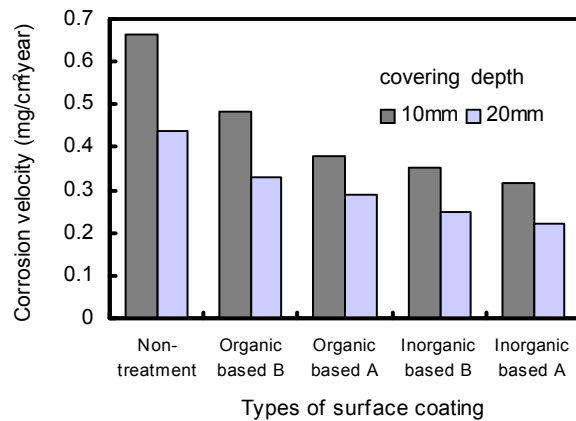

Fig.10 Corrosion velocity with types of surface cover and covering depth at 50 cycles

> Organic based A > Inorganic based B > Inorganic based A. The results indicate that corrosion of steel bar can be reduced by surface coating.

The corrosion velocity of steel bar with different types of surface coating applied to 20 mm of covering depth is shown in **Fig.9**. It shows the tendency that the corrosion velocity increase as the deterioration cycles progress, and the corrosion velocity of steel bar becomes constant value after 30 cycles. These results may be used as the fundamental data for the establishment of lifecycle prediction techniques of reinforced concrete structures through the further studying in the future. For instance, the generation time of corrosion crack can be predicted by the assessment of the corrosion velocity of steel bar of reinforced concrete structures under the combined deterioration environments.

As shown in **Fig.10**, the corrosion velocity of steel bar with different types of surface coating and covering depth at the 50 cycles of the combined deterioration process is seen to decrease in accordance with applying of surface coating and increasing of covering depth. Comparing to the Non-treatment specimen with covering depth of 10 mm, the corrosion velocity of the specimen applied with Inorganic based A was reduced by 52.5%. For the covering depth of 20 mm, the reduction ratio of corrosion velocity was 33.5%. These results suggest that the corrosion velocity of steel bar can be reduced by the application of appropriate surface coating and the security of enough covering depth.

(2) The correlation between carbonation depth and corrosion velocity of steel bar, and chloride ion penetration depth and corrosion velocity of steel bar

Fig.11 and **Fig.12** show the correlation between corrosion velocity of steel bar and carbonation depth, and corrosion velocity of steel bar and chloride ion penetration depth, respectively, for concrete specimen with covering depth of 10 mm. It shows that the corrosion velocity increases as the carbonation depth and the chloride ion penetration depth increase
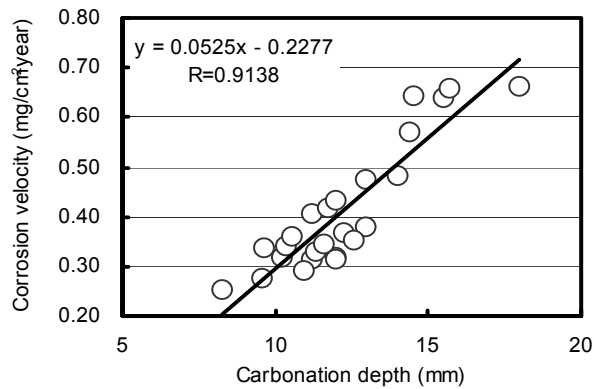
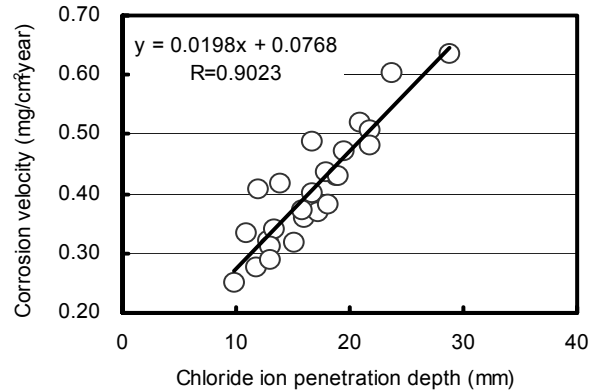**Fig.11 Correlation between carbonation depth and corrosion velocity**

Fig.12 Correlation between chloride ion penetration depth and corrosion velocity

respectively. Especially, the corrosion velocity rapidly increases when the carbonation depth and chloride ion penetration depth exceed the covering depth by 10 mm. The correlation coefficients between the carbonation depth and the corrosion velocity, and the chloride ion penetration depth and the corrosion velocity are 0.9138 and 0.9023 respectively, both showing significant correlations.

4. CONCLUSIONS

Based on the results performed in the scope of this study, the following conclusions can be drawn.
1. The accelerated combined deterioration test including carbonation, salt damage, and repetition of drying-wetting and low-high temperatures resulted in deteriorated durability of concrete comparing with the accelerated individual deterioration test.
2. Comparing with Non-treatment, resistance to permeation of deterioration factors such as carbonation and salt damage into the interior of concrete is improved and corrosion velocity is reduced by surface coating. And it was confirmed that the corrosion of steel bar progressed rapidly when the carbonation depth and the chloride ion penetration depth exceeded the covering depth.
3. The findings of this study may be used as the fundamental data for the establishment of life cycle prediction techniques such as predicting generation time of corrosion crack by the assessment of the corrosion velocity of reinforced concrete structures under the combined deterioration environments with further studies.

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