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Chloride Penetration Resistance of Concrete Containing Supplementary Cementitious Materials: Laboratory Experiments and Field Tests

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ABSTRACT

The chloride penetration resistance of concrete containing supplementary cementitious materials (SCMs) was investigated by conducting laboratory experiments and field tests. Twelve types of concrete specimens were fabricated with and without SCMs, such as ground granulated blast-furnace slag and fly ash, and subsequently used for immersion, non-steady-state migration, and outdoor exposure tests. The test results of the immersion and non-steady-state migration tests indicate that the use of SCMs contributes to the improvement in the chloride penetration resistance of concrete. In contrast, the results obtained from the outdoor exposure test indicate that the chloride penetration resistance of concrete is influenced by not only the use of SCMs, but also the progress of carbonation at the concrete surface. The concrete specimens containing high-volume SCMs showed large chloride penetration depths due to the progress of carbonation at the concrete surface.

INTRODUCTION

The use of supplementary cementitious materials (SCMs) is generally deemed to improve the chloride penetration resistance of concrete. This advantage of concrete containing SCMs has been confirmed by laboratory experiments and field tests globally [Gjørv 2014; Tang 2013; Thomas et al. 2011]. A further benefit of the use of SCMs is to reduce carbon dioxide emissions in concrete construction by replacing Portland cement [Sakai and Noguchi 2013]. These two properties of concrete containing SCMs have captured a great deal of attention regarding the sustainable use of concrete structures in the last several decades.

The chloride penetration resistance of concrete containing high-volume SCMs has, however, not been fully clarified in the real environment. Additionally, it is not well known whether conventional laboratory experiments, such as the immersion and non-steady-state migration tests, are applicable to the evaluation of the chloride penetration resistance of concrete containing high-volume SCMs. A clear understanding of the relationship between the test results derived from the laboratory experiments and those obtained by the field tests is indispensable for the utilization of concrete containing high-volume SCMs.

The purpose of the experimental program presented in this paper is to investigate the chloride penetration resistance of concrete containing high-volume SCMs by conducting laboratory experiments and field tests. Twelve types of concrete specimens were fabricated with and without SCMs, such as ground granulated blast-furnace slag (GGBF slag) and fly ash, and subsequently used for the immersion, non-steady-state migration, and outdoor exposure tests. The applicability of the conventional laboratory experiments and the chloride penetration resistance of concrete containing high-volume SCMs in the real environment are critically discussed on the basis of the test results.

EXPERIMENTAL PROGRAM

Concrete mixtures

Twelve types of concrete mixtures with and without SCMs, such as GGBF slag and fly ash, were adopted for the concrete specimens used for the laboratory experiments and the field tests. The concrete mixtures and properties are shown in Table 1. The water-to-binder ratios of the specimens are 35% and 50%. The maximum replacement ratios of GGBF slag and fly ash are 85% and 40%, respectively. The dosages of chemical admixtures were adjusted to satisfy the target values of slump and air content, 120 ± 25 mm and 4.5 ± 1.5%, respectively.

Table 1. Concrete Mixtures and Properties

Mix No.	W/B (%)	Content (kg/m^3)						Slump (mm)	Air (%)	Compressive strength (N/mm^2)
		W	B = OPC + GGBFS+ FA			S	G			
			OPC	GGBFS	FA					
N35	35	165	471 (100%)	—	—	713	968	145	4.7	67.7
N35B50			236 (50%)	236 (50%)	—	695		145	4.3	55.8
N35B85			71 (15%)	401 (85%)	—	682		125	5.1	34.3
N35F20			377 (80%)	—	94 (20%)	684		120	3.5	59.3
N35F40			283 (60%)	—	189 (40%)	655		145	4.5	41.6
N50	50		330 (100%)	—	—	827		140	5.2	44.9
N50B50			165 (50%)	165 (50%)	—	815		135	4.3	36.3
N50B70			99 (30%)	231 (70%)	—	810		125	4.5	30.5
N50B85			50 (15%)	281 (85%)	—	806		115	4.0	21.2
N50F20			264 (80%)	—	66 (20%)	807		115	4.4	37.4
N50F30			231 (70%)	—	99 (30%)	797		110	4.6	30.0
N50F40			198 (60%)	—	132 (40%)	787		145	4.0	22.9

Note: W: tap water, B: binder, OPC: ordinary Portland cement (3.16 g/cm^3, 3300 cm^2/g), GGBFS: ground granulated blast-furnace slag (2.89 g/cm^3, 4210 cm^2/g), FA: fly ash (2.30 g/cm^3, 4280 cm^2/g), S: fine aggregate (2.56 g/cm^3), G: coarse aggregate (2.67 g/cm^3).

The specimens were fabricated in a laboratory at a room temperature of 20°C and humidity of 60%, and cured in water at a temperature of 20°C for 28 days. The compressive strength was measured after 28 days by using concrete cylinders (φ100 × 200 mm). Following the water curing procedure, the specimens were brought to the laboratory for experimentation and the field for testing.

Immersion test

The immersion test was conducted in accordance with the JSCE-G 572 standard [JSCE 2013]. After the concrete cylinders (φ100 × 200 mm) were cured in water at a temperature of 20°C for 28 days, they were shaped into 150-mm-thick cylinders by cutting off a 25-mm-thick disk from both the top and bottom. The bottom and side surfaces of the shaped cylinders were sealed with epoxy resin to prevent chloride penetration. The sealed cylinders were immersed in saline solution with a NaCl concentration of 10% for 6, 12, and 20 months. Then, the cylinders were sliced into 10-mm-thick disks from the top surface and the chloride content of each disk was measured to obtain the chloride profiles.

The chloride diffusion coefficient, D_{ap}, and the surface chloride content, C_0, were determined by curve-fitting of the chloride profiles to the following equation, which is one of the solutions to Fick’s second law:

$$C(x,t) = (C_0 - C_i)\left\{1 - erf\left(\frac{x}{2\sqrt{D_{ap}t}}\right)\right\} + C_i \tag{1}$$

where $C(x,t)$ is the chloride content (kg/m^3) measured at depth x (m) and time t (s), C_i is the initial total chloride content (kg/m^3), C_0 is the surface chloride content (kg/m^3), x is the depth (m), D_{ap} is the chloride diffusion coefficient (m^2/s), and t is the test duration (s).

Non-steady-state migration test

The non-steady-state migration test was conducted on the basis of NT BUILD 492 [NORDTEST 1999] and AASHTO TP 64 [AASHTO 2007]. The chloride penetration depths measured during the non-steady-state migration tests at ages of 28 days, 1 year, and 3 years were used to investigate the long-term transition in the chloride penetration resistance of concrete.

Concrete cylinders (φ100 × 100 mm) were cured in water at a temperature of 20°C for 28 days and subsequently exposed at the outdoor exposure test site of the Public Works Research Institute until shortly before the test. This test site is located inland where no airborne salt is in contact with the cylinders. Slices 50-mm-thick cut from the center of the cylinders were used for the non-steady-state migration tests. The side surface of the slice was sealed with epoxy resin to prevent chloride migration from any source other than a test surface. Then, the slices were placed in a desiccator, depressurized with a vacuum pump for three hours, saturated with deionized water, and kept still for more than 24 hours. The saturated slices were installed in the same apparatus as that specified in ASTM C 1202 [ASTM 2010]. According to NT BUILD 492, a 10% NaCl solution was employed as the catholyte solution, and a 0.3 mol/L NaOH solution was used as the anolyte solution. A voltage of 30 V was applied to the slices using a DC power supply in a laboratory at a room temperature of 20°C for 6 hours. Upon completion of the test, the slice was split axially and a 0.1 mol/L silver nitrate solution was sprayed on the split surface to measure the chloride penetration depth at nine equally spaced points.

Outdoor exposure test

The setup of the outdoor exposure test site and a schematic of the exposed concrete specimen (100 × 100 × 200 mm) are presented in figure 1 and figure 2, respectively. Because this test site is located along a coastline in Okinawa prefecture, Japan, a significant amount of airborne salt is in contact with the specimens. After the completion of the 28-day water curing procedure, five surfaces of the specimen, excluding the exposed side surface (100 × 200 mm), were sealed with a durable coating material to prevent chloride penetration and carbonation from any source other than the exposed side surface. The specimens were collected approximately 40 months after test initiation, and subsequently used to measure carbonation depths and chloride profiles. The carbonation depths were measured by spraying a phenolphthalein solution on the split surface of the specimens. The chloride profiles were obtained by measuring the chloride content of the specimens sliced at seven layers: 0 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 25, 25 to 30, and 30 to 40 mm from the surface.

Average temperature: 22.4°C, Average ambient humidity: 74.5%, Total amount of precipitation: 7,828 mm
Note: The climate information is based on data released by the Japan Meteorological Agency.

Figure 1. Setup of Outdoor Exposure Test Site

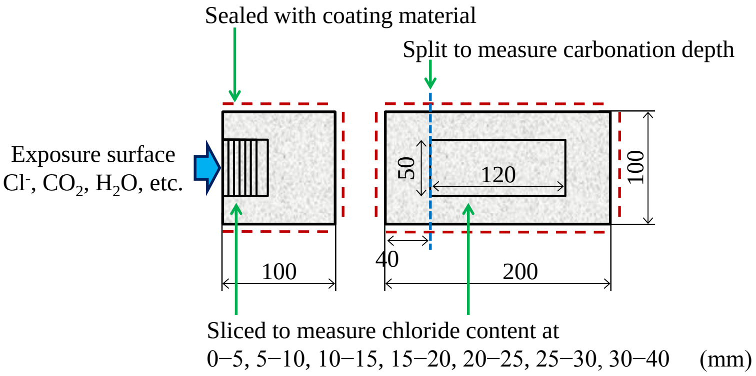


Figure 2. Schematic of Exposed Concrete Specimen

RESULTS AND DISCUSSION

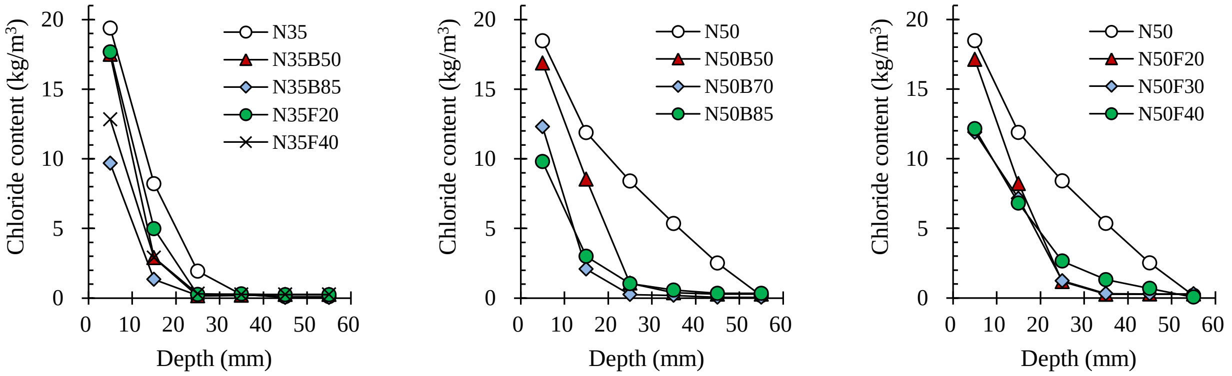
Chloride penetration resistance of concrete in laboratory experiments

The chloride profiles of the specimens after the 20-month immersion test are illustrated in figure 3. It is clear that the chloride penetration of the specimens containing SCMs are lower than those of the specimens fabricated with only ordinary Portland cement. This trend is clear in the chloride profiles of the specimens containing high-volume GGBF slag, such as N35B85, N50B70, and N50B85. It should further be noted that the decrease in the chloride penetrations due to the use of SCMs is larger than that obtained by reducing the water-to-binder ratio. Therefore, the use of SCMs is deemed to contribute to the substantial improvement in the chloride penetration resistance of concrete.

The chloride diffusion coefficients and the surface chloride contents of the specimens after 6-, 12-, and 20-month immersion tests are presented in figure 4 and figure 5, respectively. The chloride diffusion coefficients and the surface chloride contents were computed in accordance with Eq. (1). The chloride diffusion coefficients of the specimens containing SCMs are lower than those of the specimens fabricated with only ordinary Portland cement. It should further be stressed that the chloride diffusion coefficients of the specimens containing fly ash decrease as the testing period is prolonged. The reason for this phenomenon is the assumption that the pozzolanic reaction of fly ash results in long-term improvement in the chloride penetration resistance of concrete. Additionally, the surface chloride contents of the specimens containing high-volume GGBF slag, such as N35B85 and N50B85, were lower than those of the specimens fabricated only with ordinary Portland cement. The use of high-volume GGBF slag is assumed to contribute to the development of dense pore structures and the prevention of chloride penetration into concrete.

The chloride penetration depths of the specimens after the non-steady-state migration test at ages of 28 days, 1 year, and 3 years are shown in figure 6. Those of the specimens containing SCMs decrease as the testing age is extended. The decrease in the chloride penetration depths is prominent in the specimens containing fly ash; the chloride penetration depths of the specimens containing fly ash are larger than those of the specimens fabricated with only ordinary Portland cement at the age of 28 days, but substantially lower at the age of 1 year and 3 years.

The test results derived from the immersion and the non-steady-state migration test show that the use of SCMs contributes to the improvement in the chloride penetration resistance of concrete, although these two laboratory experiments are based on different rationales. Additionally, both test results indicate that the use of fly ash is beneficial for a time-dependent improvement in the chloride penetration resistance of concrete.



(A)W/B = 35%   (B)W/B = 50%, GGBF slag   (C)W/B = 50%, Fly ash

Figure 3. Chloride Profiles after 20-month Immersion Test

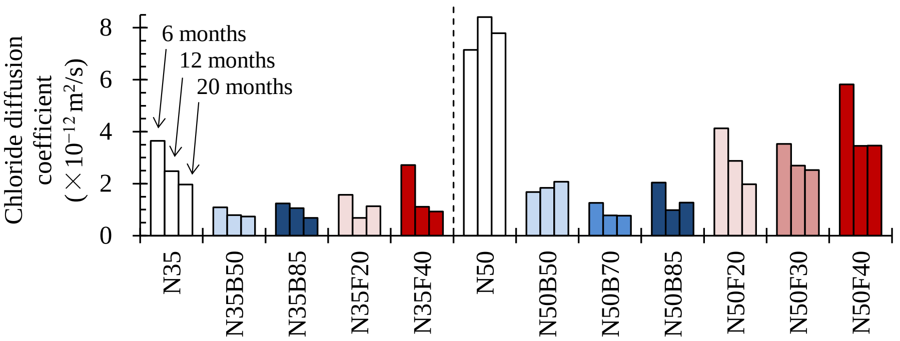


Figure 4. Chloride Diffusion Coefficients after Immersion Test

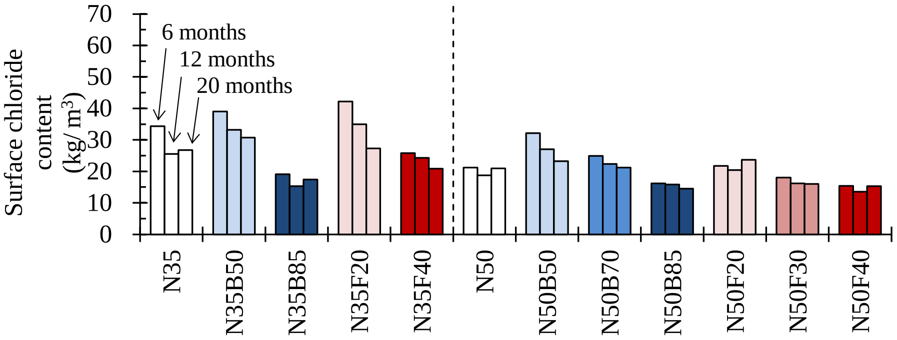


Figure 5. Surface Chloride Contents after Immersion Test

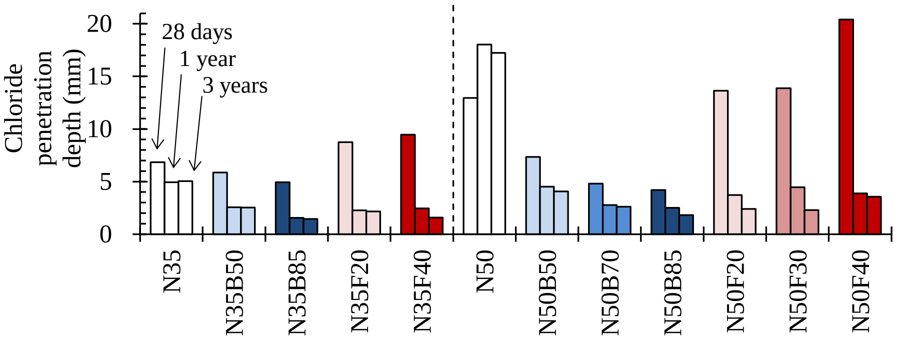


Figure 6. Chloride Penetration Depths after Non-steady-state Migration Test

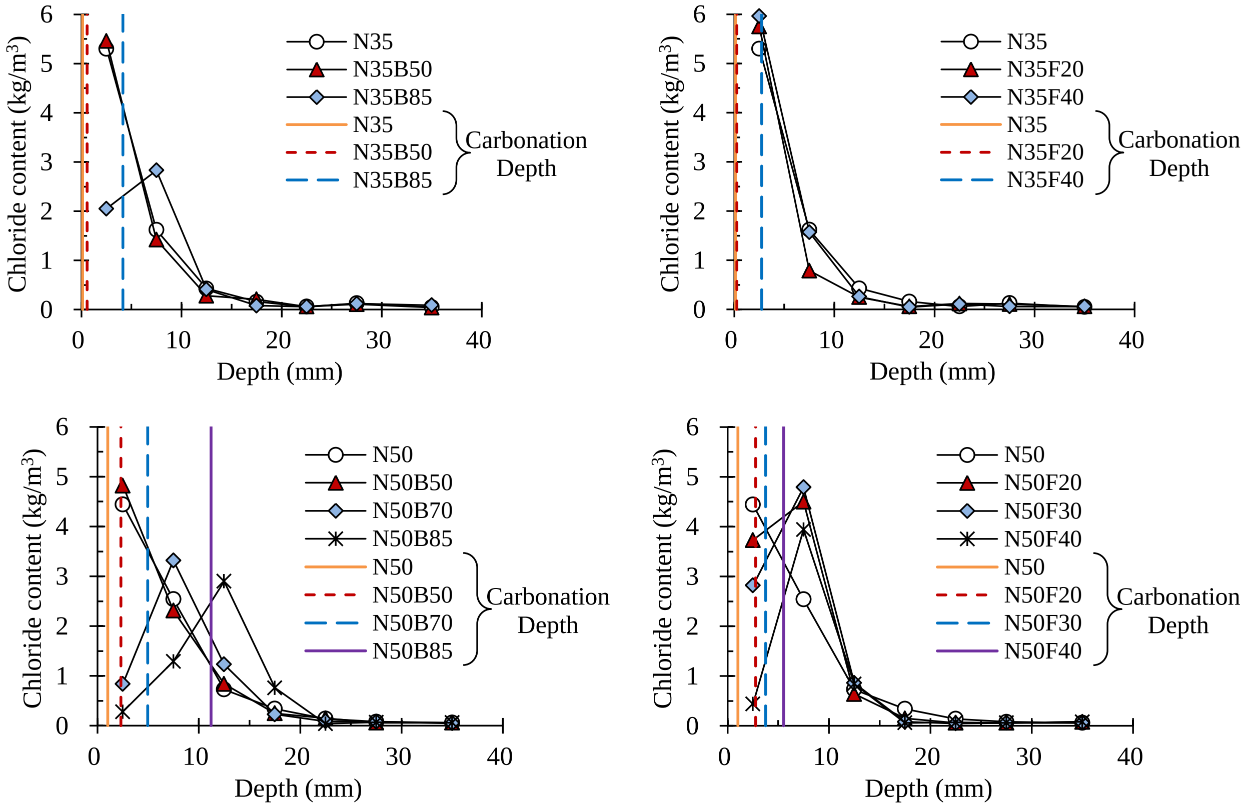
Chloride penetration resistance of concrete in field tests

The carbonation depths and the chloride profiles of the specimens after the 40-month outdoor exposure test are shown in figure 7. The carbonation depths of the specimens containing SCMs are larger than those of the specimens fabricated with only ordinary Portland cement. In a comparison of the specimens containing the same type of SCMs, the carbonation depths increase in specimens with an increase in the replacement ratio of GGBF slag or fly ash. It is reasonable to deem that the carbonation resistance of concrete is impaired owing to the use of SCMs in the real environment.

On the basis of the relationship between the carbonation depths and the chloride profiles, the large carbonation depths of the specimens containing high-volume SCMs has a substantial influence on the chloride profiles; the chloride content at the outmost layer of the specimens is lower than that inside the specimens. This inverse relationship rules out computing the chloride diffusion coefficients of the specimens containing high-volume SCMs. Additionally, the chloride contents of the specimens containing high-volume SCMs, such as N35B85, N50B70, N50B85, N50F30, and N50F40, are larger than those of the specimens fabricated with only ordinary Portland cement at depths of 5 mm to 15 mm from the concrete surface. In addition, a similar phenomenon was confirmed in the test results after the 20-month outdoor exposure test [Nakamura and Watanabe 2015].

This adverse influence of carbonation on the chloride profiles is, however, inhibited by reducing the water-to-binder ratio because the carbonation depths decrease in the specimens with low water-to-binder ratios. It should be emphasized that the reduction in this ratio is one of the solutions to prevent the progress of both carbonation and chloride penetration in concrete containing high-volume SCMs.

As mentioned in the previous section, the test results derived from the immersion and non-steady-migration tests show that the use of SCMs contribute to improving the chloride penetration resistance of concrete. In contrast, the results obtained from the outdoor exposure test show that the chloride penetration resistance of concrete containing high-volume SCMs is substantially influenced by the progress of carbonation at the concrete surface in the real environment. Therefore, it is strongly recommended that the influence of carbonation on the chloride profiles be considered in the evaluation of the chloride penetration resistance of concrete containing high-volume SCMs in the real environment where carbonation and chloride penetration progress simultaneously.



(C)W/B = 50%, GGBF Slag

(D)W/B = 50%, Fly ash

Figure 7. Carbonation Depths and Chloride Profiles after Outdoor Exposure Test

CONCLUSION

The conclusions derived from this experimental program are summarized as follows:

1. The results derived from the immersion and non-steady-state migration tests show that the use of SCMs contributed substantially to the improvement in the chloride penetration resistance of concrete. The improvement in the chloride penetration resistance of concrete because of the use of SCMs surpassed that provided by the reduction in the water-to-binder ratio.

2. The chloride diffusion coefficients of the immersion test, and the chloride penetration depths of the non-steady-state migration test, indicated that the use of fly ash was beneficial for a time-dependent improvement in the chloride penetration resistance of concrete.

3. The test results obtained from the 40-month outdoor exposure test indicate that the chloride profiles of the concrete specimens containing high-volume SCMs were influenced by carbonation at the concrete surface. The influence of carbonation on the chloride profiles should be considered in the evaluation of the chloride penetration resistance of concrete containing high-volume SCMs in the real environment where carbonation and chloride penetration progress simultaneously.

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