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# CHLORIDE MIGRATION COEFFICIENT AND RESISTIVITY OF CONCRETE CONTAINING SUPPLEMENTARY CEMENTITIOUS MATERIALS

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## ABSTRACT

This paper presents experimental results of the non-steady-state migration test and the resistivity test for simple and rapid evaluation of the chloride ingress resistance of concrete containing supplementary cementitious materials. Concrete specimens were fabricated incorporating blast furnace slag and fly ash in a laboratory and a precast concrete plant, and subsequently subjected to the non-steady-state migration test and the resistivity test. The experimental results indicated that there was a good correlation between the results derived from the two tests; both sets of results exhibited the enhanced chloride ingress resistance of concrete containing blast furnace slag and fly ash. The non-steady-state migration test was found applicable to obtaining the chloride migration coefficient and its time-dependent development. Additionally, the resistivity test was demonstrated to be a simple and rapid method to verify the chloride ingress resistance of precast prestressed concrete elements.

**Keywords:** Chloride migration coefficient, resistivity, concrete.

## INTRODUCTION

The use of supplementary cementitious materials contributes to the utilization of by-products in concrete construction and improves the chloride ingress resistance of concrete. In the last several decades, new test methods, such as the non-steady-state migration test (NT BUILD 492, AASHTO TP 64) and the resistivity test (AASHTO T 358, JSCE-G 581), have been developed for the simple and rapid evaluation of the chloride ingress resistance of concrete. However, more experimental data are needed to verify the applicability of these test methods to concrete containing supplementary cementitious materials, such as blast furnace slag and fly ash.

The purpose of the experimental program presented in this paper was to clarify the applicability of the non-steady-state migration test and the resistivity test to the simple and rapid evaluation of the chloride ingress resistance of concrete containing blast furnace slag and fly ash. Concrete specimens were fabricated incorporating blast furnace slag and fly ash in a laboratory and a precast concrete plant, and subsequently subjected to the non-steady-state migration test and the resistivity test.

## EXPERIMENTAL PROCEDURES

### Concrete Mixtures and Properties

Ten types of concrete mixtures with and without blast furnace slag and fly ash were employed for the fabrication of concrete specimens in the laboratory and the precast concrete plant. The concrete mixtures and properties for the laboratory experiment and the plant experiment are shown in Tables 1 and 2, respectively. Because all concrete mixtures were assumed to be adopted for the precast prestressed concrete elements, the water-to-binder ratios were in the range of 33 to 36%, and high-early-strength Portland cement was used. The replacement percentages of ground-granulated blast furnace (GGBF) slag and fly ash to high-early-strength Portland cement were set to the range of 30 to 50% and 20%, respectively. The mix percentages of blast furnace slag sand to fine aggregate were set to the ranges of 30 to 100%. The dosages of chemical admixtures were adjusted to satisfy the target values of slump and air content, 8.0 to 14.0 cm and 4.5 to 6.0%, respectively.

Table 1. Concrete mixtures and properties for laboratory experiment

| No. | W/B (%) | Content (kg/m$^3$) | | | | | | | | | Slump (cm) | Air (%) | Compressive Strength (N/mm$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | W | B = H + SG4 + SG6 + FA | | | | S | BFS | G | | | | |
| | | | H | SG4 | SG6 | FA | | | | | | | |
| STD | 36 | 165 | 458 | — | — | — | 721 | — | 968 | | 12.0 | 5.3 | 65.3 |
| SG430 | | | 321 | 138 (30%) | — | — | 712 | — | | | 10.0 | 5.9 | 60.5 |
| SG650 | | | 229 | — | 229 (50%) | — | 707 | — | | | 12.0 | 5.0 | 69.4 |
| FA20 | | | 367 | — | — | 92 (20%) | 696 | — | | | 8.0 | 4.8 | 60.6 |
| BFS30 | | | 458 | — | — | — | 505 | 227 (30%) | | | 9.0 | 5.4 | 67.8 |
| BFS5 | | | | — | — | — | 36 | 379 | | | 11.5 | 5. | 67.9 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | | | | | | | 1 | (50%) | | | 2 | |
| BFS70 | | | | — | — | — | 216 | 531 (70%) | | 13.0 | 5.0 | 68.7 |
| BFS100 | | | | — | — | — | — | 758 (100%) | | 13.0 | 5.3 | 68.7 |

Note 1: W: tap water, B: binder, H: high-early-strength Portland cement (3.14 g/cm$^3$, 4480 cm$^2$/g), SG4: ground-granulated blast furnace slag (2.89 g/cm$^3$, 4350 cm$^2$/g), SG6: ground-granulated blast furnace slag (2.91 g/cm$^3$, 6210 cm$^2$/g), FA: fly ash (2.35 g/cm$^3$, 4330 cm$^2$/g), S: fine aggregate (natural sand, 2.56 g/cm$^3$), BFS: blast furnace slag sand (2.69 g/cm$^3$), G: coarse aggregate (2.67 g/cm$^3$).
Note 2: The numbers in parentheses are the percentages by mass of ground-granulated blast furnace slag and fly ash to binder, and those by volume of blast furnace slag sand to fine aggregate.
Note 3: The compressive strength was measured at the age of 28 days by using three cylinders (φ100 × 200 mm).

Table 2. Concrete mixtures and properties for plant experiment

| No. | W/B (%) | Content (kg/m$^3$) | | | | | Slump (cm) | Air (%) | Temperature (°C) | Compressive Strength (N/mm$^2$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | W | B = H + SG6 | | S | G | | | | 1 day | 28 days |
| | | | H | SG6 | | | | | | | |
| STD-P | 36 | 152 | 422 | — | 753 | 1024 | 13.0 | 3.4 | 22 | 51.4 | 71.1 |
| SG650-P | 33 | 150 | 227 | 227 (50%) | 766 | 972 | 11.0 | 4.0 | 21 | 46.8 | 71.1 |

Note 1: W: tap water, B: binder, H: high-early-strength Portland cement (3.14 g/cm$^3$, 4560 cm$^2$/g), SG6: ground-granulated blast furnace slag (2.87 g/cm$^3$, 6060 cm$^2$/g), S: fine aggregate (natural sand, 2.67 g/cm$^3$), G: coarse aggregate (2.64 g/cm$^3$).
Note 2: The number in parenthesis is the percentage by mass of ground-granulated blast furnace slag to binder.
Note 3: The compressive strength was measured at the age of 1 day after steam curing and 28 days after steam curing and atmospheric curing by using three cylinders (φ100 × 200 mm).

**Concrete Specimens**

The specimens for the laboratory experiment were cylinders (φ100 × 200 mm), which were fabricated in the laboratory at a room temperature of 20 °C and humidity of 60%. They were subsequently cured in water at 20 °C starting the day after casting of concrete. The cylinders were subjected to the non-steady-state migration test and the resistivity test immediately after the water curing to ensure that the cylinders were fully saturated during the tests.

The specimens for the plant experiment were precast concrete elements (700 × 850 × 300 mm) and cylinders (φ100 × 200 mm). The fabrication procedure for the precast concrete elements and the cylinders is shown in Figure 1. These specimens were cured in a steam curing chamber of the precast concrete plant. The temperature was increased from the ambient temperature to 45 °C for two hours, maintained at 45 °C for six hours, and decreased from 45 °C to the ambient temperature naturally. To assess the effects of curing after steam curing on the chloride ingress resistance of concrete, after steam curing, the specimens were treated by atmospheric curing and water curing for three different durations, namely, 3, 7, and 14 days. After these curing procedures, cores (φ100 × 350 mm) were taken from the precast concrete elements for the non-steady-state migration test, and the cylinders were used for the resistivity test.

(A) Casting (B) Steam curing (C) Water curing

Figure 1. Fabrication procedure of specimens in precast concrete plant

**Non-Steady-State Migration Test**

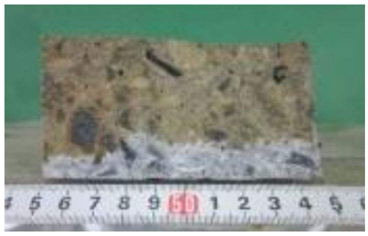
The cylinders made in the laboratory were used for the non-steady-state migration test at the ages of 14, 28, 56, 91, 182, and 365 days. Additionally, the cores taken from precast concrete elements were subjected to the non-steady-state migration test at the age of 56 days.

After the curing procedures were completed, two 50-mm-thick slices were immediately cut from the center of each cylinder and from the circular surface of each core. The side surfaces of the slices were sealed with epoxy resin to prevent chloride migration from any source other than the test surface. Then, the slices were placed in a desiccator, depressurized with a vacuum pump for 3 hours, and immersed in deionized water for more than 24 hours. Each slice was installed in the same apparatus as that specified in ASTM C 1202. The catholyte solution was a 10% NaCl solution, and the anolyte solution was a 0.3 mol/L NaOH solution. A predetermined voltage of 30 V was applied to the slice using a DC power supply in the laboratory at a room temperature of 20 °C for 6 or 24 hours as shown in Figure 2 (A). 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. The chloride penetration depth was measured at nine equally-spaced points as shown in Figure 2 (B). The chloride migration coefficient is given by

$$D_{\text{nssm}} = \frac{RT}{zFE} K \qquad (1)$$

where $D_{\text{nssm}}$ is the chloride migration coefficient ($m^2/s$); $R$ is the gas constant, 8.314 [J/(K·mol)]; $T$ is the average temperature in the catholyte and anolyte solutions during the test (K); $L$ is the thickness of the specimen (m); $z$ is the absolute value of the ion valance for chloride, 1; $F$ is the Faraday constant, $9.648 \times 10^4$ [J/(V·mol)]; $E$ is the average initial and final applied voltages measured between two solutions (V); and $K$ is the chloride penetration rate factor (m/s).


(A) Experimental setup



(B) Chloride penetration depth

Figure 2. Non-steady-state migration test

The authors proposed equation (1) in previous works (Nakamura, et al. 2013, 2015) because the original equation to compute the chloride migration coefficient in NT BUILD 492 was only applicable to specimens made with ordinary Portland cement. It should be noted that the chloride penetration rate factor, $K$, is determined as the slope of the regression line between the test duration, $t$, and the chloride penetration depth, $x_d$, which is measured by using more than one specimen with different test durations. As mentioned in previous works (Nakamura, et al. 2013, 2015), this modified computation equation of the chloride migration coefficient was introduced to avoid measurement errors due to the following two reasons. First, the rate of chloride migration decreased with increasing test duration. Second, the measured chloride penetration depth varied because the chloride content at the boundary between the silver chloride and concrete differed according to the type of concrete mixture.

**Resistivity Test**

In the laboratory experiment, the resistivity test was conducted on the cylinders at the ages of 7, 14, 21, 28, 56, 91, 182, 273, and 365 days. In the plant experiment, the resistivity test was implemented on the cylinders at the age of 1 day immediately after steam curing and at the ages of 3, 7, and 14 days after water curing. Two cylinders were used for the resistivity test in the laboratory experiment and four in the plant experiment.

A four-point Wenner concrete surface resistivity meter was used for the resistivity test according to AASHTO T 358 and JSCE-G 581. The resistivity was measured by placing the four probes of the meter on the cylinder surface at four lines, which were set at right angles to each other as shown in Figure 3. The distance between the probes was 50 mm.

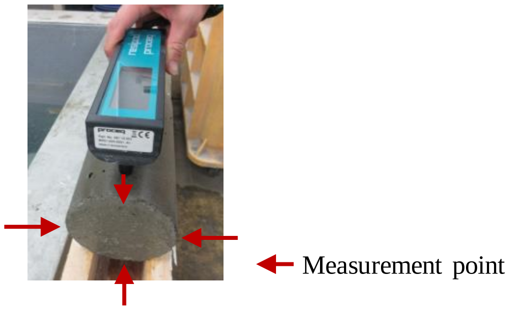



**Figure 3** Resistivity test

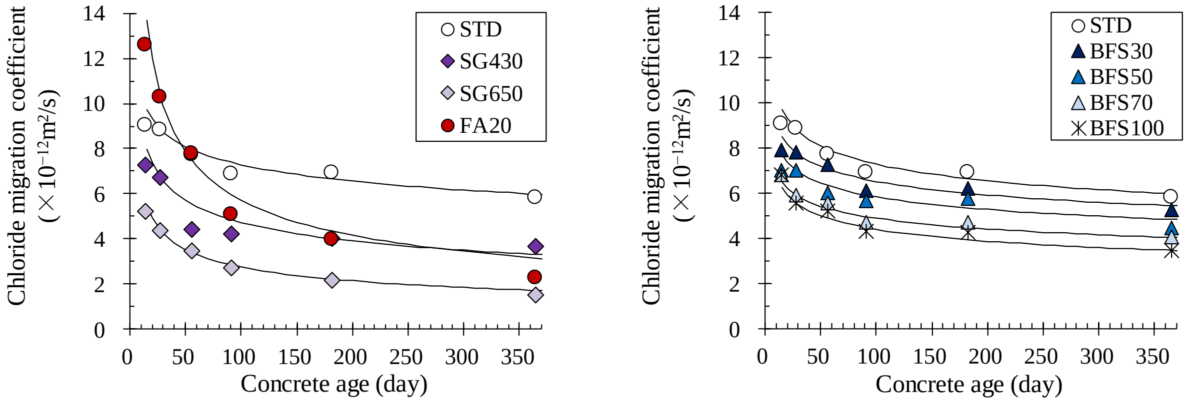
## RESULTS AND DISCUSSION

**Chloride Migration Coefficient from Laboratory Experiment**

The chloride migration coefficients measured at the ages of 14, 28, 56, 91, 182, and 365 days and the decay coefficients are shown in Figures 4 and 5, respectively. The curved lines in Figure 4 and the decay coefficients in Figure 5 were given by curve-fitting of the chloride migration coefficient of each concrete mixture to the following equation:

$$D_t = D_{28}\left(\frac{28}{t}\right)^{m_{\mathrm{nssm}}} \qquad (2)$$

where $D_t$ is the chloride migration coefficient ($m^2/s$); $D_{28}$ is the chloride migration coefficient at the age of 28 days ($m^2/s$); $t$ is the concrete age (day); and $m_{\mathrm{nssm}}$ is the decay coefficient.




(A) GGBF slag and fly ash (B) Blast furnace slag sand

Figure 4. Chloride migration coefficient obtained in laboratory experiment

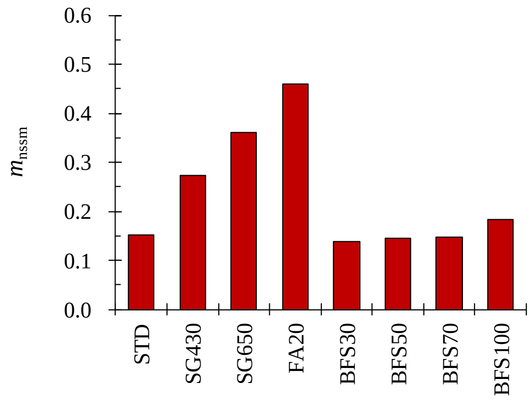
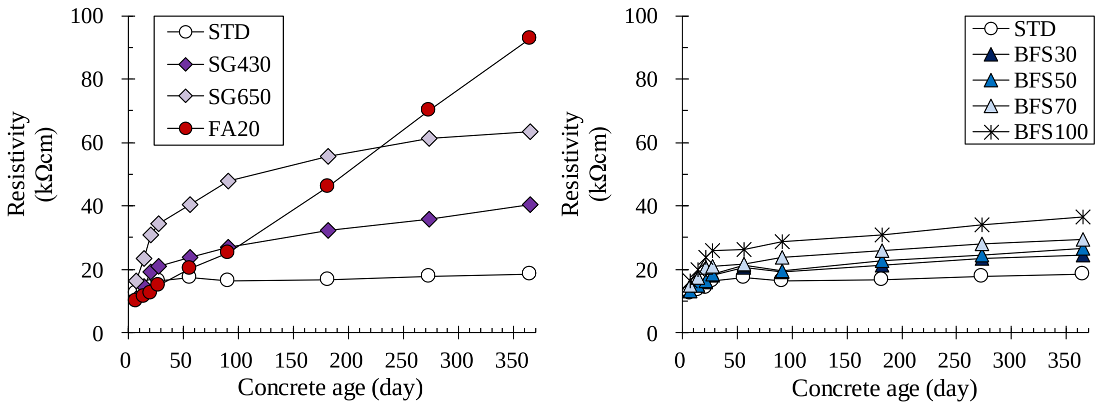



Figure 5. Decay coefficient

The chloride migration coefficients of the specimens made with GGBF slag, fly ash, or blast furnace slag sand were lower than those of the specimen fabricated with high-early-strength Portland cement and natural sand. This fact revealed that the use of GGBF slag, fly ash, or blast furnace slag sand enhanced the chloride ingress resistance of concrete. Additionally, the non-steady-state migration test was found effective to evaluate the chloride ingress resistance of concrete containing GGBF slag, fly ash, or blast furnace slag sand.

Although the chloride migration coefficients of all types of specimens gradually decreased as the concrete age increased, the transitions of the chloride migration coefficients differed according to the types of binder and fine aggregate. The chloride migration coefficients of the specimens containing GGBF slag or fly ash substantially decreased as the concrete age increased. Thus, the decay coefficients of the specimens containing GGBF slag or fly ash were larger than those of the specimens made only with high-early-strength Portland cement. Additionally, the decrease trend of the chloride migration coefficients was notable especially in the specimens containing fly ash. The chloride migration coefficients of the specimens containing fly ash were larger before the age of 56 days but lower after the age of 56 days in comparison to those of the specimens made only with high-early-strength Portland cement. This trend may be attributed to the fact that the pozzolanic reaction of fly ash progressed at a slower pace than the hydraulic reaction of high-early-strength Portland cement and GGBF slag. On the other hand, the transitions of the chloride migration coefficients of the specimens made with blast furnace slag sand were similar to those of the specimen fabricated with high-early-strength Portland cement and natural sand. These specimens showed nearly equal decay coefficients. These facts indicate that the non-steady-state migration test successfully obtained the chloride migration coefficient and clarified its time-dependent development for concrete containing blast furnace slag and fly ash.

**Resistivity from Laboratory Experiment**
The resistivity measured at the ages of 7, 14, 21, 28, 56, 91, 182, 273, and 365 days is shown in Figure 6. The resistivity of all types of specimens gradually increased as the concrete age increased. Additionally, the resistivity of the specimens made with GGBF slag, fly ash, or blast furnace slag sand were larger than that of the specimen fabricated with high-early-strength Portland cement and natural sand. This increase trend of the resistivity is opposite to the decrease trend of the chloride migration coefficient. This phenomenon is assumed to be reasonable because the enhanced chloride ingress resistance of concrete would account for a lower chloride migration coefficient and higher resistivity. Thus, the results obtained from the non-steady-state migration test and the resistivity test clearly revealed the enhanced chloride ingress resistance of concrete containing blast furnace slag or fly ash.




(A) GGBF slag and fly ash (B) Blast furnace slag sand

Figure 6. Resistivity obtained in laboratory experiment

**Chloride Migration Coefficient and Resistivity**
The relationship between the chloride migration coefficient and resistivity is shown in Figure 7. As seen in the figure, the chloride migration coefficient and resistivity showed an inverse relationship. It is reasonable to say that this inverse relationship was observed for all types of specimens regardless of the use of GGBF slag, fly ash, and blast furnace slag sand. Moreover, this fact implies that there is a strong possibility

to use the resistivity as an alternative indicator to represent the chloride ingress resistance of concrete containing blast furnace slag and fly ash.

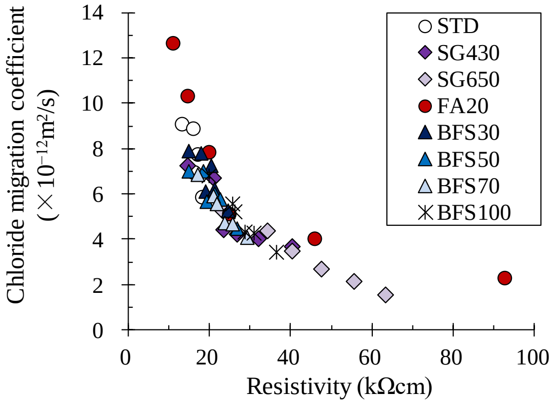


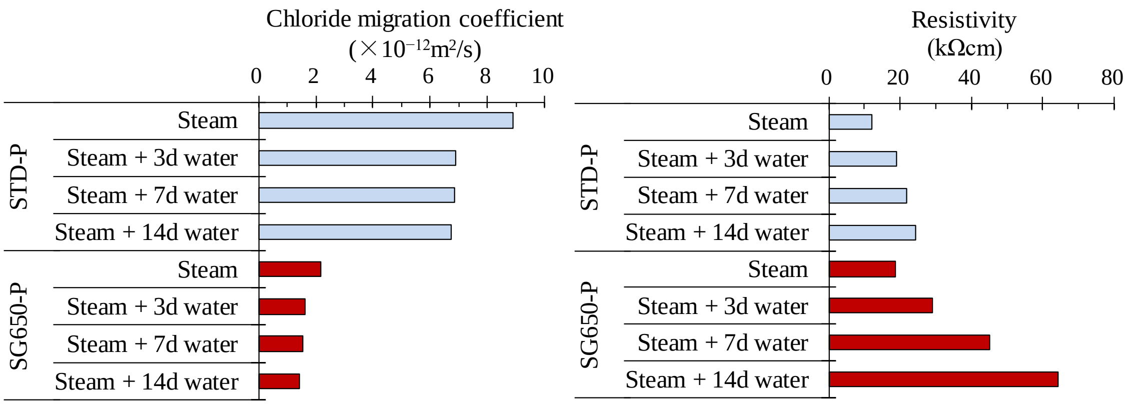

Figure 7. Chloride migration coefficient and resistivity

**Application to Precast Concrete Elements**

The chloride migration coefficient and the resistivity derived from the plant experiment are shown in Figure 8. It should be noted that the chloride migration coefficient was obtained by using the cores taken from the precast concrete elements, and the resistivity was measured by using the cylinders fabricated in the same manner as the precast concrete elements. The use of GGBF slag resulted in lower chloride migration coefficient and higher resistivity. These trends are similar to those derived from the laboratory experiment. This fact indicates that the use of GGBF slag enhanced the chloride ingress resistance of the precast concrete elements.

Additionally, the cores and cylinders treated by water curing after steam curing showed lower chloride migration coefficient and higher resistivity. Water curing following steam curing was also found effective to enhance the chloride ingress resistance of the precast concrete elements. However, it should be noted that the chloride migration coefficients remained relatively constant regardless of the length of the water curing duration. In other words, the effect of extending the water curing duration more than three days on the chloride ingress resistance was unclear. These findings indicate that the combination of steam curing and three-day water curing was effective to enhance the chloride ingress resistance of the precast concrete elements.

The relationship between the chloride migration coefficient and resistivity obtained in the laboratory experiment and the plant experiment is shown in Figure 9. It should be noted that the data derived from the laboratory experiment in Figure 9 are the chloride migration coefficient and the resistivity findings previously shown in Figure 7. Although the data derived from both the laboratory experiment and the plant experiment showed relatively good agreement, the specimens made with GGBF slag showed lower chloride migration coefficients than other specimens. This gap may be attributed to the difference in the concrete age in the tests. As mentioned previously, the non-steady-state migration test was conducted on cores taken from the precast concrete elements at the age of 56 days, and the resistivity test was implemented on cylinders after steam curing and water curing at the ages of 1, 3, 7, and 14 days in the plant experiment. The decrease of the chloride migration coefficient from the age of 1, 3, 7, and 14 days to that of 56 days was assumed to induce the gap between the results of the laboratory experiment and the plant experiment because the use of GGBF slag was shown to enhance the time-dependent development of the chloride ingress resistance of concrete. In view of the time-dependent development of the chloride ingress resistance of concrete containing blast furnace slag and fly ash, the resistivity measured after steam curing and water curing at early ages is assumed to represent the minimum chloride ingress resistance. Therefore, the resistivity test can be viewed as a simple and rapid method to verify the quality of precast concrete elements at early concrete ages.




(A) Chloride migration coefficient (B) Resistivity

Figure 8. Chloride migration coefficient and resistivity obtained in plant experiment

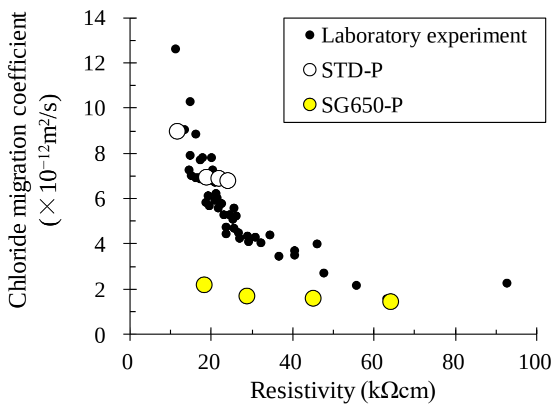



Figure 9. Relationship between laboratory and plant experiment results

## CONCLUSIONS

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

1. Both the chloride migration coefficient derived from the non-steady-state migration test and the resistivity measured with a four-point Wenner concrete surface resistivity meter clearly revealed the enhanced chloride ingress resistance of concrete containing blast furnace slag and fly ash.

2. The non-steady-state migration test successfully obtained the chloride migration coefficient of concrete containing blast furnace slag and fly ash and clarified its time-dependent development.

3. The resistivity test can be viewed as a simple and rapid method to verify the quality of precast concrete elements after steam and water curing because a good correlation between the chloride migration coefficient and resistivity was observed through the laboratory and plant experiments.

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