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EVALUATION OF MIGRATION CHARACTERISTICS OF OPC AND SLAG CONCRETE FROM THE RAPID CHLORIDE MIGRATION TEST

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EVALUATION OF MIGRATION CHARACTERISTICS OF OPC AND SLAG CONCRETE FROM THE RAPID CHLORIDE MIGRATION TEST

Rues-Wen Shiu[1], Chung-Chia Yang

Key words: distribution center; extended fuzzy preference relation; FMCGDM; location evaluation.

ABSTRACT

In this study, the non-steady state chloride migration coefficient in concrete was measured using the rapid chloride migration (RCM) test. After completing the test, we established the specimen's chloride profile by collecting concrete powder samples at predetermined, controlled depths. In order to investigate whether the RCM (NT BUILD 492) can be applied to slag concrete, we made ordinary Portland cement (OPC) concrete and slag concrete with different water binder (w/b) ratios. The combined results from the concrete chloride profile and regression analysis demonstrated that the NT BUILD 492 RCM method can be successfully applied to slag concrete. In summary, a good correlation was observed between the initial 30 V current obtained from the RCM and the chloride migration coefficient obtained from RCM. Thus, the initial current can be used to determine the chloride migration coefficient obtained using the colorimetric method.

I. INTRODUCTION

The durability of concrete exposed to marine environments is highly impacted by chloride induced corrosion of reinforcing steel. Therefore, a high quality concrete cover that is resistant to chloride ion penetration is necessary for maintaining the integrity of reinforced concrete structures.

The ponding test is commonly employed to assess the resistance of concrete to chloride ion penetration (ASTM, 2010); however, this method is both time-consuming and laborious. Thus, several methods were developed that involve applying an electrical field to accelerate the movement of chloride ions in order to shorten the testing time. Examples include the rapid chloride permeability test (RCPT) (ASTM, 2019), accelerated chloride migration test (ACMT) (Yang and Cho, 2005), and the rapid chloride migration (RCM) test (NT Build, 1999).

The RCM test was developed by Tang (1999), standardized as NT Build 492, and has been widely used throughout Europe. The standards specify the non-steady-state migration coefficient based on the colorimetric method, which in turn depends on $AgNO_3$ for measuring chloride penetration depth in the cement matrix. Essentially, the $AgNO_3$ solution is sprayed onto a freshly fractured concrete cross-section, which leads to the formation of white and brown zones separated by a clear color change boundary. The white region indicates the presence of chloride and the brown region marks chloride free areas (He et al., 2012; Real et al., 2015). Otsuki et al. (1993) sprayed silver nitrate solutions comprised of different concentrations onto the freshly fractured surface of chloride containing concrete samples. Their results showed that the chloride concentration at the color change border is on the order of 0.15% by wt. of soluble chloride cement. Furthermore, previous studies determined that the total chloride concentration values in concrete that correspond to the $AgNO_3$ detection boundary vary from 0.020 to 0.207, depending on the mass of concrete (Otsuki et al., 1993; Andrade et al., 1999; Meck and Sirivivatnanon, 2003; Baroghel-Bouny et al., 2007).

The RCM method has been used to investigate the effect of blast-furnace slag (Maes et al., 2013), fly ash (Ismail et al., 2013), and nano-silica (Du et al., 2015) on concrete's resistance to chlorides. Tang (1996) noted that the RCM method only requires measuring the penetration depth, which shortens the testing period compared to the steady state method. Among the three tested methods (NT BUILD 443, NT BUILD 355, and RCM), the RCM test in general depicted the best precision in determining the chloride diffusion coefficient for Portland cement and silica fume concrete (Tang and Sorensen, 2001). Moreover, the chloride diffusion coefficients obtained

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Table 1. Mix proportion and average compressive strength.

Mix	Unit content: kg/m^3						Compressive strength (kgf/cm^2)
	Water	Cement	Slag	Fine aggregate	Coarse aggregate	SP	
C-35	168	495	0	786	934	5	429
C-45	191	430	0	786	934	2	346
C-55	209	380	0	786	934	0	301
C-65	222	341	0	786	934	0	231
S3-35	166	341	146	786	934	5	483
S3-45	189	298	128	786	934	2	409
S3-55	207	264	113	786	934	0	372
S3-65	220	237	101	786	934	0	282
S4-35	165	292	195	786	934	5	476
S4-45	189	254	170	786	934	2	410
S4-55	207	225	150	786	934	0	364
S4-65	219	202	135	786	934	0	259
S5-35	165	242	242	786	934	5	446
S5-45	188	211	211	786	934	2	380
S5-55	206	187	187	786	934	0	307
S5-65	219	168	168	786	934	0	248

using the RCM test and the values obtained from long-term diffusion tests depicted a linear correlation (Elfmarkova et al., 2015). Spiesz et. al. (2012) developed a new theoretical model for the RCM test that considers the non-linear chloride binding isotherm and the non-equilibrium conditions between the free- and bound-chloride concentrations. Their results indicate that the migration coefficient calculated using the traditional RCM method is overestimated.

In this study, the RCM colorimetric method was used to determine the non-steady state chloride migration coefficients in concrete following the NT Build 492 procedure. Next, we established a chloride profile by measuring the chloride content at specific depth increments throughout the sample and independently obtained the migration coefficients from the chloride profile. Subsequently, we determined the relationship between chloride migration coefficients obtained from the colorimetric method and those obtained from the chloride profile; and ultimately used the initial current obtained from a voltage of 30 V during the RCM test to find the chloride migration coefficient.

II. EXPERIMENTAL PROGRAM

1. Materials and specimen preparation

Two types of binders, ASTM Type I Portland cement and slag, composed with different water binder (w/b) ratios, were used as concrete specimens. The coarse aggregate consisted of crushed limestone with a maximum particle size of 10 mm, while the fine aggregate was composed of river sand. All manufactured mixes were comprised of 786 kg/m^3 of fine aggregates and 934 kg/m^3 of coarse aggregates. The concrete ingredients proportions are summarized in Table 1. The series C binder was Portland cement. In series S3, S4, and S5, 30%, 40%, and 50% of the cement was replaced by slag, respectively. Four w/b ratios (0.35, 0.45, 0.55, and 0.65) were used in each series.

For each mix, nine cylindrical specimens (ϕ 10 x 20 cm) were cast and cured. After 24 h, the specimens were removed from the mold and cured in water at 23 ℃ for 91 days. Three specimens were used to determine the compressive strength, and the average value is reported in Table 1. The colorimetric method was performed on a second set of three specimens, and the chloride profile method was conducted using the third set of three. Samples for the RCM test consisted of 50-mm thick, 100-mm diameter concrete specimens that were cut from the cylinders' central portion. In order to avoid heterogeneity, the specimens were vacuum-saturated prior to testing. The specimens' curved side surface was coated with epoxy, placed in a vacuum desiccator, and maintained at <10 mm Hg pressure for 3 h. Next, saturated $Ca(OH)_2$ solution was added to immerse the specimen and the vacuum level was maintained for an additional hour. Finally, the specimens were soaked in the added water for 18 h after turning off the pump.

2. RCM (Rapid chloride migration test)

The RCM test was used to determine the non-steady state chloride migration coefficients in concrete following the NT

Table 2. Test voltage and duration for concrete specimen [NT Build 492].

Initial current I_0 (with 30 V) (mA)	Applied voltage U (after adjustment) (V)	Test duration t (hour)
$I_0 < 5$	60	96
$5 \le I_0 < 10$	60	48
$10 \le I_0 < 15$	60	24
$15 \le I_0 < 20$	50	24
$20 \le I_0 < 30$	40	24
$30 \le I_0 < 40$	35	24
$40 \le I_0 < 60$	30	24
$60 \le I_0 < 90$	25	24
$90 \le I_0 < 120$	20	24
$120 \le I_0 < 180$	15	24
$180 \le I_0 < 360$	10	24
$I_0 \ge 360$	10	6

Table 3. The applied voltage and test duration for different mixes.

Mix	Initial current I_0 (with 30 V) (mA)				Applied voltage U (after adjustment) (V)	Test duration t (hour)
	(1)	(2)	(3)	Avg.		
C-35	42.9	42.6	40.6	40.6	30	24
C-45	69.5	68.5	68.5	68.8	25	24
C-55	83.1	92.9	92.9	89.6	25	24
C-65	107.3	101.0	107.5	105.3	20	24
S3-35	23.4	23.7	23.3	23.5	40	24
S3-45	36.5	35.3	32.8	34.9	35	24
S3-55	41.1	42.1	41.3	41.5	35	24
S3-65	39.0	36.3	38.5	37.9	35	24
S4-35	33.4	31.6	30.6	31.9	35	24
S4-45	36.0	31.3	32.5	33.3	35	24
S4-55	37.2	35.0	38.2	36.8	35	24
S4-65	40.5	36.8	33.3	36.9	35	24
S5-35	33.0	30.5	29.3	30.9	35	24
S5-45	26.2	25.7	25.9	25.9	35	24
S5-55	31.1	33.3	30.4	31.6	30	24
S5-65	32.0	29.5	28.0	29.8	30	24

Build 492 procedure (NT Build, 1999). During the RCM test, a vacuum-saturated, 50-mm thick specimen was placed in a rubber sleeve. One side of the specimen was placed in a 300 mL anolyte solution (0.3 N $NaOH$) and the other side was placed in a 12 L catholyte solution comprised of 10% $NaCl$. The RCM test set-up is illustrated in Fig. 1. As dictated by the NT Build 492, 30 V was initially applied to the specimen to determine the initial current (I_0). The applied voltage and test duration were then adjusted according to the initial current as shown in Table 2. Table 3 shows the initial current, the applied voltage, and the test duration for the different mixes used in this study.

After the voltage was applied, the sample was split axially into two pieces. A 0.1 M silver nitrate solution was sprayed on the fractured surface of one piece. When the white silver chloride precipitation on the split surface was clearly visible (as shown in Fig. 2), the penetration depth was measured with a ruler. The chloride penetration depth was measured at 10 locations across the section and the average was calculated and reported.

3. Chloride profile determined after the RCM

After switching off the electrical field, the sample was used to establish a chloride profile. The profile Grinder PF-1100 was employed for grinding and collecting the concrete powder sample at a specified depth from the specimen surface. The chloride content at every depth increment was determined based on the ground powders in accordance with AASHTO T260 (2009).

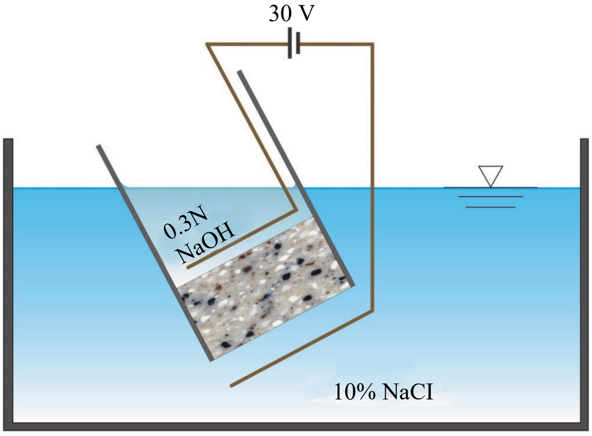

Fig. 1. The RCM test set-up

Fig. 2. Illustration of measurement for chloride penetration depth

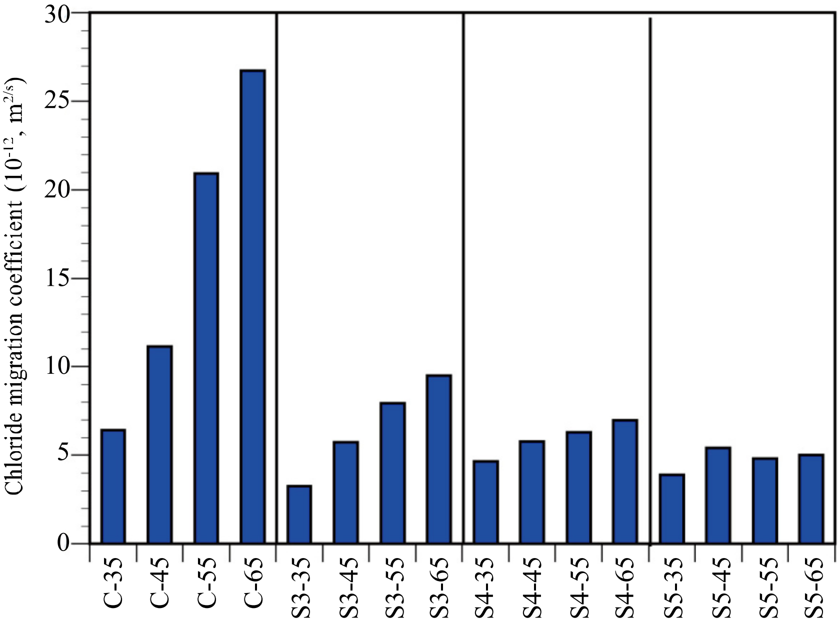

Fig. 3. The average chloride migration coefficient M_c for all mixes.

III. RESULTS AND DISCUSSION

The non-steady-state migration coefficient obtained from the RCM colorimetric method and from the chloride profile after RCM test is discussed below.

1. Non-steady-state migration coefficient from the RCM colorimetric method

During RCM test, chloride ions will be transported through the concrete sample under an applied voltage. The non-steady-state migration coefficient (M_n) was calculated from a modified expression of Fick's second law (Tang, 1996):

$$\frac{dC}{dt} = M_n\left(\frac{d^2C}{dx^2} - \frac{|z|FE}{RT}\frac{dC}{dx}\right) \tag{1}$$

where C is the ion concentration, as a function of distance x, at any time t; z is chloride's electrical charge, F is the Faraday constant ($9.648 \times 10^4\ J/(V \cdot mol)$); E is the strength of the electric field between the anode and cathode (V/m); R is the universal gas constant (8.314 J/K·mol); and T is the absolute temperature (K). For RCM, the following conditions are used to obtain the solution to Eq. (1) : initial condition: $C = 0$, $x > 0$, $t = 0$; boundary condition: $C = C_o$, $x = 0$, $t > 0$; and infinite-point condition: $C = 0$, $x = 0$ infinite, $t =$ large number. The analytical solution for Eq. (1) is expressed as (Tang, 1996):

$$C(x,t) = \frac{C_o}{2}\left[e^{\beta x} erfc\left(\frac{x + \beta M_n t}{2\sqrt{M_n t}}\right) + erfc\left(\frac{x - \beta M_n t}{2\sqrt{M_n t}}\right)\right], \tag{2}$$

Table 4. The chloride penetration depth and migration coefficient obtained from colourimetric method.

Mix	Chloride penetration depth, d_c, (mm)				Chloride migration coefficient, M_c, (m^2/s; $\times 10^{-12}$)			
	(1)	(2)	(3)	Avg.	(1)	(2)	(3)	Avg.
C-35	13.80	18.00	13.70	15.17	5.74	7.73	5.83	6.43
C-45	20.60	21.60	22.50	21.57	10.56	11.04	11.82	11.14
C-55	37.80	39.50	39.90	39.07	20.16	21.12	21.43	20.91
C-65	36.40	36.80	46.70	39.97	24.38	24.66	31.12	26.72
S3-35	12.27	10.76	7.98	10.34	3.89	3.42	2.43	3.24
S3-45	14.62	18.18	14.07	15.62	5.26	6.69	5.18	5.71
S3-55	21.41	16.43	24.13	20.66	8.34	6.04	9.43	7.93
S3-65	22.56	25.42	26.83	24.94	8.42	9.87	10.23	9.51
S4-35	12.77	14.25	12.37	13.13	4.62	4.93	4.33	4.63
S4-45	13.78	16.33	16.80	15.64	5.23	5.92	6.14	5.76
S4-55	17.74	16.53	16.90	17.06	6.69	6.08	6.14	6.30
S4-65	15.13	22.96	18.33	18.81	5.53	8.58	6.77	6.96
S5-35	12.39	13.82	11.78	12.66	3.81	4.30	3.58	3.90
S5-45	15.02	16.80	18.18	16.67	4.70	5.53	5.96	5.39
S5-55	17.14	13.87	14.19	15.07	5.56	4.31	4.60	4.82
S5-65	14.97	13.66	18.50	15.71	4.75	4.30	5.92	4.99

where $\beta = \dfrac{|z|FE}{RT}$, and $erfc$ is the complementary error function.

Based on Eq. (2), when the electrical field is large enough and the penetration depth is sufficient, the migration coefficient can be calculated as:

$$M_n = \frac{1}{\beta}\left(\frac{x-\alpha\sqrt{x}}{t}\right), \tag{3}$$

where $\alpha = 2\sqrt{\dfrac{1}{\beta}}erf^{-1}\left(1-\dfrac{C_d}{C_o}\right)$, and erf^{-1} is the inverse of the error function.

In the colorimetric method, C_o is the chloride concentration in the cathode cell, and C_d is the chloride concentration in the pore solution corresponding to the color change boundary.

After the electrical field was applied, the specimens were split and sprayed with $AgNO_3$. When $AgNO_3$ reacts with chloride, it becomes $AgCl$, which is characterized by a white color. The white $AgCl$ is visible and the chloride penetration depth can therefore be measured. The color change boundaries, i.e., the chloride penetration depths (d_c), obtained from colorimetric method for all the mixes are given in Table 4.

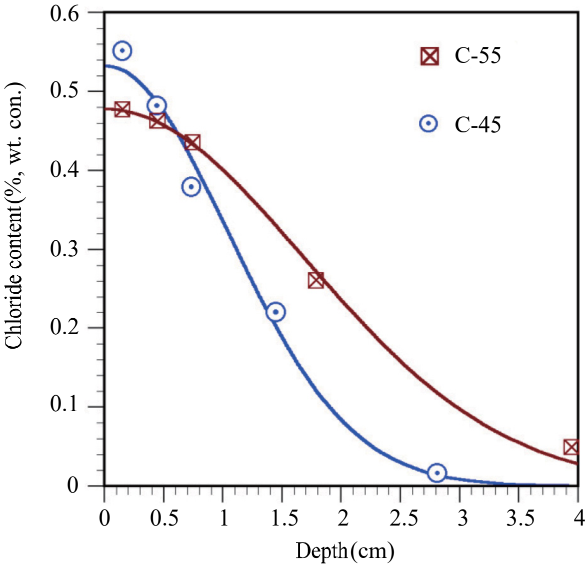

Fig. 4. The chloride profiles for C-45 and C-55 after the RCM test (voltage of 25 V).

Using the chloride penetration depth (d_c) obtained from colorimetric method (see Table 4), the applied voltage and test duration (see Table 3), $C_o = 2\ N$, and $C_d = 0.07\ N$ (NT BUILD 492, 1999), the chloride migration coefficient (M_c) was calculated from Eq. (3) and the results are listed in Table 4.

Table 5. The surface chloride content and experimental parameter for all mixes.

Mix	Surface chloride content, C_s, (%)				Experimental parameter, a			
	(1)	(2)	(3)	Avg.	(1)	(2)	(3)	Avg.
C-35	0.50	0.54	0.54	0.53	0.99	1.13	0.76	0.96
C-45	0.53	0.54	0.55	0.54	0.46	0.45	0.44	0.45
C-55	0.47	0.44	0.44	0.45	0.18	0.20	0.15	0.18
C-65	0.49	0.56	0.53	0.53	0.24	0.27	0.28	0.26
S3-35	0.61	0.57	0.59	0.59	3.96	2.48	2.16	2.87
S3-45	0.51	0.58	0.54	0.54	0.62	0.99	0.72	0.78
S3-55	0.60	0.58	0.59	0.59	0.95	0.91	1.14	1.00
S3-65	0.60	0.52	0.54	0.55	1.22	0.85	0.85	0.97
S4-35	0.50	0.57	0.61	0.56	2.50	2.05	1.69	2.08
S4-45	0.54	0.60	0.65	0.60	2.15	2.46	3.35	2.65
S4-55	0.56	0.53	0.64	0.58	1.83	1.53	1.82	1.73
S4-65	0.61	0.70	0.58	0.63	2.32	2.38	1.52	2.07
S5-35	0.70	0.57	0.58	0.62	3.09	3.14	2.00	2.74
S5-45	0.64	0.70	0.69	0.68	1.87	1.23	1.23	1.44
S5-55	0.72	0.70	0.67	0.70	1.70	1.81	1.64	1.72
S5-65	0.65	0.60	0.67	0.64	1.56	1.29	1.80	1.55

Table 6. The chloride penetration depth and the chloride migration coefficient M_n obtained from chloride profile.

Mix	Chloride penetration depth, d_p, (mm)				Chloride migration coefficient, M_n, (m^2/s; $\times 10^{-12}$)			
	(1)	(2)	(3)	Avg.	(1)	(2)	(3)	Avg.
C-35	19.9	18.8	18.8	19.2	8.51	7.97	9.88	8.79
C-45	29.3	29.9	30.2	29.8	14.89	15.24	15.84	15.32
C-55	46.8	43.9	43.8	44.8	27.78	18.85	27.91	24.85
C-65	39.9	38.6	38	38.8	26.02	24.88	24.89	25.26
S3-35	10.2	12.8	20.3	14.4	3.28	3.97	4.48	3.91
S3-45	18.3	21.1	21.5	20.3	6.81	7.35	6.88	7.01
S3-55	20.8	13.7	19	17.8	7.86	7.63	8.1	7.86
S3-65	25.2	21.6	23.5	23.4	9.76	8.14	9.01	8.97
S4-35	12.5	14	12.9	13.1	4.43	4.84	5.29	4.85
S4-45	13.3	13.4	16.1	14.3	5.43	5.28	4.38	5.03
S4-55	13.3	15.6	11.3	13.4	5.55	5.47	6.61	5.88
S4-65	14.9	15.9	15.9	15.6	6.04	6.67	6.48	6.40
S5-35	11.7	11.4	14.2	12.4	4.15	3.83	4.97	4.32
S5-45	14.9	18.6	17.5	17.0	5.29	6.6	6.35	6.08
S5-55	15.9	15.3	16	15.7	6.43	6.15	6.68	6.42
S5-65	16.4	17.8	15.3	16.5	6.65	7.27	6.34	6.75

Figure 3 shows the average chloride migration coefficient (M_c) for all the mixes. The migration coefficients obtained from RCM for the C series are higher than those of the other three series (S3, S4, and S5) with the same w/b ratios. The slag's mineral admixture can improve the concrete's pore size and pore shape distribution, since more C-S-H gel is formed when the slag concrete hydrates.

Table 7. The chloride concentration at the color change boundary (C_{dp}) and the Migration coefficient calculated by using α_{cp}.

Mix	Chloride concentration at the color change boundary, C_{dp}, (%)				Migration coefficient calculated by using α_{cp}, M_{cp}, (m^2/s; $\times10^{-12}$)			
	(1)	(2)	(3)	Avg.	(1)	(2)	(3)	Avg.
C-35	0.026	0.013	0.055	0.031	5.92	7.65	6.07	6.55
C-45	0.042	0.012	0.241	0.098	10.95	10.99	13.15	11.70
C-55	0.031	0.016	0.098	0.048	20.57	21.20	22.65	21.47
C-65	0.019	0.055	0.146	0.073	24.06	25.09	33.39	27.52
S3-35	0.149	0.116	0.164	0.143	4.30	3.72	2.79	3.60
S3-45	0.171	0.057	0.007	0.078	5.98	7.04	4.98	6.00
S3-55	0.168	0.046	0.091	0.102	8.72	6.28	9.61	8.20
S3-65	0.122	0.059	0.061	0.080	9.07	10.24	10.60	9.97
S4-35	0.082	0.070	0.035	0.062	4.99	5.51	4.59	5.03
S4-45	0.012	0.053	0.000	0.021	4.96	6.27	5.70	5.64
S4-55	0.016	0.001	0.000	0.006	6.57	5.64	5.74	5.98
S4-65	0.014	0.005	0.020	0.013	5.50	8.34	6.84	6.89
S5-35	0.045	0.006	0.007	0.019	4.62	4.85	4.09	4.52
S5-45	0.012	0.014	0.050	0.025	5.41	6.13	6.96	6.17
S5-55	0.012	0.033	0.020	0.022	7.17	5.93	5.97	6.35
S5-65	0.004	0.001	0.001	0.002	5.97	5.15	7.27	6.13

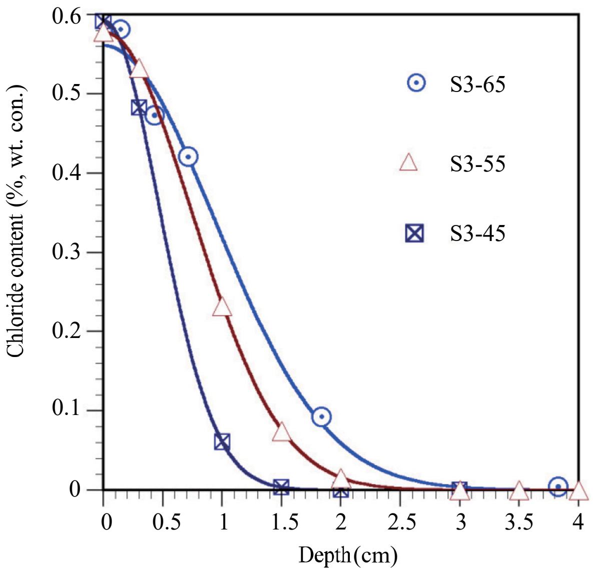

Fig. 5. The chloride profiles for series S3 after the RCM test (voltage of 35 V).

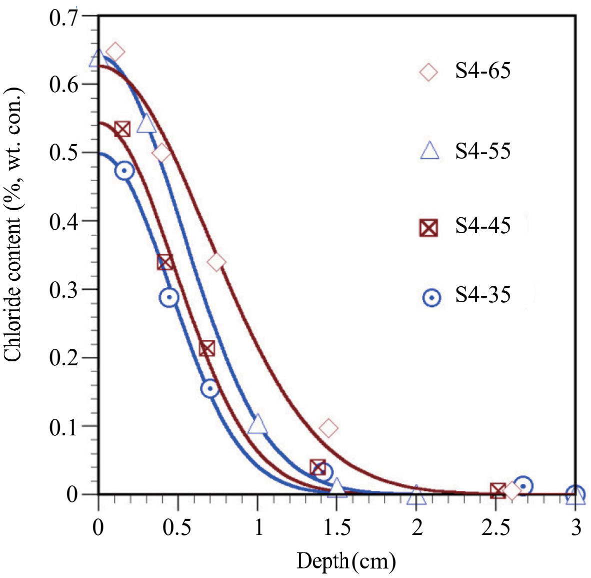

Fig. 6. The chloride profiles for series S4 after the RCM test (voltage of 35 V).

2. Non-steady-state migration coefficient from chloride profile after RCM

After the voltage was applied, three samples from each mix were used to establish a chloride profile. Figure 4 shows the chloride content for series C after the RCM at an applied voltage of 25 V. Figures 5 and 6 present the chloride content for series S3 and S4, respectively, after the RCM test at an applied voltage of 35 V. The chloride content is expressed as a percentage of the sample's dry mass and the depth represents the distance from each powder sample's mid-point to the exposed chloride surface.

Table 8. The parameter α and α_{cp}.

Mix	α	α_{cp}			
		(1)	(2)	(3)	Avg.
C-35	0.017	0.015	0.018	0.012	0.015
C-45	0.018	0.014	0.020	0.002	0.012
C-55	0.018	0.015	0.018	0.008	0.014
C-65	0.021	0.020	0.015	0.007	0.014
S3-35	0.015	0.006	0.007	0.005	0.006
S3-45	0.016	0.004	0.011	0.019	0.011
S3-55	0.016	0.005	0.012	0.009	0.009
S3-65	0.016	0.007	0.007	0.010	0.008
S4-35	0.016	0.008	0.010	0.014	0.011
S4-45	0.016	0.017	0.012	0.025	0.018
S4-55	0.016	0.016	0.025	0.025	0.022
S4-65	0.016	0.017	0.021	0.016	0.018
S5-35	0.016	0.013	0.020	0.019	0.017
S5-45	0.016	0.018	0.018	0.012	0.016
S5-55	0.017	0.020	0.015	0.017	0.018
S5-65	0.017	0.023	0.027	0.027	0.026

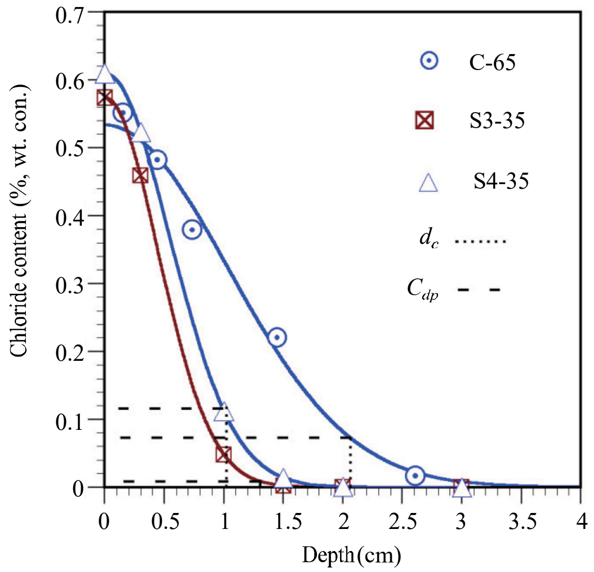

Fig. 7. The color change boundaries (d_c) and the chloride concentration at that depth.

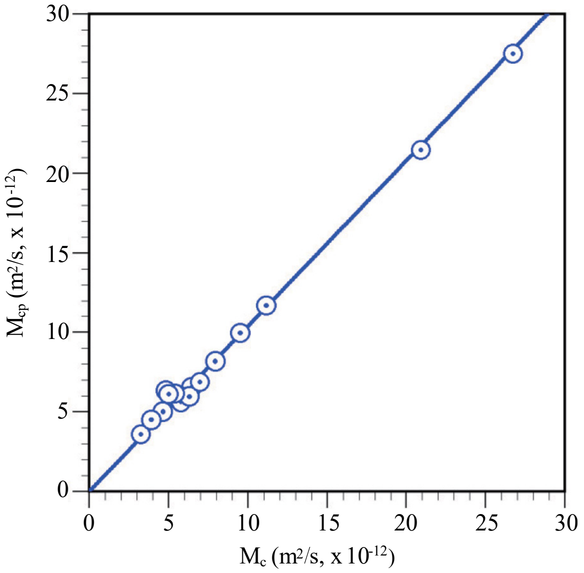

Fig. 8. The relationship between M_c and M_{cp}.

To obtain the chloride profile curve, the experimental data were fitted using nonlinear regression analysis:

$$C_p = C_s \cdot \exp(-ax^2), \tag{4}$$

where C_p is the chloride content, x is the depth, C_s is the surface chloride content in $x = 0$, and a is the experimental parameter. The fitting of Eq. (4) was performed using a commercial curve-fitting software program to search for a nonlinear, least-square, best fit for the experimental data. The experimental results obtained from the RCM test for the C, S3, and S4 series were fitted with Eq. (4) and the results are shown

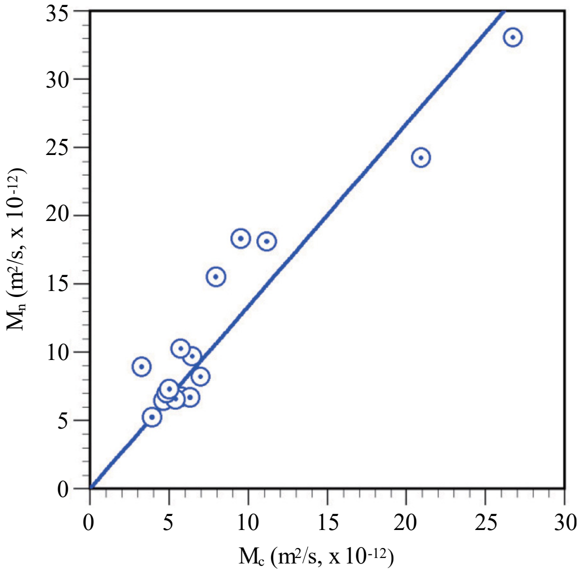

Fig. 9. The relationship between the migration coefficient M_c and M_n.

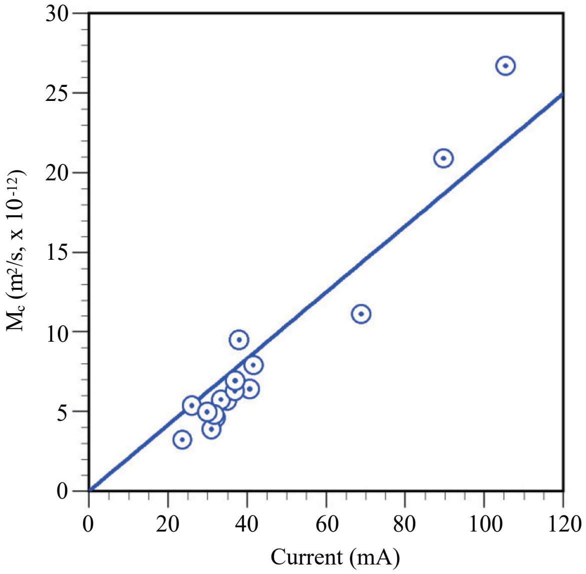

Fig. 10. The relationship between initial current and the migration coefficient.

in Figs. 4, 5, and 6, respectively. The surface chloride content (C_s) and the experimental parameter (α) were both allowed to vary. Table 5 lists the surface chloride content, and the experimental parameter for all mixes. To determine a precise and reproducible depth measurement, a value of 0.01% chloride content was arbitrarily chosen as the chloride penetration depth (d_p). The 0.01% chloride content value is the approximate point of inflection for the penetration curve's toe. Table 6 lists the chloride penetration depth for all the mixes. Using the chloride penetration depth (d_p) (see Table 6), C_s (see Table 5), the applied voltage, the test duration (see Table 3), and $C = 0.01\%$, the chloride migration coefficient obtained from chloride profile (M_n) was calculated from Eq. (3) and the results are listed in Table 6.

3. The chloride concentration at color change boundary in the chloride profile

Figure 7 shows the chloride profiles of C-45, S3-35, and S4-35 after RCM. The color change boundaries (d_c) in this figure are clearly indicated, which permitted estimation of the chloride concentration at that depth. The chloride concentration at the color change boundary is not constant for each mix and the chloride concentration values at the color change boundary (C_{dp}) are given in Table 7.

In NT BUILD 492, the chloride concentration at the color change boundary (C = 0.07N) and the surface chloride concentration ($C_o = 2N$) can only be applied to concrete using ordinary Portland cement . The α in Eq. (3) is the only parameter that is influenced by the C/C_o ratio. The parameter α is calculated by using $C_o = 2\ N$ and $C_d = 0.07\ N$, and the results are listed in Table 8. To investigate whether NT BUILD 492 can be applied to slag concrete, the surface chloride concentration (C_s) (see Table 5) and the chloride concentration at the color change boundary (C_{dp}) in Table 7 were used to calculate the parameter (α_{cp}) and the results are listed in Table 8. The migration coefficients (M_c) and (M_{cp}) were calculated by using α and α_{cp}, respectively, as shown in Table 4 and Table 7, respectively. Figure 8 shows the relationship between (M_c) and (M_{cp}). The empirical relationship is obtained through linear regression as follows:

$$M_{cp} = 1.04 M_c. \tag{5}$$

Based on the slope in Eq. (5), the migration coefficient of (M_c) and (M_{cp}) are almost identical. As such, the NT BUILD 492 RCM method can be applied to slag concrete.

4. The relationship between the chloride migration coefficient obtained from the colorimetric method and the chloride profile

The migration coefficient (M_c), obtained with the colorimetric method by using Eq. (3), was determined based on depth measurements of the color change boundary. A constant value of $C/C_o = 0.07/2$ was used. The migration coefficient obtained from the chloride profile (M_n) was determined based on chloride profile measurements after the RCM test. These results are listed in Table 6. The relationship between the migration coefficient (M_c) (see Table 4) and the migration coefficient (M_n) (see Table 6) is shown in Fig. 9. The empirical relationship between M_n and M_c is statistically derived by linear regression as follows:

$$M_n = 1.336 M_c, \tag{6}$$

where M_n and M_c are expressed in m^2/s. The linear regression's R^2 value equals 0.883, demonstrating a high linear correlation between M_n and M_c.

5. The relationship between initial current and chloride migration coefficient obtained from the colorimetric method in RCM

Since the electrical conductivity of concrete is determined by both pore structure and pore solution chemistry, the initial current obtained from RCM test may affect the pore solution's chemistry or electrical conductivity. At the beginning of RCM, the initial current (I_0) was used to determine the applied voltage and test duration as shown in Table 3. In order to compare the initial current (I_0) trend with the migration coefficient obtained from the colorimetric method (M_c), the initial current and the migration coefficient M_c are presented in Fig. 10. Using linear regression, the empirical relationship between I_0 and M_c is statistically derived as:

$$M_c = 0.2081 I_0, \tag{7}$$

where M_c and I_0 are expressed in m^2/s and mA, respectively. The correlation coefficient R^2 is 0.960.

Comparison of the initial current with the migration coefficient (M_c) reveals a close relationship between the two variables. In essence, the initial current can be used to determine the chloride migration coefficient obtained using the colorimetric method.

IV. CONCLUSIONS

The migration coefficient was determined using both the RCM test and the chloride profile established after RCM test. Based on the results obtained herein, the following conclusions can be drawn.

1. The migration coefficient for OPC concrete is higher than that of slag concrete with the same w/b ratios. The mineral admixture of slag can improve the distribution of pore size and pore shape of concrete, and more C-S-H gel is formed when the slag concrete hydrates.
2. In NT BUILD 492, both the chloride concentration at the color change boundary (C = 0.07N) and the surface chloride concentration ($C_0 = 2N$) are constant. Based on the chloride profile, the chloride concentration at the color change boundary varies within the range of 0.002% to 0.143%, and the surface chloride concentration varies within the range from 0.45% to 0.70%.
3. In NT Build 492, chloride concentration of 0.07 N at the color change boundary can also be used for slag concrete. The difference between migration coefficients (M_c) and (M_{cp}) from Eq. (5) is ~ 4 %.
4. The migration coefficient (M_c), which was obtained from RCM test, correlates linearly with the migration coefficient (M_n), obtained from the chloride profile.
5. There is a close relationship between the initial current and the migration coefficient (M_c). Measurement of the initial current provides a rapid way of predicting the migration coefficient (M_c).

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NOMENCLATURE

a	the experimental parameter
C	the concentration of ions
C_d	the concentration of chloride in the pore solution corresponding to the color change boundary
C_{dp}	the chloride concentration at the color change boundary obtained from chloride profile
C_o	the chloride concentration in cathode cell
C_p	the chloride content in the chloride profile curve
C_s	the surface chloride content
d_c	the color change boundary from colourimetric method
d_p	the chloride penetration depth obtained from chloride profile
E	the strength of the electric field
F	the Faraday constant
I_0	the initial current
M_c	the chloride migration coefficient obtained from colourimetric method
M_c	the chloride migration coefficient obtained from colourimetric method
M_{cp}	the chloride migration coefficient obtained from chloride profile by using the color change boundary
M_n	the chloride migration coefficient obtained from chloride profile
R	the universal gas constant
t	the migration time
T	absolute temperature
x	the distance of migration
z	the electrical charge of chloride.

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