the charge passed and the penetration depth of chloride for OPC concrete is statistically derived using

$$d = 1.72 \times 10^{-3} Q - 1.27, \qquad (6)$$

where d is the chloride penetration depth in cm, and Q is charge passed in coulomb. Using Eq. (6) determines the penetration depths of chloride corresponding to the charge passed of 1000 C, 2000 C, and 4000 C. The chloride permeability ratings of concrete listed in Table 4 are based on the penetration depth and the charge passed through the specimen during the 6-h test.

In Fig. 4, F1, F2, F3, and C1 represent the mixes of F20-65, F20-55, F50-65, and F0-30, respectively. The charge passed through C1 is the highest, but the penetration depth of the chloride for C1 is the lowest. The chloride profiles for F0-30 and F20-65 are provided in Fig. 5. The charge that passed through the F0-30 mix (OPC concrete) is approximately 1.5 times higher than that which passed through F20-65 (fly ash concrete), and the total amount of chloride in F0-30 is approximately 1.48 times higher than that in F20-65. Based on the charge passed, F20-65 has a lower permeability than that of F0-30. However, the penetration depth of chloride for F20-65 is nearly 1.5 times higher than that for F0-30, as shown in Fig. 5. Engineers are concerned with the advance of the critical chloride front toward the steel and not with near-surface chloride concentrations [6]. The charge passed value suggests that F20-65 has lower chloride permeability than that of F0-30, whereas the depth of penetration of the chloride is higher than that of F0-30. Therefore, improving the RCPT is crucial for overcoming this problem.

3.5 Chloride profile from the charge passed and surface chloride content

Determining the chloride profile of a concrete specimen requires grinding and collecting many samples for analysis. An alternative, less time-consuming method has been formulated to determine the chloride profile. The total amount of chloride determined in the specimen, based on the chloride profile expressed in Eqs. (4) and (2), can be calculated using

$$m = \frac{1}{L}\int C_s \exp(-ax^2)dx, \qquad (7)$$

and

$$m = \frac{C_s}{2L}\sqrt{\frac{\pi}{a}}. \qquad (8)$$

The experimental constant a can be calculated using

$$a = \frac{\pi C_s^2}{4m^2L^2}. \qquad (9)$$

By substituting the value of a into Eq. (2), the chloride profile can be expressed as

$$C = C_s \exp\left(\frac{-\pi C_s^2}{4m^2L^2}x^2\right). \qquad (10)$$

Equation (10) shows that the chloride profile can be obtained by measuring the total amount of chloride (m), the surface chloride content (C_s), and the thickness of the specimen (L).

The depth of the first slice (d_1) and the corresponding chloride content (C_1) for all mixes are obtained from the nearest surface slice of the specimen, as shown in Table 4. By substituting d_1, C_1, and the total amount of chloride obtained from charge passed (m_Q) into Eq. (10), the surface chloride content (C_{s1}) is obtained using a trial and error method (Table 3). The total amount of chloride in a specimen (m_Q) determined by measuring the total charge passed (Q) and using Eq. (4), and the surface chloride content (C_{s1}) listed in Table 4, were used to obtain the chloride profile of concrete by using Eq. (10). Table 3 lists the predicted experimental constant (a_p) and the chloride penetration depths (d_p) obtained from the profile.

Figure 6 illustrates the predicted curve of the chloride penetration profile (dashed line) and the chloride penetration profile obtained by curve fitting the experimental data (solid line) of the mixes F0-30. The predicted curve of the chloride profile effectively matches the chloride penetration profile obtained from curve fitting the experimental data. The results of the predicted chloride profiles in Fig. 6, the predicted curve of the chloride penetration profile based on measuring the coulombs, and the chloride content of the first slice confirm that the trial and error method can be used for evaluating the chloride profile rapidly.

The RCPT charge passed results and the chloride penetration depths obtained from the profiles of all of the specimens, except F0-60 and F0-65, are presented in Fig. 10. According to the coulomb specifications listed in Table 4, the concrete containing fly ash has very low chloride permeability; however, according to the chloride penetration depth specification, the concrete containing fly ash has low chloride permeability. Comparing the results of the charge passed and chloride penetration depths for F0-30 and F20-65 (Fig. 5) shows that the chloride penetration depth is an accurate criterion for assessing the chloride permeability of fly ash concrete

3.6 Modified RCPT method

Concrete with fly ash can have a reduced charge passed value during the RCPT, but its chloride penetration depth shows that it does not have low permeability. To improve the RCPT for testing concrete that contains supplementary cementing materials, the following modifications were made to the standard procedure:

(1) The procedure followed for the RCPT was the same as that described in the ASTM C1202.

(2) The value of the charge passed during the RCPT was used to calculate the total amount of chloride m by using Eq. (5).

(3) After the completion of the RCPT, the surface chloride content C_s was determined according to the nearest surface slice of approximately 3 mm in thickness.

(4) The thickness of the specimen and the values of m and C_s obtained using steps (2) and (3) were substituted into Eq. (10) to determine the chloride profile.

(5) The chloride penetration depth was determined according to the chloride profile to assess the chloride permeability of concrete by using the data listed in Table 5.

The modified RCPT method based on the chloride penetration depth is used to assess the chloride permeability of fly ash concrete, and the penetration depth is obtained from the chloride profile. The only additional step taken during the modified RCPT procedure involves measuring the surface chloride content after the completion of the RCPT.

4. Conclusion

1. For the same value of charge passed during the RCPT, concrete with fly ash shows higher a chloride penetration depth than that of OPC concrete, because of the low surface chloride content.
2. A linear relationship exists between the charge passed during the RCPT and the total amount of chloride determined according to the chloride profile at the end of the RCPT. The total amount of chloride can be determined by measuring the charge passed.
3. The chloride profile can be obtained by measuring the total amount of chloride, the surface chloride content, and the thickness of the specimen.
4. Based on the chloride penetration depth, this study proposes a modified RCPT method. The only additional step taken during the modified RCPT procedure entails measuring the surface

chloride content after the completion of the RCPT. The modified RCPT method can be used to assess the chloride permeability of concrete and fly ash concrete.

Acknowledgment

The financial support of National Science Council, ROC, under the grants NSC 102-2221-E-019 -061 is gratefully appreciated.

References

[1] D. Ravikumar, N. Neithalath, Electrically induced chloride ion transport in alkali activated slag concretes and the influence of microstructure, Cem. Concr. Res. 47 (2013) 31–42.
[2] C.C. Yang, L.C. Wang, T.L. Weng, Using charge passed and total chloride content to assess the effect of penetrating silane sealer on the transport properties of concrete, Mater. Chem. Phys. 85 (2004) 238–244.
[3] C.C. Yang, J.K. Su, Approximate migration coefficient of interfacial transition zone and the effect of aggregate content on the migration coefficient of mortar, Cem. Concr. Res. 32

(2002) 1559–1565.

[4] C.M. Aldea, F. Young, K. Wang, S.P. Shah, Effects of curing conditions on properties of concrete using slag replacement, Cem. Concr. Res. 30 (2000) 465–472.

[5] S.S. Park, S.J. Kwon, S.H. Jung, Analysis technique for chloride penetration in cracked concrete using equivalent diffusion and permeation, Constr. Build. Mater. 29 (2012) 183–192.

[6] W.J. McCarter, G. Starrs, T.M. Chrisp, Electrical conductivity, diffusion, and permeability of Portland cement-based mortars, Cem. Concr. Res. 30 (2000) 1395–1400.

[7] D.W. Pfeifer, D.B. McDonald, P.D. Krauss, The Rapid Chloride Permeability Test and Its Correlation to the 90-day Chloride Ponding Test, PCI Journal 39 (1994) 38–47.

[8] C, Shi, Effect of mixing proportions of concrete on its electrical conductivity and the rapid chloride permeability test (ASTM C1202 or ASSHTO T277) results, Cem. Concr. Res. 34 (2004) 537–545.