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A modified rapid chloride permeability test (RCPT) method to assess the permeability of fly ash concrete

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Abstract

Portland cement (OPC) concrete and fly ash concrete were subjected to the ASTM C1202 rapid chloride permeability test (RCPT). The rapid chloride permeability test (RCPT), designated as ASTM C1202, is used for rapid qualitative assessment of the chloride permeability of concrete. The RCPT standards specify the rating of chloride permeability of concrete based on the charge passing through the specimen during a 6-h test. When the RCPT was complete, the chloride profiles of the specimens were determined by collecting concrete powder samples at different depths. The chloride penetration depth is calculated according to the chloride profile, and a value of 0.01% chloride was applied. The charge that passed through the F0-30 mix (OPC concrete with w/c=0.3) is approximately 1.5 times higher than that which passed through F20-65 (fly ash concrete with w/b=0.65 and 20% of the cement was replaced with fly ash). 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. 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. Based on a linear relationship found between the charge passed during the RCPT and the total amount of chloride obtained from the chloride profile, the total amount of chloride can be determined by measuring the amount of charge passed. The chloride profile can be obtained based on the measurement of charge passed, the surface chloride content, and the thickness of the specimen. Based on the chloride penetration depth obtained from the chloride profile, a modified RCPT method was used to assess the chloride permeability of concrete. The only additional step taken during the modified RCPT procedure entails measuring the surface chloride content after the

completion of the RCPT.

1. Introduction

The RCPT has been used in recent years mainly to assess the ability of concrete to resist the penetration of chloride ions. In addition, the RCPT method has been used to investigate (1) the mineral admixture effect on the resistance of chloride ion penetration [1], (2) surface treatments [2], (3) the aggregate fraction [3], (4) the curing condition [4], and (5) the cracking of concrete [5] caused by the penetration of chloride ions. McCarter et al. [6] reported that the conductivity of the free pore fluid increases with increased temperature, and that the applied electrical potential of the RCPT heats the concrete specimen, thus affecting the flow speed. Pfeifer et al. [7] mentioned that reliable correlations might not exist between the results of the RCPT and a 90-d salt ponding test. Shi [8] observed that the transport of ions in concrete depends on the pore structure of the concrete, whereas RCPT results depend on both the pore structure characteristics and electrical conductivity of the pore solution. Thus, it is inappropriate to use RCPT results to rank the chloride permeability of concrete containing supplementary cementing materials such as blast furnace slag, fly ash, and silica fumes.

In this study, Portland cement (OPC) concrete and fly ash concrete were carried out with the RCPT, and the chloride profile in the specimen was measured after the completion of the RCPT. A modified RCPT method based on the chloride penetration depth was used to assess the chloride permeability of OPC concrete and fly ash concrete.

2. Experimental program

2.1. Materials and specimen preparation

ASTM Type I Portland cement and F type fly ash were used as binders. River sand was used as the fine aggregate, and crushed limestone with a maximum size of 10 mm was used as the coarse aggregate. Table 1 lists the concrete proportions. Five series binders (F0, F20, F30, F40, and F50), each with different w/b ratios, were used. Series F0 is OPC concrete, and 20%, 30%, 40%, and 50% of the cement was replaced with fly ash in series F20, F30, F40, and F50, respectively. For each mix, numerous cylindrical specimens (ϕ100 x 200 mm) were cast and cured. After the specimens cured in water (23 ℃) for 91 d, 50-mm-thick, 100-mm-diameter concrete specimens were cut from the central portion of the cylinders. The specimens were vacuum-saturated prior to testing, as described in the ASTM C1202.

2.2. Rapid chloride penetration test

In the RCPT, a vacuum-saturated, 50-mm-thick specimen was placed between two acrylic cells. One of the cells was filled with a 0.30-mole/L NaOH solution and the other cell was filled with a 0.52-mole/L NaCl solution. The cells were connected to a 60-V power source. The current was measured and recorded using a data logger, and the total charge passed through the specimen was computed by integrating the current and time.

2.3 Chloride profile determined after the RCPT

After the RCPT, The profile Grinder PF-1100 was used for grinding and collecting the powder sample of concrete at a specified depth from the specimen surface. The chloride ion content at every increment in depth is determined based on the ground powders in accordance with AASHTO T260.

3. Results and discussion

3.1. Charge passed during the RCPT

The total charge passed obtained from RCPT, Q, is determined by integrating the current-time curve and is calculated using

$$Q = \int I(t)dt, \tag{1}$$

where $I(t)$ is the time-dependent total electrical current and t is the elapsed time. Table 2 lists the values of Q obtained using the RCPT for all mixes

3.2 Chloride profile obtained after the RCPT

After the RCPT is conducted, a specimen is examined at different depths when the chloride migration into concrete is complete.

3.2.1 Chloride profile

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

$$C = C_s \cdot \exp\left(-ax^2\right), \tag{2}$$

where C is the chloride content, C_s is the surface chloride content, and a is the experimental constant. The fitting of Eq. (2) was conducted using a commercial curve-fitting software program. Table 2 lists the surface chloride content (C_s), correlation coefficient (R^2), and experimental constant (a) for all test specimens. The experimental results and chloride profiles for series F0 and F20 are shown in Figs. 1 and 2. Figure 1(b) shows that the chloride ions passed through the specimen and reached the anode cell. As shown in Fig. 1(a), the surface chloride content (C_s) decreased with the increasing w/b ratio for series F0. The values of surface chloride content in Table 2 and Figs. 1 and 2 indicate that using fly ash can reduce the surface chloride content at the end of the RCPT.

3.2.2 Penetration depth of chloride

The chloride penetration depth is calculated according to the chloride profile, and a value of 0.01% chloride was applied, as shown in Fig. 3. Based on Eq. (2), the chloride penetration depth (d) is calculated using

$$d = \left(\frac{-\ln\left(0.01/C_s\right)}{a} \right)^{0.5}. \quad (3)$$

Using Eq. (3) yields the chloride penetration depths obtained from the chloride profiles of all mixes, as shown in Table 2.

3.2.3 Total amount of chloride migration

This study determined the total amount of chloride migration into the specimen obtained in the RCPT. The total amount of chloride in a specimen (Fig. 2) is determined by integrating the chloride profile curve and calculated using

$$m = \frac{A}{V}\int Cdx = \frac{1}{L}\int Cdx, \quad (4)$$

where m is the total amount of chloride (%, wt. specimen), A is the cross section area of the specimen, and V and L are the specimen volume and thickness, respectively. Using Eq. (4) determines the total amount of chloride m obtained from the chloride profiles of all mixes, as shown in Table 2. The total amount of chloride increases with increasing w/b ratios for each series. For a given w/b ratio, the total amount of chloride for the concrete with fly ash is lower than that of the Portland cement concrete (F0).

3.3 Charge passed and total amount of chloride

Figure 3 illustrates the relationship between the charge passed and the total amount of chloride, both obtained using the RCPT for all mixes except F0-60 and F0-65. The data shown in Fig. 3 were subjected to linear regression analysis, and the empirical relationship between the charge passed and the total amount of chloride was statistically derived using

$$m = 2.528\times10^{-5} Q + 2.311\times10^{-3}. \tag{5}$$

Based on linear regression analysis, a linear relationship exists between the total amount of chloride (m) and the charge passed (Q). The correlation coefficient is 0.997, indicating that the total amount of chloride (m) can be determined using Eq. (5) when the value of the charge passed is known. Using the values of the charge passed (Table 2) yields the values of the total amount of chloride obtained from the charge passed (m_Q) for all mixes (Table 3).

3.4 Charge passed and penetration depth of chloride

Figure 4 illustrates the relationship between the charge passed and the penetration depths of chloride for all mixes except F0-60 and F0-65. The results of testing concrete with fly ash and OPC are subjected to linear regression analysis, separately. The empirical relationship between the charge passed and the penetration depth of chloride for OPC concrete is statistically derived using

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

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

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

and

$$m = \frac{C_s}{2L}\sqrt{\frac{\pi}{a}}. \tag{8}$$

The experimental constant a can be calculated using

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

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

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

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.

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