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New perspective of service life prediction of fly ash concrete

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HIGHLIGHTS

- The chloride migration coefficients of fly ash concrete are determined with maximum curing age of 2 years.
- *w*/*b* Ratio largely influences the chloride migration coefficients of fly ash concrete.
- A reasonable reference time, t_0 is determined for fly ash concrete.
- The service life of fly ash concrete is predicted based on DuraCrete model.
- The long-term chloride migration coefficient of fly ash concrete is predicted under laboratory condition.

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ABSTRACT

Rapid Chloride Migration (RCM) test developed in Sweden in the 90s is widely used to determine the chloride migration coefficient (D_{RCM}) of concrete because of its simplicity and rapidity. In Europe, the time-dependent D_{RCM} has been introduced in the DuraCrete project as input parameter to predict the service life of concrete. In the DuraCrete project, when determining the D_{RCM} of fly ash concrete, reference time (the maturity age of concrete) is normally set as 28 days like what used in Portland cement concrete and blast furnace slag (BFS) concrete. However, fly ash does not fully play its role in concrete at 28 days due to slow Pozzolanic reaction of fly ash. Therefore, 28 days is not a realistic reference time for predicting service life of fly ash concrete. This study is aimed at determining a reasonable reference time (t_0) for fly ash concrete. The D_{RCM} of fly ash concrete is determined by the RCM test for a long-term period of curing up to 2 years. The influences of fly ash dosage and *w*/*b* ratio on the D_{RCM} of fly ash concrete were considered. The results show that the D_{RCM} of fly ash concrete significantly decreases after 28 days of curing. The reference time, t_0 for fly ash concrete is proposed according to the concrete maturity indicated by the content of calcium hydroxide (CH) in cement paste blended with fly ash. This proposed reference time is applied to predict the service life of fly ash concrete and predict the long-term chloride migration coefficient of fly ash concrete under laboratory condition.

1. Introduction

Chloride ingression is one of the most important factors affecting the durability of reinforced concrete structure. Corrosion caused by chloride penetration leads to the deterioration of bridge, marine structure, manufacturing plant, and construction building. In Europe, around 5 billion Euros were spent on maintenance of the infrastructure due to reinforcement corrosion annually [1]. Nowadays, much attention has been devoted to extend the service life of concrete structure suffering from chloride ingress. To prevent such kind of corrosion, the concrete structure with good impermeability is desired. Until now, a number of studies [2–7] have been performed and shown that fly ash as partial replacement of Portland cement is able to improve the resistance of concrete against chloride ingress. At present, different test methods for measuring and evaluating chloride ingress have been proposed. These methods can be categorized as diffusion test, migration test, and indirect tests based on resistivity or conductivity [8]. Rapid Chloride Migration (RCM) test is a non-steady state migration test applying an external electrical field for accelerating chloride penetration. The parameter, non-steady state migration coefficient (D_{RCM}) obtained from RCM test describes the property of chloride transport under a condition of reduced chloride binding [9]. Nowadays, it is widely used in Europe.

The D_{RCM} obtained from the RCM test is not only used to estimate the resistance of concrete to chloride ingress, but used for predicting the service life of concrete by means of the model proposed in the DuraCrete-project [10]. The DuraCrete project is one of the guidelines for durability design and assessment of concrete

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structure, which is also widely used in Europe. The chloride content at certain depth and time is calculated by the following equation [11,12].

$$C(x,t) = C_s - (C_s - C_i)erf\left[\frac{x}{\sqrt{\{4kD(t)t\}}}\right] \tag{1}$$

where $C(x,t)$ is the chloride content at depth x and time t, C_s is the surface chloride content, C_i is the initial chloride content in the concrete, k is a correction factor, which depends on the binder type, the environment and the curing conditions. $D(t)$ is the apparent migration coefficient at time t. It is a time-dependent function.

$$D(t) = D_0\left(\frac{t_0}{t}\right)^n \tag{2}$$

where D_0 is the achieved chloride migration coefficient at the maturity age t_0 of the concrete [13].

The parameter n is the ageing coefficient. It is theoretically range from 0 to 1 [13]. It depends on the type of binder, the rate of cement hydration and environmental factors. D_0 and n are the parameters determined by regression analysis of the test results [13]. The ageing coefficient, n, was determined by various researchers for different concrete binders under different exposure conditions. According to Fick's second law of diffusion, some diffusion coefficients are determined for the same concrete binder at different ages. The ageing coefficient can be obtained from the slope of the diffusion coefficient against time [14]. This way is adopted in the DuraCrete and European standard [15]. Another possibility to obtain ageing coefficient is to use the actual RCM values from specimens of different age. But this RCM test results should from field exposure describing the actual use conditions [14]. In DuraCrete, the $D_{\mathrm{RCM,28days}}$ measured at the curing age of 28 days (reference time, t_0) has been suggested to use for predicting the service life of concrete structures. At 28 days, a substantial percentage of the hydration has taken place for Portland cement concrete with a typical water/cement (w/c) ratio and over 90% of final strength is reached at 28 days. When Portland cement is partially replaced by fly ash, the addition of fly ash improves the long-term resistance of concrete to chloride ingress. Cox [4] demonstrated that the D_{RCM} value of fly ash concrete decreases significantly with the increase of curing age, although fly ash concrete has a much higher D_{RCM} value at 28 days than Portland cement concrete. Most of the studies about RCM test for Portland cement concrete and fly ash concrete focused on the short-term curing age (3 months). The Pozzolanic reaction of fly ash in concrete consuming calcium hydroxide (CH) is very slow during the early age hydration [16,17]. Fly ash concrete needs longer curing time to reach equal maturity like Portland cement concrete at the same temperature. The predicted service life of fly ash concrete could be underestimated when 28 days is chosen as reference time (t_0).

The aim of this study is to determine a reasonable reference time, t_0 which can be used to predict the service life of fly ash concrete based on the DuraCrete model. In this paper, the chloride migration coefficient of fly ash concrete blended with different dosages of fly ash and different w/b ratios were determined by the RCM test and compared with Portland cement concrete. The curing periods are up to 2 years. Meanwhile, the content of CH was determined in blended cement paste. The Pozzolanic reaction of fly ash is characterized and the reference time is redefined. The long-term chloride migration coefficient of fly ash concrete is predicted under laboratory condition which is as an application on the basis of the redefined reference time.

2. Materials and methods

2.1. Materials and properties

Portland cement (CEM I 42,5 N), fly ash (low calcium) with mean particle size of 21.46 μm, aggregate, and tap water were used in preparing concrete mixtures. Graded Dutch river sands with a maximum grain size of 4 mm and gravel with a 16 mm maximum grain size were used as fine and coarse aggregates, respectively. Demineralized water was applied to cast blended cement paste. The chemical compositions of fly ash and Portland cement used are shown in Table 1.

2.2. Mix proportions and specimen preparation

The dosages of fly ash were 30% and 50% as the replacement of Portland cement by weight for fly ash concrete mixtures and blended cement paste mixtures. The water/binder (w/b) ratios used for fly ash concrete were 0.4, 0.5, and 0.6. Two w/b ratios, 0.4 and 0.5 were used to cast the cement paste blended with 30% fly ash. The w/b ratio of 0.4 was used to prepare the cement paste blended with 50% fly ash. The fly ash concrete with 50% of fly ash and with a w/b ratio of 0.6, the cement paste blended with 30% fly ash and a w/c ratio of 0.6, and the cement paste blended with 50% fly ash and two w/c ratios of 0.5 and 0.6 were excluded because of segregation and bleeding. The mixture proportions of concrete and blended cement paste are given in Tables 2 and 3.

After mixing for 2 min, the concrete mixtures used in the RCM test were cast in cylindrical molds with a diameter of 100 mm and height of 300 mm. After 24 h, the concrete specimens were demolded and cured in the fog room (95% ± 5% relative humidity and 20 °C ± 1 °C temperature). After preconditioning, the RCM test was performed at 28, 91, 180, 365 and 730 days. Before testing, the hardened concrete specimens were cut into three cylindrical samples (height = 50 mm) as shown in Fig. 1.

The blended cement pastes to be used for thermal gravimetric analysis (TGA) measurement was cast at room temperature around 20 ± 2 °C. After mixing for 3 min, the specimens were sealed in a plastic bottle to prevent moisture loss and rotated for 24 h to avoid possible segregation. Then, the specimens were stored at room temperature. At the cuing age of 28, 90, 180, 365, and 730 days, the specimens were demolded from the plastic bottle and crushed into small pieces around 1 cm diameter. Afterwards, the specimens were frozen by immersion into liquid nitrogen for 5 min in order to stop hydration [18], and then dried in a freeze-dryer until a constant weight loss (0.05%) was reached. The dried specimens were ground for TGA test.

2.3. Test methods

2.3.1. Rapid Chloride Migration (RCM) test

The Rapid Chloride Migration (RCM) test was conducted to determine the chloride migration coefficient of the concrete according to the NT Build 492 standard [19]. Fig. 2 shows the RCM test set-up used in this study.

Three slices with the thickness of 50 mm were cut from each concrete specimen. The surface-dry specimens were placed vertically in a desiccator connected to a vacuum-pump for 3 h. While the vacuum-pump was still running, the saturated limewater was slowly filled into the desiccator to immerse all the specimens completely. After that, the vacuum was maintained for an additional hour before allowing air to re-enter the desiccator. The specimens were kept in the limewater for 18 ± 2 h.

After above preconditioning, the specimens were put in a rubber sleeve and fastened with two stainless steel clamps. The used analyte solution was 0.3 M NaOH while the used catholyte solution was 10% NaCl. With the preset voltage 30 V, the initial current through each specimen was recorded. Following the standard [19], a corrected voltage and appropriate test duration were chosen. After chloride migration test, all specimens were split and sprayed with 0.1 M silver nitrate ($AgNO_3$) solution to determine the penetration depth of chloride. Fig. 3 shows a typical split specimen after RCM test. The white silver chloride precipitation on the split surface is clearly visible (after 15 min). The average penetration depth, X_d of chloride was recorded.

The non-steady-state migration coefficient was calculated by the following equation [18]:

$$D_{RCM} = \frac{0.0239\cdot(273+T)\cdot L}{(U-2)\cdot t_d}\cdot\left(x_d - 0.0238\sqrt{\frac{(273+T)\cdot L\cdot x_d}{U-2}}\right) \tag{3}$$

where D_{RCM} is the non-steady-state migration coefficient, $\times10^{-12}$ m^2/s; U is absolute value of the applied voltage, V; T is average value of the initial and final temperatures in the anolyte solution, °C; L is thickness of the specimen, mm; X_d is average value of the penetration depths, mm; and t_d is the test duration, h.