Materials Chemistry and Physics 196 (2017) 315–323

Contents lists available at ScienceDirect

Materials Chemistry and Physics

journal homepage: www.elsevier.com/locate/matchemphys

Understanding the effect of curing age on the chloride resistance of fly ash blended concrete by rapid chloride migration test

Jun Liu [a], Xiaodong Wang [a], Qiwen Qiu [b,*], Guangfeng Ou [c], Feng Xing [a]

[a] Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, College of Civil Engineering, Shenzhen University, Shenzhen 518060, Guangdong, China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China
[c] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

HIGHLIGHTS

- Curing age effect on chloride migration of fly ash concrete is studied by RCM test.
- Chloride migration coefficient of fly ash concrete reduces as curing age increases.
- Low content fly ash incorporation promotes chloride migration at early curing age.
- High volume fly ash addition resists chloride migration through entire curing age.
- Chloride migration coefficient increases proportionally with water-to-binder ratio.

ARTICLE INFO

Article history:
Received 11 November 2016
Received in revised form
30 April 2017
Accepted 7 May 2017
Available online 8 May 2017

Keywords:
Fly ash concrete
Chloride
Rapid chloride migration test
Curing age
Microstructures

ABSTRACT

Chloride ingress is considered as the most responsibility to steel corrosion for offshore concrete structure during service. Fly ash has been shown to effectively enhance the resistance of concrete to chloride penetration. Despite the numerous contributions of investigation regarding the chloride migration behavior of fly ash blended concrete composites by using rapid chloride migration (RCM) test, there is still a lack of critical understanding of curing age effect on the chloride migration in fly ash concrete under RCM testing system. The present study aims to investigate the effect of curing age on the resistance of fly ash blended concrete to chloride ion under RCM test, also considering the factors of water-to-binder ratio and fly ash content at the same time.

Based on the RCM tested results, it is found that the effect of curing age condition on the chloride migration resistance is depended on the amount of fly ash incorporated in concrete. Short term curing age can lead to increase the chloride migration coefficient of concrete with low fly ash content. But resistance to the chloride migration can still be enhanced at this curing stage when high percentage of fly ash is supplied. Long term curing age can benefit the chloride migration resistance, regardless of how much fly ash is used in concrete. However, this positive effect becomes less significant when increasing the curing time at the late curing stage. The concrete microstructure is also explored to elucidate the macro-behavior of chloride migration.

1. Introduction

With the development of composite technology in the field of civil infrastructure, the supplementary cementing materials have been widely adopted as cement replacement in concrete, due to the positive effects of energy conservation, economic and environmental consideration [1–7]. Fly ash is one of such materials, being a by-product of coal combustion in power plants and metallurgical industries [8–13]. Nevertheless, concrete composites blended with fly ash exhibit a durability concern when applied in harsh environments where the ingression of aggressive substances (*e.g.* salts, acids) can occur [14–17]. It is generally accepted that chloride ingress is considered as the most responsibility of steel corrosion and premature failure for offshore concrete structure during service [18–21]. Due to the increasing societal concerns

* Corresponding author.
E-mail address: qiuqiwen0422@gmail.com (Q. Qiu).

http://dx.doi.org/10.1016/j.matchemphys.2017.05.011
0254-0584/

Table 1
Chemical compositions of cement and fly ash.

Composition (Mass % as oxide)	Cement	Fly ash
Silica (SiO_2)	18.59	62.32
Calcium oxide (CaO)	64.67	4.74
Alumina (Al_2O_3)	4.62	23.59
Iron Oxide (Fe_2O_3)	4.17	1.33
Magnesium oxide (MgO)	2.35	2.04
Sulfur trioxide (SO_3)	3.32	1.25
Potassium oxide (K_2O)	0.92	0.76

Note: The loss on ignition for cement and fly ash is 1.03 and 3.12, respectively.

about safety of concrete structures, numerous studies have attempted to determine the resistance of chloride penetration through concrete materials. In order to measure the chloride migration coefficient, long term immersion test method has been adopted which involves in the penetration of chloride ion into the concrete due to the chlorides concentration gradient in a natural manner [22–24]. However, this method has the critical limitations of low efficiency and complexity of operation. Normally, long term immersion test requires a minimum of one year of exposure to the simulated chloride environment before the chloride migration coefficient is evaluated [25]. Compared to long-term immersion test method, the rapid chloride migration (RCM) test has been proven to be a rapid, reliable and effective way to determine the chloride migration coefficient for concrete containing different types of supplementary cementing materials [26,27]. Based on RCM test, a number of studies have been carried out to investigate the chloride migration behavior for cement and concrete materials. RCM tests conducted by C.C. Yang et al. [28,29] have found that the chloride migration coefficient of concrete increases linearly with increasing water-to-binder ratio. Besides, P. Chindaprasirt et al. [30] have used the RCM test to investigate the resistance to chloride penetration for blended Portland cement mortar containing fly ash. The tested result indicates that incorporating the fly ash can effectively improve the mortar in terms of resistance to chloride penetration. By using RCM test, the beneficial effect of fly ash on reducing the chloride penetrability has also been demonstrated in other literature [28,31–33]. However, the above studies did not consider the influence of curing age on the chloride resistance of concrete with different fly ash contents and water-to-binder ratios at the same time. In fact, only a limited number of studies are available in the literature on the correlation of curing age and the resistance of chloride migration for fly ash concrete. A study has found that the electrical resistivity can be improved as the curing age increases, and this suggests that late curing age can reduce the chloride migration coefficient of fly ash concrete [32]. Other studies also indicate the beneficial effect of long term curing age on resisting the chloride migration [34,35]. Presently, little study has considered the impact of short term curing age on the performance of chloride migration for fly ash concrete. At the early curing age, fly ash concrete may exhibit high porosity due to the slow cement hydration and weak pozzolanic reaction [36]. Short term curing age for fly ash concrete may lead to a higher chloride migration coefficient than plain cement concrete and this effect is thought to be associated with the amount of fly ash incorporation. On the other hand, there is still a deficiency of using the testing system of RCM for understanding the effect of curing age on the resistance of fly ash blended concrete against the chloride migration. Based on the above discussion, the present study focuses on investigating the curing age effect (including short term and long term curing stage) on the chloride migration coefficient of concrete with different fly ash contents and water-to-cement ratios, based on the RCM test. Microstructure of fly ash concrete is also investigated with the aim to support the research findings from RCM test.

2. Materials and methods

2.1. Materials

The cement used in this study was Type I ordinary Portland cement (OPC) provided by Haixing Onoda Cement (Shenzhen) Co. Ltd. Class I fly ash was supplied by Shenzhen Mawan Power Plant. The chemical compositions of cement and fly ash are given in Table 1. River sand was used as fine aggregate with the fineness modulus of 2.61 and the apparent density of 2632 kg/m^3. Crush stone was used as coarse aggregate with the particle size of 5–20 mm and the apparent density of 2700 kg/m^3. Distilled water with an electrical resistivity of 18.2 MΩ cm at 25 °C was used as mixing water.

2.2. Mixture proportions and specimen preparation

Three water-to-binder ratios were considered in the fabrication of fly ash concretes: 0.38, 0.47, and 0.53. Fly ash concretes with two fly ash replacement levels (15% and 30% by volume of cement) were fabricated. The mixture proportions of fly ash concretes are listed in Table 2. All specimens were mixed in a pan mixer and then cast in moulds with the dimensions of 100 $\times$ 100 mm cylinder. After 24 h, all concrete specimens were demoulded and cured at the temperature of 20 $\pm$ 2 °C and the relative humidity of 95% until the testing days. The curing ages were set as 28, 90 and 180 days.

The compressive strength and the split tensile strength of all the concrete specimens prepared at the curing ages of 28, 90, and 180 days were measured in this study and the results are listed in Tables 3 and 4, respectively. Besides, the apparent density variations for all concrete specimens before and after RCM test were investigated, and their results are discussed in the next section.

2.3. Rapid chloride migration test

After curing, 25 mm of the outermost surfaces of each cylinder sample were sliced off, leaving the core cylinder with 50 mm thick to be measured by RCM test, as shown in Fig. 1(a). The schematic diagram of the RCM test set-up for measuring the chloride migration coefficient is shown in Fig. 1(b). The specimen was placed at

Table 2
Mix proportions of concretes.

Sample	Composition (kg/m^3)					
	Cement	Fly ash	Sand	Coarse aggregate	Water	Water-to-binder ratio
C53	396	0	718	1076	210	0.53
C47	409	0	720	1079	192	0.47
C38	454	0	729	1094	173	0.38
CF47-15	348	61	697	1054	192	0.47
CF47-30	286	123	689	1041	192	0.47