Construction and Building Materials 111 (2016) 488–494

Contents lists available at ScienceDirect

Construction and Building Materials

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

A probabilistic assessment of the influence of age factor on the service life of concretes with limestone cement/GGBS binders

Azadeh Attari, Ciaran McNally *, Mark G. Richardson

School of Civil, Structural & Environmental Engineering, University College Dublin, Newstead, Belfield, Dublin 4, Ireland

HIGHLIGHTS

- The influence of varying GGBS content on age factor is determined.
- Probabilistic models for predicted service life are developed.
- Significant impact of age factor is confirmed.

ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form 7 January 2016
Accepted 22 February 2016
Available online 21 March 2016

Keywords:
Age factor
Chloride diffusion coefficient
CEM II/A-LL
GGBS
Service life modelling

ABSTRACT

The use of Supplementary Cementitious Materials (SCMs) in concrete manufacture has increased significantly in recent years. Utilising SCMs in the concrete mix reduces CO_2 footprint while also generally enhancing durability. Time-dependent characteristics of concrete become more significant as SCM replacement levels increase. Service life modelling requires incorporation of accurate age factors; however limited research has been published on the influence of time-dependent characteristics of SCM concretes when manufactured with limestone cement (CEM II/A-LL). In this study, mix-specific age factors were determined based on the chloride diffusivity of concretes produced using a limestone cement binder with varying replacement levels of ground granulated blast-furnace slag (GGBS). The experimentally-determined age factors were validated against field data. Application of the validated factors in service life assessment models indicated increased sensitivity of the models to increased GGBS replacement level while affirming the enhanced durability effect of GGBS when used in combination with limestone cement.

1. Introduction

Cement is a major global construction material and its production involves emission of a significant amount of CO_2. Previous research estimated that the cement industry was responsible for about 7% of the anthropogenic carbon dioxide generated globally [1]. This considerable contribution implies that any attempt in reducing the CO_2 footprint of the cement manufacturing industry can have a significant impact on promoting sustainable development.

1.1. Application of Supplementary Cementitious Material (SCM)

Since 1995, the cement industry has committed itself to decreasing CO_2 emissions, as part of the industry's response to improve sustainability and prevent further global warming [2]. However, the limited ability to reduce CO_2 emissions in the manufacture of ordinary Portland cement (OPC) necessitates the development of alternative cement binders. One approach to this is to replace OPC with blended cements in order to lower the share of clinker in the final product [3]. Additions such as ground granulated blast-furnace slag (GGBS), limestone, silica fume or fly ash can be mixed with ground clinker to produce blended cements such as CEM II and, in the case of GGBS, CEM III [4]; furthermore GGBS or fly ash can also be combined with CEM I or CEM II cements at the mixer to produce equivalent CEM II or ternary blend concretes. The increased use of such alternative materials to partially replace cement clinker is helping to address the environmental concerns of the global construction industry.

Ground granulated blast-furnace slag contributes to the formation of calcium silicate hydrates gel (CSH), the main product of cement hydration. The increased amount of CSH gel produced at later ages results in a more refined pore structure, which enhances

* Corresponding author.
E-mail address: ciaran.mcnally@ucd.ie (C. McNally).

http://dx.doi.org/10.1016/j.conbuildmat.2016.02.113

the impermeability and thereby durability of concrete. The quality of GGBS concrete is strongly influenced by curing, but the provision of good curing conditions reduces permeability and improves concrete resistance against aggressive chemical attacks. Performance improvement in these concretes continues well beyond the early age. Ground granulated blast-furnace slag concrete has been shown to double its 28 day strength over periods of 10–12 years [5].

1.2. Chloride-induced corrosion

Chloride-induced corrosion of reinforced concrete structures has been selected as the focus of this study, since it is known to be one of the most severe mechanisms of concrete deterioration in various environments. Penetration of chloride ions in concrete is governed by diffusion, which describes the movement of chloride ions under a concentration gradient. Diffusion occurs in a concrete medium with a continuous liquid phase and under persisting chloride ion concentration gradient [6]. The rate of chloride ingress in concrete is usually predicted using Fick's second law of diffusion and the error function solution that has been proposed to it [7] (Eq. (1)).

$$C(x,t) = C_s\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{(D_{eff} \times t)}}\right)\right] \quad (1)$$

In this equation, $C(x,t)$ represents chloride concentration (kg/m^3) at depth x from the surface of concrete specimen, at time t after the start of exposure; C_s is the effective surface chloride concentration (kg/m^3), and D_{eff} is the diffusion coefficient.

1.3. Diffusion coefficient

Diffusion coefficient (D_{eff}) is an important input parameter in evaluating the performance and durability of concrete structures exposed to aggressive chemical agents' ingress. Having accurate estimation of diffusion coefficient for a given concrete mix is essential for determining the rate and extent of penetration of aggressive ions such as chlorides. In the application of Eq. (1) it is implicit that the surface chloride concentration and diffusion coefficient remain constant over time during the exposure duration; this assumption however is not true for chloride ingress into concrete [8]. It is well established in the literature that the diffusion coefficient of cementitious systems decrease over time, mainly due to chloride binding and pore structure refinement as cement hydration continues. Application of a constant diffusion coefficient in this equation results in an overly conservative durability design, especially when SCMs are present in the mix.

1.3.1. Time-dependent behaviour

Several proposals have been advanced to model the variable value of D_{eff} more precisely. Equations were proposed using either time-dependent or composition-based models. For example, Stewart and Rosowsky [9] introduced a power function for predicting diffusion coefficient based on the water-cement (w/c) ratio of the mix. While w/c is clearly an influential concrete property, it does have limitations when it comes to modelling ionic transport. In these cases the generated models lack the capability to represent the change in diffusivity over time.

Eq. (2) is the most commonly used time-dependent model for estimating diffusion coefficient [8,10].

$$D_{eff}(t) = D_R\left(\frac{t_R}{t}\right)^m \quad (2)$$

where D_R is the diffusion coefficient at a reference time, t_R is the reference time, and m is the age factor [11]. Age factor can be determined by curve-fitting the field or experimental data of diffusion coefficient collected over time to the model of Eq. (2).

This equation is known to fit well with the data collected in marine environments [12]. Other researchers have also confirmed that Eq. (2) holds for both laboratory and field data [8,10]. Age factor is introduced to this formulation to reflect the effect of mix composition, water to cement ratio, and other concrete properties. The influence of this parameter on the values obtained for diffusion coefficient, and consequently on the service life assessment of structures is significant [13].

There are recommendations in the literature regarding the appropriate value of age factor in different mixes of concrete. A summary of these values has been provided in Table 1, where it can be seen that there is little agreement on appropriate age factors.

Furthermore, studies reporting this parameter in mixes of blended cement and additions are scarce. Studies that take into account the presence of GGBS do not make allowance for the replacement level, which can vary from 0 to 80%.

2. Experimental program

To quantify the effect of GGBS replacement level on diffusion coefficient and associated age factor, a set of four concrete mixes of particular relevance in Ireland were selected for study. The concrete mixes were manufactured using limestone aggregates, Portland-limestone cement (CEM II/A-LL) and GGBS replacement levels of 0, 30, 50 and 70%. Cylindrical specimens in the form of cores were obtained from concrete slabs with a dimension of $300 \times 300 \times 150$ mm, cast from each mix. The concrete slabs were stored under damp hessian at room temperature and were cored one week after casting. The cylindrical samples were then stored in water at 24 °C, until they were tested for diffusivity. Diffusion coefficient of these specimens was determined at pre-set time intervals using the standard Nordtest method of Rapid Chloride Migration (RCM) [21]. It should be noted that the raw data obtained from the RCM test are non-steady state migration coefficients. In order to extract the corresponding effective diffusion coefficients from this data, the methodology proposed by Tang and Nilsson [22] was followed. The results of this testing programme are presented in Table 2. The diffusivity of specimens over time showed a decreasing trend, as illustrated in Fig. 1.

It can be observed in Fig. 1 that, as the age of concrete and the GGBS replacement level increase, the diffusion coefficients generally decrease. GGBS replacement levels greater than 30% are observed to have a significant impact on further reducing the diffusion coefficients. According to the criteria proposed by Tang [23], both mixes with 50% and 70% GGBS replacement reached a 'good resistance' against chloride ingress after only one week. The mix with 70% GGBS is the only one that reaches a diffusion coefficient of less than 2×10^{-12} m^2/s, corresponding to 'very good resistance', within the period of monitoring.

Table 1
Various age factors proposed by different researchers.

Reference	Age factor (m)
Li [14]	Beta distribution $\mu = 0.5$, COV = 0.14
Bentz [15]	Normal distribution $\mu = 0.2$, COV = 0.25 (OPC) $\mu = 0.6$, COV = 0.25 (PFA/GGBS)
Thomas and Bamforth [16]	0.1 (OPC) 0.7 (PFA) 1.2 (GGBS)
Pack et al. [12]	0.06 (OPC) 0.23 (GGBS)
Thomas and Bentz [17]	0.2 + 0.4((GGBS/70) + (PFA/50)) 0 < GGBS < 70, 0 < PFA < 50
Ferreira [13]	Normal distribution $\mu = 0.37$–0.6, COV = 0.07
Costa and Appleton [18]	0.36–0.60
Nokken et al. [19]	0.55–0.77
Chisholm and Lee [11]	0.27–0.36 (75% GGBS) 0.02 (SF)
Goltermann [20]	0.75 (w/c < 0.55)