Consistent models for estimating chloride ingress parameters in fly ash concrete

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ABSTRACT

The addition of fly ash in cement or concrete is widely acknowledged to reduce chloride penetration and to enhance chloride binding capacity of cement paste fraction. This study proposes three parameter prediction models (submodels) of a chloride ingress model for fly ash concrete: time-variant surface chloride content; Langmuir and Freundlich isotherms constants; and reference chloride diffusion coefficient. The reliable evaluation of these submodels is essential to achieve more accurate estimation of the service life of concrete structures. Additionally, these submodels are required for physical modeling of coupled chloride-moisture transport in concrete. The comparison of chloride values between that estimated by incorporating submodels into the chloride ingress model with that from laboratory and field data show good agreement. The effects of submodel coefficients on the chloride ingress model are investigated through sensitivity analyses.

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1. Introduction

Concrete is the most consumed material in the world next to water, with three tonnes per year used for every person in the world. It is very likely that concrete will remain in use as a primary construction material for infrastructure in the future. Despite the availability of higher levels of know-how and equipment for quality concrete construction, in the recent past many concrete structures under chloride environments have undergone premature deterioration resulting in early reconstruction or major repairs involving a substantial investment. Chloride-induced rebar corrosion is one of the most common causes of deterioration in concrete structures exposed to chloride environments. Chloride environments can be attributed to the presence of seawater, de-icing salt, sea-salt spray or even industrial effluents [1,2]. Concrete structures exposed to chloride environments undergo not only earlier deterioration due to rebar corrosion but also severe degradation of concrete properties due to reactions of hydration products [3].

Chloride-induced rebar corrosion adversely affects the safety and serviceability of concrete structures, thus shortening their service lives. To avoid these, there are two main approaches; producing durable concrete that is capable of either stopping or slowing down the ingress of chloride ions [4,5], or applying appropriate maintenance plans [6].

Addition of supplementary cementitious materials, such as blastfurnace slag and fly ash, has been widely accepted to assist in producing both durable and sustainable concrete (e.g. Refs. [5,7]). When fly ash is added to either cement or concrete, calcium hydroxide liberated during hydration process reacts slowly with pozzolanic compounds present in fly ash. This reaction changes the pore structure of concrete thereby making it more dense, which not only reduces chloride and cation penetration but also increases chloride binding capacity of the cement paste fraction [8,9]. It is highly desirable to quantitatively assess such characteristics of fly ash as it can assist in effective service life modeling of concrete structures under chloride environments.

This study proposes three submodels for estimating the parameters involved in a chloride ingress model of fly ash concrete, namely, time-variant surface chloride content, Langmuir and Freundlich isotherms constants, and reference chloride diffusion coefficient. Reliable and careful evaluation of these submodels is essential to achieve more accurate and realistic estimation of the service life of concrete structures. Additionally, these submodels are required for physical modeling of coupled chloride-moisture transport in concrete (e.g. Ref. [10]). This work is presented in three main parts. The first part discusses relevant background, appropriate experimental data and procedure used to develop each of the three submodels. The second part provides experimental validation and comparison of the developed submodels based on the variety of real field and laboratory data while the

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third part presents a sensitivity analysis of submodel coefficients.

2. Time-variant surface chloride content

2.1. Background

In analytical and numerical models for the prediction of chloride ingress into concrete, surface chloride content (C_s) is one of the primary input parameters. C_s may depend on various parameters, such as the structure location, surface orientation, and chloride content in the environment. Table 1 lists various time-variant C_s models reported in literature for concrete specimens exposed to chloride environments. In Table 1, w/b represents water-to-binder ratio (a ratio by mass) and t represents exposure time in years. Table 1 indicates that, in the past, linear [11], power law [11,12], and natural logarithmic [13–15] functions or their combinations (e.g. Ref. [16]) have been adopted to find the trend of a given C_s data. Fig. 1 shows the plot of various C_s models listed in Table 1 along with a set of real field data reported in the literature [15,17]. Note that w/b ratios of 0.48, 0.50, 0.45, and 0.50 are adopted in Fig. 1 for C_s models reported in Refs. [11,12,15 and 16], respectively. The real field data shown in Fig. 1 reveals that chloride ions build-up progressively on the exposed surfaces of concrete under chloride environments. Additionally, Fig. 1 shows that such chloride build-up is faster during initial exposure period and becomes progressively slower with time and may even attain a constant value. The effects of binding induce progressive build-up of chloride on the surface of concrete, wetting-drying cycles also play a role, specifically when concrete is exposed to splash or tidal conditions [13]. Fig. 2 shows the plot of two of the natural logarithmic function based C_s models reported in the literature [13,14].

The following critical observations are drawn from Table 1, Figs. 1 and 2:

1. The values of are time-variant and are considerably affected by w/b ratio. Moreover, two models of C_s (i.e. Refs. [14,16]), which although are based on experiments conducted on fly ash concrete, are considered to be independent of the level of fly ash replacement (0–50%). This could mean that C_s values are not significantly affected by the level of fly ash replacement.
2. Trend lines predicted by the linear [11], power law [11,12], and combination of natural logarithm and power law [16] functions are inconsistent with real field data reported in the literature [15,17]. Instead of making reliable predictions, these functions significantly under- or over-estimate the values of C_s at different exposure periods.
3. Among various functions used to represent the trend of C_s data, natural logarithmic function provides best fit estimates under chloride environments. The natural logarithmic function most effectively represents the progressive build-up of chlorides occurring at the surfaces of concrete during the period of initial exposure.
4. Although two models reported in Refs. [13,14] (see Fig. 2) are based on natural logarithmic function, they predict negative values of C_s during initial exposure period (say 0–0.6 years). This implies that the surface chloride ions are moving out rather than penetrating into concrete, which is inapplicable in the problem of chloride ingress into concrete.

Perhaps, it needs to be added here that few studies in the past (e.g. Refs. [18,19]) have modeled chloride ingress into concrete by considering constant values of C_s, thereby ignoring the time-variant nature of C_s. This was primarily done based on the hypothesis that chloride ions at the surfaces of concrete remain in chemical
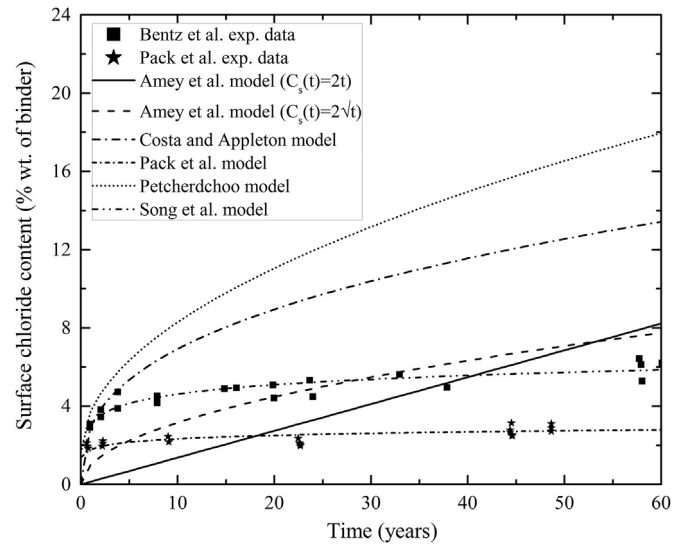

Fig. 1. Trend lines of various C_s models listed in Table 1 along with the field data of Pack et al. [15] and Bentz et al. [17].
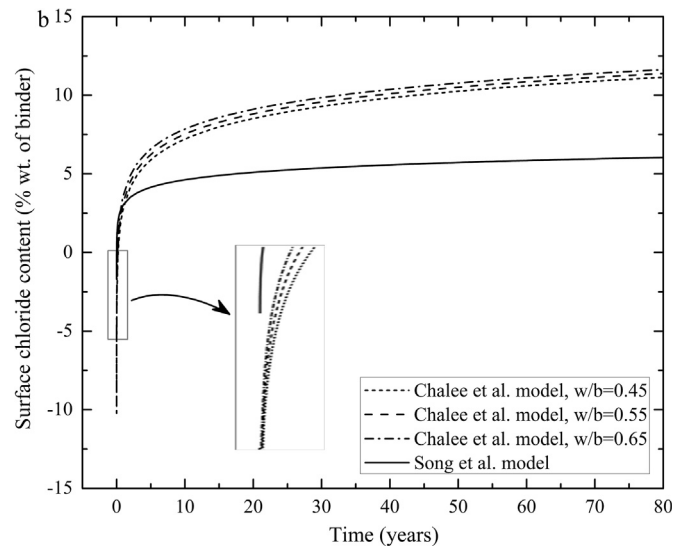

Fig. 2. C_s estimates based on Song et al. [13] and Chalee et al. [14] models.

equilibrium in the form of di-electric layer [18,19]. Moreover, among the C_s models listed in Table 1, the model proposed by Pack et al. [15] is relatively promising mainly because it predicts positive values at all times and is based on natural logarithmic function. Nevertheless, the model reported in Ref. [15] fails to account explicitly for the dependency of C_s on w/b ratio. Therefore, it is

Table 1
Published time-variant surface chloride content models.

$C_s(t)$	Source
$2\,t,\ 2\sqrt{t}$ (kg/m^3)	Amey et al. [11]
$0.38t^{0.37}$ (% wt. of concrete)	Costa and Appleton [12]
$3.0431 + 0.6856 \ln(t)$ (% wt. of binder)	Song et al. [13]
$[-0.379\,(w/b) + 2.064]\ln(t) + [4.078\,(w/b) + 1.011]$ (% wt. of binder)	Chalee et al. [14]
$0.26\,[\ln(3.77\,t + 1)] + 1.38$ (% wt. of binder)	Pack et al. [15]
$10^{[0.841(w/b) - 0.213]} + 2.11\,\sqrt{t}$ (% wt. of binder)	Petcherdchoo [16]