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Significance of chloride penetration controlling parameters in concrete: Ensemble methods

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HIGHLIGHTS

- Ensemble methods are able to determine the optimal subset of influential variables.
- Chloride migration coefficient influences the chloride transport at earlier age.
- Several early age concrete tests are impotent in predicting the chloride ingress.
- Aggregate size distribution is among the predominant predictors of chloride ingress.
- Evaluation of long-term chloride transport using short-term tests is unrealistic.

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ABSTRACT

Conventional chloride ingress prediction models rely on simplified assumptions, leading to inaccurate estimations. Reasonable simplifications can be achieved if and only if the effects of all interacting variables are clearly known. In this work, ensemble methods to discover significant parameters that control chloride ingress using long-term field data is developed and presented. The models are trained using dataset consisting of variables describing the concrete mix ingredients, fresh and hardened properties, field conditions as well as chloride profiles. The results analyses confirm that the models are able to determine the optimal subset of the influential variables that best predicts the chloride profile from the input dataset.

1. Introduction

Chloride attack is one of the predominant threats for the durability of reinforced concrete (RC) structures exposed to de-icing salts containing chloride [1–5]. The ingress of chloride ions is remarkable in countries at those latitudes where a large amount of de-icing salts are applied in winter to melt the ice on the roads. The melt ice slurry with extremely concentrated chloride ions from de-icing salt flows or splashes to RC structures by the moving vehicles. In some cases, chloride ions from de-icing salt is observed in RC structure situated 1.9 km from a busy highway and as high as 60th floor of a building [6]. In normal condition, the penetration of chloride does not result in damage to concrete directly. However, when the chloride concentration at the steel reinforcement bar (rebar) reaches a certain threshold value, they undergoes de-passivation and initiates corrosion [1–5]. Globally, corrosion of rebar induced by de-icing salt adversely affects the serviceability and safety of RC structures and has caused huge economic loss due to premature rehabilitation of civil infrastructures [1,5,7]. The total direct cost of chloride-induced corrosion in US highway bridges alone exceeds eight billion USD per annum. The indirect costs caused by traffic delays and lost productivity are predicted to be ten times more than the cost of corrosion related maintenance, repair and rehabilitation [7,8]. Hence, reliable quantitative evaluation of the amount of penetrated chloride concentration in the concrete is vital to mitigate premature failure of structures.

Through years of research, several models and input parameters have been established to foresee chloride concentration inside the concrete to make reliable and cost-effective maintenance and

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repair decisions. The complexity level of the established models vary from simple analytical models assuming uniaxial diffusion into concrete, to more sophisticated numerical models which considers the physical, chemical, and electrochemical processes of gas and ion transport [9–11]. Some of the utilized analytical models and the associated value of input parameters have been incorrect, incomplete, and/or unsuitable for the prevailing conditions. Due to these facts, the prediction results differ substantially even for the same concrete matrix exposed in identical conditions [12]. Though the complex scientific models provide reasonably accurate predictions, they lack user friendliness and demand highly skilled professional, making them suitable only for research, but not for practical design applications. Despite the accessibility of numerous models, empirical ones are widely used to foresee the chloride concentration in concrete [13–17].

Empirical chloride ingress prediction models rely on simplified assumptions, leading to inaccurate estimations. Reliable simplification can be achieved if and only if the effect of the interacting variables is understood. In this work, models based on ensemble methods are developed to discover the significance of the parameters that influence the chloride ingress in concrete. The contributions of this work are: (i) chloride ingress prediction models using long-term field data (ii) evaluating the significance of early-age chloride transport property in determining long-term chloride penetration in concrete; (iii) determining the most influential variables which govern the penetration of chloride in concrete by employing three scenarios; and (iv) validating the identified subset of influential variables in improving chloride ingress prediction accuracy.

The structure of this paper is as follows. In Section 2, the importance of this research is elaborated. The fundamental knowledge on an ensemble method is presented in Section 3 since this technique is adopted to develop chloride ingress prediction models which ultimately used to investigate the significance of the parameters which govern chloride penetration in concrete. In Section 4, details of the chloride ingress prediction models development process is presented. The models are developed by utilizing ensemble methods. It is the core part of this work, since all the influential parameters are determined using these models. The models employ long-term experimental data exposed to de-icing environment. In Section 5 results and their analyses are explained in detail. Discussions of the findings and the conclusions of the work are presented in Sections 6 and 7, respectively.

2. Research significance

In practice, empirical chloride penetration prediction models in the form of simple analytical equations on the basis of Fick's second law of diffusion are commonly adopted to model penetration of chloride into concrete. Numerous models based on Eq. (1) have been published to predict the amount of chloride penetration and thus to evaluate the full or remaining service life of RC structure. Nevertheless, these models have several limitations that create uncertainty on the accuracy of the chloride ingress prediction. One of the foremost limitations of Eq. (1) is the assumption of the non-steady diffusion coefficient (D_{nss}) as invariant [13,18–20]. In real situation, D_{nss} cannot be recognized as constants. This is due to the transport properties of chloride relying on the intrinsic permeability of the concrete, which is changing during the process of cement hydration with time. In another perspective, the alteration of capillary pore structure of concrete is controlled by cement type, water to binder (w/b) ratio, exposure time, admixtures type, and exposure condition. Due to these, D_{nss} is varying with time and space [21,22]. In addition, in Eq. (1), the error function equation considers only diffusion mechanism. However, the penetration of chloride into concrete involves a complex physical and chemical process that combines various transport mechanisms other than diffusion such as capillary sorption, and permeation. All these facts explain why Eq. (1) based models fail to deliver accurate predictions in several instances [13].

$$C_x = C_i + (C_s - C_i)\left(1 - erf_{(x)}\left[\frac{x}{2\sqrt{D_{nss}t}}\right]\right) \quad (1)$$

where C_x is the content of chloride ion measured at average depth x [m] after exposure time t [s][% by mass of concrete]; C_s is the calculated content of ion at the exposed surface [% by mass of concrete]; C_i is the initial content of chloride ion [% by mass of concrete]; D_{nss} is the non-steady state diffusion coefficient of chloride ion [m^2/s.]; and $erf_{(x)}$ is the error function [−].

In order to address the time dependency of D_{nss} and effect of other influential factors different model codes have been proposed, e.g. in fib-MC2010 [23] and DuraCrete framework [24]. Most of the codes share the same expression as in Eq. (2).

$$D_{nss}(t) = k_e.k_t.k_c.D_0.\left(\frac{t_0}{t}\right)^n \quad (2)$$

where k_e is environmental function [–], k_t test method function [–], k_c curing function [–], D_0 is experimentally determined chloride diffusion coefficient at time t_0 [m^2/s], t_0 is age of concrete at D_0 is measured [year], t is the exposure duration [year], and n is the age factor [–].

The age factor describes the time dependency of the diffusion coefficient depending on the concrete composition. Its value is usually described by few parameters from concrete mixing ingredients, especially cementitious materials. The value of the age factor is usually determined based on various concrete specimens exposed to different environments for relatively short period of time and exhibits considerable scatter. Several studies demonstrated that the age factor is the most sensitive parameter in Eq. (2) [1,25–27]. A slight variation in its value causes a substantial uncertainty in chloride profile prediction, which in turn affects estimation of the time to corrosion initiation. This uncertainty may shorten the service life of the structure and increases the lifecycle cost due to improper prediction.

As discussed above, the widely applied chloride penetration prediction models (Eq. (1) and (2)) relies on limited factors. Indeed, examination of chloride transport in concrete is performed for several years to acquire a better understanding of various controlling parameters. To recognize the influence of various parameters, a large number of experiments should be performed since the microstructure of concrete is highly complex and its transport properties are controlled by numerous interacting variables. Nevertheless, it is usually challenging to isolate the influences of particular parameters because other controlling parameters are also vary naturally at the same time [28,29]. Hence, evaluating the importance of D_{nss} and other parameters that influence chloride ingression in concrete is essential in order to develop parsimonious and accurate chloride ingress prediction model.

Variable importance analysis technique can be applied to determine the main variables that influence the chloride ingress in concrete. Identifying important variables using traditional statistical methods, such as linear regression method is not achievable. The reason for this is that chloride ingress in concrete in field environment is a complex process controlled by numerous nonlinear factors, including concrete mix composition, external chloride concentration, climatic condition, exposure time, position and surface orientation of the concrete [30]. Variable importance analysis based on linear regression methods is only applicable for linear or nearly linear models. Therefore, alternative approaches which manage high-dimensional nonlinear features that reliably identify influential predictor variables are required.