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Statistical analysis of time dependent variation of diffusion coefficient for various binary and ternary based concrete mixtures

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HIGHLIGHTS

- Enhancement of probabilistic time-dependent diffusion coefficient model for concrete.
- Suitable in analysis of durability related to chloride ingress induced corrosion.
- Laboratory data from 32 binary and ternary concrete mixtures evaluated.
- Diffusion coefficients are based on measurements of resistivity at selected ages.
- Proposed models are based on coefficient of variation (constant or time dependent).

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ABSTRACT

The numerical modelling of chloride penetration into concrete requires sound description of input parameters. One of the crucial inputs is the diffusion coefficient of concrete. The concrete is heterogeneous material and its parameters depend on the level of maturity. Therefore, the objective of this work is to describe the time dependent variability of the diffusion coefficient of chlorides into concrete. Computation of the diffusion coefficient is based on the non-destructive testing of bulk electrical resistivity following ASTM C1760 standard and Nernst-Einstein relationship. The presented results show the variation of diffusion coefficient of control OPC mixture and 32 various binary and ternary concrete mixtures where the effect of prolonged aging is even more significant. Two possibilities of the time dependent diffusion coefficient probabilistic model based on coefficient variation (mean value and regression via linear approximation) are proposed. The quality of both approaches is evaluated using Root of Mean Squared Error approach. Overall, this study provides guidance to select proper statistical tool for the assessing the time dependent variation of diffusion coefficient.

1. Introduction

The design of reinforced concrete structures is an affected by the goal to build them efficiently with high durability. More and more, the lifetime cost is stimulated. The lifetime costs include cost of rehabilitation and reconstruction. Thus, the probability related to occurrence of durability related to limit state exceeding became of interest [1–3]. In reinforced concrete structures, the long-term effects of external influences on lifetime are a significant issue. One of the most important factors influencing corrosion of reinforcement is the diffusion caused by de-icing agent penetration namely by the chloride salts. The corrosion initiation relates to concentration of chloride ions at the reinforcement level can be calculated using analytical formula [4] or numerical finite element analysis describing chloride diffusion (see e.g. [5]) or even in 2D model when necessary [6–9]. The main input for the rate of chloride penetration is the concrete diffusion parameter.

Since the aim is to increase the durability of reinforced concrete structures, there are several cornerstones to achieve that goal. First important part is research of new potential concrete mixtures with better resistance to ingress of aggressive agents see e.g. [10–12]. Second important part is the knowledge of related parameters governing the durability issue such as the diffusion coefficient [13,14]. The effect of binary components with cementations capabilities on the diffusion coefficient is already available deterministic form. See e.g. correlation between fly ash and slag content and the diffusion coefficient [15]. However, there is lack of information about ternary mixtures. The third important issue is the prediction of

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reinforced concrete structures behaviour. The probabilistic approach is of high importance considering random variability of input parameters of concrete [16,1–3]. Thus, the likelihood of the occurrence of limit states such as concrete cover cracking or corrosion initiation has been investigated in Refs. [3,12,17,18]. The common feature of these two limit state aspects is the correct determination of the diffusion parameters and their description as an input parameter for the assessment by in-depth statistical analysis.

1.1. Probabilistic idea

It is well known fact that concrete parameters show typically random variability. Hence, numerical probabilistic durability assessment (see e.g. [19–21]) related to corrosion initiation of steel reinforcement is a suitable tool [1,2,12,17,22].

The recommendation for the basic parameters or even distribution of the diffusion coefficient are proposed in Ref. [3] or in draft material [22]. The aging effect is also considered [3,18,20]. However, the time dependent variability of diffusion coefficient suitable for probabilistic durability analysis of concrete structures is still an open-end question.

1.2. Diffusion coefficient evaluation

Long term chloride penetration tests requires sampling of profile. See e.g. AASHTO T259 [23] or NT Build 443 [24] for details. Those penetration tests can estimate precisely the effective value of the diffusion coefficient over the time of the experiment. However, the effect of concrete aging can affect the computed value significantly.

There are also electrochemical procedures that are significantly faster. The accelerated chloride penetration tests (RCPT, AASHTO T277 [25], ASTM C1202 [26]) require 6 h while preparation of samples is still labour intensive. The diffusion coefficient value may be computed due to correlation between electrical properties and diffusion coefficient of concrete (see e.g. [27–31]). There is also other method for evaluation of concrete against the penetration of aggressive agents based on the passage of electrical current (electrical resistivity) (AASHTHO TP-95 [32,28,10]). The determination of the concrete electrical resistivity or conductivity parameter takes few minutes, which is extremely faster in comparison with long-term penetration tests [23,24] or even RCPT test [25,26].

The computation of the diffusion coefficient is based on the procedure given in Ref. [30], where the bulk resistivity ρ_{BR} is calculated based on both electrochemical procedures. For porous materials such as concrete, the diffusion coefficient formulation is selected according to Nernst-Einstein. The Eq. (1) is given bellow [30,33]:

$$D = \frac{RT}{Z^2F^2}\frac{t_i}{\gamma_i C_i \rho_{BR}} \tag{1}$$

where D is the diffusion coefficient [m^2/s], R is the universal gas constant [J/K.mol], T is the absolute temperature [K], Z is the valency of chloride ions [–], F is the Faraday constant [C/mol], t_i is the transport number of chloride ions [–], γ_i is the activity coefficient of chloride ions [–], C_i is the concentration of chloride ions [mol/m^3], and ρ_{BR} is the bulk resistivity [Ωm].

It is worth mentioning that resistivity ρ_{BR} is the inverse of conductivity σ and it can mimic the RCPT ASTM C1202 experiment without exposing the samples to chlorides. Thus, concentration of chlorides that represent the chloride concentration in one of the chambers in RCPT experiment nor the concentration in the concrete sample is changing over the experimental measurement of resistivity.

Although, some authors point out problems with the precision of computation of the diffusion coefficient [34,35], the procedures are generally well established [36–38]. It is also worth noticing that admixtures of salts, for example: calcium nitrate (III), calcium nitrate, calcium chloride, sodium thiocyanate causes the increase of electric charge despite the immutability of permeability of chlorides because of salts' ions ability to transfer electric charge.

1.3. Aging of diffusion coefficient

The diffusion coefficient is changing as the concrete matures. These "aging" effects cause a significant decrease in the diffusion coefficient over time [13,15]. Thus, the expected corrosion initiation time is extending. The concrete maturity process takes longer period especially in the case of binary and ternary-based HPC concrete mixtures with prolonged hydration process. Thus, diffusion coefficient is time dependent parameter [39,15] with model formulated according to [39,40] as follows:

$$D_{c,nom,t} = D_{c,28} \cdot \left(\frac{t_{28}}{t}\right)^m \tag{2}$$

where $D_{c,nom,t}$ is the nominal diffusion coefficient for a selected age [m^2/s], m is the aging factor describing the decrease of diffusion coefficient over the period of measurement for concrete ages t [years] (e.g. 7, 14, 28, 56, 91 and 161 days), t_{ref} [years] is the age related to the diffusion coefficient $D_{c,ref}$ at reference period e.g. 28 days.

It is worth mentioning that the electrochemical procedures (ASTM C1202 [26], AASHTO TP-95 [32]) are suitable to capture the effect of time dependent concrete properties in contrast to long-term ponding tests (AASHTO T259 [23] or NT Build 443 [24]) that do not have this capability to reflect the early age changes.

1.4. Variation of diffusion coefficient

During a statistical analysis of the behaviour of 32 selected high performance concrete mixtures (HPC) [10] and one reference mixture from Ordinary Portland Cement concrete (OPC) [5], it was observed that the scatter of the diffusion coefficient is the time dependent parameter. Standard deviation seemed to be reduced in proportion to the change in the average value of the diffusion coefficient over time [41]. Thus, it was considered that the time related distribution of the diffusion coefficient could be described with the help of a variation coefficient and it is a relative parameter:

$$D_{c,t} = D_{c,nom,t} + D_{c,var} \times D_{c,nom,t} \tag{3}$$

where $D_{c,nom,t}$ is the diffusion coefficient for the selected age according to Eq. (1) [m^2/s] t is the age of the concrete [years], $D_{c,var}$ is relative distribution of diffusion coefficients [m^2/s].

It shall be noted that $D_{c,var} \times D_{c,nom,t}$ may be also be time dependent standard deviation of diffusion coefficient $D_{c,std,t,}$ if normal distribution function would be considered as a suitable distribution.

If the standard deviation is proportional to the average diffusion coefficient than variation coefficient may be utilized to describe time dependent variability of the diffusion coefficient. Thus, the analysis of the time dependent behaviour of the diffusion coefficient scatter is required in order to have reasonable output data for the probabilistic numerical modelling of chloride penetration into concrete.