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Oxygen permeability of concrete and its relation to carbonation

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HIGHLIGHTS

- A relationship between permeability and carbonation is established.
- A performance-based carbonation prediction model is presented.
- Relationship between RH and carbonation is modelled.
- Carbonation coefficients are linked to diffusion coefficients.

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ABSTRACT

The corrosion of steel reinforcement due to carbonation of concrete presents one of the major deterioration mechanisms in reinforced concrete structures. The South African concrete durability design method for reinforced concrete structures incorporates a performance based approach to evaluate the penetrability and quality of the concrete cover. With respect to carbonation, the method relies on measurement of an index of the oxygen permeability of concrete, which is used as an input parameter to a carbonation model. This paper presents a revised model for concrete carbonation, which expands common carbonation models by accounting for the effect of relative humidity on both diffusion and chemical reactions. Using experimental data, oxygen permeability results are correlated with the carbonation coefficient as well as the carbon dioxide diffusion coefficient of concrete. This correlation enables prediction of time-dependent carbonation depths of concretes based on the environmental exposure, mix design and oxygen permeability of the concrete.

1. Introduction

Performance based design for durability of concrete structures incorporates testing of concrete properties which are pertinent to the degradation mechanism to which the concrete is subjected. In order to link the test data to durability performance, service life models need to be developed. The South African concrete durability design method for carbonation involves measuring the oxygen permeability of concrete samples removed from the in-situ structure to obtain a performance based representation of the penetrability of the concrete and information about the microstructure. Service life models currently used in South Africa for design and conformity assessment of concrete structures for carbonation resistance are based on empirical relationships between carbonation depth development of in-situ concrete and oxygen permeability values of the same concrete when cured in the laboratory and tested at 28 days of age [1,2]. Based on on-going research, this paper presents the development of a more fundamental relationship between oxygen permeability and the diffusion coefficient of carbon dioxide, where the former can be used as an input parameter in common carbonation prediction models.

The carbonation of concrete is affected mainly by the penetrability and chemical composition of the concrete, as well as the environmental exposure [3]. Carbonation is a reaction-diffusion process that takes place in a permeable matrix. While diffusion and permeability are two different transportation processes with different driving mechanisms, they occur in the same pore system and can thus be related [4].

The strategy adopted in this research is to develop a relationship between oxygen permeability and the carbonation coefficient of concrete, based on accelerated carbonation results and commonly applied carbonation models [5]. The analysis of the chemical composition of the concrete matrix then allows the carbonation coefficient to be related to the carbonation diffusion coefficient. Further, a refinement of existing carbonation models is proposed to take into account the dual effect of ambient relative humidity on carbon dioxide diffusion and the carbonation reaction.

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2. Refining the existing carbonation prediction model to account for the dual effects of relative humidity

A carbonation model commonly used by researchers and engineers (e.g., [6,7] is that originally derived by Meyer et al. in 1967 [8] based on Fick's first law of diffusion:

$$x = \sqrt{\frac{2Dct}{a}} \tag{1}$$

where x is the carbonation depth into the concrete, c and a are the molar concentrations (mol/m^3) of the ambient carbon dioxide and the Portlandite respectively, D is the CO_2 diffusion coefficient, and t is the time.

The model expressed in Eq. (1) is derived from first principles using diffusion, mass balance and flux and does not account for wetting periods and the concrete's internal relative humidity. The internal relative humidity (RH) of the concrete is an important parameter as it affects both the diffusion of carbon dioxide into concrete as well as the chemical reaction for carbonation. The concrete's internal relative humidity is a function of wetting periods, external relative humidity and the concrete microstructure. The effect of wetting periods can be accounted for by the effective time of exposure, or time of wetness as defined by the fib Model Code for Service Life Design [9]. The microstructure affects both the carbonation rate and the drying rate. During natural carbonation the drying rate of the concrete can be assumed to be more rapid than the carbonation rate [8] and the internal relative humidity will reach a steady state with the external relative humidity on a time-averaged basis. Based on this assumption, the authors propose that ambient relative humidity can be used as the internal relative humidity of the concrete.

It is necessary to modify Eq. (1) to account for internal relative humidity, which governs the carbonation depth by two processes which predominate depending on whether there is high or low relative humidity. At high RH the diffusion of carbon dioxide is constricted and the reaction in the pore water proceeds as fast as the carbon dioxide can diffuse and dissolve. Thus at high RH, diffusion is the dominant factor. At low RH the diffusion of carbon dioxide is high but less of the carbon dioxide can dissolve in the pore water; thus the carbonation depth is dominated by the reaction rate at low RH. This leads to the observation recorded by many researchers that the carbonation rate is highest at intermediate relative humidities around 50–70% (e.g., [10–12]).

To obtain the first modification factor for diffusion in Eq. (1), the relationship developed in [12] from experimental data is used, given by β_D in Eq. (2):

$$\beta_D = \left(1 - \frac{\text{RH}}{100}\right)^2 \tag{2}$$

where β_D is the relative humidity factor for diffusion and RH is the internal relative humidity.

To obtain the second modification factor, that for the carbonation reaction rate, in Eq. (1), a RH-reaction coefficient, β_r is introduced. Modifying the general carbonation model expressed by Eq. (1) to account for the dual effects of relative humidity yields Eq. (1):

$$x = \sqrt{\frac{2Dc\beta_D\beta_r t}{a}} \tag{3}$$

The RH-reaction coefficient β_r can be obtained empirically by curve fitting the carbonation model to long-term or accelerated carbonation data. Reliable and usable carbonation data for varying relative humidities is however limited in the literature. In order to estimate values for β_r the authors used experimental data presented by Wierig [11], who conducted long-term experiments in natural conditions where he exposed samples of the same concrete to different relative humidities. Fig. 1 shows the data presented by Wierig [11] and the curves fitted to his data with Eq. (1). Wierig tested two portland cement concretes with w/c ratios of 0.6 and 0.8 for 16 years and a 0.6 w/c ratio portland cement concrete and a 0.6 w/b ratio blast furnace cement concrete for 2 years. Fig. 2 shows the experimental results solved for β_r, indicating a power relationship between the RH-reaction coefficient β_r and the RH. Based on iterative analysis of Wierig's experimental data, the RH-reaction coefficient, β_r, was found to be:

$$\beta_r = \left(\frac{\text{RH}}{100}\right)^{2.6} \tag{4}$$

For practical application of the carbonation model, the two RH-coefficients are combined into one relative humidity coefficient β, which represents a shape function that scales the carbonation depth according to the internal relative humidity of the concrete, accounting for diffusion and reaction rate:

$$\beta = 23.32\left(1 - \frac{\text{RH}}{100}\right)^2 \left(\frac{\text{RH}}{100}\right)^{2.6} \tag{5}$$

where 23.32 is a scalar obtained from the curve-fitting exercise (Fig. 1).

Based on Eqs. (2), (4) and (5), Fig. 3 shows the individual and combined effects that the relative humidity has on diffusion of carbon dioxide and the chemical carbonation reaction. By adjusting the exposure time to an effective exposure time (to account for time of wetting ToW – see Eq. (5)), and accounting for the effect of the relative humidity on both the diffusion and reaction, the model accounts for the main mechanisms in concrete carbonation: the concrete microstructure (expressed by the diffusion coefficient D), the concrete chemistry (a) and the exposure condition (c, t_e, β). Eq. (1) thus becomes:

$$x = \frac{2Dc\beta t_e}{a} \tag{6}$$

The effective time of exposure is given by Eq. (5):

$$t_e = t\left(1 - \frac{\text{ToW}}{365}\right) \tag{7}$$

where t is the real time of exposure of the structure and ToW is the time of wetness given by the amount of days per year with rainfall $\geqslant$2.5 mm [9].

The prediction of the carbon dioxide diffusion coefficient D using oxygen permeability values will be developed based on experimental data as discussed in the following sections.

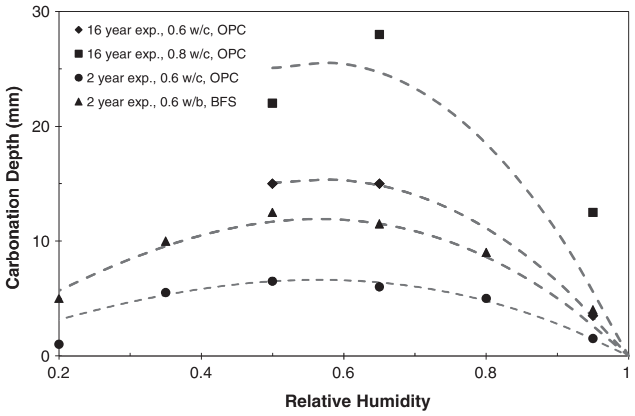

Fig. 1. Carbonation depth vs. relative humidity (based on data presented by Wierig [11], trend lines fitted with Eq. (1).