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PREDICTING THE SERVICE LIFE OF REINFORCED CONCRETE STRUCTURES-A REVIEW

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ABSTRACT: *Permeability is known to be a critical transport mechanism governing attack and degradation of concrete. As such, there is a great deal of interest in determining a functional relationship between early age permeability of concrete and its service life in real environment. Data from review of the literature clearly shows an existence of a strong empirical relationship between the permeability of concrete and its carbonation. However, while several strength-based carbonation models have been proposed, there are very few models available in the literatures that are based on the permeability of concrete. In this paper, existing empirical data from the literature is used to demonstrate the relevance of using permeability as the core parameter against which service life can be modelled. The principal intention of this work is to use the durability index approach as a basis for predicting the carbonation rate and hence, the service life of reinforced concrete structures. While examining some of the relevant models available in the literature, the significant model parameters are identified and a methodology is proposed for developing an improved model.*

Keywords: Service life; Degradation; Carbonation; Permeability
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INTRODUCTION

Service life is defined as "the period of time during which a building, structure or material meets or exceeds the minimum requirements set for it" [1]. The major factor that affects the service life of reinforced concrete (RC) structures is the corrosion of its reinforcement, which may be initiated by the ingress of carbon dioxide (CO_2) or chloride ions (Cl^-). In the inland environment, CO_2 in the atmosphere diffuses into RC structures and reacts with the hydration products of cement in a process called carbonation. This process moves as a front and lowers the concrete alkalinity, thus depassivating the steel when the carbonation front gets to the level of the reinforcing steel. Corrosion may then be initiated, reducing the service life of the structure, through cracking, unsightly staining and a reduction in the load bearing capacity of the structure. CO_2 enters concrete through its pore structure by diffusion and permeation and the carbonation processes takes place in the concrete pore structure. Hence, the permeability of concrete is a primary parameter in determining the rate of advance of the carbonation front. [2]. Permeability of concrete is influenced by two factors - the interconnected porosity in the hydrated cement paste as well as its micro cracks [3]. While the porosity is dependent on the water cement ratio, degree of hydration and compaction given to the concrete, the micro cracks are function of the thermal strains and shrinkage. To predict concrete service life, a clear and precise understanding of the characteristics of the pore structure, permeation properties of the concrete and the deterioration mechanism are essential. This paper seeks to address these needs by presenting a methodology for service life modelling based on the concrete permeability characteristics. The importance of permeability and its relationship to carbonation will also be examined.

CONCRETE CARBONATION PROCESS

Carbonation of concrete is basically the chemical reaction between atmospheric CO_2 and the products of cement hydration particularly calcium hydroxide ($Ca(OH)_2$) in accordance with the reaction shown below:

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \qquad (1)$$

The ingress of CO_2 (or its penetrability) involves a number of transport processes, namely diffusion under a concentration gradient, permeation under a pressure head and the capillary absorption [4, 5]. However, under general outdoor conditions, the main driving mechanism for carbonation is diffusion of CO_2 and this diffusivity is related to the permeability of the concrete. Fick's first law of diffusion has been used to describe the advance of carbonation in concrete and is the basis of most of the carbonation and service life models. However, Fick's Law cannot be applied directly since a further rate-controlling parameter is the amount of carbonatable material available in the pore structure of the concrete. If it is assumed that the reaction front of carbonation progresses after all carbonatable material has been reacted, and CO_2 diffusion takes place through concrete sections that are already carbonated. A further complexity arises from the fact that the products of carbonation alter the pore structure and therefore the permeability of concrete. The process of carbonation also changes the chemical reactivity of the hydrated cement paste matrix and its binding capacity for aggressive ions like chloride. These characteristic changes in carbonated concrete are accompanied by change in weight, moisture absorption [6], surface tension in pore water [7], CO_2 diffusivity [8] and moisture saturation [9]. All these factors are dependent on the changes in capillary pore structure of the concrete due to the consumed hydrates ($Ca(OH_2)$) and calcium carbonate ($CaCO_3$) formation. Carbonation causes a variation of the microstructure of mortars, concretes and material properties that are related to the microstructure, such as permeability, diffusivity, capillarity etc. The effects of carbonation on concrete pore structure and the diffusion properties of hydrated cement pastes were investigated and it was noted that the total porosity of the cement systems reduces with carbonation [10, 11, and 12].

Transport Mechanisms in Concrete

The carbonation of concrete is related to the ease with which CO_2 can move through concrete microstructure. This makes the transport properties of concrete a key factor for predicting its durability and service life in a carbonation environment. These movements are generally called penetration and occur due to various combinations of air or water pressure differentials, humidity differentials and concentration or temperature differences of solutions [13]. The movement is influenced by the penetrability of the concrete and is dependent on the concrete microstructure, the moisture condition of the material and the characteristics of the permeating fluid. Penetrability includes the concepts of permeability, sorptivity and diffusion and can be quantified in terms of the transport parameters [14]. The permeability of concrete is strongly influenced by the permeability of the cement paste, especially at the aggregate interface. To develop an early indication of concrete durability and the likely service life of a reinforced concrete structure, we need to measure and have criteria that quantify the concrete microstructure. The main parameter which represents this factor is concrete permeability. Many tests methods for concrete permeability measurement exist with good correlation to durability parameters that could be used for the assessment of concrete service life. The oxygen permeability test developed by Ballim [15] is one of such method and this test is sensitive to the important materials, environmental and constructional factors know to influence concrete durability.

Inter-relationship between Concrete Permeability and Carbonation

Different standard test methods can be used to measure the fluid transport properties relevant to the various mechanisms of deterioration. Experimental evidence exists illustrating the correlation between the relevant transport properties and either the penetration of different aggressive substances or the mechanisms of deterioration. The following section discusses the interrelationship between concrete permeability and the carbonation processes. The carbonation of concrete has been correlated with the permeability by different researchers. This is because the tests characterize the pore structure of the near surface sections of the concrete and gives an indirect measure of the open and continuous capillary porosity. The correlation between air permeability of concrete and its depth of carbonation after 1 year storage in a controlled atmosphere of 20^0C and 65% RH with natural CO_2 content was studied by Hilsdorf, *et al* [16]. Their results show a linear relationship between the square of the depth of carbonation and the logarithm of the air permeability. A linear correlation was also obtained by Basheer [17] who considered the relationship between carbonation depth and the Autoclam carbon dioxide permeability index. Similar results were obtained for carbonation and the Figg air permeability test [18]. Ballim [15] shows good correlation between 28-day oxygen permeability of concrete and its carbonation depth at 10 months for different binders under natural inland conditions and similar results were obtained by Mackechnie [19] under natural marine conditions. It can be seen in all these cases that there is good correlation between the depth of carbonation and the measured fluid flow value. However, the precise relationship depends on the method of test used to determine the fluid flow or "permeability" value. The Autoclam permeability index, Figg air permeability and the oxygen permeability are not directly comparable on a quantitative basis. Nevertheless, an established and reliable relationship between the permeability and carbonation depth allows a possible prediction methodology for the durability performance and service life of concrete structures.

EXISTING SERVICE LIFE MODELS

Parrott's Model (1998)

The model proposed by Parrott [20] was developed by studying the effect of varying concrete quality (as permeability) on the rate of carbonation. The model was developed based on results from natural carbonation testing and is presented in Equation (2).

$$d = \frac{aK^{0.4} t_i^{\,n}}{C^{0.5}} \qquad (2)$$

Where,

d = the carbonation depth (*mm*),

t_i = the initiation time (*years*),

C = the calcium oxide content in the hydrated cement matrix of the cover concrete (*kg/m*^{3}) that can react with and effectively retard the rate of CO_2

penetration and is itself a function of the cement composition and the proportion of cement reacted,

K= the air permeability of cover concrete and depends upon the moisture content of cover concrete,

n= a power exponent that is close to 0.5 for indoor exposure but decreases as the relative humidity rises above 70% to account for the slower rates of carbonation observed under wetter conditions,

a= a coefficient that, under Parrot's test conditions, has a value of 64.

In Parrot's model, the important influencing parameters for the initiation period are the calcium oxide content in hydrated cement matrix, the concrete quality and the relative humidity.

BRE Model (2001)

The BRE model [21] is similar to the Parrott's model but uses the cement content instead ofthe CaO content of the concrete. The form of this model is shown in Equation (3):

$$d = \frac{(11.2k^{0.5}+9.0)(^{t}/_{20})^{0.5}}{C} \qquad (3)$$

Where,

d= the carbonation depth (mm),

t= the exposure time (years),

k= the oxygen permeability at 28 days

C= the cement content (*kg/m*^{3}).

The influencing parameters for the initiation period are the buffering capacity, permeability, and environmental factors (RH and CO_2 concentration).

Marques and Costa's Model (2010)

Marques and Costa [22] proposed an empirical model for the determination of the initiation period of carbonation induced corrosion of reinforced concrete. The model is presented in Equations (4) and (5):

$$t_i = \left[\frac{R_{c65}\,C^2}{1.4x10^{-3}k_0k_1k_2t_0^{2n}}\right]^{\frac{1}{1-2n}} \qquad (4)$$

$$R_{c65} = \frac{a}{D} \qquad (5)$$

Where,

t_i= the initiation time,

a = the amount of CO2 that origins the carbonation of the concrete components in a concrete volume unit,

D =the coefficient of diffusion of the CO_2 through carbonated concrete,

C = the CO_2 concentration,

n=to account for the influence of wet/dry cyclesin time

K_0, K_1 and K_2= constants for test method, relative humidity and curing period respectively.

The influencing model parameters are the concrete quality, the exposure condition and the construction practice. It is evident from the models presented above that the permeability of concrete and its buffering capacity are the two most important parameters that affect the rate of concrete carbonation and thus its service life.

Based on the above models, a methodology is presented below for an improved model development:

1. Quantifying the permeability of concrete samples made from varying mix design.
2. Quantifying the carbonation rates of equivalent concretes using the square root of time law. The composition of the carbonated and uncarbonated concrete samples should also be determined – perhaps using thermogravimetric analysis.
3. Estimation of the time to corrosion activation is possible through regression analysis if the cover concrete depth is known.
4. Applying statistical analysis to these carbonation models to account for the variability and randomness of the factors that influence carbonation.
5. Finally, validation of durability and service life model with existing inland RC structure.

The developed model should then account for the following:

1. Represent the actual carbonation characteristic in are inforced concrete structure in its service environment.
2. Be applicable to a range of material and environmental conditions for reinforced concrete structures
3. Accelerated carbonation tests results should be validated using natural carbonation data.
4. The inherent variability of carbonation rate and the factors influencing it should be accounted for in the prediction models by using probabilistic methods.

CONCLUSIONS

This review strongly indicates that permeability, as a measure of the fluid flow properties of concrete, can indeed be used as a basis for developing a model to predict the long-term durability performance and service life of reinforced concrete structures in a carbonation environment especially in the inland environment. Furthermore, the review of relevant work by other researchers has confirmed that fluid flow through the pore structure of concrete is an important physical property in relation to the deterioration process. Good correlations were observed between the permeability and the process of carbonation. The paper has also presented a framework for the development of a more reliable durability and service life prediction model. This is based on existing empirical models but takes broader account of the variability of concrete making materials and the environment of exposure for reinforced concrete structures.

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