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Statistical modelling of carbonation in reinforced concrete

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ABSTRACT

As time passes the properties of concrete change as a result of its interaction with the environment and durability is affected. Reinforcement corrosion is singled out in various studies as being mainly responsible for reinforced concrete degradation. Concrete alkalinity protects the reinforcement bars from corrosion but the carbonation phenomenon significantly contributes to the destruction of their passive coating, thus favouring the corrosion onset. Therefore, concrete carbonation is considered an important problem both in Civil Engineering and in Materials Science. This study's main objective is to try to quantify the contribution of potential conditioning factors to concrete carbonation's rate. This study addresses the statistical modelling of the concrete carbonation phenomenon, using a large number of results (964 case studies), collected in the literature. A computational method (multiple linear regression analysis) is used to define a mathematical model that can estimate the carbonation coefficient as a function of a set of conditioning factors. These models allow the estimation of the carbonation coefficient, and consequently the carbonation as a function of the variables considered statistically significant in explaining this phenomenon. Two distinct models are proposed to suit predictions to two environmental exposure relative humidity ranges.

1. Introduction

Reinforced structures are subject to deterioration over time. The degradation of their mechanical characteristics jeopardizes their functional capacity. This degradation may occur due to in-service conditions, exposure to aggressive environmental agents, and inadequate use or maintenance conditions [9].

Neville [44] notes that only rarely is concrete degradation due to a single cause. The concrete degradation mechanisms can be physical, chemical or mechanical, and the chemical and physical phenomena may be synergetic [49]. The cause of deterioration of reinforced concrete that deserves most attention is reinforcement corrosion [11,56,41]. In fact, it is one of the most important pathological manifestations to affect reinforced concrete structures, and is difficult to intervene or repair [37].

The alkalinity of concrete protects the reinforcement from corrosion until chemical or physical changes occur that enable external aggressive agents to act [28]. According to Hussain and Ishida [22], two main agents initiate reinforcement corrosion by destroying its passive coating: carbonation and chloride ingress. Tuutti [60] reports that concrete carbonation is one of the main phenomena to initiate the process of reinforcement corrosion. Carbonation is characterized by a physical–chemical process in which a series of chemical reactions occur in the presence of carbon dioxide (CO_2), which fosters the reduction of pH in concrete. CO_2 penetrates concrete predominantly through a diffusion mechanism. This penetration and carbonation reaction occurs gradually, leading to a carbonated layer (limited by the so-called carbonation front) that increases in thickness over time [6].

It is generally agreed that carbonation does not occur in the same way in all mixes, nor does it occur in all circumstances; different mixes will exhibit distinct carbonation and the same mix exposed to different environments will not show the same carbonation [40]. This study's main objective is to try to understand the conditioning factors so as to explain concrete carbonation. For this purpose a large number of related studies were analysed, 17 of which were selected (because of their more complete data), amounting to 964 case studies. The statistical modelling of the concrete carbonation phenomenon was performed using multiple linear regression. Mathematical models were proposed for estimating the carbonation coefficient, and consequently the carbonation as a function of the variables considered statistically significant in explaining this phenomenon.

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2. Background

When reinforced concrete was first developed and used the main characteristic of concrete to be controlled was its compressive strength, which for a long time was considered the safest design specification [20], while durability was relegated to a second level. However, concrete does not have an infinite service life and its durability will fundamentally depend more on its composition than on its mechanical strength [43].

The durability of reinforced concrete has been widely studied in recent years. Andrade and Dal Molin [2] report that research related to the service life prediction of reinforced concrete structures in terms of carbonation-induced corrosion is very active, using mathematical models. However, developing these models may pose some difficulties, such as the number and scatter of the factors intervening in the carbonation process, lack of information and the difficulty and length of time implicit in the validation of the models [1].

A prediction model must be reliable, take into account all relevant factors of the mechanism to be modelled and have a sensitivity that suits the precision of the input parameters [40]. Modelling carbonation is a delicate issue since although several factors should be taken into account users expect research to deliver simple and user-friendly models [42].

In their critical analysis of the various carbonation prediction models, Carmona and Helene [7] observed that there are models that still need developing since they present theoretical inconsistencies, and that the values obtained by different models may be significantly distinct. Yazigi [65] refers that some models are enormously complex to apply, e.g. define some input parameters, making it difficult to confidently estimate the service life of structures in-service. In fact there are very complex models that do not have an analytical solution [4,33].

Most of the carbonation prediction models [60,47,3,19] generically assume that the carbonation depth can be estimated through the product of a carbonation coefficient by the square root of time ($h = k \cdot \sqrt{t}$). Kropp et al. [31] says that, notwithstanding the deficiencies identified in the theoretical approach behind the model, it does provide satisfactory results in stable environmental conditions, i.e. in laboratory. Papadakis et al. [45] report that the equation yields scattered results when applied to concrete with no protection from the action of climatic agents, since the changes in relative humidity cause variations in the carbonation depth. On the other hand, Wierig [62] concludes that the classical model is sufficiently accurate for natural atmospheric conditions, as long as the concrete is protected from the action of rain.

Nevertheless, several authors argue that the model is suitable to estimate the evolution of the carbonation depth over time under natural conditions [14,38,40,59]. In this case the influence of humidity on the carbonation rate may be considered in the carbonation coefficient.

In the various existing models there is not a consensus on the way the carbonation coefficient is determined. This coefficient is fundamentally a durability indicator that comprises all the variables relating to the environmental severity and the characteristics of the concrete itself [10,38]. The quantification of this coefficient is usually hard since it depends on many factors, making the modelling of carbonation depth evolution a complex task.

Most carbonation models are semi-empirical, i.e. their development starts from a theoretical basis (e.g. Fick's first law) and is completed by fitting the required parameters to experimental results ([13,48,52,54]). However, the empirical part of these models is based in the results of one study or a limited number of studies.

The main purpose of this research is to propose a simple model for concrete carbonation, founded in a large number of data and in a statistical technique, innovative in the field of carbonation modelling.

3. Statistical modelling

3.1. Assumptions of the statistical model and selection of the variables

The statistical modelling of the concrete carbonation phenomenon was performed using multiple linear regression. Regression analysis is one of the most widely used statistical techniques for studying the behaviour of a dependent variable as a function of other variables responsible for that behaviour, called independent variables [35]. In multiple linear regression analysis the relationship between the dependent variable and the independent variables is generically given by Eq. (1):

$$y = B_0 + B_1 \cdot x_1 + B_2 \cdot x_2 + \ldots + B_k \cdot x_k + \varepsilon \qquad (1)$$

where y represents the dependent variable, $B_0, B_1, \ldots, B_k$ the regression coefficients, $x_1, x_2, \ldots, x_k$ the independent variables and ε the random errors of the model.

In the definition of the multiple linear regression models, the carbonation coefficient is the dependent variable. The independent variables analysed in this study can be grouped as:

- Factors inherent to concrete – type of cement (clinker percentage, type I (practically inert) percentage of additions, percentage of pozzolanic additions, percentage of latent hydraulic additions); binder content; clinker content; water/binder ratio; water/clinker ratio; 28-day mechanical strength; admixture content; type of admixtures; slump.
- Curing and moulding conditions – relative humidity and temperature of the curing environment; curing extent; compaction type.
- Exposure (environmental) condition – relative humidity and temperature of the exposure environment; carbon dioxide content; exposure class; protection from the action of rain; exposure to action of salts.

Five of the studied variables are categorical (non-numerical) and need to be codified. The variable *compaction* was codified in two categories: it takes the value −1 for normal compaction and the value 1 for self-compacting concrete. As for the variable *protection against the action of rain*, it was codified as follows: if concrete is protected from the rain the variable takes the value −1; if not it is equal to 1. The same occurs with the variable *exposure to salts*: if the concrete is exposed to salts it takes the value −1; if not it is equal to 1. Finally, for the variable *type of admixtures* added to the mix, four categories are considered: 0 if no admixture has been added; 1 for plasticizers or superplasticizers; 2 for air-entraining admixtures; and 3 if more than one type of admixture has been added.

The fifth categorical variable is *exposure class*. The categories for this variable were established based on the exposure classes related to reinforcement corrosion due to concrete carbonation, defined in EN 206-1 [12]. This standard defines four classes for carbonation-induced corrosion: XC1, XC2, XC3 and XC4. The XC1 environmental class stands for permanently dry (e.g., buildings' interior) or permanently wet (e.g., totally immersed) concrete. The XC2 environmental class stands for concrete with long periods in contact with water (e.g., rainwater drainage systems). Environments with moderate humidity (e.g., concrete in open air structures sheltered from rain) correspond to class XC3 and with dry–wet cycles (e.g., concrete in open air structures not sheltered from rain) correspond to class XC4. The value 1 is assigned to concrete under XC1 environmental conditions, 2 to concrete in XC3