Construction and Building Materials 182 (2018) 550–560

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Statistical modelling of the resistance to chloride penetration in concrete with recycled aggregates

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HIGHLIGHTS

- Statistical modelling of chloride-penetration in recycled aggregate concrete.
- Statistical modelling performed using a multiple linear regression.
- A proposed model allows estimating the charge passed in the Rapid Chloride Penetration Test.
- A proposed model allows estimating the diffusion coefficient of chlorides.
- The influential factors on chloride-penetration in concrete are identified.

ARTICLE INFO

Article history:
Received 24 March 2018
Received in revised form 12 June 2018
Accepted 15 June 2018

Keywords:
Reinforced concrete
Chloride penetration
Recycled aggregates
Multiple linear regression analysis

ABSTRACT

Steel corrosion is one of the biggest threats to the service life of reinforced concrete structures and chloride penetration favours the corrosion process. Due to sustainability and environmental issues, the use of recycled aggregate in concrete production has been growing. The aim of this study is to develop analytical models that allow predicting the performance of concrete incorporating recycled aggregates regarding chloride penetration. Multiple linear regression analysis was applied to a dataset collated from the literature. The dataset comprised 942 case studies from 33 publications. The analyses allowed identifying the explanatory variables and developing two mathematical models. One of these models is intended to predict the chloride diffusion coefficient from accelerated non-steady state migration tests, while the other predicts the charge transfer in rapid chloride permeability tests. The obtained correlation coefficients and analysis of variance (ANOVA) test results evidence the adequacy of both models. Thus, it is possible to estimate the resistance to chloride penetration in concrete incorporating recycled aggregates through the proposed models.

1. Introduction

The chloride-induced corrosion is one of the most common degradation mechanisms that occur in reinforced concrete structures [1], promoting the development of several anomalies, namely: reduction of the cross-section area of reinforcement; cracking and spalling of the concrete cover; and loss of adherence between concrete and reinforcement steel [2]. The reinforcement's corrosion of concrete structures, due to chloride ingress is a rising concern in most countries [3], compromising the structural safety of the constructions, often reducing their durability and service life [4], with a significant economic and ecological impact [5]. Therefore, the setup of accurate models to predict the chloride diffusivity in concrete is extremely relevant, to adopt adequate measures, during the design stage, to mitigate the occurrence of these defects. In the last decades, several methodologies have been put forward to model the service life of reinforced concrete structures associated with the chloride-induced deterioration mechanism [6–8]. As mentioned by Liang et al. [3], one of the main challenges in establishing mathematical models to predict the chloride diffusivity of concrete, is identifying and encompassing all the relevant variables (material characteristics, mix design, curing conditions, among others) for the description of this phenomenon.

This study is a part of a series where statistical modelling of the resistance to corrosion-inducing major processes (carbonation and chloride penetration) of natural aggregate concrete and recycled aggregate concrete has been addressed. Based on multiple linear

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https://doi.org/10.1016/j.conbuildmat.2018.06.125
0950-0618/

regression analysis, applied to case studies collated from literature, analytical models to estimate the carbonation coefficient of natural aggregate concrete [9] and recycled aggregate concrete [10], as well as to estimate chloride diffusion coefficients of natural aggregate concrete [11] were already proposed. In this paper, the same approach is applied aiming at developing mathematical models to estimate indicators of recycled aggregate concrete performance regarding chloride penetration.

2. Background

The use of construction and demolition wastes in concrete production has gained momentum over the recent decades. This use is encouraged by taxing landfill disposal and by the need to avoid the depletion of natural aggregate sources, both envisaging an ecological footprint reduction. Steel corrosion in reinforced concrete is one of the most important deterioration mechanisms that curtails the durability of reinforced concrete structures. Chloride ingress is one of the two main phenomena that initiate reinforcement corrosion by destroying its passive coating [12,13].

Some findings about the effect of using recycled aggregate (RA) as a partial or total replacement of natural aggregate (NA) in concrete performance concerning resistance to chloride penetration are available in the literature. Regarding recent studies, Bravo et al. [14] found that the total replacement of NA with recycled aggregates from construction and demolition waste (CDW) causes chloride ion diffusion to increase in the range of 16% to 130%, for full RA incorporation ratios, dependent on the RA source. Kurda et al. [15] also concluded that full replacement of NA with RA is penalizing in terms of chloride ion penetration resistance, even if the aggregate is from recycled concrete. Kapoor et al. [16] investigated the durability performance of self-compacting concrete incorporating recycled aggregates and found increases in the total charge passed during the Rapid Chloride Permeability (RCP) test [17] up to 13.8%, corresponding to a mix containing 100% Recycled Concrete Aggregate (RCA). Kou and Poon [18] evaluated the effect of the quality of parent concrete on the durability properties of concrete mixes with 100% coarse RCA and found that, although chloride permeability [17] decreases with the increase of strength of the parent concrete, it was always higher than the chloride permeability of the reference mix with natural aggregates. Saravanakumar and Dhinakaran [19] studied the durability characteristics of Ground Granulated Blast Furnace Slag-based concrete with coarse recycled aggregate and observed that chloride permeability increases with the increase in percentage replacement of recycled aggregate. A similar study, carried out by Dodds et al. [20] came to the same conclusion. Pedro et al. [21] tested the influence of the crushing process, to obtain coarse recycled concrete aggregate from precasting industry on the performance of concrete made with those aggregates, including the chloride penetration resistance, tested through an accelerated non steady-state migration test [22]. They found that, regardless of the crushing process, the mixes with recycled aggregates exhibited lower resistance to chloride penetration than the corresponding mixes with natural aggregates. Despite the general trend of decrease of the resistance to chloride penetration with the increase of recycled aggregate content, attributed to increases in open porosity, Vieira et al. [23] reported improvements in the resistance to chloride penetration when using fine aggregate from ceramic bricks. This was attributed to the pozzolanic reaction arising from the chemical composition of the recycled aggregate. Moreover, several publications argue that the generally adverse effect of recycled aggregates in concrete production can be mitigated by means of adjusting mix design parameters, namely by adding selected mineral admixtures [16,25,26]. These mineral admixtures, amongst other effects, allow to increase the chloride binding ability [27–31]. Thus, establishing a relationship between resistance to chloride penetration in recycled aggregate concrete (RAC) and known influential parameters in concrete performance is a complex subject.

Although Asghshahr et al. [31] point out statistical modelling and machine learning methods as promising approaches to address the chloride penetration in concrete subject, tools to forecast recycled aggregate concrete resistance to chloride penetration are not found in literature. This study aims at bridging this gap. Nowadays, accelerated tests to assess concrete resistance to chloride penetration are widely used. Amongst them, the most frequently found in literature are the RCP test [17] and the modified CTH rapid test [22] that return indicators of concrete ability to resist chloride penetration. Therefore, the outcome of this study is the development of two simple and accurate analytical models to estimate the corresponding indicators of the mentioned tests. The development is carried out through the application of a multiple linear regression analysis to many data collated from the literature.

3. Statistical modelling

3.1. Statistical model and selection of the variables

The analysis of the individual influence of a given factor in the description of a complex phenomenon, such as the chloride penetration in concrete, can lead to erroneous conclusions; i.e. a given factor could seem extremely relevant when it is not or, on the contrary, a given variable may appear unrelated to the dependent variable when analysed alone but may have a strong influence when considered simultaneously with other predictors [32]. Therefore, to model and identify the main factors that influence the chloride penetration in concrete with recycled aggregates, a multiple linear regression (MLR) analysis is used, which allows examining the simultaneous effects of multiple independent variables or predictors in the variability of the dependent or explained variable [33–37]. The generic statistical relationship between the dependent variable y and the multiple independent variables x_k is given by Eq. (1).

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \varepsilon \quad (1)$$

where y represents the dependent variable (also called response variable, output, endogenous or explained), $\beta_0, \beta_1, \ldots, \beta_k$ the regression coefficients, $x_1, x_2, \ldots, x_k$ the independent variables (also called predictors, input, regressors, exogenous or covariables) and ε the random errors of the model. The regression equation given by Eq. (1) gives the value predicted for the dependent variable according to the independent variables included in the model, which lies on the best-fit regression plane, which represents the multidimensional generalization of a line [32].

In this study, the MLR model and the statistical analysis are obtained thorough the SPSS (Statistical Package for Social Sciences) software. One of the most important steps to obtain an accurate MLR model is the selection of the relevant variables. The MLR model should encompass two conflicting characteristics, which are simplicity and accuracy. Usually, models with fewer variables also contain fewer nuisance variables (which increase the complexity of the model, do not present a relevant contribution for the explanation of the variability of the dependent variable), also presenting a higher generalisation capability [38]. Therefore, only the statistically relevant variables should be included in the model. For that purpose, a *Stepwise* technique is used to select the covariables with higher explanatory power for the description of the dependent variable. In this method, the variables are introduced in the model, in a step-by-step procedure, in which the variables