Construction and Building Materials 161 (2018) 236–245

Contents lists available at ScienceDirect

Construction and Building Materials

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

Numerical service-life modeling of chloride-induced corrosion in recycled-aggregate concrete

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HIGHLIGHTS

- We present a 1D numerical service-life model for recycled aggregate (RA) concrete.
- The model accounts for both normal and chloride-contaminated RAs.
- RA concretes modeled herein ranged in service life from ~10 to 80 years.
- Location and exposure conditions most affect service life in chloride environments.
- In design, moderate to high RA content and some contamination may be acceptable.

ARTICLE INFO

Article history:
Received 10 July 2017
Received in revised form 15 November 2017
Accepted 17 November 2017

Keywords:
Recycled aggregate concrete
Supplementary cementitious materials
Service-life prediction
Chloride-induced corrosion
Numerical modeling

ABSTRACT

This paper presents the theoretical development, validation, and implementation of a 1D numerical service-life prediction model for reinforced recycled aggregate concrete exposed to internal and external sources of chlorides. The model accounts for the inclusion of supplementary cementitious materials (SCMs), namely (a) fly ash, (b) slag, (c) silica fume, and (d) metakaolin, and recycled aggregates (i) with and (ii) without initial chloride contamination from previous in-service exposure. The model is used to predict time to corrosion-induced cracking for reinforced recycled aggregate concrete in five case-study applications, namely structures in a marine splash zone (Zone I), a marine spray zone (Zone II), within 800 km of coastline (Zone III), within 1.5 km of coastline (Zone IV), and parking structures at locations greater than 1.5 km from the coastline (Zone V) in Los Angeles, California and Anchorage, Alaska. The effects of recycled aggregate size, aggregate replacement ratio, degree of aggregate pre-contamination, water-to-cement (w/c) ratio, and SCMs on time-to-cracking of reinforced recycled aggregate concrete are elucidated herein. The potential for SCMs to improve the service life of recycled aggregate concrete is investigated by estimating additions required to meet a target service life of 50 years. Results indicate that, in addition to geographic location, temperature, and severity of exposure, w/c ratio and aggregate replacement ratio exhibit the greatest impact on time to chloride-induced cracking in reinforced recycled aggregate concrete. Furthermore, initial aggregate chloride contamination and aggregate size impart minimal effects on expected service life. Finally, the results illustrate that the use of either fly ash or slag is most viable in achieving a 50-year service life for the recycled aggregate concretes in chloride-laden environments considered in this work.

1. Introduction

Worldwide, concrete is the most common building material and the second most consumed material on Earth after water [1]. Subsequently, its production, use, and disposal have global environmental consequences. The production of cement alone is responsible for 5–8% of anthropogenic carbon dioxide emissions, which exacerbates effects related to global warming and climate change [2]. In addition, debris generated by the demolition of concrete structures is a large contributor to industrial waste streams. While using recycled concrete in low-performance applications is a common practice, the use of crushed recycled concrete as aggregate in new structural concrete remains uncommon, primarily due to a lack of confidence in mechanical properties [3,4] and appropriate modeling tools to predict long-term performance.

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https://doi.org/10.1016/j.conbuildmat.2017.11.084
0950-0618/

1.1. Service-life prediction of recycled aggregate concrete

Chloride-induced corrosion is one of the most common durability issues encountered by reinforced concrete structures. Laboratory and modeling studies have consistently shown that the chloride permeability of recycled aggregate concrete increases with aggregate replacement ratio due to increases in average pore size and total concrete porosity [5–9]. Other experimental studies have shown that chloride resistance can be further compromised by initial contamination of recycled aggregates from previous in-service exposure [10,11].

To improve confidence in the long-term durability of both normal and recycled aggregate concrete, engineers require suitable modeling tools to estimate the service-life performance of concrete structures in chloride-laden environments. Despite being widely used, service-life prediction tools, such as Life-365™ [12] and STADIUM® [13], do not yet account for the use of recycled aggregates. However, several researchers have proposed models to predict chloride transport in recycled aggregate concrete, including the authors, who previously proposed the first steady-state model for chloride diffusion in both contaminated- and non-contaminated recycled aggregate concrete. Xiao, et al. [14] used the finite element method to conduct a parametric study that elucidated the effects of aggregate replacement ratio, shape, boundary conditions, and attached mortar on the effective diffusivity of recycled aggregate concrete. Ying, et al. [15] proposed a new model that described the effects of recycled aggregate distribution on chloride diffusion. Srubar [11] proposed a steady-state 1D solution to Fick's Second Law of Diffusion that accounted for pre-contamination of recycled aggregates. The model was based on dopant-diffusion principles in which a substrate is doped with concentrations of another material that diffuse throughout the bulk over time. Despite this modeling advance for contaminated recycled aggregate concrete, incapability of accounting for non-steady-state boundary conditions and time-dependent changes in the chloride diffusion coefficient is a limitation of the approach.

1.2. Scope of work

To address the limitations of the previously proposed steady-state chloride diffusion model for reinforced recycled aggregate concrete, this paper presents the formulation, validation, and implementation of a 1D numerical finite difference solution to Fick's Second Law of Diffusion that is used with a simplified cracking model to predict time to corrosion-induced cracking in contaminated and non-contaminated recycled aggregate concrete. The model, which is based on the finite difference solution employed in Life-365™ [12], accounts for non-steady-state chloride boundary conditions, recycled aggregate size, placement, replacement ratio, and initial degree of contamination, and effects of water-to-cement (w/c) ratio, time, temperature, and supplementary cementitious material (SCM) additions on the chloride diffusion coefficient. The numerical model is first validated with Life-365™ using normal aggregate concrete and is subsequently enhanced with the most current parametric relationships and implemented using a stochastic approach to estimate time to corrosion-induced cracking of recycled aggregate concrete in five case-study applications, namely structures in a marine splash zone (Zone I), a marine spray zone (Zone II), within 800 km of coastline (Zone III), within 1.5 km of coastline (Zone IV) and parking structures (Zone V) in Los Angeles, California and Anchorage, Alaska. In addition to elucidating the effects of key modeling parameters, the amount and type of SCM required to meet a target service life of 50 years in each case-study application is investigated herein.

2. Model development

The time to corrosion-induced cracking was estimated using a two-part damage model first proposed by Tuutti [16]. The model considers the total service life, t_s, of reinforced recycled aggregate concrete the sum of two successive time periods, namely, time to corrosion initiation, t_i, which is governed by the diffusion of chlorides throughout the concrete media, and the time to corrosion cracking, t_c.

2.1. Time to corrosion initiation

Time to corrosion initiation is a function of the transport properties of the concrete, geometry, the boundary conditions that exist for a given environment and application, and the required concentration of chlorides to initiate the corrosion of the reinforcing steel (i.e., chloride threshold). Corrosion initiation is defined as the time that it takes for chlorides from the surrounding environment to penetrate the concrete cover and accumulate to a sufficient concentration at the reinforcement surface to initiate corrosion. Chloride concentrations above the chloride threshold locally reduce the pH near the reinforcement, which results in depassivation of the protective oxide layer and subsequent corrosion of the steel reinforcement.

Chloride transport can take place due to a number of mechanisms including (a) diffusion under the influence of a concentration gradient, (b) absorption due to capillary action, (c) migration in an electrical field, and (d) pressure-induced flow and wick action when water absorption and water vapor diffusion are combined [17]. Ionic diffusion of chloride is the primary mechanism of chloride transport and is considered the sole mechanism for the models discussed in this study. It has been shown that the relationship between chloride concentration, diffusion coefficient, and time in the random molecular motions of chloride ions in concrete can be described using Fick's Second Law of Diffusion [18], a governing second-order partial differential equation that is used to characterize the diffusion process:

$$\frac{\partial C}{\partial t} = -D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

where C is the chloride concentration (kg/m^3), D is the apparent diffusion coefficient (m^2/s), x is the depth from the exposed concrete surface (m), and t is time (s).

A finite difference method is employed to numerically solve the diffusion equation and estimate time to corrosion initiation. The approach is based on the well-known Life-365™ service-life prediction software [12], which utilizes the Crank-Nicolson finite difference method to numerically solve the diffusion equation for normal aggregate concrete. The Crank-Nicolson approach is implemented here to account for limitations of the simple error function solution previously reported by the authors [11], namely its inabilities to account for non-steady state boundary conditions and time-dependent changes in chloride diffusion coefficients.

According to the method, a 1D representation of the concrete cover depth is divided into a finite number of slices, s, and nodes, n, where $n = s + 1$. The chloride concentration at an arbitrary node, i, at a timestep of $t + 1$ is calculated by the advection-dispersion equation:

$$-ru_{i+1}^{t+1} + (1+2r)u_i^{t+1} - ru_{i-1}^{t+1} = ru_{i+1}^{t} + (1-2r)u_i^{t} + ru_{i-1}^{t} \tag{2}$$

where the dimensionless Courant-Friedrichs-Lewy (CFL) number:

$$r = D_{t,T}\left(\frac{dt}{2(dx)^2}\right) \tag{3}$$