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Effects of coarse aggregates on chloride diffusion coefficients of concrete and interfacial transition zone under experimental drying-wetting cycles

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HIGHLIGHTS

- Effects of coarse aggregates (CAs) on chloride profiles in concrete is studied.
- Multifactor model of D_a for concrete considering the time and CAs is developed.
- Empirical model of D_{ref} for ITZ considering the effect of CAs is proposed.
- Meso-scopic model of concrete considering ITZ for chloride transport is simulated.

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ABSTRACT

Chloride ions diffusion into concrete is one of the most significant factors for reinforced concrete (RC) structures exposed to marine environment, and this can deteriorate reinforcing steel in concrete and cause steel corrosion, ultimately, shorten the durability and serviceability of RC structures. In this paper, the in-door physical experiment method was adopted to explore the effects of natural coarse aggregate on chloride concentration profiles and diffusion behaviors for concrete specimens under man-made exposure condition of drying-wetting cycles. All investigations were based on 10 concrete mixture designs containing variable volume fractions and maximum sizes of natural coarse aggregate for maximum exposure period of 170 days. The chloride profiles versus exposure time, coarse aggregate volume fraction and maximum size were discussed in this paper. The time-dependent model of surface chloride concentration, and the multifactor model of chloride diffusion coefficient of concrete specimens included exposure time, volume fraction, and maximum size of coarse aggregate were developed based on the experimental measurements. In addition, an empirical prediction model for estimating the chloride diffusion coefficient of interfacial transition zone (ITZ) by the consideration of coarse aggregate was determined. Finally, the accuracy and reasonability of the two models of chloride diffusion coefficients for concrete and ITZ considering the effects of coarse aggregate were validated in terms of the meso-scopic finite element numerical simulation method for chloride diffusion into concrete.

1. Introduction

Concrete is a composite material of heterogeneity in which composed of cement (or cement substitutes), fine and coarse aggregates (sand and crushed stone, generally), water, and some other functional admixtures. In most construction practical engineering, concrete mixtures are subject to deteriorations and variations, especially, exposed to marine salty environment, not only in quantity, but also in quality. For attaining economic, mechanical, and reliable requirements, the aggregates within concrete mixtures generally account for approximately 60–70% of the total volume fractions of concrete, particularly, as one of the main constituents, the coarse aggregates usually occupy around 40% of the concrete volume [1]. The properties of aggregate play a significant role in aggressive ions ingress and durability of concrete structures, moreover, the resulting mechanical properties attributed to aggregates existed significantly affect the performance levels

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of concrete [2]. Concrete, which casted with aggregates of various types [3–5], sizes [4,6,7], contents and particle distributions (grading) [8], etc., would show the variations for compressive strengths. The compressive strength of concrete increased with the aggregate content increasing, however, showed opposite to the chloride diffusivity of concrete [9].

The quality and durability of reinforced concrete (RC) is closely correlated to different factors, such as chloride-induced corrosion of steel bar, carbonation of concrete, w/c variation, thickness of cover, cracks influence, temperature and humidity, etc, [10]. Particularly, Chloride-induced corrosion of steel reinforcement attributed to chloride ion ingress into concrete is treated as a significant factor for premature deterioration and to decline the durability of the RC structures when exposed to marine salty environments [11]. The permeability of concrete mainly depended on its constituent materials and corresponding geometric arrangement. Delagrave et al. [12] pointed out that the inclusion of aggregates in concrete can modify the internal pore structure and capillary porosity, and the significant influence of aggregate on chloride diffusion properties is that the dilution and tortuosity effects that can reduce the diffusivity of concrete, however, the ITZ and percolation effects would increase the diffusivity for concrete. Consequently, it is very necessary to explore the comprehensive effects of various aggregate properties on chloride concentration profiles and diffusion behaviors into concrete.

Some of the efforts devoted to study the chloride transport behaviors and to evaluate the chloride diffusion coefficients of concrete considering various aggregate volume fractions, which involved the use of analytical and empirical models, in-door and in-site physical experiments, meso-scopic numerical simulation method, as well as the arbitrary combinations of aforementioned approaches.

For analytical and empirical models, Farahani et al. [10] summarized a series of prediction model types for chloride diffusion coefficients of concrete showed in Table 1 within literature [10]. Hobbs [13] derived an analytical model to evaluate the effects of the volume fraction and diffusion coefficient of aggregate on chloride diffusion coefficient of concrete. Xi and Bazant [14] established a mathematical model for chloride penetration in saturated concrete by taking into account various influential parameters of aggregate content, w/c, curing time and types of cement. Bentz [15] developed a set of multi-scale computer model for predicting the chloride diffusivity of high performance concrete considering the volume fraction of aggregate, w/c, silica fume addition and degree of hydration. Caré and Hervé [16] established an analytical model based on 'N-layered inclusion' to predict the effective chloride diffusion coefficient in mortar or concrete. Sun et al. [17] improved a multi-scale model based on the 'N-layered spherical inclusion theory' developed by literature [16] to predict the effective chloride diffusion coefficient of concrete. Oha and Jang [18] proposed a simple analytic model derived by the composite sphere assemblage model to determine the chloride diffusion coefficient of concrete and mortar considering the influence factors of capillary porosity and pore structure of cement paste, diffusivity and volume fraction of aggregate and ITZ. Wang and Ueda [19] developed a meso-scale truss network model to simulate chloride diffusion in concrete. From this literature, it can be concluded that the inclusion of aggregate particles can reduce the chloride diffusion coefficient of concrete, and the effect of tortuosity induced by aggregates is greater than that of the porosity and connectivity of the ITZ. Choi et al. [20] proposed a simple prediction model of chloride diffusion coefficient in mortar and concrete considering the effects of porosity of ITZ and spherical aggregate. Liu et al. [21] derived an analytical equation on the basis of a combined series and parallel multiphase model to examine the effects of aggregates and ITZs on chloride diffusivity of concrete, and the results estimated by this equation agreed well with those of other models, experiment and numerical simulation method. Wang et al. [22] proposed a time-and-depth-dependent chloride diffusion coefficient model (T-D model) for concrete considering the influence of coarse aggregate. The T-D model can elaborate the variation characteristics for chloride diffusion coefficient of concrete with exposure time and diffusion depth varying.

For experimental method, Delagrave et al. [12] employed the steady and non-steady accelerate chloride migration tests (ACMT) to access the chloride transport properties in three series of mortars, in which included three water-to-cement ratios (w/c) and five volume fractions of sand (aggregate). Caré [23] conducted a non-steady-state migration experiment for mortar specimens cast with a same volume content and different size distribution of aggregate. They indicated that the effect of aggregates on the chloride diffusion coefficient depended on both the ITZ volume and the length of tortuosity pathway for chloride transport. Yang and Su [24] investigated the effect of fine aggregate content on the chloride diffusion coefficient of mortar specimens using the ACMT. The chloride diffusion coefficients for mortar with different volume fractions of fine aggregate were tested and adopted to evaluate the dilution, tortuosity and ITZ effects of fine aggregate in the cement-based composites. Moreover, the approximate chloride diffusion coefficients of ITZ were derived based on the experimental measurements. Subsequently, Yang and Cho [25] also used the ACMT to further inquire into the effect of lateral surface area of the aggregate on chloride diffusion coefficient of ITZ using the cylindrical mortar specimens cast by regular cylindrical coarse aggregate, in which included a constant volume fraction with various diameters and numbers of aggregate. Similarly, the fitted functions of chloride diffusion coefficient for the mortar specimens and the ITZ were determined. Comprehensively, Yang [26] obtained the chloride migration coefficients for concrete specimens with different volume fractions and the total lateral surface areas of coarse aggregate by ACMT. A mathematical model with the three-phase composite material characteristics of concrete was built to estimate the approximate chloride diffusion coefficient of the percolated ITZ. In recent years, Yang and Weng [27] investigated the performance of ITZ and the effect of ITZ on chloride diffusion coefficient for mortar specimens cast by w/c = 0.35 with 5 different volume fractions of fine aggregates using ACMT, moreover, the chloride diffusion coefficients for mortar with a three-phase composite material were predicted using the double-inclusion method and Mori–Tanaka theory. Basheer et al. [28] carried out the air permeability test, freeze–thaw/salt scaling resistance test and an accelerated carbonation test to investigate the effect of size and grading of the coarse aggregate on the durability and the

Table 1
Compositions of OPC (P.O. 42.5).

Properties	Cement
Chemical analyzes (%)	
Calcium oxide (CaO)	63.1
Silicon dioxide (S_iO_2)	19.8
Ferric oxide (Fe_2O_3)	3.25
Aluminum oxide (Al_2O_3)	4.51
Magnesium oxide (MgO)	1.95
Sulfur trioxide (SO_3)	3.02
Potassium oxide (K_2O)	0.58
Sodium oxide (Na_2O)	0.18
Titanium dioxide (TiO_2)	0.28
Manganese oxide (MnO)	0.09
Bogue Composition (%)	
Tricalcium silicate C_3S	57.5
Dicalcium silicate C_2S	18.4
Tricalcium aluminate C_3A	7.3
Tetracalcium aluminoferrite C_4AF	10.8