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Research Progress on the Transport and Prediction of Chloride Ions in Concrete Structures

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Abstract

Reinforced concrete structures are widely used in practical engineering, and the durability issues of such structures under chloride environments have been a hot research topic. Chloride ions can cause corrosion of internal steel bars in structures under the action of chloride salt, leading to structural cracking, decreased bearing capacity, and ultimately affecting the structural safety during service life. Therefore, comprehensive and systematic research on chloride ion transport and prediction in concrete structures is crucial. This paper reviews the recent research progress on chloride ion transport in concrete structures both domestically and internationally, introduces the latest research results on chloride ion transport mechanisms, transport laws, prediction methods, and points out the limitations and future research directions in existing research on chloride ion transport and prediction in concrete structures.

Keywords: concrete structures, chloride, prediction, research progress

1. Introduction

Concrete is one of the important materials widely used in construction engineering. However, the problem of concrete structures being attacked by chloride ions has long been a concern. Chloride ions enter the interior of concrete through its pore structure under the action of external chloride environments, react with steel bars, causing corrosion and damage to concrete structures, severely affecting the service life and safety of concrete structures (Yang YM, Peng JX, Cai CS & Tang H, 2023). Therefore, accurate prediction and control of chloride ion transport in concrete structures are of vital importance. Currently, research on predicting chloride ion transport in concrete structures mainly focuses on transport mechanisms, research methods for chloride ion transport laws, and prediction methods for chloride ions. This paper will comprehensively summarize the current research progress in these aspects and discuss future research directions and possible solutions.

2. Transport Mechanism of Chloride Ions in Concrete

Due to the differences in the saturated state of concrete and the service environment, the driving force and erosion mechanism of external chloride ions and other aggressive media entering concrete are also different. Currently, chloride ion transport in concrete includes multiple methods such as permeation, diffusion, and electrochemical migration (Wang HL, Lu CH, Jin WL & Bai Y, 2011; Bao JW & Wang LC, 2017). To achieve the penetration of chloride ions into concrete, there must be a permeation pressure difference that drives chloride ions to migrate into the interior of concrete through pores. When the chloride ion content inside concrete differs from that of the external environment, a concentration gradient is formed, and chloride ions gradually migrate from high concentration areas to low concentration areas until equilibrium is reached. In the presence of an electric field, chloride ions move and migrate in a certain direction, accelerating chloride ion erosion in concrete, which is beneficial for further obtaining the anti-erosion ability of chloride ions in concrete components. Electrochemical migration is widely used in indoor accelerated tests. In actual engineering, the factors affecting chloride ion transport in concrete components are not singular, and there may be multiple combinations of diffusion, permeation, electrochemical migration, and diffusion effects. For concrete structures immersed in chloride-containing seawater solutions for a long time, the concrete structure will be in a saturated state, and chloride ion migration in concrete is mainly dominated by diffusion. The diffusion is not in a steady state, and the mass fraction of chloride ions changes over time. Non-steady-state diffusion with chloride ion mass fraction changing over time is commonly referred to as Fick's Second Law (Wang HL, Dai JG, Sun XY & Zhang XL, 2016).

3. Research on Chloride Ion Transport Laws

The research on the transport laws of chloride ions in concrete mainly falls into two categories: experimental methods and numerical simulation methods. Currently, many scholars have conducted research on the transport behavior of chloride ions in concrete under dry-wet cycles, loads, and other conditions based on experimental methods. In terms of loads, the main considerations include axial compression (continuous and cyclic) (Wang HL, Lu CH, Jin WL & Bai Y, 2011; Bao JW & Wang LC, 2017), axial tension (Wang T, Pei CD, Han WS & Chen F, 2015), bending (Ye H, Fu C, Jin N & Jin X, 2015), and other load forms and stress levels' effects on chloride ion transport behavior. Regarding environmental effects, the main considerations are the effects of different cycling mechanisms and frequencies of dry-wet cycles on chloride ion transport behavior (Han XQ, Zhang SL, Xu Q, Tang XD, Wang LB & Qian KL, 2020).

Experimental studies on chloride ion transport have limitations such as long cycles, large investments, and low efficiency and are not suitable for analyzing the influence of concrete's microstructure on chloride ion transport behavior. Therefore, scholars at home and abroad have conducted microscopic simulations of chloride ion transport. Schlangen and Mier (1992) established a model of concrete materials from a microscopic perspective and conducted finite element analysis on it, clearly representing the material's microstructure, which has been widely used. These models have been proven effective in describing the relevant properties of concrete structures (Benkemoum N, Gelet R, Roubin E & Colliat JB, 2015). Garboczi and Bentz (Roubin E, Vallade A, Benkemoun N & Colliat JB, 2015) proposed a comprehensive multiscale model that considers the interface transition zone of concrete materials to predict chloride ion transport and diffusion in concrete. Zheng et al. (2012), based on the simulated microstructure of concrete, used a lattice model to evaluate chloride ion diffusion in concrete and analyzed the effect of structural shape on chloride diffusion performance. Zeng et al. (2007) considered concrete as a two-phase composite material made of aggregate and mortar matrix and analyzed the diffusion behavior of chloride ions in concrete using finite element methods of two-dimensional structural models.

4. Prediction Methods for Chloride Ion Transport

The accumulation of chloride ions on the surface of steel bars caused by long-term transport of chloride ions is the main cause of steel bar corrosion. Reasonable prediction of chloride ion concentration distribution is crucial for the durability assessment of structures. In recent years, many scholars have extensively researched the transport mechanisms and laws of chloride ions in concrete and proposed numerous chloride ion transport models. Wang et al. (2011) obtained the relationship between the chloride ion diffusion coefficient and pressure stress through experiments and, based on this, comprehensively considered factors such as stress level, water-cement ratio, curing time, temperature, concrete age, humidity, and chloride ion diffusion coefficient to obtain models for chloride ion diffusion processes under different loading conditions. Farahani et al. (2015) conducted regression analysis based on Fick's Second Law and established a predictive model for the chloride ion diffusion coefficient in silica fume concrete considering exposure time, temperature, silica fume content, and water-cement ratio. Real et al. (2015) studied the relationship between the chloride ion diffusion coefficient and water-cement ratio and aggregate type and established a model to calculate the chloride ion diffusion coefficient in lightweight aggregate concrete. With the rapid advancement of artificial intelligence technology, data-driven prediction models for chloride ions are also gradually being proposed. Wu et al. (2021) obtained chloride ion permeability coefficient samples through orthogonal experiments and on-site accelerated chloride ion penetration tests, establishing a prediction model based on random forests and support vector machines. Van (2022) studied the predictive performance of eight machine learning algorithms for chloride ion diffusion coefficients and found that gradient boosting tree models had the best predictive effect on chloride ion diffusion coefficients.

5. Existing Research Limitations and Challenges

Although significant progress has been made in many studies, there are still some limitations and challenges. Firstly, existing research mostly focuses on simulations under laboratory conditions and theoretical derivations, lacking verification and practical experience in actual engineering applications. Secondly, the relationship between the complex pore structure in concrete structures and chloride ion transport mechanisms is not deeply researched enough, and there is a need for further comprehensive research. Additionally, the accuracy and precision of chloride ion transport predictions still need to be improved, especially in predicting under external environmental factors and engineering practical conditions, which present challenges.

6. Future Research Directions and Solutions

Future research can focus on several aspects: firstly, deepen the research on the relationship between concrete's microstructure and chloride ion transport mechanisms, combine experiments and numerical simulations to comprehensively understand the transport laws of chloride ions in concrete; secondly, develop new prediction methods and models, combine artificial intelligence and big data technologies to improve the accuracy and reliability of predicting chloride ion transport in concrete structures; thirdly, strengthen engineering practices and applications, verify and improve existing prediction models and methods through long-term monitoring and evaluation of large-scale engineering projects, achieving effective control and management of chloride ion transport in concrete structures.

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