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Combined effect of water and sustained compressive loading on chloride penetration into concrete

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HIGHLIGHTS

- Model of coupled water and chloride transport in concrete under loading was proposed.
- The combined effect of saturation degree and loading on chloride penetration was studied.
- Cumulative water content and chloride profiles under various stress levels were obtained.
- Relationship between water/chloride diffusivity and stress level was developed.
- Numerical results well agreed with experiments within a certain compressive stress level.

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ABSTRACT

This paper presents the results of an experimental investigation on the water and chloride transport properties of unsaturated concrete under combined short-term sustained compressive loading and chloride attack. Aiming for the coupled effect of sustained compressive loading and chloride penetration, an improved test apparatus, which is compared with the traditional gravimetric measurement, was designed to real-timely and continuously measure the amount of water solution absorbed by the cylindrical hollow concrete specimen under sustained loading. A series of chloride transport experiments on water/chloride diffusivity and penetration profiles of chloride were conducted on the saturated, half-saturated and fully dried concrete respectively subjected to several compressive stress levels (ranging in 0–50% of the corresponding compression loading capacity). The experimental results showed that the saturation level and sustained compressive loadings have significant influences on water and chloride transport properties of the unsaturated concrete. The quantitative relationship between water/chloride diffusivity and compressive stress level was developed by fitting the obtained experimental data. Finally, on the basis of convection-diffusion equation, the prediction model of chloride transport in unsaturated concrete under sustained compressive loading was proposed and validated by the experimental results. The comparison of chloride profiles indicates that the numerical results were in good agreement with the experimental measurements.

1. Introduction

The presence of aggressive fluids and their transport (i.e., water or chloride solution) is the most crucial factor controlling the durability of reinforced concrete (RC) structures, which are increasingly decisive for the structural design, particularly in marine environments [1–4]. In practice, for short-term cyclic drying-wetting action (i.e. located in the tidal zone or exposed to sea water spray), concrete is often found in an unsaturated condition rather than a fully saturated state. The amount of pore water in concrete can greatly affect the transport capacities of water and associated transport of dissolved chloride ions. For the non-saturated concrete exposed to a salt solution, the initial mechanism to absorb salt water appears to be capillary absorption due to the surface tension of pores, and then capillary suction for the salt water passing the interconnected pores or microcracks is followed by a more substantial diffusion of chloride due to concentration gradient [5]. Thus, the simultaneous action of diffusion and capillary absorption becomes the dominant transport mode in unsaturated concrete [6,7].

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Principally, there are various transport mechanisms that chloride ion can permeate in concrete namely, convection (i.e., capillary suction or permeability), diffusion and migration [8–10]. In reality, the movement of chloride through concrete under a marine environment can also be due to the combination of two or more of the mechanisms listed above. In all cases, the properties of chloride transport in concrete depend largely on the interconnected pore network within the hydrated cement paste and the inherent microcracking within the concrete [11–13]. Whereas in service, RC structures are usually subjected to various forms of stress due to the mechanical, thermal and chemical stress environment [14–16]. For the case of mechanical loading, as time goes on, the applied loads (compression, tension or flexure) promote crack generation and development, and in turn, result in an increase in the rate of chloride penetration in concrete. Thus, in order to realistically evaluate the durability and predict service life of RC structures, it is imperative to investigate the coupled effect of external loading and saturation level on chloride ingress in concrete.

Considerable efforts have been made by using experimental, analytical and numerical methods to investigate the influence of compressive loading-induced damage or cracking on chloride penetration into the pore space of saturated concrete [9,15–22], and accordingly, numerous models to predict chloride ingress within concretes under a saturated state have already been developed. In the experimental investigations, Yoo and Kwon [15] investigated the effect of cold joint and loading conditions on chloride diffusion in concrete containing GGBFS. They found that chloride diffusion coefficient decreases to 30% of compressive loading level and increases afterwards. When exceeding 60% of loading level, it increases to 1.34–1.78 times for normal concrete and 2.32–2.52 times for GGBFS concrete. Lim et al. [17] conducted a series of experiments to study the effect of compressive loading on the chloride diffusivity in concrete. They found that increasing stress level in a critical range decreases the chloride diffusion coefficient, and on the contrary the diffusion coefficient increases significantly when the stress level is beyond this critical value. In the research of Djerbi Tegguer et al. [23], the effect of uniaxial compressive loading-induced damage on gas permeability and chloride diffusivity for ordinary and high performance concrete was studied. Based on the damage variable, which was evaluated by elastic stiffness degradation and ultrasound pulse velocity, an exponential correlation between intrinsic permeability and diffusion coefficient was obtained. Similarly, Rahman et al. [24] investigated the influence of compressive stress-induced damage on chloride transport in concrete, and indicated that chloride diffusion in concrete was increased significantly by damage related with compressive load-induced stress. Wang et al. [19] conducted a series of experimental tests to investigate the time-dependent chloride diffusivity of concrete subjected to long-term exposure in a simulated marine environment with sustained compressive loading, and proposed an empirical model to quantify the dependence of the apparent chloride diffusion coefficient D_a and surface chloride content C_s. Yao et al. [25] proposed a test method to determine the durability of concrete exposed to the combined action of chloride penetration and tensile/compressive loads. The experimental results from five different research institutes indicated that the synergetic effects on the durability of concrete was more remarkable compared to the single environmental action without loading.

In the analytical approach and numerical simulations, a few computational models for predicting the chloride transport in concrete subjected to external loadings have been proposed [26–28]. In some instances, Li et al. [26] developed a new solution to Fick's second law for the prediction of chloride ingress in RC flexural members based on the combination of the Knudsen and the viscous flows. Wang et al. [27] applied the rigid body spring model (RBSM) and lattice network model to evaluate the chloride diffusivity of concrete subjected to compressive or tensile loading before cracking, and proposed an empirical diffusivity of mortar and the interfacial transition zone (ITZ) for accounting for the microstructure variation of concrete under loading. Likewise, on mesoscale, Šavija et al. [9] proposed a 3 D dual-lattice model to numerically simulate chloride diffusion in saturated sound and cracked concrete. Ožbolt et al. [1] also presented a 3 D numerical chemo-hygro-thermo-mechanical model to simulate the chloride-induced corrosion of reinforcement by means of a damage variable to describe the increase of diffusivity and permeability of concrete in the cracked area. Based on the theory of elasticity, Jin et al. [18], Du et al. [28] and Xu and Li [29] developed a two-phase spherical model of saturated cement paste or concrete subjected to external mechanical loadings, and theoretically proposed the quantitative relationship between chloride diffusivity and current porosity as well as loading variable (i.e., volumetric strain or external equivalent stress).

Although large volumes of literature already exists documenting chloride diffusivity of saturated concrete subjected to compressive loading [18,22,23,25,28], from what is above stated so far, surprisingly few studies have been focused on the capillary suction-induced convective effect on chloride penetration in unsaturated concrete under the short-term sustained compressive loading. Specifically, in the absence of experimental data, the theoretical interpreting of the coupled effect of saturation level and compressive loading on chloride transport in unsaturated concrete has not yet been made clear.

The major objective of this study is to fill this gap by correlating the change in water/chloride diffusivity and penetration profiles with an increasing compressive stress level on unsaturated concrete. Experimental results of the cumulative water content and chloride profiles for each series of specimens under various compressive stress levels will be presented, and the empirical quantitative relationship between water/chloride diffusivity and compressive stress level will be developed. The theoretical model for modeling chloride penetration into unsaturated concrete under sustained compressive loading will be proposed, which will then be used to illustrate the synergistic effect of loading and saturation level on chloride transport of concrete.

2. Experimental program

2.1. Concrete composition and specimen preparation

Three series of concrete cylinders (ϕ160 mm × 205 mm) with a water-cement ration (w/c) of 0.45, namely Series DC, Series HSC and Series SC, were cast and then subjected to the coupled action of chloride ingress and short-term sustained compressive loading. This experiment was conducted on non-adjuvanted ordinary concrete, using local materials. The ordinary Portland cement used in the mix, which was produced in Dalian, China, was 42.5R complied with Standards [30–32]. The local river sand and available limestone were used as the fine and coarse aggregate, respectively. The used river sand has a fineness modulus of 2.67 and apparent specific gravity of 1450 kg/m^3. The details of concrete constituents

Table 1
Concrete constituents and mixture proportions.

Mix ingredients	Quantity (kg/m^3)
Coarse aggregate, 5–20 mm	1251.25
Fine aggregate (River Sand), 0–5 mm	536.25
Cement, P·O 42.5R	422.5
Distilled water	190
Superplasticizer	0.845
Water/cement ratio	0.45