Construction and Building Materials 180 (2018) 629–642

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental research and mechanism analysis on chloride ingress at different concrete zone along altitude in marine environment. Part 1. Moisture distribution

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HIGHLIGHTS

- The net amount of water absorption during each cycle gradually drops and eventually reaches an equilibrium state.
- Both IDMTs at submerged and atmospheric zones are zero.
- Length of IDMT at the splash zone is about 20 mm, and StMC within the concrete equals EMC.
- The IDMT determines the transport depth of chloride by absorption, and the CWAA determines the amount of chloride absorbed into concrete.
- The CWAA reaches to the maximum at the highest point of the tide, and at this point the penetration of chloride ions also reaches its maximum rate.

ARTICLE INFO

Article history:
Received 6 September 2017
Received in revised form 10 May 2018
Accepted 18 May 2018

Keywords:
Marine tide simulation
Dry and wet cycles
Moisture content
Moisture influential depth
Elevated altitude

ABSTRACT

The moisture distributions in concrete of different zones are different in marine environment. The variations of moisture distribution during drying and wetting were analyzed in this paper. A laboratory test system that whole piece of real concrete was subjected to an environment close to the real marine environment was developed and used to simulate the real marine environment, by which the variations of moisture distribution in concrete of different zones along elevated altitude were studied. The test results reveal that the influential depth of moisture transport (IDMT) and the stability moisture content (StMC) in concrete of different zones are variable. The IDMTs in concrete of splash and tidal zones are larger than those of other zones. IDMT changes along elevated altitude, and the peak value of IDMT appears near the top water line of tidal zone which is the key region of durability design and maintenance.

1. Introduction

The role of chloride ions as aggressive agents in the corrosion of steel is of concern to those who own and maintain concrete structures. Although good quality concrete normally provides excellent protection for steel bar, due to both the concrete's high alkalinity and the physical protection afforded by the concrete acting as a barrier to the access of aggressive species [1], corrosion of steel reinforcement has become the most common cause of failure in concrete structures [2,3]. The chloride ion, once it penetrates to the steel reinforcement, destroys the protective film of the steel reinforcement and results in corrosion of the steel reinforcement and eventual concrete distress [4,5]. Therefore, the resistance to chloride penetration becomes more important in the design and construction of concrete structures.

The source of the chloride ion can be related either to the use of deicing salts on bridges [6] or to salt penetration from marine environments [7]. Previous researches mainly focused on cement soaking experiment and establishment of theoretical model of Fick's Law. Generally, researchers who have examined transport mechanism of chloride ion have concentrated on ionic diffusion as the primary process involved in chloride penetration of concrete [8–11]. For instance, Valipour et al [12] have demonstrated that chloride ingress in cement pastes obeys the diffusion laws and different cementing materials exhibit different degrees of resistance to chloride ion diffusion. It has now reached the stage in which the diffusion resistance of chloride ion has influenced the choice of cement materials [13]. For those structures permanently immersed in seawater or salt solution (such as submerged zone of marine concrete structures), the diffusion is the only or at least is the main trans-

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https://doi.org/10.1016/j.conbuildmat.2018.05.151

port way of chloride ions into concrete, so it should be reasonable to predict the service life of those structures on the basis of Fick's law of diffusion [14].

However, an integrated concrete structure such as wharf, dock and dolphin in marine environment is subjected to different exposure environments including atmospheric, tidal, splash, and submerged zones [15–17]. In each of these zones, the mechanism of chloride penetration into concrete may be different. The durability and longevity of concrete structures is dependent on the weakest one of the aforementioned four zones. Therefore, it is questionable to apply the research results based on Fick's law of diffusion in saturated concrete to real unsaturated concrete in tidal, splash and atmospheric zones.

Submerged part of structure is subject to sustained direct contact with seawater, and chlorides penetrate into concrete mainly by ion diffusion [18]. Concrete at atmospheric zone is never in direct contact with seawater but with a marine aerosol, and concrete is unsaturated. However, concrete in tidal or splash and spray zones is subject to cyclic exposure to seawater [7,19]. Recent research shows that there is a convection zone on the surface layer of concrete under wetting and drying cycles in which transport mechanism of chloride ion is very complex [20,21],

Yongsheng Ji [22] reported water carrying chloride ions ingress into the surface layer of concrete mainly by convection and capillary absorption under wetting and drying cycles (such as tidal and splash zones in marine environment), and the diffusion is the main transport way of chloride ions within deeper concrete region. Based on the mechanism analysis of mass transport, the boundary of non-diffusion zone in surface layer in concrete can be determined by the influential depth of moisture transport (IDMT) [23,24].

It is very important to define the boundary of convective zone. If the width of convective zone is much smaller than that of concrete cover, the influence of Cl^- transport within the convective zone is able to be eliminated by the application of modified Fick's laws of diffusion. However, if the convective zone is very large, a new rate model should be established correspondingly for its transport mechanism.

The overall aim of this study is to develop a deeper understanding of the significance of the moisture distribution to chloride penetration in concrete exposed to different zones along elevated altitude in marine environment. This is the first of two papers and it first explained the mechanism of moisture transport in concrete under wetting and drying cycles. Then a laboratory test system that whole piece of real concrete structure was subjected to an environment close to the real marine environment, which was developed and used to simulate the real marine environment. Finally the variations of moisture distribution into concrete of different zones along elevated altitude were studied and the moisture influential depths and the stability moisture contents in concrete of different zones were determined. This article presents and discusses the moisture influential depth; the measure of chloride ion profiles and the definition of convective zone will be dealt with in Part 2.

2. Theoretical

2.1. Wetting process

2.1.1. Moisture transport mechanism for wetting process

When concrete is dry or partially dry, and then exposed to water, it will imbibe the water by capillary absorption across the material surface, as shown in Fig. 1.

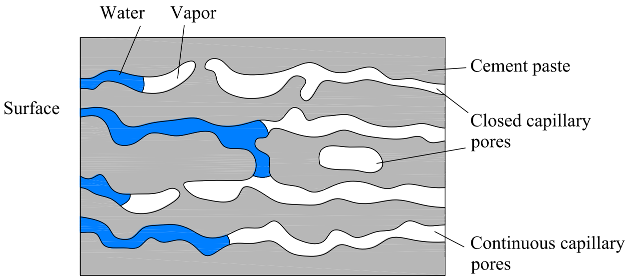

Fig. 1. Water intake of hardened cement paste.

After initial surface adsorption, the liquid water driven by humidity gradient continually transports into deeper area. The moisture distribution in concrete at some point during the wetting period is shown in Fig. 2. Flow of water through concrete at any depth below the surface can take place via a number of mechanisms, depending upon moisture content of concrete [25]. The pores within the first few millimeters of concrete surface layer (at zone A in Fig. 2) will be all filled with water in a very short time (Fig. 3(a)). Thus, there exists moisture gradient within the near surface concrete. Chloride solution transports into concrete by means of non-saturated permeation (Fig. 3(a) and (b)) driven by humidity gradient (at zone B and C in Fig. 2). In the drier areas (at zone D in Fig. 2), moisture content of concrete is relatively low, and water transports inward by means of evaporation-condensation(Fig. 3 (d)); while moisture can transfer into deeper area where there is no humidity gradient via vapor-phase diffusion(Fig. 3(e)) (at zone E in Fig. 2).

As wetting time prolongs, moisture content profiles of non-saturated concrete change from curve 1 to curve 6 (as shown in Fig. 4). The concrete will continue to suck in the salt water until saturation, moisture curve of which is curve 7 in Fig. 4.

2.1.2. Water sorptivity models

The water intake flow I_w [mm^3/mm^2] by capillary absorption during wetting period can be expressed as [26],

$$I_w = S_w\sqrt{t} \tag{1}$$

where t is the time (s); S_w is sorptivity of concrete ($mm/s^{0.5}$), which can be expressed as [25],

$$S_w = S_w^0\sqrt{\left(1-\frac{\theta_e}{\theta_s}\right)} \tag{2}$$

where θ_s is the moisture of saturated concrete in unit weight of concrete [kg/kg]; θ_e is the equilibrium moisture in unit weight of concrete [kg/kg] which denotes the in-concrete moisture level equaling

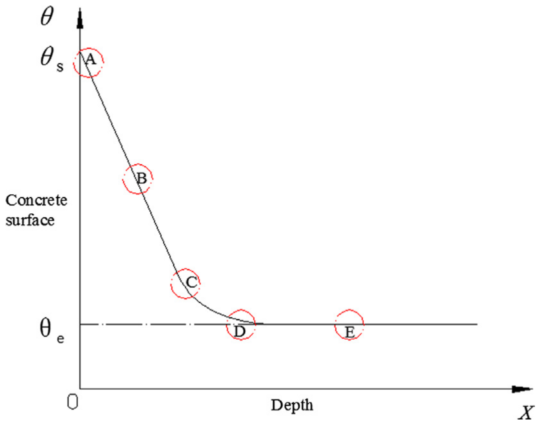

Fig. 2. Moisture distribution in concrete during wetting.