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Influence of pore structure and moisture distribution on chloride "maximum phenomenon" in surface layer of specimens exposed to cyclic drying-wetting condition

Honglei Chang [a,b,c,*], Song Mu [b], Deqing Xie [b], Penggang Wang [d]

[a] School of Materials Science and Engineering, Southeast University, Nanjing 211189, China
[b] State Key Laboratory of High Performance Civil Engineering Materials, Jiangsu Research Institute of Building Science, Nanjing 210008, China
[c] Eduardo Torroja Construction Research Institute, C/Serrano Galvache, 4, Madrid 28033, Spain
[d] School of Civil Engineering, Qingdao University of Technology, Qingdao 266033, China

HIGHLIGHTS

- Maximum phenomenon is found in specimens under cyclic drying and wetting condition.
- Exposure time is important for the formation of maximum phenomenon.
- The effect of pore structure on maximum phenomenon is discussed.
- The influence of moisture distribution on maximum phenomenon is analyzed.

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ABSTRACT

Numerical research discovers a phenomenon that chloride content first climbs to the maximum then descends with depth increasing in surface layer of concrete under cyclic drying-wetting environments, which is temporally called "maximum phenomenon" in this paper for convenience. This phenomenon consists of two characteristic parameters: the maximum chloride content $C_{\max}$ and the depth Δx at which $C_{\max}$ appears. This research mainly focuses on the impact of pore structure and moisture distribution on maximum phenomenon, specifically the two parameters of it. The influence of pore structure on maximum phenomenon is illustrated from three aspects: total porosity, the critical pore size and water absorption porosity (P_c). The increase of total porosity leads to increase of $C_{\max}$. And larger critical pore size renders $C_{\max}$ occur at a deeper position. Moreover, $C_{\max}$ and Δx both increase with water absorption porosity (P_c). The impact of moisture distribution on maximum phenomenon is investigated from non-saturation degree (S_{non}) and relative humidity (RH). The higher the S_{non} is, the greater the $C_{\max}$ and Δx are. However, both $C_{\max}$ and Δx decline with RH rising up, and the influence of RH on them is more significant approximating the exposed surface.

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1. Introduction

Chloride induced corrosion of reinforcing steel is one of the major deterioration causes affecting the service life of reinforced concrete structures exposed to aggressive environment. According to specific environment condition, only one mechanism or combined action of multi-mechanisms are responsible for chloride transport in concrete [1]. In the case of submerged parts of marine structures, considered as water-saturated concrete, diffusion seems to be the only mechanism dominating chloride ingress [2], and chloride content decreases with depth increasing. However, when subjected to drying-wetting environments, like marine tidal zone or deicing salt environment, concrete is in a non-saturated state [3]. In such condition, the process of chloride ingress becomes more complicated and both diffusion and capillary suction drive chloride transport in concrete [4]. As a consequence, the distribution of chloride is likely to be different from that in submerged condition, especially in the surface layer of concrete.

Research about chloride transport in cyclic wet-dry condition has been widely conducted, and many of which [5–9] present a phenomenon that chloride content first climbs to the maximum

* Corresponding author at: School of Materials Science and Engineering, Southeast University, Nanjing 211189, China.
E-mail address: hongleichangck072@163.com (H. Chang).

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and then decreases with depth increasing in the surface layer, and it is temporally called "maximum phenomenon in this paper for convenience. As shown in Fig. 1, maximum phenomenon has two characteristic parameters, $C_{\max}$ and Δx (also named as $C_{s,\Delta x}$ and x_0 in some literatures [14,24]). $C_{\max}$ refers to the maximum chloride content, and Δx means the depth at which $C_{\max}$ appears. In addition, C_s is the surface chloride content; $C_{(x,t)}$ is the chloride content at depth of x and time of t; x is the distance from the exposed surface.

However, the cause for the formation of this phenomenon is still not well identified. According to previous studies, several possible reasons responsible for its appearance have been recognized so far: "skin" effect, carbonation, and capillary suction/moisture evaporation. Skin effect suggests that the porosity difference between skin layer and bulk zone of concrete may result in chloride accumulation in their interface [27]. But it may not be the fundamental causation since maximum phenomenon is also found in literature [30] in which the nonhomogenous surface layer of specimens is cut off. In the aspect of carbonation, it can release bound chloride into pore solution and those dissolved chloride ions migrate to deeper position through pore solution, which is likely to contribute to the appearance of maximum phenomenon [31,32,53]. Some investigations indicate that Δx approximates the front of carbonation [31,54–56] under high CO_2 concentration condition, which proves which proves the importance of carbonation to that phenomenon. However, carbonation effect can be crippled in the normal air environment for the low CO_2 concentration. As to capillary suction/moisture evaporation, many researchers [7,21,23,33–35] consider it as a crucial factor, and some studies [15,44,57] even built models based on this theory with the maximum phenomenon predicted. Therefore, capillary suction/moisture evaporation may play a more important role in leading to maximum phenomenon under cyclic drying and wetting condition.

Maximum phenomenon is getting increasing attention. This is because its appearance in chloride profile makes it unreliable to obtain the diffusion coefficient D and the surface chloride concentration C_s through directly fitting the so called "error function equation" (Eq. (1)) with the chloride concentration acquired, and it influences the accuracy of predicting the service life of concrete using those parameters [6,10–14] obtained. The reason is that, in cyclic wet-dry conditions, diffusion is no longer the only mechanism for chloride transport, and especially in the surface layer, capillary suction is more dominating. For service life prediction taking the maximum phenomenon into consideration, Carmen [14] proposed a relative reliable method which abides by the principle of diffusion. First, neglect the external layer where the chloride concentration increases; then rescale the horizontal axis by setting the depth of Δx as zero point and fit the error function equation

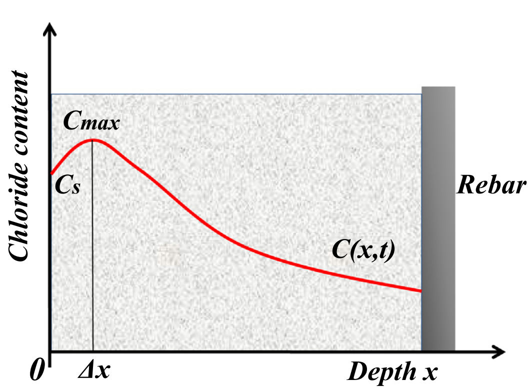

Fig. 1. Chloride profile with appearance of maximum phenomenon in the surface layer.

into the decreasing part of chloride profile to get D_{eff} (as shown in Fig. 1, fitting the chloride data in the range of Δx–x. Note that Δx is less than x); finally, use D_{eff} and $C_{\max}$ (instead of C_s as surface chloride concentration because the practical driving force of diffusion is the concentration difference between the maximum chloride content $C_{\max}$ and the minimum content) to predict the service life of concrete structures (Eq. (2)).

$$C_{(x,t)} = C_0 + (C_s - C_0)\left(1 - erf\left[\frac{x}{2\sqrt{Dt}}\right]\right) \quad (1)$$

$$C_{(x,t)} = C_0 + (C_{s,\Delta x} - C_0)\left(1 - erf\left[\frac{x - \Delta x}{2\sqrt{D_{eff}t}}\right]\right) \quad (2)$$

where

D_{eff} is the chloride diffusion coefficient obtained using method proposed by Carmen;
D is the chloride diffusion coefficient obtained using tradition method;
C_0 is the initial chloride content;
t is exposure time.

It is clear that $C_{\max}$ and Δx are of great significance for service life prediction in cases of the maximum phenomenon occurring. Since both of $C_{\max}$ and Δx are time dependent, their evaluation law along time is especially important, and there are three possibilities [14]: $C_{\max}$ moves inward but maintains the height; and $C_{\max}$ moves and increases the height; and $C_{\max}$ increases without moving. Though numerous studies [5,7,13,29,33,45–52] have discovered maximum phenomenon, only a few of them analyzed and summarized how $C_{\max}$ and Δx changed with time. Ozbolt [15] built a model about chloride transport and the predicted result indicated that the peak concentration of chloride moved progressively deeper into concrete along time. The results of Lu [6] showed that, after being exposed to cyclic dry-wet condition from 210 to 420 days, Δx increased with time increasing. But the method in her research cannot precisely characterizes the position of the maximum phenomenon for large interval of 5 mm between testing points. In the research of Xu [24], specimens were subjected to wet and dry cycles for 100–150 days, and it was found that $C_{\max}$ increased with exposure time while Δx remained at about 2 mm. In general, contradictions exist in the present findings, and more relevant investigations are needed.

The appearance of maximum phenomenon results from chloride transport under dry-wet condition, and it is widely accepted that the essence of the influence of various factors on chloride transport lies in pore structure and moisture distribution. Zhang [16] described the relation between chloride permeability and pore structure of concrete through a linear function. Loser [18] claimed that higher chloride resistance of concrete is due to finer pore size distribution. Moreover, it was also found that pore size and pore connectivity play more significant roles than total porosity in studying transport properties [17]. In terms of moisture distribution, previous investigations [20,21] have shown that the rate of water uptake and penetration depth depend on the initial moisture content of concrete greatly, and higher degree of saturation reduces uptake and penetration depth towards zero [22]. Furthermore, Arya [12,13] found that effective porosity, depending on water content of matrix, decides the quantity of solution entering matrix during wetting, and the stronger the absorption related to water content is, the deeper the chloride ingress is. Obviously, the evolution of maximum phenomenon is probably also related to pore structure and moisture distribution of matrix. However, limited investigations have been reported concerning their relation.

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