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The effect of temperature variation on chloride penetration in concrete

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HIGHLIGHTS

- A testing method for concrete under simultaneous chloride and heat transfer was established.
- An analytical equation to determine the coupling parameter based on the test data was developed.
- The coupling parameter increases with chloride concentration and temperature gradient.

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ABSTRACT

Under a service condition, there are simultaneous temperature variation, moisture fluctuation, and chloride migration in concrete. The coupling effects among them are important for evaluating long-term performance of reinforced concrete structures. In this paper, the effect of temperature gradient on chloride penetration in concrete was experimentally studied. A new experimental technique was established. A systematic experimental study was conducted using the new testing method and concrete specimens with different water-cement ratios, subjected to different temperature gradients and chloride concentrations on the boundary. The test data showed that the temperature variation can significantly increase the chloride penetration process when the gradient of temperature and the gradient of chloride are in the same direction. Gradients in the same direction means that the heat transfer and the chloride penetration are in the same direction. For example, on the right surface of a concrete wall, the temperature is higher than that on the left surface of the wall. Similarly, the chloride concentration on the right surface of the wall is higher than that on the left surface. As a result, both heat transfer and chloride penetration occur from the right to the left. A theoretical model was developed to characterize the coupled chloride penetration and temperature gradient. An additional term was included in the Fick's law to take into account the effect of temperature gradient. The proportional factor in front of the temperature gradient is defined as the coupling parameter, $D_{Cl\text{-}T}$, which represents the effect of the temperature gradient on chloride penetration. An analysis method was developed to calculate the coupling parameter $D_{Cl\text{-}T}$ based on the experimental results. $D_{Cl\text{-}T}$ is not a constant but increases with chloride concentration as well as temperature difference in the concrete and decreases with increasing age of concrete. A material model was developed for $D_{Cl\text{-}T}$ using the test data obtained in this study.

1. Introduction

Most reinforced concrete structures such as bridge decks, roadways, parking garages, marine structures, and buildings are subjected to a service environment that has simultaneous chloride ion penetration and variations of temperature. The chloride content in concrete is important because when the chloride content reaches a critical level, the corrosion of embedded steel bars in concrete will be trigged and the corrosion of steel bars is one of the important long-term durability problems of reinforced concrete structures.

There are two approaches to evaluate the chloride penetration process in concrete. One is based on the diffusion theory of Fick's law at a macroscopic level and the mass conservation of a single species of chloride [8,10,9,5]. The other one is based on Nernst-Einstein equation and the Nernst-Plank equation considering multiple species transport in concrete including chloride [4,6,7]. Xi and Bazant [11] developed material models for the two material parameters involved in the chloride penetration process in concrete: the chloride diffusivity and the binding capability. So, the transport parameters can be expressed as functions of concrete

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design parameters such as water-cement ratio and the curing conditions of the concrete such as curing period. Then, Xi et al. [12] used a multiscale approach to link the micro and meso-structural features of concrete to its macrostructural behavior. Since then, various material models have been developed for the transport properties of concrete.

Under service condition, the concrete structure is subjected to simultaneous actions of the penetration of chloride ions, fluctuation of moisture, and variation of temperature. There are mutual coupling effects among the three state variables, *Cl* for chloride ions, *RH* (relative humidity) for moisture, and *T* for temperature, which must be taken into account in the prediction models. Bazant and Chern [1] discussed about the coupling between *RH* and *T*. Swaddiwudhipong et al. [9] developed a model to calculate the coupling effects of *RH* and *Cl* in moderately saturated concrete. Ababheh and Xi [1] conducted a test for the effect of chloride penetration on moisture transfer and the test data confirmed that the chloride penetration can accelerate the moisture transport when the two processes are in the same direction. On the other hand, Abarr [2] investigated experimentally the effect of moisture transfer on chloride penetration, and the test data showed that the effect of moisture transfer on chloride penetration is significant and the moisture transfer can increase the chloride penetration process when the two are in the same direction [3].

The variation of temperature is another driving force for the ingression of chloride ions in concrete. If the temperature is a constant on both sides of a concrete wall, according to Fourier's law, there is no heat flux in the wall and thus the uniform temperature field has no effect on the chloride penetration in the concrete. It should be mentioned that with a uniform temperature distribution, a process of ionic diffusion is faster under a higher temperature. But, under ambient temperature environment (not a high temperature condition such as fire), the effect of elevated temperature is not as significant as a temperature gradient. Therefore, the dominate penetration mechanism in a saturated concrete under isotherm condition is the concentration gradient of chloride ions according to Fick's law. When there are chloride concentration gradient and temperature gradient at the same time, the temperature gradient may have an important impact on the penetration process of chloride ions, which will be the focus of the present study.

A review of available literature shows that, in 1879, the Swiss scientist Charles Soret found that the salt concentration did not remain consistent when he put a salt solution in a tube with the two ends at different temperatures. This effect is called the "Soret effect". The salt concentration was higher near the cold end than near the hot end of the tube. The conclusion from the test was that the temperature gradient can cause a flux of salt solution.

There are two aspects of the coupling effect between *Cl* and *T*. One is the effect of temperature gradient on chloride penetration, which was the focus of this study. The effect of different temperature levels (without temperature gradient) was also tested in this study. The other one is the effect of chloride penetration on heat transfer, which will not be covered in this study. Based on the present study, a theoretical model was developed for the two coupled transport processes, and the effect of temperature variation on chloride penetration can be characterized by a coupling parameter in the model. The coupling parameter was determined by using the present experimental results.

2. Research significance

The primary objective of this paper is to quantify the coupling effect of temperature variation on chloride penetration in concrete. A systematic experimental study was conducted to investigate the coupling effect and a coupling parameter was determined using the experimental results. The result will pave the way for the application of the prediction model for the chloride penetration under non-isotherm condition in the concrete. In other words, the main innovations of this paper are 1) establish a new testing method to obtain related test results for concrete under simultaneous chloride and heat transfer; and 2) to establish an analytical equation that can be used to determine the coupling parameter $D_{Cl\text{-}T}$ based on the obtained test data. $D_{Cl\text{-}T}$ represents the effect of temperature gradient on chloride transfer in concrete

3. Experimental program

3.1. Experimental method

The experimental plan is shown in Fig. 1(a). The three columns in Fig. 1(a):

Temperature condition 1 – This is a regular ponding test under isotherm condition. So, the only driving force for chloride penetration is the chloride concentration profile.

Temperature condition 2 – This is a modified ponding test, in which the chloride solution in the top pond is heated and kept at a constant temperature 35 °C [95 °F]. So, there are two driving forces for the chloride penetration. One is the chloride concentration gradient and the other is the temperature gradient.

Temperature condition 3 – This is also a modified ponding test, in which the chloride solution in the top pond is heated and kept at a constant temperature 50 °C [122 °F]. This series is similar to the second series, and the only difference is that the temperature gradient is larger than that of the second series.

The three rows in Fig. 1(a):

Series 1 – Chloride concentration of 3% as the boundary condition, with two different temperature gradients.

Series 2 – This series is similar to the first series, using a higher chloride concentration (5%) on the boundary with the same two temperature gradients. The purpose of the second testing series is to investigate the influence of chloride concentration on the boundary.

Series 3 – This series has the same temperature conditions as the first series but with a lower water-cement ratio for the concrete. The purpose of the third series is to investigate the influence of water-cement ratio on the coupled transport process.

Therefore, there were two different water-cement ratios, two different boundary chloride concentrations, and three different temperature conditions in this study. The experimental set up is shown in Fig. 1(b), which shows three specimens of the first series.

The chloride concentration profiles in the concrete specimens were tested at 3 days at seven different depths in each specimen. This was accomplished by drilling a hole from the top surface of each specimen and collect concrete powders at depths of 0.6 cm [0.24″], 1.2 cm [0.48″], 1.8 cm [0.70″], 2.4 cm [0.94″], 3.0 cm [1.18″], 3.6 cm [1.42″] and 4.2 cm [1.65″]. The chloride contents of the powder samples were tested. This approach was repeated at 6 days, 12 days, 24 days, and 48 days into the testing period.

3.2. Specimens and materials

The concrete specimens were 150 mm [6.0″] in diameter and 200 mm [8.0″] high. Six specimens with 0.65 water-cement ratio and three with 0.55 water-cement ratio were made. The mix proportions used in this study are shown in Table 1.

Each specimen was instrumented with two SHT75 Sensirion humidity and temperature sensors at two different depths at approximately 2 cm [0.79″] and 4.2 cm [1.65″] from the top surface