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Effects of load damage on moisture transport and relative humidity response in concrete

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HIGHLIGHTS

- A cylindrical concrete model was presented for relative humidity response.
- Gained relative humidity response along with moisture transport in damaged concrete.
- Damage effects were significant on moisture transport & relative humidity response.
- Drying process of concrete lagged behind wetting process as expected.
- Hysteresis time based on moisture diffusivity, humidity difference & specimen size.

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ABSTRACT

In this paper, drying and wetting processes of damaged concrete were studied in-depth along with the relative humidity response. Effects of load damage on relative humidity response and moisture transport were also studied. The results showed that the moisture loss and water absorption all represented a linear relationship with the time square root; besides, the moisture transport accelerated with the increment in load damage. However, during the drying process, moisture transport naturally lagged behind the wetting process as expected. In addition, a hysteresis effect for relative humidity response always exists in damaged concrete. The relative humidity response rate accelerated speedily with the incremental load damage, varying rapidly at first, but then assumed a steadier rate, decreasing with time. This paper also presents a moisture conductivity model for damaged concrete and a relative humidity response model for cylindrical concrete. The results revealed that moisture diffusivity affected the hysteresis time of the relative humidity response. This cannot be neglected when analyzing concrete damage causes and life span. The same holds true for the effects of humidity difference and specimen size. Moreover, the effect of load damage on relative humidity response increased with the incremental specimen size.

1. Introduction

Understanding the effect of concrete humidity fields on the durability of concrete structures is vital. Concrete damage can be preceded by many natural environmental events including chloride penetration in concrete [1–3], concrete carbonation [1,4] and steel bars corrosion [5–8], which give rise to concrete durability problems. These problems are closely related to concrete's internal humidity field. In fact, the internal relative humidity (RH) in concrete always varies with variations in ambient RH [9], afterwards, the internal RH maintaining a predictable relationship with the ambient RH for some time [10]. That is, the hysteresis effect for RH in concrete always exists, and the extent of hysteresis at different positions is different. Thus, the accurate prediction of relative humidity response (RHR) in concrete is very vital for the service life prediction and life-time design of concrete structures.

Actually, concrete structures are always damaged by loading, resulting in fluctuations in moisture conductivity, which affects moisture transport and the humidity field in concrete. Many experimental studies and numerical analyses show that moisture transport in concrete are closely related to temperature [11,12] and concrete damage induced by freeze-thaw cycling [13–15], cracks

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[16], compressive loading [17] and uniaxial tensile fatigue loading [18]; thus, the effects of concrete damage on moisture transport and RHR cannot be neglected and should be studied in-depth in damaged concrete. This research advances knowledge and understanding of both mechanisms, thereby providing new concepts on concrete durability over time, which can affect the schedule and strategies for preventive maintenance, repair, and replacement.

By regulating the load level, concrete specimens were formed with different load damage levels; then, drying and wetting tests were carried out to study moisture transport during the drying and wetting processes. Subsequently, concrete specimens were placed in a chamber where temperature and RH were designed. At the same time, the internal RH was measured in each specimen by an embedded sensor. This enabled an in-depth study of RHR in damaged concrete and a study into effects of load damage on moisture diffusivity and RHR. Eventually, the effects of moisture diffusivity and the humidity difference were studied because their close relationship to hysteresis time for RHR with different specimen sizes. A novel RHR model was also developed for cylindrical concrete in this research.

2. Experimental program

2.1. Material type and specimen preparation

Twelve cylindrical concrete specimens were cast and the dimensions were Ø100 mm × 200 mm. The density and water-cement ratio of concrete were 2319 $\text{kg}\cdot\text{m}^{-3}$ and 0.5, respectively. The particle sizes of granite aggregate were 5–16 mm. The concrete mix proportions are given in Table 1. All specimens were placed in a normal curing chamber for 28 days where the temperature was 20 ± 2 °C, and the RH was 95%. Subsequent tests were conducted as follows.

A sensor was fixed in the center of the cross-section, and the distance was 95 mm from the right end. The sensor's accuracy was ±1.8% RH and ±0.3 °C internally when tested at a lab's room temperature of 25 °C with the RH from 0 to 100% and temperature from −40 °C to 120 °C. Then, the sensors were sealed with air-permeable and waterproof sheets, which protected them from any potential damage by penetrating water.

2.2. Means for gaining damaged concrete specimens

Three specimens were placed under compression with an average cylindrical compressive strength recorded as 25.98 MPa. Three more specimens were tested to measure the elastic modulus with an average elastic modulus recorded as 2.34×10^4 MPa. Table 2 gives the specimen numbers and experiment design. One specimen, C-0, which was adopted as a control specimen, was not subjected to loading. Five other specimens numbered from C-25 to C-85 (compression percentages) were compressed up to 25%, 40%, 55%, 70% or 85% of the compressive strength under a uniaxial loading with a persistent duration of 30 min, which coincided with different load damage.

2.3. Drying and wetting tests

Six specimens remained for further testing after the mechanical tests, C-0–C-85; each one had 75 mm trimmed off both ends. After the trimming was completed, the dimensions of the middle part of each of these six specimens were Ø 100 mm × 50 mm, and the dimensions at the other end of every specimen were Ø100 mm × 75 mm, the number of which was 12.

To imitate drying and wetting tests of concrete in one dimension, the lateral surfaces and top or bottom surfaces of the 12 specimens, C-0–C-85 with dimensions of Ø100 mm × 75 mm, were all sealed with the paraffin, leaving the cut surface exposed to the environment.

Six specimens, C-0–C-85 with dimensions of Ø100 mm × 75 mm, were immersed in the deionized water for 21 days to gain saturated specimens. Then, these specimens were placed in a chamber with a temperature set at 20 °C and RH at 40% for the drying test. During the drying test, the exposed surfaces of specimens were all arranged with the exposed surface on top. These specimens were regularly weighed by a balance.

The other six specimens, C-0–C-85 with dimensions of Ø100 mm × 75 mm, were placed in a vacuum drying oven set at a room temperature until a constant weight could be recorded to allow their use in the wetting test. The purpose of this delay was to make sure the specimens did not absorb the moisture in the air, which would have affected the experimental results. During the wetting test, specimens were placed on a bracket in the water tank (Fig. 1); then, the deionized water was added until the water surface rose above the bottom surface of specimens by measuring between 3 mm and 5 mm. Water was then regularly added to maintain the water level. A dry towel was used to wipe off the water on the specimen surface before each weighing. Then, specimens were weighed on a balance according to the time interval specified in ASTM C 1585-13 [19].

2.4. RHR tests

Inside of each of the six specimens, C-0–C-85 with dimensions of Ø100 mm × 50 mm, a sensor was located 20 mm from the exposed area in the center of the cross-section (Fig. 2). Specimens after cutting were dried in a chamber for 40 days where the temperature was 40 °C and RH was 50%. Then, RHR tests in the damaged concrete were conducted under an atmospheric environment.

During the tests, specimens were put into a chamber (30 °C, 100%) until their temperatures and RHs were concordant with the ambient conditions (30 °C, 100%). Then, specimens were moved into another chamber with different ambient conditions (30 °C, 55%), providing an ideal test setup for RHR tests to dry under consistent ambient conditions for 20 days. At the same time, a sensor was used to measure the temperature and RH in the chamber. After the drying process, the temperature and RH in the chamber were adjusted to 30 °C and 100%, and then, RHR tests were conducted to measure wetting under consistent ambient conditions for 11 days.

Table 1
Concrete mix proportions.

Material	Cement	Water	Fine aggregate	Coarse aggregate
Type	#425 OPC [a]	Deionized water	ISO standard sand	Granite stone
Density ($\text{kg}\cdot\text{m}^{-3}$)	3077	1000	2620	2628
Volume fraction	0.136	0.210	0.226	0.418
Unit content ($\text{kg}\cdot\text{m}^{-3}$)	420	210	591	1098

[a] OPC refers to ordinary Portland cement.