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Mechanisms of dimensional instability caused by differential drying in wet cured cement paste

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ABSTRACT

This paper examines the mechanisms of wet curing and subsequent drying at 23 °C and 40% *RH* influencing the curling of cement paste, plate-like beams. Both experimental and model results show that as the duration of the wet curing is increased, the member peak deflection also increases from one sided drying. Experiments suggest that the extended wet curing causes a pore structure refinement resulting in greater saturation and consequently greater shrinkage. A simplified 1-D, drying diffusion and shrinkage model is able to adequately predict experimentally measured peak curling deflections, and confirms the effect of saturation on curling. The results provide important insight into the volume stability of slabs and the potential negative impact of wet curing on slab curling.

1. Introduction

Wet curing with saturated wet coverings maintains moisture and temperature, promotes hydration, and has the potential to improve durability, strength, water-tightness, and abrasion resistance of concrete [1–5]. After curing is terminated, the moisture distribution becomes non-uniform because of surface drying [6], and the member will shrink at the surface causing the element to curl upwards at the edges [7–10]. This curling could cause the member to lose contact with the base and crack if it is restrained or loaded at an edge [11]. To minimize this phenomenon it is best to allow for equal drying from all sides of a member. Unfortunately, this is not always practical for members cast on the ground or with a supporting form.

Concrete shrinkage occurs due to removal of pore water (desiccation). Desiccation of pore water occurs because of both external moisture loss (diffusive drying) and internal chemical reactions (self-desiccation). Regardless of the source of drying, negative pore fluid pressures (i.e., suction) occur and menisci form within pores [12,13]. As drying occurs pores of decreasing size will begin to empty leading to increased pore fluid pressure magnitude. In general, shrinkage from desiccation is mainly considered to be due to the following driving forces:

- capillary pressure,
- disjoining pressure, and
- interface induced pressure.

By using the Kelvin–Laplace equation one can approximate the changes in pore fluid pressure associated with capillary effects and disjoining pressure [14,15], while interfacial effects that are noticeable at lower *RH* are due to the changes in surface free energy. All three mechanisms are included in an effective pore pressure that can be applied with poromechanical constitutive functions to calculate the shrinkage of cement-based materials [13].

Prolonged wet curing is thought by many to strictly provide only improvements in concrete performance, and it has been recommended for fresh concrete of importance. Suprenant [16] has suggested that longer curing has little effect on curling. However, not all work has shown that extended wet curing is beneficial. For example, Perenchio [17] observed an increase in drying shrinkage when concrete was wet cured for up to seven days. Hedenblad [6] observed that a shorter curing time will result in a faster drying rate, which may minimize internal moisture gradients and subsequent curling. Furthermore, results from previous experiments by Hajibabaee and Ley [18,19] showed that increasing the length of wet curing caused the free curling deflection of paste and concrete beams to increase. Based on this previous work it appears that conflicting results have been reported in the literature.

While it was shown in previous research [18,19] that wet curing increases curling, this work aims to verify the mechanisms by using additional experiments and a 1-D drying diffusion and shrinkage model implementing common simplifications from the literature. This model is not meant to be fully predictive, but rather to provide insight into the mechanisms by which wet curing increases peak curling deflections. In particular, it is hypothesized that wet curing affects the desorption isotherm gradient through surface pore refinement, which accentuates curling; the model is utilized to evaluate this hypothesis. A thorough

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understanding of the mechanisms by which wet curing increases curling of slabs will provide a basis for judging under what circumstances wet curing (which is widely considered to be strictly beneficial) could result in greater curling and risk of subsequent cracking.

2. Methodology

The magnitude and rate of shrinkage for concrete are dependent on the amount of shrinkage in the paste, amount and type of aggregate used, the specimen geometry, and environmental conditions [20–23]. To simplify the experiments reported herein, paste specimens were used with a volume to surface ratio of 12.7 mm in order to obtain rapid results. Other studies that use concrete and a number of different sample sizes have been used to validate the effect of wet curing on curling of concrete [19,24], and we are thus confident that the results of this work may be utilized to better understand curling in all classes of cementitious materials.

2.1. Desorption isotherm measurements

The Portland cement used in this study meets the requirements of both a type I and II cement, according to ASTM C150 [25] and AASHTO M85 [26]. The oxide analysis and the estimated phases are given in Table 1. The paste mixtures in this experiment had a w/c 0.42, and were prepared according to ASTM C305 [27].

Paste cylinders with 12.7 mm (0.5 in. thickness and 12.7 mm (0.5 in. diameter, shown in Fig. 1, were manufactured and wet cured on the exposed surface for 0, 1, 3, 7, and 14 days with saturated wet burlap that was sealed in plastic. After curing and then demolding, samples were marked at one third from the top and the bottom surfaces. Each sample was then polished with a rotating diamond lapping plate to abrade away portions of the sample and isolate the top, middle, or bottom of the sample. The progressive polishing was done as cutting the samples would cause the material to shatter. The approach implemented here allowed the samples to be cured and then individual sections of the sample (i.e., depths from the cured surface) to be examined in order to quantify gradients in the desorption isotherm that are associated with the pore size distribution. Three samples were used for each curing duration; therefore, nine pieces (three for each depth) were made for each wet curing duration.

The sectioned samples were stored in sealed containers above saturated salt slurries at 23 °C according to ASTM E104 [28]. The storage relative humidities (generated by the salt solutions) were 86%, 72%, 50%, and 40%. Two *RH* sensors were used for each container to monitor and verify the *RH*. The samples were placed in the container and their mass was measured daily until there was less than 1% change in mass loss over a 24 h period, at which time it was presumed that the state of moisture in the pore networks had sufficiently equilibrated with their environment. The samples were then dried in an oven, weighed, and then submerged in water and weighed again. All measurements were recorded after the mass change was less than 1% in a 24 h period with a scale of 0.0001 g precision.

Table 1
Cement oxide analysis, blaine fineness, and phase concentrations.

Oxide mass fractions (%)					
SiO_2	Al_2O_3	MgO	Fe_2O_3	CaO	SO_3
20.23	4.77	1.90	3.23	64.15	2.52

Phase mass concentrations (%)				Blaine (cm^2/g)
C_3S	C_2S	C_3A	C_4AF	
63.56	10.05	7.18	9.83	3713

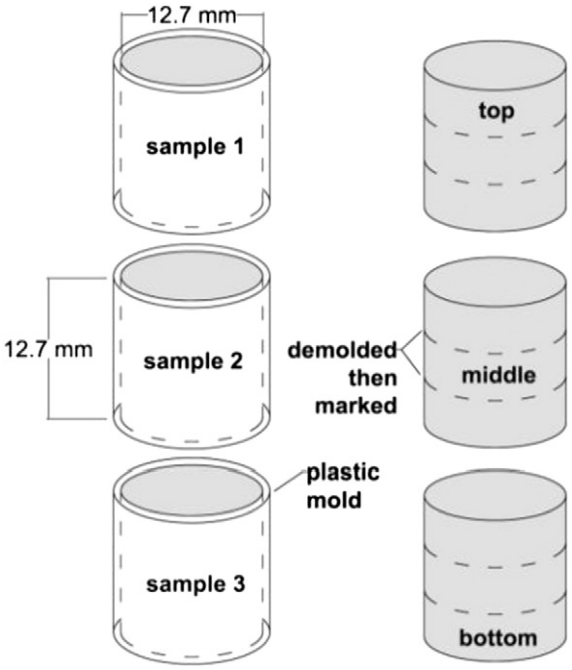

Fig. 1. Typical paste cylinders used to measure the degree of saturation.

2.2. Curling of paste beams from differential drying

The materials, mixture proportion, and curing methods used in this experiment were the same as the desorption isotherm experiments. Three paste beams with dimensions of 100 cm × 6.1 cm × 1.3 cm, as shown in Fig. 2, were consolidated in plastic molds from each mixture. This plate-like paste beam geometry had been first developed by Berke and Li [29] and later used by Hajibabaee and Ley [18] to investigate the impact of wet and sealed curing on paste beams. After casting, all specimens were cured with wet burlap on the finished surface for 24 h at 23 °C and then demolded.

After demolding, the specimens were weighed and then sealed with wax on all sides but the finished surface (the face with dimensions of 100 cm × 6.1 cm) and weighed again. The finished surface of the beams was wet cured for 0, 1, 3, 7, or 14 days in saturated wet burlap sealed in plastic and maintained at 23 °C. These are the same curing durations as were used in the desorption isotherm experiment. After the specified wet curing period, the burlap was removed from the sample. The sample was then stored in a 23 °C and 40% relative humidity environmental chamber. As the member lost the moisture from the unsealed surface it caused a moisture gradient in the sample that then led to differential shrinkage that caused curling of the member.

To measure the curling, rubber bands were used to hold the ends of the specimen to a flat aluminum beam with the drying surface of the specimen facing the beam, as seen in Fig. 2. The distance between the aluminum beam and the specimen was measured at regular locations along the length with a caliper of 0.0127 mm accuracy. The curling of the beams was symmetric with a maximum at the middle of the beam. The loss of moisture of the sample was measured through the mass loss over time with 0.1 g accuracy. More details about this experiment can be found in Hajibabaee and Ley [18].

2.3. Modeled diffusion, shrinkage, and peak curling deflection

In order to predict the shrinkage gradient and resulting peak curling of the cement paste beams it is necessary to quantify the spatially and time dependent effective pore pressure. This pore pressure is a function of both the local internal *RH* and the local degree of liquid saturation, *S*.