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Assessment of shrinkage-induced cracks in restrained and unrestrained cement-based slabs

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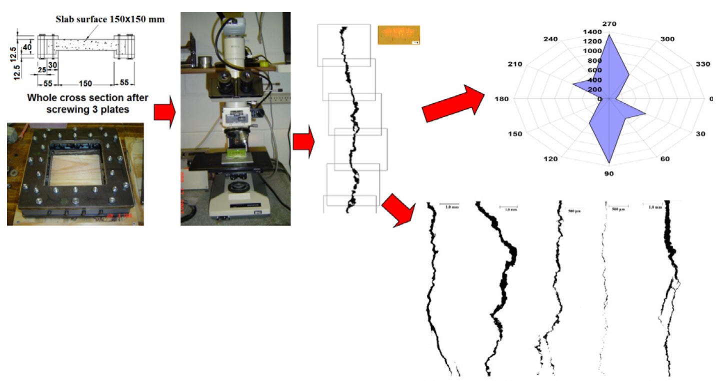
HIGHLIGHTS

- Shrinkage-induced cracking in cement-based slabs is investigated and quantified.
- Measurements of crack length, width, and density were performed.
- Drying shrinkage developed few, randomly distributed cracks in unrestrained specimens.
- Restrained slabs developed perpendicular cracks with respect to the drying surface.
- Cracks widths increase and new branches grew up with further drying.

GRAPHICAL ABSTRACT



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ABSTRACT

Concrete slabs and bridge decks experience early ages cracks mainly due to volumetric changes associated with moisture and temperature variations. These cracks have no immediate effect on their safety, but they have detrimental effects on their durability and long-term performance. This paper presents an experimental investigation on quantification of shrinkage-induced cracks in slabs made from different cement-based materials. An experimental test setup was used to simulate the shrinkage-induced damage of restrained slabs. Vacuum pressure impregnation with ultra-low viscosity epoxy was used for the preparation of concrete samples for image analysis. Crack measurements in terms of crack length, width, density were performed on the concrete samples. Crack orientation was recorded and shown in a radar diagram. The results showed that drying of unrestrained specimens develop few and randomly distributed cracks, neither connected to each other nor to the specimen surface, with short extensions into the slab depth. Therefore, they had no significance effect on the transport properties. On the other hand, restrained slabs developed localized cracks, oriented perpendicular to the drying surface and extending through the whole depth of the slab. Further drying, increases the crack width and new branches grew up on the vertical basic cracks. Understanding crack patterns and their effect on the concrete transport properties, allows for more accurate prediction of the long-term performance of concrete slabs and bridge decks.

1. Introduction

Concrete structures experience drying shrinkage when exposed to dry ambient conditions. As concrete dries, it shrinks and

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consequent shrinkage strains developed in it. If concrete is restrained (prevented from shrinking freely), internal tensile stresses will develop. As the tensile stress reaches to the tensile strength of concrete, micro-cracks are initiated. In restrained concrete structures, the development of cracks and damage of concrete can cause a significant degradation in the concrete properties such as strength and modulus of elasticity.

There are different types of restraints in structural concrete, and they can be divided into two main groups: external restraining and internal restraining. External restraining is achieved using components that are not part of the concrete member such as joints connecting a member to adjoining member with high stiffness. Internal restraining is achieved by elements that are part of the material of the concrete member such as the aggregates that have higher stiffness than the cement paste matrix. Also, restraining may be imposed by alien bodies acting on the concrete material, such as reinforcing bars inside the member. The volumetric change gradient across a member or a specimen may cause it to serve as a restraint, which is called self-restraint.

Majority of the previous studies addressed the creep, shrinkage and cracking of high performance restrained concrete as well as the impact of aggregate size and paste volume on drying shrinkage micro-cracking in cement-based composites using methods such as image analysis, a modified Weibull function, and scanning electron microscopy [1–8]. Although some researchers studied the type of shrinkage cracks for unrestrained cement paste or concrete samples, their tests were under very dry conditions, which rarely occur in concrete structures [4,9–10]. When unrestrained concrete samples were tested under 21 °C (stepwise: 93% RH → 55% RH), micro-cracks were significantly much less extensive compared to samples dried at 50 °C and 105 °C [11].

Yoo et al. [5] studied the effect of expansive admixture and shrinkage-reducing admixture on the cracking and shrinkage behaviors of restrained six full scale ultra-high-performance fiber-reinforced concrete slabs with three different thicknesses of 40, 60, and 80 mm. Also, Shadravan et al. [6] investigated the full scale behavior of concrete slabs on ground in a controlled environment in terms of different concrete materials properties and the evaluating their performance as real slabs which exposed to the controlled environment and ground moisture from the top and bottom, respectively. But the shape or morphology of shrinkage cracks were not studied. The AASHTO ring specimen method has now been adopted by a number of researchers [7,8] due to its symmetry, simplicity and reproducibility, and others [8] introduced some modification to that test such as the restrained eccentric ring test method (RERTM) and the restrained squared eccentric ring test method (RSERTM). However, all these tests still have limitations regarding capturing the growth and shape of the drying cracks in concrete slabs.

A major goal of this study was to develop a scale test method to simulate the behavior of restrained slabs. With this restraining, the crack types, width, growth, orientation, and their effect on the moisture transport are studied using different image analysis methods. Also, this test may simulate a structural element with low volume to surface area ratio, such as building slabs and bridge decks that are more exposed to drying shrinkage. To meet this goal, scale slabs were cast and restrained on all edges. Also, both external restrained and unrestrained conditions were explored. For the restrained specimens, an experimental test setup was used to simulate the shrinkage-induced damage behavior of structural element with low volume to surface area ratio when exposed to dry environment. This setup allows for studying the crack growth and patterns inside the restrained slabs. A brief description of the setup is presented in this paper; complete details about the setup can be found in Sheban [12].

2. Research significance

Review of previous studies on the drying shrinkage crack growth and patterns of cement-based slabs with external restraining shows a shortage of reliable data in this area. Accordingly, this study is conducted to investigate the crack length, width, density, and orientation due to drying shrinkage for cement-based slabs with and without external restraining. The availability of such important data is essential for accurate understating of the effect of drying shrinkage-induced damage on the concrete transport properties and also to allow for accurate modeling of the drying shrinkage damage.

3. Testing program

An experimental program was developed to evaluate the effect of the drying shrinkage-induced damage on cement-based slabs (cement paste, mortar and concrete). The properties and proportions of each slab specimen, drying procedure, and dimensions for both restrained and unrestrained specimens are presented in the following sections.

3.1. Materials properties

Crushed stone with a maximum size of 9 mm was used as coarse aggregate as shown in Table 1. The coarse aggregates met the standard gradation requirements as specified in ASTM C33 [13]. Table 1 presents the Graded river sand, which was used as a fine aggregate with standard gradation according to ASTM C33 [13]. Commercially available Type I/II Portland cement was used for all mixtures described in this study. The cement specific gravity is 3.2 and the compound composition is: C3S = 51% and C3A = 8%. Table 2 provides a summary of the cement composition as supplied by the manufacturer.

3.2. Mixture proportions

Three mixtures were cast including: cement paste, mortar, and concrete. The ingredient ratio and water-cement ratio are listed in Table 3. Cubes 50 × 50 × 50 mm were used for testing the cement paste and mortar strength, and cylinders 100 × 200 mm were used for testing the concrete strength. The dimensions of slabs and prisms are presented in the following section. Then, the specimens were covered with a thin plastic film, maintained at standard room temperature, and kept for 24 h before de-molding.

3.3. Drying condition

The specimens were cured in tap water saturated with calcium hydroxide according to ASTM C511 [13]. Compressive strength

Table 1
Course and fine aggregate properties.

Properties	Value	Type of test
Course aggregate		
Moisture content	0.09%	ASTM C566 [13]
Bulk specific gravity (SSD)	2.393	ASTM C127 [13]
Oven dry bulk specific gravity	2.361	ASTM C127 [13]
Absorption capacity	1.38%	ASTM C127 [13]
Dry rodded unit weight	1594.6 kg/m^3	ASTM C29 [13]
Fine aggregate		
Fineness modulus	2.54	ASTM C136 [13]
Moisture content	0.08%	ASTM C566 [13]
Bulk specific gravity (SSD)	2.648	ASTM C127 [13]
Oven dry bulk specific gravity	2.621	ASTM C127 [13]
Absorption capacity	1.05%	ASTM C127 [13]