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Effects of specimen size on assessment of shrinkage cracking of concrete via elliptical rings: Thin vs. thick

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ABSTRACT

An elliptical ring test method is proposed to replace the circular ring test recommended by ASTM and AASHTO for faster and more reliable assessment of cracking tendency of concrete. Numerical models are also established to simulate stress development and crack initiation/propagation in restrained concrete rings. Cracking age, position and propagation in various rings are obtained from numerical analyses that agree well with experimental results. Elliptical thin rings of certain geometry can shorten the ring test duration as desirable. In thin rings, crack initiation is caused by external restraint effect so that a crack occurs at the inner circumference and propagates towards the outer one. In thick rings, crack initiation is mainly due to the self-restraint effect so that a crack occurs at the outer circumference and propagates towards their inner one. Therefore, thick elliptical concrete rings do not necessarily crack earlier than circular ones as observed from experiment.

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1. Introduction

Shrinkage cracking of concrete occurs when the tensile stress generated due to restrained volume contraction of concrete exceeds its tensile strength. Shrinkage cracking is a major problem for flat concrete elements/structures with a large exposed surface area-to-volume (A/V) ratio, such as industrial floors, concrete pavements and bridge decks. The cracking of concrete can reduce its load carrying capacity and accelerate deterioration, increasing maintenance costs and shortening the service life of concrete structures. So far, several test methods have been developed to assess how susceptible a given concrete mixture may be to cracking. ASTM C 341 [1] adopts 400 mm long and 100 mm square concrete prisms, with all surfaces exposed for drying, to assess free shrinkage of concrete by monitoring their longitudinal length change. Although free shrinkage measurement is helpful in comparing different mix proportions, they do not provide sufficient information to determine how concrete will crack in service [2]. Rather, the cracking tendency of concrete has been mainly evaluated under restrained conditions by qualitative means through a range of tests, such as the bar, the plate/slab and the ring tests. Among these, the circular ring test has been widely used for assessing cracking tendency of concrete and other cement-based materials due to its simplicity and versatility [3–4].

As a standard test method, the circular ring test was first approved by the American Association of State Highway and Transportation (AASHTO). The standard AASHTO PP34-99: Standard Practice for Estimating the Cracking Tendency of Concrete is used for the determination of the cracking tendency of restrained concrete specimens.

This consists of a concrete ring with an inner diameter of 305 mm, a wall thickness and height of 75 and 150 mm, respectively. The concrete ring surrounds a restraining steel ring with an outer diameter of 305 mm and a wall thickness of 12.5 mm. A 75 mm thick concrete ring is called a thick ring in this study. ASTM also follows by recommending the circular ring test (ASTM C1581/C1581M-09a: Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage). Different from AASHTO, ASTM recommends thin rings with a reduced wall thickness of 37.5 mm to initiate cracking at an earlier age and to shorten the duration of the ring test. Casting a concrete ring around a steel core, usually a steel ring is the basic principle of the circular ring test. This restrains the concrete shrinkage, resulting in tensile stress developing in the concrete ring and compressive stress in the steel core. If the tensile stress exceeds the critical material limit of concrete, cracks will initiate. It has been found that the cracking age depends not only on the properties of concrete but also on the degree of restraint provided by the central restraining steel core in the ring test. Detection of the first cracking may result in a long waiting period due to either the restraining core not being stiff

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enough or the concrete being characterised with high cracking resistance. Sometimes a visible crack may not even be generated in concrete rings [5,6]. Although AASHTO and ASTM recommended standard dimensions of circular ring specimens, other circular ring geometries [3,4,6–10] have been used in various studies. Alternatively, novel elliptical ring geometries were adopted to replace circular ring geometries [11–14]. Although not proven in studies [11–14], cracks initiating earlier in elliptical ring rather than in circular ones due to stress concentrations caused by geometrical effects is the generally accepted theory. Besides, in contrast with the fact that a crack may initiate anywhere in a circular ring specimen, for an elliptical ring specimen of a given geometry, it tends to be at a determinable position, reducing the resources needed for detecting crack initiation/propagation in the ring test. Therefore, elliptical ring specimens have been employed for assessing cracking tendency of cement-based materials as an improved ring test by some researchers [11–16]. However, most of those studies focused on investigating the effects of variations in material proportions/additives on the restrained shrinkage cracking of concrete or other cement-based materials.

The mechanism of the elliptical ring test has been largely unexplored since only Zhou et al. [15] and Dong et al. [16] have conducted research trying to figure out under which conditions the elliptical ring cracks earlier than circular ones. However, those studies only focused on thin rings. No study has been carried out on investigating the mechanism of the thick ring test. It should be noted that ASTM thin rings are not appropriate for concrete with large aggregates whereas the AASHTO thick rings are. In addition, no comparison test has been conducted using thick circular and elliptical rings, so there is no scientific evidence available to indicate whether thick elliptical rings crack earlier than thick circular ones. Furthermore, the geometrical effect of the central restraining ring on initial cracking age of a thick concrete ring is not reported in literature. Therefore, it is significant to quantify the impact of ring geometry including ring wall thickness on the degree of restraint to concrete surrounding it in the ring test.

Many studies have been carried out so far on analysing cracking of concrete in restrained circular ring specimens. In a circular concrete ring specimen, the restraining effect from the central steel ring on the surrounding concrete ring can be conveniently replaced by a pressurising force applied to the interface between the steel and concrete rings in numerical analyses [3,6,17–19]. In comparison, very limited analytical/numerical research has been carried out on elliptical concrete rings under restrained shrinkage. He et al. [11] assumed that an elliptical concrete ring is subject to a uniform internal pressure provided by the central steel core. This is the same assumption taken in analysing shrinkage cracking in circular ring specimens by many other researchers [3,6,17–19].

In fact, due to geometrical effect, the radial deformation of the central restraining elliptical steel ring is not uniform along its circumference when concrete shrinks [15,16]. Therefore, it is believed that the uniform internal pressure assumption is not appropriate for elliptical ring specimens. Meanwhile, the degree of restraint is largely dependent on the geometry of the central restraining steel ring. Especially important is its major and minor semi-axes which are believed to have a significant effect on the initial cracking age and cracking position of a concrete ring surrounding it.

Moreover, it is believed that the thickness of a concrete ring wall has a significant effect on stress development in concrete under restrained shrinkage. AASHTO PP34-99 recommends thick rings with a concrete wall thickness of around 75 mm while ASTM C1581/C1581M-09a recommends thin rings with a wall thickness of around 37.5 mm. Therefore it is necessary to investigate how a concrete mixture may exhibit different cracking behaviours in thick and thin rings respectively. Experiments have indicated that thicker concrete sections exhibited higher resistance to cracking than thinner ones, suggesting that the age of concrete cracking is different in structures with different thickness [20]. Due to the increase in wall thickness, a complex stress field occurs across the wall of a concrete ring specimen when drying from its outer circumferential cylindrical surface. Unlike for thin rings, the analysis of thick rings using the assumption of uniform stress across a concrete ring is considered inappropriate. Besides, experiments have indicated that a crack initiates at the outer circumference and propagates towards to the inner one in thick rings when drying from their outer circumferential surface [21]. Alternatively, a crack would initiate at the inner circumference of a thick ring and propagate towards the outer one if based on the assumption of uniform strain across the ring wall. In order to characterise stress development while considering the effect of ring geometry and drying direction, analytical models were developed to assess residual stress in restrained ring specimens [4,6,7,20,21]. However, it should be noted that those analytical models were developed for circular rings only and may not be appropriate for elliptical ones.

In line with this, a numerical approach is developed to simulate the behaviour of concrete in restrained ring specimens. Fictitious temperature fields are applied on a concrete ring specimen to simulate the mechanical effect of concrete shrinkage on the ring under a restrained condition. The fictitious temperature fields are derived based on free shrinkage tests of concrete prisms. When the exposed drying surface area-to-volume ratio of a concrete ring specimen is equal to that of a concrete prism in a free shrinkage test, both specimens can be regarded as being under the same temperature field. To obtain the internal stress in the concrete, the fictitious temperature field is used to generate thermal loading on the restrained concrete rings through combined thermal and structural analyses. Moreover, the stress intensity factor can be obtained by fracture analysis. Cracking age, position and propagation in a series of circular and elliptical, both thin and thick concrete ring specimens subject to restrained shrinkage are analysed using the numerical model established in this study. Besides, experiments have also been conducted on those concrete rings under restrained shrinkage conditions. To verify the numerical analysis approach, its results are compared with the initial cracking ages of those rings. Finally, the effects of ring geometry on cracking age, position and propagation in concrete rings under restrained shrinkage are also discussed to explore further the mechanism of the ring test. From this, it is aimed to propose practical guidance in choosing appropriate ring geometry for assessing cracking tendency of concrete and other cement-based materials. By extending the Zhou et al. conference paper [22], a deeper investigation is made and includes the following additional research:

(1) The numerical analysis adopts a nonlinear distribution of moisture loss, hence drying shrinkage, across a thick concrete ring wall. In comparison, a linear distribution of moisture loss, across a thick concrete ring wall was employed in the numerical model established in the conference paper. It is regarded that a nonlinear distribution of moisture loss is more appropriate for a thick concrete ring wall [4,6].
(2) A fracture mechanics-based analysis model and concrete cracking criterion are adopted in this paper for analysing thick concrete rings subject to restrained shrinkage. While in the conference paper, an elastic analysis was employed on thick concrete rings with the maximal tensile stress cracking criteria for concrete. A fracture mechanics-based analysis model and concrete cracking criterion are regarded to be more appropriate for analysing thick concrete rings [2,10,16].
(3) A deeper analyses on the restraining effect on thick concrete rings has been conducted in this paper, in which the restraining effects are separated into the following two

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