

NUMERICAL ANALYSIS TO EVALUATE THE EFFECT OF RESTRAINED EDGE DISTANCE ON EARLY AGE CRACKING DUE TO DRYING SHRINKAGE

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ABSTRACT Drying shrinkage can be defined as the reduction of volume that concrete undergoes as a result of the moisture relocation when exposed to a lower relative moist surrounding environment than the foremost one of its basic pore structure system. Finite element model(FEM) is developed and implemented, to simulate and analyses the early age restrained cracking behavior due to drying shrinkage. The Simulation focus on the evaluation of the impact of restrained edge distance on early age cracking due to deformation resulting from drying shrinkage. The FEM analysis Model deals with phenomena of temperature, humidity exchange, thermal diffusion, and mechanical behavior which can take a place at the three first days followed the concrete casting, to evaluate the diameter, distance effects on the early age crack. The effect of the diameter of the restricted steel ring was studied on the diameter of the concrete and the spacing between them. The results were compared with the results of the experiments discussed in the published literature; it was found that there is an excellent agreement for all the performed analysis.

Key words: Drying Shrinkage, Finite Element Model (FEM), Early Cracking, Edge Distant

1. INTRODUCTION

Cement hydration is an exothermic chemical reaction; this reaction yields release of heat during the hardening age of the cement paste. For the massive concrete components, the heat of hydration yields thermal gradients, leading in thermal stresses and cracks. In the case of the concrete element is released or moved, no tensile strain or stress due to restraint will be developed. However, movements of concrete mass are restrained, to some extent, by the structural supporting elements or by different parts of the element itself. These restraints induce different stresses due to temperature variation and humidity change. If there is tensile stress developed in concrete, it will result in cracking because concrete can withstand compressive stresses. There are two restraint types; internal and external which are interconnected and generally to some extent exist in concrete members[1]. Three-dimension finite element simulation is presented to model the behavior of the concrete at an early age. It was taken in the account the deformation due to restrained shrinkage.

At an early age, the chemical reaction and the formulation of hydration products the thermal and mechanical properties of the concrete are continuously changing, but in the simulation, the transit temperature and relative humidity fields and their influence to stress (strain) field of experiment condition must be exactly matched.

Many numerical tools have been formulated to evaluate the acquired to reduce the cracking risk at an early age caused by drying shrinkage[1, 2]. Based on mathematical models capable, these tools are taken to depict the coupling of thermal, moisture diffusion, chemical, and mechanical analysis. In the thermal analysis, the released heat from cement hydration raises the temperature inside the body. The nodal temperature is evaluated from the body thermal and properties [3]. The analysis of the moisture diffusion, taking in the account the similarity between the differential equation that regularizes the heat transfer analysis and the moisture diffusion, the same procedure used to measure the nodal temperatures in the previous step are used to find out the nodal values of relative pore humidity. The stresses because of the temperature and humidity changes are evaluated. When the stress state in any sample point accomplishes the failure surface, this point is considered cracked[4,5]

To assess the cracking tendency at early age, part of previous studies is evaluating the cracking due do autogenous, drying and thermal shrinkage by using standard test method (Circular Ring Test), the other part of researchers is adopting novel geometry to generate new stress pattern and when conduct the test (elliptically, eccentrically ring) [6,7].

An eccentric ring test method is proposed to assess the cracking potential of concrete based on experimental efforts. A numerical model is presented for predicting stress evolution and

cracking age in concrete ring specimen subject to restrained shrinkage to support the mechanism of the proposal eccentric ring test. Assuming shrinkage in cementitious composites materials results from a change of humidity from the internal and external specimens represented in this study by temperature variation, crack initiates when the maximum circumferential tensile stress developed in cementitious ring exceeds the corresponding cementitious tensile strength.

The primary aims in this study are a numerical investigation organized to assess the effect of restrained edge distance (Ed) on early age cracking due to deformation resulting from drying shrinkage. Three related parameters were investigated to determine the restrained edge distance and position of the cracks at an early age. The first parameter is the effect of the inner steel ring location and drying direction (with/without eccentricity). The second parameter is the materials used in the experiments to prepare the specimens (concrete grade and water-cement ratio). The last parameter was studied is the ratio between the specimen (outer ring) and the steel ring (inner ring). All these parameters were investigated to find and specify which ring is suitable to evaluate the drying shrinkage cracks due to restrained and change in the humidity.

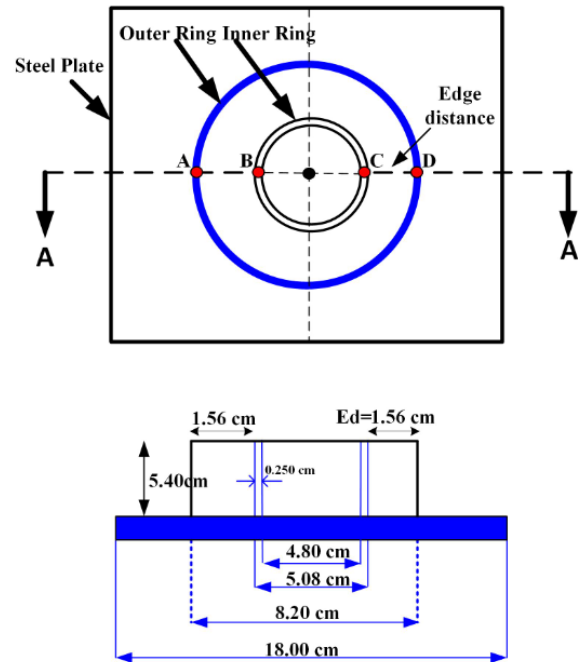


Fig 1 The steel part in the center of the specimens with non-centricity($e=0$)

2. SIMULATION OF EARLY AGE CONCRETE PRISM CASES:

The Simulation focus on evaluation and discussion of three influential parameters, to provide quantitative information on early age stress development and used to assess the potential for early-age cracking time appearance and location.

2.1 The locations of the restrained steel part (inner steel ring)

It believed that the steel ring size and location have a substantial influence on stress development distribution, actual crack initiation, and final propagation. Previous studies have shown that the stiffness of the steel ring to be too high, that the outer radius of the steel did not deform under loading to simplified calculations. On the other hand, recent study to investigate the location of the steel ring and it is an influence on the cracks appear.

2.1.1 The steel part in the center of the specimens with non-centricity $e=0$ $ed=1.56$ cm

In this case, there are uniform drying along the radial direction according to [2], moisture gradient develops due to circumferential drying, which can significantly influence the stress distribution as illustrated in the figure below

2.1.2 The steel part is located with eccentricity $e = (1.7$ cm), $ed=1.05$

In this case, there are ununiform drying along the radial direction according to [3], moisture gradient develops due to circumferential drying, which can significantly influence the stress distribution as illustrated in the figure below

2.2 Effect of materials and drying direction on stress development

Previous researchers will assess the influence of drying direction[4]; the specimens are exposed to drying from the outer circumferential surface except for the bottom surface. In this study, it was proposed that the restrained ring specimens were dried from the outer circumferential surface. Consequently, the shrinkage is unformed throughout the height of specimen, and the radial direction to allow the specimen loses the majority of water in the circumferential (drying surface); the stresses are highest at the drying face [5-7] which eventually leads to a complicated stress distribution that changes over time in this study. Fig.3 illustrates the Conceptual of the restrained components in the concrete ring(with/without) eccentricity.

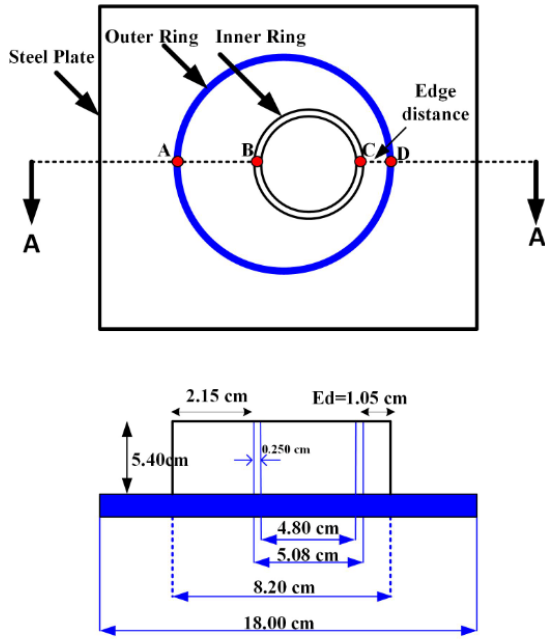


Fig.2 The steel part is located with eccentricity $e = (1.7\text{cm})$

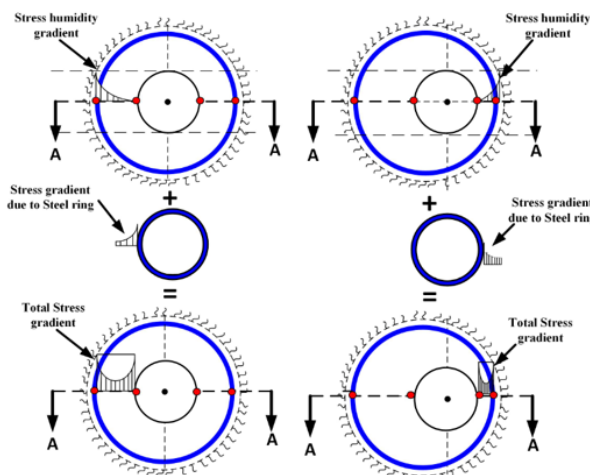


Fig.3 Conceptual illustration of the restrained components in a concrete ring

2.3 Effect of steel ring geometry restraining stiffness, (the ratio between specimen (Outer circle) and steel ring (Inner circle)).

The specimen’s diameter over the restrained steel ring diameter (d/r) is studied in this paper to show that the effect of both the ring size and specimen on the residual stress level and stress development map. By studied and focus on the three different ratios of (d/r) is renamed as $d/r1$, $d/r2$, and $x3$ respectively to assess the crack distance effects.

3.ANALYTICAL ANALYSIS:

Early age cracking sensitivity has become a universal phenomenon associated with a mechanism which is related to microstructural changes, chemical reactions, taking place during the first few days after mixing the binder (cement) and water. Volumetric change of concrete is usually discovered two board categories of effects: thermal shrinkage and drying shrinkage[8, 9]. Thermal shrinkage in concrete is as a result of hydration and changes in environmental temperature while drying shrinkage results from internal and external moisture movement in concrete [10].

3.1 Thermal analysis:

The numerical process performed represented of two steps for each sample as thermal and structure module steps, in the thermal analysis module, there is a compatibility between temperature and model boundary that changes the humidity distribution to be analyzed in a similar pattern to temperature distribution[5,9].

The temperature base concept is shown in Eq1:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\partial T}{\partial t} \tag{1}$$

3.2 Moisture diffusion analysis:

In the diffusion the most general case, according to specification gases, liquids and solutions are transported, via a porous medium, according to the Fick’s First Law of Diffusion, conceiving transient development, such as drying of the concrete. The humidity balance equation concept is given by Eq2:

$$\frac{\partial H}{\partial t} = D \nabla^2 h + \frac{\partial H}{\partial t} \tag{2}$$

Where

H: $H(x,y,z,t)$, pore relative humidity as a function location x,y and z and time variable t

D: Diffusivity,

The change of humidity due to the moisture diffusion and self-desiccation can be expressed as Eq 3 shown below:

$$\frac{\partial H}{\partial t} = D(H) \left[\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} \right] \tag{3}$$

Eq 4 from the previous relationship evolved by[10]

$$\alpha = \frac{\lambda}{c\rho} = \frac{D \times D_{sat} \times \rho}{D_{sat} \times \rho} \tag{4}$$

The above equation, Considering $\rho=1$ shows that $(\alpha) = D$

The boundary condition in the moisture

diffusion analysis can be written as Eq 5:

$$D \left(\frac{\partial H}{\partial n} \right) = \alpha_m (H_e - H^s) \tag{5}$$

Where

$\frac{\partial H}{\partial n}$: moisture gradient at the surface

α_m : mass transfer factor

H_e : pore relative humidity at the surface of the porous medium.

H^s : relative humidity of the ambient space.

The temperature and humidity variables comprised, the base concept of the variables applied in the thermal analysis module are listed in table 1.

Table 1: similarities and corresponding terms in the differential equations for moisture diffusion and temperature concept

Temperature based	Humidity based
$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\partial T}{\partial t}$	$\frac{\partial H}{\partial t} = D \nabla^2 h + \frac{\partial H}{\partial t}$
T(x,y,z,t)	H(x,y,z,t)
The correlation coefficient of the thermal diffusivity	Moisture diffusion coefficient
Boundary condition:	Boundary condition:
$\lambda \frac{\partial T}{\partial n} = \beta (T_a - T)$	$D \left(\frac{\partial H}{\partial n} \right) = \alpha_m (H_e - H^s)$
λ, β part of the coefficient of R-curve	
T_a :initial Temperature	H_e
T : Temperature at x,y and z direction	H^s

3.3 Mechanical analysis:

The finite element for 3D plane stress analysis has been implemented; the concrete shrinkage and thermal expansion strain are considered as prescribed deformation on the structure.

Due to restrain effect and change of the humidity the stress can be assumed grounded on general stress equation shown below:

$$\sigma_{(t)} = E \times \varepsilon_{(t)} \tag{6}$$

Where:

$\sigma_{(t)}$ refer to stress at time t, E refer to the

modulus of elasticity and $\varepsilon_{(t)}$ is shrinkage strain at time t obtained based on eqs:

$$\Delta \varepsilon = K \Delta h$$

$$\varepsilon = K \int (\Delta h) dt, = Kh \tag{7}$$

Where:

$\Delta \varepsilon$ is a change in the shrinkage strain, is a change in humidity and K is coefficient thermal expansion.

4. NUMERICAL APPLICATIONS AND BOUNDARY CONDITIONS:

Numerical applications of the described methodologies throughout this work are presented in those items. The experimental is developed by utilizing an eccentrically restrained shrinkage sample (ERS) to study the cracks at an early age. The aim of implementing the eccentric sample is to adequately provide a modern method to assess the cracks at an early age by subjecting a complicated and non-uniform circumferential stress to the concrete in the eccentric ring.

The specimens were prepared and cured for 1 day at 20c and 97% RH, and then after demolding exposed to drying in the humidity in the humidity and temperature of 40%RH,20C respectively. Fig (2) illustrates the position of the steel ring.

To analysis, the algorithm result, this paper studies the eccentrically concrete test for the concrete ring D=8.2cm and steel ring r=5.2cm, there are good results in term of stress and cracks time comparing with the numerical result.

Three dissimilar positions and three different diameters of the steel ring to track the stresses development maps are simulated, and the result for the stress development is presented.

The mechanical properties were considered as input parameters, for each concrete ring and this included poison ratio 0.2 and elastic modulus 4.16*103 (MPa). The thermal conductivity 2.33(KJ/cm.day.°c) and diffusion coefficient 0.06048 m²/s as thermal and diffusions properties respectively.

Boundary conditions around samples structure may be summarized for thermal and moisture diffusion: the environment temperature and humidity are 20C and 40RH% respectively.

For the steel shrinkage sample (eccentrically ring) the boundary condition for mechanical analysis is considered simple support at the bottom with a total rigidity of the steel plate and core (due to its stiffness and does not deform during the analysis).

5. MODEL RESULTS AND VERIFICATION

5.1 Stress due to inner steel ring locations

5.1.1 Stress distribution in the circular concrete

ring subjected to restrained shrinkage under isothermal conditions. $E=0$

It is advantageous if the position of the cracking can be predicted in advance so that the resources required for detecting cracking occurrence and propagation can be minimized during the test. However, due to the geometrical effect, the stress concentration which causes the crack may take place elsewhere in the eccentric ring specimen, from point C to point D along the line when the edge distance ($E_d=1.05$ cm) and angle equal zero as illustrated in the Fig4 below.

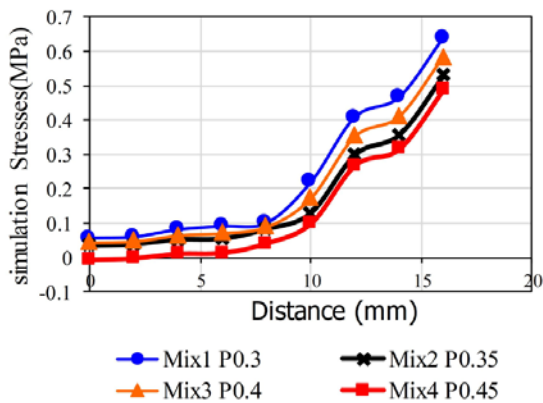


Fig.4 Stress distribution in the circular concrete ring ($e=0$)

5.1.2 Stress distribution in the circular concrete ring subjected to restrained shrinkage under isothermal conditions, $e=1.74$ cm and edge distance, $ED=1.05$ cm

It is obviously observed that the stress induced due to the eccentricity of inner steel are higher than those induced when the inner steel located in the center as shown in fig 5 below.

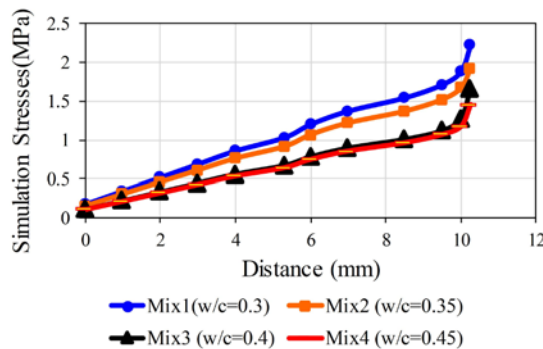


Fig.5 Stress distribution in the circular concrete ring ($e=1.74$ cm, $E_d=1.05$ cm)

5.2 Stresses results due to materials verities and drying directions

The Second parameter was taken in this study the varying of the water-cement ratio and concrete grade. The influence of the water-cement ratio is an important parameter as previous studies were reported [6]. It is clear that the lower water to cement ratio gets the higher rate of drying evaporation and the drop of temperature leads to higher stress development rate, which rapidly exceeds the tensile strength of the sample; which consequently, leads to the earliest crack. Also, higher concrete grade (higher strength) cracked earlier due to similar restraint and therefore has a higher crack tendency. This result is symmetrical to the findings from previous studies[11]. Whereas different water to cement ratio leads to different cracking time, and the higher ratio of water to cement paste needs a long time to reach its drying at an early age[8]. The specimen loses the majority of water in the circumferential (drying surface), and complicated stress distribution that changes over time as shown in the figures below:

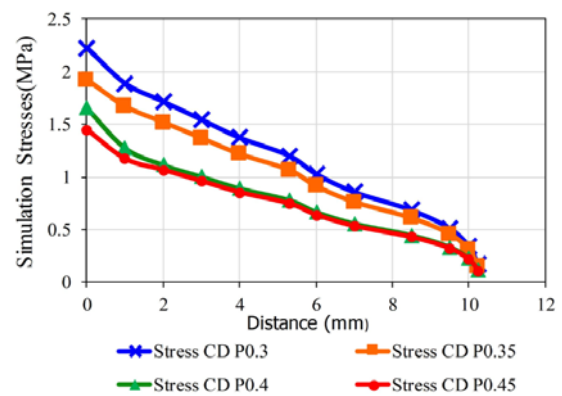


Fig.6 Stress development on day 2

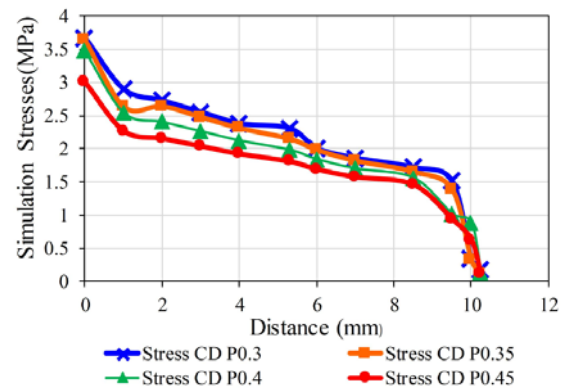


Fig.7 Stress development on day 3

5.3 Stresses results due to d/r ratios

Fig (6) demonstrated the stress development as a result of different d/r ratios($d/r=1.7, r=4.7$), ($d/r=2.2, r=3.7$), ($d/r=4.8, r=1.7$), with considering of the

restrained steel ring located in the center of the sections. It can be observed that the drying process due to the relative environmental humidity change is lesser than the initial relative humidity of the concrete ring, which is occurred from external to the central zone of the concrete ring.

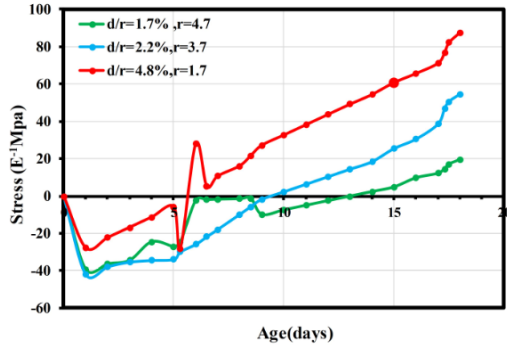


Fig 8. Computed stress under different restrain steel diameter

6. EFFECTIVE EDGE DISTANCE (ED)

Starting with eccentricity index, intuitively the eccentricity will give rise to the stress concentration phenomenon, and consequently, shrinkage cracking will occur in specimens where stress concentration peaks. FEM calculations support this intuition. The residual stress developed in the eccentric ring test would be a superposition of the self stress due to non-uniform humidity drying and the restraint stress induced by the steel ring. The stress gradient dominated by both of self-stress and restrained stress, in this case, the crack should start near/ at Point-A as high-stress point and then propagate to point B as a low-stress point. But this did not prevent some cracks from initiating at the outer circumference and propagated towards in restrained cementitious composite rings inner one.

7. EXPERIMENTS

Based on the numerical evaluation and engineering intuition, cracking location now is predicted to be somewhere along the line between Point-C to Point-D. The experimental is developed by utilizing an eccentric restrained shrinkage sample (ERS) to study the cracks at an early age after was compared to the results of the numerical stresses development map. After the eccentric mold check is completed, chosen of the dimensions of mold and materials were proposed under the above results from numerical investigations. Two w/c ratios with w/c being 0.3 and 0.5 are selected. The concrete mix proportion consists of cement of grade P.O. 42.5, which is widely used in China, sand with fineness modulus being 2.5, aggregate with the size between less than 5 mm and water.

The specimens were prepared and cured for 1 day at 20c and 97% RH, and then after demolding exposed to dry in the humidity in the humidity and temperature of 40%RH,20C respectively, Fig (2) illustrates the position of the steel ring. To analysis, the algorithm result, this paper studies the eccentrically concrete test for the concrete ring D=8.2cm and steel ring r=5.2cm, there are good results in term of stress and cracks time comparing with the numerical result.

Three experiments are conducted with the same mix proportions and the average experimental results of the concrete eccentric ring test will be contrasted with the developed software results for the time at which the cracks occur and the increase of the crack opening[3]. The comparison yields a good result which is signified that results of the other samples are reasonable, Fig (9) illustrated (ESC) model and Table (1) show the relationship between stress from the analysis, and actual tensile stress.

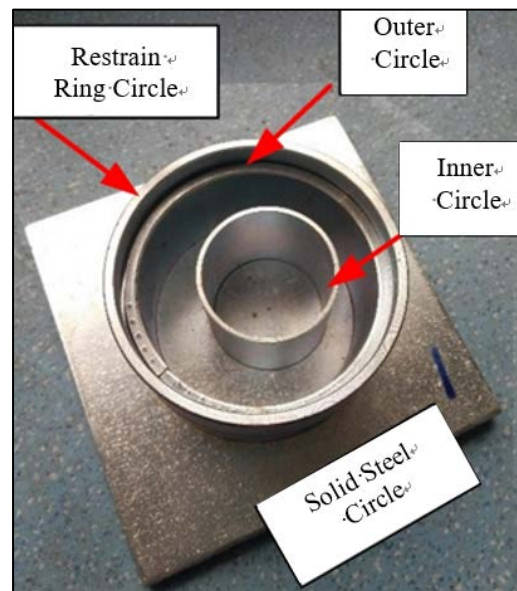


Fig 9. Eccentric Steel Crack frame

Table.2 Cracking time, Software stresses and Location of the Cracks

Specimens Index	C50(w/c=0.3)	C30(w/c=0.5)
Avg.Experimental Crack Time(hours)	50.22	70.2
Avg.Numerical Crack Time(hours)	48	69
Numerical Stresses(MPa)	2.05	1.9
Actual tensile strength(MPa)	2.2	2.1
Maximum Stresses Location	C-D	C-D

8. CONCLUSION

1. The eccentricity will give rise to the stress concentration phenomenon, and consequently, shrinkage cracking will occur in specimens where stress concentration peaks. FEM calculations and the experiments support this intuition. The stress gradient dominated by both of self-stress and restrained stress, in this case, the crack should start near/ at Point-A as high-stress point and then propagate to point B as a low-stress point.
2. There is good Agreement between the numerical and experimental results for the time at which the crack occurs and the increase of the crack width.
3. As much as a small steel ring diameter was used, the drying surface area directly increases and stress will distribute along with all concrete rings.
4. With the reducing of the restrain edge, the stress reaches the level equivalent to the concrete tensile strength faster, and the crack directly considered for these edges.

9. ACKNOWLEDGMENTS

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