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Methods for Assessment of Early Age Shrinkage Cracks in Higher Strength Concrete: A Review

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Abstract*— High-strength concrete is a type of concrete with compressive strength greater than 40 MPa (megapascals), which is much higher than the strength of normal concrete. High-strength concrete is often used in construction projects where greater strength is required, such as high-rise buildings, bridges, and other structures that need to withstand heavy loads or harsh environments. The high strength is achieved through the use of high-quality materials and careful proportioning and mixing of the concrete. Higher strength concrete experiences excessive early age cracking due to low water binder ratio. This early age shrinkage cracking directly affects the strength and durability of concrete. This paper discusses a review of methodologies used to assess the early age shrinkage cracks in concrete which will help in further high strength concrete shrinkage cracking study. In this review restrained shrinkage ring test, free shrinkage tests are discussed.

***Index Terms*— Early age cracking, restrained ring test, shrinkage in concrete, shrinkage cracking.**

I. INTRODUCTION

The High-Performance Concrete (HPC) having higher strength is widely used in many of the concrete structures. High performance concrete has higher strength, high workability, and durability also has long term performance than normal concrete. The mix design of the HPC is different than other concrete keeping the water binder (w/b) ratio as low as possible for the improvement of performance of the concrete. Ground granulated blast furnace slag (GGBS), Fly ash (FA) and Silica fume (SF) is used as mineral admixtures and super plasticizers are used as chemical admixtures in high performance concrete. Due to lower w/b ratio self-desiccation will cause shrinkage in high performance concrete. [1]

1.1 Shrinkage in Concrete:

Shrinkage of concrete occurs due to small amount of volume reduction causes by the hydration process in water and binder material/cement consumes less space than initial products. Addition to that the shrinkage will occur due to drying process. Due to more shrinkage the volume of concrete reduces causes cracks and the structures durability is severely compromised due to cracks.

Holt E. et al. [2] described the shrinkage effect in two different stages, one is early age and another is later age. The term early age is commonly defined as the age at first 24 hours while the process of setting occurs in the concrete and it will start to harden. The term later age refers to the concrete at an age beyond 24 hours.

In the high-performance concrete mixtures, a low water to binder (w/b) ratio and addition of mineral admixtures like silica fume causes a significant drop of the relative humidity during the process of hydration. As a result of this self-desiccation will occur causes the shrinkage of cement paste [3]

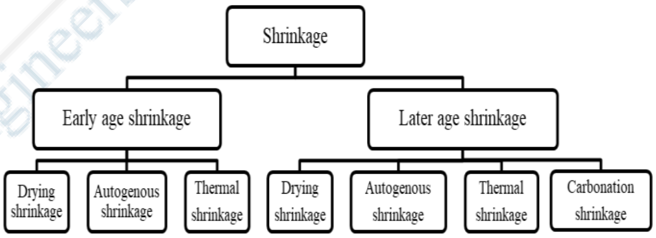

Figure 1. Stages in shrinkage in concrete [2]

1.2 Early Age Shrinkage:

Shrinkage at early ages in concrete is a concern because it occurs before 24 hours, immediately after casting. At this stage concrete has low strain capacity and mostly sensitive to internal stresses. Chang C. et al. [7] explains the term early age as the stage when the rate of hydration reaction approaches to steady state. The stage is retarding stage, where the shrinkage in concrete is less than the age between 3-12 hours. As this stage known as temperature decline stage, the concrete will affect by the environmental temperature and moisture. A drop in the temperature causes shrinkage; as a result, development of cracks occurs in concrete because of internal swelling and the shrinkage of concrete.

The long-term performance of the concrete is dependent on the properties develop by the concrete at the early age and

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its ability to resist the stresses acting on it. Hence it is necessary to control the early age shrinkage considering the long-term durability.

II. METHODS TO EVALUATE THE SHRINKAGE AND CRACKS DUE TO SHRINKAGE AT EARLY AGE OF CONCRETE

Free shrinkage test (ASTM C157) [4], Restrained ring test (ASTM C1581, AASHTO T334) [5, 6] are commonly used by the researcher for assessment of shrinkage cracking. Several other methods are used to assess the cracking potential of concrete like self designed edge restrained plate by Chang C. et al. [7], Longitudinal closed loop instrumented restrained system is used by Kovler K. [8,9], the plate test method used by author Yokoyama et al. [10]. Free shrinkage test and restrained ring test is discussed in this study due to its simplicity and common use to assess the shrinkage cracks occur in the concrete.

2.1 Free Drying Shrinkage:

Free drying shrinkage has to monitor by use of the ASTM C157 [4] test, is commonly used test to determining the change in length of hardened concrete specimen of size 75mm × 75mm × 285mm (Figure 2).

In this method first 75mm × 75mm × 285mm prism mold was casted. Then the specimens were separated from the mold before 24 hours after casting. The specimens were stored in a moist room of temperature 23 ± 2 °C for the desired curing. At the end of curing duration specimen were moved to environmental chamber with controlled dying condition of 23 ± 2 °C with 50% RH. The change in length of prism is monitored by length compactor every day and the mass change is also recorded.

Figure 2. Free shrinkage test setup

2.2 Restrained Shrinkage Ring Test:

Free shrinkage test parameters are not enough strong to predict the shrinkage cracking time so that the restrained shrinkage ring test is commonly used by the researchers to evaluate the cracking potential of concrete and mortar.

In this test the concrete is cast around the steel ring, such that as the concrete will shrink. Compressive stresses are developed in the inner steel ring which is balanced by a tensile stress in the concrete ring specimen. If the tensile stresses are more than the allowable tensile stresses occur in the concrete specimen, the crack will occur in concrete specimen.

Two standard methods based on the similar principle of restrained ring are ASTM C1581 [5] and AASHTO T334 [6]. The main difference between these methods is the thickness of concrete ring specimen. The thickness of concrete ring specimen in ASTM is 38.1mm and the thickness of AASHTO ring is 76.2mm. ASTM test specify maximum size of aggregate should less than 12.7mm, while in AASHTO test no specification given for the size of aggregates. The AASHTO concrete ring allows evaluation of larger size aggregates because it's more thickness of concrete ring specimen than ASTM. The ASTM limits its duration of test to 28 days, but in AASHTO test no specified duration is mention.

2.2.1 Retrained ring test as per ASTM 1581:

In the ASTM 1581 ring test, Steel ring used has a thickness of 13 ± 0.12 mm and an outside diameter 330 ± 3.3mm. The height of the ring is 152 ± 6mm. The outside mold have diameter of 406 ± 3 mm to produce the thickness of concrete specimen 38mm (Figure 3). The freshly mixed concrete was compacted in mold around inner steel ring. The specimens were moist cured by the use of wet burlap also covered with polyethylene film for 24 hours at 23 ± 2 °C. The compressive strain developed in steel ring due to restrained shrinkage of specimen was measured at the time of casting.

The outer ring was removed after 24 hours and the moist curing should continue. The same burlap has to rewet for maintaining the 100 % relative humidity under polyethylene film. When curing process ends the burlap was removed and the specimen was sealed with silicon sealant at top so that drying is allowed in radial/ circumferential direction. At the mid height of internal ring four strain gauges are fixed. The data acquisition system compatible with strain gauges is used to measure strain in steel ring. The readings are recorded automatically by the data acquisition system at interval of not more than 30 minutes. The ring specimen is fixed on resin coated plywood.

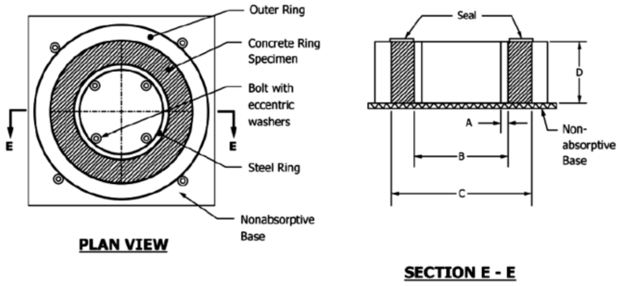

Figure Dimensions	SI Units	Inch-Pound Units
A	13 ± 1 mm	0.50 ± 0.05 in.
B	330 ± 3 mm	13.0 ± 0.12 in.
C	405 ± 3 mm	16.0 ± 0.12 in.
D	150 ± 6 mm	6.0 ± 0.25 in.

Figure 3. Restrained Shrinkage Test (ASTM C1581)

When a sudden decrease in strain readings occurs as shown in fig 4, this age is considered as the age of cracking. The readings are recorded from the time of casting of specimen.

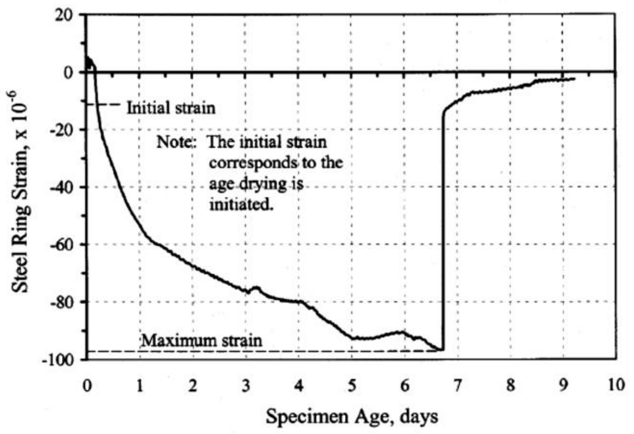

Figure 4. Sample graph showing steel ring strain in µm/m versus specimen age. (ASTM 1581)

See et al. [11] presented the potential for cracking classification (Table 1) to classify the shrinkage cracks with age of cracking.

Table 1: Potential for cracking classification (ASTM C1581; See et al. 2004)

Age of Cracking tcr in days.	Stress rate (average) S (psi / day)	Stress rate (average) S (MPa/day)	Cracking potential
0 < tcr ≤ 7	S ≥ 50	S ≥ 0.34	High
7 < tcr ≤ 14	25 ≤ S < 50	0.17 ≤ S < 0.34	Moderate - High
14 < tcr ≤ 28	15 ≤ S < 25	0.17 ≤ S < 0.17	Moderate - Low
tcr > 28	S < 15	S < 0.10	Low

2.2.2 AASHTO T334:

The AASHTO process is similar to ASTM. In AASHTO inner ring has a thickness of 12.7 ± 0.4 mm and outer ring having radius of 305mm.

Inside steel ring has a thickness of 12.7 ± 0.4 mm, outside diameter of 305mm, and a height of 152mm similar to ASTM. The outer ring can made of cardboard having thickness of 6.4 mm with inside diameter 457mm. Four strain gauges are attached at mid height of the inner surface of steel ring. The data acquisition system compatible with strain gauges is used to measure strain in steel ring. The readings are recorded automatically by the data acquisition system. Curing is done as per the ASTM standards. The outer mold is removed after 24 hours. The strain gauge readings are recorded at interval of 30 minutes. Visual inspection is done ever 2-3 days for cracking. The sudden decrease more than 30µε in any one of strain gauge indicates cracking in specimen. After cracking of concrete ring specimen, the time, the crack length and crack width are recorded.

III. PREVIOUS WORK ON SHRINKAGE CRACKS

The restrained ring test is used by number of researchers because of its simplicity. Carlson et al. [12] used the restrained ring test to investigate cracking behavior. See et al. [11] investigate wide range of concrete by using specific steel ring.

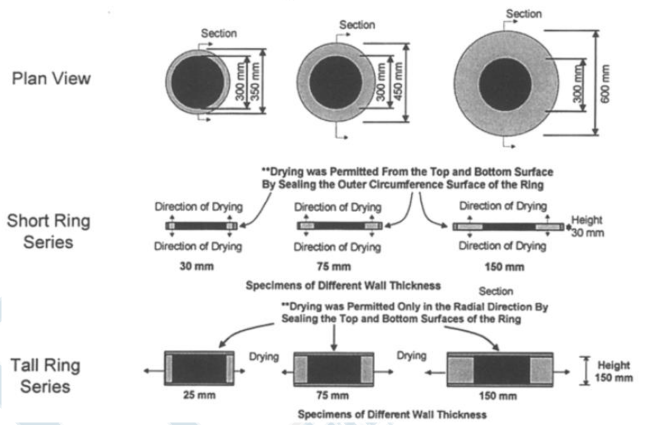

Figure 5. Specimen geometry for short ring and tall ring specimens [13]

Weiss et al. [13] studied and observed the influence of geometry of specimen on shrinkage cracks by using restrained ring specimen. The study compares two series of experiments as shown in fig.5, for better understanding the role of specimen geometry in ring test. In the first series concrete ring specimens of size 25, 75, and 150 mm were used for the same rate of shrinkage and max strain development in the ring. Maximum tensile stresses (residual) developed were nearly same for all used geometry in this study, the shrinkage cracking age varied with thickness of specimen. In the second set combined effect of moisture gradients and geometry of specimen was observed. Three different concrete walls of thicknesses 25, 75, and 150 mm were used for the study.

In first series of experiments, named as short ring series, 30 mm height samples were cast and drying permitted through the top surface and bottom surface of the ring specimen by sealing outer circumference. By doing this a uniform moisture gradient was achieved along the radial direction which would result in uniform shrinkage. In second series height were 150 mm with circumferential drying as shown. Free shrinkage specimens of 100x100x400 mm dimensions were cast to compare the drying shrinkage of the mixes under investigation. All samples were stored in a controlled environment with 30oC and 40% RH for the duration of the tests.

Author concludes that the potential for cracking was reduced as the thickness of concrete ring specimen was increased. The difference in cracking potential was related to

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the geometry since surface to volume ratio and drying shrinkage was same for all samples under consideration.

See et al. [11] studied the characteristics of shrinkage in concrete with different concrete mixes by using ring test method. The steel ring used had inside diameter of 305 mm and outside diameter of 330mm. The height of the concrete ring specimen is 152 mm as per standard with outer diameter 406mm. The strain in the ring was monitored by using two strain gauges attached to inner surface of steel ring. The strain gauge readings were recorded at 30 minutes interval from time of casting of the ring until the ring cracks. As per the results obtained the plain, normal mix concrete without shrinkage reducing admixtures cracked at 17 days, while mix with shrinkage reducing admixtures cracked at 19 days. The author found that tensile creep has a significant role in the cracking behavior of concrete.

Shah et al. [14] studied the restrained ring geometry, used to quantify the behavior of fiber reinforced concrete. The concrete ring specimen used was of 75mm thick. The Steel ring outer diameter kept as 300mm with 9.38 mm thickness. The height of the each ring was kept 75mm. The concrete ring specimens were allowed to dry from top surface and bottom surface of the ring by sealing the circumference of specimen. Steel ring were equipped with four strain gauges at mid height of inner steel ring. The author concludes that the age of visual cracking is delayed by the use of randomly distributed steel fibers due to the ability of fibers to arrest the cracking before crack propagates across the specimen. It was observed that stress developed prior to visible cracking is similar at early age irrespective of volume of fiber.

Hossain et al. [15] studied the residual stress development with different type of ring specimens of concrete had an inner diameter 300mm and an outer ring diameter of 450 mm (Figure 6). In this study author used steel ring having thicknesses 3.1 mm, 9.5 mm, and 19.0 mm. All ring specimens had a concrete wall thickness of 75 mm but many steel ring thickness were utilized to study the effects of the degree of restraint. The ring test setup in the study was very similar to the AASHTO provisional test with two exceptions. Initially the outer circumference of concrete ring specimen was sealed by aluminum tape to allow drying from top surface and bottom surface. This was done to eliminate the moisture gradient that occurs when circumferential drying is permitted. As a consequence, uniform moisture loss long the radial thickness was achieved, simplifying modeling of stress development.

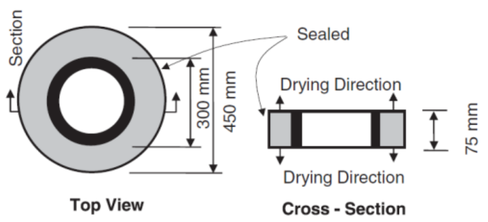

Figure 6. Restrained ring specimen geometry. [15]

The author concluded that higher the degree of restraint in the thicker ring corresponded to higher elastic stresses, greater stress relaxation and earlier the shrinkage cracking age.

Hossain et al. [16] studied the effects of boundary conditions and roll of geometry on the stress development in the concrete ring specimen. This study compared the effects when the drying allows from the outer circumference of concrete specimen. Also, effects of using different thicknesses of steel ring and concrete ring were investigated. The authors used three different test methods to compare the effects of geometry and drying conditions. First they used two different free shrinkage tests in which they measured the shrinkage of unrestrained ring specimens and standard linear free shrinkage specimens that are used by ASTM C-157 test.

Restrained shrinkage test samples were separated into three different series to study the various effects under consideration. The first series, where the degree of restraint was studied, concrete outer diameter was fixed to 450 mm, and the steel ring thicknesses were varied by use of 3.1, 9.5 and 19mm thick rings.

In the second series, the steel ring is 9.5mm thick; however, the concrete ring thicknesses were varied to include rings with wall thicknesses of 37.5mm, 75mm, 112.5mm, and 150mm. Finally, in the last series rings similar to the first two series were used but the drying conditions were changed. The rings were sealed with aluminum tape to obtain two different boundary conditions, such as drying from the outer circumference, and drying from top and bottom as shown in Fig.7. The heights of the ring were 75 mm, and the inner diameters of the concrete rings were 300 mm.

In this study authors also used acoustic emission sensors to detect crack development, and compare the cracking behavior of rings with different boundary conditions. One of the important conclusions of the study was the significant difference in cracking behavior of rings which had different boundary conditions. On the specimens which had circumferential drying (top and bottom sealed) visual cracks were observed earlier even though the interface pressures on the steel rings were lower.

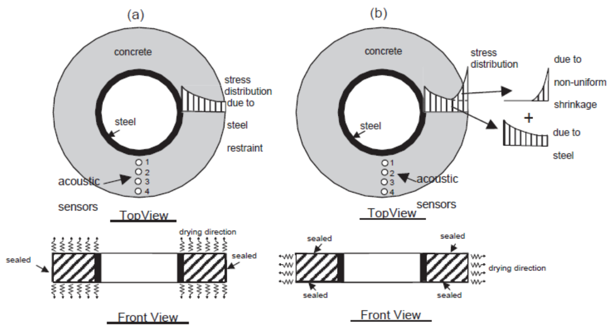

Figure 7. Restrained ring specimens.

The rings which were allowed to dry from top and bottom (sides sealed) experienced higher ring pressures, but cracked at a later age. The authors explained this by comparing the moisture profiles of the two boundary conditions. When concrete is allowed to dry from the outer circumference, the outer surface loses moisture much more quickly due to the larger surface area that is exposed to drying. This creates a moisture gradient in the ring, which results in cracking starting from the outer circumference moving towards the inner steel ring.

In the case where the top and bottom drying is allowed moisture is lost more uniformly along the radius and therefore a more uniform moisture profile is attained. The acoustic sensors showed that the cracks developed on the outside surface and moved inwards for the samples that dried from the circumference. The cracking for the top and bottom drying was exactly the opposite. The effects of using various steel and concrete thicknesses were as expected. Thicker steel rings would lead to higher restraints and therefore earlier cracking. Whereas thicker concrete rings would lead to higher resistance to cracking, which would delay the age of cracking.

Nguyen Q. et al (2010) [17] suggest that the free shrinkage test is not sufficient to predict the cracking behavior of the concrete specimen i.e., whether cracking will occur or not. So that in the most studies of cracking behavior many authors have used the restrained ring. The author studied two different concrete mixes having water to binder ration 0.22 and 0.44. The result from the study shows that greater the steel ring thickness, higher the degree of restrain results in earlier cracking in the concrete ring. In the study with steel thickness of 6mm, 19mm. and 30mm the age of cracking were 12, 8 and 5.4 days respectively with water binder ratio of 0.22.For the water binder ratio of 0.40 for same thickness the age of were 22.5,12.6 and 7.1 days respectively. For the concrete ring thickness of 37.5mm, 75 mm, 112.5mm with water binder ratio 0.22, cracking occurred at 3.4,8 and 9.8 days respectively. With water binder ratio of 0.4 the specimen cracked at an age of 7.1, 12.6 and 16 days respectively. This concludes thicker mortar rings had slightly higher maximum stresses. With the decrease in the water/binder mass ratio of mixture, the cracking happens earlier and the area of cracking is nearer to the inner surface of the mortar ring.

Elliptical ring specimens also developed recently by author Dong, Zhou et al. [18, 19]. The purpose behind development was mainly overcoming the barriers of the traditional ring type specimens. The authors performed various studies to identify and assess the effect of thickness of steel ring and concrete ring as well as drying conditions. Study concludes that with given conditions of specimen, the cracking in concrete specimen is reduced and its location can be predicted. The elliptical ring method is not yet standardized and it is in under development stage.

IV. CONCLUSION

The study conducted in this paper reveals following concluding remarks-

1. Free shrinkage method and restrained shrinkage methods are commonly used by the researchers.
2. Free shrinkage test is used by many researches to compare the results with restrained shrinkage results.
3. Restrained ring method is found suitable by the many authors to identify shrinkage crack in the concrete as compare with free shrinkage test because crack will not identify in the free shrinkage specimen.
4. In ring test authors used different drying conditions of specimen one is drying from circumference and other is dying from top and bottom. From most of the cases it is conclude to use drying from circumference as mentioned in ASTM 1581. When concrete is allowed to dry from the outer circumference of specimen, the outer surface loses moisture much more quickly due to the larger surface area that is exposed to drying.
5. The thicker steel ring shows early cracking of concrete wall, than thinner steel ring because of higher restrain. Whereas thicker concrete rings would lead to higher resistance to cracking, which would delay the cracking age.
6. Ring geometry influence the cracking age, as the highly restrained ring will prefer to get result earlier for the practical considerations.

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