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Investigation Of Early Age Cracking In High Strength Concrete

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Abstract
Early-age cracking in concrete is a penetrating issue impacting the structural integrity, durability and lifespan of concrete structures. This phenomenon typically occurs within the first few hours to weeks after placement, primarily due to plastic shrinkage, thermal changes during curing, drying shrinkage, autogenous shrinkage, and settlement. Addressing early-age cracking is essential for ensuring structural durability and longevity, and requires a comprehensive understanding of concrete properties, environmental influences, and construction practices. In this paper, appraisement of early age cracking in restrained concrete with ring specimens is focused. The experimental results of the assessment of strain are used for detecting cracks and crack width analysis is presented. It is seen that no cracking is observed in the normal concrete (M20, M40), while early-age cracking is observed in the high-strength concrete (M120, M100, M80, M60), respectively. The crack width assessment at the end of assessment duration reveals that the crack width is less in M120 and more in M60. With thoroughly checking for early cracks, engineers and contractors can significantly enhance the strength, safety and appearance of concrete structures by adopting the appropriate prevention methods.

Keywords: *Early age concrete, restrained concrete, ring specimen, shrinkage, crack width.*

1. INTRODUCTION

Concrete is a composite construction material formed by incorporating cement, water, and aggregates—such as sand (fine aggregate) and gravel or crushed stone (coarse aggregate). This mixture binds together to create a robust, hardened structure. Concrete mixtures are typically defined by the proportions of their key components: cement, fine aggregate (sand), and coarse aggregate (gravel or crushed stone). It hardens over time to create a solid, strong substance that is best suited for construction projects. It is well known for its strength, durability, versatility, and ability to get moulded in any shape and size. The strength of concrete is primarily influenced by the water-cement ratio, the type of cement employed, and the curing conditions. Adequate curing is critical to achieving the material's full strength and long-term durability. This process entails maintaining moisture in the concrete over a specified duration, typically 28 days, to ensure proper hydration of the cement [1].

Early-age cracking in restrained concrete is a prevalent issue in construction, primarily caused by the interplay of shrinkage and restraint. As concrete cures, it undergoes shrinkage, reducing its volume due to moisture loss [2]. When this shrinkage is restricted by surrounding structures or formwork, tensile stresses develop within the concrete. Cracking takes place if these stresses are greater than the concrete's tensile strength. This phenomenon is further exacerbated by factors like high temperatures and low humidity, which accelerate shrinkage [3]. The cracks in concrete affect the structural integrity, durability and strength of structures [4].

The efficacy of cement concrete under restrained situations can be assessed through various methods, such as flat panel tests, linear restrained shrinkage tests, and restrained shrinkage ring tests. Of these, the restrained shrinkage ring test has emerged as a commonly adopted practice due to its straightforward implementation and economical nature [5]. In this method, concrete is cast to encase an inner steel ring, which mechanically restricts the concrete's natural shrinkage behavior. This restraint generates compressive stress within the steel ring, while tensile stress develops in the concrete to balance the steel's compression. Cracking appears when the tensile stress in the concrete surpasses its capacity. To accurately identify the onset of cracking and observe strain evolution, strain gauges are affixed to the steel ring, providing real-time data on stress dynamics [6].

Standardized procedures for the ring test have been established by ASTM [7]. This method can be effectively employed to evaluate the properties of concrete incorporating [8]. A study in [9] demonstrates the applicability of the ring test in evaluating the cracking potential of high-strength concrete. The add mixtures also contributes towards improved susceptibility for cracking of concrete [10].

High-Performance Concrete (HPC) is defined by its enhanced strength, durability, and workability, surpassing the properties of conventional concrete. Characterized by significantly higher compressive and tensile strengths, HPC enables the design of more slender and efficient structures [11]. Its enhanced durability provides resistance to freeze-thaw cycles, chemical attacks, and abrasion, ensuring long-term performance in demanding environments. Furthermore, HPC often demonstrates rapid strength gain, accelerating construction schedules [12]. This exceptional performance is achieved through a unique combination of materials, in addition to supplementary cementitious materials like fly ash and silica fume, carefully selected aggregates, and specialized admixtures that enhance specific properties. Also due to lower w/c ratio concrete is more durable [13]. These characteristics make HPC an indispensable material for modern construction projects, particularly in applications like bridges, high-rise buildings, tunnels, and marine structures [14].The hydration in the concrete causes the rise in temperature causes self-desiccation tends to autogenous shrinkage at early ages. The internal water present in the capillary pore evaporates in higher strength concretecausing the tension in the small pores to causeshrinkage.A detailed review of early age cracking in concretes along with causes and remedies is presented in [15] with future needs towards the development of sensors and instrumentation for analysis of cracking as well as cracks. The concrete exposedto temperature and/or shrinkage differences, reinforced concrete elements with added reinforcing, and edge-restraint were applied to reinforced concrete slabs and walls in which concrete tensile stresses and restraint forces brought on by shrinkage strainand temperature have been taken into consideration. A practical example [16] is provided to demonstrate how to determine the crack's width and spacing brought on by any one of these restraints alone or in combination. The causes, consequences, and remedial measures to lower the chance of early age cracking are discussed in [18]. Table 1 indicates the cracking potential for concrete mixtures.

Table 1 Classification of potentials for cracking of concrete mixtures

Time to cracking in days	**Stress (S) in MPa/day**	**Cracking possibilities**
0 to 7	$S >= 0.34$	High
7 to 14	$0.17 <= S < 0.34$	Medium
14 to 28	$0.10 <= S < 0.17$	Low
> 28	$S<0.10$	Very Low

The restrained concretes are subjected to constraints that restrict free movement or deformations. Some of these constraints are temperature changes, external loads, curing conditions, etc. These constraints increase the chance of early age cracking [19]. In concretes not only the cracking potential but the size (length and width) of the crack also matters in ensuring structural integrity, durability, and aesthetic appeal of the structure. Wide cracks can compromise concrete's structural integrity, lowering its ability to support loads and stiffness. Cracks can allow water and other aggressive agents to penetrate the concrete, leading to corrosion of reinforcement, deterioration of the concrete matrix, and reduced service life [20]. The investigation of crack width involves experimental and numerical analysis [21]. The crack width measurement is conducted with a dedicated 'crack width gauge'. When the concrete mix is set into the specimen mould and kept for curing, the cracking is developed across the curing interval. At the initial stage, the cracks are very narrow and the crack width increases up to a saturation level over the curing period due to the shrinkage of concrete [22]. The constituents of the concrete mix like the water-cement ratio influence the strength, durability, and workability of the final concrete. The high strength concretes have a lower water-cement ratio. Low water content makes the concrete mix stiffer and more difficult to place and consolidate, which can increase the likelihood of entrapped air voids. These voids can weaken the concrete and contribute to cracking at an early age [23].

In this paper, investigation of early age cracking is investigated for mix design of various strengths namely M20, M40, M60, M80, M100, M120. Restrained ring specimen methods is used for assessment of early age cracking and crack width analysis is presented.

2. DESIGN OF CONCRETE MIX

Concrete mix design refers to the essential procedure of calculating the ideal ratios of constituent materials (such as cement, aggregates, water, and admixtures) to attain targeted performance characteristics in the cured concrete. During this experimentation, the concrete mix design was carried out for strengths ranging from M20 to M120. The mix design proportions (in kg/m^3) of cement, fine aggregates, coarse aggregates, water, fly ash, silica fume, and admixture as well as the W/B ratio for each of the concrete mixes are mentioned in Table 2. In mix design, Ultratech Make ordinary Portland cement of 53grade (confirming to IS12269) is used. Natural sand is used as fine aggregates and 12.5mm crushed stone is used as coarse aggregate. For designing higher strength concretes of M60, M80, M100, and M120, ADDMIX® 300 - Polycarboxylic ether (PCE Based) admixture is used along with silica fume obtained from Elkem Materials. The specific gravity of the materials used is mentioned in Table 3. For designing a concrete mix, the Aitcin [1] method is used.

Table 2: Concrete Mix design proportions

Grade	M20	M40	M60	M80	M100	M120
W/B ratio	0.5	0.45	0.35	0.30	0.25	0.23
Cement (Kg/m^3)	360.0	388.9	365.7	416.0	436.1	540.9
FA (Kg/m^3)	773.9	762.9	705.0	723.9	757.4	680.5
CA (Kg/m^3)	1100	1100	1100	1100	1100	1100
Water (Kg/m^3)	180	175	160	156	138	143
Fly Ash (Kg/m^3)	0.00	0.00	91.4	52.0	49.7	31.1
Silica fume (Kg/m^3)	0.00	0.00	0.00	52.0	66.24	49.74
Admixture (%)	0.00	0.00	0.4	0.5	0.6	1.3

Table 3: Specific gravity of materials used

Sr. No.	Material	Specific Gravity
1	Cement	3.15
2	Fly ash	2.06
3	Superplasticizer	1.10
4	Course aggregate	2.84
5	Fine aggregate	2.66

6	Silica fume	2.22

To validate the mix design for intended strength, concrete cubes of 150X150X150 mm and cylinders of 150X300 mm dimensions for each of the mix design (as per IS standards) were casted, cured for 7 and 28 days and tested for compressive strength. The test results of compressive strength are mentioned in Table 4.

Table 4: Results of compressive strength

Concrete Mix	CubeCompressive strength in MPa		CylinderCompressive strength MPa	
	for 7 days	for 28 days	for 7 days	for 28 days
M20	12	26	11	22
M40	31	44	26	41
M60	44	65	36	61
M80	54	85	44	76
M100	64	104	56	95
M120	88	124	70	114

EXPERIMENTATION AND RESULT ANALYSIS

To develop a mould for restrained concrete for the experimentation work, a ring specimen is prepared with the dimensions mentioned inTable 5. The specimen is prepared with steel material as the walls of the mould and non-absorptive epoxy-coated plywood as the base. The specimen cross-section is represented in Figure 1. It is to be noted that the specimen is installed with strain gauges on the internal side of the inner ring at the center of the height. Four strain gauges are installed at a mutual angle of 90^o. They are oriented to measure strain along the circumference of the inner ring. The foil-type resistive strain gauge of 330Ω is used. The Wheatstone's bridge and instrumentation amplifier are used for signal conditioning and strain measurement is carried out with ADC enabled Arduino Uno board. The data acquisition is done with a thermal printer which prints the strain value every 30 minutes. Also IoT interface is provided to enable the remote monitoring of temperature, humidity, and strain. The photographs of the developed specimen and data acquisition system are shown in Figure 2.

Table 5: specifications of ring specimen

Specification	Value
Base	Wooden (non-absorptive) Epoxy coated plywood
Inner ring	Material : steel Inner diameter: 310mm Outer diameter: 334mm Height: 150mm
Outer ring	Inner diameter: 420mm Outer diameter: 425mm Height 150mm
Concrete mould	Thickness: 40 ±3 mm Inner diameter: 334 mm Outer diameter: 420 mm Height: 150mm

Specification	Value
Strain gauge	Foil type Resistive Resistance: 330Ω
Signal conditioning	Wheatstone bridge, instrumentation amplifier
Data acquisition	Thermal printer and IoT Thing Speak

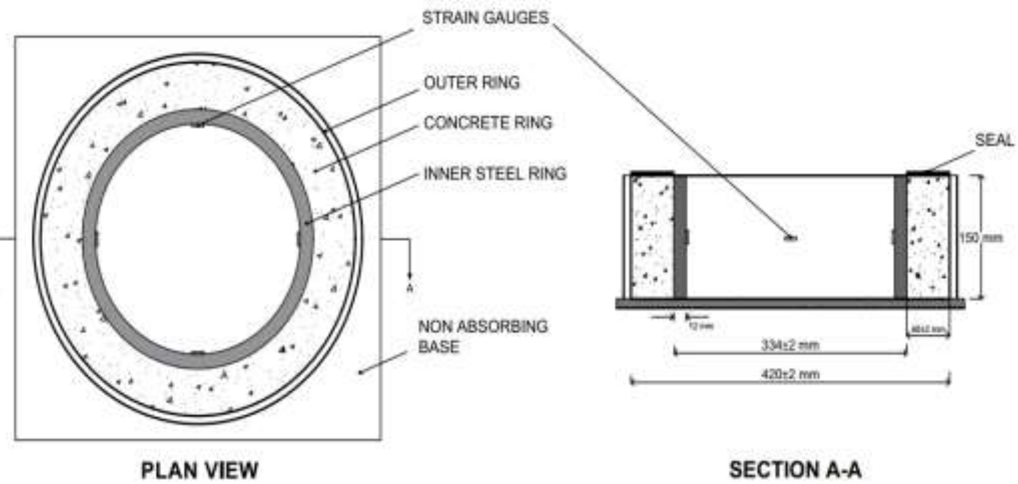

Figure 1: schematic of ring specimen

Figure 2: Photograph of ring specimen and data acquisition system

Early-age cracking in restrained concrete is a significant concern within the construction industry as it can compromise the structural integrity and durability of concrete structures. To mitigate this issue, it's crucial to understand the factors influencing early-age cracking.In this experimentation work, six concrete mixes of strengths 20MPa, 40MPa, 60MPa, 80MPa, 100MPa, and 120MPa (hereafter refereed as M20, M40, M60, M80, M100 and M120) are considered. As mentioned by the ASTM C1581, the ring structure is fabricated for the mould, and an instrumentation (with data acquisition) system of strain gauges is attached for monitoring of strain. The concretes are poured into the ring moulds as shown in Figure 1.

The concrete moulds were demoulded 24 hours after casting and kept in acontrolled environment with humidity of 50 ± 5%and a surrounding temperature of 23±2°C.

The strain is monitored at the walls of the mould with the help of four strain gauges placed at a right angle to each other and arranged in Wheatstone's bridge configuration. The strain monitoring is done for a period of 30 days and the reading is updated every 30 minutes. The graphs of strain versus time (no. of days) are plotted as seen inFigure 3 to Figure 8.

Figure 3 shows the graph of strain vs. time for the M20 concrete mix and that for the M40 mix is shown in Figure 4. It is to be noted that no cracks are observed over the period of observation for the M20 and M40 design mix. As shown in Figure 5, a sudden drop in strain is observed on day 17, which is indicative of the cracking for the M60. Similarly, the graphs for M80, M100, and M120 are shown in Figure 6, Figure 7, and Figure 8, respectively. In which it is observed that the cracking is occur for M80 on day 14. For M100 and M120 the cracking occurs on day 8 and day 6 respectively. The results and cracking potentials for all mixes is mentioned in table 7.

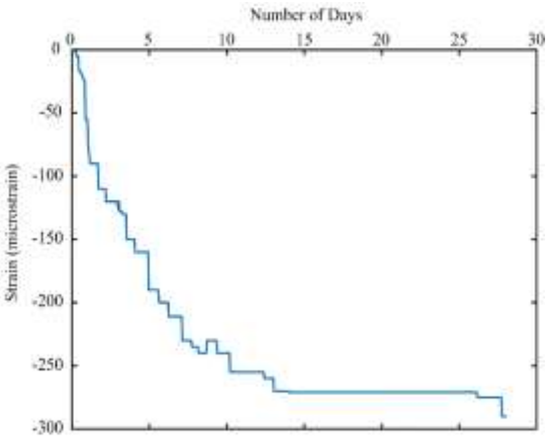

Figure 3: strain vs. time for M20 concrete

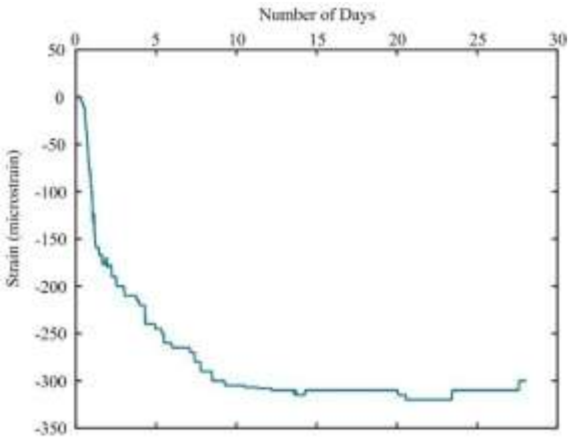

Figure 4: strain vs. time for M40 concrete

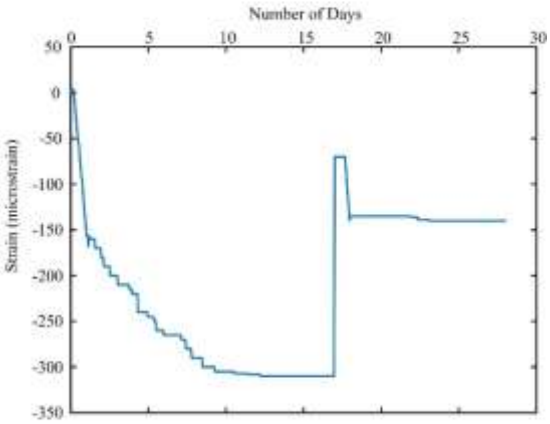

Figure 5: strain vs. time for M60 concrete

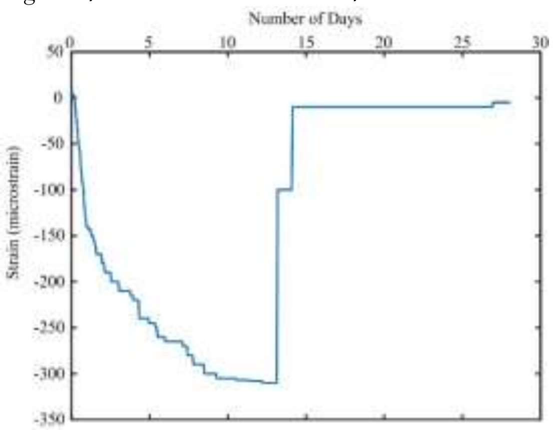

Figure 6: strain vs. time for M80 concrete

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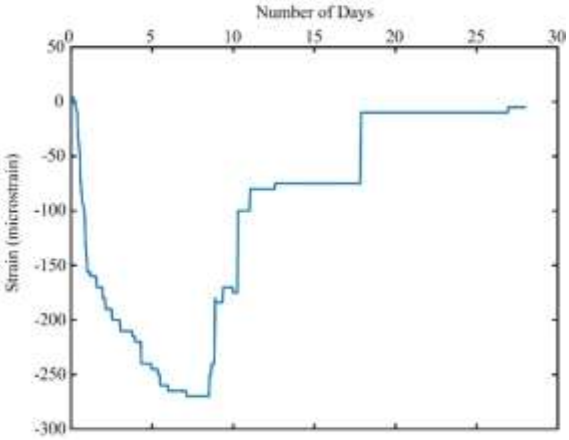

Figure 7: strain vs. time for M100 concrete

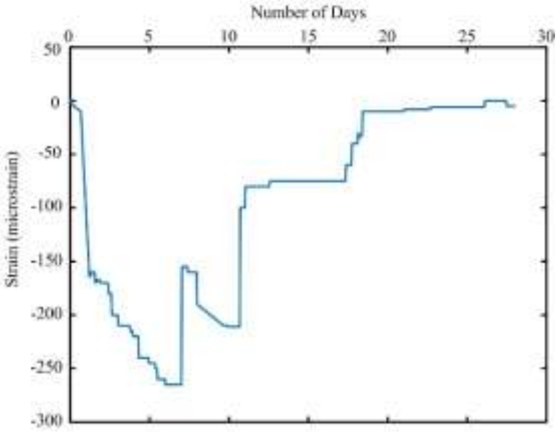

Figure 8: strain vs. time for M120 concrete

3. Crack Width Analysis

The cracking of concrete is not observed in M20 and M40 concretes. In M60, M80, M100, and M120 concretes, cracking is observed. The cracking is observed at the earliest age in M120 and the cracking age was observed to be increasing for M100, M80, and M60 grade concretes. The photograph of the crack of M100,M80, and M60 grade concrete is shown in Figures 9, 10, and 11 respectively. The observations of the crack width of concrete alongwith cracking age are recorded in Table 6.

Figure 9 (a): M100 moulded concrete

Figure 9 (b): Photo showing of crack and crack width measurement

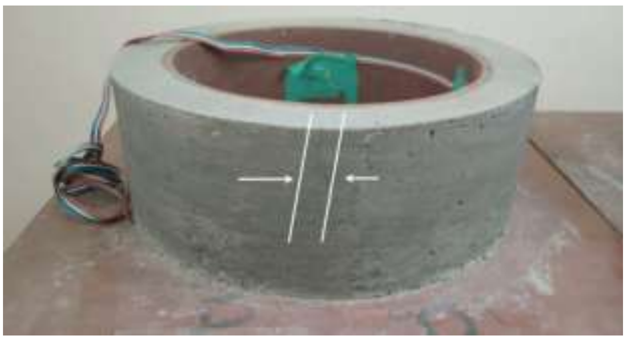

Figure 10 (a): M80 moulded concrete

Figure 10 (b): Photo showing crack and crack width measurement

Figure 11 (a): M60 concrete cracking

Figure 11 (b): Photo showing crack and crack width measurement

Table 6 cracking age and Crack width of concretes

Concrete mix	Age of cracking in days	Cracking Potential	Average Crack width (mm)
M20	---	Very Low	---
M40	---	Very Low	---
M60	18	Low	0.2
M80	14	Low	0.15
M100	8	Medium	0.12
M120	6	High	0.08

While preparing concrete, the materials mentioned in Table 2 are mixed in different proportions to achieve the desired strength. The change in the proportion of materials in the concrete mix leads to a change in strength and hence change in the overall properties of the concrete. Lower-strength concretes have shown elasticity and hence no cracking is observed in M20 and M40 concretes. A sizeable crackwidth is observed in M60, M80, M100, and M120 concretes and it is noticed that, when the strength of concrete develop, the crackwidth is seen to be decreasing.

4. CONCLUSIONS

In this paper, appraisement of early age cracking in restrained concrete with ring specimens is focused. The experimental results of the assessment of strain are used for detecting cracks and crack width analysis is presented. By effectively assessing the early-age cracking, engineers and contractors can notably heighten the durability, safety, and aesthetics of concrete structures by using the appropriate mitigation techniques. The following conclusions are made from the current study:

- The cracking was not observed in the normal strength concrete (M20 and M40) having a high water to binder ratio as compared to high strength concrete in the early ages of hydration shows negligible volume changes.
- The sudden drop in strain was observed on day 6 in M120 concrete indicates cracking with high cracking potential. For M100 concrete the crack was measured on day 8, the M80 concrete cracks on day 14 and on day 17 the cracking was observed in M60 grade concrete.

- On account of the water cement ratio, the cracking potential is marked to be very high in M120 and comparatively low in M60. With increasing concrete grade, increase in cement contents causes increased volume reduction.
- The crack width of M120 was measured to be 0.08 which is less than those of M100 (0.12mm), M80 (0.15mm) and M60 (0.20mm). As the concrete strength increases, the width of cracks reduces up to 60% significantly. As the concrete compressive strength increases, the average width of the crack is found to be reducing due to dense microstructure.
- By thoroughly checking for early cracks, engineers and contractors can significantly enhance the strength, safety and appearance of concrete structures by employing the appropriate prevention methods

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