

Restrained Shrinkage-Induced Cracking of Light Weight High Performance Fiber Reinforced Cementitious Composites

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Abstract: Problem statement: Shrinkage induced cracking cause damage to reinforced concrete structures. An experimental study was conducted on restrained shrinkage test of cement mortar and light weight High Performance Fiber Reinforced Cementitious Composites (HPFRCC). **Approach:** Two types of light weight HPFRCC and a premix mortar containing small amount of fiber were included in the experiment. **Results:** Results showed the multiple cracks, as many as 49, in light weight HPFRCC specimens compared to few cracks (about six cracks) in the premix mortar specimen. At the end of shrinkage test, the width of the cracks in the mortar specimen was more than 250 μm with the largest crack width of about 400 μm . However, the scenario was quite different in light weight HPFRCC specimens, where the width of almost all cracks was less than 100 μm . **Conclusion:** The higher number of multiple cracks with small cracks width in light weight HPFRCC specimens due to drying shrinkage was due to their strain hardening and ductile behavior compared to quasi brittle behavior of premix mortar where less number of wide cracks was observed.

Key words: Shrinkage, high performance fiber reinforced cementitious composites, Cement mortar.

INTRODUCTION

Shrinkage is unavoidable in concrete. The amount of shrinkage depends on many factors including the cement content, aggregate properties, the mixture composition, temperature and the relative humidity of the environment, the age of the concrete and the size of the structure. If concrete is restrained from shrinking, tensile stresses develop and once the tensile stresses exceed the tensile strength of concrete, the concrete cracks. One way to reduce the crack opening is to reinforce the concrete with short randomly distributed fibers.

Ring test is commonly used to assess the potential for restrained shrinkage induced cracking due to its simplicity and versatility. In the ring test the concrete is cast around the hollow steel cylinder. As the concrete dries, shrinkage is prevented by the steel ring, thus resulting in the development of tensile stresses in the concrete. The ring specimen geometry is frequently preferred because of the difficulties associated with providing adequate end restraint in other methods. The simple geometry allows the specimen to be fabricated easily and the low cost of the system enables several tests to be conducted concurrently over a long period of time.

Several projects have investigated the restrained shrinkage induced cracking of ordinary concrete^[1-3] and fiber reinforced concrete^[4-7]. Grzybowski and Shah^[4] investigated the shrinkage cracking of fiber reinforced concrete using a ring-type specimen to simulate restrained shrinkage cracking. Two types of fibers (steel and polypropylene) with the amount of fibers ranged from 0.1-1.5% by volume were used. The results indicated that the addition of small amount of steel fibers (0.25% by volume) reduced the average crack widths by about 20% and the maximum crack width by about 50% in comparison with plain concrete. Polypropylene fibers showed much less effective in reducing crack widths than steel fibers. However, the maximum number of cracks was limited around 2 or 3. Voigt *et al.*^[6] also used different types of steel and polypropylene fibers in fiber reinforced concrete and reported that steel fiber is the best performing reinforcement concerning maximum crack width compared to its counterpart polypropylene fiber. Multiple cracks were not observed in those composites. High Performance Fiber Reinforced Cementitious Composites (HPFRCC) that exhibit strain hardening and multiple cracking behavior in uni-axial tension have also been used to evaluate their performance

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against restrained shrinkage induced cracking by^[8,9]. Weimann and Li^[8] reported multiple cracks (as many as 10) of much smaller width (as small as 0.03mm) in ring specimens made with Engineered Cementitious Composites (ECC) containing 2% PVA (polyvinyl alcohol) fiber by volume. Multiple cracks with small crack width are also reported by Wittmann *et al.*^[9] in PVA fiber reinforced HPFRCC specimen in the ring test.

While little studies are evaluated the restrained shrinkage induced cracking of HPFRCC, however, no study is reported on the light weight HPFRCC. This study presents the results on the restrained shrinkage induced cracking of light weight HPFRCC due to drying. Comparison is also made with premix mortar.

MATERIALS AND METHODS

Materials and mix proportions: Two types of light weight HPFRCCs and two types of mortar are considered in this study. The matrixes for the light weight HPFRCCs in this study are consisted of ordinary Portland cement and two types of light weight sands in 14% by volume. Both light weight HPFRCCs are reinforced with two different types of PVA fibers in different volume fractions containing 2% PVA fiber of 12mm in length and 100 µm in diameter and 1% PVA fiber of 6 mm in length and 40 µm in diameter. The first composite contained light weight sand type FL1 while the second contained type FL0. The light weight sand type FL0 is finer but heavier than FL1 (Table 1). Both light weight composites exhibited strain hardening and multiple cracking behaviors in bending, while the premix mortars did not exhibit strain hardening behavior (Fig. 1). The light weight HPFRCCs are about 22-38% lighter than the mortar^[10]. The properties of light weight sands are given in Table 1, while the properties of Polyvinyl Alcohol (PVA) fibers are shown in Table 2. Table 3 shows the mix proportions for light weight HPFRCCs and premix mortar. Series 1 and 2 are for light weight hybrid composites containing light weight sand type FL0 and FL1, respectively, while series 3 in Table 4 is the mix proportions for premix cement mortars.

For each series, two cylindrical specimens and two ring specimens were cast. The cylindrical specimens were used to measure the free shrinkage while the ring specimens were used for the restrained shrinkage test. All cylindrical specimens were demolded after 24 h of casting and wet cured for approximately 7 days. The top surface of the ring specimens were covered with wet burlap for one day after casting. On the second day, the top surface of the ring specimens was sealed with silicon resin. After 3 days the outer PVC ring was removed. A schematic of the ring test setup is shown in Fig. 2.

Table 1: Properties of light weight sand

Type	Size of sand grain (mm)	Unit weight (gm cm ⁻³)	Surface area (cm ² gm ⁻¹)
FL0	0.6	0.675	24.7
FL1	0.6-1.2	0.220	75.8-37.9 (50.5 avg.)

Table 2: Properties of PVA fibers

Types	Length (mm)	Diameter (mm)	Modulus of elasticity (GPa)	Fiber strength (MPa)	Elongation (%)
Thinner	6	0.04	40	1600	6
Thicker	12	0.10	25	1100	10

Table 3: Mix proportion of light weight HPFRCC materials

Series	Light weight sand type	Mix proportion by wt. (%)				
		Cement	Sand	Viscous powder	Thicker PVA fiber	Thinner PVA fiber
1	FL0	86.5	8.9	0.8	2.5	1.3
2	FL1	92.1	3.1	0.8	2.7	1.3

Note: Water/cement ratio in both series was 0.62 by weight

Table 4: Mix proportion of cement mortars

Series	Mix proportion by wt. (%)				
	Cement	Other cementitious materials	Sands	Fiber	Viscous powder
3 (Premix mortar)	48	26.3	25.4	0.2*	0.1

Note: Water/cement ratio was 0.54 by weight; *: Length: 6 mm and diameter: 20 µm

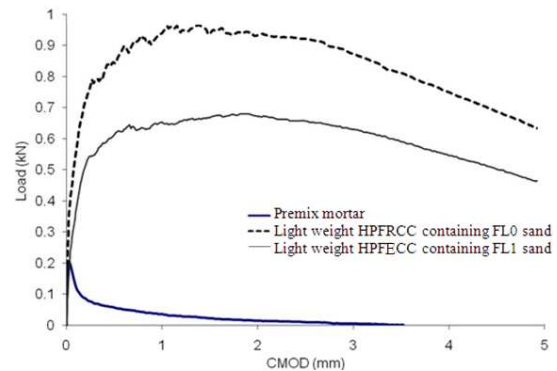


Fig. 1: Strain hardening behavior of light weight HPFRCCs and Premix mortar

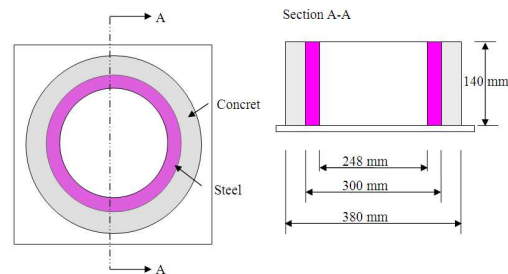


Fig. 2: Dimension of ring specimen used in restrained shrinkage test (not to scale)

Free shrinkage test: Free shrinkage of cement mortars and the light weight hybrid composites was measured on cylinders with a length of 100 mm and a diameter of 50 mm. A gauge was placed at the center of all cylindrical specimens in order to measure the free shrinkage automatically (Fig. 3). All cylindrical specimens were placed into the laboratory atmosphere with RH = 60% at 20°C. A typical experimental setup is shown in Fig. 4.

Restrained shrinkage test: Metallic rings are the most widely used devices to test the restrain shrinkage of concrete. A mortar ring is cast around a steel ring. Because steel is stiffer than cement mortar, volume change of mortar is prevented to a certain extent, which depends on the ring's dimensions and properties of mix. In this study, the depth of the mortar and steel rings is considered as 140 mm (Fig. 2). The inner radius of the steel ring is 125 mm, while the outer radius of steel ring and the inner radius of the mortar ring is 150 mm.

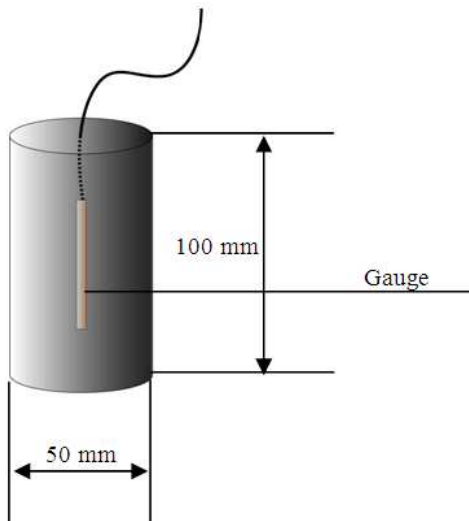


Fig. 3: Dimension of cylindrical specimen



Fig. 4: Instrumentation for free shrinkage test

The outer radius of the mortar ring is 190 mm therefore its thickness is 40 mm. Then radial drying of ring specimens was conducted in the laboratory atmosphere with RH of 60% and at 20°C. Drying was only allowed from the outer circumferential surface. The large depth-to-thickness ratio was chosen to provide uniform drying across the thickness^[4].

RESULTS AND DISCUSSION

The results of free shrinkage testing of premix mortar and light weight hybrid composites are shown in Fig. 5. It can be seen that the drying shrinkage of premix mortar is nearly half the value of light weight hybrid composites. The rate of increase of shrinkage for all materials was high during the first 2 weeks, after that period the rate slowed down and became constant after about 50 days of drying. It is well known that shrinkage of concrete depends on cement, water, sand and paste content^[11]. The higher the paste content of a concrete, the higher the shrinkage is, since it is the paste property. It is clear that the cement content in light weight hybrid composites is higher than that of premix mortar (compare Table 3 and 4). Therefore, the higher drying shrinkage of light weight hybrid composites than that of premix mortar is due to higher cement content, lower sand content and higher water/cement ratio. Similar results are also reported by Kayali *et al.*^[12] where the drying shrinkage of light weight FRC was found twice as compared to normal weight concrete. The light weight hybrid composites containing FL1 type light weight sand exhibited slightly higher drying shrinkage than the one containing FL0 type light weight sand. This can be attributed to the higher surface area of FL1 type light weight sand than that of FL0 type light weight sand. The increase of drying shrinkage with increase in surface area of aggregates in the concrete was recently observed by Imamoto *et al.*^[13].

The results of restrained shrinkage test (ring test) are shown in Fig. 6 and 7. Figure 6 shows the occurrence of cracks in the ring specimens with progress of time.

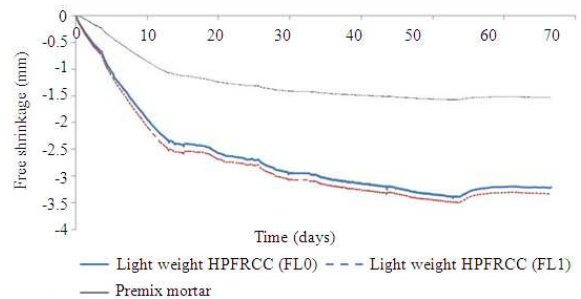


Fig. 5: Free shrinkage of premix mortar and light weight HPFRCC

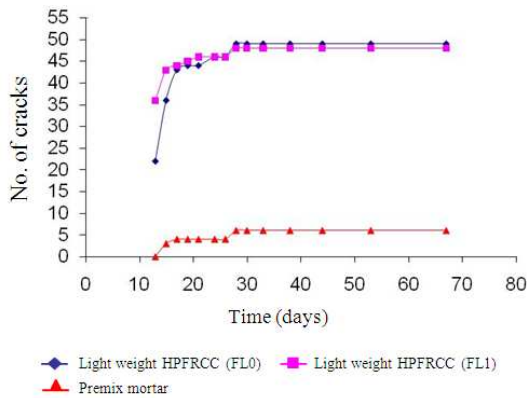


Fig. 6: Number of cracks appeared in premix mortar and light weight HPFRCC ring specimens

It can be seen from the Fig. 6 that after about 2 weeks of drying first crack appeared in the premix mortar specimen whereas at the same time the light weight hybrid HPFRCC specimens containing FL1 and FL0 type light weight sand exhibited about 22 and 35 cracks, respectively. It should be noted that the cracks started to appear in the light weight HPFRCC specimens after about 3 and 4 days of drying. The higher number of cracks observed in the light weight hybrid HPFRCC specimens is due to the strain hardening behavior of this material as compared to its counterpart premix mortar which contained very low amount of fibers. The strain hardening and multiple cracking behavior of light weight HPFRCC materials was observed in the three point bending test as shown in Fig. 1, whereas the premix mortar exhibited quasi brittle behavior. After about four weeks, the formation of cracks in all ring specimens was stabilized and remained constant until the end of the test. At the end of the test, the light weight HPFRCC specimens exhibited about 48 or 49 cracks compared to six cracks in premix mortar specimen.

Throughout the drying shrinkage test, the width of the cracks were monitored and measured. The width of each crack was measured using a microscope at every 48 h during first few days after cracking and then measured at every four days. The crack width reported here is an average of at least four to six measurements. Figure 7 shows the development of the maximum crack width with progress of time for premix mortar and light weight HPFRCC specimens. It can be seen from the Fig. 7 that the maximum crack width in the premix mortar increases with time meaning that once crack is initiated, it continued to open up with continued drying. This is due to the quasi brittle behavior of this material.

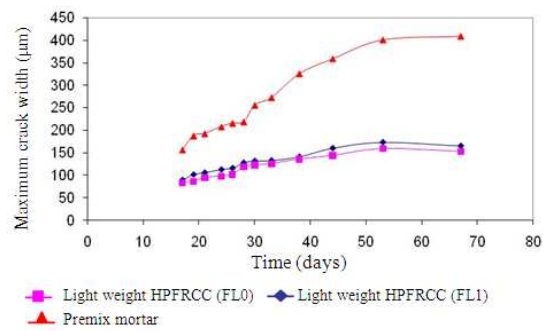


Fig. 7: Maximum crack width in premix mortar and light weight HPFRCC ring specimens

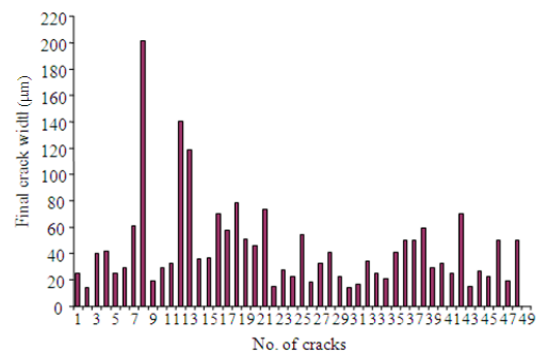


Fig. 8: Final crack width in light weight HPFRCC ring specimen (FL0)

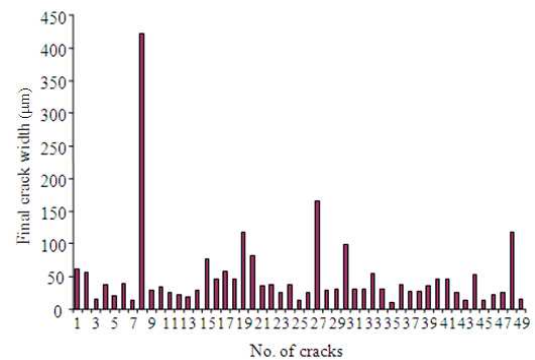


Fig. 9: Final crack width in light weight HPFRCC ring specimen (FL1)

On the other hand, the rate of increase of the maximum crack width in light weight HPFRCC specimens was almost flat. At the end of the test, the width of all cracks of premix mortar and light weight HPFRCC specimens were measured and are plotted in Fig. 8 and 9. Figure 8 shows the measured crack width of light weight HPFRCC material containing FL0 type light weight sand.

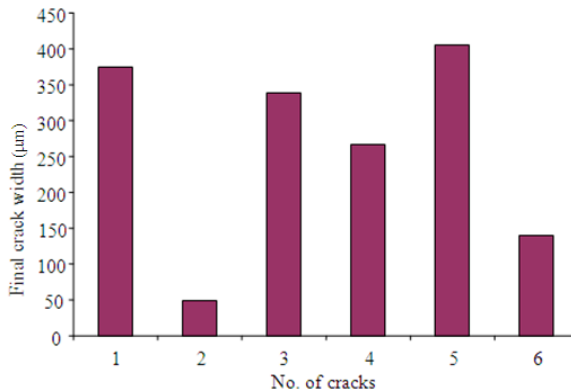


Fig. 10: Final crack width in premix mortar ring specimen

It can be seen from the Fig. 8 that the crack width remain less than 100 µm except one or two cracks whose width are about 140-200 µm and are believed to be the localized cracks. Similar behavior is also observed in HPRCC containing light weight sand type FL1 where a localized crack with a maximum crack width of about 430 µm is observed (Fig. 9).

The scenario is completely different in case of premix mortar. In Fig. 10 the measured final crack width of premix mortar is shown. As can be seen in the Fig. 10, the number of cracks is limited to only 6 with crack width of most of the cracks ranged between 250 and 400 µm.

CONCLUSION

Multiple cracking behavior is observed in the light weight HPRCC ring specimens in the restrained shrinkage test compared to few cracks (about six) in the premix mortar specimen. The final width of all cracks in the premix mortar specimen is found to be more than 250 µm with largest crack width of about 400 µm. In case of light weight HPRCC specimens, the width of almost all cracks are less than 100 µm except only one crack the width of which is about 400 µm. The higher numbers of cracks with small crack width observed in light weight HPRCC materials is due to its strain hardening and high toughness properties which lead to multiple cracking.

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