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Influence of Restraint Conditions and Reinforcing Bar on Plastic Shrinkage of Self-consolidating Concrete

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ABSTRACT

Restraint conditions and reinforcing bars are important factors for plastic shrinkage performance of concretes. The results of laboratory investigation reported herein concerns the influence of the restraints conditions and embedded steel on restrained strain plastic shrinkage of self-consolidating concrete(SCC) as repair material . The results showed that the more roughness in the surface of substrate, more restraints induced in overlay, which during shrinkage, higher restrained strain generated in repair material. The results also revealed that when a slab is reinforced with one single bar, with relatively large diameter as used in this study, cannot improve plastic shrinkage behavior; even it causes plastic settlement cracking.

INTRODUCTION

Plastic shrinkage occurs in fresh concrete. It occurs within few hours after mixing the concrete. Plastic shrinkage is caused by capillary tension in pore water. Due to evaporation of the pore water, the capillary forces are active. When water evaporates from the surface of plastic concrete in higher rate than bleeding water, the concrete are prone to plastic shrinkage cracks. When the plastic concrete is allowed shrinks freely, it never cracks. But in practice, there is restraint condition provided by the concrete below the drying surface layer which results development of tensile stresses in plastic concrete and hence resulting cracks on the surface of concrete. The cracking prone is aggravated when the fresh concrete is placed on the hardened concrete as repairing practice. As already mentioned, when a concrete is on a debonded surface and it has free movement, concrete does not crack. But if shrinkage of concrete is restrained, concrete susceptible to cracking. Meanwhile, the strains which usually are measured are differing from restrained strain. But there is correlation between these strains as mentioned by the authors in another study [Abbasnia , Ghoddousi and Ahmadi 2005] which is as following:

$$\varepsilon_{rc} = \varepsilon_{fc} - \varepsilon_{mc} \quad (1)$$

Where ε_{rc} is restrained strain, ε_{fc} is free strain (debonded), and ε_{mc} is measured strain.

The restrained strain can be expressed in terms of restraint factor as:

$$\varepsilon_{rc} = R\, \varepsilon_{fc} \quad (2)$$

or

$$\varepsilon_{mc} = (1\text{-}R)\ \varepsilon_{fc} \tag{3}$$

If there is free movement of the member $R=0$, and $\varepsilon_{mc} = \varepsilon_{fc}$. For a fully restrained member, $R=1$ and hence $\varepsilon_{rc} = \varepsilon_{fc}$. However, restraint is not limited to external condition, but there are sources of inner restraint in concrete too. Aggregate and reinforcing bars provide restraint of concrete displacements. The response of concrete to these restraints is inducing local stresses, thereby local micro cracks develop. There are other many factors such as environmental condition, and concrete itself affect plastic shrinkage behavior of concrete. The majority of investigation works are concrete on these variables [Ghoddousi and Raiss ghasemi 2007; Ma ,Tan and Wu 2004; Wongtanakitcharoen and Naaman 2007; Hammer 2001; Sivakumar and Santhanam 2007]. However , there are few studies on plastic shrinkage of SCC [Turcry and Loukili 2006], and behavior of SCC a repair material [Hwang and Khayat 2008]. Even, there are much limited studies on effect of embedded steel in different types of repair SCC [Khayat and Hwang 2005] .

Sule and Van Breugel [2004] have introduced "strain enhancement factor" to account for the role of reinforcement in early age cracking in high strength concrete. They found that reinforcement can induce the formation of smaller cracks. These smaller cracks can postpone the moment at which major cracks are formed. The proposed factor η_{cr} is as follow:

$$\eta_{cr} = \varepsilon_{cr,\ reinforcement}\ /\ \varepsilon_{cr,\ plain} \tag{4}$$

In which: η_{cr} = strain enhancement factor, $\varepsilon_{cr,reinforcement}$ = the cracking strain of the reinforced concrete, and $\varepsilon_{cr,\ plain}$ = the cracking strain of the plain concrete. According to proposed factor " η_{cr} ", the presence of reinforcement enables the concrete to make its pre-peak strain capacity operational so that the moment of cracking is postponed.

The purpose of the present study is to investigate experimentally the effects of restraint conditions and embedded steel on strain and cracking plastic shrinkage.

EXPERIMENTAL PROGRAMS

Substrate bases

The substrate was ordinary concrete made with 350 kg/m^3 ordinary portland cement, 710 kg/m^3 fine aggregate, and 1102 kg/m^3 coarse aggregate. The W/C ratio used was 0.55, and its compressive strength at 28 days was 22MPa. The substrate bases were 600 × 400 mm with 50 mm thickness. In one series of the bases, the surface left smooth without any roughness. To roughen the surface of the other substrate bases, dents (semi-circular notch) with three different areas provided while the concretes were in fresh state. The cross section of dents was semi-circular. The ratio of the surface area of dents to the total surface area of the slab refers to restraint index (RI). These dents provided to restrain shrinkage. Hence, three restraint indices for different degree of restraint were made. Figure 1 shows different types of RI. In one of the series slabs, a Plastic sheet was covered the base to eliminate friction between substrate and repair concrete. This considered as debonded.

Repair materials and mix proportions

In the present study, portland cement (PC) type II was used. river sand with a specific gravity of 2.60 was used as fine aggregate. Crushed limestone with maximum size of 9.5 mm and specific gravity of 2.68 was used as coarse aggregate. The mineral admixture was limestone powder (LP) with average particle size of 2 μm. The chemical admixtures were high–range water reducing admixture (HRWR). The mixture proportions of repair SCC is given in Table 1. All the mixtures have the same 0.45 w/c.

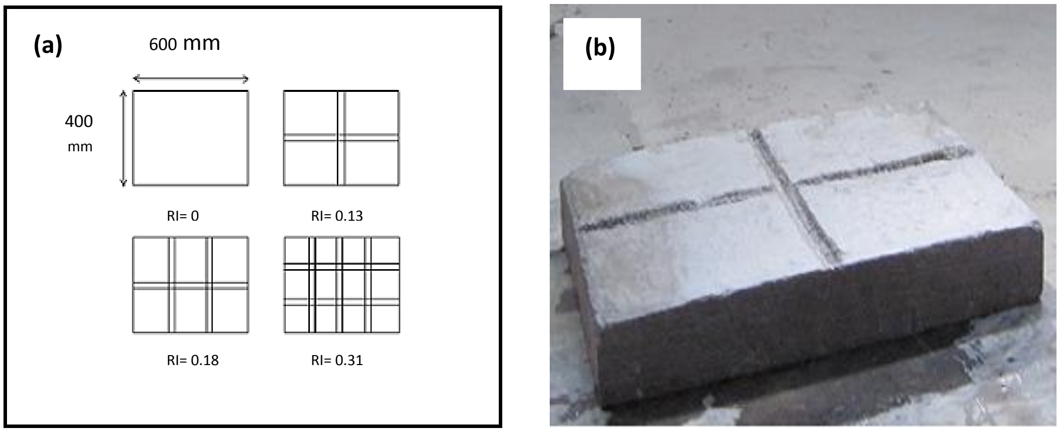

Fig. 1. (a) Plan Views of Substrate Slabs Without Dent and With Dents With Different Restraint Indices, R.I, (b) Substrate Slab at R.I=0.13

Table 1. The Mixture Proportion of Repair SCC

PC (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	LP (kg/m^3)	HRWR (% cement)
400	1190	283	212	0.6

Exposure condition

The exposure condition of the slabs was controlled to simulate hot weather. Hence a chamber was made, which equipped with heater and fan. The fan generated wind velocity of 3 km/hr and the temperature maintained at 40 ˚C. The relative humidity (RH) of the chamber was same as laboratory RH, which was between 30 to 35 %.

Placement of repair concretes

Since, differential shrinkage between substrate concrete and repair concrete may have effect on the testing results; the substrate bases were cured using wet burlap and plastic sheet for three months prior to overlay application. On the day of the test, repair concrete poured over the substrate base and finished with a steel trowel. Then, the whole base and overlay transferred to the exposure chamber. Similar series of concrete slabs as mentioned earlier (repair concretes without bars), were casted with reinforcing bars (for RI = 0.13). The configuration of the bars is two Φ16 which they were embedded in repair layer in the same directions as ride in slabs with RI = 0.13. For concrete repair 's' , Three different locations were chosen including at interface between substrate surface and repair layer (They place in rids), at middle of repair layer depth (25 mm from top of the repair surface), and at 5 mm from top of the repair surface). But, for other types of concretes, the location of bars was at 25 mm from top of the repair surface. Table 2 presents the list of slabs used in this study.

Table 2. List of Slabs

Slab no.	Restraint index (RI)	Position of steel bars
1	Debonded	-
2	0.0	-
3	0.13	-
4	0.18	-
5	0.31	-
6	0.13	At interface
7	0.13	At 25 mm from top of slab
8	0.13	At 5 mm from top of slab

Test procedures

Shrinkage test

The shrinkage was measured horizontal displacement of two plastic studs which they were specially designed and made for this purpose. The bases of studs were embedded into concrete surface which were 300 mm apart. The reflection of laser beam on the tips of studs could be observed as two black points on a wall, in front of the slab. At desire time intervals, the distance of two points on the wall was measured. By considering, the distance of the wall from studs, the horizontal deformation as plastic shrinkage (measured strain) is calculated. The test set up is shown in Figure 2.

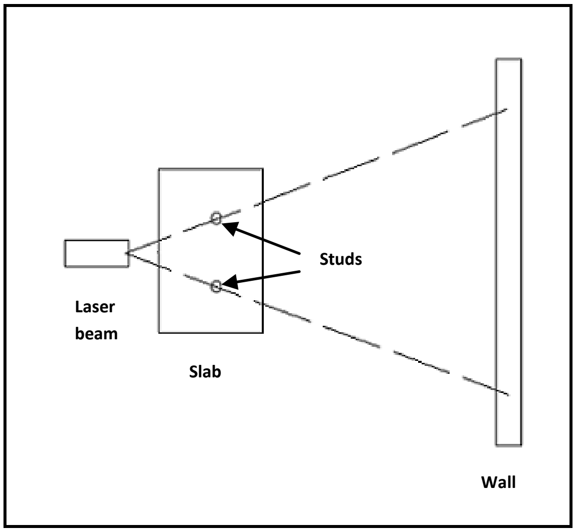

Fig. 2. Test Setup to Measure Shrinkage Strain

Cracks parameters

During the course of plastic shrinkage tests, crack width and crack length were recorded at every 20 min. interval crack width is measured using hand- held microscope with an accuracy of 0.02mm. The initial cracking time was also recorded through observation. Then, the crack parameters such as total length, total crack area, maximum and average crack width were determined. To calculate the mean crack width a total of l0 arbitrary points was chosen along the crack profile. Using mean crack width and crack length, the crack area was obtained.

RESULTS AND DISCUSSIONS

Slabs without steel bar

Free and measured plastic shrinkage

The free and measured plastic shrinkage strains of concrete S, at different restraint indices (R.I) are plotted in Figure 3. The term free shrinkage used in this study is defined as the shrinkage of the debonded overlay induced by plastic sheets. The results show that by more restraining shrinkage, the measured shrinkage decreases as expected. It is evident from the figure that the roughest surface of the substrate decreased the shrinkage strains about two times lower compared to smooth surface of the substrate (debonded), at their maximum strains.

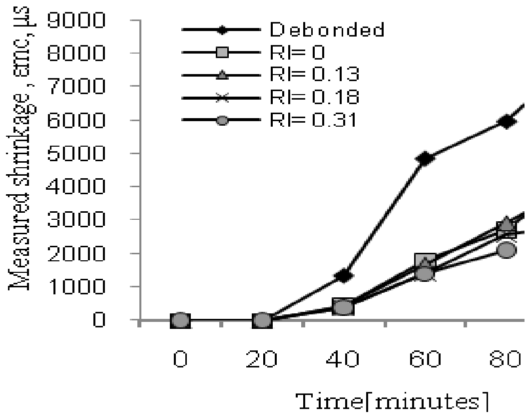

Fig. 3. Measured Shrinkage,ε_{mc}, Vs. Time of Testing For Concrete 'S' at Different Restraint Indices(RI]

Restrained plastic shrinkage

According to the Eq. 1, the restrained shrinkage is given by:

$\varepsilon_{rc} = \varepsilon_{fc} - \varepsilon_{mc}$

The calculated values of restrained shrinkage strains (ε_{rc}) Vs. Time for plane self-consolidating concrete (S) at different restraint degree (RI) are shown in Figure 4. The data in the figure indicate that with increasing RI the restrained strains are increased as expected. But, even when, the substrate is smooth (RI= 0) and no plastic sheet is provided (debonding), the strain is considerable, and reaches to about 4000 μs at 100 min. It implies that, even at very low roughness of substrate surface,significant restrained strains are induced. The calculated restraint factors (R) for concrete S at different RI Vs. time are shown in Figure 5. It is evident from the figure that, even there is no significant difference between R Values for different RI values, but the data clearly show that, at higher values of roughness index (RI), the restraint factors are also higher and vice versa. It indicates that at highest value of RI (i.e. 0.31), the R value is closer to 1, while for a fully restrained members R=1. Overall, the results show that, for all RI values, the restraint factors reduced with time, which imply that increase in restrained strains are greater that increase in free strains. In Figure 6, the variation of relative strain with time for concrete 'S' at different RI. Relative strain calculated by:

Rilative strain (RS) = (Measured strain at different RI) / (Debonded concrete strain) (4)

It is evident from the figure that, all curves have the same trend with sudden drop of RS at 40 minutes time and then sudden increase. This can be attributed to increase the amount of bleeding at that particular time, but it needs further investigation.

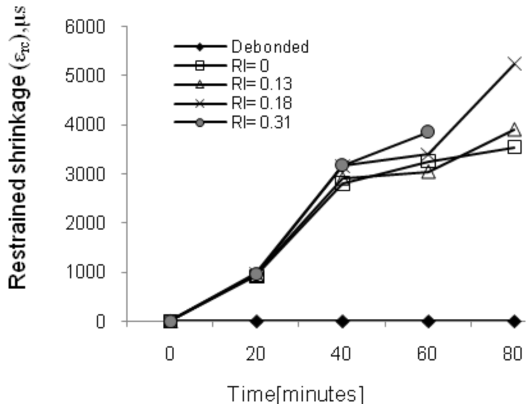

Fig. 4. Restrained Shrinkage Strain (ε_{rc}), Vs. Time of Testing For Concrete 'S' at Different Restrained Indices (RI)

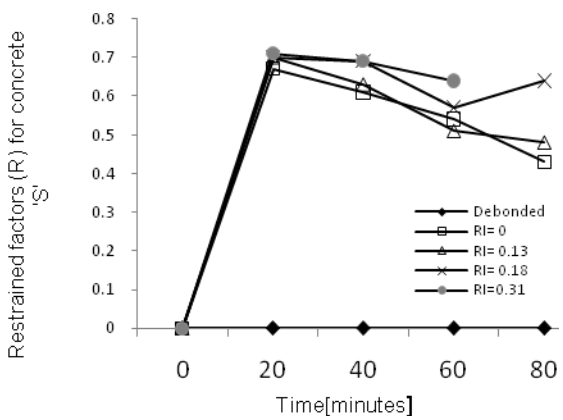

Fig. 5. Variation of Restraints Factor (R) , With Time For Concrete 'S'

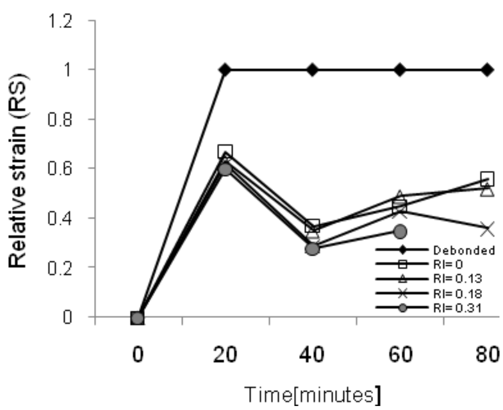

Fig. 6. Relative Strain (RS) Vs. Time For Concrete 'S' at Different RI

Crack Parameters

Table 3 compare the crack parameters of concrete 'S' at RI = 0.13 at their final state, when there was no significant change thereafter. For concrete repair layer which was debonded from substrate surface by plastic sheet (free shrinkage), crack did not appear up to 4 hours of observation. Except crack initiation time and crack length, other crack parameters including average crack width and number of cracks did not exhibit a systematic trends. However, inspection of the table reveals that there is correlation between restraint conditions and crack initiation time and crack length.

Table 3. Crack Parameters For Concrete 'S' at Different RI

Restraint condition (RI)	Crack initiation time (min.)	No. of cracks	Crack length (mm)	Average crack width (mm)	Total cracking area (mm^2)
Debonded	-	-	-	-	-
0	105	5	750	0.3	2500
0.13	95	6	760	0.3	2533
0.18	95	6	826	0.3	2753
0.31	75	6	1040	0.51	2039

Slabs with steel bars

Free and measured shrinkage

Figure 4 shows a comparison between measured shrinkage strains of concrete 'S' without reinforcing bars , ε_{mc} and with reinforcing bars, ε_{ms} at different locations in the depth of the slab. The free shrinkage strains of concrete 'S' (debonded) ε_{fc} also plotted in the figure. As mentioned earlier, until the restrained strains are not calculated, the measured shrinkage strain does not give the picture of the influencing factors on shrinkage.

Restrained shrinkage

The results of calculated restrained strains of concrete 'S' without reinforcing bars, ε_{rc} and with reinforcing bars, ε_{rs} at different locations in the depth of the slabs are plotted in Figure 5. The restrained strain of concrete without reinforcing bars, ε_{rc} calculated according to equation 2 as:

$$\varepsilon_{rc} = \varepsilon_{fc} - \varepsilon_{mc}$$

The same equation can be applied for concrete

with reinforcing bars as:

$$\varepsilon_{rs} = \varepsilon_{fc} - \varepsilon_{ms} \qquad (5)$$

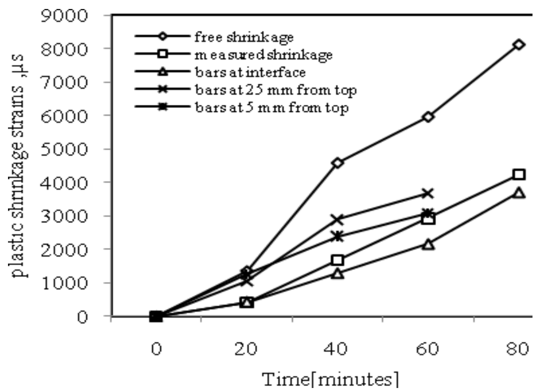

Fig. 4 Free and Measured Strains of Concrete 'S' With and Without Reinforcing Bars

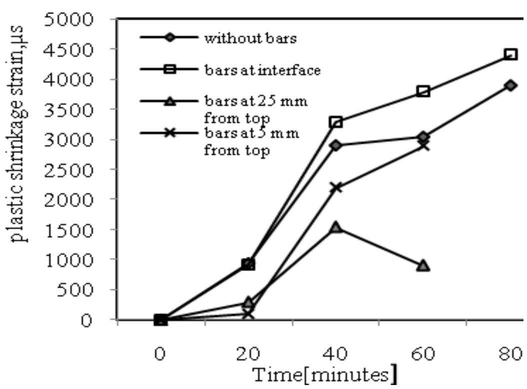

Fig. 5 Restrained Shrinkge Strains of Concrete 'S'

Reference to equation shows that the values free shrinkage of concrete without reinforcing bars , ε_{fc} were used for calculating restrained strain of concrete with reinforcing bars, ε_{rs}. The purpose was to adopt the same base for calculating the restrained strains, ε_{rc} and ε_{rs} . Inspection of Figure 5 reveals that, when the reinforcing bars are located at interface between substrate and repair layer, there is no significant difference between ε_{rc} and ε_{rs}. The maximum difference is about 600 µs, and the restrained strains of concrete with bars are higher than concrete without bars. However, when the bars are located at 25 mm and 5 mm from top of the slab surface, restrained strain of the slab with reinforcing bars, ε_{rs} were smaller than plain slab without bars $\varepsilon_{rc.}$. According to sule and Breugel [2004], the strain enhancement factor, η can be expressed as (with this study notations):

$$\eta_{mean} = \varepsilon_{rs} / \varepsilon_{rc} \tag{6}$$

Where, ε_{rs} and ε_{rc} are strains at pre-cracking. Hence, for bars located at interface, 25 mm, and 5 mm from top, η are 1.3, 0.3 and 0.7 respectively. The results indicated that , when the bars are located at interface, a small amount improvement in strain capacity (η >1) can be achieved . But for other locations of the bars, there is no improvement (η <1). Overall, these results show that, while the bars are located at interface, they act as additional source of restraint. This deduction was verified by making a slab in which a rigid plastic bars embedded in concrete at interface instead of steel bars in the study. The restrained strains of concrete and initiation time of cracking were similar to results obtained with steel bars. Meanwhile, when the bars were located at 25 mm and 5 mm from top of slab, domination of plastic settlement deformation instead of plastic shrinkage observed. This deduction is discussed with more details later in this paper.

Crack parameters

Table 4 presents crack parameters for concrete ‘S’ without reinforcing bar and with reinforcing bars at different Locations. The slabs without bar and with bar at interface, exhibited random cracks, but the slabs with bars at 25 mm and 5 mm from top surface cracked either random pattern or wall-defined pattern along the directions of bars (Figure 6). The pattern of cracks reveals that when the bars are located near the surface, plastic settlement is dominating mechanism over plastic shrinkage.

Table 4 Cracks Parameters for concrete 'S' at RI = 0.13

Type of slab	Crack initiation time (min.)	No. of cracks	Cracks Length (mm)	Average crack width (mm)	Total cracking area (mm^2)	Crack pattern
Without bar	95	6	760	0.3	2533	Random
bars at interface	80	7	870	0.27	3222	Random
bars at 25 mm from top	65	5	1200	0.59	2033	Random and on bar
bars at 5 mm from top	65	3	1300	0.52	2500	on bar

CONCLUSIONS

The following general conclusions can be drawn from the study provided in the paper:

- The more roughness in the surface of substrate (more restraints) induced higher values of restrained strain in repair SCC. This conclusion was supported by crack measurement. There was direct correlation between the crack initiation time and restraint conditions. The higher restraint index reduced the crack initiation time.

- Single reinforcing bar with relatively large diameter did not improve plastic shrinkage behavior, even it was source of crack due to plastic settlement.

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