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Prediction of restrained shrinkage based on restraint factors in patching repair mortar

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Abstract

Shrinkage of repair material, especially in patching repairs, is the major factor inducing cracking in concrete repairs. Induced cracks in repair materials are due to restrained shrinkage. Although in usual practice, the free shrinkage of the repair mortar is measured, in reality, cracking is not due to free shrinkage. It is well known that cracking is due to restrained shrinkage. It is very hard to measure the restrained shrinkage; therefore, to overcome this problem a restraint factor (R) is used to modify the free shrinkage and come up with the restrained shrinkage. The restraint factor is influenced by the surface and boundary condition.

In this study, the restraint factor for patching repair with different boundary conditions (with eaves and without eaves) and surface condition (rough and smooth) of the substrate concrete is investigated.

The results show that the restraint factor R lies between 0.1 and 0.94; with an increase of restraint, the restraint factor is increased. In situations with a high level of restraint (eaves at the perimeter and a rough surface of substrate), the average R is 0.83. while with a low level of restraint (without eaves at the perimeter and a smooth surface of the substrate), the average R is 0.22.

Keywords: Aging; Shrinkage; Strain effect; Concrete; Restraint factor

1. Introduction

Drying shrinkage of repair materials is the major problem of concrete repair. In patch repairs, the existing substrate concrete restrains the shrinkage of the repair mortar and this shrinkage of the repair mortar under restraint is termed restrained shrinkage. If there is no restraint, the shrinkage of the repair material is referred to as free shrinkage and does not induce any stress in the repair material [1].

In reality, the measured deformation of restrained shrinkage is the actual strain ε_a, and stresses in the element are proportional to the difference between the free shrinkage ε_f and the measured shrinkage ε_a, and not to the measured shrinkage itself. In other words,

$$\varepsilon_r = \varepsilon_f - \varepsilon_a$$

where ε_r is the restrained strain. It is also possible to express the restrained strain in terms of a restraint factor R in the form

$$\varepsilon_r = R\varepsilon_f \quad (1)$$

Or

$$\varepsilon_a = (1 - R)\varepsilon_f \quad (2)$$

For a completely free member $R=0$ and hence $\varepsilon_r=0$ and $\varepsilon_a=\varepsilon_f$, while for a fully restrained member, $R=1$ giving $\varepsilon_r=\varepsilon_f$ and $\varepsilon_a=0$.

In the literature, the restrained shrinkage in repair materials has been investigated [2,5], but there exist no widely accepted relationship between the measured shrinkage and the restrained shrinkage, especially under different conditions of restraint in patch repair. Free shrinkage can be monitored by measuring the length change according to ASTM C 157-93 [3], but the actual shrinkage of a repair mortar is related to the restrained shrinkage.

Poston et al. [4] conducted a ring-type test to evaluate the restrained shrinkage or cracking potential of the concrete

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repair material. Although this type of restrained shrinkage provides useful information about the time to cracking of concrete, this test does not indicate a correlation with free shrinkage.

The results obtained by Poston et al. [4] showed that there is a relation between the values of free shrinkage and the time of cracking from the ring test. However, the ring test also does not simulate the real restraint condition of the substrate. As the surface roughness changes, the value of restrained shrinkage change also.

The significance of the present investigation is to find the correlation between free shrinkage and restrained shrinkage of repair mortar. The effect of surface condition (rough and smooth) and boundary condition (with eaves and without eaves) of the substrate concrete on the measured shrinkage is investigated and the restraint factor R is predicted.

2. Experimental program

The experimental program, mixture properties and the test method is summarized as follows.

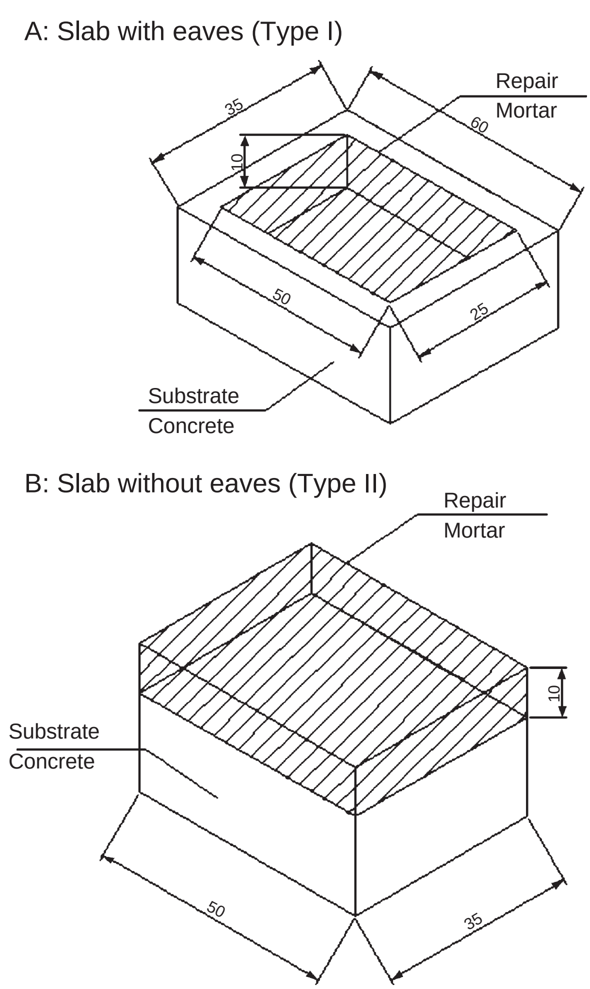

Fig. 1. Boundary condition between substrate concrete and repair mortar.

Table 1
Boundary and surface condition of slabs

Restraint type	Boundary condition	Surface condition
1	With eaves (I)	Rough
2	With eaves (I)	Smooth
3	Without eaves (II)	Rough
4	Without eaves (II)	Smooth

2.1. Materials and mixes specification

The cement for the substrate concrete and the repair mortar was ordinary portland cement. The coarse and fine aggregates were crushed, and the maximum size of coarse aggregate was 10 mm. The fine aggregate grading complied with the grading of ASTM C33 [6].

The base concrete mixes consisted of 1:3:3.5 cement/sand/gravel, respectively (proportions by weight). The cement content was 325 kg/m^3 and the water/cement ratio (w/c) was 0.55. The repair mortar mixes consisted of 1:3 cement/sand. The cement content was 450 kg/m^3 and water cement ratio (w/c) was 0.30. In the mortar mixes, a superplasticizer was used to maintain a workability suitable for trowel-applied repair.

2.2. Specimen preparation and curing

To measure the restrained shrinkage, two types of slabs were prepared (Fig. 1). Type (I) were with eaves. To provide end restraint, type (II) slabs were cast without eaves around the perimeter (eaves dimension were $50 \times 25 \times 10$ mm).

Both types of slabs were prepared with two different surface conditions, rough and smooth with the roughness

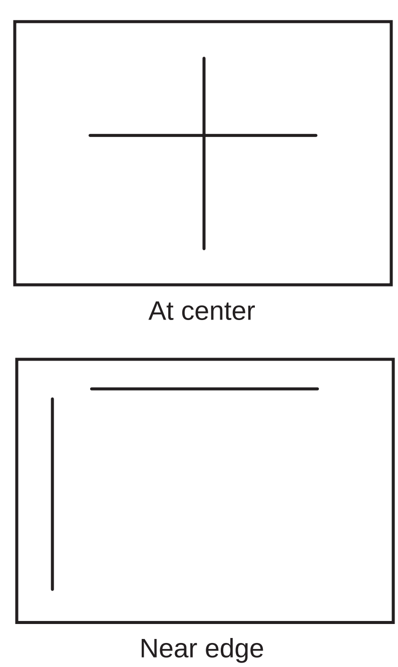

Fig. 2. The locations of Demec points.

Table 2
Free shrinkage and actual shrinkage under different restraint conditions (micro strain)

Time[a] of test (day)	Position		
	Free shrinkage	At near edges	At center
(A) With eaves—rough			
3	270	125	95
10	420	282	235
20	640	360	330
40	720	450	415
60	835	490	460
(B) With eaves—smooth			
3		217	190
10		380	315
20		450	420
40		542	510
60		570	550
(C) Without eaves—rough			
3		20	17
10		80	72
20		170	140
40		205	175
60		220	200
(D) Without eaves—smooth			
3		60	42
10		185	150
20		280	230
40		330	300
60		365	360

[a] Time: the time after applying the repair mortar on substrate concrete.

index equals about 6 and 1, respectively (EN 1766:2000 [9]). Hence four types of slabs with different boundary and surface condition were tested as listed in Table 1.

The cast substrate slabs were kept in laboratory condition and covered with burlap and plastic sheet for 24 h. After the moulds were removed, the slabs were cured under the same condition as above for a further period of 4 days. Then they were exposed to laboratory condition (25±5 °C 35±5% RH) for 40 days. At this time the repair mortars were applied on the surface of the slabs with a 100-mm thickness. The surfaces of the repair mortars was kept covered with damp burlap and plastic sheet for 4 days, and then they were exposed to laboratory condition. These specimens were used for restrained shrinkage measurement.

Concrete and mortar cubes were also prepared (10 × 10 × 10 cm) for measuring the compressive strength. The cube specimens were kept in standard condition (ASTM) for 28 days. The compressive strength of the concrete was 31 MPa and of the mortar was 42 MPa.

The unrestrained or free shrinkage of the repair mortar was measured by using cylindrical specimens (75 mm diameter and 285 mm height). These specimens cured and exposed in same condition as mentioned for slabs.

2.3. Shrinkage testing procedure

Free shrinkage of the repair mortars was measured using two cylindrical specimens. At the first day of exposure to laboratory condition, Demec points were attached to the curved surface of each cylinder across a length of 200 mm as described in ACI 209 R-94 [7].

Restrained shrinkage of the repair mortar was carried out using slabs. At the first day of exposure to laboratory condition, Demec points were attached to the surface of each slab across a length of 200 mm. Locations of the Demec points are illustrated in Fig. 2. As shown in Fig. 2, restrained shrinkage was measured in two directions perpendicular to each other, near the edges of the slabs and at the center of the slabs.

3. Results and discussion

The free shrinkage results of the repair mortar are given in Table 2; this table also shows the actual shrinkage (measured) ε_a. The effects of different types of restraint (based on Table 1) on actual shrinkage can also be seen in this table. All results in Table 2, are average results of two specimens. Strains near the edges of the slabs are the average of strains near the edges perpendicular to each other.

The highest strain near the edge was obtained in the slab with a smooth surface and with no eaves (type 4 restraint); the lowest strain near the edge belongs to the slab with a rough surface and with eaves (type 1 restraint).

Similar results were also obtained for strains at the center of slabs. Hence, it can be concluded that increasing restraint in the substrate causes a reduction of the measured or actual shrinkage strain. This is to be expected, because with

Table 3
Restrain shrinkage strain at different restraints conditions

Time of test (days)[a]	Restrain shrinkage ε_r for different restraints condition based on Table 1 (microstrain) (restrain condition type as in Table 1)							
	Type 1		Type 2		Type 3		Type 4	
	At near edges	At center	At near edges	At center	At near edges	At center	At near edges	At center
3	253	250	228	210	145	175	53	80
10	348	340	270	235	138	185	40	105
20	500	470	410	360	280	310	190	220
40	545	515	420	390	270	305	178	210
60	635	615	475	470	345	375	265	285

[a] Time: the time after applying the repair mortar on substrate concrete.

Table 4
Restraint factor in different restraint condition

Restraint condition	Position	Restraint factor (*R*)	Average of *R*
1 (highest)	At near surface	0.76–0.94	0.83
	At center	0.72–0.93	
2 (high)	At near surface	0.57–0.83	0.69
	At center	0.54–0.78	
3 (low)	At near surface	0.38–0.53	0.52
	At center	0.42–0.56	
4 (lowest)	At near surface	0.10–0.32	0.22
	At center	0.25–0.34	

increasing restraints the restrained shrinkage ε_r will be increased [8].

The results in Table 2 also show that for slabs with eaves, the actual shrinkage is greater at the center of slabs as compared to the edges, but for the slabs with no eaves the shrinkage at the center of the slabs is less than near the edges.

Table 3 shows the restrained shrinkage ε_r, which is calculated from the difference between the free shrinkage ε_f and the actual shrinkage ε_a.

Comparing the restrained shrinkages presented in Table 3, it can be seen that with increasing restraint, the restrained shrinkage is increased. In other words, restrained shrinkage under restraint type 4 is much lower than under restraint type 1.

Based on Eq. (1), the restraint factor *R* at different time of testing was evaluated, as presented in Table 4. Both ε_r and ε_f change proportionally with time, but since their variation is not the same, the restraint factor *R* changes with time. The values of *R* are between 0.10 and 0.94. The lower values of *R* belong to lower restraints and higher values of *R* belong to higher restraints. In other words, when boundary and surface conditions of the slabs induce restraints from the lowest level to the highest level, the average value of *R* are 0.22, 0.52, 0.69 and 0.83, respectively.

The variation of *R* is independent of the restraint condition when the surface is smooth, but when the surface is rough the restraint factor *R* depends considerably on the existence of restraint. This dependency is proportional (i.e. with an increase of restraint, *R* increases).

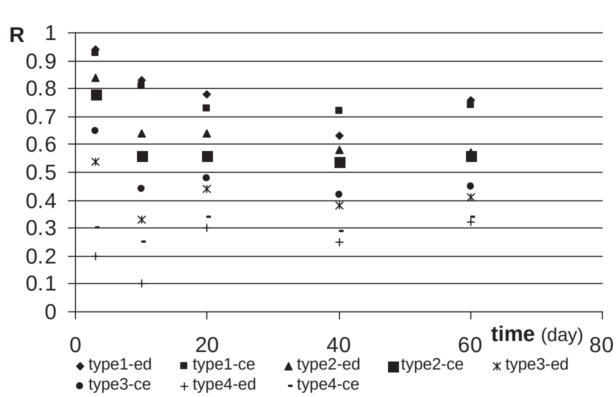

Fig. 3. The effect of time variation over the *R* at near edges.

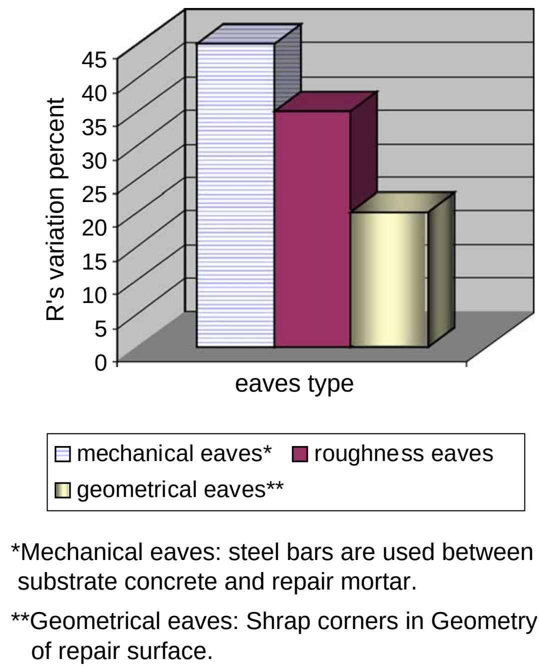

Fig. 4. The effect of mechanical eaves, roughness eaves and geometrical eaves on *R*.

It should be noted that the effect of surface condition on *R* is more evident at earlier age of the mortar, and as the age increase the variation of *R* decrease. Therefore the value of *R* reaches a constant value at late ages (Fig. 3).

To check the accuracy of the proposed method, the experimental results were compared with those obtained from Eqs. (1) and (2) at the time of first cracking. The result of the comparison show that the method provides a good estimation of the time of first cracking of the specimen (having *R* and measuring free shrinkage, the tensile stress of the specimen can be calculated and compared with tolerable limits).

According to importance and having effect on *R*, mechanical eaves, roughness eaves and geometrical eaves have higher effects respectively (Fig. 4).

4. Conclusion

Based on the results obtained in this investigation the following can be concluded.

The measured restrained shrinkage of a repair mortar is the actual shrinkage. The restrained shrinkage can be calculated, using the difference between the free shrinkage and the actual shrinkage. When the free shrinkage is measured by using a restraint factor, it is possible to calculate the restrained shrinkage and hence there is no need to measure it.

The restraint factors obtained are between 0.10 and 0.94, which is related to different restraint conditions. Restraint factors are affected by time of exposure. In the lowest induced restraint, the average value of R is 0.22 and in the highest induced restraint, the average value of R is 0.83.

The restraint factor R is a time-dependent parameter. The variation of R (for mortar) with time at early ages is high, but will decrease over time.

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