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Behavior of bonded concrete overlays under restrained shrinkage

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ABSTRACT: Dimensional compatibility between repair concrete and substrate is one of the important factors in cracking or delamination of bonded concrete overlays. This paper presents the nonlinear finite element analysis of bonded concrete overlays to investigate the cracking tendency of them under restrained shrinkage. Four different mix designs were chosen as a repair concrete when some part of cement is respectively replaced by silica-fume (SF), ground granulated blast-furnace slag (GGBS) and a combination of SF and GGBS (ternary system). The new method was used to determine the restrained shrinkage values by free shrinkage measurements. Results showed that among the investigated mixtures, the ternary system had the best performance as a repair material for overlaid slabs.

1. INTRODUCTION

Surface cracking and interface delamination in bonded concrete overlays have recently become of great concern and every year in North America, billions of dollars are spent to repair bridge deck delaminations (Lachemi et al. (2007)). In repair concretes, restraint from the surrounding structure prohibits the concrete from moving freely and then tensile stresses are set up in the repair layer together with the shear and peeling stresses at the interface (Rahman et al. (2000)). The level of these stresses depends on the various parameters such as degree of restraint, material stiffness, shrinkage rate and the amount of stress relaxation (Yang et al. (2000)). Also, the thickness and dimensions of overlay and substrate are effective in changing the stress distribution in repair system. If the tensile stress exceeds the tensile strength of repair material or the stresses at the interface exceed the bond strength, cracking or delamination will occur in patch repair, respectively.

While the roughness of the interface is constant, the stiffness and dimensions of overlay have a direct influence on the behavior of repair system and can control the stress distribution. With increasing the length of repair concrete, the tensile and shear stresses increase (Silfwerbrand(1997)) and with increasing the thickness of it, the tensile stress decreases (Beushausen(2006)). McDonald et al. (2002) proposed that for reducing the risk of cracking and delamination in patch repairs, using the repair materials with low stiffness will be suitable. However, Mangat and O'Flaherty (1999-2000) reported that the patch repair should have a greater elastic modulus than the substrate to display an efficient interaction with structure and be more effective in attracting the external loading in long-term.

Although the cracking of repair system is not due to the free shrinkage of repair materials, but low values of free shrinkage and expansion of repair materials at early ages can reduce the induced stresses in repair concrete. Decter (1999) suggested that to ensure the durability of repaired areas, cementitious repair mortars must exhibit low shrinkage and low permeability as well as the compatibility with the substrate. Brown et al. (2007) commented that the materials used for overlays should have low free shrinkage strains, low initial modulus of elasticity, high creep potential and high early tensile strength. Yuan and Marosszeky (1994) developed an analytical model for restrained shrinkage of repaired reinforced concrete members and concluded that the high shrinkage values can lead to cracking in patch repair and additional tensile strains in substrate. However, the expansion of repair material and reduction of tensile stresses due to the creep effect can delay the formation of cracking.
In repair construction, different mineral admixtures are often used due to various purposes such as improving the mechanical properties and reducing the heat of hydration and permeability. In high performance concrete (HPC), the use of pozzolanic materials such as silica fume (SF) and slag (GGBS) is very usual. Whiting et al. (2000) studied the effects of different contents of SF on drying shrinkage and cracking tendency of concrete bridge decks. They concluded that the cracking tendency of concrete is affected by SF only when concrete is not properly cured. Jianyong and Yan (2001) concluded that drying shrinkage is greatly reduced when GGBS is used as a replacement of cement. Li et al. (2002) studied the effects of SF, GGBS and the combination of SF and GGBS (ternary) on drying and autogenous shrinkage of concrete. They concluded that the ternary mixture had the minimum drying shrinkage and the maximum autogenous shrinkage, with respect to the binary mixtures.
In this study, four different mix designs were chosen as a repair material when some part of the cement was respectively replaced by silica fume (SF), ground granulated blast-furnace slag (GGBS) and a combination of SF and GGBS (ternary system). Then, the cracking tendency of these materials due to the restrained shrinkage was investigated by the numerical modeling of the repair system.

2. NUMERICAL SIMULATION

2.1 Finite element model

Finite element program (ANSYS) was used to simulate the 3-dimensional modeling of bonded concrete overlay (Fig. 1). It is assumed that the bottom surface of substrate is fixed to the ground and it hasn't any motion.

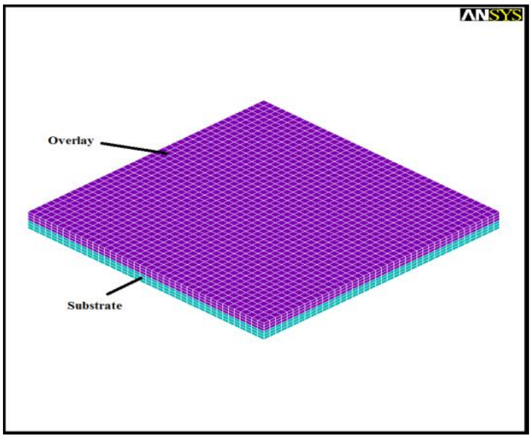


Fig. 1 Modeling of bonded concrete overlay in ANSYS

The width and length of all slabs were assumed 200 cm. The thickness of overlay and substrate is assumed to 75 mm (both). It should be noted that the cracking tendency of repair concretes under differential shrinkage at 28 days is studied in this paper.

2.2 Properties of repair materials and substrate

Four groups of Repair materials were designed: C-C, C-SF, C-S, C-SFS as the repair concrete and substrate concrete. Mixture C-C is plain repair concrete; In the c-SF Concrete, SF is replaced cement by 7.5% of cement weight; In Concrete C-S, GGBS replaced cement by 25% of cement weight while in Concrete C-SFS, 32.5% of cement was substituted by GGBS (25% of cement weight) and SF (7.5% of cement weight). Non pozzolanic material is used in substrate concrete. The properties of repair concretes and substrate are listed in table 1.

Table 1. Properties of materials

	C-C	C-SF	C-S	C-SFS	Substrate
Compressive strength (MPa)	51	59	58	70	61
Tensile strength (MPa)	3.8	4.3	4.8	5.2	4.5
Bond strength (MPa)	1	1.5	0.9	1.5	0.8
Modulus of elasticity (GPa)	37	38	37	39	36
Free shrinkage (micro strain)	381	433	317	296	-

It should be noted that free shrinkage test was conducted according to ASTM C157 (98). The test method involves measuring the length change of 100mm×100mm×500mm concrete prisms. After fabricating, these specimens were covered with wet burlap for 24 hours; and then the specimens were removed from the steel molds. Initial measuring of the specimens was taken by a comparator regarding to ASTM C490 (98). After that the specimens were placed in the curing water at 23Cº ± 1Cº for 6 days and length changes were measured every two days in the curing time and then removed and placed in a controlled environment of 25Cº ± 1Cº and 50% ± 2 RH. The bond strength tests were done on the 15×15 cubic with Bi-surface shear method (Momayez et al. (2004)). In all of the shear specimens, the roughness of the substrate surface is visually kept almost constant in a middle range of 4-5 mm.

2.3 Concrete modeling

An eight-node solid element (solid65) was used to model the concrete materials. The element is capable of plastic deformation, cracking in three orthogonal directions and crushing. In this study, the crushing capability of the concrete element is turned off to avoid the convergence problems. So, the cracking of concrete controls the failure of the models. It is assumed that the concrete is a homogeneous and initially isotropic. The compressive uniaxial stress-strain relationship for the concrete model was obtained using the following equations to compute the multilinear isotropic stress-strain curve MacGregor(1992)). The multilinear isotropic material uses the von- Mises failure criterion along with the Willam and Warnke (1975) model to define the failure of the concrete. Figure 2 shows the compressive uniaxial stress-strain relationship that was used in this study.

$$f = \frac{E_c \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \quad (1)$$

$$\varepsilon_0 = \frac{2 f_c^{'}}{E_c} \quad (2)$$

It should be noted that as shown in figure 2, the first point is assumed as $0.3 f_c^{'}$ for calculating the linear part. Poisson ratio of concrete is assumed to be 0.2 for both repair concretes and substrate. Shear transfer coefficient (β_t) represents the conditions of the crack face. The value of β_t ranges from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer). But based on the recommendations (Bangash (1989) and Hemmaty (1998)) the values between 0.05 and 0.25 should be considered as a value of β_t . In this study, the coefficient for open cracks (β_t) was set to 0.25 and 0.15 and the coefficient for closed cracks is assumed to be 0.7 and 0.55 for substrate concrete and repair material, respectively. The density for the concrete was not added in the material model.

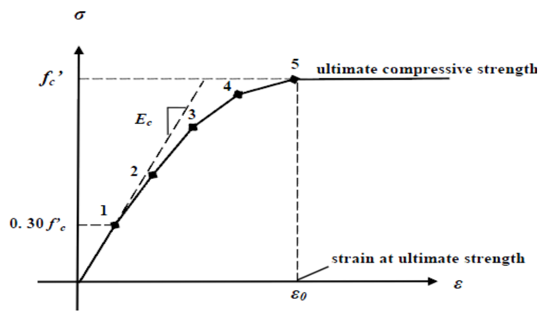


Fig. 2 Simplified compressive uniaxial stress-strain curve for concrete

2.4 Contact behavior

For proper assessment of contact behavior between repair material and concrete substrate, the contacts parameters should be determined from bond strength tests such as pull off test, direct tension test, direct shear test, slant shear test and etc. In this study, perfect bonding between repair materials and substrate is assumed

2.5 Shrinkage gradient at the depth of overlay

In this investigation, the restrained shrinkage of overlaid slabs for investigated mixtures wasn't measured by experiment. However, the free shrinkage values exist and it is possible to calculate the gradient of restrained shrinkage in the depth of overlay by free shrinkage values. To do this, the rational method is introduced in the following:

- The gradient of shrinkage can be determined by the following equation (Kim and Lee (1998)):

$$\varepsilon_{sh}(y,t) = a e^{b \frac{y}{\sqrt{t}}} \quad (3)$$

where a and b are regression parameters that depend on the mixture proportions and obtained by experiments and y is distance from the top surface of overlay. If we define the shrinkage values at the top surface of overlay and at the interface, by applying the boundary conditions, these parameters can be determined.

- The restrained shrinkage on the top of the surface of overlay can be defined by the following equation (Abbasnia et al. (2005)):

$$\varepsilon_a = (1-R)\varepsilon_f \tag{4}$$

where R is the restraint factor that depends on the surface roughness and restraint conditions and ε_f is the free shrinkage of concrete.

- The restrained shrinkage a t the interface can be calculated by the following equation (Beushausen and Alexander (2006)):

$$\varepsilon_{\text{interface}}(t) = \psi(t,t_0).\varepsilon_f.\frac{1}{1+\frac{E_s}{E_O(t)}.C_\varepsilon + 0.8.\varphi_s(t,t_0)}.(1+0.8.\varphi_s(t,t_0)) \tag{5}$$

where $\psi(t,t_0)$ is the overlay relaxation coefficient, E_s is elastic modulus of substrate, $E_O(t)$ is the elastic modulus of overlay at time t, C_ε is the coefficient denotes the combined influences of member dimensions and strain profiles in substrate and overlay and $\varphi_s(t,t_0)$ is creep factor of substrate.

The boundary conditions for solving the equation (3) are:

1) If $y = 0\,(top\ surface) \Rightarrow \varepsilon_{sh}(y,t) = \varepsilon_a$
2) If $y = d\,(\text{int}\,erface) \Rightarrow \varepsilon_{sh}(y,t) = \varepsilon_{\text{interface}}$

where d is the thickness of overlay. After applying the above boundary conditions to equation (3), the restrained shrinkage at the depth of overlay can be determined by following equation:

$$\varepsilon_{sh}(y,t) = \varepsilon_a.\left(\frac{\varepsilon_{\text{interface}}}{\varepsilon_a}\right)^{\frac{y}{d}} \tag{6}$$

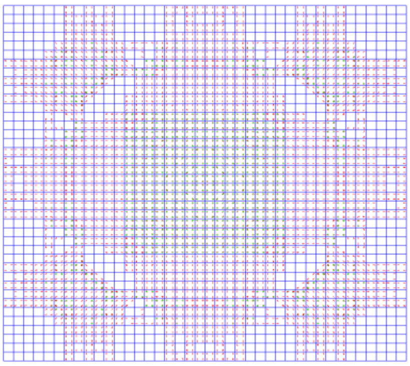
3. RESULTS AND DISCUSSIONS

By assuming $\psi(t,t_0) = 0.55$, $C_\varepsilon = 1$ [23], $R = 0.37$ for center of slab with moderate roughness (based on the average values of restraint factor for rough and smooth surfaces) and calculating the $\varphi_s(t,t_0)$ from CEB 90-99 equation (CEB (1999)), the restrained shrinkage for various mixtures can be determined from table 2.

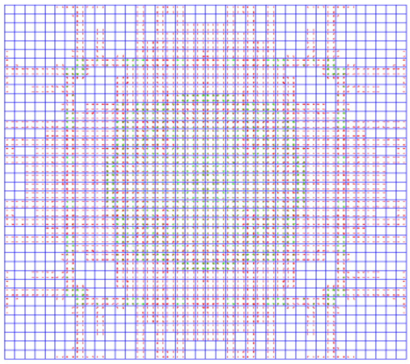
Table 2. Restrained shrinkage equations in the depth of overlay

	C-C	C-SF	C-S	C-SFS
Restrained shrinkage (micro strain)	$240\times(0.61)^{\frac{y}{d}}$	$273\times(0.62)^{\frac{y}{d}}$	$200\times(0.62)^{\frac{y}{d}}$	$186\times(0.62)^{\frac{y}{d}}$

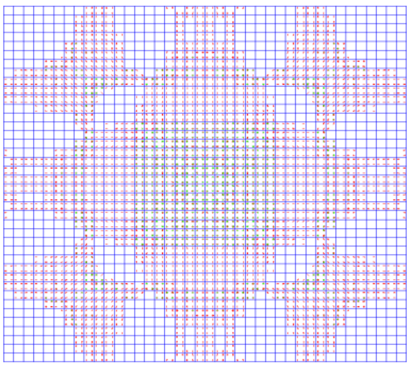
Figure 3 shows the cracking tendency of overlaid slabs for investigated mixtures in moderate thickness. As seen in the figure, the ternary mixture (SF+S) had the lowest potential of cracking with respect to the others. This is due to the high tensile strength and low shrinkage values of this mixture as a repair concrete that can reduce the potential of cracking in repair system. Also, the elastic modulus of repair concrete with respect to the substrate can effect on the distribution of stresses and formation of cracks. Concrete mix designs C-C and C-SF had the high probability of cracking at short term. So, it seems that the use of fibers for reducing the restrained shrinkage values and increasing the tensile strength of concrete is necessary in these mixtures as a repair concrete. Increasing the age of curing can also be used as a solution for avoiding the cracking of these concretes.



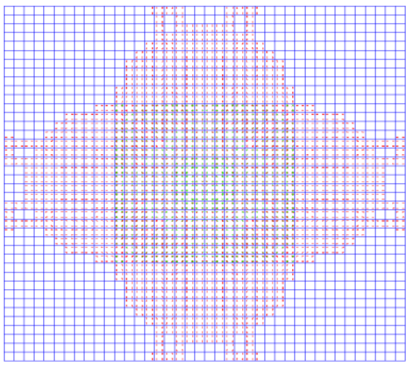
C-C



C-SF



C-S

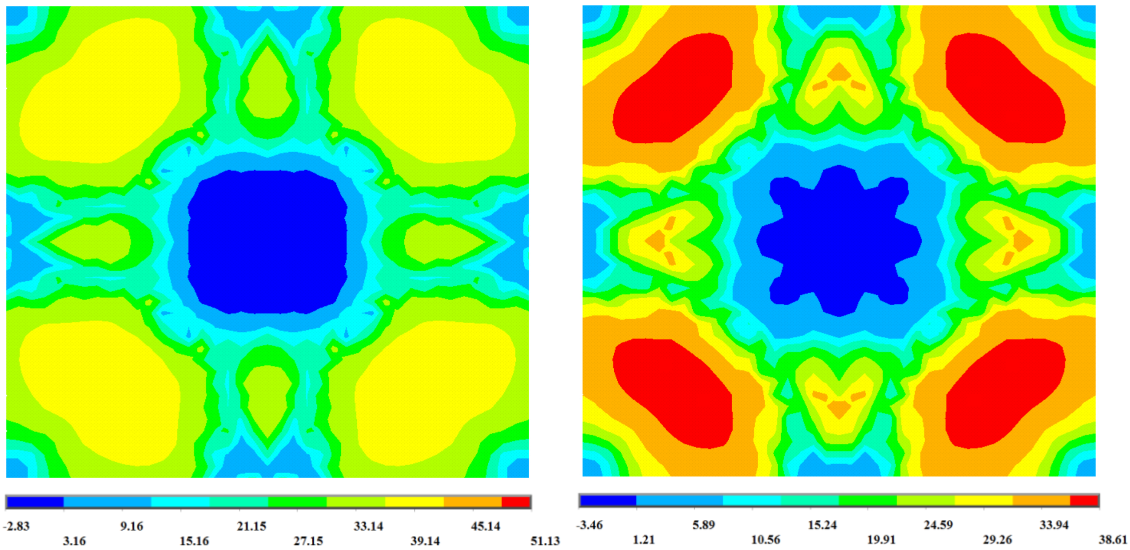


C-SFS

Fig. 3 Crack distribution for various overlays

From the results, the concentration of cracks at the center of slabs is higher than the edges. Because as expected, the maximum values of tensile stress occurs at the center of slab and so the cracking tendency for the center of slab is higher than the edges. However, the debonding tendency for the edges is higher. It should be noted that in this study, free shrinkage values was used for calculating the restrained shrinkage in the depth of overlay. So, for accurate assessment of the overlaid slabs under restrained shrinkage and considering the effects of overlay thickness,

direct measurement of restrained shrinkage in the laboratory is necessary.Based on the results of this study, no cracking formed in the substrate. However, the cracks in the depth of overlay was observed.
Figure 4 shows the principal stress (kg/cm2) distribution in overlaid slabs for C-S and C-SFS mixtures in cracked condition. The stress distribution in the overlays depends on the stiffness of materials, overlay thickness and restrianed shrinkage values in the depth of overlay.By finite element analysis of overlaid slabs, the role of these parameters in the stress distribution and crack formation can be considered.



C-S C-SFS

Fig. 3 Principal stress distribution in two different overlays

4. CONCLUSIONS

The new method by combination of three equations was used for determining the restrained shrinkage values from free shrinkage measurements including the role of free shrinkage, surface roughness of substrate, overlay relaxation and stiffness of substrate and overlay. Then, nonlinear finite element analysis was used to determine the cracking tendency of four different mix designs. Based on the results of this study among the investigated overlays, C-SFS had the lowest cracking tendency, due to the low free shrinakge and high tensile strength values. In all cases, the concentration of cracks at the center of overlay was high. In concrete mix desing C-SF with silica fume pozzolan, the cracking tendency was so high. So, it seems that in the mixtures which made by this pozzolan, the use of fibers or incresing the curing time or overlay thickness is neccessary for avoiding the cracking in early ages. Cracks also formed in the depth of overlay.However, no cracks was observed in the substrate.

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