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Restrained shrinkage cracking of self-consolidating concrete roads

https://doi.org/10.1515/secm-2017-0146
Received June 14, 2017; accepted September 18, 2017; previously published online November 28, 2017

Abstract: The present study is dedicated to investigate the liability of continuously reinforced concrete pavement (CRCP) cast with self-consolidating concrete (SCC) to restrained shrinkage cracking and the values of restraint stresses in these pavements. SCC, which is becoming increasingly popular due to its several superiorities over conventionally vibrated concrete (CVC), has higher amounts and rates of shrinkage compared to CVC. The higher risk of restrained shrinkage cracking of SCC is a great cause of concern in pavement construction as the penetration of water, chemicals, and salts increases the risk of corrosion of reinforcement. In the present study, an analytical restraint stress expression was developed for typical CRC pavements by modifying the restraint stress equation developed previously for RC beams. Using this equation, the restraint stresses induced to the longitudinal reinforcement by the rigid pavement, cast with CVC or SCC, were calculated for eight different example sections. These restraint stress values were found to reach up to 50% of the limit stresses of bars, allowed by the design guidelines, when the pavement is cast with SCC. The amounts of longitudinal reinforcement used in typical CRCP roads were found to be more critical when the pavement is cast with SCC.

Keywords: concrete roads; restraint stress; self-consolidating concrete; shrinkage cracking.

1 Introduction

The rigid pavements offer several advantages in road construction, including, but not limited to, the higher strength and durability, with regard to flexible pavements. The use of reinforcement in rigid pavements also increases the service lives of the roads by resisting the tensile stresses in the pavements originating from various sources (shear, bending, temperature changes, restrained shrinkage, etc.). Besides their several advantages, concrete roads have major drawbacks, including the high initial construction and surface repair costs, noise pollution, and presence of cracks.

Among the various types of rigid pavements, the continuously reinforced concrete pavements (CRCPs) are generally preferred in heavily congested routes with high traffic load. CRCPs are considered the type of pavement requiring the least maintenance cost if designed and constructed properly [1]. CRCP roads possess limited number of expansion and contraction joints and considerable ratios of longitudinal reinforcement, which reduce the need for transverse joints. The longitudinal reinforcement in CRCPs limits the widths of the transverse cracks in the pavement. However, the reinforcement constitutes a major source of restraint to free the shrinkage of the pavement and increases the tendency of the pavement to restrained shrinkage cracking. Choi et al. [2] stated that “hydration cracking at early hydration state of concrete, the plastic shrinkage cracking, the environmental cracking caused by thermal changes at the top of the pavement, the drying shrinkage cracking according to the hardening of concrete, and the cracking caused by the long-term process of alkali-silica reaction” are the major types of cracking in rigid pavements. Not only reinforcement in the pavement but also the shoulders, the base, and the subbase courses, the tie bars and dowel bars connecting the adjacent concrete slabs are among the major sources of restraint to free shrinkage deformations in rigid pavements, which trigger “the plastic shrinkage cracking” and “the drying shrinkage according to the hardening of concrete”.

Several studies were carried out to investigate the mechanisms of restrained shrinkage cracking in rigid pavements, particularly in CRCPs, and to offer effective types of crack control to limit the widths of the cracks. Based on the width measurements of numerous cracks in the experimental test sections from real pavements by Houston, Suh and McCullough [3], it was found that the construction season, coarse aggregate type, amount of steel, and time of crack occurrence are the main factors affecting the crack width of a CRCP. Cracks initiating within the first 3 days of construction were found to reach

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much greater widths during the service life of the pavement. Kohler and Roesler [4] analyzed full-scale CRCP sections and found out that the crack width in the pavements varied in the range of 0.031–0.116 mm, and the crack width reduced with increasing reinforcement ratio. The field testing carried out by Al-Qadi and Elseifi [5] on the CRCP test sections indicated that the design spacing of transverse steel bars directly determines the mean crack spacing of the pavement. Al-Qadi and Elseifi [5] identified two controlling mechanisms for the initiation of transverse cracks in the pavement, namely, "built-up of uniform compressive longitudinal stress at the pavement surface" and "tensile stress concentration in the vicinity of the transverse steel bars". Vandenbossche et al. [6] suggested that the crack width in the CRCP should be below 0.5 mm, contrary to the AASHTO Design Guide [7]. Ouzaa and Benmansour [8] carried out an analytical and experimental study to investigate the influence of the length, thickness, and reinforcement ratio of the pavement and the ambient relative humidity on the number and widths of the cracks in the pavement. The spacing of the cracks was found to decrease with increasing reinforcement ratio, and a steel ratio between 0.5% and 0.8% was shown to limit the crack width in the pavement to 0.3 mm.

The self-consolidating concrete (SCC) has gained tremendous popularity over the last decades, particularly in the Western Hemisphere. Unlike conventionally vibrated concrete (CVC), which needs mechanical compaction, the SCC is capable of spreading in the form under its own weight by flowing through the web of reinforcement. This highly flowable nature increases the speed of construction by reducing the labor. Nowadays, SCC is commonly used in high-rise buildings, industrial structures, bridge piers, dams, etc., where mechanical vibration is a major cause of concern due to the congested reinforcement and massive amount of concrete. The SCC is not preferred in rigid pavements due to its low shape-holding ability. In an extensive research project conducted for the Iowa Department of Transportation in the US, Wang et al. [9] were able to develop a new type of SCC, denoted as semi-flowable self-consolidating concrete (SFSCC), which can be used in rigid pavements. The use of fines, nano-clay materials, and superplasticizers in the concrete mixture provided SFSCC with adequate green strength to be appropriate to be used in pavement construction, as well as with a flowable nature similar to the SCC. SFSCC was successfully used by the researchers in different field applications with the slip-form pavers, having longer skids compared to the conventional pavers.

The use of SFSCC raises the concern on the increase in the widths of cracks in the pavement as various studies in the literature [10–12] indicated that the SCC is more prone to shrinkage cracking compared to the CVC. Furthermore, the same studies showed that restrained shrinkage cracks initiate at earlier ages in SCC due to the higher rates of shrinkage in this type of concrete. The early initiation of cracks in the pavement results in wider cracks in the pavement during the service life of the road, which will increase the risk of reinforcement corrosion due to the penetration of water, deicing salts, and chemicals through these wide cracks. Kalkan and Lee [13] were able to show the influence of restrained shrinkage cracks on the in-plane flexural behavior of reinforced concrete (RC) beams, experimentally. According to the tests reported in this study, RC beams cast with SCC undergo significantly greater deformations under transverse loading as a result of the significant reduction in the flexural rigidity of a beam caused by restrained shrinkage cracking prior to loading. Kalkan and Lee [13] suggested that the heavy longitudinal reinforcement in these beams might have prevented the free shrinkage of the concrete and triggered restrained shrinkage cracking. Similar to beams, flexure dominates the behavior of rigid pavements, and therefore, the restrained shrinkage cracks will play an important role in the behavior of concrete pavements. The problem of restrained shrinkage cracking is more pronounced in CRCP due to the presence of high amounts of reinforcement and the lack of regular joints along the pavement unlike jointed concrete pavements (JCP).

The present study was dedicated to investigate the restraint stresses developing in the CRCP cast with the SCC rather than the CVC. First, an analytical expression was developed for estimating the restraint stresses in the CRCP road cast with the SCC, based on a formula developed by Scanlon and Bischoff [14]. Later, the restraint stresses were calculated for different rigid pavement models cast with the SCC and the CVC. Suggestions were made for the amounts of longitudinal reinforcement needed to prevent the formation of wide cracks in the pavement cast with the SCC.

2 Analytical study

Structural concrete codes present analytical expressions for estimating the restraint stresses induced to concrete members by the longitudinal reinforcement. The Australian code AS3600 [15], for instance, gives the following equation:

$$f_{\mathrm{res}} = \left(\frac{2.5\rho_w - 0.8\rho_{cw}}{1 + 50\rho_w} \right) \cdot E_s \cdot \varepsilon_{shf} \tag{1}$$

where ρ_w and ρ_{cw} are the ratios of the tension and compression reinforcement, respectively, E_s is the modulus of elasticity of reinforcement, and ε_{shf} is the ultimate value of the free (unrestrained) shrinkage strain of concrete. Eq. (1) is specifically developed for reinforced concrete beams, whose reinforcement can be grouped into tension and compression reinforcement. In concrete pavements, on the other hand, the longitudinal reinforcement is not composed of tension and compression reinforcement. For this type of members, the restraint stress equation of the Australian AS 3600 standard [16] is more appropriate:

$$f_{\text{res}} = \left(\frac{1.5\rho}{1+50\rho} \right) \cdot E_s \cdot \varepsilon_{sh} \tag{2}$$

where ρ is the longitudinal reinforcement, ratio and ε_{sh} is the free shrinkage strain of concrete at a specific time. According to the Canadian structural concrete code A23.3-14 [17] and Eurocode 2 [18], the shrinkage restraint stresses in concrete members can be assumed to be in the order of 50% and 30% of the modulus of rupture of concrete, respectively.

The restraint stress expressions given in the codes were developed based on the approximate dimensions and details of RC beams. Therefore, they are not directly applicable to rigid pavements. In the present study, a shrinkage-induced restraint stress expression applicable to the CRCP was developed. This expression originates from the equation of Scanlon and Bischoff [14], which is used to estimate the restraint stresses induced by the reinforcement in RC members:

$$f_{\text{res}} = \left[\frac{\rho \cdot \left(\frac{d}{h} \right) \cdot (1+6\xi)}{1+\bar{n} \cdot \rho \cdot \left(\frac{d}{h} \right) \cdot (1+12\xi^2)} \right] \cdot E_s \cdot \varepsilon_{sh} \tag{3}$$

where d is the effective depth of tension reinforcement; h is the overall depth; $\bar{n}$ is the long-term modular ratio of concrete, which considers the reduction in the modulus of elasticity of concrete in time due to creep; and ξ is the eccentricity factor, i.e. the ratio of the distance between the centroid of longitudinal reinforcement and the centroid of cross-section to the overall member depth.

Eq. (3) is applicable to all RC flexural members, including beams and slabs [14]. CRC pavements have similar aspect ratios to RC slabs, and therefore, this equation can be modified to estimate the restraint stresses in the CRCP roads. The only difference between the section of an RC slab and the section of a CRCP is the effective depth of the longitudinal reinforcement and the eccentricity of the reinforcement with respect to the centroid of the section, and this difference should be incorporated into the equation. The previous studies of Kalkan and Lee [13] indicated that the expression of Scanlon and Bischoff [14] closely estimates the restraint stresses developing in the SCC beams, while significantly over-predicting the restraint stresses developing in the CVC beams. The experimental measurements reported by Kalkan and Lee [13] indicated that the restraint stress values measured in CVC beams were about 20% of the values calculated from Eq. (3).

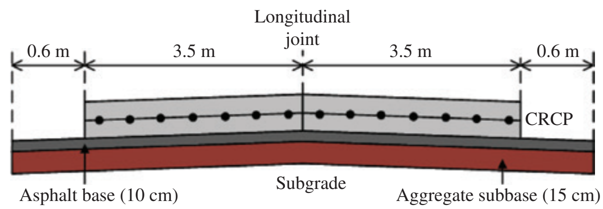

Figure 1: Typical section for CRCP.

To modify Eq. (3) for the case of the CRC pavements, the pavement model illustrated in Figure 1 was used. This model represents the dimensions and reinforcement of a standard CRCP section given in the Continuously Reinforced Concrete Pavement Design and Construction Guidelines [19]. The pavement has a thickness of 25 cm. The concrete and reinforcement are of Grade M40 (40 MPa compressive strength) and M420 (420 MPa yield strength), respectively. The transverse and longitudinal reinforcement consist of M16 bars at 900 mm center-to-center spacing and M19 bars at a spacing of 150 mm on the center, respectively. This reinforcement corresponds to longitudinal and transverse reinforcement ratios of 0.7% and 0.085%. The longitudinal reinforcing bars are located at an average depth of 90 mm from the upper surface of the pavement.

Considering this typical CRCP section, the d/h ratio can be calculated as 0.36 and the eccentricity factor ξ as 0.14. Scanlon and Bischoff [14] suggested that a value of 20 is appropriate for the long-term modular ratio. Incorporating all these values into Eq. (3) yields to the following equation for the shrinkage-induced restraint stress calculation of CRCP:

$$f_{\text{res}} = \left[\frac{0.70 \cdot \rho}{1+8.90 \cdot \rho} \right] \cdot E_s \cdot \varepsilon_{sh} \tag{4}$$

Eq. (4) is similar to Eq. (2). The difference between the constants of these two equations stems from the fact that Eq. (2) was originally developed for typical RC beams, where the ratio d/h has a value of 0.8–0.9, and the eccentricity

Table 1: Analyzed CRCP sections [1].

Section	Location	Pavement thickness (mm)	Longitudinal reinforcement ratio (%)	*d*/*h*	*ξ*
1	Trans-Canada Highway, Calgary, Alberta, Canada	152	0.82	0.50	0
2	A6 Freeway, France	178	0.72	0.33	0.17
3	Freeway System, Belgium	165	0.67	0.50	0
4	Northern Spain	140	0.85	0.50	0
5	La Porte, TX, USA (thick pavement with two layers of reinforcement)	330	0.59	0.65	0.15
6	Highway I-20, AL, USA	203	0.70	0.36	0.14
7	Highway I-80, CA, USA	203	0.62	0.50	0
8	MI, USA	229	0.70	0.50	0

factor has a value of 0.3–0.4, while Eq. (4) was developed for the CRC pavements, where d/h has a value of 0.35–0.50, and the eccentricity factor has a value below 0.15.

ε_{sh} in Eqs. (2)–(4) is the free (unrestrained) shrinkage strain of concrete at time t (in days). The shrinkage strain at time t is related to the ultimate value of the free shrinkage strain (ε_{shf}) according to the following equation:

$$\varepsilon_{sh} = S(t - t_c) \cdot \varepsilon_{shf} \tag{5}$$

where t_c is the duration of curing after the concrete cast. The time function $S(t-t_c)$ indicates the change of strain in time up to its ultimate value. Different time functions were proposed in the structural concrete codes and in previous studies [13]. However, the analytical expressions in the present study focus on the long-term restraint stresses in the CRC pavements. Therefore, the ultimate value of the shrinkage strain (ε_{shf}) was used in the calculations rather than the strain ε_{sh} at a specific time.

3 Case study

To investigate the influence of the use of SCC in CRC pavements, the restraint stress values for eight different CRCP sections (Table 1), constructed in different parts of the globe, were calculated for two different types of concrete, CVC and SCC. These roads sections were taken from the U.S. Federal Highway Administration Report FHWA-RD-94-178 [1]. For the sections with no information about the location of the longitudinal reinforcement in the section, the d/h ratio and the eccentricity factor (ξ) were taken as 0.50 and 0, respectively, by assuming that the longitudinal reinforcement was placed at mid-depth of the pavement. In the report [1], the CRCP section of Alabama (Section 6) was stated to be constructed according to the CRCP Design and Construction Guidelines [19]. The longitudinal reinforcement ratio, the d/h ratio, and the eccentricity factor ξ were, therefore, taken from the model road in Figure 1.

The CRCP Pavement Design and Construction Guidelines [19] presents allowable stress limits for the reinforcing bars in a pavement so that these bars do not undergo plastic deformations under the traffic load and due to the volumetric changes of the pavement. Plastic deformations of the reinforcing bars need to be prevented to limit the widths of the cracks in the pavement. The allowable stress limits for different sizes of reinforcing bars are presented in Table 2. The ratios of the restraint stresses developing in the example CRCP sections (Table 1) to the allowable stress values of the reinforcing bars (Table 2) are illustrated in Figures 1–3 for M13 (#4), M16 (#5), and M19 (#6) bars, respectively. The #4, #5, and #6 bars correspond to the reinforcing bars with 4/8 in. (13 mm), 5/8 in. (16 mm), and 6/8 in. (19 mm) diameters, respectively. In the present study, the indirect tensile strength (f_{ct}) values of the CRCP sections were calculated from the compressive strength values based on the ACI 318M-14 [20] formula:

$$f_{ct} = \sqrt{f'_c} / 1.8 \tag{6}$$

Table 2: Allowable working stress limits (MPa) for Grade 420 reinforcement [19].

Indirect tensile strength of concrete (MPa)	#4 (M13)	#5 (M16)	#6 (M19)
2.1 or less	448	393	372
2.8	462	414	379
3.4	462	421	386
4.1	462	434	400
4.8	462	448	407
5.5 or greater	462	462	414

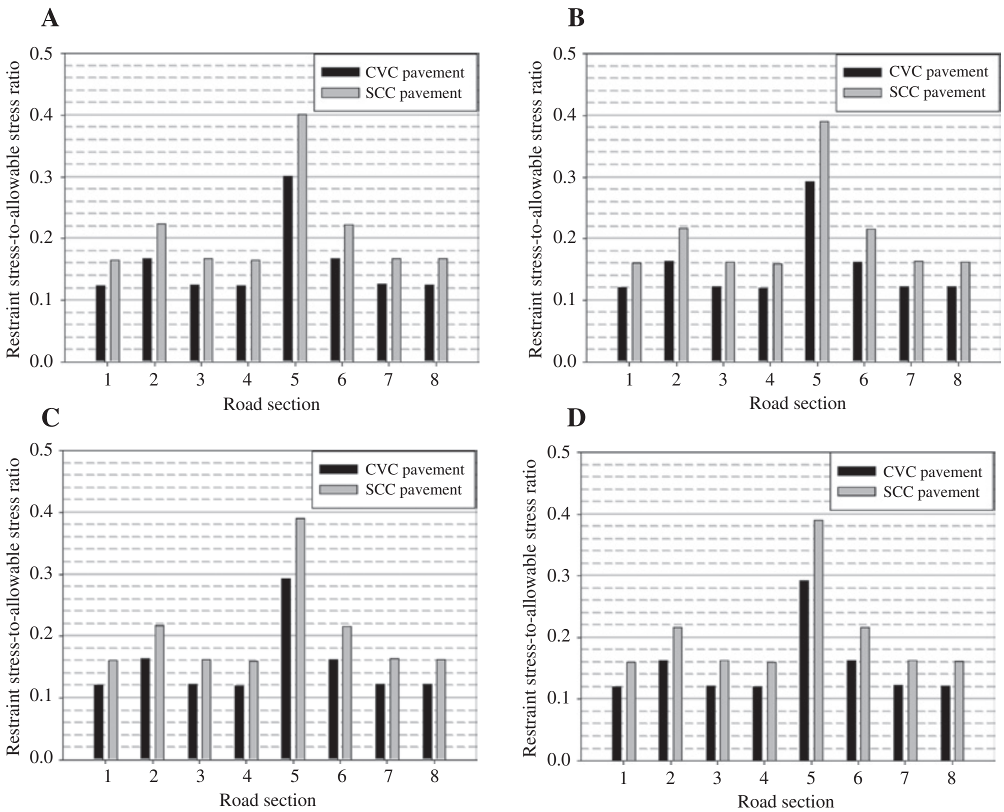

Figure 2: Restraint-to-allowable stress ratios of the CRCP sections in the presence of M13 bars. (A) Grade 10 concrete. (B) Grade 20 concrete. (C) Grade 30 and 40 concrete. (D) Grade 50 and 60 concrete.

where f_c' is the cylinder compressive strength of concrete in MPa. The values of the restraint-to-allowable stress ratio for each CRCP model are tabulated in Table 3 for various concrete grades and different sizes of longitudinal reinforcement.

The restraint stresses in concrete were calculated from Eq. (3), using the parameters tabulated in Table 1. Each reinforcing bar was assumed to resist the restraint stresses in the concrete section between adjacent bars (hxs). Accordingly, the restraint stress in the longitudinal reinforcement (f_s) caused by the shrinkage-induced restraint stresses in concrete (f_{res}) was obtained from the following formula:

$$f_s = \frac{f_{\text{res}} \cdot (h \cdot s)}{A_o} = \frac{f_{\text{res}}}{\rho} \qquad (7)$$

where h is the thickness of the pavement; s is the center-to-center spacing of the longitudinal reinforcing bars; A_o is the cross-sectional area of a single reinforcing bar; and ρ is the longitudinal reinforcement ratio of the pavement.

The two different types of concrete, SCC and CVC, differed in the value of the ultimate free shrinkage strain (ε_{shf}). As conventional SCC cannot be used in road construction due to its low shape-holding ability, the term SCC in this discussion refers to the semi-flowable self-consolidating concrete (SFSCC), which is more appropriate to be used in the CRCP. The ε_{shf} value of CVC was taken as 0.0006, which is the value given by the Turkish concrete code TS 500 [21] for conventional concrete. The ε_{shf} value of SFSCC was obtained from the summation of the autogenous shrinkage strain (0.000150) and the drying shrinkage strain (0.000650), which are the experimental values reported by Wang et al. [9]. Finally, the long-term modular ratio of concrete was taken as 20, as suggested by Scanlon and Bischoff [14].

The restraint-to-allowable stress values, tabulated in Table 3, indicate that the additional stresses in reinforcing bars induced by the shrinkage deformations of concrete varied between 12% and 36% of the allowable stress of the bars when the pavement is cast with CVC. In the case of SFSCC, on the other hand, the additional stresses in the reinforcing bars varied in the range of 16–48% of the allowable bar stress. Accordingly, the use of SFSCC in the pavement in replacement for CVC results in an increase of about 33% in the shrinkage-induced additional stresses in the reinforcement. When the pavement is cast with

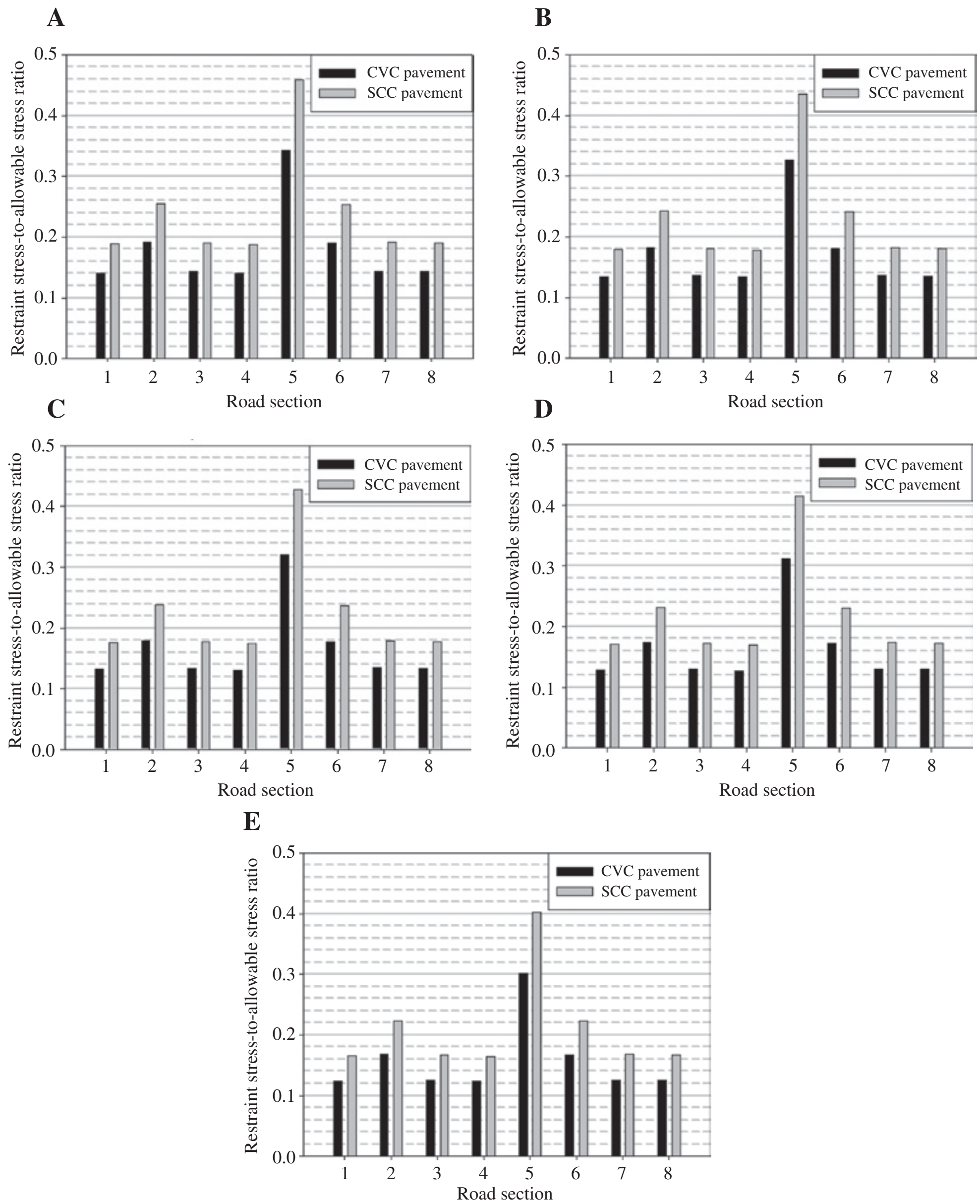

Figure 3: Restraint-to-allowable stress ratios of the CRCP sections in the presence of M16 bars. (A) Grade 10 concrete. (B) Grade 20 concrete. (C) Grade 30 and 40 concrete. (D) Grade 50 concrete. (E) Grade 60 concrete.

SFSCC, the restraint stresses in the reinforcement might reach values as large as 50% of the allowable stress of the bar. Consequently, the longitudinal reinforcing bars in the CRCPs cast with the SFSCC are highly prone to undergo plastic deformations under the traffic loading, if necessary precautions are not taken.

Figures 2–4 indicate that the CRCP Section 5 had the highest restraint stress values among all sections, although this pavement had the lowest longitudinal reinforcement ratio. The high restraint stresses in this section was mainly caused by the greater eccentricity of the longitudinal bars with respect to the centroid of the road section. Section 5 represents the test sections on the Pasadena Freeway in La Porte, TX, USA, constructed in 1991 [1]. This section differs from the remaining sections in Table 1 in the number of layers of reinforcement. In Section 5, both the transverse reinforcement and the longitudinal reinforcement consisted of two layers of bars. The placement of the longitudinal reinforcing bars caused the centroid of the longitudinal reinforcement to be farther from the open surface of the pavement than the centroid of the road section. The high d/h value (0.65) increased the calculated restraint stress values. The findings of the

Table 3: Restraint-to-allowable stress values for various concrete grades and rebar sizes.

Road section	Concrete grade	Size of the reinforcing bar					
		M13		M16		M19	
		CVC	SFSCC	CVC	SFSCC	CVC	SFSCC
1	10 Grade	0.124	0.165	0.141	0.188	0.149	0.199
	20	0.120	0.160	0.134	0.179	0.146	0.195
	30 and 40	0.120	0.160	0.132	0.176	0.144	0.192
	50	0.120	0.160	0.128	0.170	0.139	0.185
	60	0.120	0.160	0.124	0.165	0.136	0.182
2	10 Grade	0.168	0.224	0.191	0.255	0.202	0.269
	20	0.163	0.217	0.182	0.242	0.198	0.264
	30 and 40	0.163	0.217	0.179	0.238	0.195	0.260
	50	0.163	0.217	0.173	0.231	0.188	0.251
	60	0.163	0.217	0.168	0.224	0.185	0.246
3	10 Grade	0.126	0.167	0.143	0.191	0.151	0.202
	20	0.122	0.162	0.136	0.181	0.148	0.198
	30 and 40	0.122	0.162	0.134	0.178	0.146	0.194
	50	0.122	0.162	0.130	0.173	0.141	0.187
	60	0.122	0.162	0.126	0.167	0.138	0.184
4	10 Grade	0.123	0.165	0.141	0.188	0.149	0.198
	20	0.120	0.160	0.134	0.178	0.146	0.195
	30 and 40	0.120	0.160	0.131	0.175	0.143	0.191
	50	0.120	0.160	0.127	0.170	0.138	0.184
	60	0.120	0.160	0.123	0.165	0.136	0.181
5	10 Grade	0.301	0.402	0.344	0.458	0.363	0.484
	20	0.292	0.390	0.326	0.435	0.356	0.475
	30 and 40	0.292	0.390	0.321	0.428	0.350	0.466
	50	0.292	0.390	0.311	0.415	0.338	0.450
	60	0.292	0.390	0.301	0.402	0.332	0.442
6	10 Grade	0.167	0.223	0.190	0.254	0.201	0.268
	20	0.162	0.216	0.181	0.241	0.197	0.263
	30 and 40	0.162	0.216	0.178	0.237	0.194	0.258
	50	0.162	0.216	0.172	0.230	0.187	0.249
	60	0.162	0.216	0.167	0.223	0.184	0.245
7	10 Grade	0.126	0.168	0.144	0.192	0.152	0.202
	20	0.122	0.163	0.136	0.182	0.149	0.199
	30 and 40	0.122	0.163	0.134	0.179	0.146	0.195
	50	0.122	0.163	0.130	0.174	0.141	0.188
	60	0.122	0.163	0.126	0.168	0.139	0.185
8	10 Grade	0.125	0.167	0.143	0.190	0.151	0.201
	20	0.121	0.162	0.135	0.181	0.148	0.197
	30 and 40	0.121	0.162	0.133	0.178	0.145	0.194
	50	0.121	0.162	0.129	0.172	0.140	0.187
	60	0.121	0.162	0.125	0.167	0.138	0.184

present study confirm the statements in the FHWA-RD-94-178 report [1], which presents different crack control techniques applied to this specific CRCP in the Pasadena Freeway (Section 5) due to the significant cracking in the pavement.

The values shown in Figures 2–4 and Table 3 indicate that the shrinkage-induced restraint stresses significantly increase as the eccentricity factor (ξ) increases. As the distance between the centroid of the longitudinal reinforcement and the centroid of the road section increases, the shrinkage deformations of the pavement introduce not only axial forces but also bending moments to the section. These bending moments increase the shrinkage-induced additional stresses in the reinforcement. Consequently, concentric placement of the longitudinal reinforcement with respect to the centroid of the road section effectively increases the shrinkage-induced stresses in the longitudinal bars.

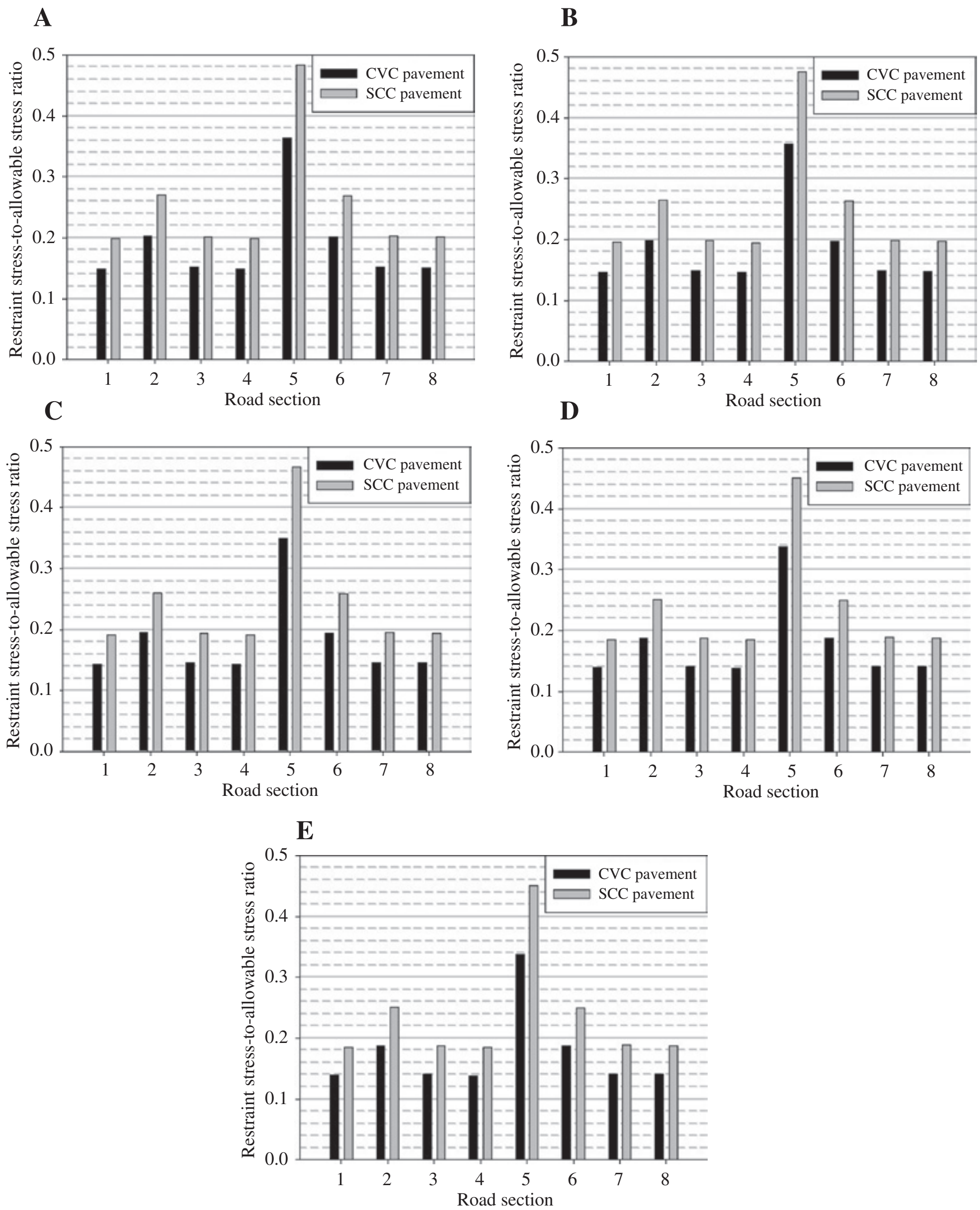

Figure 4: Restraint-to-allowable stress ratios of the CRCP sections in the presence of M19 bars. (A) Grade 10 concrete. (B) Grade 20 concrete. (C) Grade 30 and 40 concrete. (D) Grade 50 concrete. (E) Grade 60 concrete.

The concrete grade and reinforcing bar size have no influence on the shrinkage restraint stresses in concrete and reinforcement, as long as the reinforcement ratio is constant. The shrinkage-induced restraint stress in concrete and the corresponding stress in the longitudinal reinforcement are calculated from Eqs. (4) and (7), respectively. These two equations indicate that the restraint stresses depend on the reinforcement ratio (ρ), the elastic modulus of steel (E_s) and the unrestrained shrinkage strain of concrete (ε_{sh}). Therefore, the concrete strength and the bar size did not change the restraint stress values for a certain model pavement. The reinforcement ratio was kept constant for varying bar diameters in the restraint stress calculations by adjusting the bar spacing to comply with the reinforcement ratio of each CRCP model (Table 1). Nevertheless, the allowable working stress of the bar decreases with decreasing concrete strength and increasing bar diameter (Table 2). Therefore, closely spaced bars with smaller diameters can be used and/or concrete with higher compressive strength can be preferred in pavements with high risk of shrinkage cracking (low relative humidity and high temperature) and heavy traffic loading. In this way, the penetration of the corrosive agents into the pavement can be minimized.

4 Conclusions

The present study focused on the additional stresses developing in the longitudinal reinforcing bars of CRCPs as a result of the shrinkage deformations of concrete. The shrinkage-induced restraint stresses in the longitudinal bars were calculated for two different types of concrete, namely, the CVC or conventional concrete and the SFSCC. The SFSCC, which is a new type of SCC developed by Wang et al. [9], is appropriate for use in the rigid pavement construction, thanks to its higher shape-holding ability compared to the SCC. The use of the SFSCC increases the speed and decreases the labor and cost of construction as it does not require mechanical vibration for settlement. Despite its superiorities over the CVC, the SFSCC has a higher tendency to restrained shrinkage cracking than the CVC, which was the primary focus of the present study.

In the first part of the study, an analytical expression was developed for estimating the shrinkage-induced restraint stresses in the CRCPs. This expression was developed based on a model pavement, designed according to the Continuously Reinforced Concrete Pavement Design and Construction Guidelines [19] of the Federal Highway Administration. The longitudinal reinforcement in the pavement was considered as the primary source of restraint in this expression. In the second part of the study, the restraint stresses in concrete and the corresponding additional stresses in the longitudinal reinforcing bars were calculated for eight different CRCP examples from different parts of the globe. The pavement examples differed in the longitudinal reinforcement ratio and the location of the longitudinal bars with respect to the centroid of the road section. The calculated restraint stress values of the pavements were compared to the allowable stress values of the longitudinal bars, presented in the CRCP Design and Construction Guidelines [19]. The primary findings of the study can be summarized as follows:

- The analytical restraint stress estimates indicated that the use of the SFSCC in pavement construction instead of the CVC results in an increase of about 33% in the additional stresses in the longitudinal reinforcing bars, induced by the shrinkage of concrete. In the case of the CRCP cast with the SFSCC, the additional stresses in the bars due to shrinkage might reach as high as 50% of the allowable stress of the bar. Considering the fact that traffic loading results in much higher stresses in the bars in a majority of pavements compared to temperature changes and shrinkage, the CRCP cast with the SFSCC is liable to significant transverse cracking due to the plastic deformations in the bars.
- Concentric placement of the longitudinal reinforcement with respect to the centroid of the road section should be preferred to decrease the shrinkage-induced restraint stresses in concrete and reinforcement. The bending moments created by the shrinkage deformations of concrete increase as the eccentricity of the reinforcement increases. The stresses originating from bending moments and axial forces add up in the case of eccentric placement of longitudinal bars, increasing the vulnerability of the longitudinal bars to plastic deformations.
- The restraint-to-allowable stress ratio of the longitudinal bars decrease as the concrete strength increases, and the bar diameter decreases. In pavements, where restrained shrinkage cracking is a greater cause of concern, such as in the case of low relative humidity and high temperature or when using SFSCC in the pavement, more closely spaced longitudinal bars and/or higher concrete grades can be preferred to decrease the liability of the pavement to heavy restrained shrinkage cracking.
- The restraint stresses in the pavement increase as the longitudinal reinforcement is placed farther from the upper surface of the pavement. Consequently, the longitudinal bars should not be placed below the centroid of the road section in the aspect of restrained shrinkage cracking.

The analytical calculations of the present study only focused on Grade 420 reinforcement and the influence of the longitudinal reinforcement in the pavement. Further studies will be useful to incorporate the influence of the transverse bars to restrained shrinkage of concrete and to investigate the vulnerability of bars with different grades to exceed the allowable working stresses. Furthermore, restrained shrinkage cracking of JCPs needs also to be investigated in prospective studies both for the use of the CVC and the SFSCC in the pavement.

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