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Evaluation of Transverse Cracks in Cracked Seated and Overlaid Concrete Pavements

Ashraf Rahim[1+], Gregg Fiegel[2], and Khalid Ghuzlan[3]

Abstract: The performance of Crack, Seat, and Overlay (CS&O) pavement rehabilitation technique is evaluated with respect to observed transverse cracking. Pavement sections rehabilitated using the CS&O technique were extracted from the Long Term Pavement Performance (LTPP) database and divided into two categories based on weather region, namely Wet-with-Freeze (WF) and Wet-with-No-Freeze (WNF). California sections from the LTPP database were also extracted but evaluated separately. It was observed that the overlay thickness and the type of base material both play important roles in minimizing transverse cracks. Sections with bound bases outperformed those with unbound bases with the same overlay thickness. Sections built in California with thicker leveling course exhibited slightly less transverse cracks than those built following the California Department of Transportation (Caltrans) normal practice. Three prediction models were developed for pavement sections in the WF and WNF regions and in California. The models predict that LTPP-California sections are expected to experience almost twice as much transverse cracks as the WF and WNF sections with similar cumulative traffic levels, layer thicknesses, and base types.

***Key words**: Crack, seat, and overlay; JPCP rehabilitation; SPS-6; Transverse cracks.*

Background

Highways that were constructed using Portland Cement Concrete (PCC) have shown long-lasting durability with regular maintenance. In fact, many PCC highway sections last longer than their expected design lives. However, as these pavements near the end of their service period and begin to deteriorate, maintenance and restoration costs can become extremely high. In the late 1950's highway engineers began to use Asphalt Concrete (AC) overlays in an effort to restore PCC slabs. The overlays were much thinner than conventional AC pavement sections because the PCC was assumed to act as a high strength base. Soon after overlaying damaged slabs, however, it was discovered that cracks and joints in the PCC reflected through the AC. The primary causes of reflection cracking were found to be the expansion and contraction of the concrete due to temperature changes, vertical movement of the concrete due to softened base (commonly because of moisture intrusion), frost heave, and heavy vehicle traffic.

Engineers have developed various construction methods which help to rehabilitate PCC pavements while minimizing subsequent reflection cracking. Today, three different techniques are used primarily for rehabilitating PCC pavements. These techniques include Crack, Seat, and Overlay (CS&O), Break, Seat, and Overlay (BS&O), and Rubblization. Each technique effectively reduces the length of the concrete slab by cracking or breaking it to smaller isolated pieces. This action helps to reduce tensile strain in the AC overlay due to concrete thermal expansion and contraction.

The selection and performance of the rehabilitation techniques depends on the method used to construct the original slab and the condition of the pavement when maintenance is performed. If the slab is not reinforced, the CS&O technique is used. If steel reinforcement exists in a slab, the BS&O technique is used to break the bond between the steel and concrete. Rubblization is used for highly deteriorated slabs with very little remaining strength.

Al Hakim and Jenison reported that fracturing and seating distressed concrete pavements appeared to be an effective means of retarding the formation of reflective cracking in AC overlays [1]. Gulen and Noureldin, of Indiana Department of Transportation (DOT), investigated the performance of three concrete pavement rehabilitation techniques [2]. It was reported that the cracked and seated segment experienced the highest deflection as measured by the Falling Weight Deflectometer (FWD). In the same study based on annual visual surveys, the cracked and seated segment was ranked third in terms of distresses developed in the AC overlay.

In a separate study, the Indiana DOT constructed several experimental sections to evaluate two different methods for reducing reflective cracking in asphalt overlays over concrete pavement on I-74 [3]. The first method included cracking, seating, and overlaying with a conventional asphalt overlay, while the second method included the addition of fibers to the asphalt overlay (with no cracking and seating). Also, control sections were constructed where a conventional asphalt overlay was used without cracking and seating the concrete slabs. Based on pavement performance data collected over a 7-year period, the cracking and seating technique was deemed successful. It was reported that most transverse cracks were delayed for 5 years using this technique. In the same study it was found that thicker overlays did not appear to

[1] Associate Professor, Civil and Environmental Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA.

[2] Professor, Civil and Environmental Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA.

[3] Assistant Professor of Civil Engineering, Department of Civil Engineering, Jordan University of Science and Technology, Jordan.

[+] Corresponding Author: E-mail arahim@calpoly.edu

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reduce the intensity of transverse cracks.

Kilareski and Stoffels reported that the effectiveness of CS&O ranged from poor to very good [4]. They reported that smaller sized cracked slabs meant less chance of movement due to temperature change and the more structural support from the existing slab. Darter and Hall provided design guidelines for asphalt concrete overlays with cracked and seated slabs [5]. They stressed that, while the crack and seat method can be applied to more deteriorated concrete pavements, serious reflective cracking may develop unless the process produces uniform support with good load transfer. They added that a high traffic level may result in detrimental rocking of the concrete pieces.

In a study published in 1991 by Pavement Consultancy Services deflection testing of CS&O and rubblization projects were conducted [6]. According to this study, "the lower the concrete modulus, E_{pcc} value, the greater the effectiveness of the construction operation in minimizing the potential for eventual reflective cracking in hot mix asphalt (HMA) overlay. The same study recommended crack spacing of 760*mm* when the slab is placed on subgrade soils, 610*mm* when the slab is placed on granular subbase, and 305*mm* when the slab is placed on stabilized subbase.

The Special Pavement Studies (SPS-6) sections that were built on I-80 in Pennsylvania were evaluated by Morian et al. [7]. After 10 years of service under heavy traffic loads, the crack and seat sections had the best functional performance among the standard SPS-6 sections. Freeman compared CS&O and control sections in Virginia and found that the CS&O sections retarded reflective cracking for a longer period of time [8]. Typically, cracking in these sections did not begin to reflect until after the third year. The control sections began to crack two years earlier.

A survey form was prepared to collect information regarding the current practice of rehabilitating concrete pavements as well as performance data for sections rehabilitated using CS&O technique [9]. The survey was sent to all 50 US DOTs as well as a transportation agency in Canada. With a total of 51 surveys were sent; 25 survey responses were received. It was reported that, no CS&O performance prediction models were developed by any of the DOT agencies that responded to the survey.

It is believed that the occurrence of transverse cracking in asphalt pavements is related to thermal changes in addition to traffic load repetitions. Therefore, the main objective of this study was to investigate the occurrence of transverse reflective cracks in sections rehabilitated using CS&O technique in different US weather regions. In addition, regression models were developed to predict the occurrence of transverse reflective cracks for pavement sections located in different weather regions and in California. Distress prediction models are considered crucial for a successful Pavement Management System. Data employed in this study were extracted from the SPS-6 module in the Long Term Pavement Performance (LTPP) database.

Data and Analyses

Performance Data

Performance data used in this study were extracted from the LTPP Specific Pavement Study (SPS-6), which included sections rehabilitated using the CS&O technique. These data are available online via a user-friendly web application that contains all LTPP releasable data [10]. Our search of the SPS-6 module revealed 61 different CS&O pavement sections built in 13 states across the US. These sections cover two weather regions, namely the Wet-with-Freeze (WF) region and the Wet-with-No-Freeze (WNF) region. Sections in the WF and WNF regions were analyzed separately. Even though California sections are included in the WNF region, we analyzed the data for these sections separately in an attempt to compare the performance of California sections with pavement performance observed in different weather regions, nationwide. Also, it is noted that all California sections were built in the northern part of the state within Siskiyou County.

Inventory, layer, construction, traffic, materials, maintenance, and International Roughness Index (IRI) information were extracted from the database and incorporated into our analyses. It is noted that Equivalent Single Axle Load (ESAL) traffic data were missing for several pavement sections for several of the survey years. For these cases we employed an interpolation/extrapolation approach in order to estimate the missing ESAL data.

Data Analyses and Discussion

Table 1 summarizes the range of transverse cracking reported for the two weather regions (WF and WNF) and for the California pavement sections. Also shown in the table are important pavement layer dimensions and traffic data. The data show that California CS&O sections exhibited the highest average transverse crack percentage. This could be attributed to the fact that the California sections have the smallest overlay thickness coupled with the highest average KESAL, which is the annual ESAL in millions. Note that all of the CS&O sections that were built in California and included in the SPS-6 module had bound bases. A search for the type of these bound bases revealed cement-treated bases. This was the case for bound bases in the two weather regions (WF and WNF) in this study where the vast majority of sections had cement-treated bases and only a few sections with asphalt treated bases (mainly in the WF region).

Transverse cracks in pavement sections rehabilitated using the CS&O technique are mainly reflection cracks. These cracks are most likely the result of thermal-induced horizontal slab movements and traffic-induced vertical slab movements, In the following sections we discuss the performance of CS&O pavement sections in relation to overlay thickness and base type for the WF and WNF weather regions and California.

Wet-with-Freeze Region Sections

Fig. 1 presents the relationship between percentage transverse cracks and Cumulative Single Axle Load (CESAL) for different overlay thicknesses and base types. For different ranges of overlay thickness, pavement sections built with bound bases exhibited lower percentages of transverse cracks when compared with sections with unbound bases. It is noted that the majority of the transverse cracks developed during the first 6 million traffic repetitions, which translates to about 5.5 years of service based on the average KESAL shown in Table 1. Transverse cracks began their initiation after

Table 1. Summary of Pavement Variables for the WF, WNF, and California Regions.

Region	Variable	Description	Range	Units	Mean
WF	TRANS	Percentage Area Effected by Transverse Cracking	(0 to 8.93)	%	2.03
	AGE	Time between Construction and Survey Dates	0 to 15	Years	5.4
	H_{AC}	The Depth of Asphalt Overlay(s)	50.8 to 292.0	*mm*	157.5
	H_{PCC}	The Depth of Concrete Slab	178.0 to 259.0	*mm*	232.0
	BASE	The Type of Base (0= Bound, 1= Un-bound)	0 or 1	Binary	-----
	KESAL	Equivalent Single Axle Loads Per Year	0.07 to 3.96	Million	1.117
WNF	TRANS	Percentage Area Effected by Transverse Cracking	(0.0 to 3.99)	%	0.63
	AGE	Time between Construction and Survey Dates	0 to 8.5	Years	3.2
	H_{AC}	Thickness of Asphalt Overlay(s)	101.0 to 243.8	*mm*	170.2
	H_{PCC}	Thickness of Concrete Slab	254.0 to 254.0	*mm*	254.0
	BASE	The Type of Base (0= Bound, 1= Un-bound)	0 or 1	Binary	-----
	KESAL	Equivalent Single Axle Loads Per Year	NA[a]	Million	NA
CA	TRANS	Percentage Area Effected by Transverse Cracking	(0.0 to 13.7)	%	4.40
	AGE	Time between Construction and Survey Dates	0 to 12.5	Years	7.7
	H_{AC}	Thickness of Asphalt Overlay(s)	94.0 to 205.7	*mm*	133.35
	H_{PCC}	Thickness of Concrete Slab	210.8 to 221.0	*mm*	213.4
	BASE[b]	The Type of Base (0= Bound, 1= Un-Bound)	0	Binary	-----
	KESAL	Equivalent Single Axle Loads Per Year	1.93 to 3.22	Million	2.6

[a]Data Not Available.
[b]All CS&O Sections in California had Cement Treated Bases (Bound).

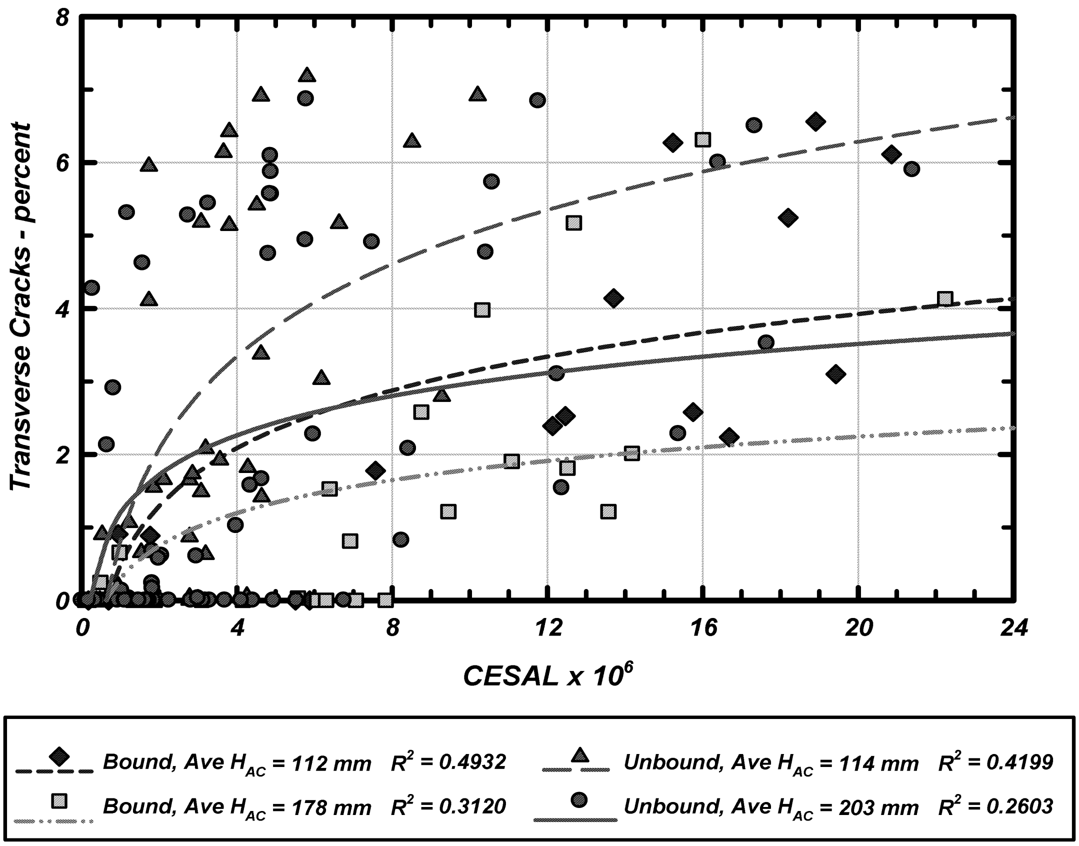

Fig. 1. Transverse Cracks versus Cumulative Traffic for WF Region Sections with Different Overlay Thicknesses and Base Types.

approximately 1million traffic repetitions of the standard axle for all overlay thicknesses and base types included in the data shown on Fig. 1. For the same base type, transverse crack percentage decreased as overlay thickness increased. At the same cumulative traffic level, a 112-mm overlay on a bound-base pavement section experienced approximately the same crack percentage as a 203-mm

Table 2. Statistical Data for Sections in the WF Region.

Variable	Bound Base			Unbound Base		
	Average	SDV[a]	CV[b] (%)	Average	SDV[a]	CV[b] (%)
H_{AC}	149.86*mm*	35.56*mm*	23.7	157.48*mm*	48.77*mm*	31.0
H_{PCC}	198.12*mm*	14.48*mm*	7.3	242.57*mm*	21.59*mm*	8.9
KESAL[c]	1.1	0.821	76.0	0.80	0.452	56.2

[a]Standard Deviation.
[b]Coefficient of Variation.
[c]Annual ESAL in Millions.

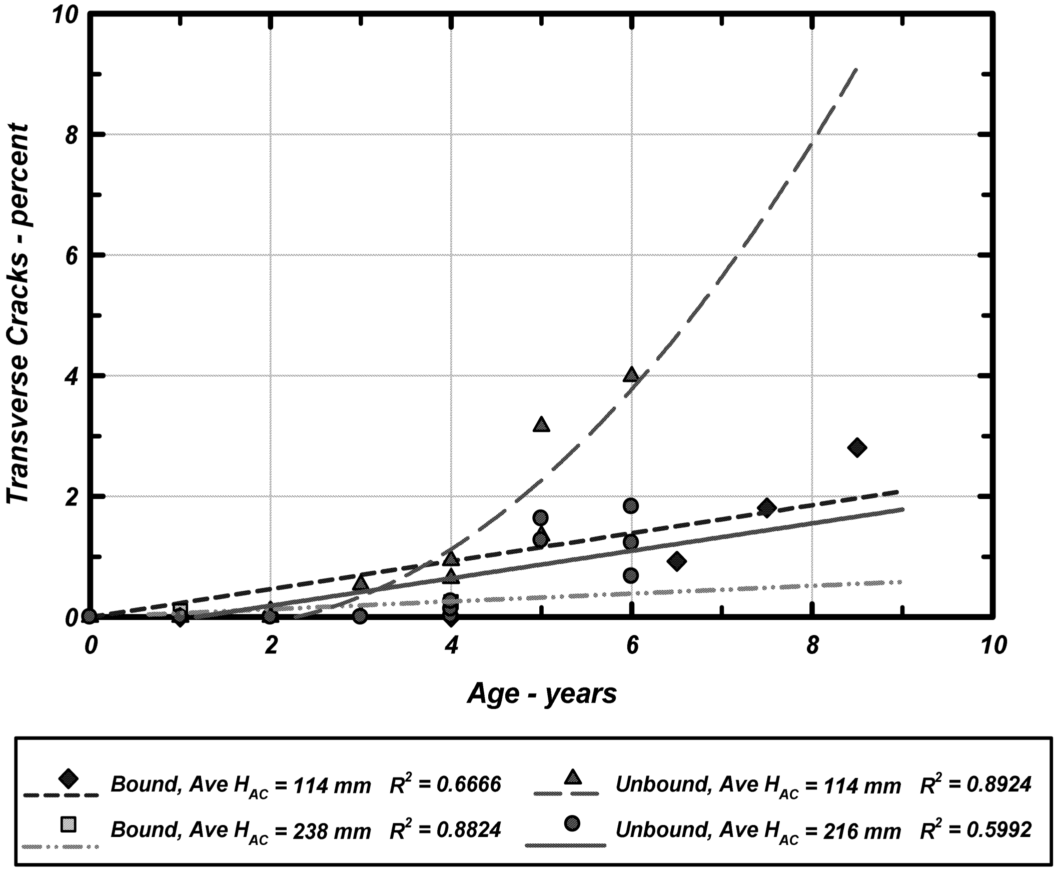

Fig. 2. Transverse Cracks versus Age for WNF Region Sections with Different Overlay Thicknesses and Base Types.

overlay on an unbound-base section. This trend could be explained by the increased tendency of the PCC pieces to rock under heavy traffic in sections with unbound bases. Another possible explanation could be the drainage characteristics of these pavement sections. Drainage and drainage quality are not described in the LTPP database.

Table 2 lists important statistical data for sections in the WF region. As evident, the average overlay thickness for sections with bound bases was only about 7*mm* smaller than that for sections with unbound bases. Also, the average concrete slab thickness for sections with bound bases was approximately 45*mm* smaller than that for sections with unbound bases, and the average KESAL for sections with bound bases was approximately 0.3-million higher than that for sections with unbound bases. Yet, sections with bound bases in the WF region outperformed those with unbound bases, as shown in Fig. 1. This indicates that base type is apparently a significant factor to consider when rehabilitating PCC pavement using the CS&O technique.

Wet-with-no-Freeze Region Sections

As previously mentioned, no traffic data are available in the LTPP database for CS&O sections in the WNF region. Therefore, we correlated transverse cracks with the age of pavement sections, as shown in Fig. 2. It is noted that the CS&O sections in the WNF region were younger than those located in the WF region and in California. From the trend lines shown in Fig. 2, it is apparent that relatively thick overlays limit the occurrence of transverse cracks for unbound base sections that are older than 4 years. It is also apparent that sections with bound bases experience approximately the same percentage of transverse cracks as sections built on unbound bases with overlays nearly twice as thick. However, for sections with relatively thick overlays built over bound and unbound bases, the crack percentage does not vary significantly. Therefore,

Table 3. Statistical Data for Sections in the WNF Region.

Variable	Bound Base			Unbound Base		
	Average	SDV[a]	CV[b] (%)	Average	SDV[a]	CV[b] (%)
H_{AC}	152.4*mm*	58.2*mm*	38.0	172.7*mm*	58.2*mm*	33.0
H_{PCC}	254.0*mm*	0.0*mm*	0.0	254.0*mm*	0.0*mm*	0.0
Age	4.6 years	3.0 years	76.0	2.85 years	2.1 years	72.0

[a]Standard Deviation.
[b]Coefficient of Variation.

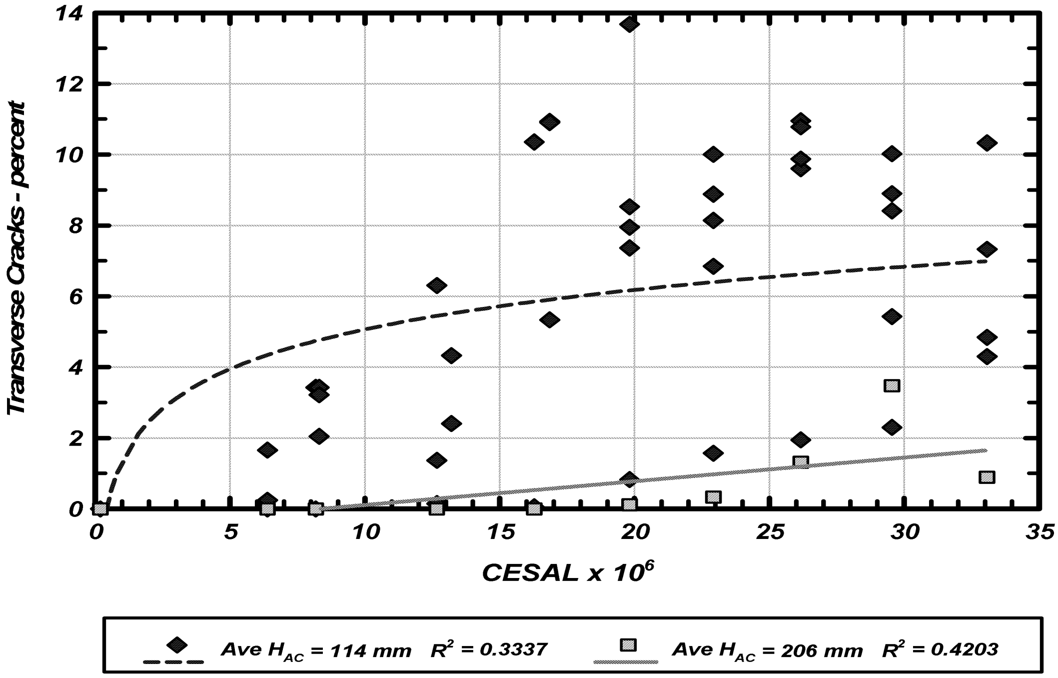

Fig. 3. Transverse Cracks versus Cumulative Traffic for LTPP-California Sections with Different Overlay Thicknesses.

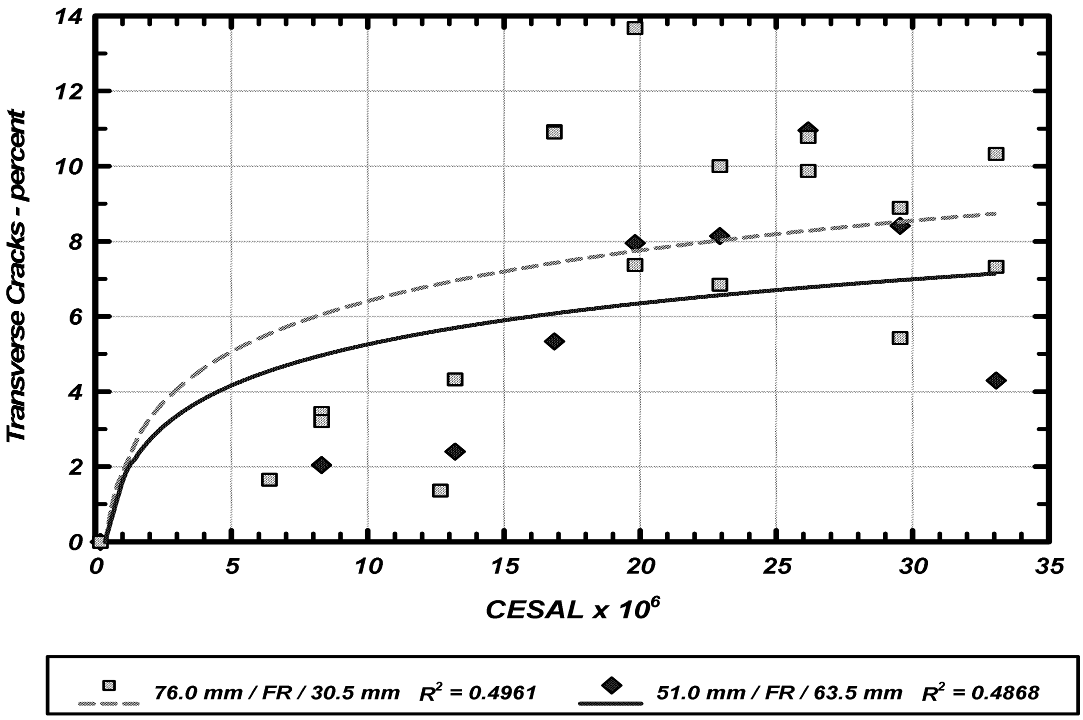

Fig. 4. Transverse Cracks versus Cumulative Traffic for LTPP-California Sections with Different Overlay Scenarios.

for the CS&O rehabilitation projects, the type of base should be carefully considered when designing the overlay thickness.

Table 3 summarizes important statistical data for sections in the WNF region. As evident, the average overlay thickness for sections with bound bases was approximately 20*mm* smaller than that for sections with unbound bases. Also, the slab thicknesses for sections with bound and unbound bases were both 254*mm*. Since traffic data for sections in the WNF region were not available in the LTPP database, the age of these sections was used for comparison. Table 3 shows that the bound-base sections were approximately 1.75 years older than the unbound-base sections, on average. However, as evident in Fig. 2, sections with bound bases outperformed those with unbound bases in terms of the percentage of transverse cracks observed.

California Sections

The effect of overlay thickness on transverse cracks is presented in Fig. 3. It is noted that all California sections in the LTPP database were constructed on bound bases, hereafter referred to as Cement-Treated Bases (CTBs). Therefore, the effect of base type on transverse cracks was not investigated for the California sections.

Fig. 3 shows that thicker overlays significantly reduced the percentage of observed transverse cracks, as compared with thinner overlay thicknesses. For overlay thicknesses of about 114*mm*, the majority of the transverse cracking occurred during the first 5 million traffic repetitions. It is noted that the rate of increase in transverse cracks was much smaller after this number of repetitions was realized.

As part of the SPS-6 project, the order of overlay lifts in California sections was investigated. Two sections were built following standard practices outlined by the California Department of Transportation (Caltrans). These sections incorporated (from bottom to top) a 30.5-mm thick leveling course followed by a fabric reinforcement (FR) layer and a top layer of dense graded AC approximately 76*mm* thick. These sections are hereafter referred to as the “Caltrans-overlay scenario” sections. For the other California sections, the bottom overlay lift was approximately 64*mm* thick, and this layer was followed by the FR layer and a top layer of AC that was approximately 51 millimeters thick. These sections are hereafter referred to as the “reversed-overlay scenario” sections. The performance of these sections, in terms of transverse cracks, is summarized in Fig. 4. Even though transverse cracks appeared almost simultaneously in the two overlay scenarios, it is noted that the "reversed-overlay scenario" sections slightly outperformed the “Caltrans-overlay scenario” sections. More data are needed to evaluate the influence of these different overlay-lift scenarios on pavement performance.

Transverse Cracking Prediction Models

Regression modeling of data is largely empirical and employs past experience to predict future occurrences. Therefore, the one-to-one correlations and analyses discussed in previous sections, combined with expectations of data behavior, were employed as guidance in developing rational regression prediction models. The SPSS statistics software was used in developing the prediction regression models [11]. Both linear and non-linear regression options were employed in relating the dependent variable (percentage transverse cracks) with multiple independent variables in various combinations. To select a model, some basic principles were followed. First, we attempted to minimize the Standard Error of estimate (SE) since the smallest SE would result in the narrowest confidence intervals and largest test statistics. Second, relatively simple prediction models with as few explanatory variables as possible were attempted. Third, we tried to maximize the coefficient of determination, R^2. Fourth, models with relevant cause-and-effect relationships between the dependent variable and each of the explanatory variables were selected. And fifth, we ensured that the prediction models never represent implausible values such as negative distress values, or distresses that contradict the trends well known within the pavement engineering community.

The explanatory variables used in developing transverse cracks models were examined initially based on simple correlation coefficients to rule out multicollinearity among explanatory variables. Models were then evaluated and checked against other forms of the model (i.e., isolation of one variable, combining variables, and/or variable transformation). After numerous trials with both linear and non-linear model forms, we selected the following models:

Wet-with-Freeze Region Model:

$$TRANS = 0.1954(AGE)^{1.25}(KESAL)^{0.1335}\left(\frac{H_{pcc}}{H_{ac}} + BASE\right)^{0.347} \quad (1)$$

$R^2 = 0.686$, RMSE = 1.34, and $N = 170$.

Wet-with-No-Freeze Region Model:

$$TRANS = 0.247(AGE)^{1.59}(H_{ac})^{-0.157} \quad (2)$$

$R^2 = 0.633$, RMSE = 0.75, and $N = 37$.

LTTP-California Sections Model:

$$TRANS = 0.1752(CESAL)^{0.7112}\left(\frac{H_{ac}}{H_{pcc}}\right)^{-2.335} \quad (3)$$

$R^2 = 0.51$, $RMSE = 2.98$, and $N = 57$.

where

TRANS = Percentage of Transverse Crack, %,
AGE = Time between rehabilitation and survey dates,
KESAL = Annual ESAL in millions,
H_{pcc} = The depth of concrete slab,
H_{ac} = The depth of asphalt overlay(s),
BASE = Base type (0= bound, 1= unbound),
CESAL = Cumulative Equivalent Single Axle Load in millions,
R^2 = Coefficient of determination,
RMSE = Root Mean Squared Error, and
N = Number of data points used to develop the models.

The significance of individual coefficients was tested employing the *t*-test. At a confidence level of 95%, all of the coefficients are

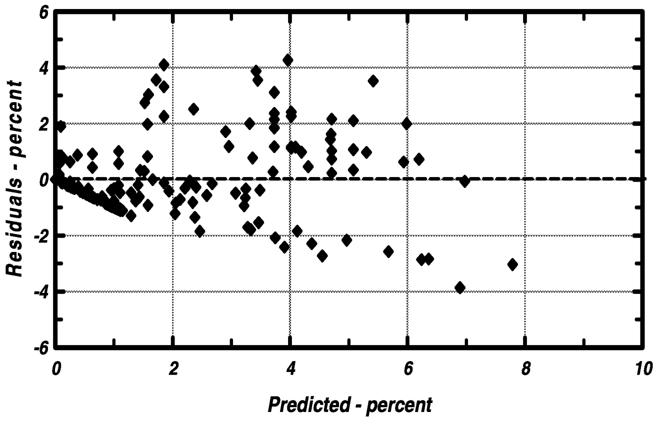

Fig. 5. Predicted versus Residuals for the WF Region Model.

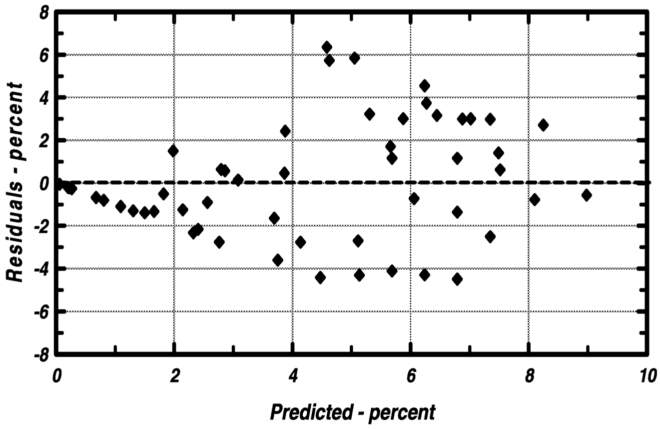

Fig. 7. Predicted versus Residuals for The California Model.

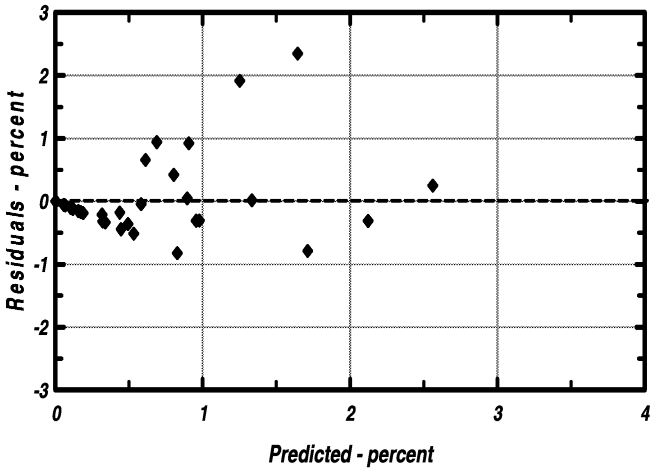

Fig. 6. Predicted versus Residuals for the WNF Region Model.

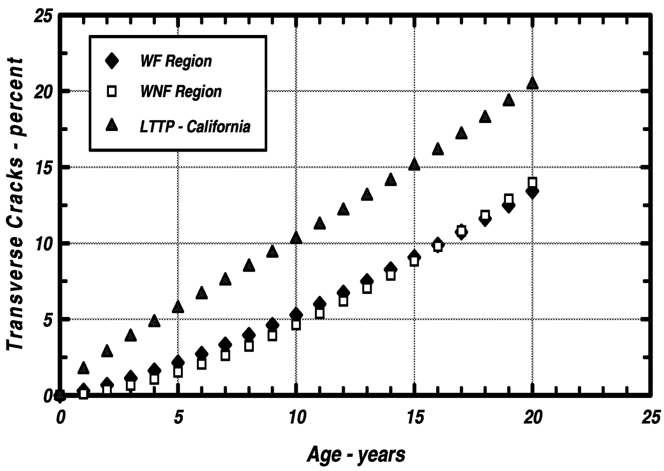

Fig. 8. Variation of Transverse Cracks with Age for the WF, WNF, and California Prediction Models.

significant, as $t^* > 1.96$ [12]. Residuals-predicted plots were examined after developing the models to check for inherent multicollinearity. With no-specific trends apparent in Figs. 5 to 7 for the WF, WNF, and California models, respectively, multicollinearity was ruled out.

Model Comparison

Models developed using data extracted from LTPP database was used to compare the performance of the CS&O rehabilitation technique for different regions of the US and California. Recall that all of the LTPP-California sections are located in the northern portion of the state in Siskiyou County.

When comparing performances, important variables were estimated using the following procedures:

1- Initial KESAL was assumed based on ESAL values included in both the LTPP database and in Caltrans data for fourteen pavement sections in the Central Valley. An initial KESAL equal to 2 million and a growth rate of 5 percent were assumed. The following equation was used to estimate CESAL [13]:

$$CESAL = \frac{KESAL_0}{\ln(1+i)}\left[(1+i)^n - 1\right]$$

where

$KESAL_0$ = Initial annual ESAL (in millions) during the first year after rehabilitation,

i = Growth rate as a percent per year, and

n = Number of years (or age of section).

2- An average overlay thickness of 102*mm* was used, which is the overlay thickness normally specified by Caltrans.

3- The thickness of the concrete slab was assumed to be 216*mm*, which represents an average of the thickness reported for the LTPP-California sections as well as the Caltrans as-built record.

4- Bound base was assumed since all of the California sections were built using bound bases.

Presented in Fig. 8 is the comparison of pavement performance in terms of transverse cracking. The results in the figure show that at the same age (during the first 10 years), California sections are expected to experience almost twice as much transverse cracking as sections with the same layer thicknesses and base types in both the WF and WNF regions. After 10 years of service life the California sections are expected to exhibit approximately 10 percent transverse cracks. Sections in the WF and WNF regions are expected to perform almost the same in terms of crack percentage and rate of increase.

Conclusions and Recommendations

The objective of this paper was to analyze, in terms of transverse cracks, the performance of the CS&O rehabilitation technique. The analyses were based on information available in the LTPP database. Based on our analyses, prediction models were developed for predicting the occurrence of transverse cracks in CS&O sections built in different weather regions. The performance of the CS&O technique for different weather regions was evaluated by comparing the prediction models. The following conclusions are drawn from the study:

1. Overlay thickness coupled with base type plays a significant role in minimizing transverse cracks for sections rehabilitated using the CS&O technique.
2. Sections with bound bases have outperformed sections with unbound bases, assuming the same overlay thickness.
3. Based on the limited data available for the LTPP-California sections, increasing the leveling course thickness from 30 to 64*mm* helps in reducing transverse cracks. However, more data is needed for a conclusive finding.
4. The explanatory variables used in the prediction models provide physically meaningful relationships with the response variables, which indicate that the prediction equations assume a cause-effect relationship.
5. Based on the prediction models developed in this study, CS&O sections in both the WF and WNF regions outperformed their counterparts built in northern California.

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