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Evaluation of Fatigue (Alligator) Cracking in the LTPP SPS-6 Experiment

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Abstract: The performance of Crack, Seat, and Overlay (CS&O) pavement sections is evaluated in terms of fatigue cracking (also known as alligator cracks). Data extracted from the Long Term Pavement Performance (LTPP) SPS-6 experiment were divided into two categories based on weather region, namely Wet-with-Freez (WF) and Wet-with-No-Freeze (WNF). These data were then analyzed and regression models were developed. Data for pavement sections in California were evaluated separately leading to the development of a third regression model. In the WF region, thicker overlays did not appear help to minimize alligator cracks in sections with unbound bases. Sections with bound bases outperformed those with unbound bases in the WF region. Increasing the leveling course thickness from about 30.5 to 63.5mm helped to reduce alligator cracks in the California sections. Regression analyses suggest that sections in the WNF region will outperform their counterparts in the WF region and in California up to an age of approximately 12 years. The California sections are expected to exhibit approximately 56 percent alligator cracks after 10 years of service.

Key words*: Crack, seat, and overlay; Fatigue (alligator) cracking; JPCP rehabilitation; LTPP.*

Introduction

Crack, Seat, and Overlay (CS&O) is a rehabilitation technique that is used for rehabilitating Jointed Plain Concrete Pavements (JPCP). This technique is intended to reduce the incidence of thermal- and traffic-induced reflection cracking within the asphalt overlay by creating shorter slabs and distributing the thermal induced strains more evenly in the asphalt overlay. At the same time, the concrete pieces need to be large enough to maintain the structural integrity of concrete slab. Seating after cracking is intended to reestablish support between the broken slabs and subbase/subgrade and minimize the risk of crack propagation due to shear movement at crack faces and also to minimize slab rocking under traffic load. Different Departments of Transportation employ different techniques in cracking and seating concrete slabs. In California, Caltrans' standard provisions require that slabs be cracked to, approximately 0.6 to 1.0*m* sections using a guillotine style with approximately 5.5*ton* drop hammer. Cracking through the slab must be verified by coring test sections.

During the past 20 years, thousands of miles of roadway nationwide were rehabilitated using the CS&O technique. However, very few of these sections have been evaluated for long-term performance. Furthermore, the effect of weather on performance has not been fully investigated. The majority (if not all) of the previous studies have focused on the performance of CS&O sections in terms of reflection cracking and surface roughness with no effort has been made to evaluate fatigue cracking in CS&O sections. The plausible reason could be due to the belief that the cracked concrete slab would provide a stable platform/base layer that would help eliminate failure in fatigue under heavy traffic. However, in a recent survey four Departments of Transportation of the fifteen that have adopted the CS&O rehabilitation technique reported that fatigue (alligator) cracking was considered one of the dominant failure modes in their CS&O sections [1]. Therefore, the objective of this research is to evaluate the performance, in terms of fatigue cracks, of sections rehabilitated using the CS&O technique. Data used in this study were obtained from the Long Term Pavement Performance (LTPP) Specific Pavement Study (SPS-6), which included sections throughout the U.S. that were rehabilitated using the CS&O technique. The influence of different U.S. weather regions is investigated. Separate regression models are developed to predict the percentage of fatigue cracks for sections in different weather regions and in California. Presented in this paper are results from the first phase of a research study sponsored by the California Department of Transportation (Caltrans) to evaluate the performance of CS&O rehabilitation technique in California.

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Literature Review

Previous studies have reported mixed results when evaluating the performance of the crack, seat, and overlay rehabilitation technique. It was reported that fracturing and seating distressed concrete pavements appeared to be an effective means of retarding the formation of reflective cracking through asphalt overlays on jointed, un-reinforced concrete pavements [2]. In a study conducted by the Indiana Department of Transportation (DOT), Gulen and Noureldin investigated the performance of three concrete pavement rehabilitation techniques: (a) fiber-modified Hot Mix Asphalt (HMA) overlay on top of cracked and seated concrete pavement; (b) an HMA overlay on top of rubblized concrete pavement; and (c) an un-bonded concrete overlay [3]. The cracked and seated segment experienced highest deflection measured employing Falling Weight

Deflectometer (FWD) and was ranked third among the three rehabilitation techniques. In the same study and based on annual visual surveys the un-bonded concrete segment performed the best, followed by the rubblized and the cracked and seated segment. The Indiana DOT constructed several experimental sections to evaluate two different methods for reducing reflective cracking on asphalt overlays over concrete pavement on I-74 [4]. The first method included cracking, seating, and overlaying; the second method included the addition of fibers to the asphalt overlay (with no cracking and seating). Also, control sections were constructed where conventional asphalt overlay was used without cracking and seating the concrete slabs. Based on pavement performance data collected for a 7-year period, the cracking and seating technique was deemed successful. It was reported that most transverse cracks were delayed for 5 years. In the same study it was found that thicker overlays did not reduce the intensity of transverse cracks.

In a study conducted by Kilareski and Stoffels, it was reported that the effectiveness of CS&O ranged from poor to very good [5]. In the same study it was reported that the smaller the size of the cracked slab, the 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 [6]. 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.

A major study published in 1991 by the Pavement Consultancy Services included deflection testing of crack and seat and rubblization projects [7]. 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 HMA overlay." The same study recommended crack spacing of 762*mm* when the slab is placed on subgrade soils, 609.6*mm* when the slab is placed on granular subbase, and 12*inches*. when the slab is placed on stabilized subbase.

Morian et *al*. evaluated SPS-6 sections built on I-80 in Pennsylvania under the Strategic Highway Research Program (SHRP) [8]. 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 [8]. Note that functional performance was defined as the level of acceptability provided to the traveling public.

Witczak and Rada developed a linear model to predict the overall Pavement Condition Index (PCI) for CS&O sections [9]. Data were collected from 34 states for sections with at least partial design, construction, and performance data available. They hypothesized that a nonlinear time variable would best model the behavior; however, this was not the case in the models. The model variables included time, AC overlay thickness, annual average temperature, annual average precipitation, and subgrade modulus.

Data and Analyses

Overview

A search of the SPS-6 experiment revealed sixty-one CS&O sections built in Alabama, Arizona, Arkansas, California, Illinois, Indiana, Iowa, Michigan, Missouri, Oklahoma, Pennsylvania, South Dakota, and Tennessee. These sections included forty-six in the WF region and fifteen in the WNF region. Sections in the WNF region include eight sections within California, which were eventually analyzed separately to compare their performance with sections in different weather regions nationwide. Two cracked and seated sections in California did not have HMA overlays and therefore, they were excluded from the analyses. Also, it is noteworthy to mention that all California sections were built in the northern part of the state, namely Siskiyou County. Inventory, layers information, construction, traffic (Equivalent Single Axle Load, ESAL), materials, maintenance, and fatigue cracks information was extracted and used for the analyses. The ESAL data for these sections were missing for some of the survey years and an interpolation/extrapolation approach was employed to estimate the missing ESAL data. Moreover, for sections in the WNF region traffic data were completely missing in the LTPP database.

Data Analyses and Discussion

The ranges of percentage fatigue cracks reported for two weather regions (WF and WNF) and for the LTPP-California sections are summarized in Table 1. Also shown in the table are pavement layers and traffic data. The data show that California CS&O sections exhibited the highest average percentage fatigue cracks. This could be attributed to the fact that the California sections have the highest average age coupled with the highest average KESAL (the annual ESAL in millions) as compared with sections in the WF and WNF regions. Even though they have the highest average KESAL, the California sections have the smallest average asphalt overlay and concrete slab thicknesses compared with WF and WNF regions sections as shown in Table 1. Note that all CS&O sections that were built in California and included in the SPS-6 had bound bases (Cement Aggregate Mixture). Also, fatigue cracks data for two sections with bound base and overlay thicknesses of 119.4 and 238.8*mm* in the WNF exhibited zero percent fatigue cracks during the four years for which survey data were available.

Fatigue cracks are normally not considered as a serious issue in asphalt overlays over concrete pavements due to the high stability provided by the stiff concrete under-layer. However, since the concrete slabs are cracked and turned into smaller slab pieces as a result of the CS&O technique, the slabs lose much of their stiffness and tend to no longer act as a rigid pavement. Therefore, there is a possibility for fatigue cracking to occur in CS&O sections, especially under heavy repeated traffic. The problem can be exacerbated if the cracked slabs are not seated properly. Note that four states that responded to the nationwide survey reported fatigue (alligator) cracking as one of the dominant failure modes in their CS&O sections. As shown in Table 1, sections in the WF region and in California experienced fatigue cracks as high as 99 and 97%, respectively.

Fatigue Cracks in the Wet-with-Freeze Region Sections

The percentages of fatigue cracks for CS&O sections in the WF region are presented in Fig. 1. As evident in Fig. 1, the thicker overlays did not help to minimize fatigue cracks in sections with un-bound bases. Sections in the WF region are susceptible to

Table 1. Summary of Variables' Range for Different Climatic Regions and California.

Region	Variable	Description	Range	Units	Mean
WF	FATG	Percentage area effected by fatigue cracking	(0 to 98.5)	%	3.6
	Age	Time between rehabilitation and survey dates	0 to 15	years	5.4
	H_{AC}	The depth of asphalt overlay(s)	101.0 to 292.0	*mm*	157.5
	H_{PCC}	The depth of concrete slab	178.0 to 259.0	*mm*	231
	Base	Base type (0= bound, 1= un-bound)	0 or 1	binary	-----
	KESAL	Equivalent Single Axle Loads per year	0.063 to 2.25	million	0.93
WNF	FATG	Percentage area effected by fatigue cracking	(0.0 to 11.5)	%	1.1
	Age	Time between rehabilitation and survey dates	0 to 8.5	Years	3.2
	H_{AC}	The depth of asphalt overlay(s)	101.0 to 243.8	*mm*	170.2
	H_{PCC}	The depth of concrete slab	254.0	*mm*	254.0
	Base	Base type (0= bound, 1= un-bound)	0 or 1	binary	-----
	KESAL	Equivalent Single Axle Loads per year	NA[a]	million	NA
CA	FATG	Percentage area effected by fatigue cracking	(0.0 to 96.7)	%	34.7
	Age	Time between rehabilitation and survey dates	0 to 12.5	Years	7.7
	H_{AC}	The depth of asphalt overlay(s)	94.0 to 205.7	*mm*	133.35
	H_{PCC}	The depth of concrete slab	210.8 to 221.0	*mm*	213.4
	Base[b]	Base type (0= bound, 1= un-bound)	0	binary	-----
	KESAL	Equivalent Single Axle Loads per year	1.93 to 2.76	million	2.6

a Data Not Available

b All CS&O sections in California had cement treated bases (bound)

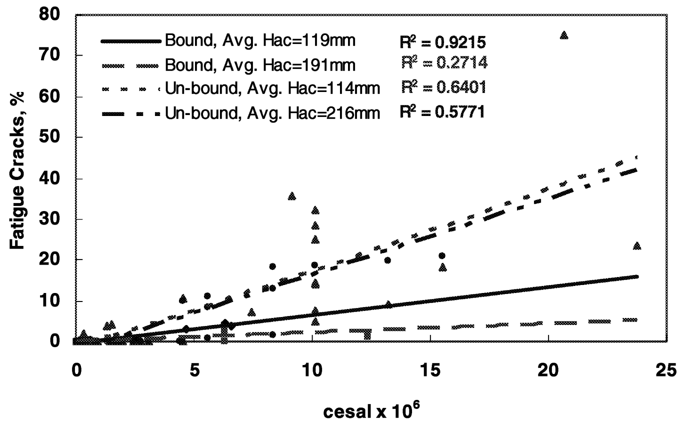

Fig. 1. Fatigue Cracks for Sections with Different Overlay Thicknesses and Base Types in WF Region.

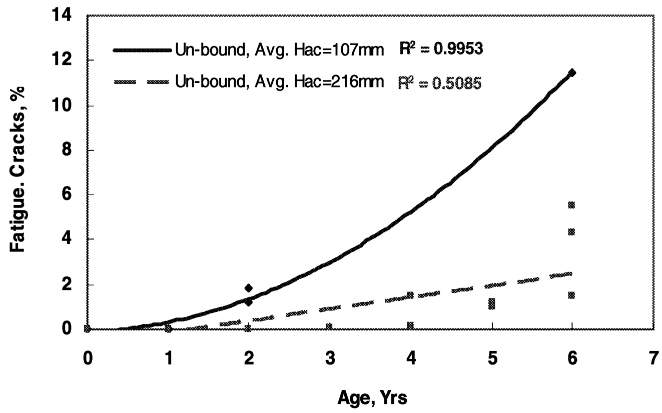

Fig. 2. Fatigue Cracks vs. Age for Sections with Different Overlay Thicknesses in WNF Region.

freeze-thaw cycles, which could have detrimental effect on un-bound bases in the thaw period. This could be the reason behind the trend evident in Fig. 1, which suggests that most of fatigue cracks in these sections could have developed due to the weak under-layers due to freeze-thaw cycles. However, for sections with bound bases, thicker overlays helped in minimizing fatigue cracks as depicted by trend lines in Fig. 1.

Fatigue Cracks in Wet-with-no-Freeze Region Sections

For the WNF region, only two sections with bound base had fatigue cracking data available. The two sections remained free of fatigue cracks for all four years of the condition survey. Therefore, only data for sections with un-bound bases are shown in Fig. 2. The thickness of the overlay played a significant role in minimizing fatigue cracks in sections built in the WNF region. In the absence of traffic data for sections in the WNF region, the traffic effect could implicitly be included by looking at the age of the section. The thickness of overlay coupled with traffic loading are significant factors affecting fatigue cracks in CS&O sections with un-bound bases in the WNF region. However, since these sections are relatively young (average age equal to about 3 years), more data are needed to investigate the long term performance of these sections.

Fatigue Cracks in LTPP-California Sections

The effect of overlay thickness on fatigue cracks for LTPP-California sections is shown in Fig. 3. It is clear from Fig. 3 that thick overlays help in minimizing the percentage of fatigue cracks. Also, a thick overlay (about 206.0*mm*) retarded the appearance of fatigue cracks by approximately 6 million ESAL as compared with sections with average overlay thicknesses of about

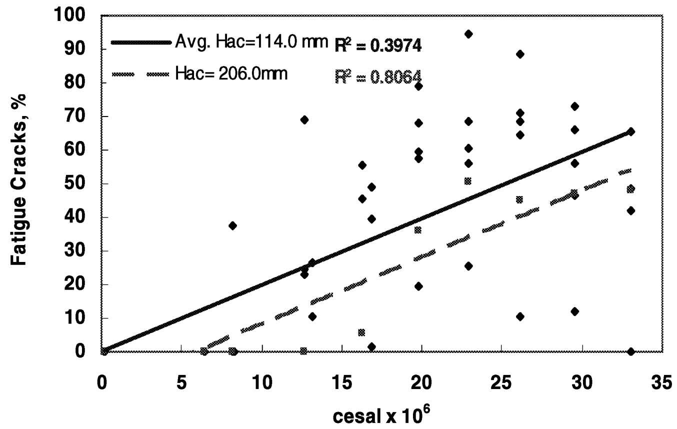

Fig. 3. Fatigue Cracks vs. Traffic for LTPP-California Sections with Different Overlay Thicknesses.

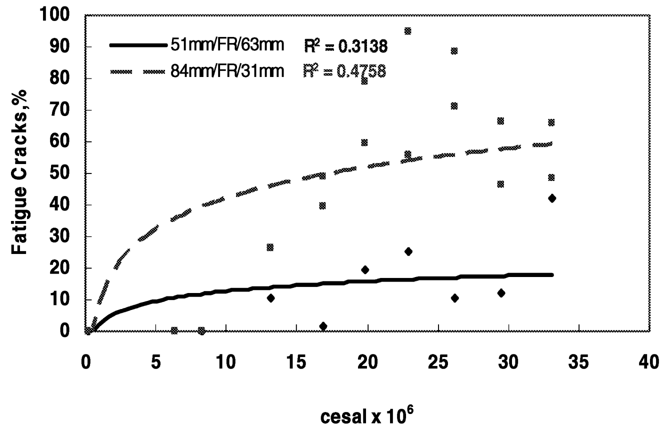

Fig. 4. Fatigue Cracks for LTPP-California Sections with Different Overlay Scenarios.

114.0*mm*. Note that the average annual ESAL on these sections was calculated to be about 2.6 million, as shown in Table 1. For such a high level of traffic, a thick overlay would be needed to reduce and/or retard fatigue cracks. The thick overlay would limit tensile strain at the bottom of the overlay while protecting the under-layers.

As part of the SPS-6 experiment, the order of overlay lifts was investigated. Two sections were built following Caltrans normal practice (from bottom to top) using about 30.0*mm* leveling course followed by a fabric reinforcement (FR) layer and a top layer of asphalt approximately 76.0*mm* thick. In another section, the bottom overlay lift was built with approximately 63.0*mm* thick, and this layer was followed by the FR layer and a top layer of approximately 51.0*mm* thick. The effect of the order in which overlay lifts were constructed on fatigue cracks is presented in Fig. 4. It can be seen in that sections with thick leveling course (63*mm*) exhibited lower percentages of fatigue cracks at the same cumulative traffic level, as compared with sections that followed Caltrans-normal-practice with a leveling course of 30.0*mm* thickness. With only a few sections analyzed, more sections and further analyses will be needed to draw more solid conclusions with regard to this issue

Fatigue Cracks Prediction Models

In this study the Statistical Package for Social Science (SPSS) was used in developing the regression models by employing the non-linear regression option [10]. For a reliable regression model, the explanatory variables should be such that there should not be a strong correlation amongst them. Highly correlated explanatory variables would weaken the prediction capability of the model by resulting in unstable regression coefficients, a problem referred to as multicollinearity [11]. To eliminate the effect of multicollinearity variables coining and/or transforming variables is used.

To select a model, some basic principles are followed: first, minimum Mean Square Error (MSE); the smallest MSE would result in the narrowest confidence intervals and largest test statistics. The model with the smallest MSE involving the least number of independent variables would be the most appropriate. However, a model with the absolute smallest MSE may not provide the best intuitive model. That is, a model providing a slightly larger MSE but with explanatory variables that are more relevant to the problem may be more desirable. Second, the model should be as simple as possible; or in other words, it should have as few explanatory variables as possible. Third, the larger the coefficient of determination, R^2, the better the model is. Fourth, the cause-and-effect relationship between the dependent variable and each of the explanatory variables should be relevant. Fifth, the model should satisfy the physical requirements of the boundary conditions.

Explanatory variables were combined, if necessary, and different model forms with different explanatory variables with and without interaction terms were examined to improve the model overall coefficient of determination (R^2). The following model forms with the highest R^2 and lowest MSE were selected.

Wet-with-Freeze (WF) Region:

$$FATG = 0.425(CESAL)^{1.423}\left(\frac{H_{pcc}}{H_{ac}} + BASE\right)^{0.364} \tag{1}$$

$R^2 = 0.55$ RMSE = 2.85 N = 130

Wet-with-no-Freeze (WNF) Region:

$$FATG = 1.21\times10^{4}\left(\frac{AGE}{H_{ac}}\right)^{2.41} \tag{2}$$

$R^2 = 0.76$ RMSE = 1.22 N = 29

LTPP-California Sections:

$$FATG = 1.975(CESAL)^{1.06}(H_{ac})^{-0.022} \tag{3}$$

$R^2 = 0.59$ RMSE = 20.36 N = 51

where:
FATG = Percentage area effected by fatigue cracking,
CESAL = Cumulative Equivalent Single Axle Load,
H_{pcc} = The depth of concrete slab,
H_{ac} = The depth of asphalt overlay(s),
BASE = Base type (0= bound, 1= un-bound),
AGE = Time between rehabilitation and survey dates,
R^2 = Coefficient of determination,
RMSE = Root Mean Squared Error,
N = Number of data points used to develop the models.

Note that traffic data (ESAL) for all sections (other than California sections) in the WNF region was missing from the LTPP

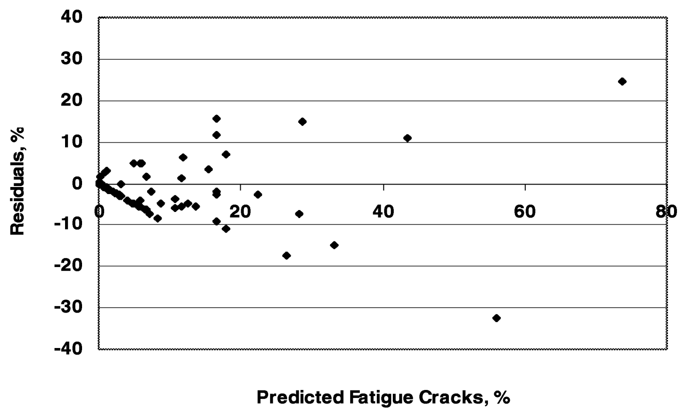

Fig. 5. Residuals vs. Predicted Fatigue Cracks for the WF Region Model.

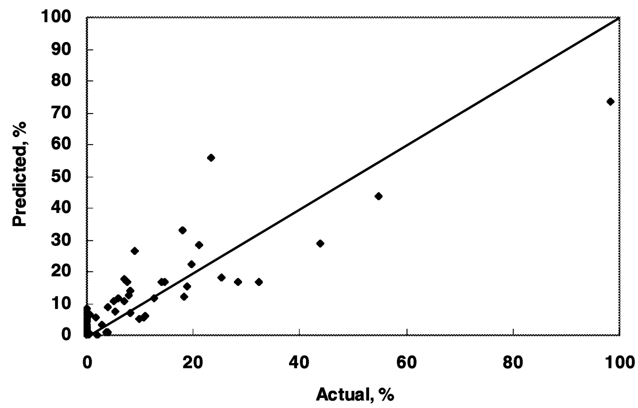

Fig. 8. Actual vs. Predicted Fatigue Cracks Percentage for the WF Region Model.

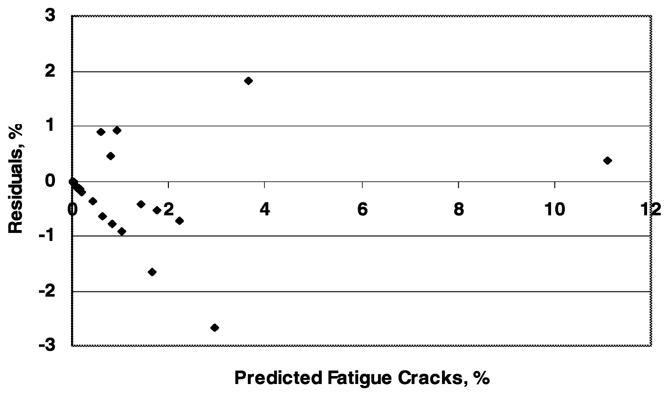

Fig. 6. Residuals vs. Predicted Fatigue Cracks for the WNF Region Model.

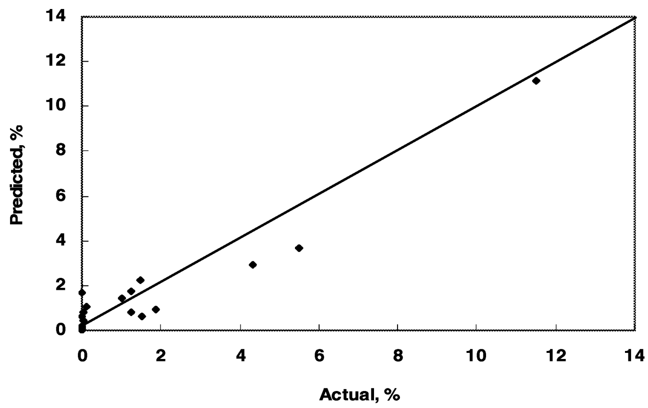

Fig. 9. Actual vs. Predicted Fatigue Cracks Percentage for the WNF Region Model.

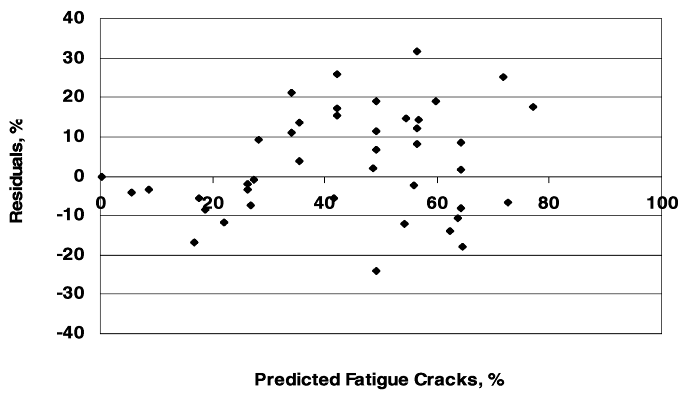

Fig. 7. Residuals vs. Predicted Fatigue Cracks for the LTPP-California Sections Model.

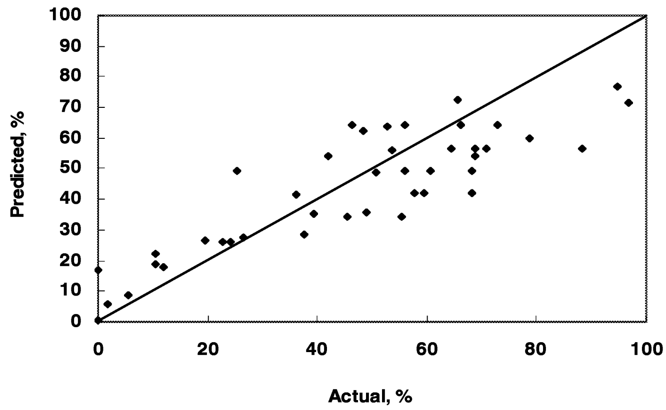

Fig. 10. Actual vs. Predicted Fatigue Cracks Percentage for LTPP-California Sections Model.

data and therefore *CESAL* was not included as a variable in developing the WNF region model. However, by using *AGE* as a variable it is believed that the effect of traffic is implicitly included in the model. It is also noted that the effect of concrete slab thickness (H_{pcc}) did not appear to be significant in both the WNF and California models. This is attributed to the fact that CS&O sections in these two regions had H_{pcc} with a very narrow range as seen in Table 1.

The significance of individual coefficients was tested employing *t*-test. At a confidence level of 95%, all of the individual coefficients are significant, as $t^* > 1.96$.

In order to check the robustness of the models, residuals are plotted against the percentages of predicted fatigue cracks in Figs. 5, 6, and 7 for the WF, WNF, and LTPP-California models, respectively. These plots help to detect multicollinearity among explanatory variables after the models are being developed [11]. No specific pattern is observed for the three models, ruling out multicollinearity among explanatory variables and ensuring well-specified models. The predicted fatigue crack percentages are

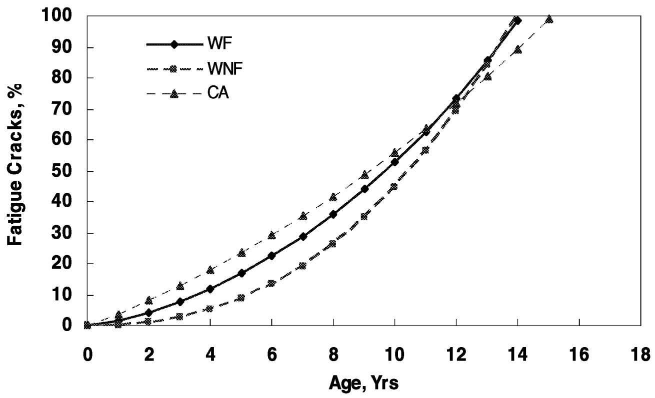

Fig. 11. Variation of Fatigue Cracks with Age.

plotted against the actual percentages with points clustering along the line of equality suggesting good predictability as shown in Figs. 8, 9, and 10 for the WF, WNF, and LTPP-California models, respectively.

Models Comparison

The models developed were used to compare the performance of the CS&O rehabilitation technique for different regions of the U.S. 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 as follows using the following procedures:

1- Initial KESAL was assumed based on ESAL values included in the LTPP-database. An initial *KESAL* equal to 2 million and a growth rate of 5 percent were assumed. The following equation was used to estimate *CESAL* [12]:

$$CESAL = \frac{KESAL_0}{\ln(1+i)}\left[(1+i)^n - 1\right] \tag{4}$$

where:
$KESAL_0$ = Initial annual ESAL (in millions) during the first year after rehabilitation,
i = Growth rate as a percent per year,
n = Number of years (or age of rehabilitated 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- Sections were assumed to be underlain by bound bases since all of the California sections were built using bound bases.

Presented in Fig. 11 is the variation of alligator cracks with age for sections in the WF region, the WNF region, and in California. As shown, sections in the WNF region are expected to outperform their counterparts in the WF region and in California up to an age of approximately 12 years. It is noted that all sections are expected to experience approximately 100 percent fatigue (alligator) cracks after about 14 years of service. The California sections are expected to exhibit approximately 56 percent alligator cracks after 10 years of service.

Conclusions

The focus of this paper was to evaluate fatigue (alligator) cracks for CS&O sections built in different regions in the U.S. and in California. Data for the analyses were collected from the SPS-6 module of the LTPP database. Listed below are the significant conclusions that can be drawn for the data analyzed:

1- Overlay thickness coupled with base type plays a significant role in minimizing fatigue cracks for sections rehabilitated using the CS&O technique.

2- Sections with bound bases in the WF region exhibit a reduction in fatigue cracks percentage over those with un-bound bases. The percentage reduction varies based on the weather region and the average 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 are needed for a conclusive finding.

4- Prediction models were developed for CS&O sections in different weather regions. The explanatory variables used in the models provide physically meaningful relationships with the response variables, which is an indication that the predictive 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.

Acknowledgments

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