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16. ABSTRACT

During the past 20 years hundreds of highway miles in California have been rehabilitated employing CS&O technique with little performance data available. This study was conducted to evaluate the performance of CS&O for sections built in different climatic regions in CA. The study also included developing performance prediction models for CS&O sections. These models can be incorporated into Caltrans Pavement Management System (PMS) to predict future performance, assist in LCCA and optimize the allocation of resources. The study was conducted in two phases. In phase I, CS&O sections built throughout the U.S. were identified in the Long Term Pavement Performance (LTPP) database. Inventory and performance data were then extracted and analyzed for these sections. Also, fourteen (14) CS&O sections in the Central Valley (CV) region of California were examined. Performance data for these sections were obtained from the Caltrans Pavement Condition Report (PCR) and were analyzed along with inventory data obtained from as-built sheets. In Phase II, seventeen (17) CS&O sections (eight (8) on the Central Coast and nine (9) in Northern California) were identified and examined. Performance data were extracted from the Caltrans PCR. As-built and maintenance history data were obtained from the Caltrans District 05 (D05) and District 02 (D02) offices. Data for these sections were combined with data from the Central Valley region (Phase I) to evaluate the performance of CS&O sections throughout California. Also, performance models were developed for three different regions, namely Central Valley (CV), Central Coast (CC), and Northern California (NCA).

The analysis results indicate that sections in CV reach an IRI threshold of 170 in/mile after about 10 years of service while sections in CC and NCA are expected to serve for more than 10 years before reaching this threshold value. Differences in construction techniques and quality control are evident for the three regions, as observed from the difference in initial IRI. Reflection cracking in the transverse and longitudinal directions is not a significant issue for the CS&O sections examined as part of this study. Alligator cracking 'A' and 'B' were reported for a considerable number of California sections investigated in this study. Also, alligator cracking 'C' was observed for a few number of sections in the CC, NCA and CC regions. Also, Alligator cracks of low, medium and high severity were reported for CS&O sections in the LTPP database.

The developed models provide a basis for predicting distress in Caltrans CS&O pavements. Among the model forms attempted, the nonlinear form proved to be the best fit, while still satisfying important boundary conditions. The ratio of asphalt overlay to concrete slab thickness proves to be a significant variable affecting all types of cracking in CS&O pavements. The results of a sensitivity-study suggest that age is the most significant factor affecting the deterioration of CS&O pavements. Annual traffic level, in terms of ESAL, and layer thickness ratio are secondary model variables influencing alligator cracking and IRI. Layer thickness ratio is a secondary model variable affecting reflective cracking.

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AN EVALUATION OF THE CRACK, SEAT AND OVERLAY METHOD IN CALIFORNIA

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Final Report

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This report summarizes the results of Phase II of a study titled "An Evaluation of Crack, Seat and Overlay Method in California", which was completed by the Department of Civil and Environmental Engineering at California Polytechnic State University, San Luis Obispo and in cooperation with the California Department of Transportation (Caltrans). The authors wish to thank Dr. David Lim and Dr. Joe Holland of the Caltrans Division of Research and Innovation (DRI) for their assistance and technical input on this project. The hard work of graduate student Reed Calkins is also acknowledged. Graduate student Tom Nguyen assisted during pavement coring and visual surveying. In addition, undergraduate students Ryan Milhous, Eva Klentos, and Alberto Reynoso assisted with the development of the logistic models.

DISCLAIMER STATEMENT

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ABSRACT

Crack, seat, and overlay (CS&O) is a technique used to rehabilitate Jointed Plain Concrete Pavement (JPCP). The intent of cracking a deteriorated concrete pavement is to create shorter concrete pieces, which help reduce horizontal slab movements and minimize the risk of reflection cracking. Seating after cracking is intended to reestablish the support between the broken slabs and the subbase/subgrade. During the past 20 years, hundreds of miles of highways in California have been rehabilitated using this technique; however, little performance data is available. Therefore, this study was conducted to evaluate the performance of this rehabilitation technique for sections built in different climatic regions in California. The study also included the development of performance prediction models for CS&O sections. These models can be incorporated into the Caltrans Pavement Management System (PMS) to predict future performance, assist in life-cycle cost analysis, and optimize the allocation of resources.

The study was conducted in two phases. In Phase I, CS&O sections built throughout the U.S. were identified in the Long Term Pavement Performance (LTPP) database. Inventory and performance data were then extracted and analyzed for these sections. Also, fourteen (14) CS&O sections in the Central Valley (CV) region of California were examined. Performance data for these sections were obtained from the Caltrans Pavement Condition Report (PCR) and were analyzed along with inventory data obtained from as-built sheets. In Phase II, seventeen (17) CS&O sections (eight (8) on the Central Coast and nine (9) in Northern California) were identified and examined. Performance data were extracted from the Caltrans PCR. As-built and maintenance history data were obtained from the Caltrans District 05 (D05) and District 02 (D02) offices. Data for these

sections were combined with data from the Central Valley region (Phase I) to evaluate the performance of CS&O sections throughout California. Also, performance models were developed for three different regions, namely Central Valley (CV), Central Coast (CC), and Northern California (NCA).

The analysis results indicate that sections in CV reach an IRI threshold of 170 in/mile after about 10 years of service while sections in CC and NCA are expected to serve for more than 10 years before reaching this threshold value. Differences in construction techniques and quality control are evident for the three regions, as observed from the difference in initial IRI. Reflection cracking in the transverse and longitudinal directions is not a significant issue for the CS&O sections examined as part of this study. Alligator cracking 'A' and 'B' were reported for a considerable number of the sections investigated in this study. Alligator cracking 'C' was observed for a few number of sections in each region. Also, alligator cracking of low, medium and high severity were reported in the LTPP database.

The developed models provide a basis for predicting distress in Caltrans CS&O pavements. Among the model forms attempted, the nonlinear form proved to be the best fit, while still satisfying important boundary conditions. The ratio of asphalt overlay to concrete slab thickness proves to be a significant variable affecting all types of cracking in CS&O pavements. The results of a sensitivity-study suggest that age is the most significant factor affecting the deterioration of CS&O pavements. Annual traffic level, in terms of ESAL, and layer thickness ratio are secondary model variables influencing alligator cracking and IRI. Layer thickness ratio is a secondary model variable affecting reflective cracking.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

1.1.1 Deterioration of PCC Pavements

Roadway maintenance is the major challenge of transportation departments seeking to extend the lives of roadways. Construction materials are in high demand and the cost of materials for highway maintenance is ever increasing. In addition, highways cannot go without maintenance for very long before safety becomes an important issue.

Highways that were constructed using Portland Cement Concrete (PCC) have shown long lasting durability with regular maintenance. In fact, many PCC highway sections have lasted longer than their design lives. However, as these pavements reach the end of their actual service lives, maintenance and restoration costs become high. In fact, deteriorated PCC slabs commonly need to be replaced when they reach the end of their service lives. Typical problems for these slabs include pumping, cracking, spalling, or other failures, all of which require extensive maintenance.

1.1.2 Rehabilitation Techniques for PCC Pavements

In the late 1950's engineers began to use Hot Mix Asphalt (HMA) concrete overlays 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 slabs reflected through the HMA. The main causes of reflection cracking were found to be the expansion and contraction of the concrete due to temperature changes, vertical movement of the concrete slabs due to softened base (commonly because of moisture intrusion), frost heave, and heavy vehicle traffic.

Three different rehabilitation techniques have been used to help reduce the potential for reflection cracking in HMA overlay. These techniques include: Crack, Seat, and Overlay (CS&O); Break, Seat, and Overlay (BS&O) and Rubblization. Each technique reduces slab length by cracking or breaking it to smaller isolated pieces, which reduces the tensile strain in the HMA overlay. The selection and performance of the rehabilitation techniques depends on the construction of the original slab and the condition of the pavement when rehabilitation is performed.

Slabs that were originally constructed with steel reinforcement continue to act as an entire slab unless the bond between concrete and steel is broken. Also, if slabs are cracked without eliminating the aggregate interlock between individual concrete pieces, then the strength of cracked slab is much higher than if that interlock is lost. Separating the steel from the concrete without breaking the aggregate interlock between the two slab pieces is difficult because separating the steel requires large amounts of energy. If a slab is not reinforced with steel, then it can be cracked by a similar method where the aggregate interlock is not lost between pieces and the slab is not left as a continuous piece before overlay. The energy required for this technique is lower and the slab pieces are more likely to retain the aggregate interlock.

With both of the above techniques, the pieces must be seated into the base layer to reestablish contact and to help prevent vertical movement. These methods depend on the original construction materials. If steel reinforcement exists in a slab, the first technique, break and seat, is used. If the slab is not reinforced, the second method, crack and seat, is used. These two techniques are not alternatives to each other because each one is used in a specific situation.

An alternative to either of these techniques is to completely destroy the slab by reducing it to loose aggregate particles that are usually less than 9 inches in any dimension. This technique is known as rubbilization and is commonly used for slabs with very little remaining structural strength.

1.2 RESEARCH INVESTIGATION

1.2.1 Objectives

The primary objectives of this Phase (II) research investigation included the following:

- Compare the performance of existing CS&O pavement sections in different climatic regions of California; and
- Develop performance prediction models for sections in the Central Coast (CC) and Northern California (NCA) regions.

1.2.2 Approach

To achieve the aforementioned objectives, a comprehensive literature review was completed. Performance data of seventeen (17) CS&O sections (eight (8) in the CC and nine (9) in the NCA regions) were extracted from the Caltrans PCR. Traffic data were obtained from Caltrans traffic count reports available on the Caltrans website. Sections inventory data were obtained from Caltrans construction records and as-built sections

In addition, pavement sections were cored to verify the thicknesses and types of different layers. Visual surveys were conducted for all seventeen sections. Analyses were then conducted and prediction regression models were developed for the CC and NCA regions.

1.2.3 Report Organization

The outcomes of the project are presented in the following chapters. Chapter 2 includes a summary of the Phase I research investigation. Chapter 3 includes a summary of the data extracted from Caltrans records and a comparison of pavement performance between regions. Chapter 4 describes the performance prediction models and the methods followed to develop these models. Finally, Chapter 5 concludes the study by summarizing the significant findings drawn from the data analyses.

CHAPTER 2

SUMMARY OF PHASE I RESEARCH INVESTIGATION

2.1 INTRODUCTION

In July of 2008, the investigators submitted a report to Caltrans titled "An Evaluation of the Crack, Seat, and Overlay Method in California" (Rahim and Fiegel 2008). This report summarized the results of an initial Phase I study on the performance of jointed plain concrete pavements (JPCP) rehabilitated using the crack, seat, and overlay (CS&O) technique. The research objectives and findings of the Phase I study are summarized in this chapter.

2.2 RESEARCH OBJECTIVES AND TASKS

The primary objectives of the Phase I research study were as follows: (1) evaluate the performance of sections rehabilitated using the CS&O technique; and (2) develop performance prediction models for sections rehabilitated using the CS&O technique. Numerous research tasks were completed in support of these objectives, including the following:

- Completing a comprehensive literature review on the CS&O technique and available data regarding pavement performance;
- Surveying pavement engineers and officials, nationwide, on their experience with the CS&O technique and observed pavement performance;
- Extracting relevant CS&O performance data from the Long Term Pavement Performance (LTPP) database;

- Evaluating the performance of fourteen (14) CS&O rehabilitated pavement sections in the Central Valley of California, as identified from the Caltrans pavement database; and
- Analyzing the performance data from the LTPP database and for the Central Valley sections to develop performance prediction models.

Important research findings and principal conclusions from the Phase I investigation are described in the following sections of the report.

2.3 PHASE I RESEARCH FINDINGS

2.3.1 Review of Literature

The Phase I report summarizes the general procedure followed and equipment employed when rehabilitating a concrete pavement using the crack, seat, and overlay method. The report also summarizes a number of important design factors that have been found to influence the performance of pavements rehabilitated using the CS&O technique, including subgrade preparation, slab size, and asphalt overlay thickness. Studies are referenced for recent CS&O projects occurring throughout the U.S.

Relative to CS&O work in California, Caltrans standard provisions require concrete slabs be cracked into two- to three-foot sections using a guillotine type drop hammer (PCC Pavement Rehabilitation Guidelines, Caltrans 2004). Cracking through the slab must be verified by coring test sections. Caltrans then requires placement of a 0.35-foot (105 mm) thick HMA overlay (minimum) and 0.10-foot Leveling Course (LC) with a reinforcing fabric interlayer (PCC Pavement Rehabilitation Guidelines, Caltrans 2004). However, as a result of a previous Caltrans study, it was proposed that the overlay consist of a 0.1-foot (30 mm) Dense Graded Asphalt Concrete (DGAC) leveling course, a layer of Reinforcing Fabric (RF), and a 0.50-foot (150 mm) layer of DGAC, where the need for structural adequacy governs (Wells et al. 1991). In the same study, it was reported that the reinforcing fabric in an asphalt concrete overlay over cracked and seated concrete pavement was used primarily as moisture barrier. However, this fabric can retard initial cracking an average of 1 year longer than overlays without the fabric.

As noted in the Phase I report, limited data exists in the literature relative to the performance of CS&O pavement sections. Researchers have used test sections to evaluate the occurrence of reflective cracking, rutting, and roughness for pavements rehabilitated using the CS&O technique (e.g. Felter, 1989; Choubane and Abdenour, 2005; Freeman, 2002; Harris, 1993; Heckel, 2002; Marks And Anderson, 1993; Witczak and Rada, 1992; and Wells et. al., 1991). However, few performance prediction models have been proposed. Witzak and Rada (1992) proposed models to predict the Pavement Condition Index (PCI) of asphalt concrete overlays for CS&O sections. Data from 250 CS&O test sites were used in the evaluation. Independent model variables included time, HMA overlay thickness, annual average precipitation, annual average temperature range, and subgrade modulus. Using data available at the time, Witczak and Rada (1992) projected that CS&O pavement sections would support traffic for 18 years before reaching a PCI of 50, which represents a commonly accepted rehabilitation point for heavily used pavements.

2.3.2 Nationwide Survey

Pavement engineers and officials, nationwide, completed a survey designed to solicit information regarding the current practice of rehabilitating concrete pavements. In addition, the survey queried these individuals on the availability of performance data for sections rehabilitated using the crack, seat and overlay technique. The survey was sent to all 50 U.S. DOTs and a transportation agency in Canada. Survey answers from the 25 engineers and officials who responded are summarized in the Phase I report (Rahim and Fiegel 2008). Of the DOT agencies that responded to the survey, none had developed CS&O performance prediction models. Those responding to the survey reported that reflection cracking and fatigue cracking are the most observed distresses for these types of rehabilitated pavements.

2.3.3 CS&O Sections in the LTPP Database

The performance of the CS&O technique was evaluated by examining data available in the Long Term Pavement Performance (LTPP) database. A search revealed sixty-one (61) 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 (46) in the WF region and fifteen (15) in the WNF region. Sections in the WNF region include eight (8) sections within California, which were eventually analyzed separately. Note that these eight (8) California sections were all in Siskiyou County bordering the State of Oregon. The WF and WNF terms are used to specify general climatic conditions for pavement sections within the LTPP database, namely Wet-with-Freezing (WF) and Wet-with-No-Freezing (WNF).

Inventory, layers, construction, traffic, materials, maintenance, and distress data were extracted from the database and used in the performance analyses. Performance data in the database were collected at varying intervals from annually to every four years. Tables 2.1, 2.2 and 2.3 summarize the available data for the WF region, the WNF region, and

California, respectively. Table 2.4 presents more detailed information for eight CS&O California sections that were well documented in the LTPP database. As shown in Table 2.4, two CS&O sections in California did not receive a Hot Mix Asphalt (HMA) overlay. Therefore, only six (6) California sections were considered in the analyses.

As summarized in Tables 2.1, 2.2, and 2.3, pavement distresses investigated in this study included the percentage of transverse cracking (TRANS), the percentage of longitudinal cracking (LONG), the percentage of fatigue cracking (ALLG), the International Roughness Index (IRI), and rut depth (RUT). CS&O performance was investigated by evaluating the effects of several explanatory (independent) variables, which are also summarized in Tables 2.1, 2.2, and 2.3. These variables included asphalt overlay thickness (H_{ac}), concrete slab thickness (H_{pcc}), traffic level (ESAL) and type of base layer (Base), and the age of pavement (Age). Performance was measured in terms of the aforementioned distresses. Performance analysis results for the LTPP data are summarized in the Phase I report in some detail and are not repeated here.

Table 2.1: Summary of variable ranges for LTPP sections in the WF region.

Variables		Description	Range	Units
Dependent	TRANS	Percentage area effected by transverse cracking	(0 to 8.93)	%
	LONG	Percentage area effected by longitudinal cracking	(0 to 36.5)	%
	ALLG	Percentage area effected by alligator cracking	(0 to 98.5)	%
	IRI	International Roughness Index	(50.8 to 207.8)	in/mile
	RUT	Depth of Rutting	(0.04 to .51)	in
Independent	Age	The difference between rehab. and survey dates	(0 to 15)	Years
	H_{ac}	The thickness of asphalt overlay	(4 to 11.5)	in
	H_{pcc}	The thickness of concrete slab	(7 to 10.2)	in
	Base	The type of base beneath the original slab (0= bound 1= unbound aggregate)	(0 to 1)	Binary
	ESAL	Equivalent Single Axle Loads per year	0.06 to 2.25	Million

Table 2.2: Summary of variable ranges for LTPP sections in the WNF[1] region.

Variables		Description	Range	Units
Dependent	TRANS	Percentage area effected by transverse cracking	(0.0 to 3.99)	%
	LONG	Percentage area effected by longitudinal cracking	(0.0 to 17.0)	%
	ALLG	Percentage area effected by alligator cracking	(0.0 to 11.5)	%
	IRI	International Roughness Index	(54.6 to 225.4)	in/mile
	RUT	Depth of Rutting	(0.04 to 0.24)	in
Independent	Age	The difference between rehab. and survey dates	(0.0 to 8.5)	Years
	H_{ac}	The thickness of asphalt overlay	(4 to 9.6)	in
	H_{pcc}	The thickness of concrete slab	(10 to 10)	in
	Base	The type of base beneath the original slab (0= bound 1= unbound aggregate)	(0 to 1)	Binary
	ESAL	Equivalent Single Axle Loads per year	NA[2]	Million

[1] WNF sections do not include California sections
[2] ESAL data not available

Table 2.3 Summary of variable ranges for the LTPP-California sections.

Variables		Description	Range	Units
Dependent	TRANS	Percentage area effected by transverse cracking	(0.0 to 13.7)	%
	LONG	Percentage area effected by longitudinal cracking	(0.0 to 58.0)	%
	ALLG	Percentage area effected by alligator cracking	(0.0 to 96.7)	%
	IRI	International Roughness Index	(43.6 to 196.7)	in/mile
	RUT	Depth of Rutting	(0.04 to .28)	in
Independent	Age	The difference between rehab. and survey dates	(0.0 to 12.5)	Years
	H_{ac}	The thickness of asphalt overlay	(3.7 to 8.1)	in
	H_{pcc}	The thickness of concrete slab	(8.3 to 8.7)	in
	Base	The type of base beneath the original slab (0= bound 1= unbound aggregate)	1	Binary
	ESAL	Equivalent Single Axle Loads per year	1.93 to 2.76	Million

Table 2.4 Construction data for California CS&O sections in the LTPP-data[1].

Sec. ID	Rehab. date	AC overlay Thick, in.	PCC, in.	Base Layer		Comment
				Type	Thick, in.	
0607	9/1/1992	4.8	8.4	CAM[3]	4.3	Overlay layer consists of one 4.8-in lift
0608	9/1/1992	8.1	8.3	CAM	4.2	Overlay layer consists of one 8.1-in lift
0659	8/31/1992	4.9	8.7	CAM	4.9	Overlay layer consists of one 4.9-in lift
0660	8/30/1992	4.2	8.3	CAM	4.8	Overlay consists of: 1.9-in HMA, 0.2-in interlayer, 2.3-in binder course
0661	8/30/1992	4.8	8.4	CAM	5.5	Overlay consists of: 3.3-in HMA, 0.2-in interlayer, 1.5-in binder course
0662[2]	5/26/1992	0.6	8.0	CAM	5.3	0.6-in surface treatment identified as AC type
0663[2]	5/13/1992	1.0	8.0	CAM	5.1	1.0-in Modified Latex Emulsion PC overlay
0664	9/1/1992	4.6	8.4	CAM	4.6	Overlay consists of: 3.2-in HMA, 0.2-in interlayer, 1.4-in binder course

1 Data from Tables SPS6_CRACK_SEAT_PCC and SPS6_LAYER
2 Sections excluded from the analyses
3 Cement Aggregate Mixture (CAM)

2.3.4 California Central Valley Sections

2.3.4.1 Section Inventory: Caltrans identified fourteen (14) CS&O sections in the California Central Valley, which were examined as part of the Phase I study. These sections are summarized in Table 2.5. Data extracted from the Caltrans Pavement Condition Report (PCR) and spreadsheets provided by Caltrans included construction dates, distress survey results, and traffic data. However, traffic data for all of the sections were not complete. Missing data were estimated using extrapolation; then, the 18-kips Equivalent Single Axle Load (ESAL) for each section was determined. Distresses obtained from the Caltrans PCR and spreadsheets included percentage alligator cracks, percentage transverse cracks, percentage longitudinal cracks, and IRI. Rutting was reported as "True" or "False" and not in terms of rut depth. A summary of the distresses observed for the Caltrans-sections is presented in Table 2.6.

Table 2.5 Section locations and CS&O rehabilitation dates.

County	Route	Bound	PM[1] Range	CS&O Date
Fresno (Fre)	I-05	SB[2] and NB[3]	20.4 - 66.1	1995
Fre	SR99	SB and NB	20.2 - 31.6	2000
Kern (Ker)	I-05	NB	4.4 – 10.2	1995
Ker	I-05	SB	44.8 – 62.6	2002
Ker	I-05	SB	73.0 – 82.1	1997
Ker	SR-58	EB[4]	77.0 – 81.0	1998
Ker	SR-99	SB	0.0 – 9.0	1999
Ker	SR-99	NB	50.2 – 54.0	2001
Ker	SR-99	NB	54.0 – 58.0	1996
Kings (Kin)	I-05	SB	0.0 – 16.0	1997
Tulare (Tul)	SR-99	NB	0.0 – 0.1	1996
Tul	SR-99	NB	12.8 – 18.0	1998

[1] Post Mile [2] South Bound [3] North Bound [4] East Bound

Table 2.6 Summary of variables' range for Caltrans sections.

Variables		Description	Range	Units
Dependent	TRANS	Percentage area effected by transverse cracking	(0.0 to 5.0)	%
	LONG	Percentage area effected by longitudinal cracking	(0.0 to 8.0)	%
	ALLG[1]	Percentage area effected by alligator cracking	(0.0 to 100)	%
	IRI	International Roughness Index	(31 to 227)	in/mile
Independent	Age	Difference between CS&O rehab. and survey dates	(0.0 to 9.0)	Years
	H_{ac}	The thickness of asphalt overlay	(4.0 to 6.5)	in
	H_{pcc}	The thickness of cracked and seated concrete slab	(8 to 13.5)	in
	Base	The type of base beneath the original slab (0= bound 1= unbound aggregate)	1	Binary
	ESAL	Equivalent Single Axle Loads per year	1.2 to 4.1	Million axle

[1] Alligator type A and type B

Table 2.5 shows that the lengths of the CS&O sections ranged from 0.1 to 45.7 miles. For meaningful performance analyses to be completed, the sections needed to be uniform in terms of layer thicknesses and type throughout their entire length. As-built records were searched in an attempt to obtain layer thicknesses. The as-built records specified 4 inches of HMA over existing cracked and seated PCC for all the sections. As part of this study, the different sections were cored to verify layer uniformity. In addition, each section was visually surveyed so that observed distresses could be mapped and quantified. Table 2.7 presents specific section information including County, route number, bound direction, post mile, and the date when the sections were cored and visually surveyed. Each section included in the study was assigned a section ID, as shown in Table 2.7.

Table 2.7 Sections IDs and visual survey dates.

County	Route/Dir	PM[1]	# of Cores	Sec_ID	Date Cored/ Surveyed
Fresno	05 /N	25.5	2	Fre_5N_25.5	11/28/2007
Fresno	05 /S	26.5	2	Fre_5S_26.5	11/27/2007
Fresno	99 /N	25.0	2	Fre_99N_25	11/29/2007
Fresno	99 /S	26.0	2	Fre_99S_26	11/30/2007
Kern	05 /N	5.5	2	Ker_5N_5.5	12/4/2007
Kern	05 /S	78.75	2	Ker_5S_78.7	11/20/2007
Kern	05 /S	51.5	2	Ker_5S_51.5	12/5/2007
Kern	58 /E	77.5	2	Ker_58E_77.5	8/30/2007
Kern	99 /N	53.0	2	Ker_99N_53	8/27/2007
Kern	99 /N	55.0	2	Ker_99N_55	8/27/2007
Kern	99 /S	8.0	2	Ker_99S_8	8/30/2007
Kings	05 /S	6.0	2	Kin_5S_6	11/21/2007
Tulare	99 /N	0.1	2	Tul_99N_0.1	8/28/2007
Tulare	99 /N	14.5	2	Tul_99N_14.5	8/28/2007

[1] Post mile where cores were extracted

Two cores spaced approximately 1,000 feet apart were removed from each pavement section. Each core was drilled through the asphalt and into the base layer. The post miles shown in Table 2.7 represent the approximate midpoint between the two core locations. Each core was later examined to measure layer thicknesses. Results are presented in Table 2.8. Photographs of the cores are included in the Phase I report.

Even though the cores were only about 1,000 feet apart, variations in layer thicknesses and type were encountered. Therefore, we only considered distress data within about 1,000 feet, plus or minus, of the coring locations. This decision was made to limit errors associated with the layer thicknesses. No distress survey data for section Tul_99N_0.1 was provided as it was believed that this section was a continuation of section Ker_99N_55. However, cores extracted from these two sections showed significant differences in layer thicknesses, as shown in Table 2.8.

2.3.4.2 Transverse Cracks: Figures 2.1 and 2.2 show the relationships between transverse cracks and the Cumulative ESAL (CESAL) for sections with different overlay thicknesses and thickness ratios, respectively. The two figures show that transverse cracking tends to decrease as the overlay thickness and thickness ratio increase. A similar trend was observed for the LTPP-California sections, as discussed in the Phase I report. For the ranges of overlay thickness available, trend lines in Figure 2.1 suggest that transverse cracks start almost simultaneously. However, for a CESAL of approximately 25 million, which is approximately equivalent to 10 years of service life for an average annual KESAL of 2.6 million, a 1-inch thicker overlay would reduce transverse cracks by approximately 3 percent.

Table 2.8 Layers thicknesses measured from cores removed from each section.

Section ID	Core #	HMA			PCC[1], in.	Base	
		# of layers	Thick, in	Fabric		Thick, in.	Type
Fre_5N_25.5	1	3	6.00	yes	8.75	3.0	CTB[2]
	2	3	6.00	yes	8.50	5.25	CTB
Fre_5S_26.5	1	3	5.25	yes	9.00	3.75	CTB
	2	3	4.50	yes	8.75	3.75	CTB
Fre_99N_25	1	3	5.25	yes	10.25	8.75[b]	PCC
	2	3	5.50	yes	8.00	8.75[b]	PCC
Fre_99S_26	1	3	5.25	yes	9.40	2.5	CTB
	2	3	5.25	yes	9.50	4.25	CTB
Ker_58E_77.5	1	3	4.00	yes	8.00	NA[3]	CTB
	2	3	5.25	yes	8.00	NA	CTB
Ker_5N_5.5	1	2	5.00	yes	9.00	4.75	CTB
	2	2	5.00	yes	9.25	NA	CTB
Ker_5S_51.5	1	3	5.50	yes	8.75	4.25	CTB
	2	3	5.00	yes	8.50	4.25	CTB
Ker_5S_78.75	1	2	4.75	yes	9.25	5.00	CTB
	2	2	5.00	yes	9.00	5.25	CTB
Ker_99N_53	1	3	4.75	yes	13.50	NA	CTB
	2	3	4.75	yes	12.40	NA	CTB
Ker_99N_55	1	3	4.75	yes	8.25	3.0	CTB
	2	3	4.65	yes	8.50	2.5	CTB
Ker_99S_8	1	2	4.00	yes	8.75	------[4]	------[4]
	2	2	3.90	yes	9.00	------	------
Kin_5S_6	1	3	5.50	yes	9.5	5.5	CTB
	2	3	4.50	yes	9.25	NA	CTB
Tul_99N_0.1	1	3	5.50	yes	12.40	------	------
	2	3	5.00	yes	13.50	------	-----
Tul_99N_14.5	1	4	6.00	yes	8.13	NA	CTB
	2	4	6.00	yes	8.00	2.75	CTB

[1] Portland Cement Concrete
[2] Cement Treated Base
[3] Not Available (base core crushed while extracted)
[4] No CTB base was found

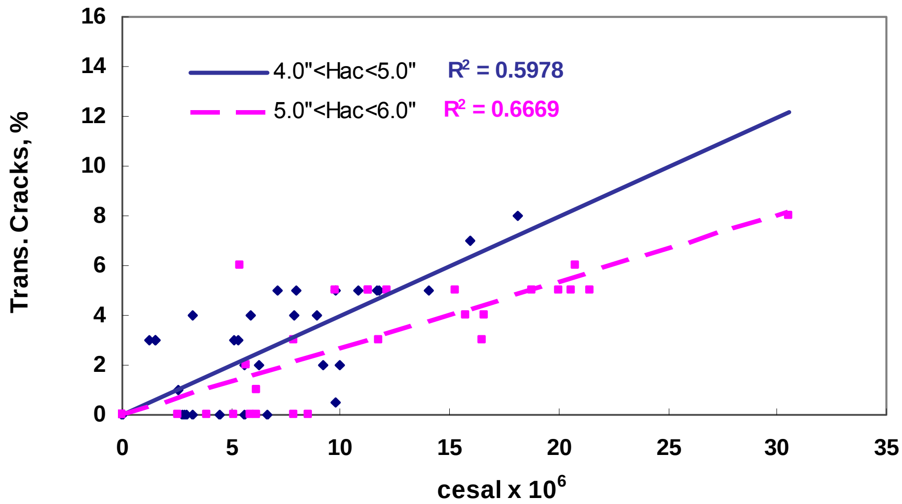


Figure 2.1 Transverse cracks for sections with different overlay thicknesses in the Central Valley.

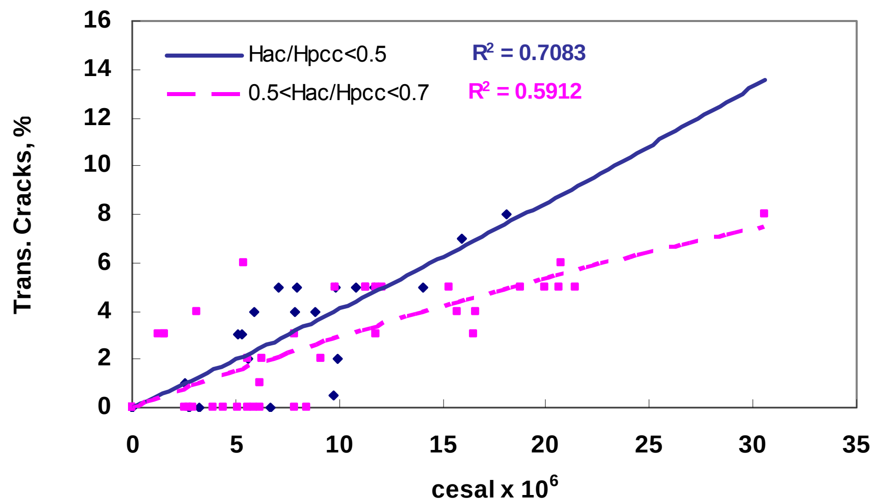


Figure 2.2 Transverse cracks for sections with different thickness ratios in the Central Valley.

2.3.4.3 Longitudinal Cracks: From the trend lines shown in Figures 2.3 and 2.4, the longitudinal cracks start at approximately the same time for the two overlay thickness and thickness ratio ranges, respectively. Overlays with thicknesses ranging from about 5 to 6 inches slightly reduced the percentage of longitudinal cracks over those with overlay thicknesses ranging from 4 to 5 inches. Similar trends are evident in Figure 2.4 for overlays with different thickness ratios.

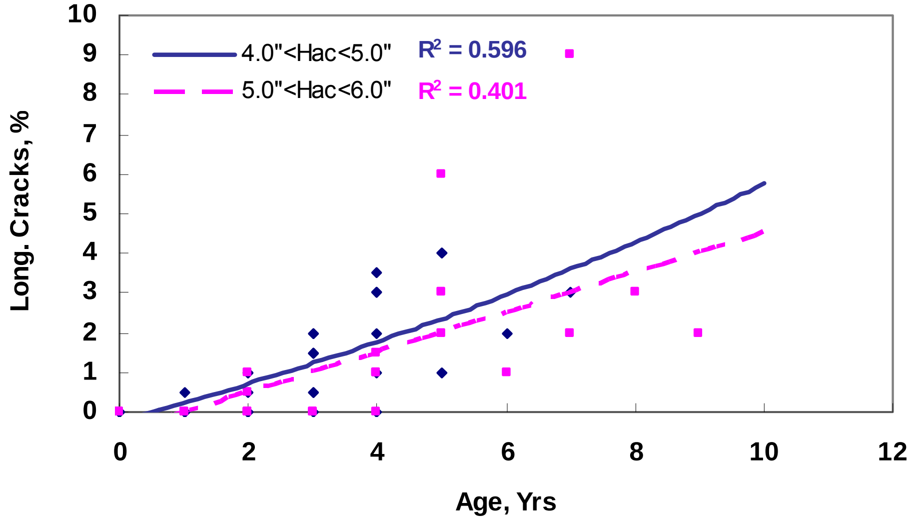


Figure 2.3 Longitudinal cracks for sections with different overlay thicknesses in the Central Valley.

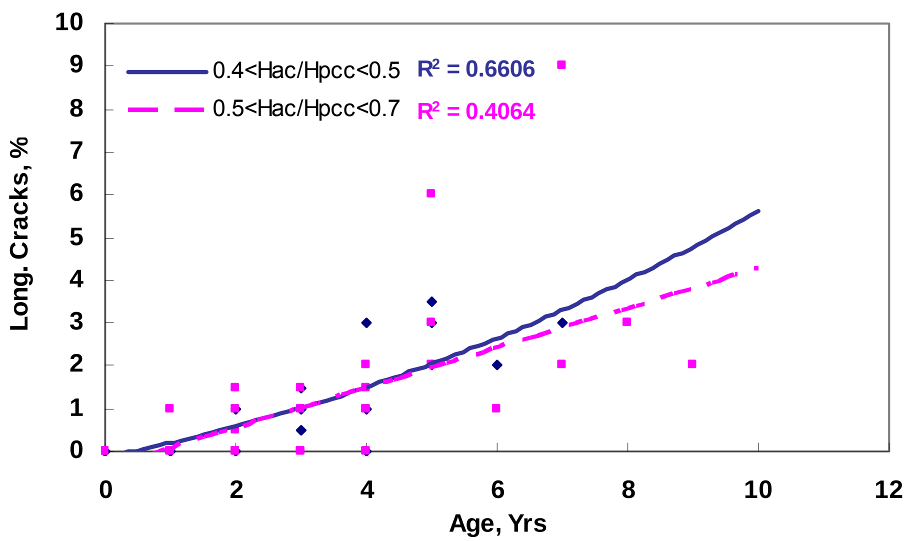


Figure 2.4 Longitudinal cracks for sections with different thickness ratios in the Central Valley.

2.3.4.4 Alligator Cracks 'A' and 'B': For the range of data available and from the trend lines in Figures 2.5 and 2.6, it can be seen that overlay thickness ratio has a more significant effect on alligator cracking than the thickness of overlay itself, especially at high cumulative traffic levels. For the same cumulative ESAL, pavement sections with thickness ratios in the range of 0.5 to 0.7 outperformed sections with thickness ratios in the range of 0.4 to 0.5, as shown in Figure 2.6.

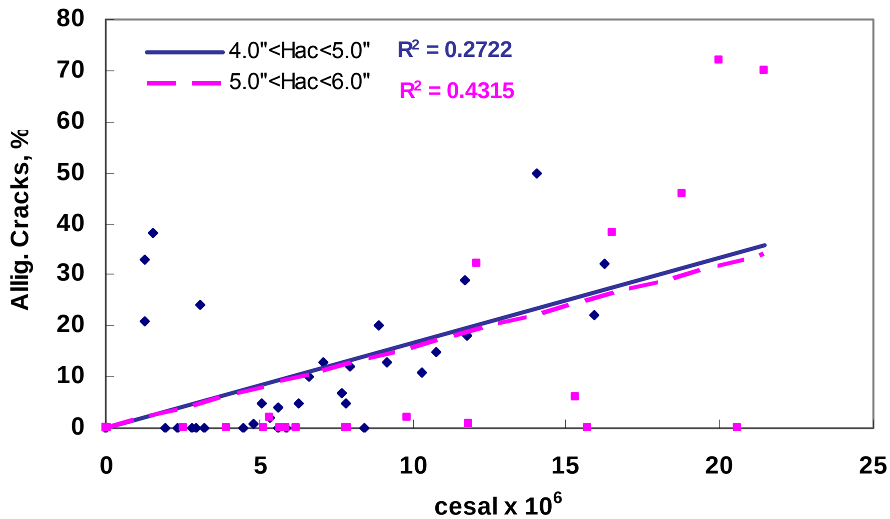


Figure 2.5 Alligator cracks for sections with different overlay thicknesses in the Central Valley.

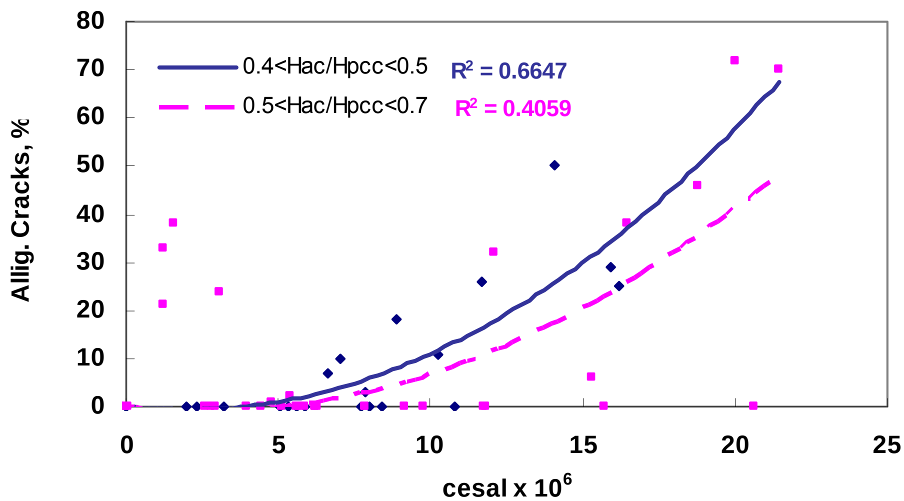


Figure 2.6 Alligator cracks for sections with different thickness ratios in the Central Valley.

2.3.4.5 IRI: The effect of overlay thickness and thickness ratio on IRI values for CS&O sections in the Central Valley is presented in Figures 2.7 and 2.8, respectively. The trend lines seen in Figure 2.7 suggest that sections with overlay thicknesses in the range of 5 to 7 inches exhibited lower initial IRI values than sections with overlay thicknesses in the range of 4 to 5 inches. As the cumulative traffic increases, IRI for the two thickness groups increases. At cumulative traffic levels equal to approximately 20 million repetitions, sections within the two thickness ranges exhibit the same IRI value. A similar trend can be seen in Figure 2.8 for the effect of thickness ratio.

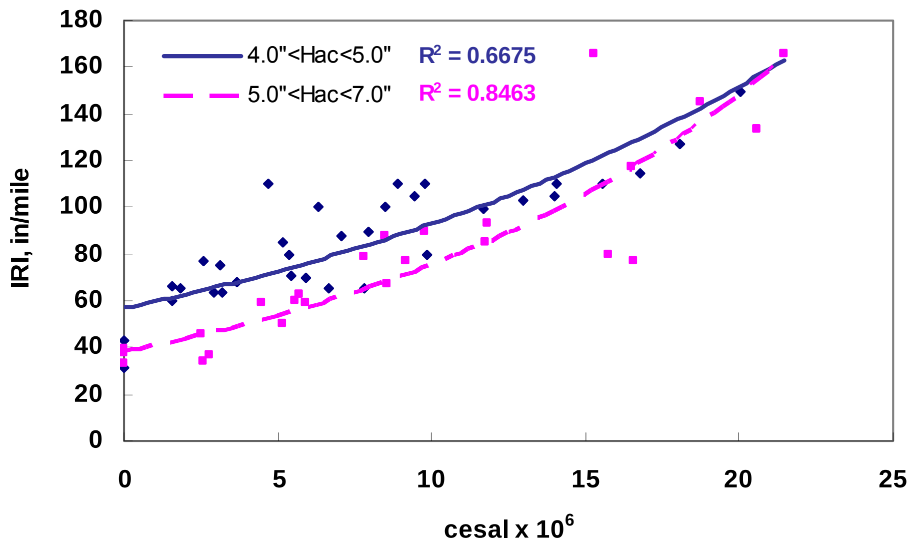


Figure 2.7 IRI for sections with different overlay thicknesses in the Central Valley.

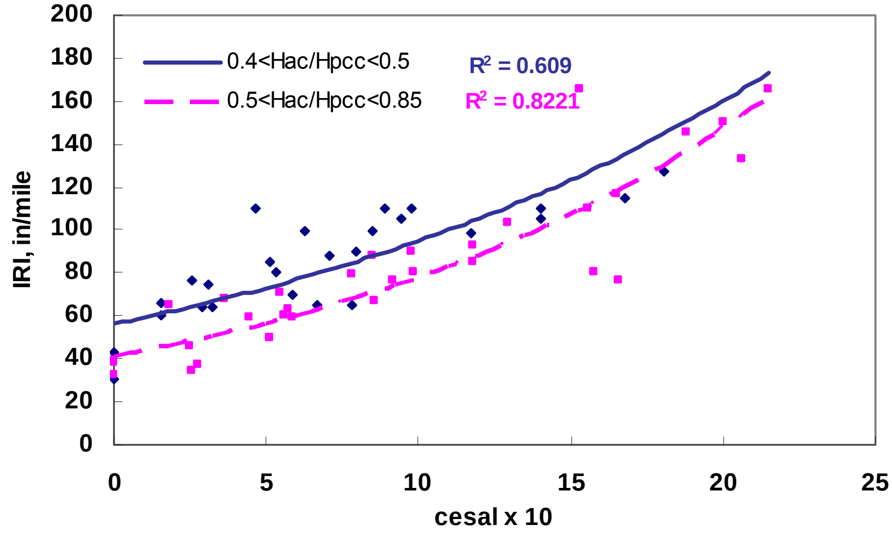


Figure 2.8 IRI for sections with different thickness ratios in the Central Valley.

2.3.5 Performance Prediction Models

The typical procedure for modeling pavement performance is to employ time series data in the development of regression models. In the Phase I study, regression models were developed for five (5) different response variables: alligator cracking, transverse cracking, longitudinal cracking, IRI, and rutting. Data extracted from the LTPP database were used to develop separate models for the Wet–with-Freeze (WF), Wet–with-No-Freeze (WNF), and California regions. At the same time, data obtained from Caltrans for fourteen (14) sections in the Central Valley were evaluated to develop regression models for four response variables: alligator cracking, transverse cracking, longitudinal cracking, and IRI. The Phase I report describes in some detail the regression modeling techniques that were employed.

2.3.5.1 LTPP-data Models: The LTTP-data performance models are summarized in the tables 2.9 through 2.13. Variable definitions, appropriate units, and data ranges are found in Tables 2.1, 2.2 and 2.3.

Table 2.9: Transverse Cracking (*TRANS*) Performance Models for the LTTP-Data

Region	LTPP-Data Performance Model		
WF Region	$TRANS = 0.1954(AGE)^{1.25}(ESAL)^{0.1335}\left(\frac{H_{pcc}}{H_{ac}} + BASE\right)^{0.347}$		
	$R^2 = 0.69$	RMSE = 1.34	N = 170
WNF Region	$TRANS = 0.411(AGE)^{1.59}(H_{ac})^{-0.892}$		
	$R^2 = 0.63$	RMSE = 0.75	N= 37
California	$TRANS = 0.1752(CESAL)^{0.7112}\left(\frac{H_{ac}}{H_{pcc}}\right)^{-2.335}$		
	$R^2 = 0.51$	RMSE = 2.98	N = 57

Notes: AGE: The difference between CS&O rehab. and survey dates in years
H_{ac}= The thickness of asphalt overlay and H_{pcc}= The thickness of cracked and seated concrete slab
ESAL: Equivalent Single Axle Loads per year, in millions
CESAL = Cumulative Equivalent Single Axle Load, in millions
R^2 = Coefficient of determination, RMSE = Root Mean Squared Error
N = Number of data points used to develop the models

Table 2.10: Longitudinal Cracking (*LONG*) Performance Models for the LTTP-Data

Region	LTPP-Data Performance Model		
WF Region	$LONG = 1.09(AGE)^{1.18}\left(\frac{1}{H_{ac}} + BASE\right)^{0.131}$		
	$R^2 = 0.57$	RMSE = 5.93	N = 188
WNF Region	$LONG = 0.4734(AGE)^{1.79}\left(\frac{1}{H_{ac}} + BASE\right)^{0.06}$		
	$R^2 = 0.86$	RMSE = 2.51	N = 39
California	$LONG = 0.70(CESAL)^{0.98}\left(\frac{H_{ac}}{H_{pcc}}\right)^{-0.796}$		
	$R^2 = 0.523$	RMSE = 10.66	N = 57

Table 2.11: Alligator Cracking (*ALLG*) Performance Models for the LTTP-Data

Region	LTPP-Data Performance Model		
WF Region	$ALLG = 0.425(CESAL)^{1.423}\left(\frac{H_{pcc}}{H_{ac}} + BASE\right)^{0.364}$		
	$R^2 = 0.55$	RMSE = 8.13	N = 130
WNF Region	$ALLG = 4.969\left(\frac{AGE}{H_{ac}}\right)^{2.41}$		
	$R^2 = 0.76$	RMSE = 1.22	N = 29
California	$ALLG = 1.84(CESAL)^{1.06}(H_{ac})^{-0.022}$		
	$R^2 = 0.59$	RMSE = 20.36	N = 51

Table 2.12: Rutting Performance (*RUT*) Models for the LTTP-Data

Region	LTPP-Data Performance Model		
WF Region	$RUT = 0.0952(CESAL)^{0.3033}\left(\frac{H_{pcc}}{H_{ac}} + BASE\right)^{0.073}$		
	$R^2 = 0.53$	RMSE = 0.063	N = 304
WNF Region	$RUT = 0.27(AGE)^{0.30}(H_{ac})^{-0.68}$		
	$R^2 = 0.51$	RMSE = 0.102	N = 53
California	$RUT = 0.0316(CESAL)^{0.48}$		
	$R^2 = 0.44$	RMSE = 0.036	N = 81

Table 2.13: IRI Performance Models for the LTTP-Data

Region	LTPP-Data Performance Model		
WF Region	$IRI = 69.502 + (AGE)^{1.6764}\left(\dfrac{ESAL}{H_{ac}}\right)^{0.164}(1 + BASE)^{-1.103}$		
	$R^2 = 0.50$	RMSE = 11.8	N = 320
WNF Region	$IRI = 104.658 + 4.758AGE - 9.059H_{ac} + 36.11BASE$		
	$R^2 = 0.49$	RMSE = 5.82	N = 35
California	$IRI = 47.78 + (CESAL)^{1.07}\left(\dfrac{H_{ac}}{H_{pcc}}\right)^{-1.242}$		
	$R^2 = 0.62$	RMSE = 22.51	N = 270

2.3.5.2 Caltrans-Data Models: The Caltrans-data updated performance models (based on data for sections in the California Central Valley) are summarized in Table 2.14.

Table 2.14: Performance Models for the Caltrans-Data

Alligator Cracks 'A' and 'B', %	$ALLIG = 0.009\,(ESAL)^{1.789}(AGE)^{3.03}\left(\dfrac{H_{ac}}{H_{pcc}}\right)^{-1.771}$		
	$R^2 = 0.67$	RMSE = 10.22	N =98
Transverse Cracks, %	$TRANS = 0.154\,(AGE)^{1.272}\left(\dfrac{H_{ac}}{H_{pcc}}\right)^{-1.275}$		
	$R^2 = 0.70$	RMSE = 1.24	N= 101
Longitudinal Cracks, %	$LONG = 0.01\,(AGE)^{2.367}\left(\dfrac{H_{ac}}{H_{pcc}}\right)^{-3.623}$		
	$R^2 = 0.58$	RMSE = 4.70	N = 132
IRI, in/mile	$IRI = 52.49 + 14.922\left(\dfrac{ESAL \times AGE}{H_{ac}}\right)^{1.37}$		
	$R^2 = 0.60$	RMSE = 23.68	N = 129

2.4 MODELS COMPARISON

Models developed using data extracted from LTPP database were used to compare the performance of the CS&O rehabilitation technique in different regions. Also compared were the models that were developed for California sections using both the LTPP-data and the Caltrans-data. The final report for Phase I includes a detailed discussion of the model comparison.

2.5 PHASE I CONCLUSIONS

Listed below are the principal conclusions that were formulated based on the results of the Phase I research study:

- 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.
- Overlay thickness coupled with the ratio of overlay thickness to concrete slab thickness plays a significant role in minimizing transverse cracks for CS&O sections. However, this was not the case with respect to longitudinal cracks.
- Overlay thicknesses in the range of 4 to 6 inches perform similarly in terms of alligator cracks for sections in the Central Valley. However, by increasing the overlay thickness to 8 inches for the LTPP-California sections, the appearance of alligator cracks is retarded by approximately 2.5 years and crack density is reduced by approximately 10 percent at all service lives.
- In terms of transverse and alligator cracks, sections founded on bound bases exhibit a reduction in cracks percentage in comparison with those founded on un-bound bases.

The percentage reduction varies based on the weather region and the average overlay thickness.

- Based on the limited data available for the LTPP-California sections, increasing the leveling course thickness from 1 to 2 inches helps to reduce transverse and alligator cracks in LTPP-California sections. However, more data is needed for a conclusive finding.
- For sections with bound bases in the WF region, thick overlays provide a smoother surface (lower initial and over time IRI). However, the effect of overlay thickness on IRI for sections with un-bound bases in the WF region does not appear to be significant. This finding is reversed for sections in the WNF region.
- LTPP sections in northern California have initial IRI values that are smaller than those found for sections in the WF and WNF regions. However, California sections develop higher IRI values over time, as compared to those sections in the WF and WNF regions. This could be attributed to the fact that the LTPP-California sections exhibit smaller average overlay thicknesses and are subject to higher traffic levels.
- At the similar cumulative traffic levels, the LTPP-California sections outperform sections in the WF and WNF regions with respect to rut depth.
- CS&O Caltrans sections in the Central Valley region of California are expected to generally outperform LTPP sections in Northern California (all in Siskiyou County) over the 10-year design life, except when examining performance in terms of IRI.
- Based on the prediction models developed in this study, CS&O sections built following Caltrans normal practice are expected to develop approximately 7 percent transverse cracks, 25 percent longitudinal cracks, and 100 percent alligator cracks

(‘A’ and ‘B’) during the 10-year design period. However, the predicted IRI value of 183 inch/mile for these sections, at the end of the 10-year design period, is expected to exceed the 170 inch/mile threshold specified by Caltrans.

- Alligator cracks ‘C’ is not a concern in CS&O sections built in the Central Valley region.
- The use of base type as a categorical variable helps account for the effect of base type on the performance.

CHAPTER 3

DATA ANALYSES AND DISCUSSION

3.1 INTRODUCTION

The performance of the Crack, Seat, and Overlay (CS&O) rehabilitation technique is evaluated in this chapter. Data obtained from Caltrans PCR for eight (8) CS&O sections in the Central Coast (CC) region and nine (9) sections in the Northern California (NCA) region were used in the analyses. Distresses that were investigated in this study included alligator (fatigue) cracking, longitudinal cracking, transverse cracking, and the International Roughness Index (IRI). Rutting distress was not quantified; rather, it was reported as True (rutting exists) or False (no rutting).

The effect of several explanatory variables on CS&O performance was investigated. Explanatory variables that are expected to affect performance include overlay properties and thickness, concrete slab thickness, base type and thickness, traffic level, weather conditions, pavement age, and drainage conditions. The limited data available in the Caltrans Pavement Condition Report (PCR), as-built plans, and construction records precluded the use of a number of the aforementioned explanatory variables. Therefore, the performance prediction models were developed using explanatory variables available from Caltrans database, which include overlay and concrete slab thicknesses, pavement age, and traffic load. The performance of CS&O sections from Phase II for the CC and NCA regions and Phase I for Central Valley (CV) region are compared in this chapter.

3.2 CALTRANS PAVEMENT CONDITION SURVEY (PCS)

The California state highway network is surveyed each year to evaluate pavement surface conditions (Caltrans Pavement Survey Evaluation Manual, January 2000). During this survey, the severity and extent of different surface distresses are observed and recorded. The ride quality in terms of International Roughness Index (IRI) is also measured. Per the Pavement Condition Survey (PCS) manual, flexible pavements are surveyed by identifying and measuring distresses over 100-foot sample sections, over which non-load related distresses are also rated. Multilane highways are normally surveyed in the outside lanes where the majority of distresses exist due to heavy truck travel.

During the survey, the number of transverse cracks, the total length of longitudinal cracks, and alligator cracks are measured as they exist in each wheel path (Caltrans Pavement Survey Evaluation Manual, January 2000). The following is a brief discussion of distresses that are quantifiably measured and reported in Caltrans PCR. These distresses were employed in this study in analyzing pavement performance.

3.2.1 Alligator Cracks

Alligator cracks are considered load-related distress caused by vehicle wheel loads. These cracks can develop due to insufficient load carrying capacity of the roadbed or due to fatigue failure of asphalt surface. The PCS classifies alligator cracks into three categories:

1- Alligator 'A' cracking is characterized by a single longitudinal crack in the two wheel paths and is measured in feet;

2- Alligator 'B' cracking is characterized by interconnected cracks forming a series of small polygons in the two wheel paths and is measured in feet; and

3- Alligator 'C' cracking is characterized by interconnected cracks outside the two wheel paths forming a series of small polygons and is measured in feet. Alligator ‘C’ is not quantified in the PCR, but rather reported as “False” (for no cracks) or “True” (in case cracks exist).

Alligator cracks ‘A’ and ‘B’ were combined and used for analyses in this study. Alligator cracks ‘C’ are not considered a concern in CS&O sections investigated in this study as it was reported “False” (not existing) in the PCR for the sections included in this research study.

3.2.2 Transverse Cracks

Transverse cracks appear at right angles to the centerline of the road and are not associated with vehicle loads. These cracks are caused primarily by contraction/shrinkage of the asphalt surface or reflection from underlying joints. The severity of transverse cracking is based on crack width (less than or greater than 0.25 inch). The extent is recorded as the total number of transverse cracks (up to a maximum of 5) within the 100-foot sample section being surveyed.

3.2.3 Longitudinal Cracks

Longitudinal cracks are single cracks parallel to the centerline of the roadway between the two wheel paths. These cracks are not associated with vehicle wheel loads. Causal factors for longitudinal cracks include the contraction and shrinkage of asphalt surface, reflection from underlying joints, and poorly constructed longitudinal joints. The severity of longitudinal cracking is based on crack width (less than or greater than 0.25 inch). The extent is based on the total length of all longitudinal cracks in the 100-foot sample section being surveyed. The total of all Longitudinal cracks in the sample area are rated as being <100 feet, between 100 to 200 feet, or > 200 feet (PCS, 2000).

3.2.4 International Roughness Index (IRI)

IRI summarizes the longitudinal surface profile in the wheel path. IRI data is collected by either a topographic survey or a mechanical profilometer. IRI is normally presented in in/mile or m/km (Huang, 2004). Information regarding the International Roughness Index (IRI) and how it is measured is not covered in the PCS manual.

3.3 SECTIONS DATA

Seventeen (17) sections (eight (8) in the CC region and nine (9) in NCA region) were identified and selected for this phase of the research. Section age was used as the main selection criterion; sections that were in service for ten (10) years or more were selected to ensure sufficient performance data. Distress data were extracted from Caltrans Pavement Condition Report (PCR). Inventory, layer, construction, material, and maintenance data were obtained from Caltrans as-built plans and construction records. Traffic data were extracted from Caltrans traffic count spreadsheets available at http://traffic-counts.dot.ca.gov/. These data were used to determine Equivalent Single Axle Loads (ESALs) for the pavement sections. Conversions were conducted using factors obtained from Table 613.3A in Caltrans Highway Design Manual (HDM) (http://www.dot.ca.gov/hq/oppd/hdm/pdf/english/chp0610.pdf, accessed January 2010).

3.3.1 Central Coast (CC) Sections

Eight CS&O sections that had been in service for at least ten (10) years in the central coast (CC) region were identified and selected in this study. All the sections are located on State Route (SR) 101 in San Luis Obispo (SLO) and Santa Barbara (SB) counties (see Table 3.1). A summary of the distresses extracted from PCR for the CC sections is presented in Table 3.2. Note that the categorical classification for both transverse and longitudinal cracks obtained from the PCR was converted into percentage of the pavement sample section of 100-foot long. The following approach to calculate cracks percentage was adopted:

1) For transverse cracks, it was assumed that all cracks developed along the full lane width. The total length of transverse cracks was multiplied by one foot (i.e. the width assumed to be affected by the crack). This value was then divided by the total area of the segment surveyed (100 × 12 = 1,200 square feet). 2) For longitudinal cracks, some assumptions needed to be made. For longitudinal cracks that were reported in the PCR as categories 1, 2 and 3, the total lengths were assumed to be 75 feet, 150 feet, and 200 feet, respectively. Percentage cracking was then calculated using a calculation similar to one presented for percentage transverse cracking.

Table 3.1 Locations and CS&O rehabilitation dates for sections in CC region.

County	Route	Direction	PM[1] Range	CS&O Date
SLO[2]	U.S. 101	N[3]	55.8-58.8	2000
SLO	U.S. 101	N	58.9-63.6	2002
SLO	U.S. 101	S[4]	58.9-63.6	2002
SB[5]/SLO	U.S. 101	N	88.1-91.0/0.0-0.1	1995
SB	U.S. 101	N	78.7-84.3	1995
SB	U.S. 101	N	27.2-28.6	1999
SB	U.S. 101	N	21.0-24.5	1995
SB	U.S. 101	N	14.2-21.2	1995

[1]Post Mile [2]San Luis Obispo [3]North [4]South [5]Santa Barbara

Table 3.2 Summary of variable ranges for sections in the CC region.

Variables		Description	Range	Units
Dependent	TRANS	Percentage area affected by transverse cracks	(0 to 5)	%
	LONG	Percentage area affected by longitudinal cracking	(0 to 20.33)	%
	ALLG	Percentage area effected by alligator cracking 'A' and 'B'	(0 to 82)	%
	IRI	International Roughness Index	(36 to 236)	in/mile
Independent	Age	The difference between CS&O rehab. and survey dates	(0 to 12)	Years
	H_{ac}	The depth of all layers of the asphalt overlay as measured after coring	(4.75 to 5.75)	in
	H_{pcc}	The depth of cracked and seated concrete slab as measured after coring	(8 to 8.75)	in
	KESAL	Equivalent Single Axle Loads per year	0.565 to 1.75	Million axle

Table 3.1 shows that the lengths of the sections in the CC region ranged from 1.4 to 7.0 miles. For meaningful performance analyses, the sections needed to be uniform in terms of layer thickness and type throughout their entire length. As-built records specified about 4 inches of Hot Mix Asphalt (HMA) over cracked and seated concrete pavement. As part of this study, the different sections were cored to verify layer thicknesses and types. In addition, each section was visually surveyed so that observed distresses could be mapped and quantified. Table 3.3 presents specific section information including county, route, bound direction, post mile, and the date when sections were cored and visually surveyed. Every section in the study was assigned a section ID, as shown in Table 3.3.

Results from visual survey are shown in Table 3.4. Caltrans District 05 maintenance records indicated that sections **SLO_101N_56.06**, **SLO_101N_60.98**, **SLO_101S_61.00**, **SB_101N_90.06**, and **SB_101N_21.66** received an Open Graded Friction Course (OGFC) overlay as Capital Maintenance (CAPM) during or shortly after 2005. This would imply that these sections would show small amount of cracks (if any), an assumption that was supported by the PCR performance data and was confirmed during the visual survey. Therefore, only performance data for survey years before 2005 were included in the performance analyses of these sections. Two cores spaced approximately 750 feet apart were removed from each pavement section. Each core was drilled to the base layer. The post mile value shown in Table 3.3 represents the approximate midpoint between the two core locations. Each core was later examined to measure layer thicknesses and to identify the layer type. Results are presented in Table 3.5 including thickness from as-built. As evident in this table, the different layer thicknesses were nearly uniform. Appendix A includes photos of cores extracted from the eight sections in the CC region.

Table 3.3 Sections IDs and visual survey dates.

County	Route/Direction	PM[1]	# of Cores	Section ID	Date Cored/ Surveyed
SLO	101/N	56.06	2	SLO_101N_56.06	9/8/2009
SLO	101/N	60.98	2	SLO_101N_60.98	9/8/2009
SLO	101/S	61.00	2	SLO_101S_61.00	9/8/2009
SB	101/N	90.06	2	SB_101N_90.06	9/9/2009
SB	101/N	82.85	2	SB_101N_82.85	9/9/2009
SB	101/N	27.59	2	SB_101N_27.59	9/10/2009
SB	101/N	21.66	2	SB_101N_21.66	9/10/2009
SB	101/N	15.24	2	SB_101N_15.24	9/10/2009

[1] Post Mile representing the midpoint between core locations

Table 3.4 Visual survey results for the CC sections.

Section ID	Alligator Cracks, %	Long. Cracks, ft	Trans. Cracks, #
SLO_101N_56.06	0	0	0
SLO_101N_60.98	0	0	0
SLO_101S_61.00	0	0	0
SB_101N_90.06	0	0	0
SB_101N_82.85	0	0	0
SB_101N_27.59	20	45	1
SB_101N_21.66	0	75	2
SB_101N_15.24	30	150	3

Table 3.5 Layers thicknesses for cores removed from each section.

Section ID	Core #	Overlay[1]		PCC, in	Base		As-built		
		Thick, in	Fabric		Thick, in	Type	Overlay	PCC	CTB
SLO_101N_56.06	1	5.25	Yes	8.00	4.0	CTB[2]	4.00	8.00	4.00
	2	4.75	Yes	8.00	4.0	CTB	4.00	8.00	4.00
SLO_101N_60.98	1	5.00	Yes	7.75	NA[3]	NA[3]	4.00	8.00	4.00
	2	4.50	Yes	8.00	NA[3]	NA[3]	4.00	8.00	4.00
SLO_101S_61.00	1	4.75	Yes	7.75	4.0	CTB	4.00	8.00	4.00
	2	4.75	Yes	8.25	4.0	CTB	4.00	8.00	4.00
SB_101N_90.06	1	5.00	Yes	8.00	4.0	CTB	4.00	8.00	4.00
	2	4.90	Yes	8.00	4.0	CTB	4.00	8.00	4.00
SB_101N_82.85	1	5.00	Yes	8.00	5.0	CTB	4.00	NA	NA
	2	5.00	Yes	8.00	5.0	CTB	4.00	NA	NA
SB_101N_27.59	1	4.75	Yes	8.25	NA[3]	NA[3]	4.75	8.00	4.00
	2	4.75	Yes	8.25	NA[3]	NA[3]	4.75	8.00	4.00
SB_101N_21.66	1	4.25	Yes	8.75	4.5	CTB	4.00	8.00	4.00
	2	4.25	Yes	8.40	3.0	CTB	4.00	8.00	4.00
SB_101N_15.24	1	5.00	Yes	8.00	4.0	CTB	4.00	NA	NA
	2	5.00	Yes	9.50	3.3	CTB	4.00	NA	NA

[1] Total overlay thickness [2] Cement Treated Base [3] Not available in as-built or core crushed

3.3.2 Northern California (NCA) Sections

Nine (9) CS&O sections that had been in service for at least ten (10) years in the NCA region were identified and selected for further examination in this study. All of the sections are located on I-5 in Tehama, Shasta, and Siskiyou counties. Table 3.6 shows that the lengths of the CS&O sections ranged from 1.5 to 13.63 miles.

Similar procedures (to those used for the CC sections) were employed to gather data and essential survey information for the NCA sections. Tables 3.6, 3.7, 3.8, and 3.9 summarize this information for the NCA sections. Table 3.9 presents a summary of the pavement distress data (extracted from the PCR), layer thicknesses, age (as defined in Table 3.7) and traffic level (in terms of Equivalent Single Axle Load (ESAL)).

Caltrans District 02 maintenance records indicated that sections **TEH_I5_1.87**, **TEH_I5_11.88**, **SIS_I5_42.60** and **SIS_I5_60.29** were rehabilitated using a thin blanket overlay during or shortly after 2008. For these sections, the same assumptions made for the CC region sections that received similar treatments during and after 2005 were employed.

Table 3.6 Locations and CS&O rehabilitation dates for sections in NCA.

County	Route	Direction	PM[1] Range	CS&O Date
TEH[2]	I 5	N[3]	0.0-8.8	1998
TEH	I 5	N	8.77-22.4	1998
TEH	I 5	N	27.1-28.6	1993
SHA[4]	I 5	N	18.1-23.3	1998
SHA	I 5	N	36.8-40.2	1998
SHA	I 5	N	56.2-60.5	1993
SHA/SIS[5]	I 5	N	60.5-67.3/0.0-2.6	1994
SIS	I 5	N	36.7-43.1	1993
SIS	I 5	N	58.1-69.3	2001

[1]Post Mile [2]Tehama [3]North [4]Shasta [5]Siskiyou

Table 3.7 Summary of variable ranges for sections in NCA.

Variables		Description	Range	Units
Dependent	TRANS	Percentage area affected by transverse cracking	(0 to 5)	%
	LONG	Percentage area affected by longitudinal cracking	(0 to 20.33)	%
	ALLG	Percentage area effected by alligator cracking ‘A’ and ‘B’	(0 to 100)	%
	IRI	International Roughness Index	(50 to 143)	in/mile
Independent	Age	The difference between CS&O rehab. And survey dates	(0 to 13)	Years
	H_{ac}	The depth of all layers of the asphalt overlay	(3.5 to 7.0)	in
	H_{pcc}	The depth of cracked and seated concrete slab	(8 to 12)	in
	KESAL	Equivalent Single Axle Loads per year	0.94 to 2.08	Million axle

Table 3.8 Sections IDs and visual survey dates.

County	Route/Bound	PM[1]	# of Cores	Section ID	Date Cored/Surveyed
TEH	I-5	1.87	2	TEH_I5_1.87	3/16/2010
TEH	I-5	11.88	2	TEH_I5_11.88	3/16/2010
TEH	I-5	27.53	2	TEH_I5_27.53	3/16/2010
SHA	I-5	19.44	2	SHA_I5_19.44	3/17/2010
SHA	I-5	39.50	2	SHA_I5_39.50	3/17/2010
SHA	I-5	60.04	2	SHA_I5_60.04	3/17/2010
SHA	I-5	60.57	2	SHA_I5_60.57	3/17/2010
SIS	I-5	42.60	2	SIS_I5_42.60	3/18/2010
SIS	I-5	60.29	2	SIS_I5_60.29	3/18/2010

[1] Post Mile at mid-point where the two cores were drilled

Table 3.9 Visual survey results for NCA sections.

Section ID	Alligator Cracks, %	Longitudinal Cracks, ft	Transverse Cracks, #
THE_I5_1.87	0	0	0
THE_I5_11.88	0	0	1
THE_I5_27.53	100	200	5
SHA_I5_19.44	0	0	0
SHA_I5_39.50	0	0	0
SHA_I5_60.04	0	0	0
SHA_I5_60.57	0	0	0
SIS_I5_42.60	0	0	0
SIS_I5_60.29	0	0	0

Two cores were drilled through to the base layer for each NCA section. These cores were spaced approximately 750 feet apart. Each core was later examined to measure layer thicknesses and to identify the layer type. Results are presented in Table 3.10. The thicknesses for the different layers were nearly uniform and in agreement with as-built records and the maintenance history described earlier. A close examination of cores indicated that sections **THE_5N_1.87**, **SHA_5N_19.45**, **SHA_5N_60.04** and **SIS_5N_42.60** had 1 to 2-inch thick OGFC overlays, which agrees with information obtained from the District 02 maintenance records. Appendix A includes photos of the cores extracted from the nine sections in NCA region.

Sections SHA_I5_60.57 and SIS_I5_42.60 were not included in the group of sections that received recent maintenance/rehabilitation. During the visual survey, the 1000-feet stretches surveyed did not show any type of distresses. However, in the PCR these two sections have transverse, longitudinal and alligator cracks (‘ A’ and ‘B’) reported.

Table 3.10 Layers thickness from cores removed from each section in NCA.

Section ID	Core #	Overlay[1]		PCC, in	Base		As-built		
		Thick, in	Fabric		Thick, in	Type	Overlay	PCC	CTB
THE_5N_1.87	1	5.75	Yes	9.13	4.5	CTB[2]	5.50	8.00	4.00
	2	5.50	Yes	8.50	3.0	CTB	5.50	8.00	4.00
THE_5N_11.88	1	6.75	Yes	8.50	NA[3]	NA[3]	5.50	8.00	4.00
	2	6.25	Yes	8.50	NA[3]	NA[3]	5.50	8.00	4.00
THE_5N_27.53	1	5.00	Yes	8.50	4.0	CTB	4.00	NA	NA
	2	5.00	Yes	8.50	4.0	CTB	4.00	NA	NA
SHA_5N_19.45	1	7.00	Yes	8.00	4.0	ATB[4]	6.50	NA	NA
	2	7.00	Yes	9.00	4.0	CTB	6.50	NA	NA
SHA_5N_39.50	1	5.00	Yes	8.00	5.0	CTB	4.75	8.00	4.00
	2	5.00	Yes	8.00	5.0	CTB	4.75	8.00	4.00
SHA_5N_60.04	1	4.50	Yes	8.50	4.0	CTB	3.50	8.00	4.00
	2	4.50	Yes	8.50	4.0	CTB	3.50	8.00	4.00
SHA_5N_60.57	1	3.75	Yes	9.00	4.0	CTB	3.75	8.00	4.00
	2	3.75	Yes	9.00	4.0	CTB	3.75	8.00	4.00
SIS_5N_42.60	1	5.00	Yes	8.00	4.0	CTB	3.50	8.00	4.00
	2	5.00	Yes	9.50	3.3	CTB	3.50	8.00	4.00
SIS_5N_60.29	1	5.75	Yes	12.00	4.0	CTB	5.75	8.25	5.50
	2	10.50[5]	Yes	0.00	NA[3]	NA[3]	5.75	8.25	5.50

1 Total overlay thickness   2 Cement Treated Base   3 Not Available or core crushed
4 Asphalt Treated Base   5 Core revealed full-depth asphalt with no PCC located

3.4 PERFORMANCE COMPARISON

Data used in this study were extracted from the Caltrans PCR, which includes the results of pavement condition surveys conducted between 1998 and 2007. Performance indicators including alligator cracks, transverse cracks, longitudinal cracks and IRI were assessed in the evaluation of the CS&O sections. Database spreadsheets were prepared for each section in each of the two regions. A systematic procedure was then followed to ensure data consistency for each section, before the data for all sections were compiled into a single database. The combined data were further scrutinized to identify outlier points and points that were not realistic.

The performance of CS&O sections in the three California regions (CV, CC, and NCA) is discussed in this section, relative to the performance indicators discussed earlier in this section. Two different types of analyses were employed to compare performance. The first analysis used the paired t-test to investigate if there is a significant difference in pavement performance among the three regions (the Minitab 16 Statistical Software was used for this analysis). The second analysis for which the same software was used employed logistic regression to develop prediction models that depended upon several explanatory variables. These logistic regression models are used to predict crack occurrence in the HMA overlays (for the CS&O sections) as well as the time it takes for these cracks to develop. Discussion of each of the two approaches and results of the analyses are included in the following sections.

3.4.1 Comparison Using the Paired t-test

The paired t-test compares the means of the same or related subject over time or in differing circumstances by testing if there is a difference between two observations (Neter, et al., 1988). So, if D represents the difference between the means, the test hypotheses are:

H_o: $D = 0$ (the difference between the two observations is 0), and

H_a: $D \neq 0$ (the difference is not 0)

Where H_o represents the null hypothesis that the means of the two data populations are statistically equal and H_a represents an alternative hypothesis that the means of the two populations are statistically different. The test statistic is t with n_1+n_2-1 degrees of freedom, where n_1 and n_2 are the number of observations for each of the two data populations. If the α-value (the confidence level), associated with the calculated t, is low (< 0.05 for 95% confidence level), there is evidence to reject the null hypothesis. Thus, it will be evident that there is a difference between the means across the paired observations.

In this study, the comparison is done for different types of distresses in regions CV, CC, and NCA. Note that data from the CV region was analyzed in Phase I of this investigation. Data for this region were again analyzed in Phase II and compared with the CC and NCA data. To prepare data for the analyses, the following steps were taken, in order, to ensure proper pairing of the data points:

- All distresses were normalized by dividing by the Cumulative ESAL (CESAL) of the pavement segment;
- Data points were grouped based on HMA overlay thickness; and
- Data points with the same age were averaged.

3.4.2 Logistic Regression Analysis

Logistic regression analyses are used to predict the probability of occurrence of certain events. Like many forms of regression analysis, this method makes use of several predictor variables that may be either numerical or categorical (e.g. 1 and 2) (Abraham and Ledolter, 2006 and Agresti, 2007). The probability of occurrence (p) is calculated as follows, where p>0.5 means the likelihood of crack occurrence:

$$p = \frac{e^z}{1+e^z} \tag{3.1}$$

Note that $z = a_o + a_1x_1 + a_2x_2 + a_3x_3 + \dots\dots\dots\dots + a_nx_n$ where a_o is the intercept and a_1, a_2, a_3, and a_n, are regression coefficients of explanatory variables x_1, x_2, x_3 and x_n respectively (Abraham and Ledolter, 2006 and Agresti, 2007).

In this analysis, the event for which probability is determined is the occurrence of cracks (i.e. alligator, transverse and longitudinal). The explanatory variables that were investigated included age of pavement section, thickness of HMA, thickness of concrete, ESAL and regions (i.e. CV, CC and NCA), where region is input as a binary variable. This model can also be used to compare CS&O performance in these three regions by determining the time it takes before different cracks occur in the overlay.

3.5 ALLIGATOR CRACKS

3.5.1 Paired t-test

The results of the paired t-test for alligator cracks in the three California regions are shown in Table 3.11.

Table 3.11 Paired t-test results for alligator cracks comparison

Regions Comparison	Region	Mean[1]	Standard Deviation	t-value	p-value
CV vs. CC	CV	0.0122	0.0255	**2.84**	**0.01**
	CC	0.0307	0.0438		
CV vs. NCA	CV	0.0084	0.0114	1.15	0.288
	NCA	0.0234	0.0427		
CC vs. NCA	CC	0.0373	0.0360	**3.10**	**0.008**
	NCA	0.0093	0.0263		

[1] Average of percentage alligator cracks after being normalized by dividing by CESAL

As noticed from Table 3.11, the null hypothesis is rejected for CV vs. CC and CC vs. NCA, which suggest a statistical difference between the mean values of the alligator cracks observed. The CC sections experienced higher percentages of alligator cracks than sections in the CV and NCA regions, as judged by the normalized mean values as shown in Table 3.11. The visual survey conducted during summer of 2009 for the CC sections showed that the majority of alligator cracks concentrated in CS&O sections in the southern part of District 05 (Santa Barbara County). Traffic data showed that these sections experienced higher traffic than the sections in San Luis Obispo County.

Why CS&O sections in the CV and NCA regions outperformed the CS&O sections in the CC region in terms of alligator cracks needs explanation. It is noted that alligator crack percentages for the three California regions were normalized with respect to

CESAL for each section, after being grouped based on HMA thickness and age. This grouping/normalizing was done to eliminate the effect of these three main factors on the appearance and evolution of alligator cracks. Other explanatory variables that influence alligator cracks, such as subgrade type/condition and HMA properties, were not available from Caltrans data files. Explanatory variables such as these could explain the differences in performance.

3.5.2 Logistic Regression

A total of 236 data points from the PCR were considered with 159 of them have alligator cracks of zero (0) percent. The data include 60, 71, and 105 points in the CC, NCA, and CV regions, respectively. Table 3.12 presents the descriptive statistics of alligator cracks data.

Table 3.12 Descriptive statistics for alligator cracks data.

Region (no. of points)	Variable	Mean	Standard Deviation	Minimum	Median	Maximum
CV (105)	Age, yrs	3.90	1.80	0.00	4.00	8.00
	HMA, inch	4.50	0.37	3.93	4.25	5.00
	PCC, inch	8.90	0.96	8.00	8.75	13.00
	ESAL, million	2.80	0.82	1.25	2.60	4.93
	Allig. Cracks, %	8.33	21.00	0.00	0.00	100.00
CC (60)	Age, yrs	4.40	2.81	0.00	3.50	12.00
	HMA, inch	5.15	0.48	4.75	4.88	6.00
	PCC, inch	8.23	0.25	8.00	8.25	8.75
	ESAL	0.91	0.29	0.56	0.80	1.75
	Allig. Cracks, %	17.50	26.30	0.00	0.00	82.00
NCA (71)	Age, yrs	5.60	3.60	0.00	5.00	13.00
	HMA, inch	5.40	1.11	3.50	5.00	7.00
	PCC, inch	8.90	1.30	8.00	8.50	12.00
	ESAL	1.50	0.30	0.94	1.51	2.1
	Allig. Cracks, %	22.00	34.02	0.00	0.00	100.00

The analysis of PCR data using the Minitab software resulted in the following logistic model:

$$Z = 61.17 + 1.47age - 15.14HMA - 22.6ESAL - 32.82NCA - 56.27CC + 6.81(HMA)(NCA) + 12.51(HMA)(CC) + 4.9(HMA)(ESAL) \qquad 3.2$$

where:
Z = Alligator cracks (in percent)
Age = Difference between survey and original construction dates (in years)
HMA = Thickness of HMA overlay (in inches)
ESAL = Annual Equivalent Single Axle Load (in millions)
NCA = Binary variable (1 when z is calculated for NCA region and 0 otherwise)
CC = Binary variable (1 when z is calculated for CC region and 0 otherwise)

Note that the NCA and CC binary variables in Equation 3.2 are set to zeros when the equation is used to determine z for the CV region.

The logistic model in Equation 3.2 is used to determine parameter z, which is used in Equation 3.1 to determine the probability of the occurrence of alligator cracks in a certain CS&O segment for one of the three regions included in the study. This model can also be used to predict the time it takes for alligator cracks to form in the HMA overlay for CS&O sections built in each of the regions.

The average values for explanatory variables in all regions combined (see Table 3.13) were used to determine the probability of a pavement section developing alligator cracks over the section service-life and the results are presented in Figure 3.1.

Based on the regression results shown in Figure 3.1, alligator cracks are expected to develop after 7.5, 3.5 and 6.5 years for identical pavement sections built in the CV, CC and NCA regions, respectively. These results are in general agreement with the trends shown in Figure 3.2 which displays actual alligator cracks percentages as a function of time (age) for the three regions sections.

The difference could be attributed to several factors, including construction-related issues, subgrade soil type/condition, climatic issues, and drainage issues. Another factor to consider is the thickness of PCC layer. As shown in Table 3.12, sections in the CC region have smaller average PCC layer thicknesses, when compared with those observed in the CV and NCA regions. Assuming similar energy levels were used to crack the concrete slabs in the three regions, the thinner PCC layer in the CC region could have damaged the underlying CTB layer during cracking, making it more susceptible to progressive damage under traffic loading and environmental conditions. The effects of the aforementioned factors were not investigated in this study due to the lack of data.

Table 3.13 Average values used to compare alligator cracks.

Variable	Mean
HMA, inch	5.00
ESAL, million	1.75

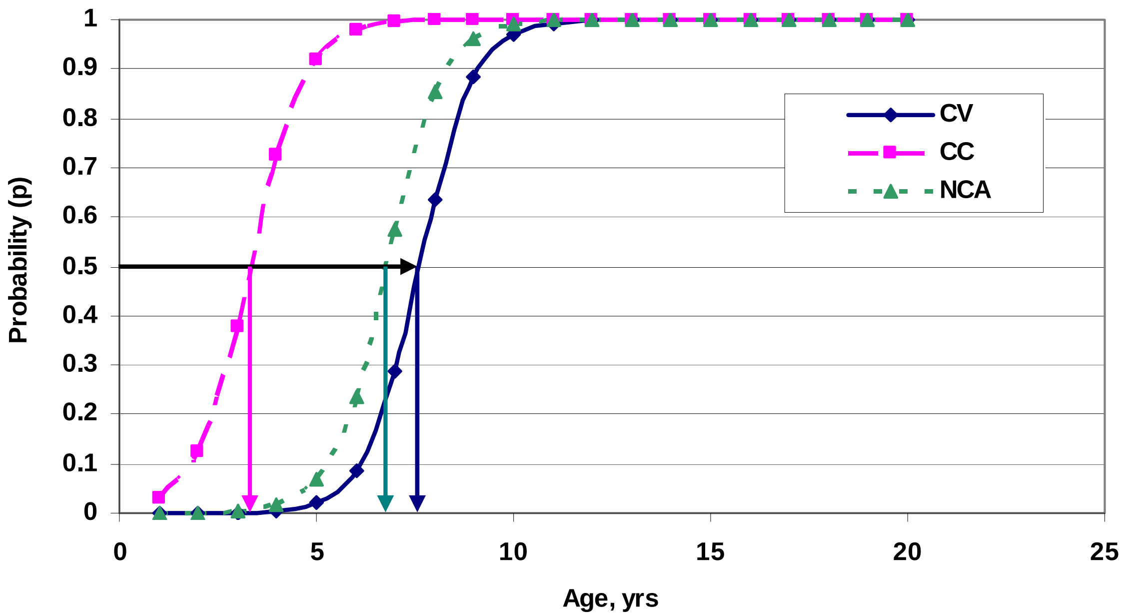
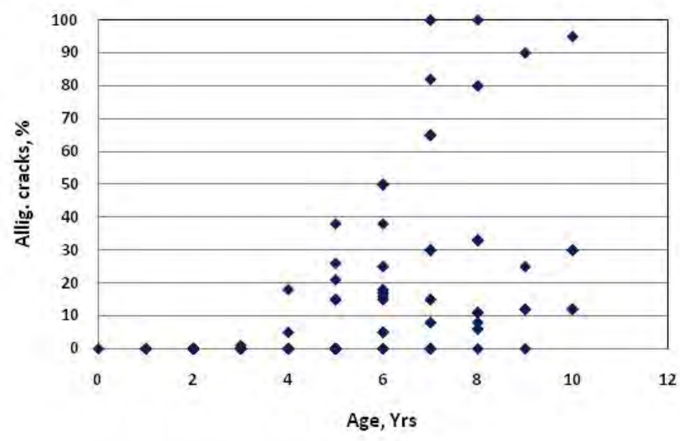
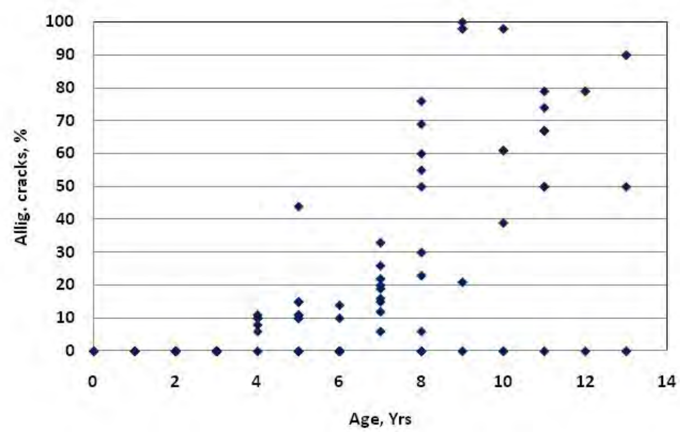


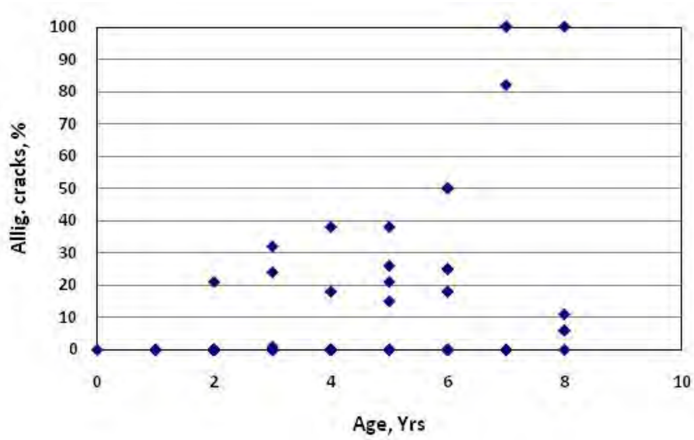
Figure 3.1 Probability of alligator cracks occurrence vs. time.



a) CV region sections



b) NCA region sections



c) CC region sections

Figure 3.2 Actual percentages of alligator cracks vs. age for CV, NCA and CC region sections.

3.6 TRANSVERSE CRACKS

3.6.1 Paired t-test

The results of the paired t-test for transverse cracks in the three California regions are shown in Table 3.14. Based on the results, the null hypothesis was not rejected for any of the region comparisons. These results suggest no statistically significant difference in the mean values of transverse cracks from one region to another.

Table 3.14 Paired t-test results for transverse cracks comparison

Regions Comparison	Region	Mean[1]	Standard Deviation	t-value	p-value
CV vs. CC	CV	0.0173	0.0120	1.45	0.177
	CC	0.0069	0.0197		
CV vs. NCA	CV	0.0232	0.0089	1.76	0.104
	NCA	0.0457	0.0470		
CC vs. NCA	CC	0.0222	0.0300	0.99	0.343
	NCA	0.0122	0.0259		

[1] Average of percentage transverse cracks after being normalized by dividing by CESAL

3.6.2 Logistic Regression

A total of 227 data points were considered with 122 of them have transverse cracks of zero (0) percent. The data points include 52 points in CC region, 82 points in NCA and 93 points in CV region. Table 3.15 presents the descriptive statistics of alligator cracks data for the three regions.

A logistic regression model to determine the likelihood of transverse cracks occurring in the HMA overlay was developed:

$$Z = -24.23 + 5.12(Age) + 38.17(HMA/PCC) - 3.44(ESAL) - 5.25(CC) - 8.05(NCA) + 0.89(Age)(ESAL) - 6.92(Age)(HMA/PCC) \quad 3.3$$

Where Z = Transverse cracks (in percent)

Table 3.15 Descriptive statistics for transverse cracks data.

Region (no. of points)	Variable	Mean	Standard Deviation	Minimum	Median	Maximum
CV (93)	Age, yrs	4.80	2.45	0.00	5.00	10.00
	HMA, inch	4.60	0.35	3.93	4.50	5.00
	PCC, inch	8.90	0.98	8.00	9.00	13.00
	ESAL	2.76	0.82	1.25	2.70	5.25
	Trans. Cracks, %	2.57	2.24	0.00	2.00	5.00
CC (52)	Age, yrs	3.60	2.81	0.00	3.00	12.00
	HMA, inch	5.20	0.48	4.75	5.00	6.00
	PCC, inch	8.20	0.25	8.00	8.25	8.75
	ESAL	0.84	0.29	0.56	0.78	1.75
	Trans. Cracks, %	0.63	1.27	0.00	0.00	5.00
NCA (82)	Age, yrs	6.04	3.60	0.00	6.00	13.00
	HMA, inch	5.30	1.10	3.50	5.00	7.00
	PCC, inch	8.60	1.21	8.00	8.50	12.00
	ESAL	1.56	0.28	0.94	1.52	2.10
	Trans. Cracks, %	1.95	2.40	0.00	0.00	5.00

Note that other variables in Equation 3.3 are the same as those defined for Equation 3.2. This equation was used to investigate the performance of CS&O pavement sections relative to transverse cracking, assuming similar layer thicknesses, layer types, and traffic levels. Average values for explanatory variables in all regions (see Table 3.16) were used to develop a plot similar to that shown in Figure 3.1. The results are presented in Figure 3.3. Transverse cracks are expected to develop after about 3.5, 5.0 and 5.5 years for an identical section built in the CV, CC and NCA regions, respectively. Figure 3.4 presents the actual data from the PCR as a function of time (age) for sections in the three regions. It noticed that Figure 3.4 is in general agreement with the results of the paired t-test and the logistic regression analysis.

Transverse reflection cracks in sections rehabilitated employing the CS&O technique result mainly due to thermal-induced horizontal slab movements and traffic-induced vertical slab movements caused by the rocking of un-properly seated PCC panels. From Table 3.15 it is noticed that the average HMA thickness for the CV region sections is the smallest among all the three California regions. Sections with thinner HMA overlays are expected to develop reflection cracks faster than those with thicker HMA overlays. Also, in Table 3.15 it is noticed that sections in the CV region experienced the highest average value of ESAL. Another observation is the average thickness of PCC slabs for sections in the CV region, which were generally thicker than sections in both CC and NCA regions. If it is assumed the same compaction energy is adopted statewide, sections with thicker PCC could have not been seated properly. This assumption coupled with the high traffic level experienced by the CV region sections could explain the early initiation of transverse reflection cracks for CS&O sections in that region. More data are needed to support the aforementioned hypothetical explanation.

Table 3.16 Average values used to compare transverse cracks.

Variable	Mean
HMA, inch	5.00
PCC, inch	8.70
ESAL, million	1.72

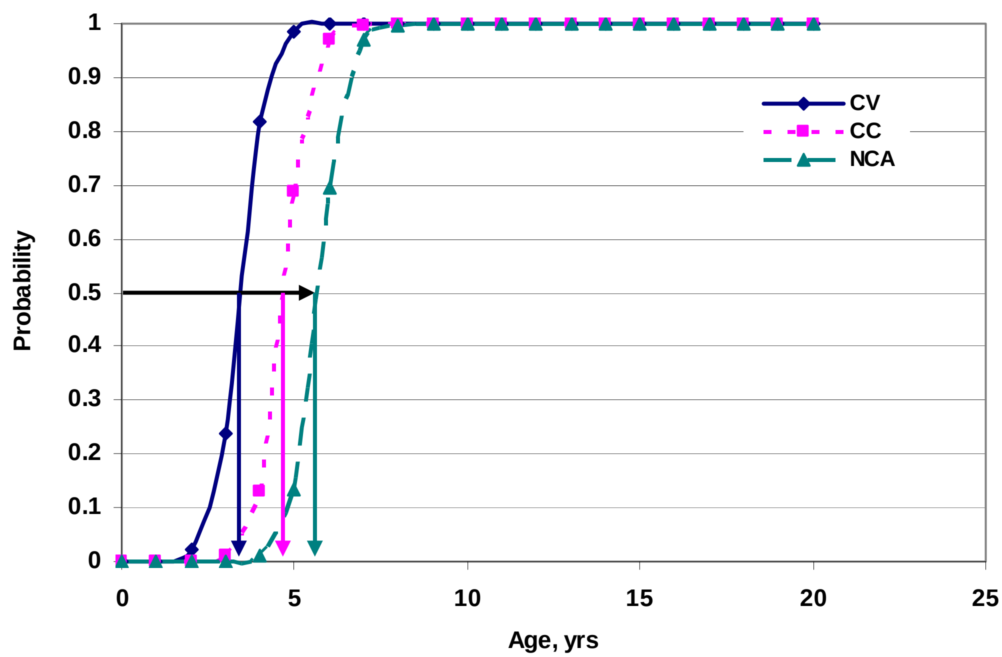
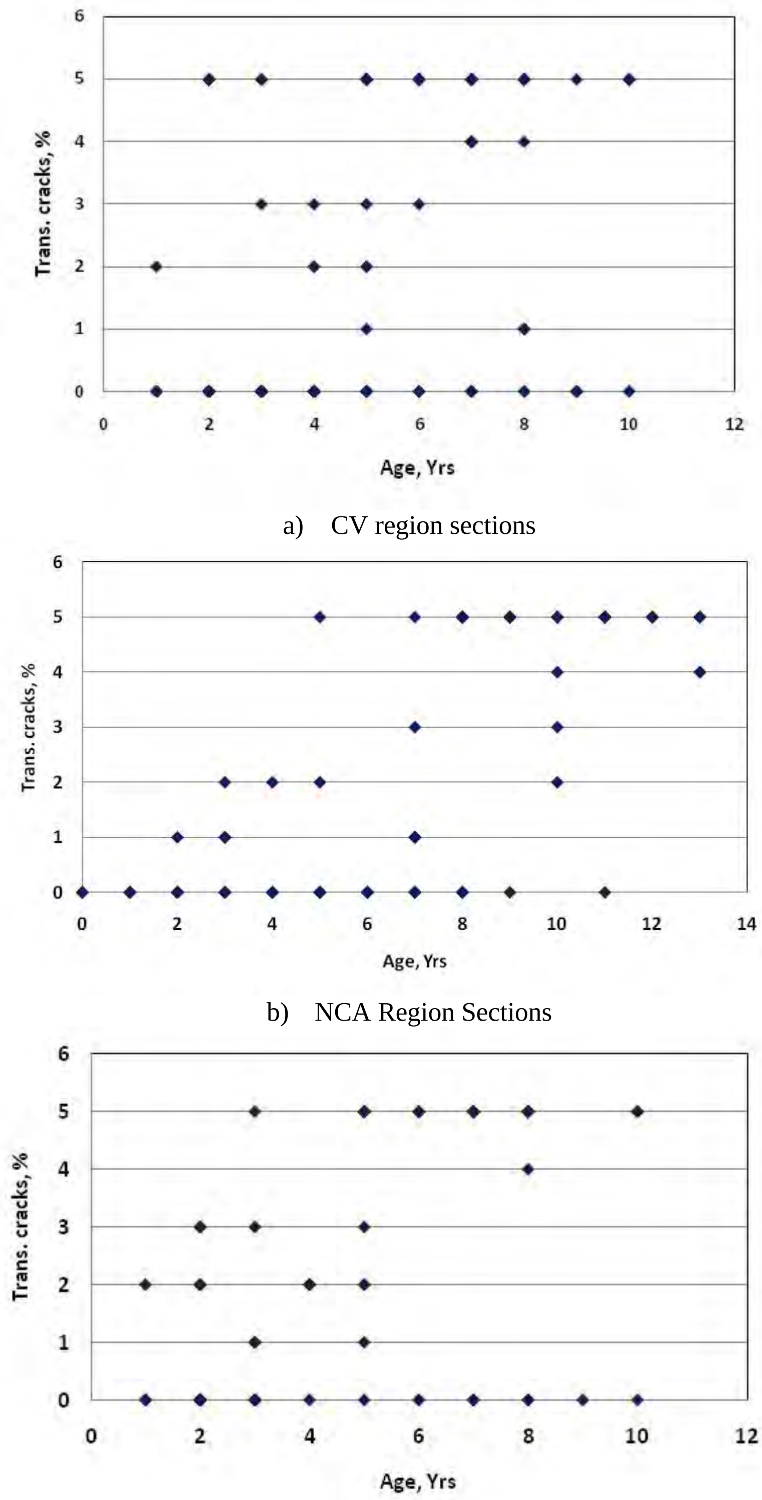


Figure 3.3 Probability of transverse cracks occurrence vs. time.



a) CV region sections

b) NCA Region Sections

c) CC Region Sections

Figure 3.4 Actual percentages of transverse cracks vs. age for CV, NCA and CC region sections.

3.7 LONGITUDINAL CRACKS

3.7.1 Paired t-test:

The results of the paired t-test for longitudinal cracks in the three California regions are shown in Table 3.17. As noticed from Table 3.17 the null hypothesis is not rejected for all regions comparison suggesting no significant difference in the observed longitudinal cracks.

Table 3.17 Paired t-test results for longitudinal cracks comparison

Regions Comparison	Region	Mean[1]	Standard Deviation	t-value	p-value
CV vs. CC	CV	0.064	0.062	1.04	0.310
	CC	0.084	0.113		
CV vs. NCA	CV	0.078	0.070	1.06	0.310
	NCA	0.120	0.148		
CC vs. NCA	CC	0.095	0.120	0.39	0.704
	NCA	0.086	0.123		

[1] Average of percentage longitudinal cracks after being normalized by dividing by CESAL

3.7.2 Logistic Regression

A total of 304 data points were considered with 165 of them have longitudinal cracks of zero (0) percent. The data points include 85 points in CC region, 82 points in NCA and 137 points in CV region. Table 3.18 presents the descriptive statistics of longitudinal cracks data for the three regions.

A logistic regression model similar to those described in Equations 3.2 and 3.3 was developed for the occurrence of longitudinal cracks in CS&O sections:

$$
\begin{aligned}
Z = {} & 91.662 + 1.81(Age) - 15.42(HMA) - 13.37(PCC) - 20.76(ESAL) + 16.38(CC) - 0.45(NCA) \\
& + 2.31(HMA)(PCC) + 2.1(PCC)(ESAL) - 4.331(HMA)(CC) - 6.16(HMA)(NCA) \\
& + 1.35(ESAL)(CC) + 15.47(ESAL)(NCA)
\end{aligned}
\tag{3.4}
$$

Where Z = Longitudinal cracks (in percent)

Table 3.18 Descriptive statistics for longitudinal cracks data.

Region (No. of points)	Variable	Mean	Standard Deviation	Minimum	Median	Maximum
CV (137)	Age, yrs	5.10	2.25	0.00	5.00	10.00
	HMA, inch	4.52	0.38	3.93	4.50	5.00
	PCC, inch	8.86	0.88	8.00	9.00	13.00
	ESAL, million	2.80	0.85	1.25	2.70	5.25
	Long. Cracks, %	6.42	7.00	0.00	6.25	20.83
CC (85)	Age, yrs	5.84	3.23	0.00	5.00	12.00
	HMA, inch	5.17	0.48	4.75	5.00	6.00
	PCC, inch	8.30	0.32	8.00	8.25	9.50
	ESAL, million	0.91	0.26	0.56	0.82	1.75
	Long. Cracks, %	5.47	6.74	0.00	0.00	20.83
NCA (82)	Age, yrs	5.92	3.46	0.00	5.50	13.00
	HMA, inch	5.29	1.12	3.50	5.00	7.00
	PCC, inch	8.60	1.22	8.00	8.50	12.00
	ESAL, million	1.54	0.27	0.94	1.53	2.03
	Long. Cracks, %	3.56	5.00	0.00	0.00	20.83

Note that the variables in Equation 3.4 are the same as those defined for Equations 3.2 and 3.3.

Average values for the explanatory variables shown in Equation 3.4 were used to determine the probability of longitudinal cracks developing in CS&O sections. These average values are presented in Table 3.19. Equation 3.1 was used to determine the probability (p), and a plot similar to those presented in Figures 3.1 and 3.3 was prepared. Figure 3.5 shows the probability of longitudinal cracks occurring in CS&O sections, as a function of time.

Table 3.19 Average values used to compare longitudinal cracks.

Variable	Mean
HMA, inch	5.00
PCC, inch	8.60
ESAL, million	1.75

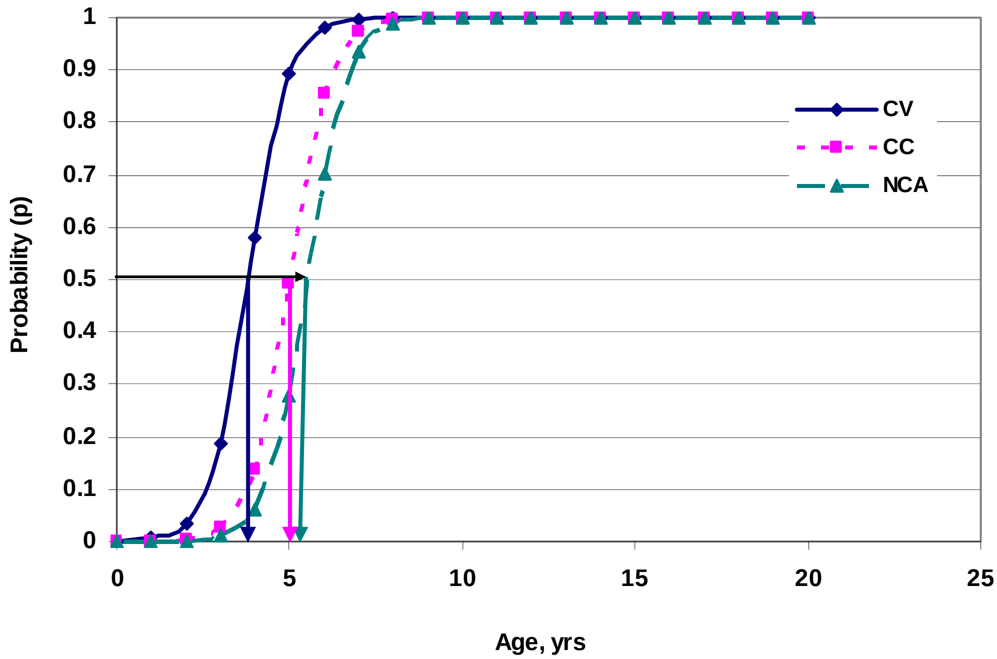
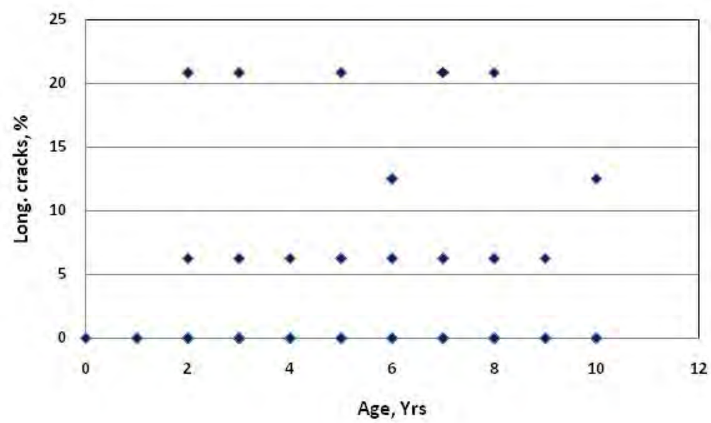


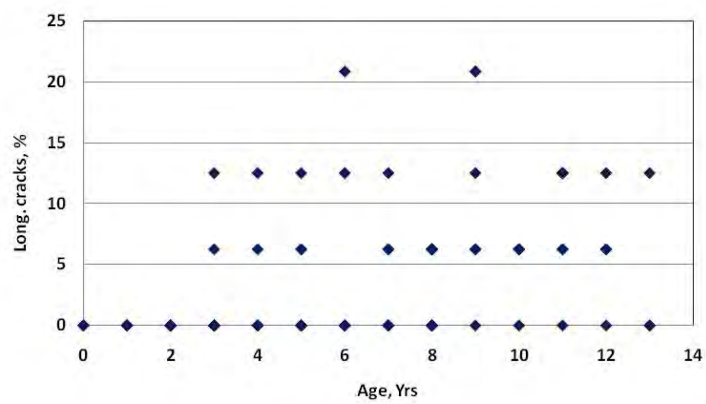
Figure 3.5 Probability of longitudinal cracks occurrence vs. time.

From Figure 3.3 it is noted that longitudinal cracks are expected to develop after about 4.0, 5.0, and 5.0 years for same section structure built in CV, CC and NCA region, respectively. Actual percentages of longitudinal cracks for sections in the three regions are presented in Figure 3.6.

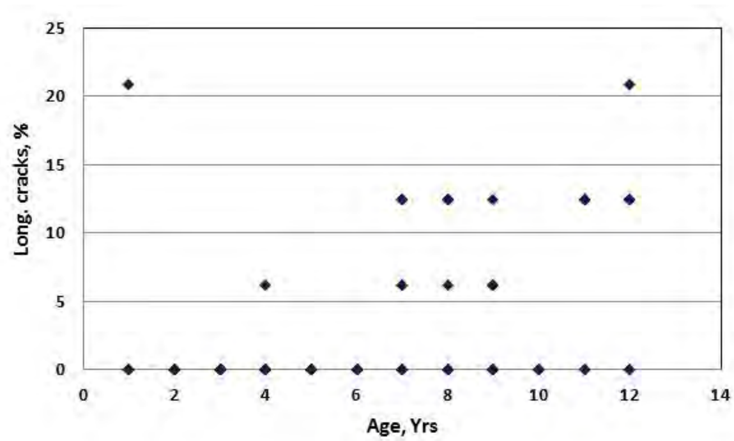
This is in agreement with pavement performance in terms of transverse cracks discussed in section 3.6.2. The formation of longitudinal cracks in CS&O sections is similar to that of transverse cracks and the same hypothetical explanation offered under section 3.6.2 is adopted.



a) CV region sections



b) NCA region sections



c) CC region sections

Figure 3.6 Actual percentages of longitudinal cracks vs. age for CV, NCA and CC regions sections.

3.8 IRI

3.8.1 Paired t-test

The results of the paired t-test comparing IRI in the three California regions are shown in Table 3.20.

Table 3.20 Paired t-test results for IRI comparison

Regions comparison	Region	Mean[1]	Standard Deviation	t-value	p-value
CV vs. CC	CV	0.091	0.037	**5.66**	**0.000**
	CC	0.295	0.119		
CV vs. NCA	CV	0.061	0.019	**4.35**	**0.001**
	NCA	0.225	0.146		
CC vs. NCA	CC	0.300	0.224	**2.17**	**0.042**
	NCA	0.222	0.163		

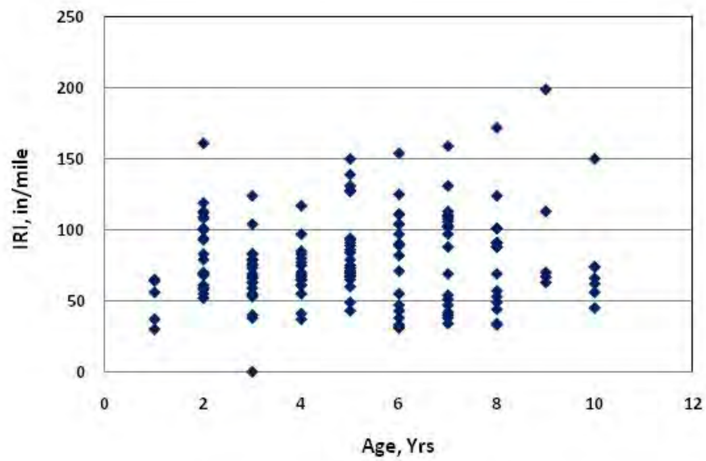
[1] Average of percentage longitudinal cracks after being normalized by dividing by CESAL

As noticed from Table 3.20 the null hypothesis is rejected for all regions comparison suggesting statistically significant difference in the observed IRI among all regions.

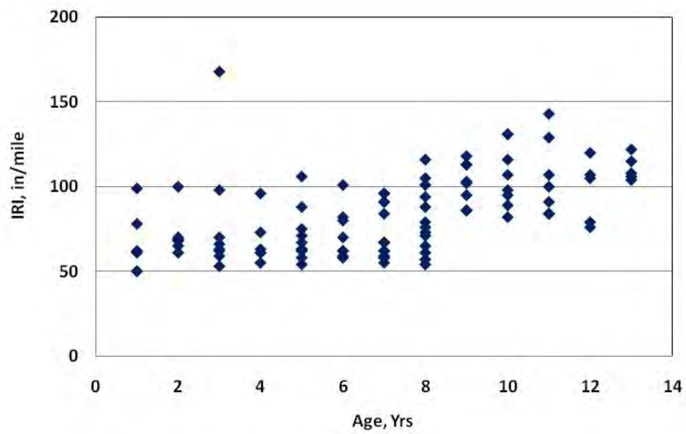
The actual IRI data for the CV, NCA and CC sections are presented in Figure 3.7 as a function of age.

3.8.2 Logistic Regression

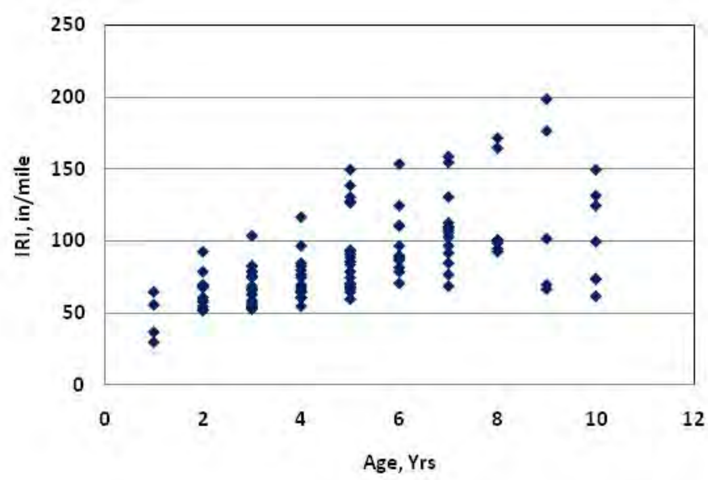
A logistic model similar to those described in Equations 3.2, 3.3 and 3.4 is not feasible for IRI. The logistic models shown in Equations 3.2, 3.3 and 3.4 are used to determine the probability of event occurrence, and IRI is a built-in pavement characteristic (i.e. a characteristic that starts with an initial value immediately after the pavement is constructed). This initial value is mainly construction-related and is never zero. Therefore, a logistics regression model to predict the initiation of IRI is considered not feasible. IRI prediction models will be discussed in details in Chapter 4.



a) CV region sections



b) NCA region sections



c) CC region sections

Figure 3.7 Actual IRI vs. age for CV, NCA and CC region sections.

3.9 SUMMARY

Performance data for CS&O sections in the CV, CC and NCA regions were analyzed employing two different approaches. The analyses revealed that CS&O sections in the CC regions are expected to develop alligator cracking (‘A and ‘B’) earlier than sections built in the CV and NCA regions. However, based on the PCR all sections investigated in the three regions did not experience alligator cracks ‘C’. Statistically speaking, there were no significant differences observed regarding the occurrence of transverse and longitudinal cracks (both are reflection cracks) in sections built in the three regions. Sections in the CV region are expected to develop reflection cracks (both longitudinal and transverse) earlier than those built in the CC and NCA regions. However, there was a statistically significant difference in IRI measurement from one region to another.

CHAPTER 4

PERFORMANCE PREDICTION MODELS

4.1 INTRODUCTION

Pavement performance prediction models are normally used to predict the future state of a pavement section as a function of explanatory variables such as pavement layers thicknesses, age, traffic load, environmental, and drainage conditions. As the performance and distress history of pavements depend on many variables in extremely complex ways, pavement deterioration models are, in general, empirical or semi-empirical (George, 2000). The prevalent method used to model pavement performance is to employ time series data and develop regression models.

Empirical regression models developed from measured/observed data are employed in this study. Certain requirements must be satisfied for the development of a reliable regression prediction model (George, 2000). These requirements include a reliable database with sufficient data and a good understanding of how different variables may affect the performance characteristic being investigated. It is also important to understand boundary conditions that govern the real world situation.

In this study, regression analyses were performed to develop prediction models for CS&O pavements assuming four response variables: alligator cracking, transverse cracking, longitudinal cracking and International Roughness Index (IRI). Separate models were developed for the Central Coast (CC) and Northern California (NCA) regions.

4.2 REGRESSION MODELING TECHNIQUES

As noted, performance prediction models were developed using regression analyses. Initially, scatter plots were generated showing the relationship between the response variables and potential explanatory variables. The scatter plots were then examined to evaluate likely relationships between the response and explanatory variables. During this process, each scatter plot was examined to identify obvious data errors and data outliers, if any.

Various model forms were investigated during the regression analyses. Trials were conducted using various techniques, including multiple linear regression, model with interacting terms regression, stepwise regression, and non-linear regression. The statistical software package SPSS (Ver. 17) was utilized for the regression analyses.

4.2.1 Multiple Linear Forms

Multiple linear regression is one of the most widely used regression techniques for the study of linear relationships among a group of measurable variables (George, 2000). The basic assumptions of multiple linear regression are that the random errors are independent and normally distributed with zero mean and constant variance. Given these assumptions, a multiple linear regression analysis results in a set of parameters for which the sum of the squared residuals is minimized (i.e. least-squares method). The linear model uses the following general form of the equation:

$$y = a_o + a_1 x_1 + a_2 x_2 + \ldots\ldots + a_n x_n \quad \text{.........4.1}$$

where y is the response variable to be predicted, such as pavement condition, pavement distress, etc. Multiple linear models are simple to develop and yield solutions relatively easily, as described in the literature (Dunteman and Ho, 2006 and George, 2000).

4.2.2 Nonlinear Regression

Nonlinear regression models account for model parameters that are nonlinearly related. In many cases, nonlinear models are sought instead of linear models because of the reasons outlined below (George, 2000):

- To retain a clear interpretation of parameters;
- Uncertainty of linear approximation used for inference can be avoided;
- Parameter estimates of linear models may have undesirable properties; and
- Practical, real-world problems are often nonlinear in nature.

When developing nonlinear regression models, one must use either an iterative procedure employing a mathematical algorithm or an exhaustive search procedure. Also, nonlinear regression models with more than one explanatory variable tend to be algebraically complicated, with a few exceptions. Different forms of nonlinear models were considered for the performance modeling in this study. The nonlinear regression tool in SPSS release 17 (SPSS Inc, 2009) was used to relate a single dependent variable with multiple independent variables in a variety of combinations.

4.3 PERFORMANCE MODELS

The sequential steps that are followed when completing a classical regression analysis are outlined below:

- Create a database containing the response variables and all of the potential explanatory variables;
- Prepare scatter plots relating each response variable to each potential variable;

- Identify and exclude erroneous data;
- Choose a model form and analyze the data using a stepwise regression procedure to identify significant explanatory variables; and
- Develop regression models while evaluating predictive capability and the existence of multicollinearity.

The principles used to determine the best model were as follows: First, the Coefficient of Determination or R^2-value, a measurement of the variation between actual and predicted data points, was used to identify the predicted points that most closely fit the actual points. The R^2-value ranges from 0 to 100 where a "0" means there is no correlation between points and "100" means there is perfect correlation. Therefore, higher R^2-values are more desirable. Second, the Standard Error of Estimate (SEE) was used to determine the variation of predicted values. The SEE values give a range over which the actual value will fall, in comparison with the predicted value from the model. Lower SEE values mean that the model is more reliable.

The following rules were considered when developing the regression models:

- Prediction models must begin with values of zero for cracking at an age of zero;
- Prediction models must begin with a minimum constant value for IRI distress at an age of zero;
- Prediction models must be capable of representing small distress values for the first five years of age and much larger values for later years; and
- Prediction models must never represent implausible values or scenarios such as negative distress, distress that decreases with time, or distress that contradicts established data trends.

At the same time, expected behavior was considered during the development and evaluation of each model. Expected behavior is the reasonable physical reaction of the pavement to a certain variable. For example, failures should increase with age and loading. Also, failures should decrease with increased subgrade stiffness, increased pavement thickness, and ideal weather. Models were not automatically rejected based on unexpected behavior; rather, they were evaluated and checked against similar forms of the model to determine if a statistical anomaly could be causing an apparent trend. Models were analyzed based on the statistical coefficient R^2. The goal of the modeling was to produce a predictor of the dependent variable with the lowest variation and highest accuracy.

4.3.1 Models for the CC Region

The performance models for the CC region are summarized in Table 4.1. Variable definitions, appropriate units, and data ranges are found in Table 3.2.

Table 4.1 Performance models for CS&O sections in the CC region.

Alligator Cracks, %	$ALLIG = 0.72\,(ESAL \times AGE)^{1.188}\left(\frac{HMA}{PCC}\right)^{-2.345}$		
	$R^2 = 0.634$	RMSE = 16.20	N = 60
Transverse Cracks, %	$TRANS = 0.055\,(AGE)^{1.518}\left(\frac{HMA}{PCC}\right)^{-1.518}$		
	$R^2 = 0.572$	RMSE = 0.82	N= 50
Longitudinal Cracks, %	$LONG = 0.054\,(AGE)^{1.924}\left(\frac{HMA}{PCC}\right)^{-1.924}$		
	$R^2 = 0.805$	RMSE = 3.03	N = 65
IRI, in/mile	$IRI = 48.51 + 30.723\left(\frac{AGE \times ESAL}{HMA}\right)^{0.851}$		
	$R^2 = 0.538$	RMSE = 17.53	N = 76

Note: R^2 = Coefficient of determination
RMSE = Root Mean Squared Error
N = Number of data points used to develop the models

4.3.2 Models for NCA

The performance models for the NCA region are summarized in Table 4.2. Variables definition, appropriate units, and data ranges are found in Table 3.7.

Table 4.2 Performance models for CS&O sections in the NCA region.

Alligator Cracks, %	$ALLIG = 0.233\,(ESAL \times AGE)^{1.77}\left(\frac{HMA}{PCC}\right)^{-0.729}$		
	$R^2 = 0.777$	RMSE = 16.43	N = 71
Transverse Cracks, %	$TRANS = 0.052\,(AGE)^{1.635}\left(\frac{HMA}{PCC}\right)^{-0.861}$		
	$R^2 = 0.802$	RMSE = 1.03	N= 80
Longitudinal Cracks, %	$LONG = 0.043\,(AGE)^{2.152}\left(\frac{HMA}{PCC}\right)^{-1.113}$		
	$R^2 = 0.885$	RMSE = 2.602	N = 78
IRI, in/mile	$IRI = 62.395 + 4.558\left(\frac{AGE \times ESAL}{HMA}\right)^{1.56}$		
	$R^2 = 0.58$	RMSE = 14.54	N = 103

4.4 MODELS COMPARISON

The regression prediction models developed in Phase II were used to compare the performance of the CS&O rehabilitation technique in three climatic regions in California. When comparing performance, important variables were estimated as follows:

1- Initial ESAL was assumed based on ESAL values calculated for each region. An initial average ESAL equal to 1.5 million and a growth rate of 3 percent were assumed. The following equation was used to determine future ESAL:

$$ESAL_n = ESAL_0\left[(1+i)^n\right]$$

where:

$ESAL_o$= initial annual ESAL (in millions) during the first year after rehabilitation;

i = growth rate per year (in percent); and

n = number of years

2- Average overlay thickness was assumed to be 4.2 inches, which is the overlay thickness normally specified by Caltrans for 10-year design life pavements.

3- The thickness of the concrete slab was assumed to be 8 inches, following Caltrans specifications and as-built records.

4.4.1 Alligator Cracks

Figure 4.1 shows the predicted development of alligator cracks in CS&O sections in the CV, CC and NCA regions. It is noted from this figure that sections in the CV and NCA regions outperform those in CC region throughout the pavement service life. This trend agrees with the results from the logistic regression model analysis covered in Chapter 3. As mentioned in Chapter 3, the trend could be attributed to the type and condition of subgrade soils, especially for those coastal sections in Santa Barbara County.

In addition, sections in the CV region slightly outperform those in the NCA region until year eight, when the trend reverses. This reverse in the trend could be attributed to continued hardening of asphalt binder coupled with the high traffic level on those sections. Data concerning the type and properties of asphalt binder were not available for investigation in this study.

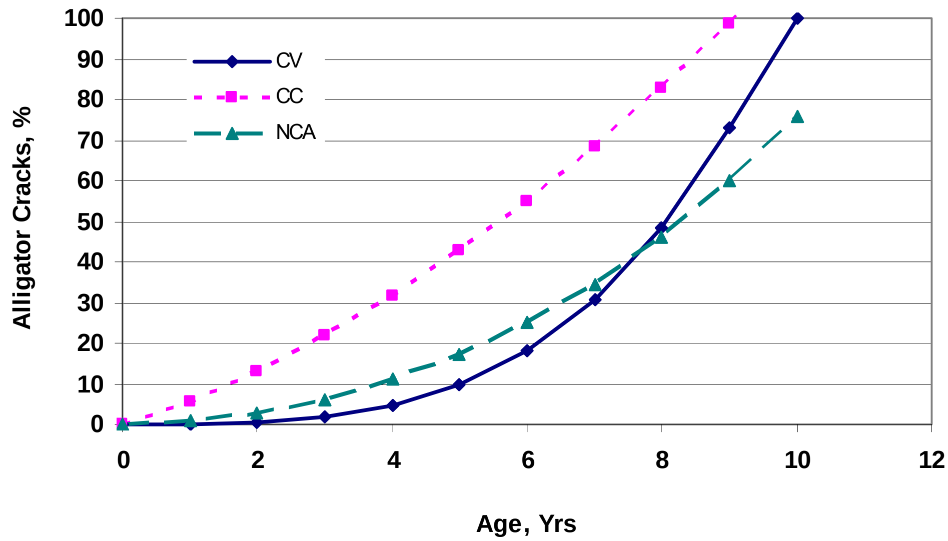
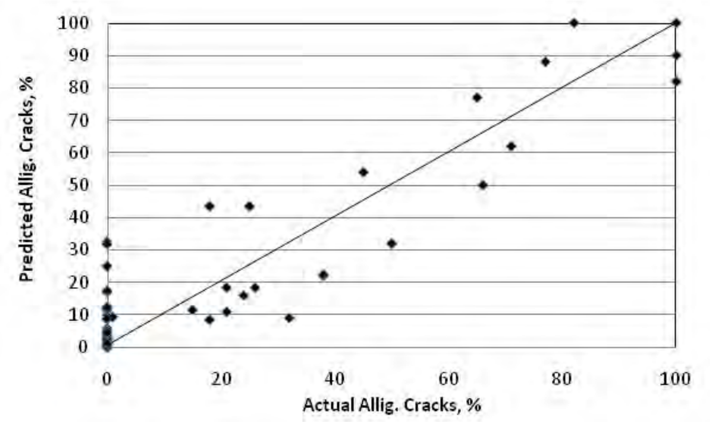


Figure 4.1 Variation of alligator cracks with time for a 10-year design life.

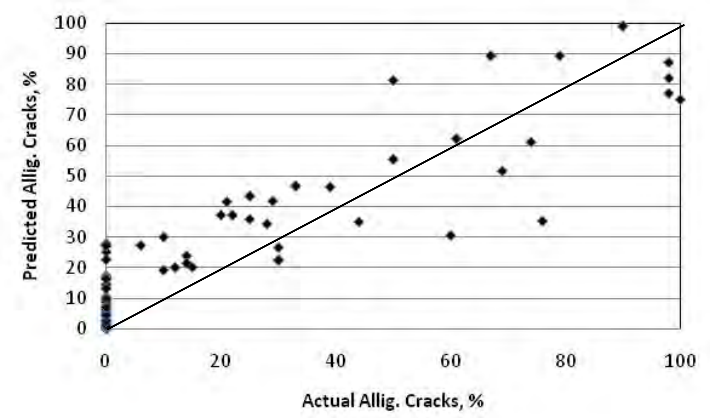
The actual alligator cracks percentages were plotted against the predicted values calculated from the regression models for each region (see Figure 4.2). The points clustering along line of equality is an indication of the satisfactory prediction capabilities.

4.4.2 Transverse and Longitudinal Cracks

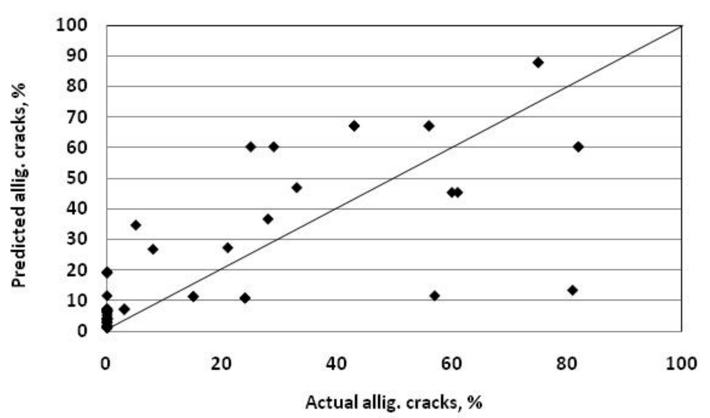
Comparisons of transverse crack development are presented in Figure 4.3. The models predict that CS&O sections in the CV region will develop more transverse cracks at a higher rate (especially for the first five years) when compared with sections in both the



a) CV Region



b) NCA Region



c) CC Region

Figure 4.2 Actual alligator cracks vs. predicted for three regions

CC and NCA regions. Figure 4.4 compares the development of longitudinal cracks for the three regions. A trend similar to that for transverse cracks is observed in this figure. Transverse and longitudinal cracks are primarily reflection cracks from the underlying cracked concrete slabs. Thermal expansion/contraction coupled with the rocking of unstable concrete pieces are considered the primary causes of reflection cracks. Sections in the CV region received the highest traffic repetitions, as compared with sections in the other two regions. Also, the extreme hot summer and cold winter in the CV region could trigger excessive cracks movement in the underlying concrete, which would eventually propagate through HMA overlay. The actual percentages of transverse and longitudinal cracks are plotted against the predicted values and are shown in Figures 4.5 and 4.6, for transverse and longitudinal cracks, respectively

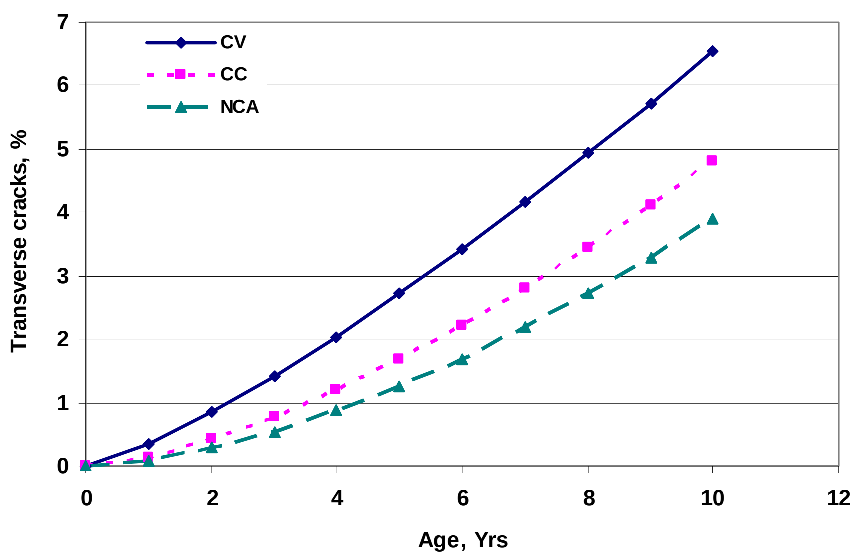


Figure 4.3 Variation of transverse cracks with time for a 10-year design life.

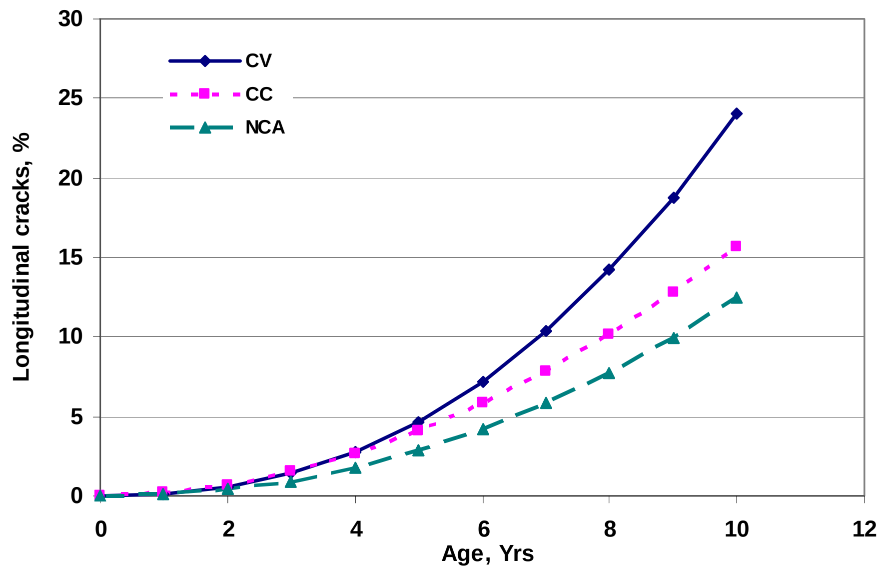
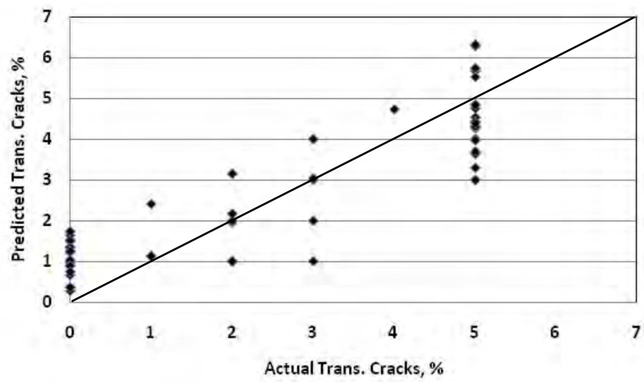


Figure 4.4 Variation of longitudinal cracks with time for a 10-year design life.

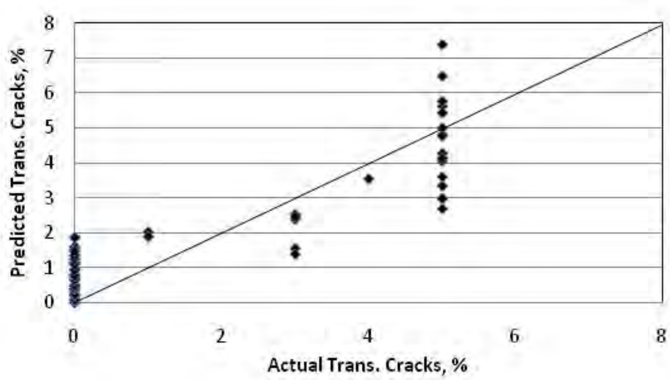
4.4.3 IRI

The variation of IRI with time for CS&O sections in the CV, CC, and NCA regions is presented in Figure 4.7. Even though sections in NCA started with an initial IRI higher than those for the CV and CC regions sections, the rate of increase in IRI for the NCA region outperformed that for both the CV and CC regions. Sections in the CV region slightly outperformed those in the CC region during the first eight years of service. However, the trend reversed afterward presumably due to the higher traffic volume experienced by the CV sections. The IRI-models predict that CS&O sections in the CV region would exceed the threshold of 170 in/mile after 10 years of service (see the Caltrans Highway Design Manual (HDM), Chapter 630), as compared with 165 in/mile and 115 in/mile for the CC and NCA regions, respectively.

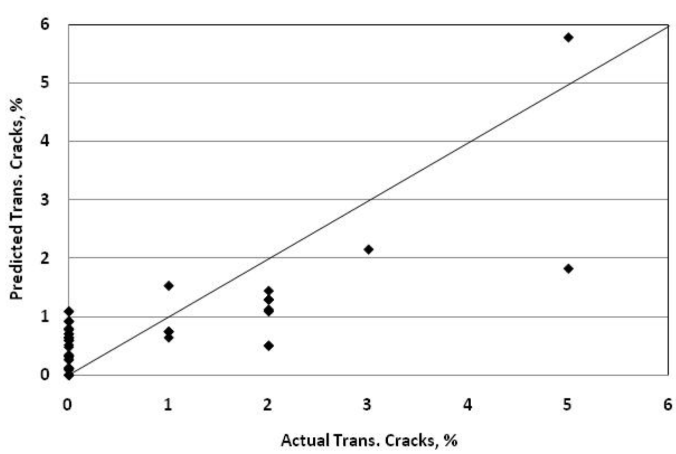
The actual IRI are plotted against predicted IRI values for all three regions (see Figure 4.8)



a) CV Region

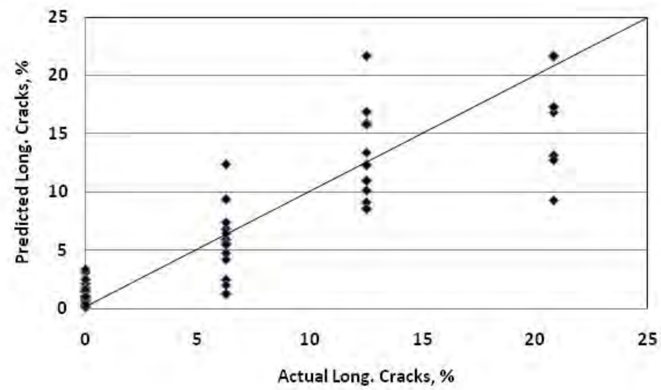


b) NCA Region

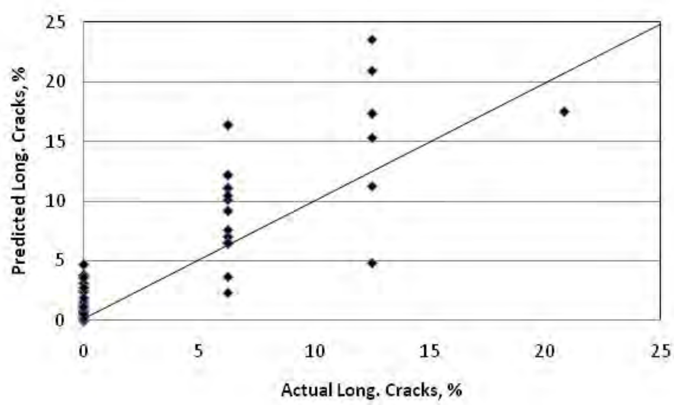


c) CC Region

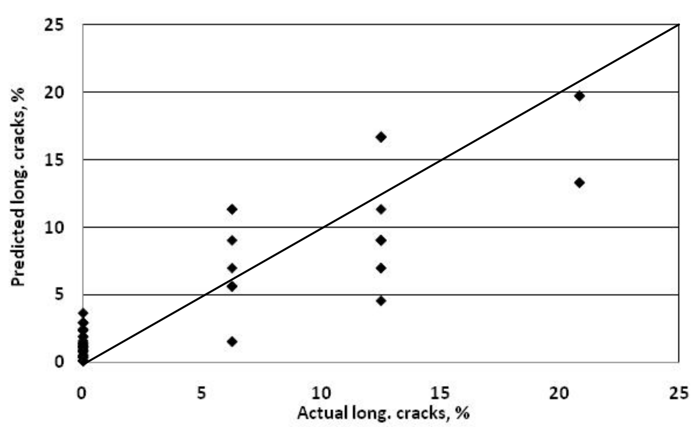
Figure 4.5 Actual transverse cracks vs. predicted for three regions.



a) CV Region



b) NCA Region



c) CC Region

Figure 4.6 Actual longitudinal cracks vs. predicted for three regions.

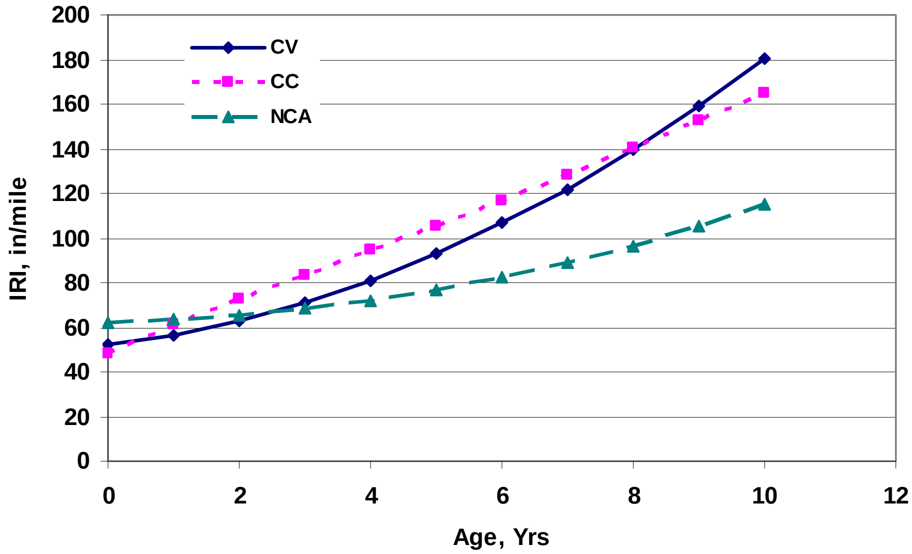
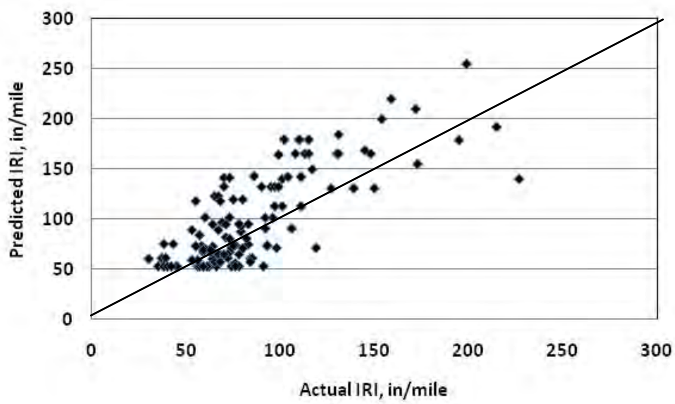


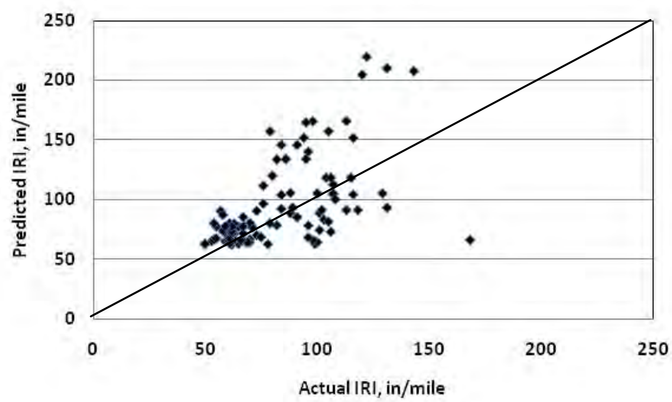
Figure 4.7 Variations of IRI with time for 10-year design life.

4.5 SENSITIVITY ANALYSIS

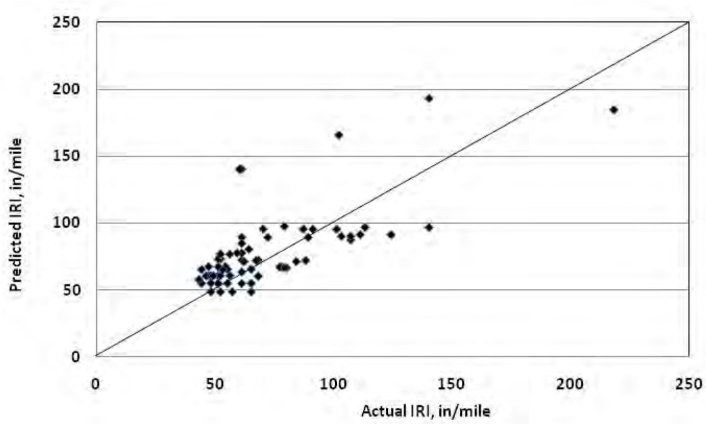
Sensitivity analyses are used to investigate how different independent variables will affect a particular dependent variable under a given set of assumptions. Sensitivity analyses were used in this study to examine the effect of varying the explanatory/independent model variables on pavement response. For these analyses, the dependent variables were evaluated at the mean values of the independent variables. Each independent variable was changed by one standard deviation above and below the mean value and the dependent variables were recalculated. The percent changes in the dependent variables are plotted and slope steepness is used as indication of response sensitivity to the change of particular independent variables. In these plots, the negative sign is used when the values for response/dependent variables fall below those calculated at the mean values. A positive sign is used when the values for response/dependent variables fall above those calculated at the mean values.



a) CV Region



b) NCA Region



c) CC Region

Figure 4.8 Actual IRI vs. predicted values for three regions.

4.5.1 Alligator Cracks

4.5.1.1 Effect of age

Figure 4.9 presents the percent change in alligator cracks as the age of the sections deviates above and below the average. The steepness of lines slope in all three plots indicates that each of the models are sensitive, to various extents, to a change in age. The model developed for sections in the CC region is the least sensitive as compared with those developed for sections in the CV and NCA regions. This could be attributed to the relatively mild climatic/temperature changes during the year, when compared with the CV and NCA regions. The extreme changes in pavement temperature accelerate asphalt hardening, which makes both the binder and asphalt mix stiffer and more brittle. Also, sections in both the CV and NCA regions experienced higher traffic levels than sections in the CC region. This will result in cumulative traffic over the sections in the CV and NCA region higher than that over the CC sections, therefore developing more alligator (fatigue) cracks in a faster rate. This is also supported by the trend in Figure 4.9, where the percent change in alligator cracks is significantly higher as pavement sections in both the CV and NCA regions grow older.

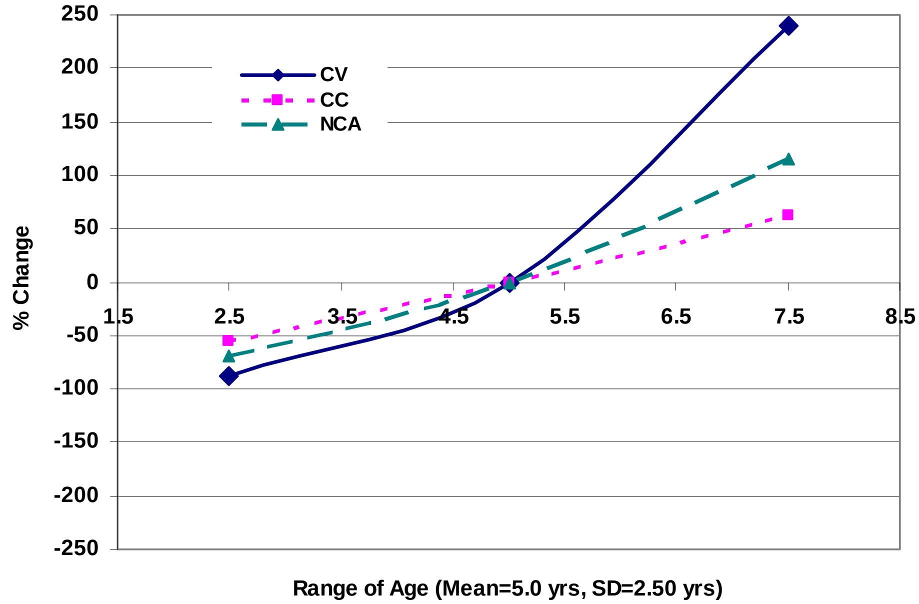


Figure 4.9 Percent change in alligator cracks with age.

4.5.1.2 Effect of ESAL

The change in the percentage of alligator cracks as a function of ESAL is presented in Figure 4.10 for the three regions. As noticed in this figure, sections in both the CV and NCA regions are expected to exhibit changes in alligator cracks that are higher than those for sections in the CC region. The percent changes are higher for traffic levels higher than the mean for all regions..

4.5.1.3 Effect of thickness ratio (HMA/PCC)

Figure 4.11 presents the change in alligator cracks as the thickness ratio (HMA/PCC) varies around the mean. The three performance models are sensitive to changes in thickness ratio, especially for values below the mean. The percent change is higher for the CC model, which could be attributed to the effect of subgrade type and drainage issues. These issues were discussed in sections 3.4.2.1.2 and 4.4.1.

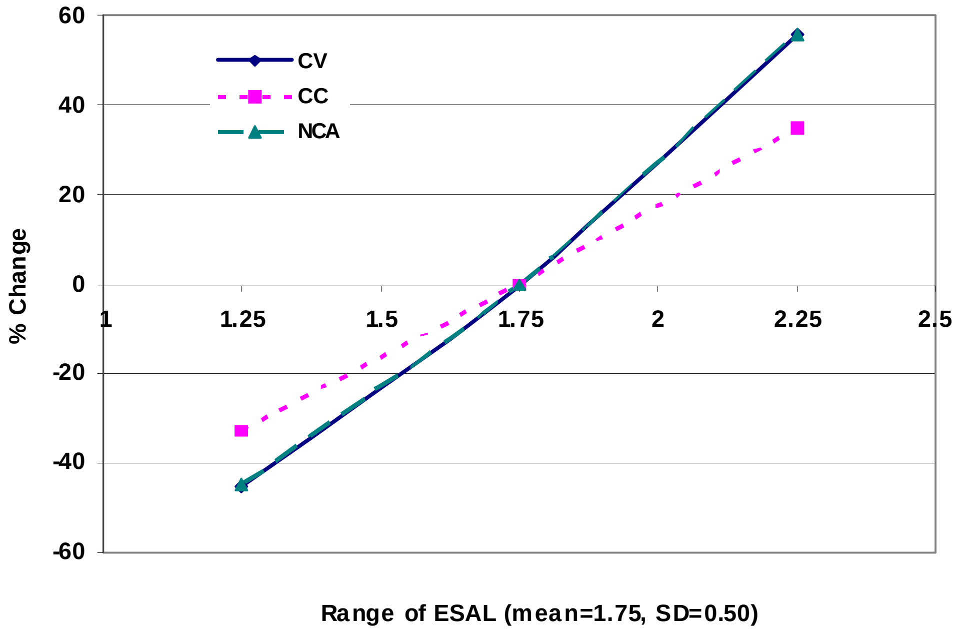


Figure 4.`0 Percent change in alligator cracks with traffic (ESAL).

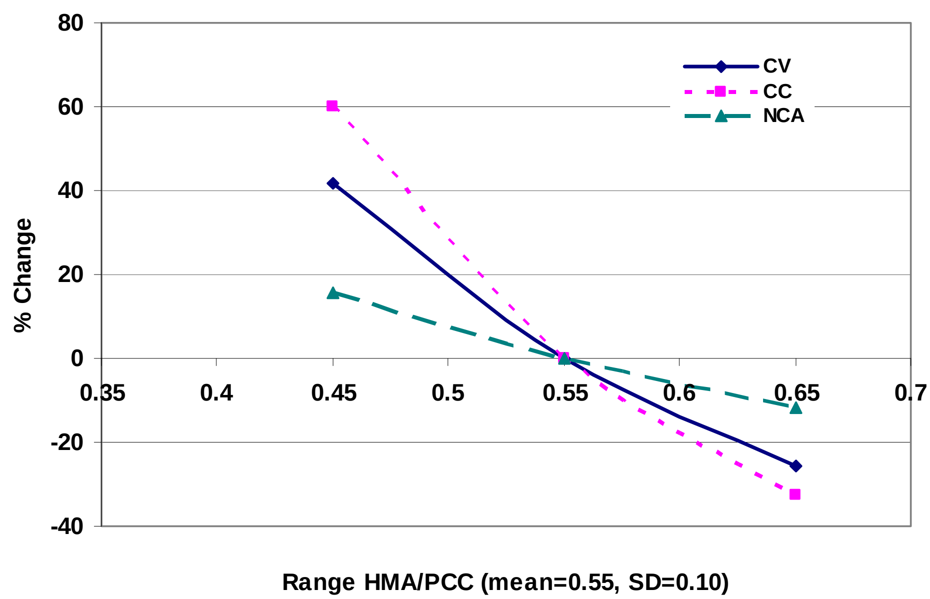


Figure 4.11 Percent change in alligator cracks with thickness ratio (HMA/PCC).

4.5.2 Transverse and Longitudinal Cracks

4.5.2.1 Effect of age

Sensitivity analyses for transverse and longitudinal cracks, as a function of pavement age, are presented in Figures 4.12 and 4.13, respectively. It is evident from these figures that the models for the three regions exhibit approximately similar trends. The percent change and the rate of the change both increase as pavement sections grow older. Older pavements are expected to receive more traffic in addition to more thermal change cycles, which leads to the formation of reflective cracks.

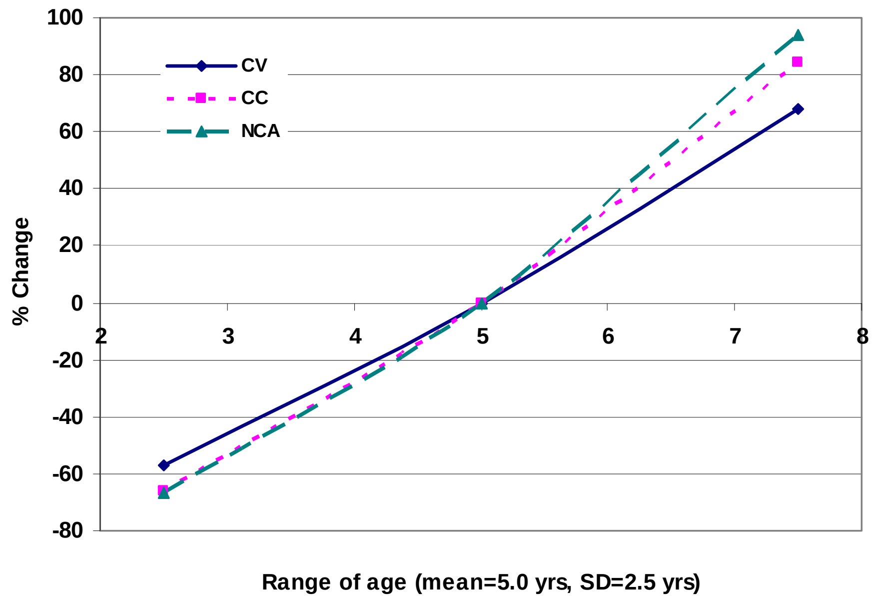


Figure 4.12 Percent change in transverse cracks with age.

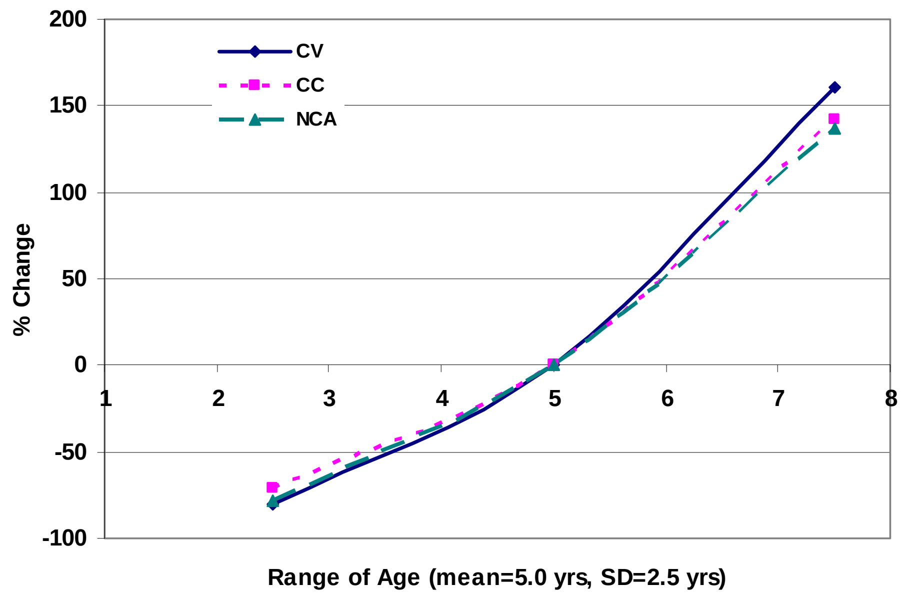


Figure 4.13 Percent change in longitudinal cracks with age

4.5.2.2 Effect of thickness ratio (HMA/PCC)

The plots for the sensitivity of reflective cracks to the changes in thickness ratio are presented in Figures 4.14 and 4.15. As noticed in the figures, both the percent change and the rate of the change increase as thickness ratio decreases. In general, a higher thickness ratio would mean thicker HMA overlay, assuming uniform PCC thickness was originally used in the construction of rigid concrete pavements. A thick HMA overlay helps retard the development of reflective cracking and also reduces the rate of crack formation. Since concrete slab thicknesses are not uniform (as evident from comparing section cores with the as-built data), it is recommended that PCC pavements be cored for slab thickness verification before employing CS&O to make sure that adequate thickness ratio (HMA/PCC) is used.

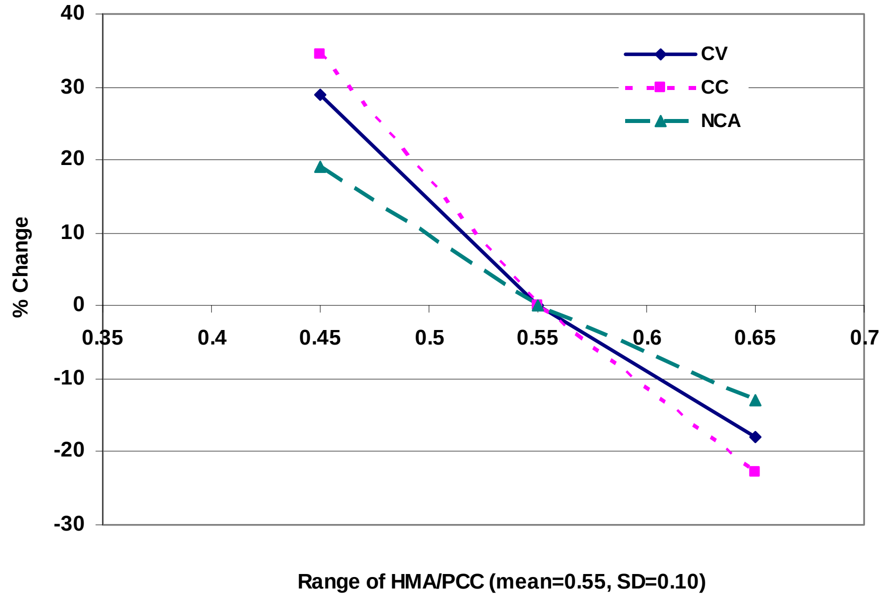


Figure 4.14 Percent change in transverse cracks with thickness ratio (HMA/PCC).

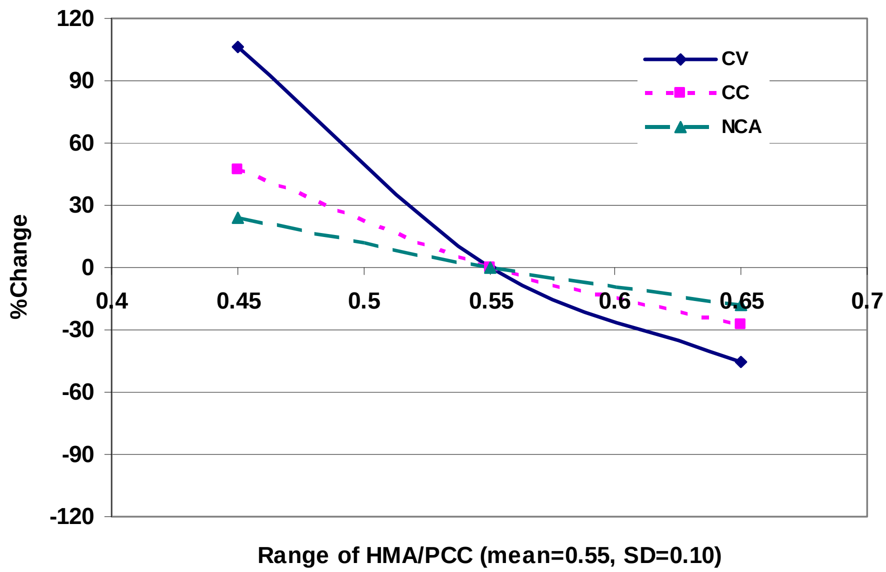


Figure 4.15 Percent change in longitudinal cracks with thickness ratio (HMA/PCC).

4.5.3 IRI

4.5.3.1 Effect of age

Figure 4.16 presents the changes in IRI with age, as predicted from the three performance models developed for the CV, CC and NCA regions. The models predict a similar trend for sections in the three regions. However, the model for the NCA sections exhibits smaller changes and slower rate of change when compared with models for the CV and CC regions, even though the NCA sections receive higher traffic (ESAL) than those in the CC region (see Table 3.11). This trend could be attributed to construction practices, subgrade, and subsurface drainage issues that were not investigated as part of this study.

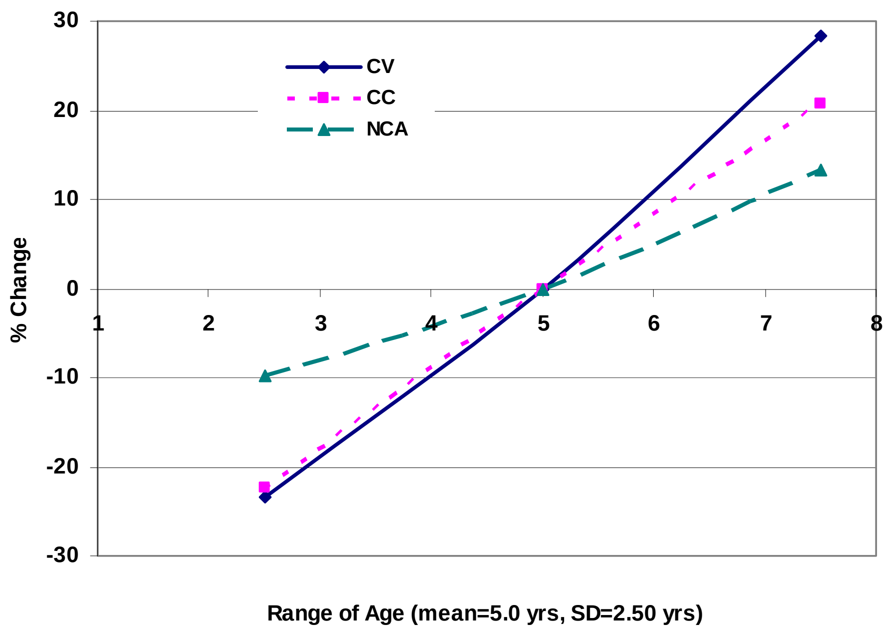


Figure 4.16 Percent change in IRI with age.

4.5.3.2 Effect of ESAL

Performance model results as ESAL varies around the mean value are presented in Figure 4.17. Trends similar to those observed in Figure 4.16 are evident, which could be attributed to the same factors mentioned in section 4.5.3.1.

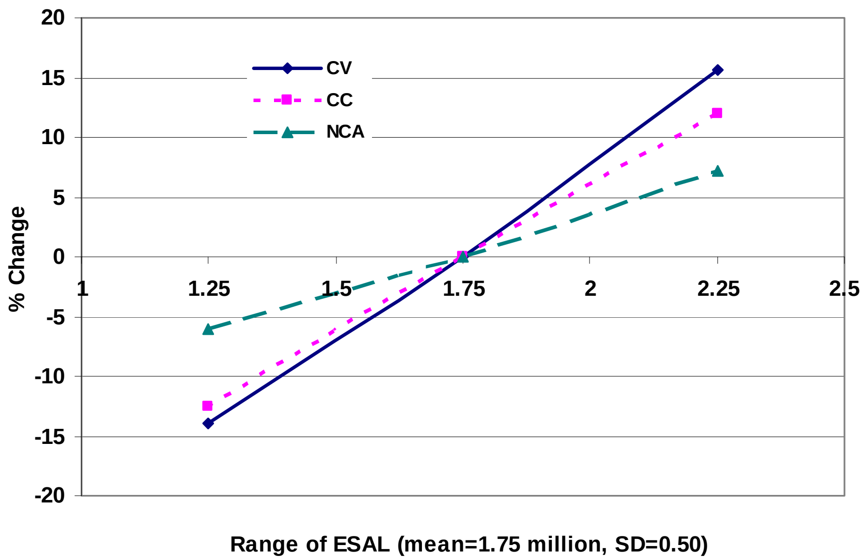


Figure 4.17 Percent change in IRI with ESAL.

4.5.3.3 Effect of HMA thickness

The sensitivity of the IRI models to the changes in HMA thickness is summarized in Figure 4.18. As evident in this figure, sections in all three regions are expected to experience higher IRI for thinner HMA overlays and lower IRI for thicker HMA overlays. The rate of change is approximately the same for both the thinner and thicker overlays. For the three regions, the percent change in IRI as result of overlay thickness variations is much lower than that resulting from variations in age and ESAL (see Figures 4.16 and 4.17).

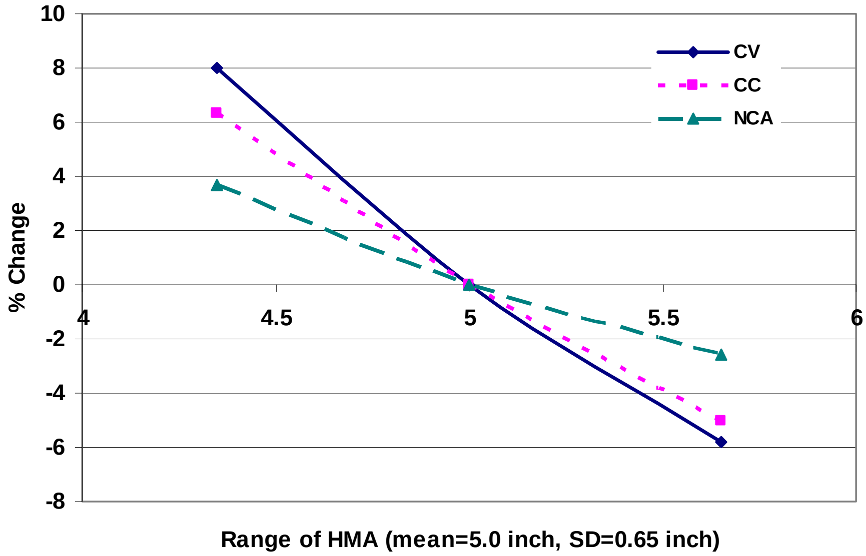


Figure 4.18 Percent change in IRI with HMA thickness.

4.6 SUMMARY

The models developed in the study indicate that the most important variables affecting the deterioration of CS&O pavements are age, traffic, HMA overlay thickness and thickness ratio (HMA/PCC). An age factor appears in all of the models. This factor represents deterioration of pavements due to the environment and/or other damage that cannot be accounted for by traffic. Age can be determined precisely, making it the most significant variable in the models. Also, it reflects the impacts of both cumulative traffic and environmental loading cycles.

The results of the sensitivity study suggest that age is the most significant factor affecting the deterioration of CS&O pavements. The sensitivity analyses revealed that the effect of traffic level (in terms of ESAL) and layer thicknesses follow that of age for alligator cracks and IRI. The effect of thickness ratio on reflective cracking follows that of age, as evidenced from the model sensitivity analyses.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 SUMMARY

The objective of this study was to evaluate the performance of the Crack, Seat, and Overlay (CS&O) rehabilitation technique, as used in three climatic regions in California. Performance, construction, and maintenance data for sections in the Central Valley (CV), Central Coast (CC) and Northern California (NCA) were analyzed. The performance of the CS&O sections was measured in terms of cracking (transverse, longitudinal, and alligator) and IRI. Performance comparisons were completed using two statistical approaches, namely the paired t-test and the logistic regression analysis. Several explanatory variables were used to develop performance prediction models. These variables included age of overlay, thicknesses of asphalt overlay and concrete slab, traffic level, and type of base layer. The explanatory variables present physically meaningful relationships with the response variables, indicating that the equations assume a cause-effect relationship.

5.2 CONCLUSIONS

The principal conclusions of this research investigation are as follows:

- Pavement age, coupled with the ratio of HMA to concrete slab layer thickness, are considered the most significant predictor of deterioration in terms of reflection cracks. With traffic, these variables significantly affect alligator cracks and surface roughness.
- Identical CS&O sections built in the CV and NCA regions are expected to outperform those in the CC region with respect to alligator cracks ‘A’ and ‘B’.

- No statistically significant difference was observed for transverse and longitudinal cracks among the three regions.
- In terms of IRI, CS&O sections in NCA region are expected to outperform their counterparts built in the CV and CC regions.
- Sections in the CV region are expected to reach an IRI of 180 in/mile after 10 years of service. However, after 10 years in service, sections in NCA and CC regions are expected to reach 115 in/mile and 160 in/mile after 10 years in service, respectively.
- Reflection cracking in the transverse and longitudinal directions was not significantly observed in the CS&O sections investigated as part of this study. However, alligator cracking 'A' and 'B' seems to be of concern for a number of the sections in the three regions.
- Differences in construction techniques and quality control are evident for the CC, CV, and NCA regions, as observed from the difference in initial IRI values.
- The ratio of HMA thickness and PCC thickness proved to be an important factor affecting CS&O performance.

5.3 RECOMMENDATIONS

The outcomes of this study (Phases I and II) suggest the following recommendations:

- The effect of the fabric interlayer location within the overlay on the CS&O performance needs to be investigated. This could be accomplished through building test sections where short-term and long-term performances are monitored annually.

- Depth (thickness) profile of pavement sections before cracking should be evaluated. This evaluation is intended to help use the appropriate cracking energy. Same energy level may not be applied for all sections without thickness verification. Also, this will help verify the actual thickness ratio used in the prediction models.
- Continue employ CS&O, but the condition on PCC before applying CS&O needs to be carefully examined. Stringent criteria need to be developed for slab panels that qualify for CS&O versus others that could receive other rehabilitation techniques (for example, rubblization, slab replacement, dowel retrofitting, or thin concrete overlay, etc.).
- The effect of subgrade type/condition and the conditions of concrete slabs before applying CS&O on sections performance need to be investigated.
- More CS&O in each of the three regions need to be identified and used for model calibration.
- Cores extracted from the sections included in this research investigation need to be tested for possible correlation between materials properties and sections performance.

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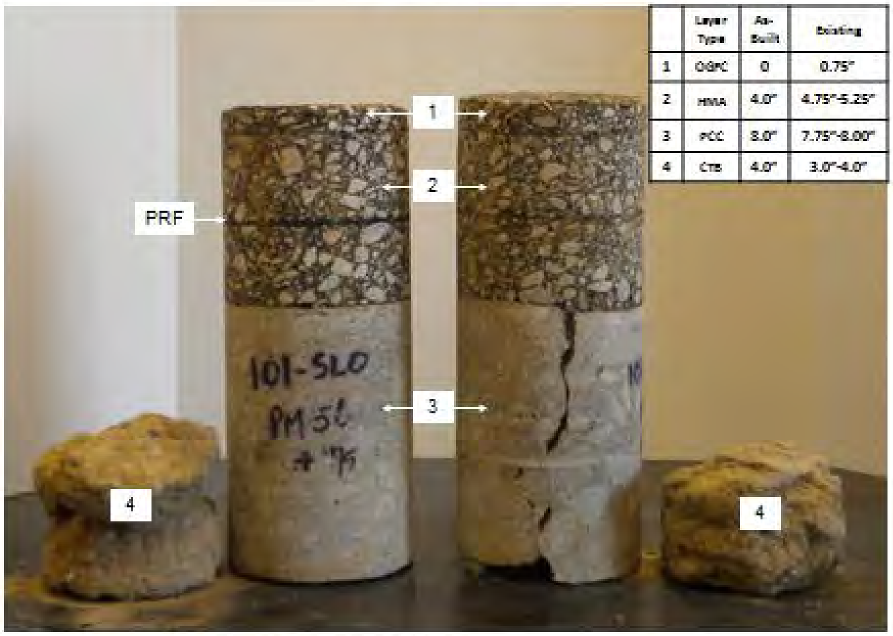
Appendix

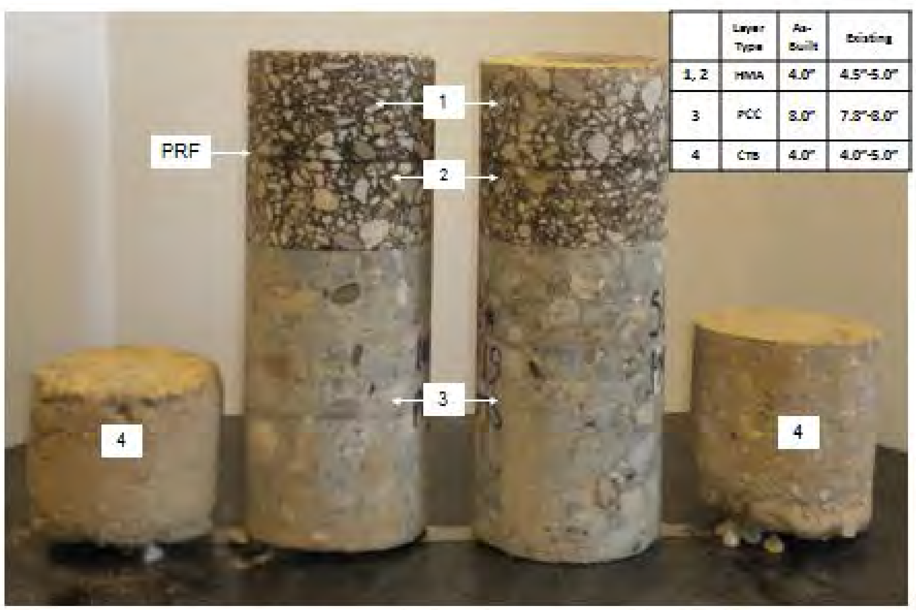
SLO_101N_56.06



	Layer Type	As-Built	Existing
1	OGFC	0	0.75"
2	HMA	4.0"	4.75"-5.25"
3	PCC	8.0"	7.75"-8.00"
4	CTB	4.0"	3.0"-4.0"

Figure A.1 Cores extracted from Section SLO_101N_56.06

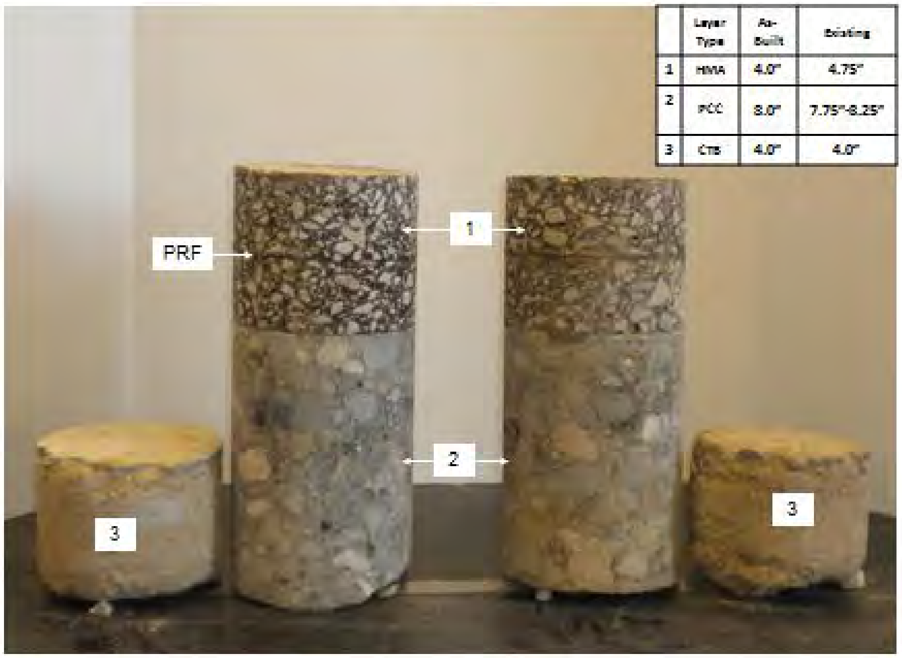
SLO_101N_60.98



	Layer Type	As-Built	Existing
1, 2	HMA	4.0"	4.5"-5.0"
3	PCC	8.0"	7.8"-8.0"
4	CTB	4.0"	4.0"-5.0"

Figure A.2 Cores extracted from Section SLO_101N_60.98

SLO_101S_61.00



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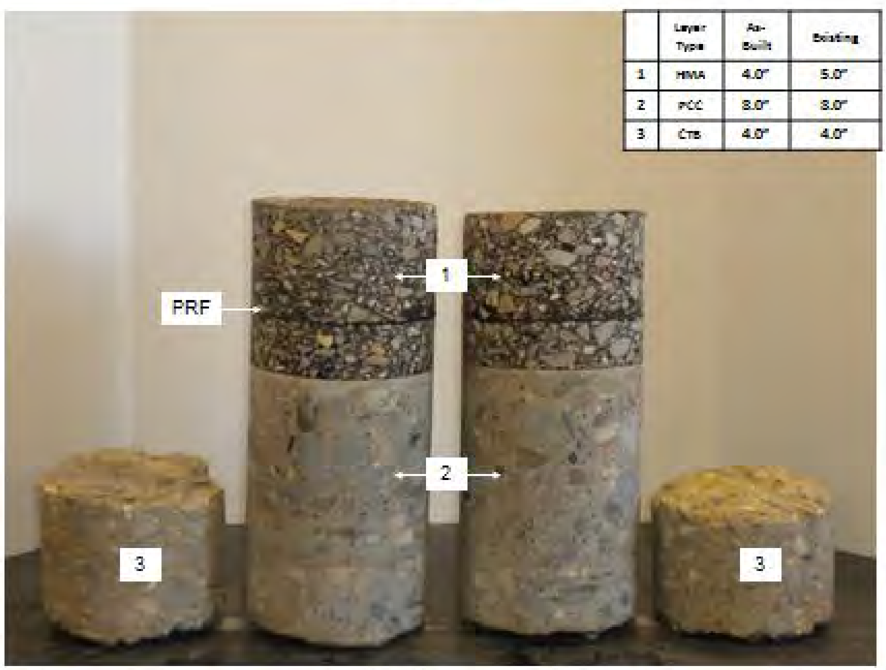
1	HMA	4.0"	4.75"
2	PCC	8.0"	7.75"-8.25"
3	CTB	4.0"	4.0"

Figure A.3 Cores extracted from Section SLO_101S_61.00

SB_101N_90.06



	Layer Type	As-Built	Existing
1	HMA	4.0"	5.0"
2	PCC	8.0"	8.0"
3	CTB	4.0"	4.0"

Figure A.4 Cores extracted from Section SB_101N_90.06

SB_101N_82.85

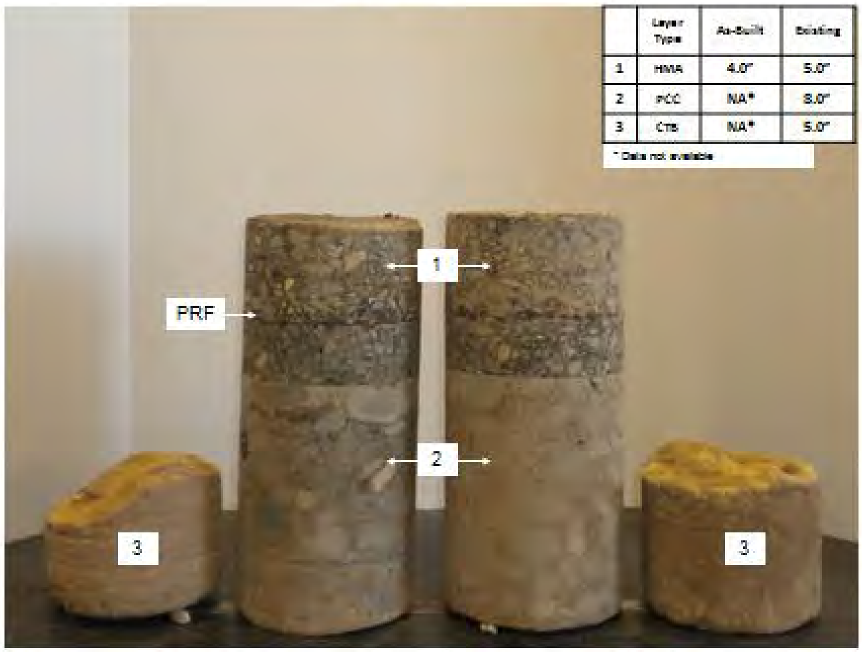


Figure A.5 Cores extracted from Section SB_101N_82.85

SB_101N_27.59

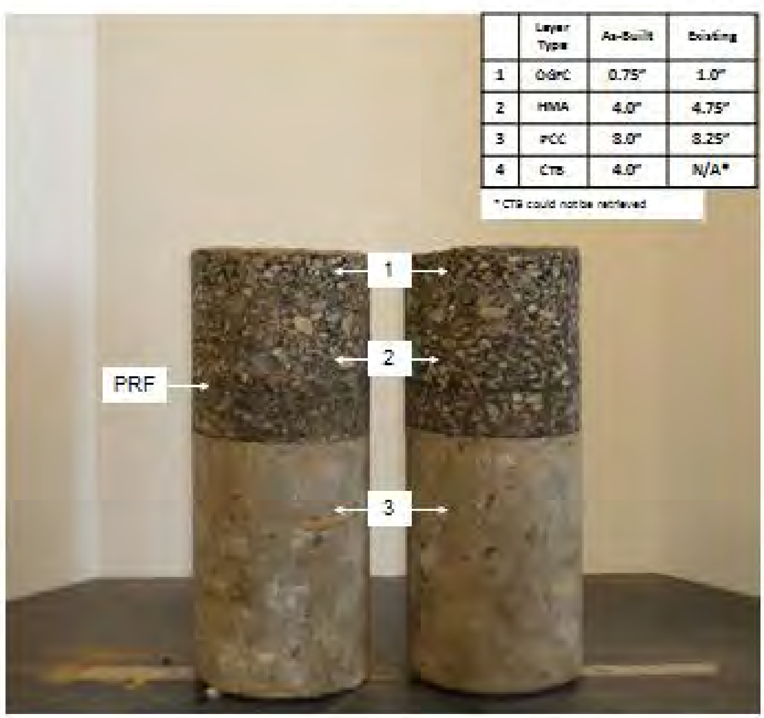
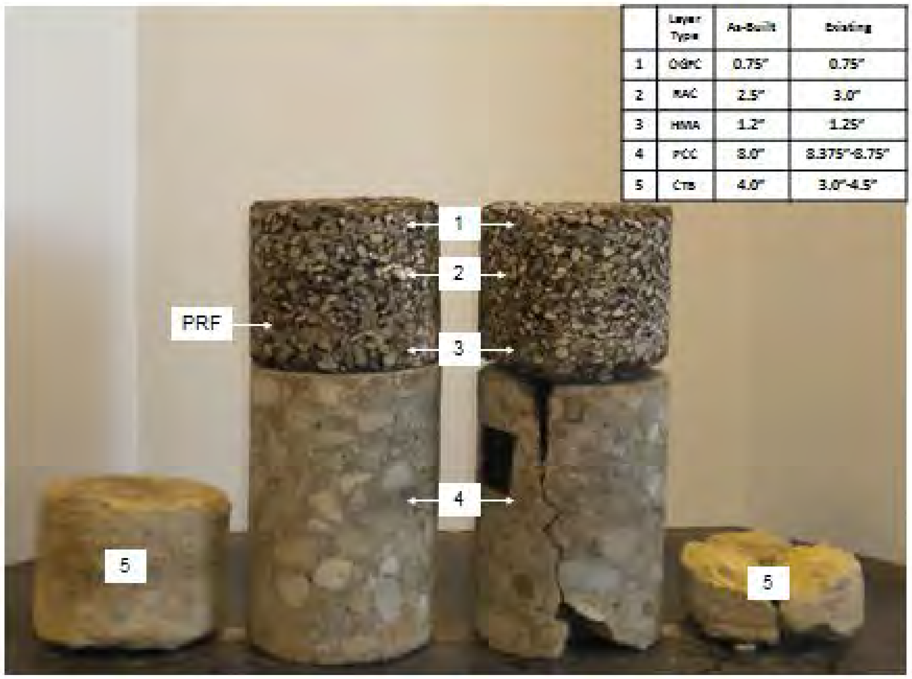


Figure A.6 Cores extracted from Section SB_101N_27.59

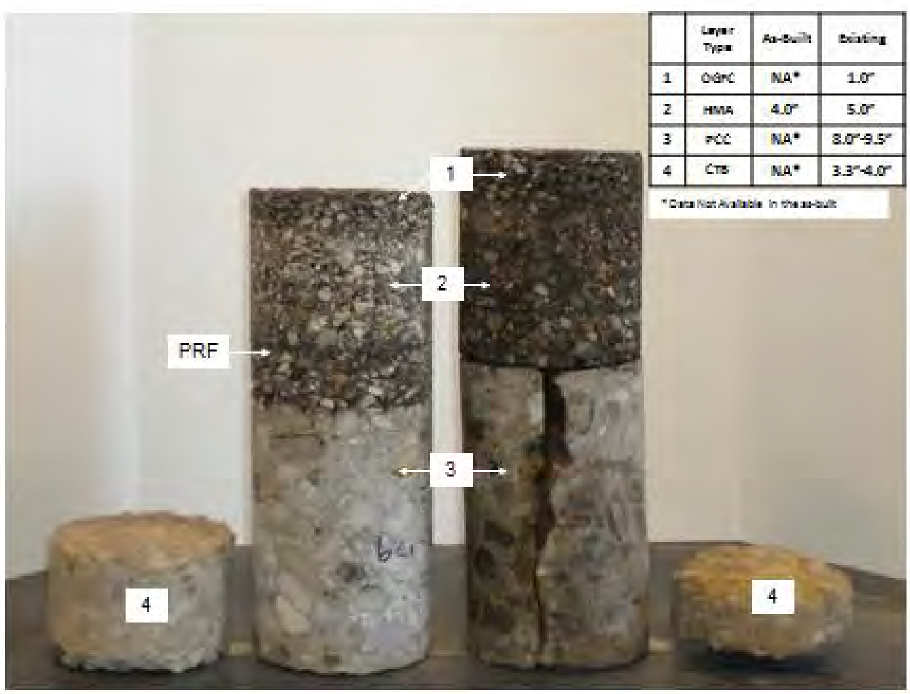
SB_101N_21.66



	Layer Type	As-Built	Existing
1	OGFC	0.75"	0.75"
2	RAC	2.5"	3.0"
3	HMA	1.2"	1.25"
4	PCC	8.0"	8.375"-8.75"
5	CTB	4.0"	3.0"-4.5"

Figure A.7 Cores extracted from Section SB_101N_21.66

SB_101N_15.24



	Layer Type	As-Built	Existing
1	OGFC	NA*	1.0"
2	HMA	4.0"	5.0"
3	PCC	NA*	8.0"-9.5"
4	CTB	NA*	3.3"-4.0"

* Data Not Available in the as-built

Figure A.8 Cores extracted from Section SB_101N_15.24

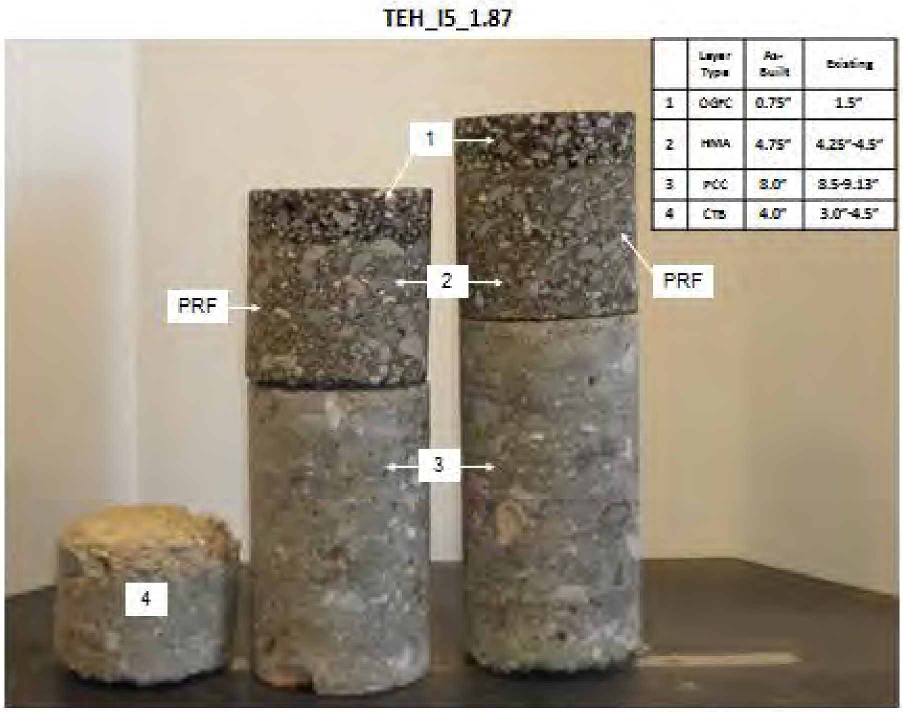


Figure A.9 Cores extracted from Section TEH_I5N_1.87

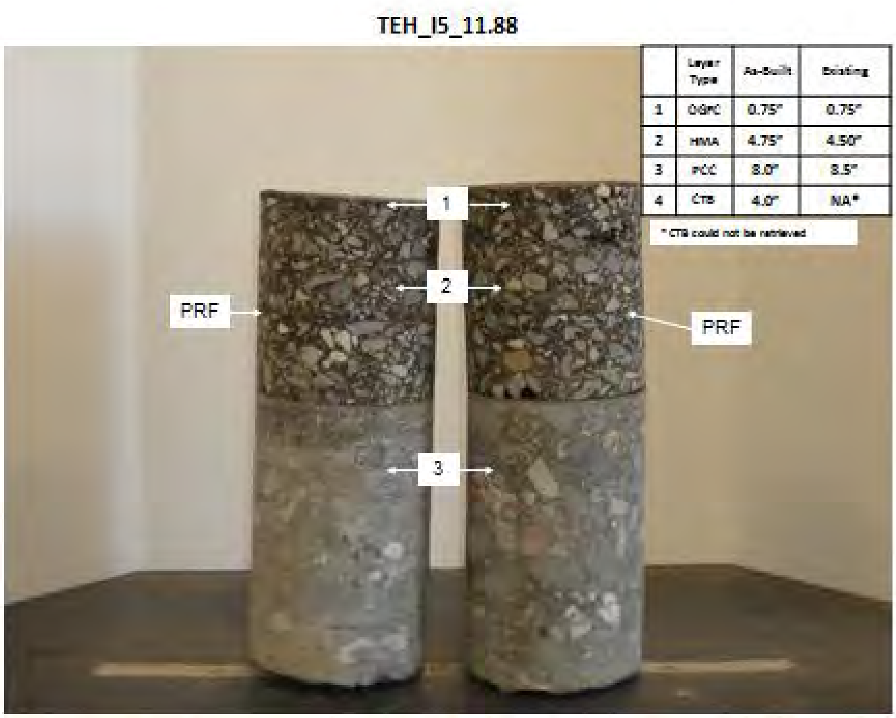


Figure A.10 Cores extracted from Section TEH_I5N_11.88

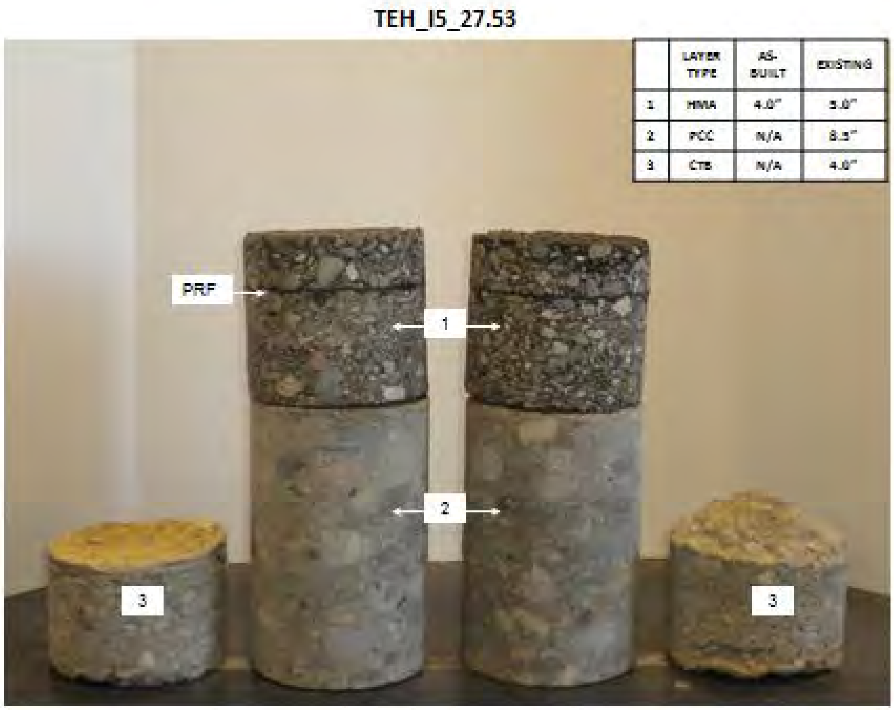


Figure A.11 Cores extracted from Section TEH_I5N_27.53

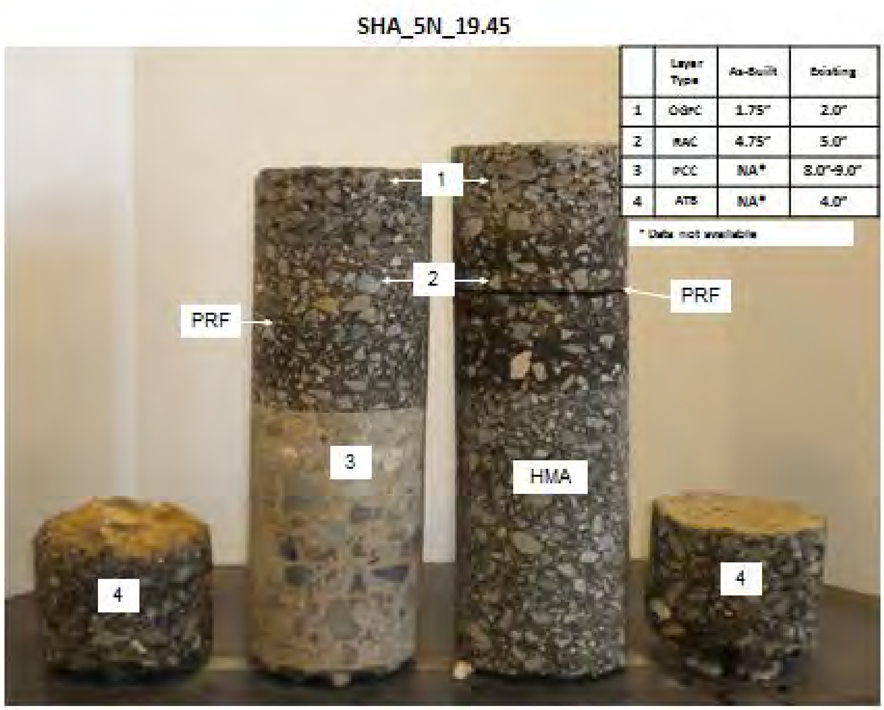


Figure A.12 Cores extracted from Section SHA_I5N_19.45

SHA_I5N_39.50

Figure A.13 Cores extracted from Section SHA_I5N_39.50

SHA_I5N_60.04

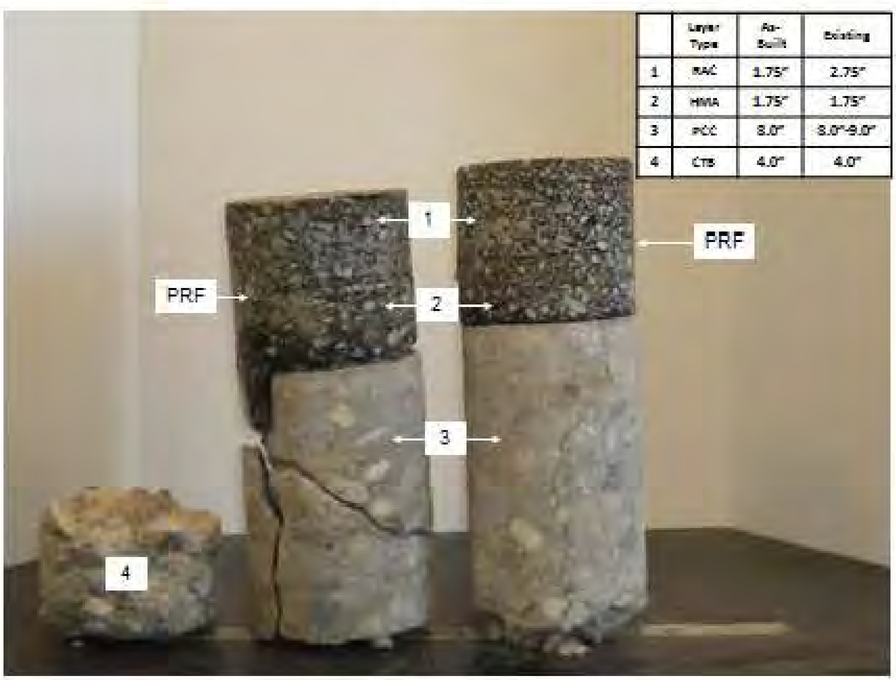
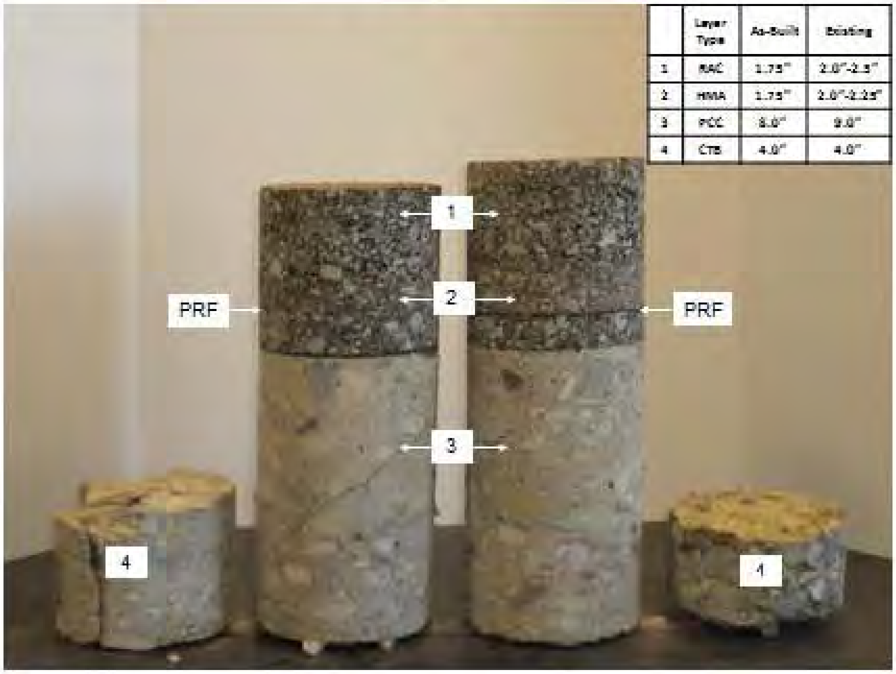


Figure A.14 Cores extracted from Section SHA_I5N_60.04

SHA_I5N_60.57



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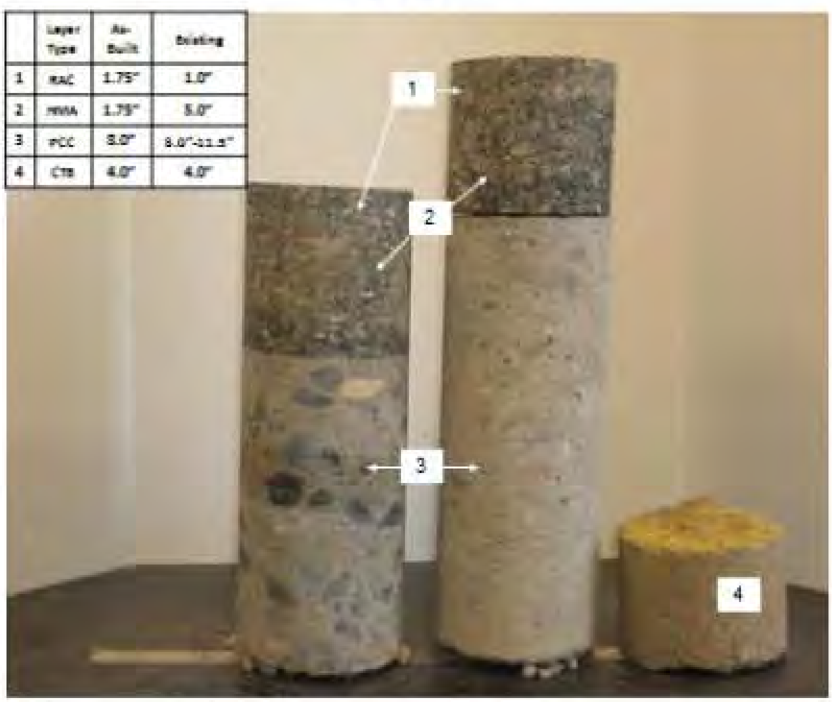
2	HMA	1.75"	2.0"-2.25"
3	PCC	8.0"	9.0"
4	CTB	4.0"	4.0"

Figure A.15 Cores extracted from Section SHA_I5N_60.57

SIS_I5N_42.60



	Layer Type	As-Built	Existing
1	RAC	1.75"	1.0"
2	HMA	1.75"	5.0"
3	PCC	8.0"	8.0"-11.5"
4	CTB	4.0"	4.0"

Figure A.16 Cores extracted from Section SIS_I5N_42.60

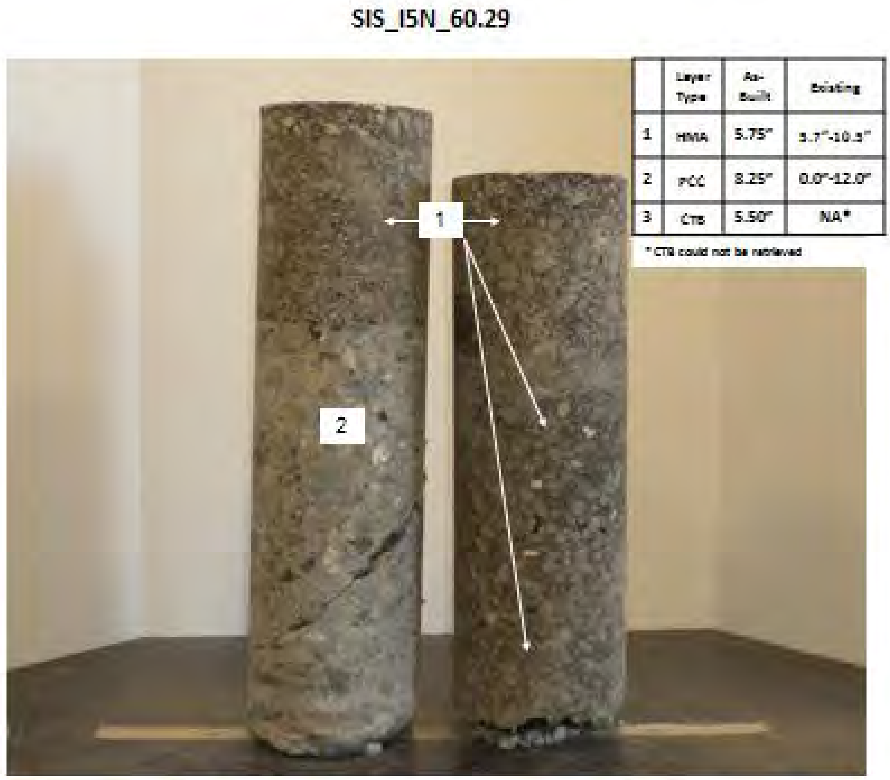


Figure A.17 Cores extracted from Section SIS_I5N_60.29