INVESTIGATION OF THE EFFECT OF CURLING ON AS-CONSTRUCTED SMOOTHNESS AND RIDE QUALITY OF KDOT PORTLAND CEMENT CONCRETE (PCC) PAVEMENTS

Report Number: K-TRAN: KSU-01-7

By

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RESEARCH

Introduction

Smoothness plays a significant role in the construction, functionality, and performance of roadways. Many state highway agencies including the Kansas Department of Transportation (KDOT) have adopted specifications that require minimum levels of smoothness for newly built pavements. A number of factors contribute to the roughness or a lack of roughness: pavement distresses, built-in construction irregularities, traffic loading, environmental effects, and construction materials. Environmental effects such as temperature and/or moisture gradient across the thickness of the concrete pavement slab can cause curling, which also affects the roughness.

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The objectives of this research were to evaluation and quantify the effect of PCC slab curling on the as-constructed and short-term smoothness and to identify the factors that affect curling and roughness, so that the occurrence of curling could be minimized through modifications to the design and/or construction techniques.

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Twelve test sections on six newly built concrete pavement projects on Interstate routes 70 and 135 were selected. Periodic longitudinal profile data was collected by a South Dakota-type profiler on each wheel path of both the driving and passing lanes. A digital method was developed to separate curling from the longitudinal profile using Fast Fourier Transform (FFT). International Roughness Index (IRI) values were calculated for the original profile, curled profile, and profile without curling. The contribution of curling to the measured roughness was found to be significant. Analysis of variance (ANOVA) was performed to compare mean IRI values with respect to different factors. Rate of application of curing compounds and time of the year when data was collected were found to be significant factors affecting the as-constructed smoothness and early life roughness of PCCP's. Double application of curing compound can reduce the curling as well as help retain short-term smoothness of newly built concrete pavements.

Project Results

A set of models was developed to describe early-life roughness in terms of different construction, geometric, and climatic variables. The as-constructed smoothness and early-life roughness are affected by the PCC slab thickness, compressive strength of concrete and base layers, percent air in concrete, and grade. The smoother a pavement is built, the smoother it stays over time. The factors that affected curling were: slab thickness and the stabilized base stiffness. Curling could be minimized using a subbase that would yield when the concrete slab expands or contracts. If curling could be minimized, roughness in terms of IRI becomes a function of the slab thickness, compressive strength of the concrete, change in Plasticity Index of the subgrade soil after lime treatment, and strength of the base layer.

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16 Abstract

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In this report, the effect of curling on as-constructed smoothness as well as early-life roughness of Portland Cement Concrete Pavements (PCCP) was investigated. Twelve test sections on six newly built concrete pavement projects on Interstate routes 70 and 135 were selected. Periodic longitudinal profile data was collected by a South Dakota-type profiler on each wheel path of both the driving and passing lanes. A digital method was developed to separate curling from the longitudinal profile using Fast Fourier Transform (FFT). International Roughness Index (IRI) values were calculated for the original profile, curled profile, and profile without curling. The contribution of curling to the measured roughness was found to be significant. Analysis of variance (ANOVA) was performed to compare mean IRI values with respect to different factors. Rate of application of curing compounds and time of the year when data was collected were found to be significant factors affecting the as-constructed smoothness and early life roughness of PCCP's. Double application of curing compound can reduce the curling as well as help retain short-term smoothness of newly built concrete pavements.

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Final Report

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TOPEKA, KANSAS

KANSAS STATE UNIVERSITY
MANHATTAN, KANSAS

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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ABSTRACT

Smoothness plays a significant role in the construction, functionality, and performance of roadways. Many state highway agencies including the Kansas Department of Transportation (KDOT) have adopted specifications that require minimum levels of smoothness for newly built pavements. A number of factors contribute to the roughness or a lack of roughness: pavement distresses, built-in construction irregularities, traffic loading, environmental effects, and construction materials. Environmental effects such as temperature and/or moisture gradient across the thickness of the concrete pavement slab can cause curling, which also affects the roughness.

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A set of models was developed to describe early-life roughness in terms of different construction, geometric, and climatic variables. The as-constructed smoothness and early-life roughness are affected by the PCC slab thickness, compressive strength of concrete and base layers, percent air in concrete, and grade. The smoother a pavement is built, the smoother it stays over time.

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Chapter 1

Introduction

1.1 Introduction

Smoothness of newly constructed Portland Cement Concrete Pavements (PCCP) is now one of the major concerns in the highway industry. It is believed that motorists perceive a good road as the one that provides a smooth ride. Pavement smoothness is probably the single most important indicator of performance from the standpoint of traveling public. Studies at the road test sponsored by the American Association of State Highway Officials (AASHTO) showed that the subjective evaluation of a pavement, based on mean panel ratings, was also primarily influenced by roughness (*1*). Smoothness plays a significant role in the construction, functionality, and performance of roadways. Many state highway agencies have recently adopted specifications that require minimum levels of smoothness for newly built pavements, with some specifications incorporating significant incentive/disincentive provisions to try and ensure that agencies get what they want. Pavement roughness is mostly controlled by the longitudinal profile of the pavement. Different wavelengths have different effect on the ride quality of pavements depending on vehicle characteristics as well as driving speed. Thus, smoothness is an important measure of pavement performance. Rough roads result in discomfort, reduction in speed, potential damage to vehicles, and increase in operating cost (*1*).

There are many factors that contribute to the roughness of the in-service pavements. The most common cause of roughness is pavement distress. Common PCCP distresses that contribute to roughness include joint faulting, spalling, deteriorated transverse cracks, and punchouts. Over time, swelling soils or frost heave can also contribute to the roughness of a pavement. Roughness can also be “built in” during construction because of such factors as variability in the base and subgrade, inconsistency in paving operations, the presence of embedded items in the pavement, and random construction deviations (*2*). Environment also plays a significant role towards the pavement roughness. Environmental effects such as temperature and moisture gradient across the thickness of slab can cause curling, which in turn affects the roughness of the pavement (*3*).

The American Concrete Institute (ACI) (*4*) defines curling as “the distortion of any originally essentially linear or planar member into a curved shape such as the warping of a slab due to creep or to differences in temperature or moisture content in the zones adjacent to its opposite faces.” A concrete slab tends to curl when it is subjected to a temperature and or moisture gradient across the thickness of the slab. Curling induces stresses in the slab as the pavement is restrained by its weight and the reaction from the subgrade. The thermally induced stress caused by such interaction can be a significant factor in contributing to early pavement cracking (*5*). This may be critical, particularly within a few hours after placement, since concrete in the early stage of hydration may have insufficient strength to prevent cracking. Ytterberg (*3*) reported that curling is caused by drying shrinkage and by moisture and temperature gradients across the thickness of the slabs. Negative drying shrinkage and moisture gradients are usual in slabs on grade and they cause upward curling. Negative moisture gradients and upward curling are increased if the slab is made from high shrinkage concrete, if the slab is exposed to low humidity air, or if the subgrade or sub-base under the hardened slab has a high moisture content. The most common positive temperature gradient with its downward edge curling is that caused by heat from the sun on the upper slab surface (*3*). Upward edge curling is caused by negative moisture gradients, and can be increased by cold slab surface temperatures or by hotter slab bottom temperatures.

Tremper and Spellman (6) made displacement profilograms of a number of highway pavements. They found that upward curling was the dominant condition. The upper portion of a pavement slab is nearly always drier than the bottom part, and that upward curling due to a moisture difference may be offset wholly or partially in the afternoon by a higher temperature at the top than the bottom. Temperature rise due to solar radiation was not thought to be high enough to produce downward curling in the daytime. At night, the upward curling increased and reached a maximum (6).

Recently it has been reported that some concrete pavement slabs are built with "locked in" curvature, a physical phenomenon due to uneven shrinkage caused by nonuniform temperature rise and uneven curing (7). Thick slabs, with top faces exposed during curing, will generally curl up on the ends because of drying shrinkage. This curling could affect the future development of concrete pavements (7).

1.2 Study Objectives

The objectives of this research were:

1. To evaluate and quantify the effect of PCC slab curling on the as-constructed and short-term smoothness.
2. To identify the factors that affect curling and roughness, so that the occurrence of curling could be minimized through modifications to the design and/or construction techniques.

1.3 Organization of the Report

This report is divided into seven chapters. Chapter 1 is the introduction to the problem. Chapter 2 describes the test section details. Chapter 3 describes data collection methodology and includes some data collected for the study. Chapter 4 presents data analysis details. Quantification of PCCP slab curling and its contribution to the roughness is described in Chapter 5. Chapter 6 deals with the statistical analysis, which includes Analysis of Variance (ANOVA) and development of multiple linear regression models. Finally, Chapter 7 provides some conclusions and recommendations based on this study.

Chapter 2

Test Sections

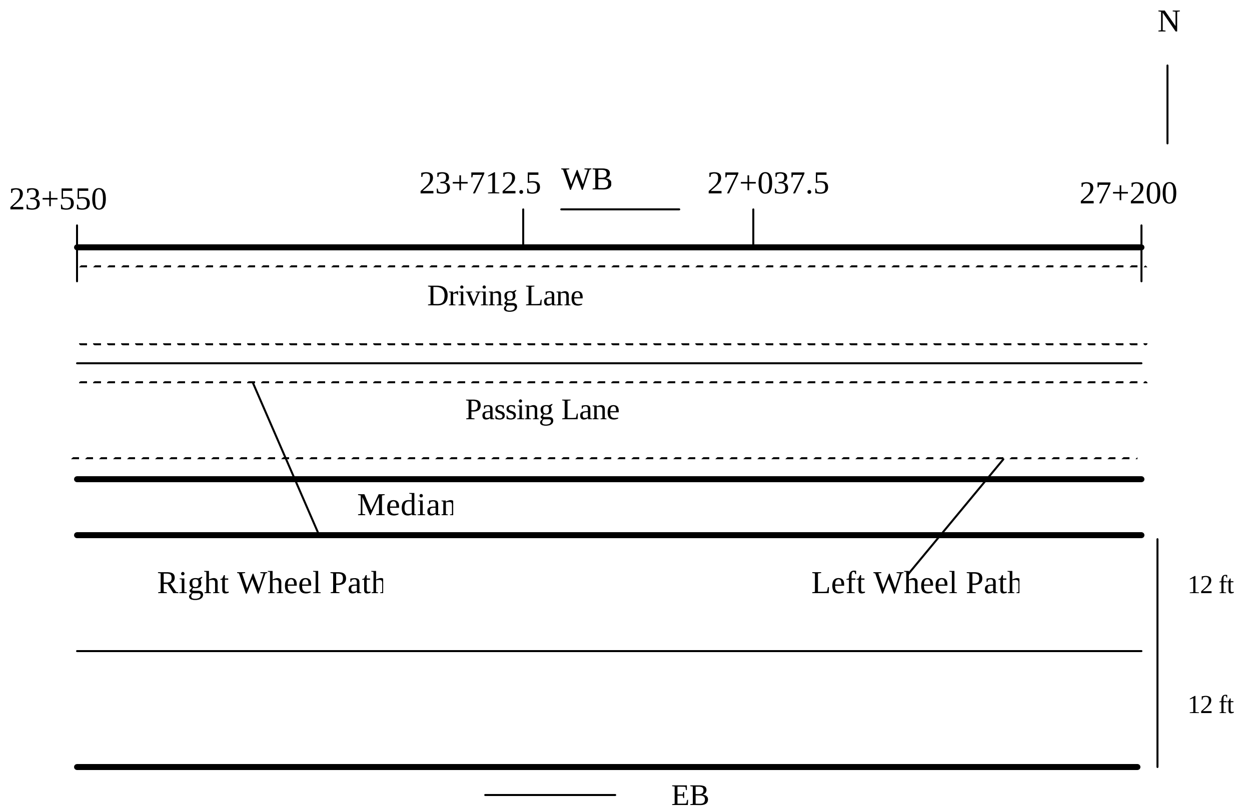
2.1 Test Sections

Twelve (12) different newly built PCCP sections on six different sites on two routes were selected for this study. Six (6) of these sections were built in summer and fall of 2000, and rest were built in the summer of 2001. Table 2.1 shows the location and important features of these sections. Eight of these sections are on interstate route I-70, and the rests are on I-135. All sections are jointed plain concrete pavements with 16.4 feet (5 meter) joint spacing and doweled joints. All sections have identical cross-section except the concrete slab thickness. They have 4 inch (100 mm) stabilized subbase and 6 inch (150 mm) lime-treated subgrade. This subbase was stabilized with cement and cement-fly ash binder and was drainable. A drainable base (known as Bound Drainable Base (BDB)) in Kansas is defined as the one with a minimum permeability of 1000 ft/day (303 m/day). Most of the subgrade materials are fine and plastic and were treated by lime.

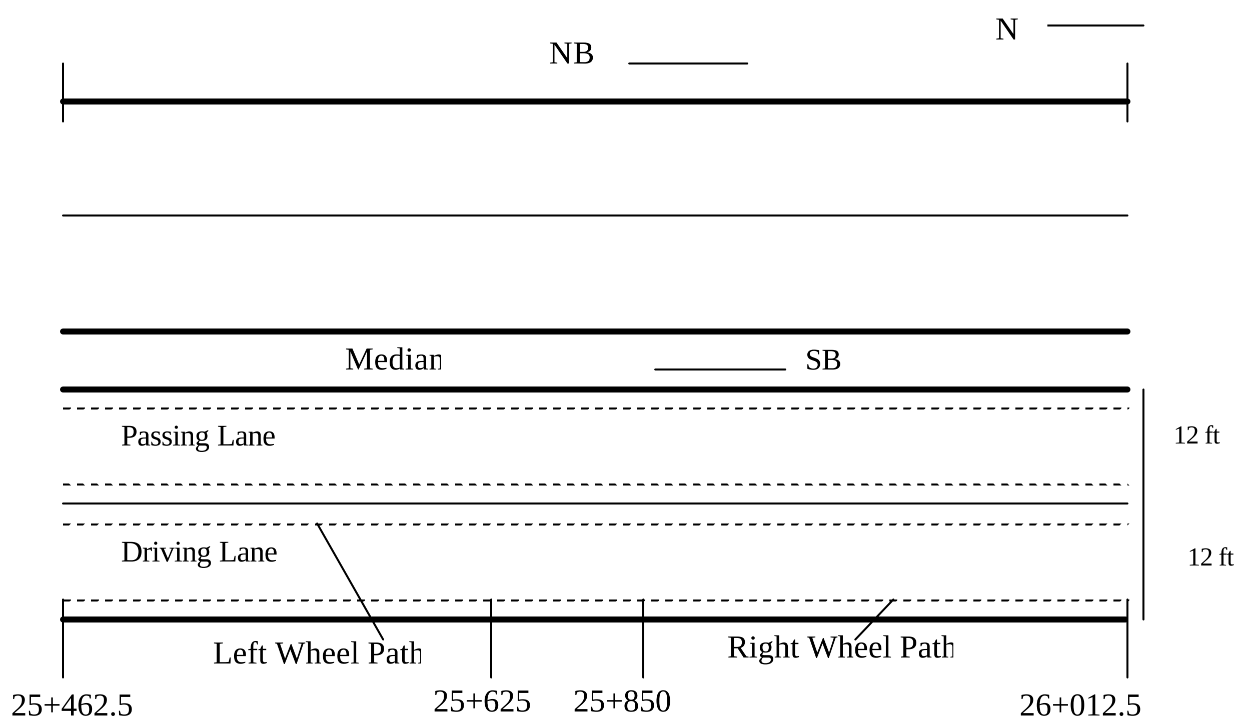
As tabulated in Table 2.1, these test sections have different slab thicknesses. The test sections at Paxico on I-70 have the highest thickness of 12.5 inch (320 mm) whereas the Salina sections constructed in 2001 have the lowest slab thickness (10 inch or 250 mm). The test sections were selected in such a way that they were located on the tangents and were away from any physical structures like bridges. Only the Topeka sections were constructed on a vertical slope with a 4% grade. All test sections consist of 32 continuous slabs (i.e. approximately 525 ft or 160 m) and are located on both lanes in one direction. Figures 2.1(a) and 2.1(b) show the layout of Paxico and Salina Test sections respectively.

TABLE 2.1 Location and Salient Features of Test Sections

Test Section Name	Section Symbol	Route	County	Project No.	Construction Date	Station		Slab Thickness (inch)	Grade (%)
						Begin	End		
Paxico 1	PTS-1	I-70W	Wabaunsee	70-99K-5633-01	July 26, 2000	27+200	27+037.5	12.5	0
Paxico 2	PTS-2	I-70W	Wabaunsee	70-99K-5633-01	July 26, 2000	23+712.5	23+550	12.5	0.4
Salina 1	STS-1	I-135S	Saline	135-85K-5263-01	July 26, 2000	25+850	26+012.5	11.0	0.1
Salina 2	STS-2	I-135S	Saline	135-85K-5263-01	July 26, 2000	25+162.5	25+325	11.0	0.1
Topeka 1	TTS-1	I-70E	Shawnee	70-89K-5087-01	July 25, 2000	346+25	351+50	11.5	4.0
Topeka 2	TTS-2	I-70E	Shawnee	70-89K-5087-01	July 25, 2000	339+70	344+95	11.5	4.0
Wamego1	WTS-1	I-70W	Wabaunsee	70-99K-5643-01	June 13, 2001	19+087.5	18+925	12.0	0.5
Wamego 2	WTS-2	I-70W	Wabaunsee	70-99K-5643-01	June 13, 2001	18+925	18+762.5	12.0	0.3
New Paxico 1	NPTS-1	I-70E	Wabaunsee	70-99K-5633-01	August 02, 2001	26+137.5	26+300	12.5	0.5
New Paxico 2	NPTS-2	I-70E	Wabaunsee	70-99K-5633-01	August 02, 2001	26+300	26+462.5	12.5	0.5
New Salina 1	NSTS-1	I-135S	Saline	135-85K-5644-01	July 07, 2001	15+387.5	15+550	10.0	0.5
New Salina 2	NSTS-2	I-135S	Saline	135-85K-5644-01	July 07, 2001	15+550	15+712.5	10.0	0.5



a) Paxico Test Sections



b) Salina Test Sections

FIGURE 2.1: Layout of Test Sections

For most of the sites, test sections are adjacent to each other and were built on the same day. Both sections of a particular site have the same characteristics (geometry, structure, concrete mix etc.) except for the rate of curing compound applied on them. A single coat of curing compound was applied on the sections designated as “1” (PTS-1, TTS-1, STS-1, WTS-1, and, NSTS-1) except on NPTS-1 test section. The sections designated as “2” received two coats of curing compound. Because of the extreme ambient temperature during paving, two coats of curing compound were applied on both New Paxico sections (NPTS-1 and NPTS-2) to avoid cracking. White pigmented curing compound (wax based), meeting AASHTO M-148, Class A, Type 2 requirements, was used for curing application. For single application, the rate of curing compound application was approximately 17 yd^2/gal (3.7 m^2/liter). Carter Water’s Envirocure W-3 was used on the Paxico, Wamego and New Salina test sections. W.R. Meadows’ Sealtight 1610 Kansas White curing compound was used on the other sections. Table 2.2 shows the properties of these compounds. Both are wax-based, Class A compounds and satisfied all required KDOT criteria. However, the Sealtight Kansas White has a much higher density and lower drying time than Envirocure W-3. Moisture loss for 1610 Kansas White is almost half of that for Envirocure W-3. The curing compound was applied at a variable rate because of the fact that curing quality was judged to be a factor affecting the curling of slabs during construction. It is hypothesized that nonuniform temperature rise in fresh concrete and evaporation of water from the top of the slab contribute to the “as-built” curling. This curling is known to contribute to excessive roughness of PCCP’s and if the curing is proper, such curling could be minimized (*7*).

TABLE 2.2: Curing Compound Properties

Product Name	Vehicle	Test Duration (hrs)	Density (lb/ft^3)	Moisture Loss (lb/ft^2)	Dry Time (hours)	Non-Volatiles (%)	4- hour color
Carter Water Corp. Envirocure W-3	Water	72	51.25	0.078	4	26.28	Yes
W.R Meadows Sealtight 1610 Kansas White	Water	72	62.40	0.041	1/2	24.3	Yes

Chapter 3

Data Collection

3.1 Introduction

Data was collected at different phases of construction. Data collection started right from the beginning of the construction process i.e. the preparation of subgrade. The collected data for this study can be divided into three broad categories: a) inventory; b) climatic; and c) profile. Each of these categories is described below.

3.2 Inventory Data

Inventory data includes properties of different layers of the pavement structure as well as traffic and road geometry data.

3.2.1 Layer Property Data

3.2.1.1 Subgrade Data

Subgrade soil was stabilized/modified with lime on sections because of the clayey nature of the soil. The properties of the soil that are deemed important in pavement construction are volume stability, strength, permeability, and durability. Soil stabilization enhances these properties and lime stabilization is applicable to the clayey soils (*8*). Soil samples were collected from each section before and after lime treatment, and Atterberg limit tests were performed. Table 3.1 shows the Plasticity Index (PI) values before and after lime treatment. The TTS-1 section had the highest change in PI due to lime treatment. The table also shows the percent of subgrade materials passing US sieve No. 200 (75-micron) for each section. For all sections 90% or more subgrade materials passed through the #200 sieve.

TABLE 3.1: Subgrade Material Properties

Section	Plasticity Index (%)			Subgrade Material Passing #200 (75-Micron) Sieve (%)
	Before Lime Treatment	After Lime Treatment	Change	
PTS-1	22.5	20.0	2.5	96
PTS-2	20.5	18.5	2.0	96
STS-1	20.0	N/A	-	90
STS-2	23.0	N/A	-	90
TTS-1	26.5	19.5	7.0	97
TTS-2	22.0	21.5	0.5	97
WTS-1	19.0	18.0	1.0	98
WTS-2	21.9	19.5	2.4	98
NPTS-1	20.5	20.25	0.25	96
NPTS-2	22.5	21.5	1.0	96
NSTS-1	22.3	20.3	2.0	92
NSTS-2	22.5	21.0	1.5	92

3.2.1.2 Subbase Data

Lean concrete was used as the subbase (BDB layer) material. Two 6 inch × 12 inch (150 mm × 300 mm) cylinders were collected from each section to determine the compressive strength. Cylinders were tested after 28 days of curing. Figure 3.1 shows the average compressive strength for each of the test sections. The results show a large variability of the BDB compressive strength. The Topeka test sections have much higher 28-day BDB compressive strength than any other sections. The Paxico section, PTS-1, has the lowest BDB strength. No BDB compressive strength data was available for PTS-2, NPTS-1, and NPTS-2 sections because cylinder samples obtained from these sections crumbled during handling.

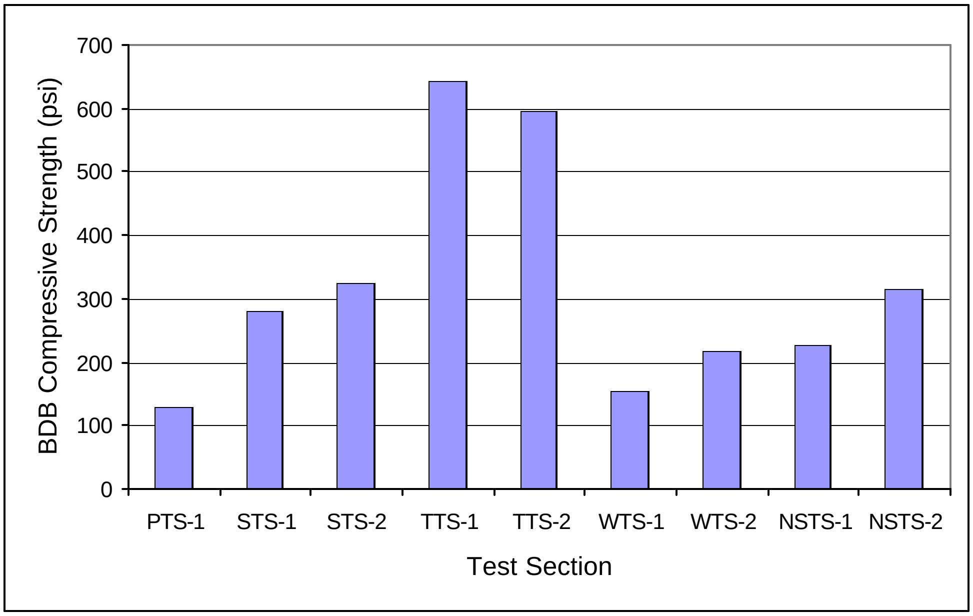


FIGURE 3.1: 28-day Compressive Strength of Bound Drainable Base Layer

The KDOT special provisions related to BDB on these sections require that the seven (7) day compressive strengths for mix designs bound with fly ash or Portland cement shall be between 595 psi to 1200 psi (4.1 to 8.3 MPa) for 6 inch × 6 inch (150 × 150 mm) cylinders. Since the cylinders tested in this study were 6 inch × 12 inch (150 mm x 300 mm), the height-to-diameter ratio correction was applied to convert the compressive strengths obtained in this study into equivalent strength of 6 inch × 6 inch cylinders. Results show that materials from none of the sections had required strength.

3.2.1.3 Concrete Layer Data

Concrete mix design data was collected from contractor's Quality Assurance/Control (QA/QC) report. Table 3.2 shows different mix design parameters for these sections. Two different aggregate compositions were used in the concrete mixture. Sixty percent fine and 40% coarse aggregates were used for the concrete mixture on eight (8) sections. The

Rest of the sections had 55% fine and 45% coarse aggregates. Air-entrainment of concrete varied between 5.25 and 7.50 percent. The Paxico sections constructed in 2000 had the highest water-cement ratio (0.49), whereas Salina sections constructed in the year 2001 had the lowest (0.41) water-cement ratio. There was a lot of variability in 28-day core compressive strength too. It varied from 3950 psi (27.2 MPa) for the Paxico section "2" constructed in 2001 to 6450 psi (44.5 MPa) for the Salina test section built in 2000. The sections with higher 3-day modulus of rupture tended to show lower 28-day compressive strength.

TABLE 3.2: Concrete Mix Design Properties

Section	% Aggregate in Mix		% Air	Water-Cement Ratio	Cement Content (lb/yd^3)	28-day Core Compressive Strength (psi)	3-day Modulus of Rupture (psi)
	Coarse	Fine					
PTS-1	40	60	6.50	0.49	556	4600	595
PTS-2	40	60	6.50	0.49	556	4600	595
STS-1	45	55	7.00	0.45	548	6450	480
STS-2	45	55	7.00	0.45	548	6450	480
TTS-1	45	55	7.50	0.47	565	6000	570
TTS-2	45	55	7.50	0.47	565	6000	570
WTS-1	40	60	6.50	0.42	529	5200	625
WTS-2	40	60	6.50	0.42	529	5200	625
NPTS-1	40	60	6.75	0.41	546	4090	630
NPTS-2	40	60	6.75	0.41	551	3950	630
NSTS-1	40	60	5.25	0.41	526	4710	522
NSTS-2	40	60	5.25	0.41	526	4710	522

3.2.2 Traffic Data

Traffic data was collected from the KDOT design files. The design Average Equivalent Single Axle Loads (ESAL) per day for the study sections are shown in Figure 3.2. It shows that Salina test sections constructed in the year 2001 has the lowest truck traffic.

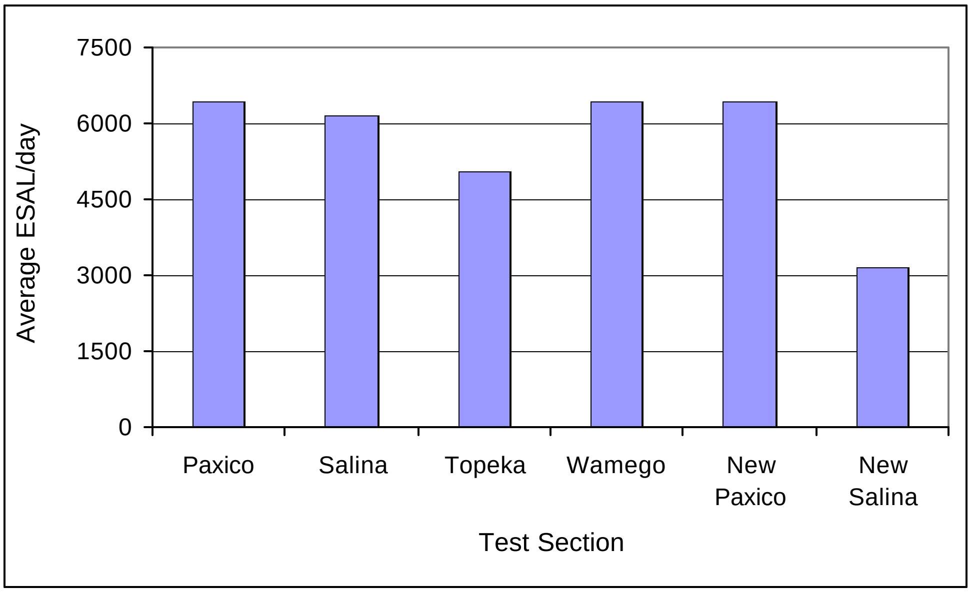


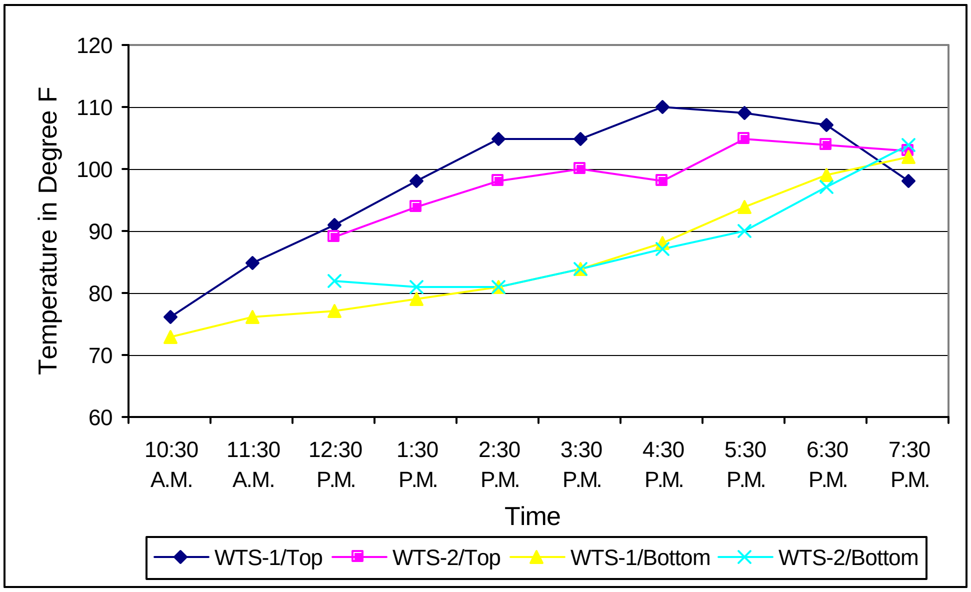
Figure 3.2 Average ESAL/day on Study Sections

3.2.3 Climatic Data

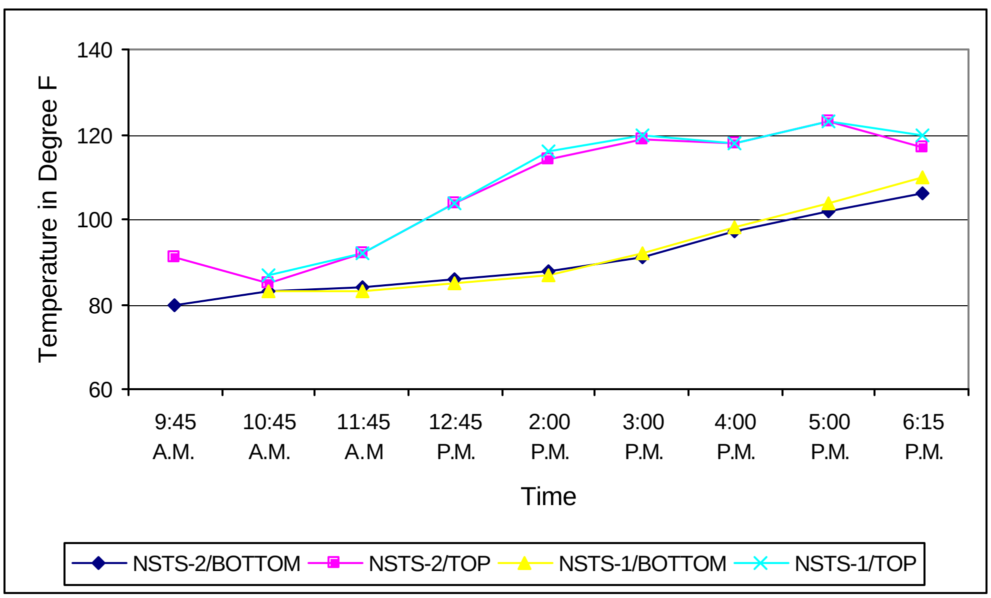
Climatic data collected include: temperature at the pavement top and bottom during and after construction, ambient temperature, and monthly precipitation data. Thermocouples were placed on the top of the subbase layer to obtain temperature at the bottom of the concrete slabs as shown in Figure 3.3. Temperature at the surface of the PCC slab was collected by a hand-held infrared thermometer. For the sections constructed in 2001, pavement top and bottom temperature data was collected hourly during the day of construction. Figure 3.4 (a) and (b) show the temperature variation between pavement top and bottom in the newly placed concrete slab at Wamego and New Salina test sections, respectively. These figures show that a high temperature differential exists between the pavement top and bottom throughout the day. For the most of the daytime, temperature at the top of the slab is higher than that at the bottom, but at around 7 P.M. in the evening temperature at the bottom of the slab is higher than the top. Section cured with single application of curing compound (WTS-1, and NSTS-1) experienced higher temperature than the section cured with double application of curing compound (WTS-2, and NSTS-2) for both pavement top and bottom presumably due to better reflectance at the surface. Double application of curing compound was found to decrease the temperature differential between the top and bottom of the slab in fresh concrete by about 2 to 11^0F compared to the single application of curing compound.

FIGURE 3.3: Thermocouple to Collect Temperature of Pavement Bottom

Ambient air temperature, mean monthly precipitation and temperature variation during the month of construction was collected from the Kansas State University Weather Station. Since there is no weather station at Paxico, data collected from the nearest Wamego weather station was used for the Paxico test sections.



a) Wamego Test Section



(b) New Salina Test Section

FIGURE 3.4: Temperature Variation of Newly Placed Concrete Slab

3.3 Profile Data

A South-Dakota type high-speed inertial profiler, shown in Figure 3.5, was used to collect profile data for this study. It is an International Cybernetics Corporation (ICC) profiler with laser sensors.

FIGURE 3.5: KDOT South Dakota-Type Profiler

After construction, longitudinal profile data was collected periodically. For all sections, as constructed data was collected about two to three weeks after construction before opening the sections to traffic. After the sections were opened to traffic, profile measurements were done at approximately four-month intervals. Table 3.3 shows the dates of profile data collection. The sections constructed in 2000 were tested on a cycle of fall, spring, summer, and fall whereas those constructed in 2001 were tested on a cycle of summer, fall, spring, and summer.

TABLE 3.3: Dates of Profile Data Collection

Profile Age	Time of Data Collection
Sections Constructed in the Year 2000	
As-constructed	October 07, 2000
4-Month	February 21, 2001
8-Month	July 17 &18, 2001
12-Month	November 26 & 27, 2001
16-Month	February 21 & 22, 2002
20-Month	June 27, 2002
24-Month	November 25 & 26, 2002
Sections Constructed in the Year 2001	
As-constructed	July 17& August 30, 2001
4-Month	November 26 & 27, 2001
8-Month	February 21, 2002
12-Month	June 27, 2002
16-Month	November 25 & 26, 2002
20-Month	March 07, 2003
24-Month	June 30 & July 1, 2003

Approximately 70 percent of the vehicles travel in a well-defined wheel path with the right wheel located 2.5 to 3.5 ft (0.76 to 1.07 m) from the pavement edge. The wheel tracks of automobiles and trucks are approximately 6 and 7 ft (1.8 and 2.1 m) apart, respectively. Therefore, the measurement of the longitudinal profile in the wheel path provides the best sample of road roughness (*1*). Profile data was collected on both wheel paths (left and right) of both the driving and the passing lanes, and three replicate runs were made. All profile data was collected at about 3 inch (75 mm) intervals with the profiler operated at highway speed of 50 mph (80 km/hr).

Chapter 4

Data Analysis

4.1 Introduction

Pavement profile data consists of relative elevations at discrete intervals along a pavement surface in the longitudinal direction. The raw profile data cannot be readily used by the pavement engineers nor does it give any readily understandable indication of how rough a pavement is. The data must be processed in some manner to produce a meaningful representation of the pavement roughness. A number of summary statistics are available to represent road roughness using road profile data. Recently International Roughness Index (IRI) has become the most common roughness summary statistic used by different agencies primarily because of Federal Highway Administration (FHWA) reporting requirements for the Highway Performance Monitoring System. (HPMS) and the Long-Term Pavement Performance (LTPP) program (*2*,*9*). Thus IRI was used in this study.

The IRI was developed in 1982 by the World Bank using quarter car simulation model, which has a unit of slope i.e. inch/mile, or m/km. The IRI is a property of the true pavement profile, and as such can be measured with any valid profiler. Influenced by wavelengths ranging from 4 to 100 ft (1.2 to 30.5 m), the IRI has been shown to describe profile roughness that causes vehicle vibrations and is correlated to the user response (*10*). Furthermore, it has been found to be reproducible, portable, and stable with time. For this study, IRI was calculated using RoadRuf software developed by the University of Michigan Transportation Research Institute (UMTRI) (*11*).

4.2 As-Constructed IRI

As mentioned earlier, the as-constructed profile data was collected two to three weeks after construction and before opening the test sections to the traffic. Three replicate runs were made for each wheel path on both the driving and the passing lanes. As-constructed IRI values for all sections are shown in Figure 4.1. These IRI values represent the average IRI of both wheel paths of both lanes with three replicate runs on each wheel path. The variability among the three measurements in a single wheel path was found to be small (about 5%). Figure 4.1 shows that the Salina test sections constructed in 2001 have the lowest as-constructed IRI values. These sections have relatively thinner slabs and lower entrained air, cement content and water-cement ratio in the concrete mixture. The TTS-2 section has much higher as-constructed IRI value than all other sections. The concrete mixture in this section has the highest air entrainment and the section is also located at a vertical grade. For all sections, the as-constructed IRI values for sections cured with a single application of curing compound are lower than those for the sections cured with double application. It is to be noted here that both New Paxico test sections received double coat of curing compound to avoid cracking because of excessive ambient temperature on the day of construction. The average IRI value for all the sections cured with a single application of curing compound was 75 inch/mile (1.19 m/km), whereas that for all sections cured with double application was 81 inch/mile (1.28 m/km).

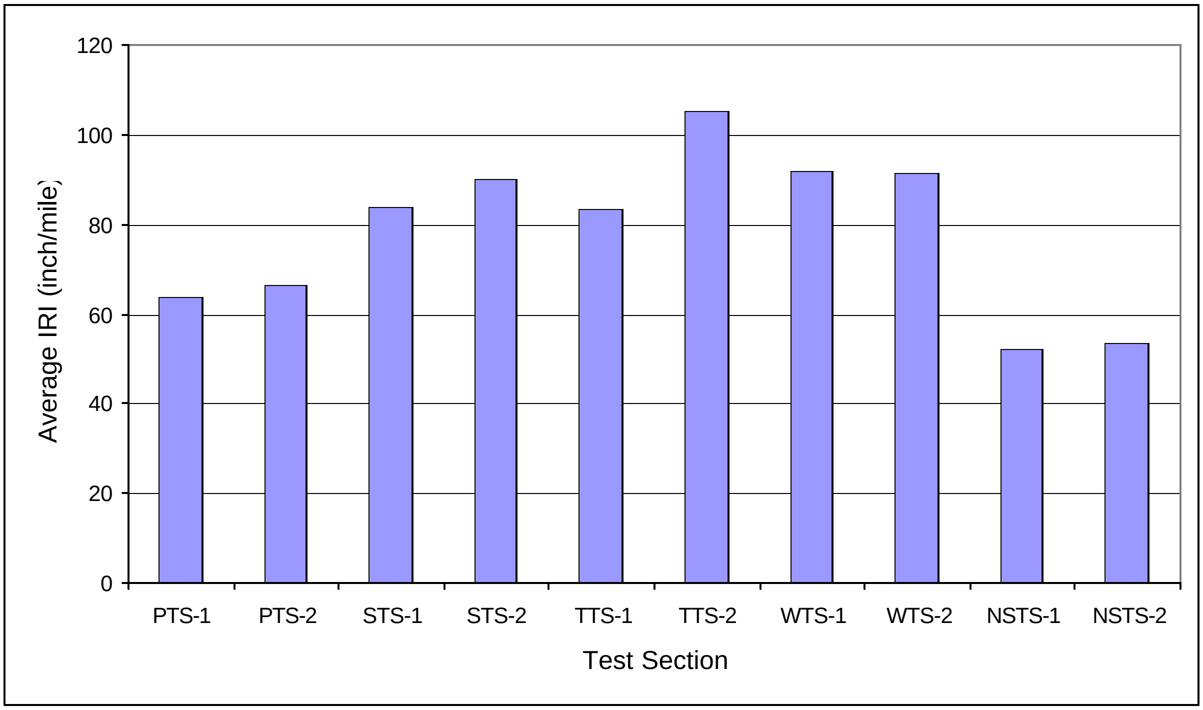


FIGURE 4.1: As-Constructed IRI Values for Different Test Sections

4.3 Short-Term Roughness Progression

After collecting as-constructed data, profile data was collected at approximately 4-month intervals. Table 4.1 shows the variation of the IRI values with respect to time. Unlike as-constructed IRI values, mean IRI value for all the measurements for the sections cured with double application of curing compound is slightly lower (78 inch/mile or 1.24 m/km) than that for the sections cured with a single application (80 inch/mile or 1.26 m/km).

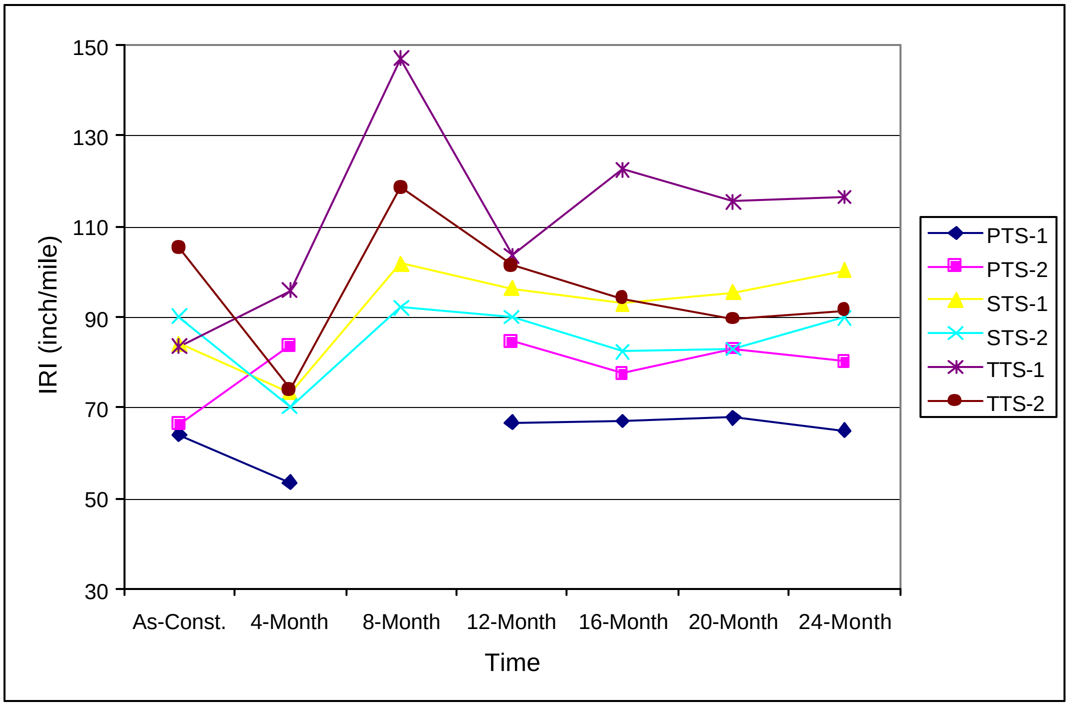
Figure 4.2 shows the typical pattern of roughness progression. Almost all sections exhibit definite patterns of roughness progression. IRI values for TTS-1 were highest for all measurements. This section has the highest grade. Eight-month profile data for PTS-1 and PTS-2, and 12-month data for NSTS-1 and NSTS-2 were not available as those sections served two-way traffic during that time period. The variation of IRI with time for the Paxico test sections built in 2000 was the lowest. The concrete on this section had relatively higher 3-day modulus of rupture than other sections. A previous study in Kansas found that pavements sections with high early flexural strength tend to retain as-constructed smoothness longer (*12*). Figure 4.2 (b) shows that for the sections constructed in 2001, the difference between the IRI values for the sections with different curing application rates is very low for each measurement. However, this is not true for the sections constructed 2000 (Figure 4.2 (a)).

For the Wamego and New Paxico sites, constructed in 2001, roughness decreased with time (up to eight months), then it started increasing. Ride quality of the pavements on both sites was deemed unacceptable by the contractor. The driving lane on both projects was diamond ground shortly after opening to traffic. For all measurements except the as-construed measurement, the IRI values for the sections with double application of curing compound were lower than those with a single application of curing compound. This may indicate that the double application of curing compound is beneficial in the long run.

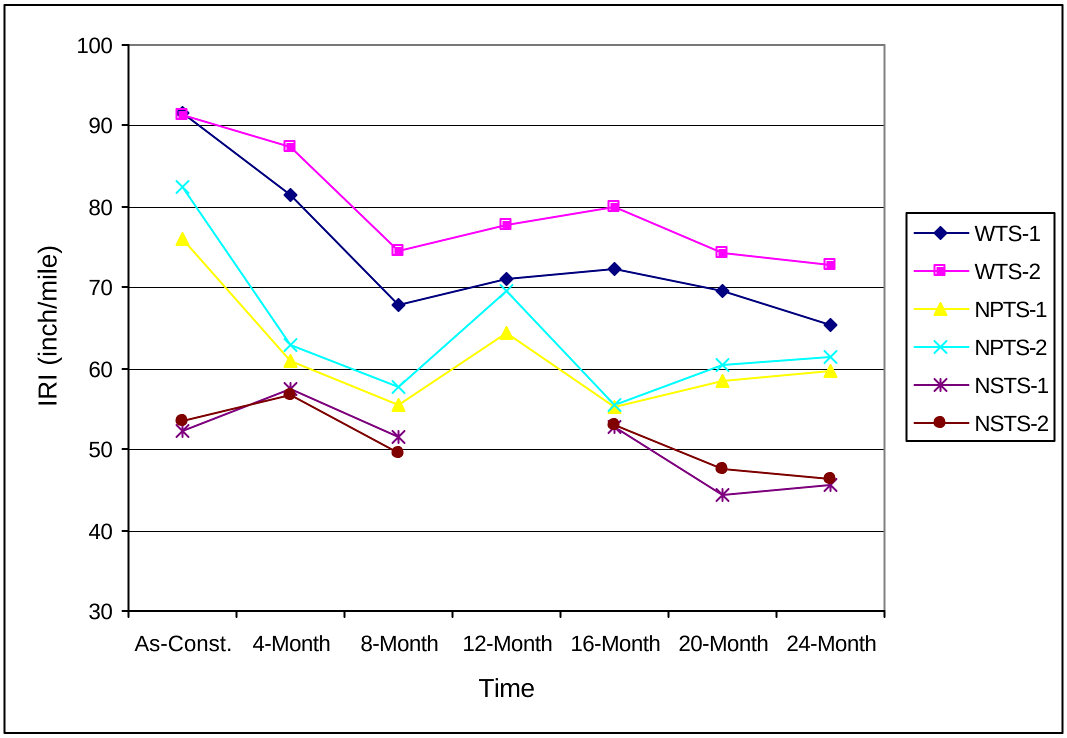
TABLE 4.1: Mean IRI values for Different Sections with Respect to Time

Time	Test Section	Mean IRI (inch/mile) Value			
		Curing Application			
		Single		Double	
		DL[#]	PL[+]	DL	PL
As-constructed	Paxico	63.4	64.6	62.7	70.3
	Salina	84.3	84.3	90.0	90.6
	Topeka	91.2	76.0	100.1	110.2
	Wamego	99.5	84.3	94.4	88.1
	New Salina	50.7	53.9	51.3	55.8
4-Month	Paxico	53.9	52.6	62.7	76.7
	Salina	72.2	74.8	74.8	65.9
	Topeka	93.8	98.2	79.8	68.4
	Wamego	85.5	77.9	88.7	86.2
	New Salina	55.8	59.6	57.0	57.0
8-Month	Paxico*	-	-	-	-
	Salina	100.1	103.3	88.7	90.6
	Topeka	139.4	155.2	118.5	118.5
	Wamego	72.2	64.0	80.5	68.4
	New Salina	48.2	55.1	50.7	48.8
12-Month	Paxico	69.7	64.0	89.3	80.5
	Salina	96.9	95.7	91.9	88.1
	Topeka	109.0	98.2	103.9	98.2
	Wamego	76.7	65.9	79.2	75.4
	New Salina*	-	-	-	-
16-Month	Paxico	71.0	62.7	85.5	75.4
	Salina	92.5	93.1	86.2	78.6
	Topeka	113.4	131.8	95.7	92.5
	Wamego	76.7	68.4	85.5	75.4
	New Salina	51.3	54.5	53.2	52.6
20-Month	Paxico	71.6	64.0	91.9	75.4
	Salina	95.7	95.0	80.5	90.0
	Topeka	101.4	133.1	93.8	85.5
	Wamego	72.9	65.9	81.1	67.8
	New Salina	45.0	44.4	46.9	48.8
24-Month	Paxico	67.8	60.8	86.2	74.1
	Salina	99.5	101.4	90.0	90.0
	Topeka	91.9	141.3	84.3	99.5
	Wamego	69.3	61.5	77.3	69.1
	New Salina	42.5	48.3	46.2	46.2
Average		80.0		78.8	

Note: New Paxico Section is skipped from this table, because curing compound application rate is not a variable for this site.
DL: Driving Lane + PL: Passing Lane
* Served two-way traffic



(a) Sections Constructed in 2000



(b) Sections Constructed in 2001

FIGURE 4.2: Variation of IRI Values with Respect to Time

Chapter 5

Digital Separation of Curling

5.1 Introduction

As mentioned earlier, curling contributes to the road roughness. Curling occurs due to the temperature and/or moisture differential between the pavement top and bottom. No comprehensive study has been conducted so far to find the contribution of curling to the pavement roughness/smoothness. Thus far no universally accepted method has been proposed to identify and separate curling from the profile data. Byrum (*7*) has proposed an empirical method to quantify the effect of as-constructed curling from the roughness data obtained by a K.J. Law 690 DNC high-speed profiler in the LTPP program. In this study, a digital method has been developed to separate curling from roughness and to quantify the contribution of curling to the road roughness.

5.2 Separation of Curling

Curling was separated digitally based on the Fast Fourier Transform (FFT) of the pavement profile obtained with the South Dakota-type profiler. The Fourier Transform decomposes or separates a waveform or function into sinusoids of different frequency which sum to the original waveform. It identifies or distinguishes the different frequency sinusoids and their respective amplitudes. Fast Fourier Transform has many applications in the field of physical science that utilizes sinusoidal signals in its theory, such as engineering, physics, and applied mathematics. It is one of the most widely used techniques to analyze signals. The output of the transducers in the profilers like the South Dakota-type profiler are converted to numbers and processed by a computer (*13*). Several series of numbers exist in an inertial profiler. Each of these sequences is called a signal. Signals are processed mainly for two reasons: to improve the quality of a measurement by eliminating unwanted "noise" from the data, and to extract information of interest from the signal. The analysis of a road profile falls into the category of signal processing. Also, the calculation of profile from transducer signals is a form of signal processing (*13*). Profile data collected by a profiler is discrete and non-periodic signals. The Discrete Fourier Transform (DFT) is used to produce frequency analysis of this type of signals. But DFT is quite complicated to work with as it involves many additions and multiplications involving complex numbers. Even a simple eight sample DFT would require 49 complex multiplications and 56 complex additions to work out. However, a realistic signal, like the road profile data has many samples, making the DFT procedure unmanageable to work with. The Fast Fourier Transform (FFT) is simply a method of laying out the computation, which is much faster for a large number of samples. The idea behind FFT is to break up the original N-point sample into two N/2 sequences. This is done because a series of smaller problems are easier to solve than one large one. The DFT requires $(N-1)^2$ complex multiplications and N(N-1) complex additions as opposed to the FFT's approach of breaking it down into a series of 2-point samples that only require one multiplication and two additions and recombination of the points. Thus the effort needed in signal processing is minimal (*14*).

In this study, MATLAB software was used to separate curling from the road profile. It was assumed that curling is uniform for all slabs. An example of separation of curling from the profile data is presented here for the right wheel path of the driving lane on STS-2. Uniform curling was detected using elevation data from the profile of this section. The elevation plot of this section (525 ft or 160 m long) is shown in Figure 5.1. The FFT of the elevation data is shown in Figure 5.2. The figure shows spikes at every 32 data-point intervals. These spikes are the Fourier components of the fundamental frequency. The first distinguishable spike in Figure 5.2 (at 33 data points) represents a wavelength that is most likely caused by curling and also shows the distinct harmonics associated with it. Thus these spikes represent a wavelength of one slab length [5 m = 16.404 ft = (No. of data points (2,100) * sample interval (3 in.))/(33-1) where 33 is the Fourier coefficient and "1" is the origin indexing used by MATLAB] and all of its harmonics. Then these spikes were separated from the other FFT coefficients. The inverse FFT of these separated spikes resulted in the separated curled profile of the section as shown in Figure 5.3. The subtraction of the separated curled profile from the actual elevation profile resulted in the profile due mainly to the construction process as depicted in Figure 5.4. IRI values were calculated for the profiles with and without curling. The IRI values for the actual profile and the profile without curling were found to be 93 inch/mile (1.47 m/km) and 75 inch/mile (1.18 m/km), respectively. The IRI value for the profile data from the separated curled portion (shown in Figure 5.3) was 42 inch/mile (0.66 m/km). For this particular section, the contribution of curling was approximately 20% of the total roughness. It is to be noted that the IRI's calculated for the separated curling profile and profile without curling will not add up algebraically equal to the actual profile IRI since the IRI calculation algorithm is nonlinear.

This digital separation of curling technique was not found to be applicable to some sections. It is possible that some curled slabs do not curl uniformly enough to produce distinguished spikes in the Fourier components at wavelengths that are multiples of the slab length. This is especially true during early life of some concrete pavements. This condition was noticed for almost all sections constructed in 2000 after four months. Since these measurements were taken during spring, it is quite possible upward curling was not very prominent on these sections at that time.

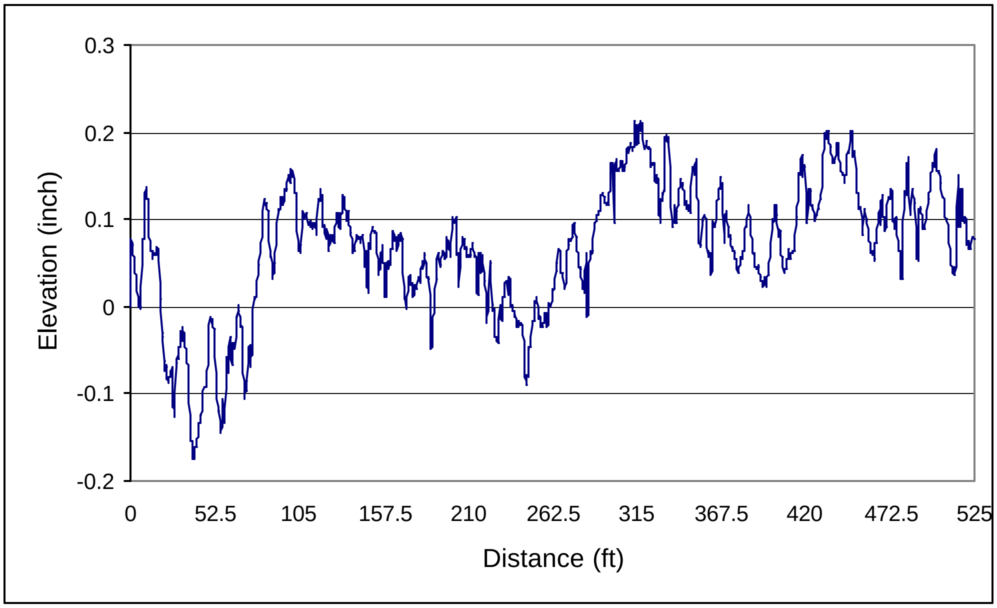


FIGURE 5.1: Elevation Plot of Right Wheel Path of STS-2 (As-constructed)

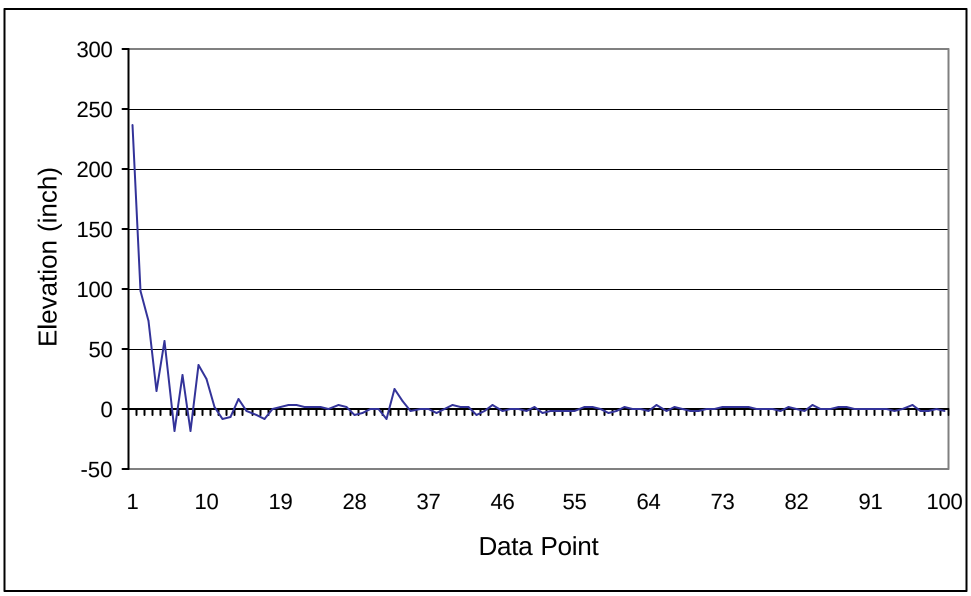


FIGURE 5.2: FFT of Elevation Plot of Right Wheel Path of STS-2

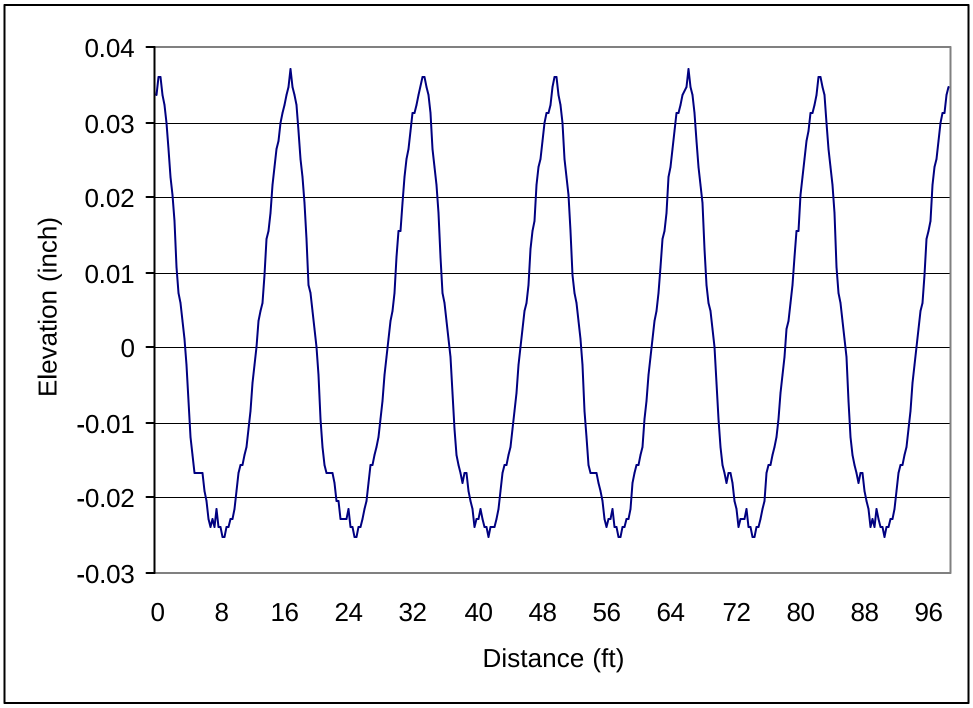


FIGURE 5.3: Elevation of Curled Profile for Right Wheel Path of STS-2

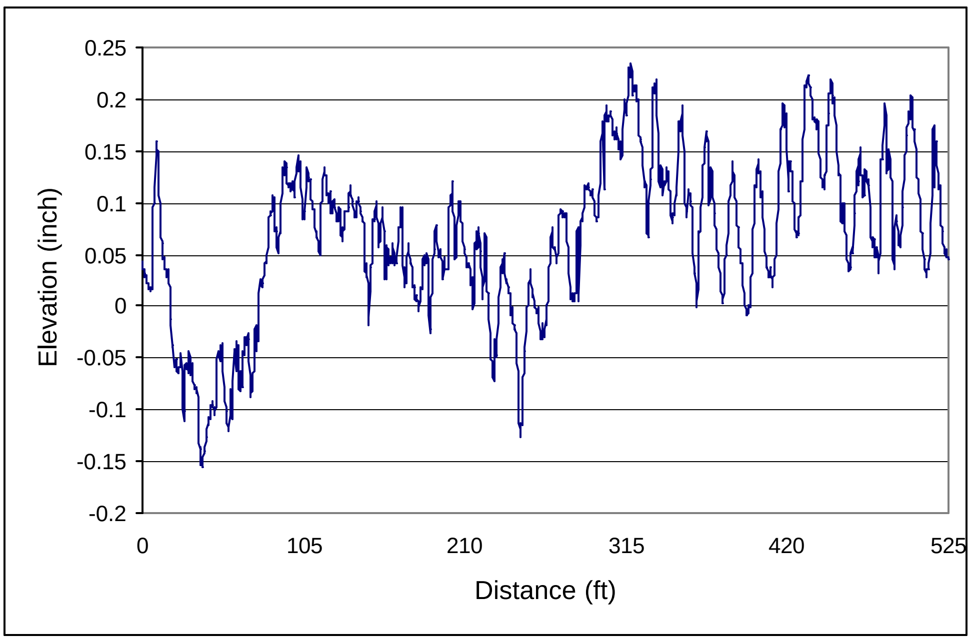


FIGURE 5.4: Elevation of Profile without Curling for Right Wheel Path of STS-2

5.3 Contribution of Curling to Roughness

Curling was separated from profile data collected on all sections. Table 5.1 tabulates the contributions of curling to roughness in the form of percent reduction of IRI values. The effect of curling on as-constructed smoothness was the highest for the Topeka test sections. After 12 months, on WTS-2 section, curling contributed as much as 54% to the roughness in the summer of 2002. It also shows that contributions of curling to roughness for 20-month (Summer 2002), and 8-month (Summer 2001) measurements for the sections constructed in the year of 2000 and for 12-month (Summer 2002) measurements for the sections constructed in 2001 were much higher than other measurements. Since these measurements were taken during summer time, the contribution of curling to roughness appears to be the highest for the summer months. This is quite plausible given the temperature gradients developed in the PCCP slabs during hot summer days and relatively cooler nights in Kansas. Figure A.1 through A.7 in the Appendix A show the contribution of curling to the early life roughness progression for different sections.

TABLE 5.1: Percent Decrease in IRI Values after Separation of Curling for Each Time Period

(a) Sections Constructed in 2000

Section	Reduction in Average IRI Values (%)						
	As-Constructed	4-Month	8-Month	12-Month	16-Month	20-Month	24-Month
PTS-1	5.5	*	#	5.3	2.4	23.8	3.7
PTS-2	4.5	6.4	#	8.1	0.7	26.7	4.7
STS-1	3.7	*	9.5	5.1	6.7	38.9	7.0
STS-2	7.8	*	6.7	10.5	4.0	34.1	7.8
TTS-1	16.5	7.2	2.8	4.7	0.5	11.3	12.3
TTS-2	12.7	*	30.5	5.5	2.32	14.8	15.8

(b) Sections Constructed in 2001

Section	Reduction in Average IRI Values (%)						
	As-Constructed	4-Month	8-Month	12-Month	16-Month	20-Month	24-Month
WTS-1	15.9	10.4	6.5	44.3	8.8	8.2	3.9
WTS-2	11.6	14.0	12.1	53.9	14.3	10.3	12.1
NPTS-1	8.6	11.1	5.6	44.5	20.7	19.6	9.6
NPTS-2	14.5	7.0	4.9	35.2	1.1	21.1	13.4
NSTS-1	10.4	12.3	6.2	#	7.2	2.9	1.4
NSTS-2	8.0	18.7	6.8	#	10.7	6.7	1.4

* Curling Separation algorithm didn’t work perfectly
\# Profile data was not collected, as those sections served two-way traffic at that time period

Chapter 6

Statistical Analysis

6.1 Introduction

Two types of statistical analyses were done. Analysis of Variance (ANOVA) was performed to find the significant factors that affect curling and short-term PCCP roughness and to compare the population means of those factors. Later multiple regression analysis was performed to find the quantitative relationships between the significant factors and the IRI values. SAS and SYSTAT software programs were used for these purposes (*15*, *16*).

6.2 ANOVA

ANOVA allows testing the difference between two or more population means. This is done by examining the ratio of variability between two conditions and variability within each condition. The process compares the variability that is observed between the two conditions to the variability observed within each condition. When the variability that can be predicted (between the two groups) is much greater than the variability that cannot be predicted (within each group), then it can be concluded that those population means are significantly different from each other.

Separate analyses were done for the IRI values of original profile, profile without curling, and curled profile. The response variable in each case was the calculated IRI values from the measured and separated profiles. Four treatment variables were selected in this study: a) Lane (driving and passing); b) Wheel path (left and right); c) Application of curing compound (single and double coats); and d) Time of data collection (0, 4, 8, 12, 16, 20, and 24 months for the sections constructed in 2000 and 0, 4, 8, 12, 16, and 20 months for the sections constructed in 2001). The interaction effects of these treatment variables were also examined. Since different sections have different characteristics (material properties, geometry, traffic, etc.), each site was analyzed separately. Application of curing compound was not used as a treatment for analyzing New Paxico test site since both sections on this site were cured with double application of curing compounds. The statistical model for this experiment is:

$$IRI_{ijkl} = LN_i + WP_j + CAPP_k + TIME_l + (LN \times WP)_{ij} + (LN \times CAPP)_{ik} + (LN \times TIME)_{il} + (WP \times CAPP)_{jk} + (WP \times TIME)_{jl} + (CAPP \times TIME)_{kl} + (LN \times WP \times CAPP)_{ijk} + (LN \times WP \times TIME)_{ijl} + (WP \times CAPP \times TIME)_{jkl} + (LN \times WP \times CAPP \times TIME)_{ijkl} + e_{ijkl} \quad (1)$$

where: IRI_{ijkl} is the International Roughness Index (m/km);

LN_i is the ith Lane effect;

WP_j is the jth Wheel Path effect;

$CAPP_k$ is the kth effect of Curing Compound Application ;

$TIME_l$ is the lth effect of Time of Data Collection; and

e_{ijkl} is the error term;

The rest of the terms in Equation (1) refer to the interaction effects of the treatment variables.

All conclusions were drawn at 95% confidence level. The means of the response variable at different time periods was compared by the least square means (LSMean) approach. This technique weighs the estimates of each treatment or treatment combination effect equally, but not each observation. The LSMean model deals with the average of individual treatment measurements and for treatment combination, it gives unequal weight to each observation. The effects of one or more factors on treatments for comparison are eliminated since it estimates the average of the averages. Increased sample size increases the precision of the estimate of the treatment combination mean response (*17*).

6.2.1 Original Profile

The results of ANOVA for the IRI computed from the original/measured profiles are shown in Table 6.1. On almost all sections, the number of applications of curing compound and the pavement's age have significant effect on the mean IRI values. In other words, mean IRI values for the sections cured with a single application of curing compound were significantly different from those for sections cured with double application of curing compounds. As mentioned earlier, as-constructed IRI values for the sections cured with a single application of curing compound were lower than those for the sections cured with double applications. Considering all time periods, mean IRI values for the sections cured with double application of curing compound were significantly lower than those for the sections cured with a single application. Table 6.1 also shows that for all sections interaction between the curing compound application and time was significant. Figure 6.1 shows this interaction for the Salina section. It shows that as-constructed IRI for the section cured with a single application of curing compound section is lower than that of the section cured with double application. However, the scenario is just opposite for the rest of the time periods. Similar trend was observed for the Topeka and New Salina test sites. However, this factor is not statistically significant for the New Salina test site. For the Paxico and Wamego sites, IRI values for the single application of curing compound was lower than that for double application for all time periods.

6.2.2 Profile Without Curling

Table 6.2 presents the results of ANOVA for the IRI values calculated from the profiles without curling. The results are similar to those in Table 6.1. For most sections, factors that were found to be significant for the IRI values calculated from the original profiles were also found to be significant for the IRI values calculated from the profiles without curling. One notable exception is the Wamego section where the mean IRI values for all three factors considered were significantly different from the IRI values calculated from the original profiles. For the IRI calculated from the profiles without curling, mean IRI values were significantly different for only one factor (Time).

TABLE 6.1: Effect of Different Factors on IRI Values Calculated from Original Profiles

Test Site	Effect on Mean IRI				Significant Interactions
	Lane	Wheel Path	Curing Application	Time	
Paxico	Different	Different	Different	Different	Curing Application & Time
Salina	Equal	Equal	Different	Different	Curing Application & Time
Topeka	Equal	Equal	Different	Different	Curing Application & Time
Wamego	**	Different	Different	Different	Curing Application & Time
New Paxico	**	Equal	-	Different	-
New Salina	Different	Different	Equal	Different	Curing Application & Time, Wheel path & Time

** Lane was not considered a variable as driving lane was diamond-grounded

6.2.3 Curled Profile

The results of ANOVA for the IRI computed from the curled profiles are shown in Table 6.3. The results obtained are very similar to the results obtained for the original profiles and profile without curling for the Paxico, Salina, and New Paxico sections. For the Wamego section, the mean IRI values for all treatment variables were significantly different for different treatment levels similar to the results for the original profiles. Interaction effects for different sites were somewhat comparable with those obtained from the analysis of original profile.

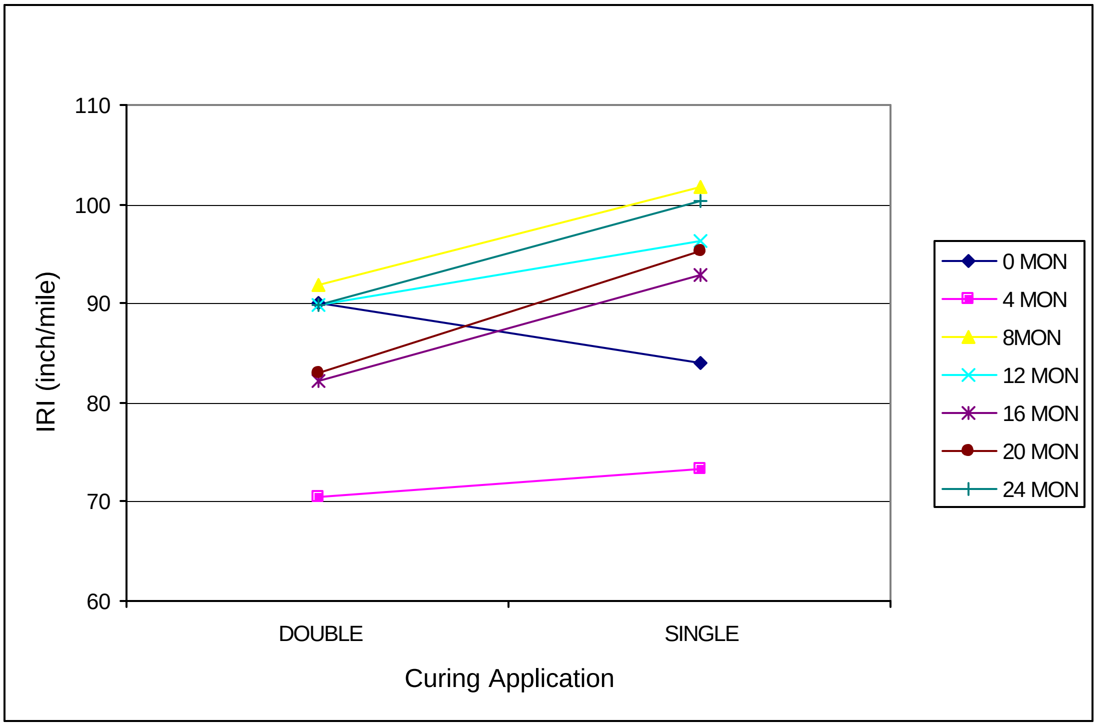


FIGURE 6.1: Interaction Effects of Time and Curing Application on IRI

TABLE 6.2: Effects of Different Factors on IRI Values Calculated from Profiles without Curling

Test Site	Effect on Mean IRI				Significant Interactions
	Lane	Wheel Path	Curing Application	Time	
Paxico	Different	Different	Different	Different	Curing Application & Time
Salina	Equal	Equal	Different	Different	Curing Application & Time
Topeka	Equal	Equal	Different	Different	Curing Application & Time
Wamego	**	Equal	Equal	Different	Curing Application & Time
New Paxico	**	Equal	-	Different	-
New Salina	Different	Equal	Equal	Equal	Wheel path & Lane

** Lane was not considered a variable as driving lane was diamond-grounded

TABLE 6.3: Effects of Different Factors on IRI Values Calculated from Curled Profiles

Test Site	Effect on Mean IRI				Significant Interactions
	Lane	Wheel Path	Curing Application	Time	
Paxico	Different	Different	Different	Different	Curing Application & Time
Salina	Equal	Equal	Different	Different	Curing Application & Time
Topeka	Different	Different	Different	Different	Curing Application & Time
Wamego	**	Different	Different	Different	Wheel Path & Time
New Paxico	**	Equal	-	Different	-
New Salina	Equal	Different	Equal	Different	Wheel path & Lane

** Lane was not considered a variable as driving lane was diamond-grounded

6.3 Effect of Seasonal Variation on IRI Values

ANOVA was also performed to examine the effect of seasonal variation on the mean IRI values. The time periods when all roughness data were collected can be categorized in three distinct seasons- spring (4- and 16-month data for the Paxico, Salina, and Topeka sections; and 8-and 20-month data for the Wamego, New Paxico, and New Salina sections); summer (8- and 20-month data for the Paxico, Salina, and Topeka sections; and 12-month data for the Wamego, New Paxico, and New Salina sections); and winter (12- and 24-month data for the Paxico, Salina, and Topeka sections; and 4- and 16-month data for the Wamego, New Paxico, and New Salina sections). As-constructed data was not included in this analysis. The model used for this analysis is:

$$IRI_i = SEASON_i + e_i \qquad (2)$$

where: IRI_{ijkl} is International Roughness Index (inch/mile or m/km);

$SEASON_i$ is the ith effect of season; and

e_i is the error term.

Table 6.4 shows the result of this ANOVA. The results indicate that season has significant effect on the measured mean IRI values. LSMean analysis shows that the IRI values calculated from the profiles collected in the spring were significantly lower than those calculated from the profiles collected in the winter and summer for all test sites. Again, the IRI values calculated from profiles collected in the summer were higher than those calculated from profiles collected in the winter. However, the difference in mean IRI values between the winter and the summer measurements was not significant for the Paxico and Salina test sections. It is evident in most cases, the high daily temperature extremes like those encountered in Kansas in the summer months significantly affects the IRI measurements.

TABLE 6.4: Effect of Seasonal Variation on IRI Values

Test Site	Effect
Paxico	Different
Salina	Different
Topeka	Different
Wamego	Different
New Paxico	Different
New Salina	Different

6.4 Regression Analysis

Regression analysis is a statistical tool that uses the relation between two or more quantitative variables so that one variable can be predicted from the other, or others (*18*). In the multiple regression analysis, more than one independent variable is used. Multiple regression analysis was used for this study to find out the functional relationships between the IRI values calculated from different profiles (original, curled, and profile without curling) at different time periods and significant factors that influence IRI. The general form of the model is:

$$IRI = b_0 + b_1 X_1 + b_2 X_2 + \ldots\ldots\ldots\ldots \quad (3)$$

where: b_0 is the intercept;

$b_1, b_2, \ldots.$ are the parameters; and

$X_1, X_2, \ldots.$ are the independent variables.

A list of independent variables that were used to develop the models for this study is given in Table 6.5. The independent variables include a variety of traffic, construction, geometric, and climatic factors. As-construed IRI was used as the independent variable for the models developed for the IRI values at other time periods (4, 8, 12, 16, 20, and 24 months). The best models were selected based on a number of statistical information, such as, R^2, t-test statistic, as well as engineering judgment. Multi-colinearity test was also performed to check the correlation among the independent variables.

Different model selection methods are available to determine which model best explains the data. The backward selection method was used in this study to select the optimum model. This model development process starts with a complete model with all independent variables entered and eliminates one variable at a time until a reasonable regression model is obtained. The main advantage of this method is that it shows the analysts the implications of models with many variables (*18*). Separate models were developed for each time period. Details are given below.

TABLE 6.5: Parameters Used to Derive Models

Traffic Data	Construction Data	Road Structure and Geometry	Climatic Data
Cumulative Equivalent Single Axle Load (ESAL)	Percent Coarse and Fine Aggregate Water-Cement Ratio Percent Air Concrete Unit Weight 28-day Core Compressive Strength Concrete Modulus of Rupture Compressive Strength of Bound Drainable Base, Change in Plasticity Index (before and after lime treatment)	Pavement Thickness Grade	Temperature Differential of Slab Top and Bottom, Mean Monthly Precipitation, Air Temperature

6.4.1 Models Derived for the IRI Values from the Original Profiles

Table 6.6 lists the significant independent variables that affect IRI values calculated from original profiles, parameter coefficients, and other statistical information.

1. Model for As-Constructed IRI: In this model, slab thickness, 28-day core compressive strength, and 28-day BDB compressive strength are the significant factors. Traffic was not considered as an independent variable since the projects were yet to be opened to traffic. Parameter estimates of all significant factors were positive indicating that with the increased values of these parameters, as-constructed IRI would increase. A good R^2 value of 0.87 was obtained for this model.
2. Model for 4-month IRI: Four factors were found to be significant for this model: slab thickness, longitudinal grade, % materials passing #200 (75-micron) sieve, and as-constructed IRI. All parameter estimates were positive i.e. IRI would increase for increased values of these parameters. The R^2 value obtained for this model was 0.78.
3. Model for 8-month IRI: Three factors that appeared to be significant are: slab thickness, 28-day BDB compressive strength, and as-constructed IRI.

All parameter estimates were positive. An R^2 value of 0.82 was obtained for this model.

4. Model for 12-month IRI: 28-day compressive strength of the BDB layer, % subgrade materials passing #200 (75-micron) sieve, and as-constructed IRI were found to be significant factors for this model with relatively high R^2 value of 0.94. All parameter estimates were positive.
5. Models for 16-month IRI: Only two variables appeared to be significant for the 16-month IRI values: percent air in concrete and as-constructed IRI value. All parameter estimates were positive. The R^2 value obtained for this model was 0.623, which is much lower than those obtained for other models.
6. Model for 20-month IRI: Two factors were found to be significant for this model with R^2 value of 0.895: 28-day compressive strength of BDB and as-constructed IRI. Both factors have appeared in some of the previous models. The parameter estimates were positive for this model.
7. Model for 24-month IRI: Temperature differential of air and longitudinal grade were the significant factors for this model with a low R^2 value of 0.64. This is the only model obtained for the IRI values calculated from original profile where as-constructed IRI did not appear as a significant parameter in the model.

TABLE 6.6: Models Derived for Original IRI Values

Variable	Description	Parameter Estimate	R^2 Value
As-Constructed IRI Model			
Intercept	Vertical Intercept	-140.20	0.871
THICK	Thickness of slab (inch)	12.70	
CSTR	28-day Core Compressive Strength (psi)	0.0134	
BDBSR	Compressive Strength of BDB (psi)	0.0398	
4-Month IRI Model			
Intercept	Vertical Intercept	-45.18	0.803
THICK	Thickness of slab (inch)	3.54	
Grade	Grade (%)	0.691	
PASS200	% Subgrade Material Passing # 200 (75-micron) Sieve (%)	0.076	
IIRI	As-constructed IRI (inch/mile)	47.04	
8-Month IRI Model			
Intercept	Vertical Intercept	-55.69	0.820
THICK	Thickness of slab (inch)	4.03	
BDBSR	Compressive Strength of BDB (psi)	0.1154	
IIRI	As-constructed IRI (inch/mile)	40.90	
12-Month IRI Model			
Intercept	Vertical Intercept	-32.88	0.938
PASS200	% Subgrade Material Passing 75-micron (#200) Sieve (%)	0.2661	
BDBSR	Compressive Strength of BDB (psi)	0.078	
IIRI	As-constructed IRI (inch/mile)	48.37	
16-Month IRI Model			
Intercept	Vertical Intercept	-98.90	0.623
AIR	% Air in Concrete (%)	18.80	
IIRI	As-constructed IRI (inch/mile)	0.644	
20-Month IRI Model			
Intercept	Vertical Intercept	-65.52	0.836
BDBSR	Compressive Strength of BDB (psi)	0.224	
IIRI	As-constructed IRI (inch/mile)	40.83	
24-Month IRI Model			
Intercept	Vertical Intercept	-126.78	0.644
TDAIR	Temperature Differential of Air (^{0}C)	9.082	
GRADE	Grade (%)	15.777	

6.4.2 Models Derived for IRI Values Without Curling

Significant independent variables along with relevant statistics obtained for different models for IRI values calculated from profiles without curling are shown in Table 6.7.

1. Model for As-constructed IRI: The thickness of the concrete slab, 28-day core compressive strength, change in Plasticity Index of subgrade soil due to the lime treatment, and 28-day compressive strength of BDB were found to be significant for the IRI values. Parameter estimates of all significant factors except the change in plasticity index are positive, i.e. the as-constructed IRI values increase with the increase in values of these factors. The negative coefficient of the parameter, change in Plasticity Index value, indicates that higher the change, the lower would be the as-constructed IRI values calculated from profiles without curling.
2. Model for 4-month IRI: Four factors were found to be significant for the IRI values from the profile without curling: slab thickness, 28-day core compressive strength, change in plasticity index, and percent subgrade materials passing the #200 (75-micron) sieve. As in the previous model, parameter estimates of all factors except change in plasticity index are positive.
3. Model for 8-month IRI: Only one factor appeared significant for this model: longitudinal grade. The positive sign of parameter indicates that with increase in grade IRI value increases.
4. Model for 12-Month IRI: 28-day core compressive strength of concrete, which was also appeared as significant factor for as-constructed and 4-month IRI model, appeared as significant for this model with positive parameter estimate.
5. Model for 16-Month IRI: Model obtained for this case is same as that obtained for 8-month IRI with a relatively low R^2 value.
6. Model for 20-Month IRI: Only one factor (longitudinal grade) appeared as significant factor for this model.
7. No model was obtained for 24-month IRI values.

TABLE 6.7: Models Derived for IRI without Curling

Variable	Description	Parameter Estimate	R^2 Value
As-Constructed IRI Model			
Intercept	Vertical Intercept	-142.24	0.852
THICK	Thickness of slab (inch)	5.31	
CSTR	28-day Core Compressive Strength (psi)	0.0275	
CHGPI	Change in Plasticity Index (%)	-1.622	
BDBSR	Compressive Strength of BDB (psi)	0.020	
4-Month IRI Model			
Intercept	Vertical Intercept	-127.48	0.740
THICK	Thickness of slab (inch)	2.414	
CSTR	28-day Core Compressive Strength (psi)	0.0217	
CHGPI	Change in Plasticity Index (%)	-3.35	
PASS200	% Subgrade Material Passing #200 (75-micron) Sieve (%)	0.627	
8-Month IRI Model			
Intercept	Vertical Intercept	67.63	0.755
GRADE	Longitudinal Grade (%)	18.70	
12-Month IRI Model			
Intercept	Vertical Intercept	-72.55	0.672
CSTR	28-day Core Compressive Strength (psi)	0.0246	
16-Month IRI Model			
Intercept	Vertical Intercept	76.67	0.690
GRADE	Longitudinal Grade (%)	1.014	
20-Month IRI Model			
Intercept	Vertical Intercept	35.42	0.711
GRADE	Longitudinal Grade (%)	0.697	
PASS200	% Subgrade Material Passing #200 (75-micron) Sieve (%)	0.025	

6.4.3 Models Derived for IRI Values Calculated from Curled Profiles

Only three models were obtained for IRI values calculated from curled profiles. These models are shown in Table 6.8. No models were obtained for 8-month, 12-month, 20-month, and 24-month IRI values. For as-constructed IRI values and 16-month IRI values, thickness of the concrete slab and compressive strength of BDB layer were significant. 28-day core compressive strength of concrete, and grade appeared as significant factors for 4-month IRI model. R^2 values obtained for all of these cases were very low.

TABLE 6.8: Models Derived for IRI Values of Curled Profiles

Variable	Description	Parameter Estimate	R^2 Value
As-Constructed IRI Model			
Intercept	Vertical Intercept	-102.64	0.626
THICK	Thickness of slab (inch)	13.358	
BDBSR	Compressive Strength of BDB (psi)	0.092	
4-Month IRI Model			
Intercept	Vertical Intercept	10.33	0.390
CSTR	28-day Core Compressive Strength (psi)	0.0023	
GRADE	Longitudinal Grade (%)	0.165	
16-Month IRI Model			
Intercept	Vertical Intercept	-91.87	0.612
THICK	Thickness of slab (inch)	9.17	
BDBSR	Compressive Strength of BDB (psi)	-0.0035	

Models described in sections 6.4.1 through 6.4.3 show that road roughness and curling are influenced by the strength of concrete, base, and the paving process. These models indicate that higher IRI would result from a concrete mixture whose 28-day compressive strength is higher. It is to be noted that such a mixture usually will have a lower water-cement ratio and will be somewhat difficult to handle. This assertion is further supported by the fact that thickness of the slab is also a significant factor that appeared in most of the models (The greater the slab thickness, the higher the IRI values). Similar observations for long-term roughness were made by Perera and Kohn (*9*) in their analysis of Long Term Pavement Performance (LTPP) profile data.

The strength of the stabilized base also affects roughness and curling. The models show that higher base strength results in higher roughness as well as higher as-built curling. It can be assumed that if the base is very stiff it will be somewhat "unyielding" and the profile of the base would significantly affect curling of concrete slab. Stabilized bases are known to have pronounced effect on curling. The average as-constructed annual IRI values on the SPS-2 project on I-70 in Kansas were 74.2 inch/mile (1.17 m/km), and 85.5 inch/mile (1.35 m/km) for lean concrete base (LCB) and dense graded aggregate bases, respectively. The study by Perera and Kohn also showed that the high IRI values at the early ages for pavements with LCB were also obtained on other SPS-2 projects in LTPP program (*9*). An earlier Arizona study also showed that concrete pavements built without LCB outperformed the sections built with LCB in terms of roughness progression (*19*).

6.5 Sensitivity Analysis

Sensitivity analysis was done to examine the effect of the independent variables found significant in the models described above.

Table 6.5 shows that slab thickness, 28-day concrete core compressive strength, and 28-day compressive strength of BDB are the factors that affect as-constructed IRI model. Figure 6.2 shows the effects of these factors on as-constructed IRI values.

Other parameters being constant, an increase in the concrete slab thickness by 0.5 inch (12.5 mm) will increase the as-constructed IRI value by about 8%. Similarly an increase in 28-

day concrete core compressive strength by 500 psi (3.5 MPa) will increase the as-constructed IRI by about 9% and about 5% for 100 psi increase in BDB compressive strength. This figure also shows that BDB compressive strength has the most significant effect on this model. It is to be noted that the cumulative effect of these factors would be very high since each factor has positive coefficient value in the IRI prediction equation.

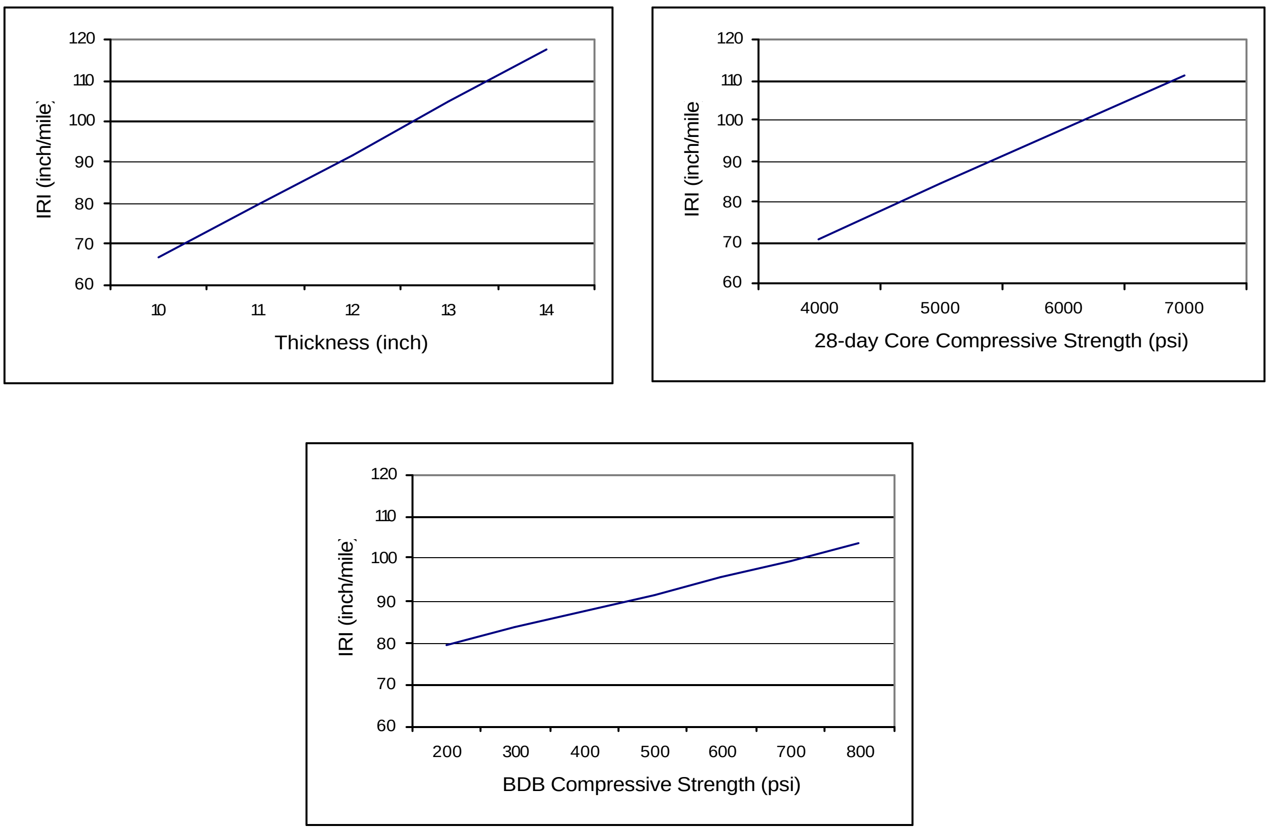


FIGURE 6.2: As-Constructed IRI Model Sensitivity Analysis

Similar analyses were made for the IRI values of other time period. They revealed that as-constructed IRI value is the most sensitive parameter that affects the IRI value for a particular time period. Compressive strength of BDB appeared to be significant in four different models and for all cases, this parameter was found to be very large effect on the IRI values. Factors like percent subgrade materials passing #200 sieve (75-micron) and grade do not influence the IRI values as much as the BDB strength.

6.6 PCCP On Asphalt Treated Base (ATB)

Since the BDB strength has a very significant influence on the IRI values, another project was chosen where the base strength would be lower. It is expected that this lower strength base would result in lower IRI values or smoother pavements. The project on US-75, north of Topeka, was built in the fall of 2002 with an Asphalt Treated Base (ATB). The ATB base was also drainable with a required permeability of 1000 ft/day. The ATB mixture consists of 38% crushed limestone (CS-1), 27% crushed limestone screening (Cs-2) and 35% natural sand (SSG). Ninety four percent of the aggregate was retained on the #200 (75-micron) sieve. The proportion of the asphalt binder (PG 64-22) used in the mixture was 5.2% (including 10% RAP). The mixture was designed as a Marshall mixture and the relevant properties are given in Table 6.9.

TABLE 6.9: Marshall Mixture Test Results

Properties	Test Result
Air Voids (%)	3.18
VFA (%)	72.3
Bearing Capacity (psi)	383
Density (lb/ft^3)	148
Stability (N)	15499

Profile measurements were done just after construction of the PCCP slab and before opening to traffic and after six months in service. The roughness progression of this section is shown in Figure 6.3. The average IRI in this figure represents the mean IRI values of three replicate runs of both wheel paths of both driving and passing lanes. As-constructed IRI value of this project with ATB was lower than IRI values of most of the sections built with BDB.

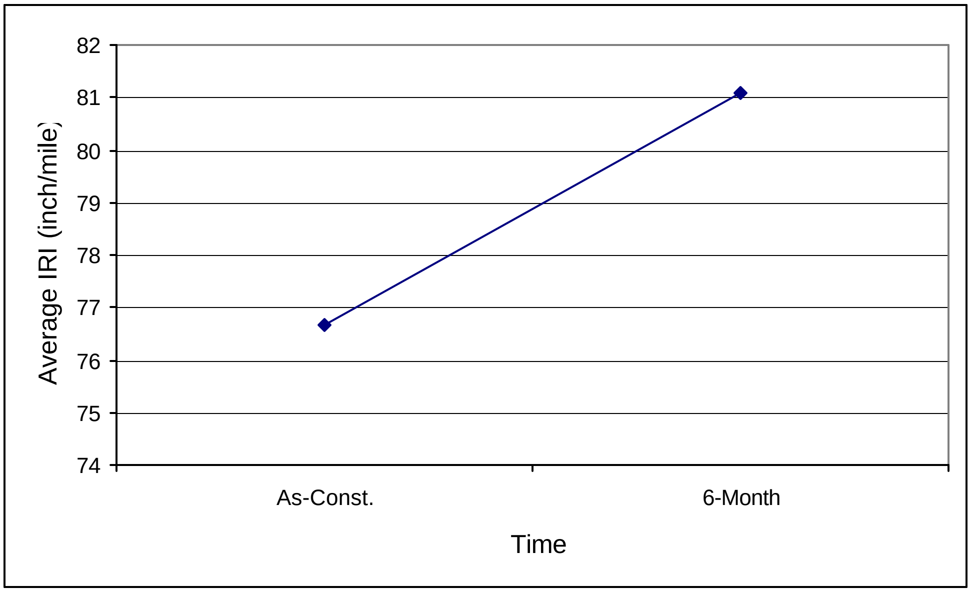


FIGURE 6.3: Roughness Progression of US-75 Section

Curling was separated using the same methodology described earlier. Contribution of curling toward the as-constructed and six-month IRI roughness values was 5.8 and 6.2 percent, respectively. A comparison of these IRI values with the IRI values of the sections built over BDB (shown in Table 5.1) reveals that for both time periods, contribution of curling to the IRI roughness was lower for the section built with ATB.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

Based on this study, the following conclusions can be made:

1. A large temperature gradient (as high as 29^o F) between the top and bottom of the concrete pavement slab can build up during concrete placement in Kansas. Double curing compound application tends to decrease the temperature differential between the top and the bottom of the slab in freshly placed concrete pavement slab. The temperature gradients were 2 to 11^0 F lower when compared to the slabs with a single application of curing compound.
2. Contribution of curling to the roughness of newly built pavements on cement or cement-fly ash stabilized base was found to be significant. This contribution was higher during summer. However, for the pavement with an asphalt-treated base, the contribution of curling toward the roughness is lower.
3. Application of curing compound significantly affects early life roughness as well as curling. The mean as-constructed IRI values of the sections cured with single application of curing compound were lower than those of sections cured with double application. However, for IRI values later in the life of pavement, double application of curing compound resulted in lower IRI values for some sections. Statistical analysis showed that, sections cured with double application of curing compound performed better in terms of lower IRI values. Thus better curing appears to help retain the as-constructed smoothness longer.
4. IRI values of different time periods were significantly different from one another for most of the sections. For a given section, IRI value of a particular time period (e.g. four months after construction) was

significantly different from another time period (e.g. as-constructed IRI). However, IRI values after 12 months for all of the sections didn't vary much.

5. The short-term IRI is a function of as-constructed IRI. Some other variables that affect the short-term roughness are: thickness of the concrete slab, 28-day concrete core compressive strength, 28-day stabilized base compressive strength, percent subgrade materials passing the #200 sieve, grade, and percent entrained air in the concrete. These factors are no longer significant after 24 months.
6. Profiles without curling are influenced by concrete compressive strength, base stiffness, and the paving process. The models indicate that higher as-constructed and early life IRI would result from a concrete mixture whose 28-day compressive strength is higher. This is also true for thicker slabs.
7. As-constructed and early-life curling of concrete pavements are affected by slab thickness and the stiffness of the base layer. Higher slab thickness and base strength result in higher curling.

7.2 Recommendations

The recommendations of this study are:

1. Double application of curing compound can reduce the curling as well as help retain short-term smoothness of newly built concrete pavements.
2. Higher base strength results in higher roughness as well as higher as-built curling. Further studies should be done to find the optimum base strength.
3. The smoother a pavement is built, the smoother it stays over time. Better paving operation and proper selection of materials including base would ensure a concrete pavement with lower as-constructed IRI values. Also, particular attention during paving needs to be paid when the section is on a grade.
4. Curling could be minimized using a subbase that would yield when the concrete slab expands or contracts.

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APPENDIX A

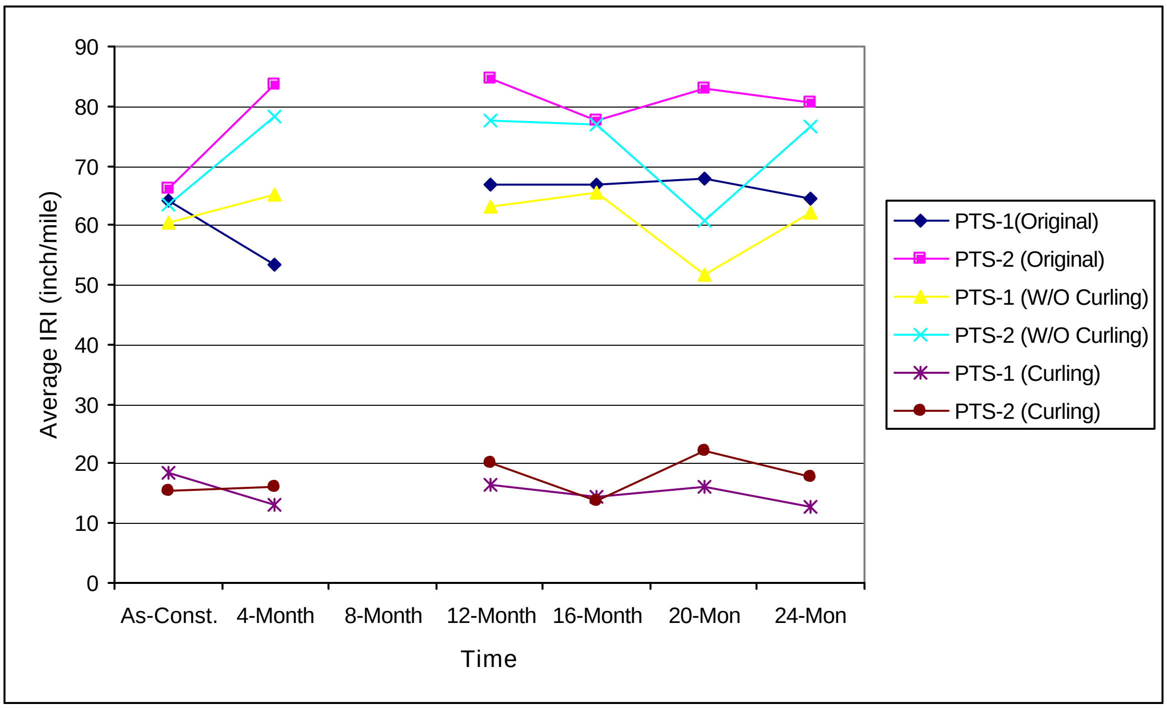

FIGURE A.1: Variation of IRI Values for Paxico Test Sections

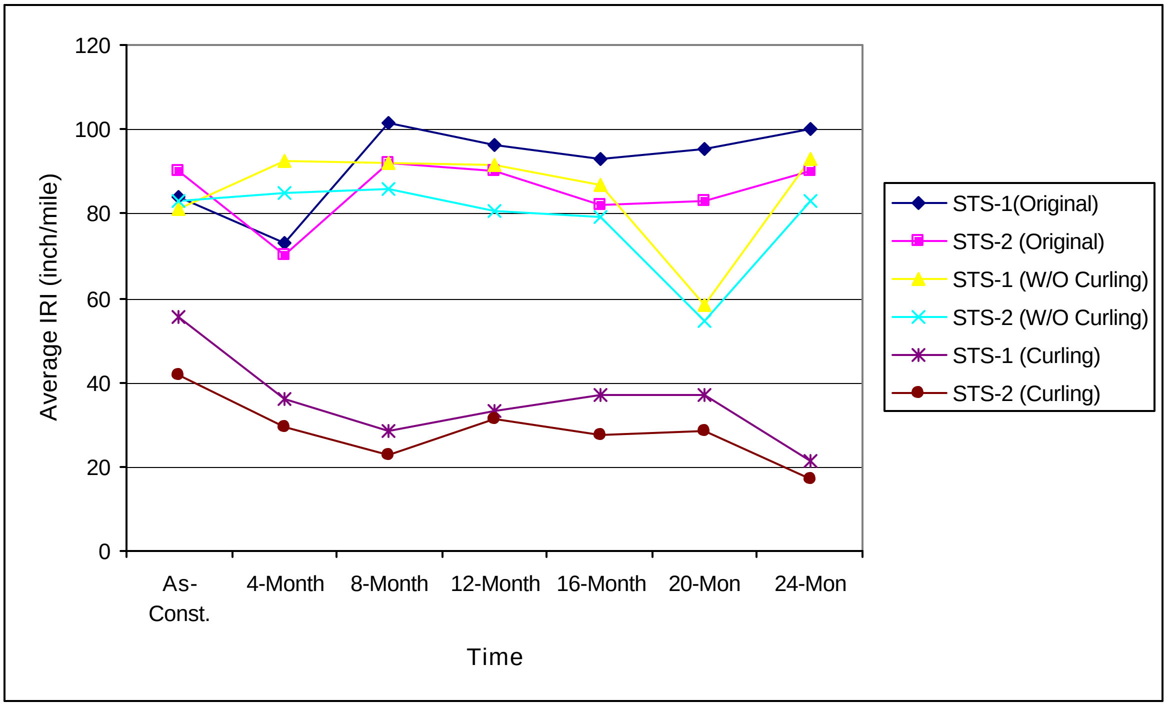

FIGURE A.2: Variation of IRI Values for Salina Test Sections

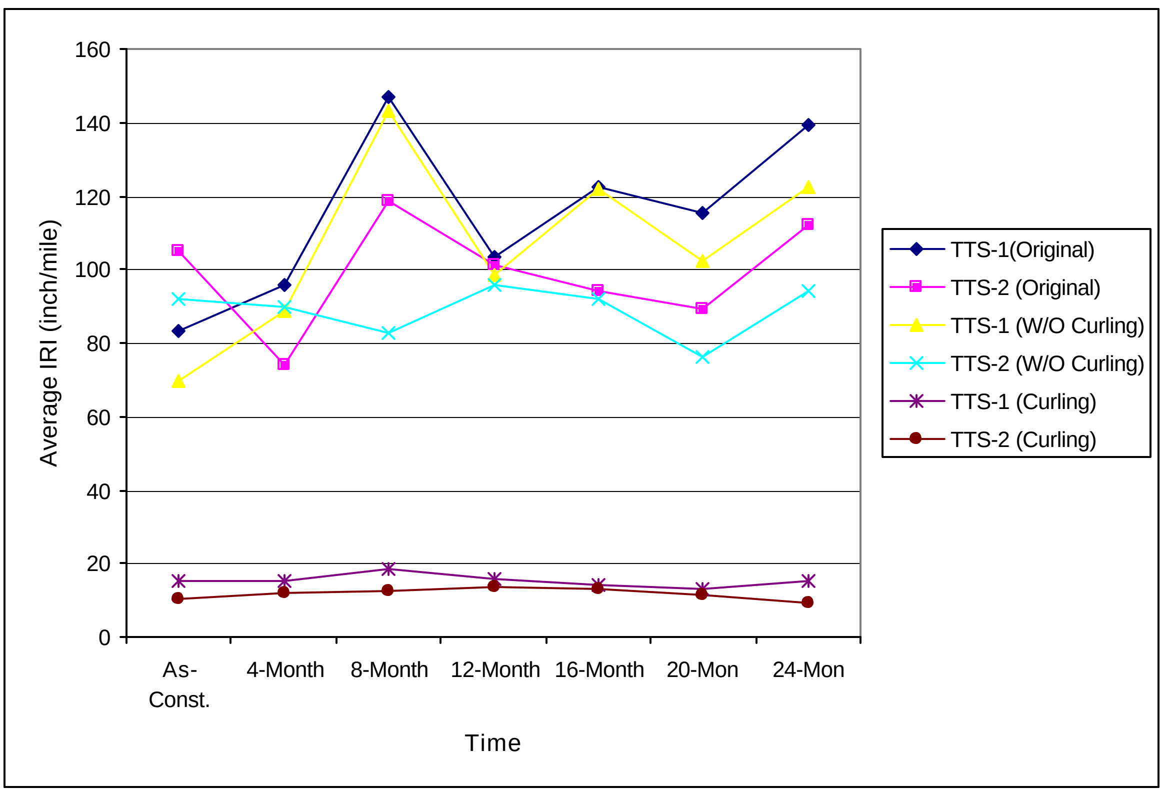

FIGURE A.3: Variation of IRI Values for Topeka Test Sections

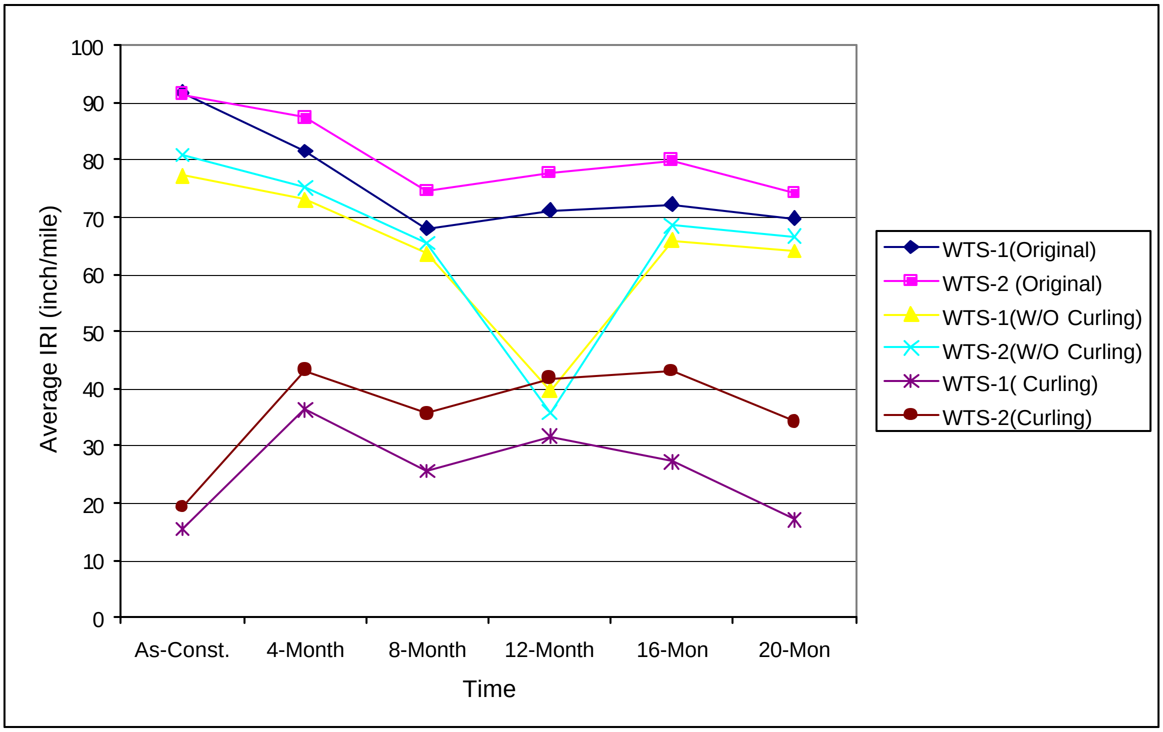

FIGURE A.4: Variation of IRI Values for Wamego Test Sections

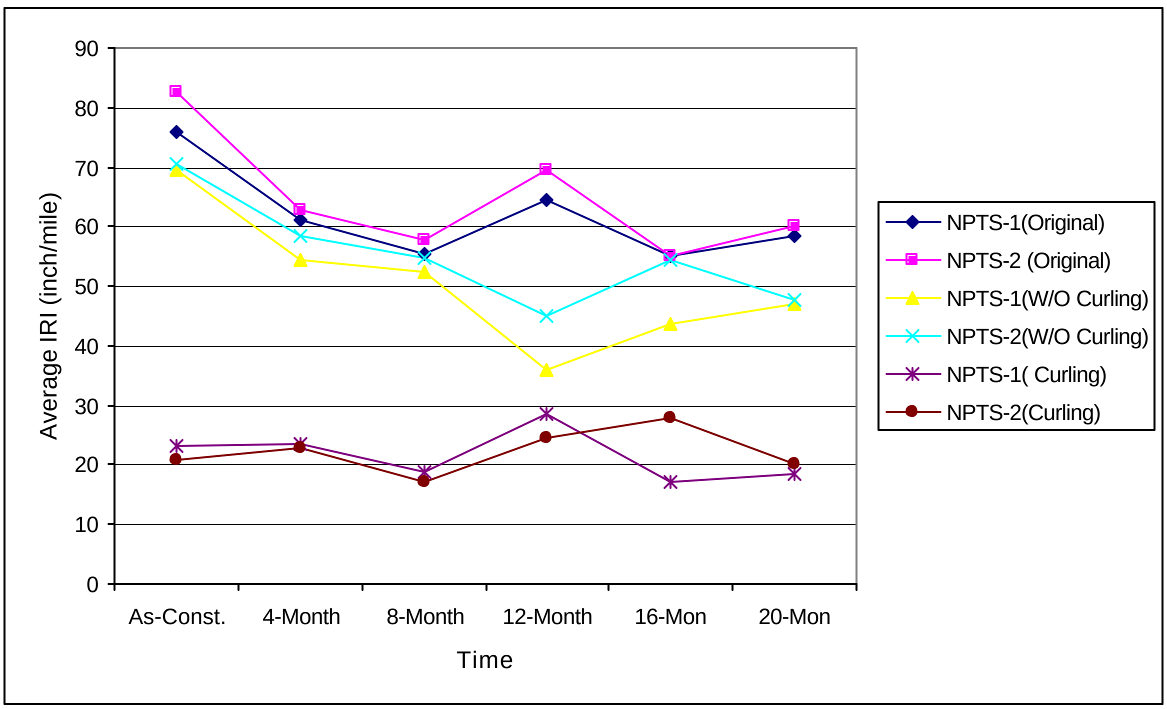

FIGURE A.5: Variation of IRI Values for New Paxico Test Sections

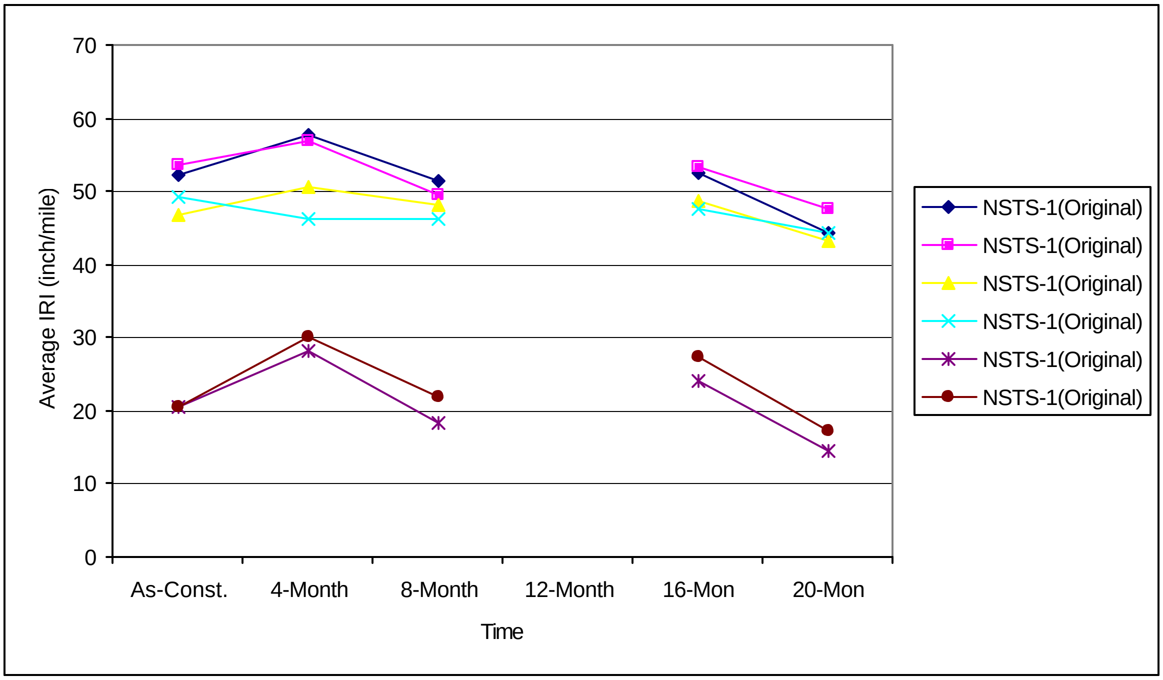

FIGURE A.6: Variation of IRI Values for New Salina Test Sections

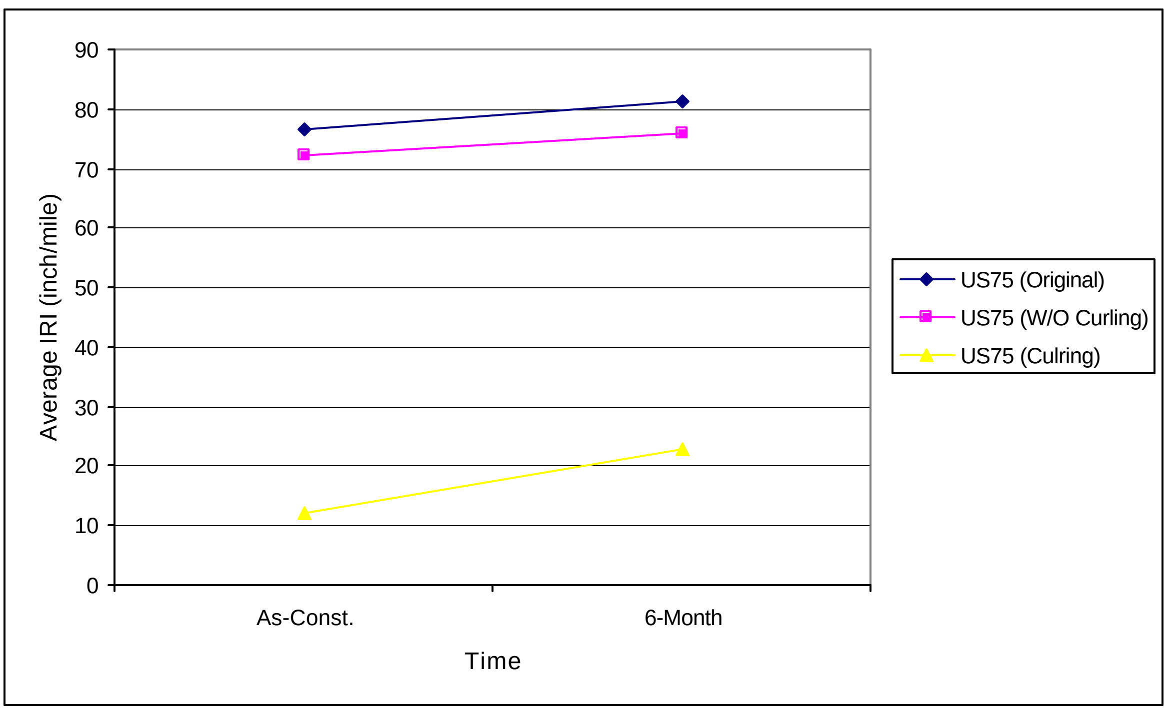

FIGURE A.7: Variation of IRI Values for US75 Test Section