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Final Report

IMPLEMENTATION OF PROVEN PCCP PRACTICES IN COLORADO

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16. Abstract
This paper is an overview of the proven concrete pavement practices that the Colorado Department of Transportation (CDOT) has implemented over the last several years. These include implementation of the following practices:

1- **Implementation of Longitudinal Tining**: Nine test sections were constructed on I-70 near Denver, Colorado with varying textural characteristics. Texture depth, skid numbers at different speeds, and their noise properties were measured. Based on the finding of this research study CDOT adopted the longitudinal tining (uniformly spaced ¾ inch) as a preferred method of texturing concrete pavements in 1997. Longitudinally tined PCC pavement exhibits low noise levels and provides adequate friction.

2- **Implementation of the Wider Slab, SPS-2 Experiment Spin-Off Product:** This experiment dealt with various structural factors in concrete, one of which was the wider slab (14-ft slab). The results of this study revealed that 2 feet of widening was adequate. Structurally speaking, their contributions were found to be equivalent to 1 inch of slab thickness.

3- **Implementation of Single-Cut Joints, SPS-4 Experiment Spin-Off Product:** The results of this study revealed that the single cut (1/8" joints) were as effective as CDOT's standard double cut (3/8 joints). The only difference was that the narrower joints were less labor-intensive and required much less sealant material. Based on a cost-benefit analysis, a saving of 57 cents per linear foot of joint was realized, which equates to approximately 1.7 million dollars per 100 miles of 2-lane concrete pavement.

4- **Addressing Premature PCCP Longitudinal Cracking:** This experiment presents an evaluation of several Portland cement concrete pavements with premature longitudinal cracking. All of the locations discussed are in Region 1 of the Colorado Department of Transportation (CDOT). This study resulted in 2 new specifications: 1- Requiring the engineer to measure saw-cut depth at intervals of 1 per 1/10 of a mile (528 ft.). 2- Requiring paving contractors to equip their paving machines with vibrator monitoring devices.

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Implementation of Proven PCCP Practices in Colorado

By
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Prepared by
Colorado Department of Transportation
Research Branch

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Implementation of Proven PCCP Practices in Colorado

Ahmad Ardani, P.E., Colorado Department of Transportation

Abstract

This paper is an overview of the proven concrete pavement practices that the Colorado Department of Transportation (CDOT) has implemented over the last several years. These include implementation of the following practices:

1-Implementation of Longitudinal Tining

Nine test sections were constructed on I-70 near Denver with varying textural characteristics. Texture depth, skid numbers at different speeds, and their noise properties were measured and compared. A review of the acquired data revealed a definite relationship between speed, types of surface texture, and the magnitude of skid numbers. As speed increased, the skid numbers declined. This relationship was clearly more pronounced and consistent using the smooth tire. Longitudinal macrotexture and microtexture were the quietest surfaces. State standard transverse tining with 1-inch uniform spacing exhibited the highest noise level among all the test sections when measured with the microphone at the rear tire position. CDOT adopted longitudinal tining as its preferred method of texturing concrete pavements in 1997. The results of this study indicated that longitudinal tining, in addition to possessing adequate frictional properties, provides lower noise than the CDOT's standard transverse tining.

2-Implementation of the Wider Slab, SPS-2 Experiment Spin-Off Product

This experiment dealt with various structural factors in concrete, one of which was the wider slab (14-ft slab). The concept being investigated was the belief that wider slabs, by keeping heavy trucks away from the longitudinal joints at the shoulder where pavements are most sensitive to bending stresses, can improve the load carrying capacity of the concrete pavements and ultimately eliminating faulting and corner breaks. The results of this study revealed that 2 feet of widening was adequate. Structurally speaking, their contributions were found to be equivalent to 1 inch of slab thickness.

3- Implementation of Single-Cut Joints, SPS-4 Experiment Spin-Off Product

This experiment was originally designed to examine the effectiveness of various sealant materials and also to examine the effects of sealed vs. non-sealed joints on the performance of rigid pavements. CDOT modified the experiment and added the joint geometry as one of the experimental factors. Test sections were established with joint opening from single cut 1/8" to ¼" and 3/8" double cut. The results of this study revealed that the single cut (1/8" joints) were as effective as CDOT's standard double cut (3/8 joints). The only difference was that the narrower joints were less labor-intensive and required much less sealant material. Based on a cost-benefit analysis, a saving of 57 cents per linear foot of joint was realized, which equates to approximately 1.7 million dollars per 100 miles of 2-lane concrete pavement. Since 1996, CDOT has been using this joint design on 100s of miles of concrete.

4-Addressing Premature PCCP Longitudinal Cracking

This experiment presents an evaluation of several portland cement concrete pavements with premature longitudinal cracking. All of the locations discussed are in CDOT's Region 1. Included in this report is an overview of the causes of the premature longitudinal cracking, a description of field and laboratory investigations, and a list of strategies to eliminate such occurrences. This study resulted in 2 new specifications: 1- Requiring the engineer to measure saw-cut depth at intervals of 1 per 1/10 of a mile (528 ft.). 2- Requiring paving contractors to equip their paving machines with vibrator monitoring devices.

1.0 Implementation of Longitudinal Tining

Surface texture in rigid pavements plays an important role in providing safety for the traveling public. The depth, spacing, and orientation of the surface texture can significantly affect the frictional characteristics, noise properties, and quality of ride. In general, transverse tining has been the only permitted method of texturing used by the Colorado Department of Transportation (CDOT) and the majority of the other transportation agencies. There are a few states that use longitudinal tining or sawing to texture their pavements on a regular basis and are quite satisfied with its performance. Among them is the State of California, which has continued to this date to longitudinally texture concrete pavements.

The frictional characteristics of the concrete pavement surface can be divided into two general groups: microtexture and macrotexture. Microtexture comes primarily from exposing the sand particles in the mortar (1), while macrotexture refers to grooves and channels formed in the plastic and/or in the hardened concrete. Forster (2), in the Transportation Research Record 1215, defines microtexture as those "surface asperities less than 0.5 mm in height and macrotexture as those with surface asperities of greater than 0.5 mm in height."

Macrotexture, with its channels and grooves, provides a drainage system that allows water to escape from under the tire, and consequently plays an important role in reducing the likelihood of hydroplaning. As discussed by the American Concrete Institute Committee (3), the term "hydroplaning" refers to the separation of tire contact from the pavement surface by a layer of water which causes loss of steering and braking control of the vehicle. This phenomenon is complex and is a function of water depth, vehicle speed, tire-inflation pressure, pavement texture, and tire-tread depth and design.

The type and quality of fine aggregate used in a concrete mix plays an important role in maintaining adequate skid resistance characteristics. As discussed in the FHWA Technical Advisory T 5050.17 (4), "regardless of the finishing or texturing method used, adequate durable skid resistance characteristics cannot be attained unless the fine aggregate has suitable wear and polish resistance characteristics." Research by the Portland Cement Association indicates that the siliceous particle content of the fine aggregate should be greater than 25 percent in order to maintain longer lasting skid resistance characteristics. However, it should be noted that the presence of siliceous particles in a concrete mix might pose the possibility of alkali-silica reactions (ASR). Remedial measures should be taken to overcome the ASR reactions.

1.1 Objectives

The primary objectives of this study were:

1. To document the constructability, costs, and the functional practicability of several PCCP surface textures installed on I-70 for the project IR (CX)70 - 4 (153) in Colorado.
2. To assess the long-term impacts of various surface textures on the frictional characteristics,

noise properties, and the ride quality of concrete pavements.

3. To identify the best performing surface texture that is cost-effective, minimizes tire noise and provides adequate frictional characteristics over a long period.

1.2 Description of the Test Sections

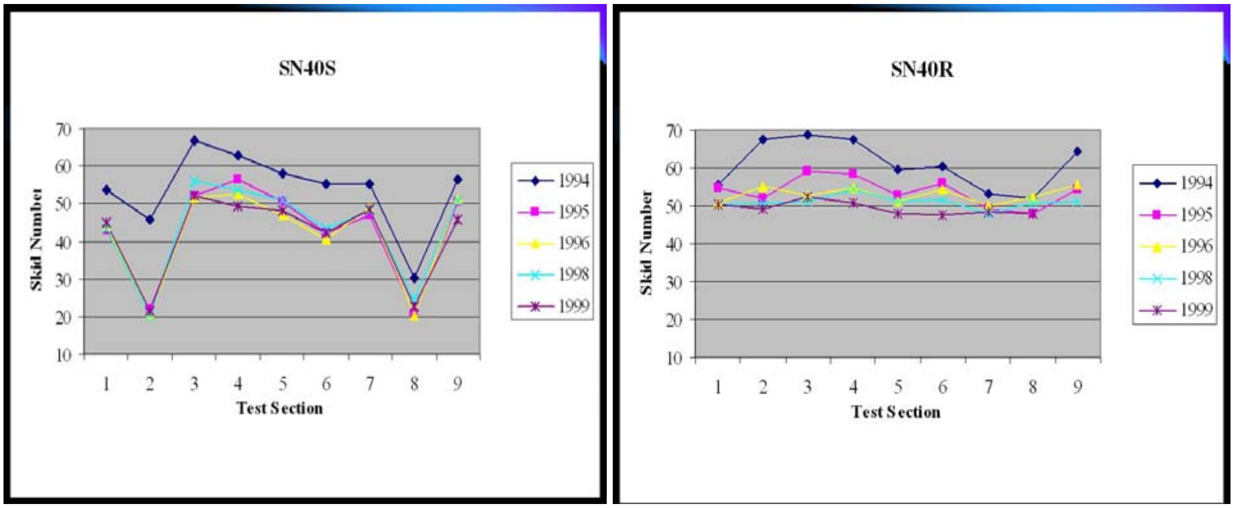
The subject research site is located on I-70, approximately 60 miles east of Denver. It has an average daily traffic (ADT) of 6600 vehicles, with 40 percent of that consisting of heavy vehicles. The 30-year design called for a full depth overlay of concrete Class P with a nominal thickness of 11 inches over the badly deteriorated existing concrete pavement. This divided four-lane interstate highway will receive an accumulated 18-K ESAL of 21,300,000 over the next 30 years. Nine test sections were installed with the following characteristics:

1. 1-inch uniformly spaced transverse tining (state standard)
2. Transverse astro-turf
3. Random transverse tinning
4. ½-inch uniformly spaced transverse tinning.
5. Random grooving (sawing)
6. 1-inch uniformly spaced transverse tining preceded with longitudinal astro-turf
7. ¾-inch uniformly spaced longitudinal grooving
8. Longitudinal astro-turf
9. ¾-inch uniformly spaced longitudinal tining

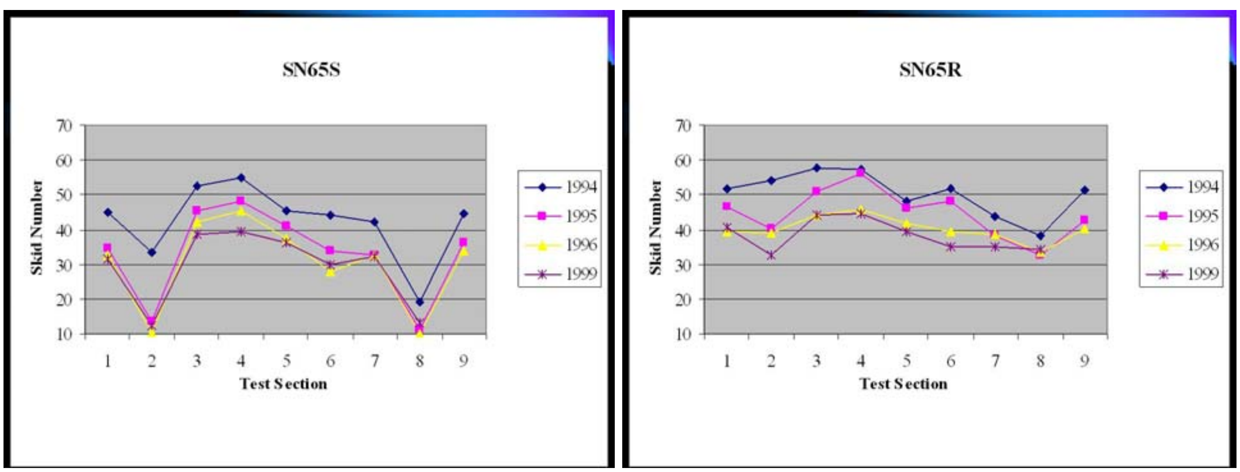
1.3 Data Acquisition & Analysis

1.3.1 Frictional Data

To evaluate the frictional characteristics of individual test sections, skid numbers were acquired according to ASTM skid testing procedure E 274. This procedure measures the locked-wheel frictional forces between a tire of standardized design, size, and inflation pressure, and the wetted road surface at a constant speed of 40 miles per hour (7). Ribbed-tire (ASTM E 501) and Smooth-tire (ASTM E 524) were used to obtain skid numbers at 40, 50, and 65 mph for all the test sections. The following figures show the ribbed and smooth-tire skid numbers at 40 and 65 mph for years 1994 through 1999.



Figures 1 and 2: Smooth and Ribbed-Tire Skid Numbers at 40 MPH



Figures 3 and 4: Smooth and Ribbed-Tire Skid Numbers at 65 MPH

A review of the above graphs reveals a definite relationship between speed, types of surface texture, and the magnitude of skid numbers. As speed increased, the skid numbers declined. This relationship was clearly more pronounced and consistent using the smooth tire. The smooth and ribbed-tire speed gradients for individual test sections were acquired and compared. The relationship between the skid numbers and the speed appeared to be approximately linear for the smooth tire declining at a consistent rate; however, using the ribbed tire this relationship was not as linear for most of test sections.

1.3.2 Texture Measurement

Several different types of texture measuring devices were used to measure the amount of texture in each of the test sections. These devices included Texture Van, Outflow Meter, Texture Beam, Sand Patch Test, and Tire Gauge. The description of the Outflow Meter and Sand Patch Test is presented blow:

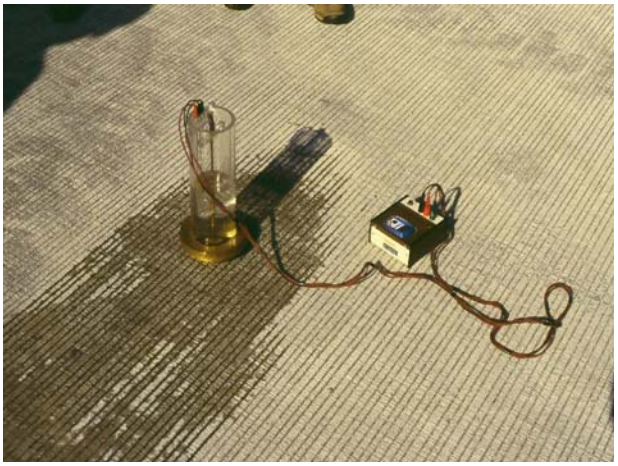
Sand Patch Test

This method is a volumetric measurement using the ASTM procedure E-965. A given amount of fine sand or glass beads particles (1.5 cubic inches) are spread in a circular motion to form a circle. By knowing the volume of the sand and the Diameter of the circle one can measure the depth of the texture as shown below.

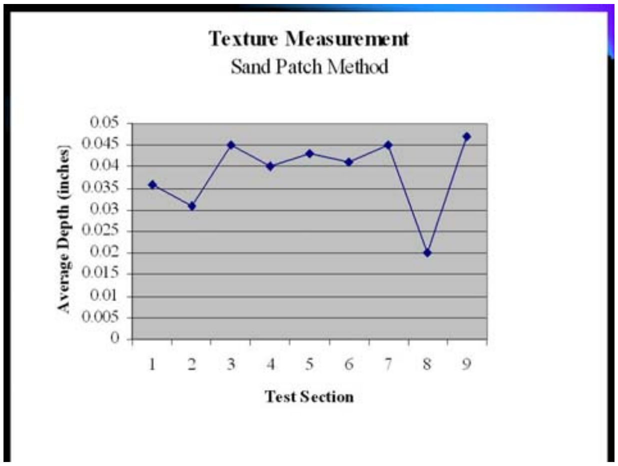
Outflow Meter

This is an indirect measure of texture as shown below. A cylinder with rubber seals on its lower end is placed on the surface and loaded by weights to assure good contact. An electric timer is connected to probes inside the cylinder. The cylinder is filled with water. To start the test, the plunger sealing of the outlet is lifted and the water escapes between the rubber seals and the pavement surface. The time for the water to escape is a measure of texture. Deep textured surfaces will allow fast escape of water; i.e., the outflow time for deep textured surfaces is shorter than the outflow time for shallow textured surfaces.

For a complete explanation of the texture measuring devices used on this study refer to the Link: http://www.dot.state.co.us/Publications/PDFFiles/texturing.pdf

Figures 5 and 6: Sand Patch and Outflow Meter Testing



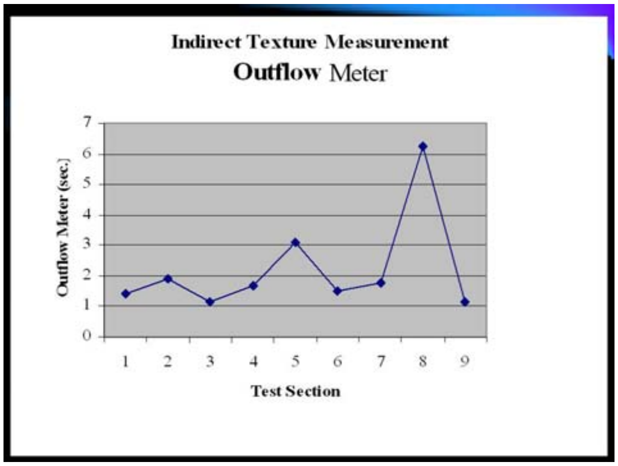


Figure 7: Texture Depth Using Sand Patch   Figure 8: Time of Dissipation Using Outflow Meter

1.3.3 Noise Measurement

Noise measurements were acquired using a test vehicle, a 1994 Oldsmobile Cutlass station wagon provided by CDOT. Sound pressure level (SPL) measurements were recorded through a sound level meter to a digital tape recorder at three different locations:

- Inside the test vehicle
- 25 feet from the center line (3 feet away from the right shoulder)
- Near the right rear tire of the test vehicle, away from the exhaust pipe

The data extracted from the recordings were A-weighted sound levels, as well as 1/3-octave SPL with frequencies between 100 and 5000 Hz.

Figure 9: SPL Measurements at Roadside and Behind the Rear Tire

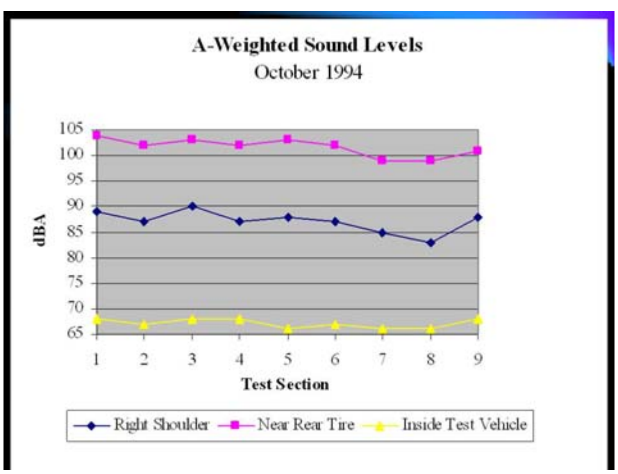


Figure 10: A- Weighted Sound Level

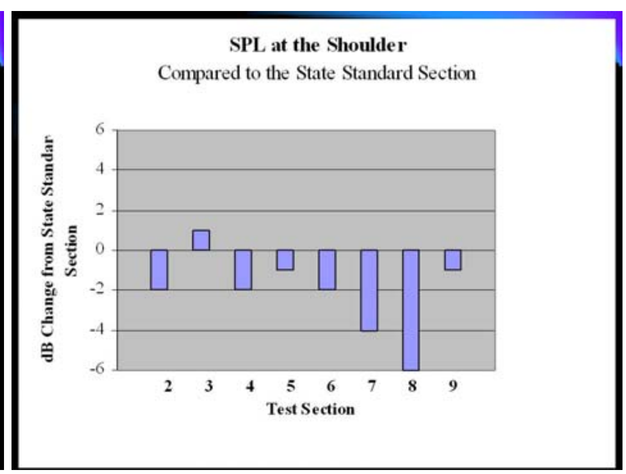
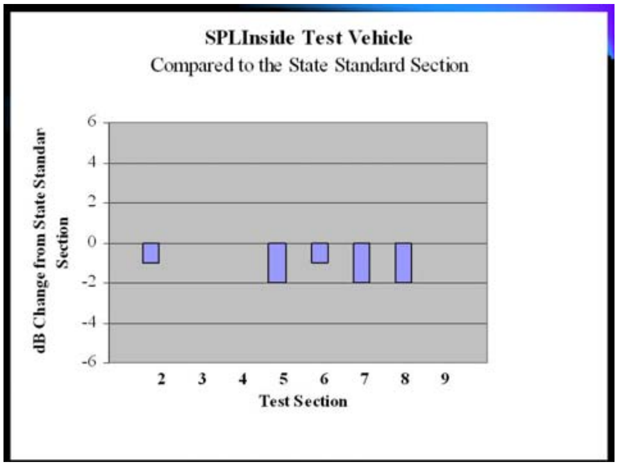
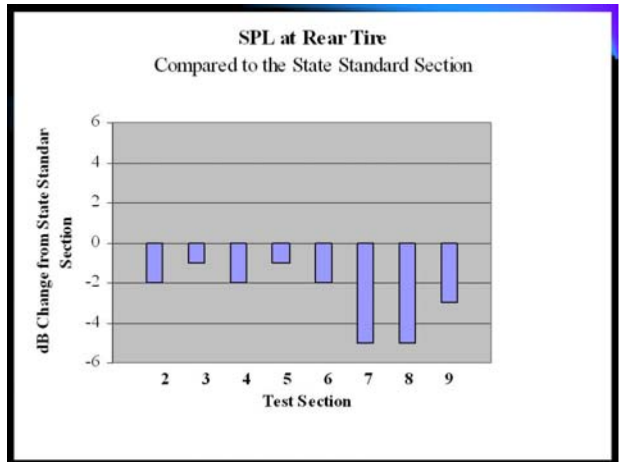


Figure 11: SPL at the Shoulder





Figures 12 and 13: SPL Inside and at the Rear Tire of the Test Vehicle

1.4 Conclusions

- The PCC surface texture has a profound effect on frictional properties and traffic-induced noise characteristics generated at the interface of the tire and the pavement surface.

- Texture depth taken with various texture-measuring devices correlated favorably with the smooth-tire skid numbers taken at 40, 50, and 65 mph, indicating a linear relationship with excellent correlation factors. The results were not as linear with the ribbed-tire skid numbers.

- Section 3 (combination of longitudinal astro-turf and random transverse tining) and section 8 (longitudinal astro-turf) showed the highest and lowest skid numbers respectively, using both the ribbed- and the smooth-tire.

- The largest drop in skid numbers occurred between the first year and the second year, and then significantly leveled off after the second year.

- The relationship between the skid numbers and the speed appeared to be approximately linear for the smooth-tire, and not as linear for the ribbed-tire.

- Longitudinal macrotexture and microtexture were the quietest based on the sound pressure levels

(SPL) taken at the shoulder, inside the test vehicle, and at the rear tire.

- The State standard test section (combination of burlap drag and uniform 1" transverse tining) exhibited the highest noise level among all the test sections with the microphone at the rear tire position.

- SPL taken at the shoulder showed the A-weighted dB of a semi- truck to be approximately 7 dB higher than the A-weighted dB of the test vehicle.

1.5 Recommendations

- The use of smooth-tire over the ribbed-tire as a method of acquiring skid numbers is recommended. The smooth-tire (ASTM E 524) showed more sensitivity to both microtexture and macrotexture than the ribbed-tire (ASTM E 521).

- Longitudinally tinned PCC Pavements exhibit the lowest noise level and provide adequate friction. Their use is highly recommended.

- The use of the sand patch test method as a texture-depth measuring device is highly recommended. Excellent correlations were achieved using the sand patch test method and smooth-tire skid numbers.

- A research study to document the effects of various surface textures on safety in wet weather conditions is highly recommended.

2.0 Implementation of Widened Slab, SPS-2 Experiment Spin-Off Product

The SPS-2 experiment, “Strategic Study of Structural Factors in Rigid Pavements” was developed as a coordinated national experiment to address the effects of various strategic environmental and structural factors on the performance of rigid pavements. The factors studied under this experiment included concrete thickness, concrete strength, base type, lane width, drainage, and environmental factors such as temperature, moisture and soil type.

(CDOT) participated in this national study by constructing 13 different test sections with the following combination of structural factors:

- Concrete thickness at two levels of 8 and 11 inches
- 14-day flexural strength of 550, 650 (state standard) and 900 psi
- Non-draining bases - lean concrete base (LCB) and dense-graded aggregate base (DGAB).
- Draining bases - permeable asphalt-treated base (PATB) with edge drain and transverse interceptor drain
- Slab width at two levels of 12 and 14 feet with untied shoulders.

With respect to environmental factors, the SPS-2 experiment is divided into 4 climatic zones: wet-freeze, wet-no-freeze, dry-freeze, and dry-no-freeze. These climatic zones are further subdivided into coarse and fine subgrades. Considering these environmental factors, Colorado's site is characterized as the zone of dry-freeze with coarse subgrade.

Climate Zones

Wet				Dry			
Freeze		No Freeze		Freeze		No Freeze	
Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse

Structural Factors

Drain	Base Type	Thickness	Strength	Lane Width
NO	DGAB	8	550	12'
			900	14'
		11	550	12'
			900	14'
NO	LCB	8	550	12'
			900	14'
		11	550	12'
			900	14'
YES	PATB	8	550	12'
			900	14'
		11	550	12'
			900	14'

Tables 1 and 2: Climatic Zones and Structural Factors

As indicated above, one of the factors studied was the widened slab (14' wide slab). The concept being investigated was the belief that wider slabs, by keeping heavy trucks away from the longitudinal joints at the shoulder where pavements are most sensitive to bending stresses, can improve the load carrying capacity of the concrete pavements, and ultimately eliminating faulting and corner breaks.

Intuitively speaking, the engineers at CDOT knew that the 14' slab was going to enhance performance, for the reason mentioned above; however, CDOT engineers did not want to wait for 20 years for Long-Term Pavement Performance (LTPP) program to validate this phenomenon. To expedite the implementation process and assure CDOT of the validity and benefits of the wider slabs, Dr. Mike Darter and Mr. Tom Yu of ARA (formerly ERES) were contacted to analytically investigate the overall effectiveness of the wider slabs (16).

2.1 Objectives

The primary objective of the Colorado's SPS-2 experiment was to establish relationships among strategic factors that influence concrete pavement performance with emphasis on evaluating the impact of widened slabs. The ultimate goal of this experiment was to build better, safer, longer-lasting and cost-effective portland cement concrete pavements.

2.2 Description of the Test Sections

To achieve the objectives of this study test sections were established with following experimental factors:

1. Section 1: Widened slabs (14 ft) with tied PCC shoulder
2. Section 2: Widened slabs (14 ft) with untied PCC shoulder
3. Section 3: Standard slabs (12 ft) with tied PCC shoulder

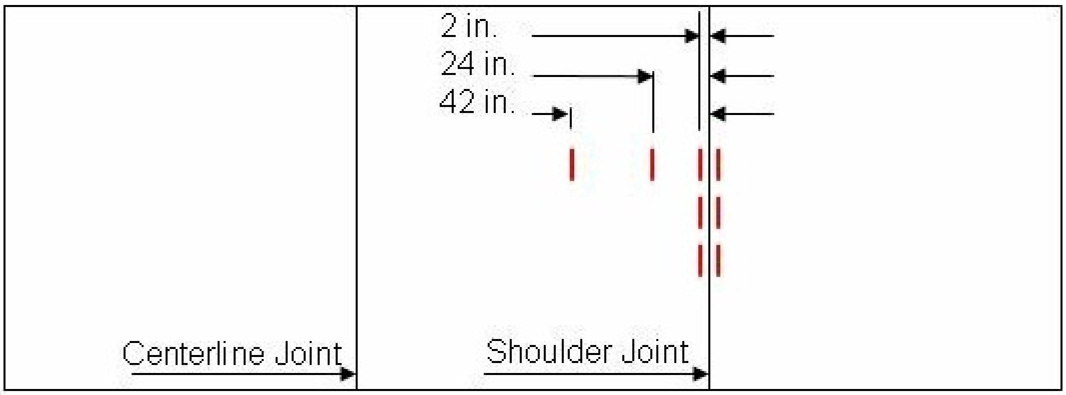
The test sections are located on I-70 westbound 2 miles west of the Kansas-Colorado border, near Burlington. All three test sections are 11 ¼ inch thick, jointed plain concrete pavements (JPCP) with uniform 15 foot joint spacing, constructed over a 7-inch hot mixed asphalt concrete base (the old pavement surface).

2.3 Data Acquisition & Analysis

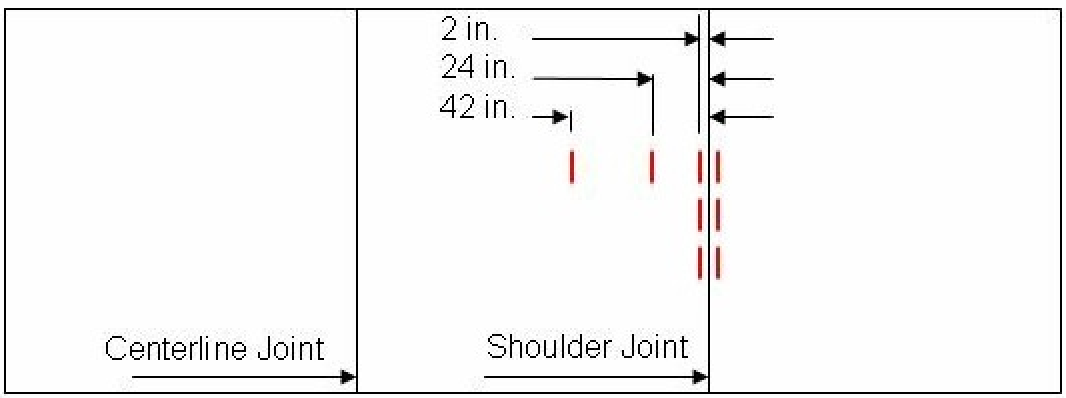
During the field testing conducted in July 1994, several selected slabs were instrumented with dial gauges, thermocouples, and surface mounted strain gauges to measure the temperature and load induced deflections and strains. Pavement temperatures during the testing were monitored by installing several thermocouples at different depths of the pavement slabs and recording them at regular intervals. Instrumentation and data collections were conducted by Construction Technologies Laboratories (CTL). Analysis of the data from the instrumented slabs included:

2.3.1 Curling

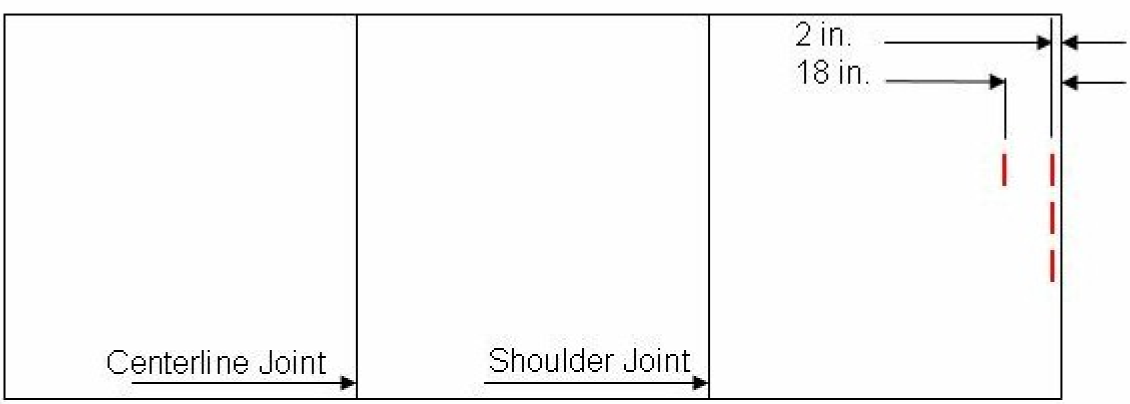
Temperature differences between the top and bottom of concrete slabs cause the pavement slab to curl. The direction (upward lifting or downward dropping of the slab corners) and the magnitude of curling depend on the sign and magnitude of the temperature gradient. Downward curling happens when the slab surface is hotter than the bottom (as typically is the case during a sunny day); if the surface is colder than the bottom, the slab curls upward (corners lifted). The amount of curling depends on the temperature gradient and slab length.



Instrumentation layout for the tied and non-tied 14-ft. lane sections.



Instrumentation layout for the tied 12-ft. lane section.



Instrumentation layout for the free edge.

Figure 14: Instrumentation Layout

In this study, curling was measured directly using dial gauges installed at the corners and middle of the slabs. This was accomplished by anchoring reference rods 6 foot below the pavement surface, thus isolating the rods from the movements of the upper layers. The movement of the middle slab and corners were measured with respect to the reference rods. Measurements were acquired at approximately 30 minute intervals throughout the day, starting at about 6:00 am and continuing to 5:30 pm.

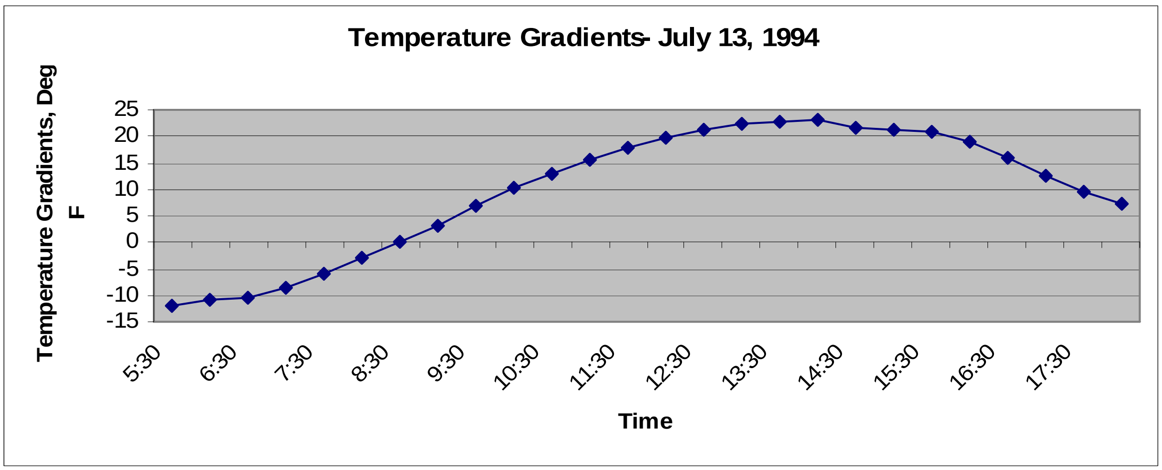


Figure 15: Temperature Gradients

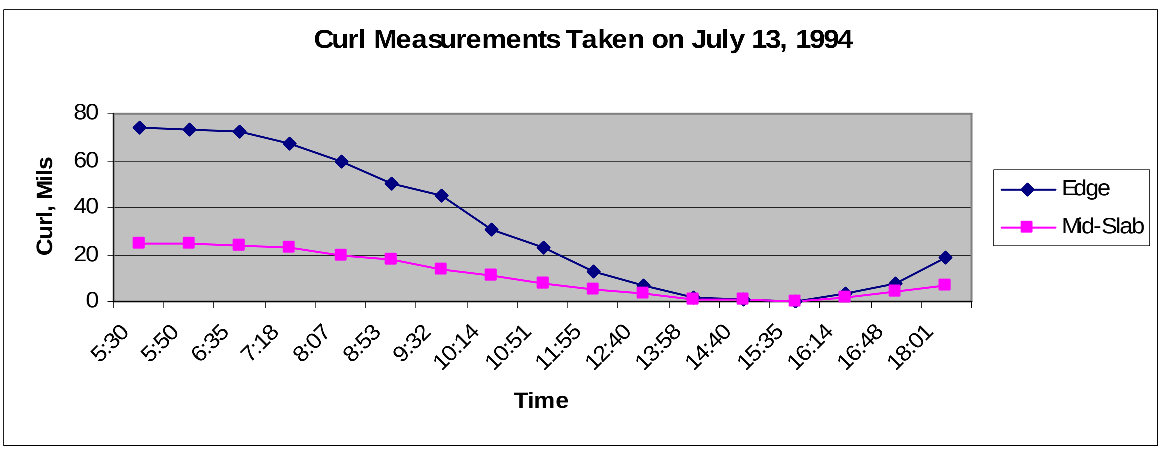


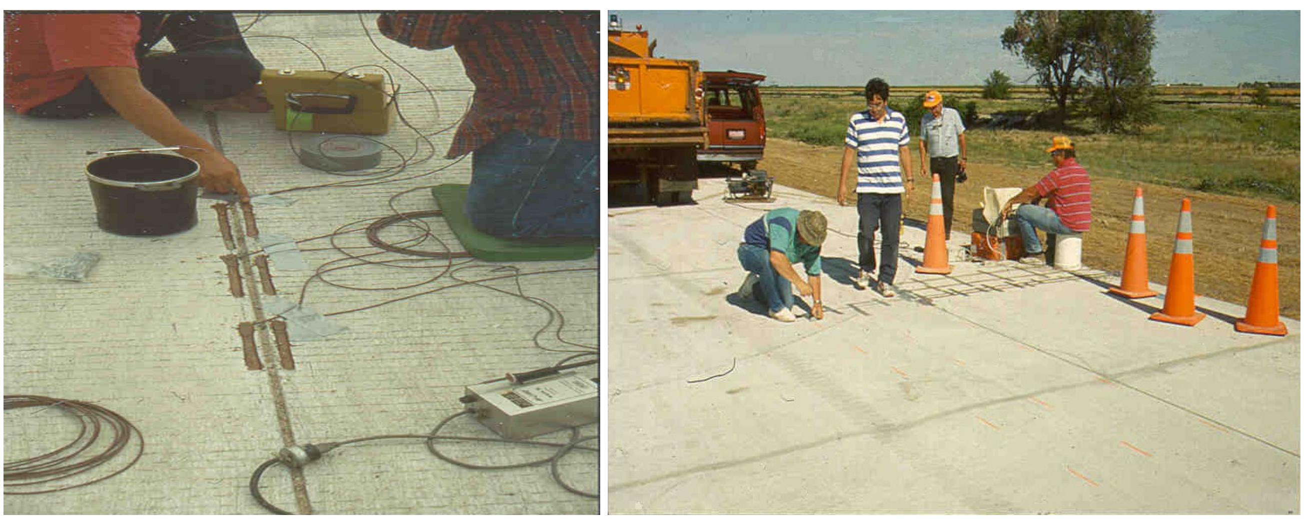
Figure 16: Curl Measurements

Large positive or negative temperature gradients during the placement of the concrete could result in built in curling. In addition, moisture gradients in the slabs (a difference in the moisture content between the top and bottom also causes the slab to curl. Typically, moisture contents in pavement slabs are higher at the bottom than the top, causing upward curling (negative built in curling) of the slabs.

Figures 17 and 18: Acquisition of Curl Data at Mid-Slab and Corners Using Dial Gauges

2.3.2 Strain

Surface-mounted strain gauges were installed at selected locations to measure load-induced strains at the free edge (shoulder edge), at longitudinal edges of lane-shoulder joint (for the 12 ft tied, 14 ft tied, and 14 ft untied) as shown in the instrumentation layout above.



Figures 19 and 20: Surface Mounted Strain Gauges

A loaded truck of 18-kip rear axle was used to acquire static and creep strains throughout the day to evaluate the effects of temperature variations on load-induced strains. The strain data were obtained using an automated data acquisition system capable of sampling data at 20,000 times per second. In general, the analysis of the load strains data revealed no appreciable difference for different temperature gradients. Strains were much higher for the free edge.

2.3.3 Deflection and Load Transfer Efficiency Testing

CDOT performed the deflection testing using a Foundation Mechanics falling weight deflectometer (FWD). The deflection testing was conducted to examine:

- Load carrying capacity and load response of the pavement structure at several different locations
- Load transfer efficiency (LTE) between the slabs, and between shoulder and slabs
- Determine the backcalculated modulus of the subgrade reaction, K-value

Overall, the testing results showed no appreciable differences between the three different designs. The untied shoulder section showed somewhat lower LTE across the slab-shoulder joints. High LTE for all three designs may be attributed to the presence of the stiff AC layer beneath the slabs.

2.3.4 Fatigue Analysis

The long-term performance of the test sections was evaluated by performing a fatigue analysis. Several assumptions were made in this analysis to ensure that reliable, conservative results were obtained:

- The structural contribution of the AC layer was ignored. Although, the field testing results showed that pavement structure exhibits bonded behavior, the long-term reliability of this bonded behavior could not be substantiated, particularly at the slab corners and edges, where large deflections occur. The widened-slab sections were expected to maintain the bonded behavior better, because the critical location for fatigue damage occurs in the wheel path away from the longitudinal edge.

- The effect of negative built-in curling was ignored as this upward curling counteracts the positive temperature gradients at the longitudinal edge.

- The critical stress under the corner loading occurs at the maximum negative temperature gradients, and the effects of the built-in upward curling is additive to the curling due to negative temperature gradients.

2.3.5 Conclusions and Recommendations

- Tied concrete shoulders and widened slabs can significantly improve fatigue life of the concrete pavements.

- The structural benefits of tied concrete shoulder and widened-slab were found to be similar, but for the tied PCC shoulder to provide significant structural benefits, high LTE across the lane-shoulder joint must be achieved (LTE greater than 80 percent). The required level of LTE across the lane-shoulder joint may be achieved by providing adequate-sized tie bars (no. 5 bars at 30 inch intervals).

- The measured curling is consistent with the calculated values if the slabs are assumed curled up in their relaxed state. Such a phenomenon is not uncommon, and may be the result of the temperature conditions at the time of concrete placement, or presence of moisture gradients, or both. The amount of equivalent temperature gradient needed to produce the initial curling necessary to match the field data was about -20 Deg F.

- The finding that the PCC pavement is curled up at zero temperature gradient translates to having a significant amount of built-in negative temperature gradient, and has a great impact on estimated fatigue life of the test sections. Curling caused by high positive temperature gradients could easily double the critical edge stresses in most highway pavements. If this positive temperature gradient is largely offset by the negative built-in temperature gradient, the curling stress would become insignificant, resulting in a substantial increase in estimated fatigue life of the concrete pavement.

The width of widening of 2 feet is recommended for several reasons:

- The widening of pavement slabs by less than 2 feet does not offer the maximum level of stress reduction needed significantly improve performance. An important factor for considering widened slabs is the fact that wider slabs, by keeping heavy trucks away from the longitudinal joints at the shoulder where pavements are most sensitive to bending stresses, can improve the load carrying capacity of the concrete pavements, ultimately eliminating faulting and corner breaks. If sufficiently wide slabs are not provided, it may not be possible to keep all traffic off of the slab edge.

- Two feet of widening is adequate to obtain most of the benefits of using widened slabs, especially when tied PCC shoulders are used in conjunction with the widened slabs. Even on AC shoulder sections, the widening of the mainline slabs beyond 2 feet does not provide significant reduction of the critical stresses.

- Excessive curling stress can develop in the transverse direction if much wider slabs are used. The excessive curling stresses in the transverse direction can then lead to longitudinal cracking.

For a complete review of this report refer to CDOT Report No. CDOT-DTD-R-95-18, Titled "*Field and Analytical Evaluation of the Effects of Tied PCC Shoulders and Widened Slabs on Performance of JPCP*" by Thomas Yu, Kurt Smith, Michael Darter.

3.0 Single-Cut Joints, an SPS-4 Experiment Spin-Off Product

The SHRP SPS-4 experiment, "Preventive Maintenance Effectiveness of Rigid Pavements" was originally developed to examine the effectiveness of various sealant materials, methodologies used to install them, and the effects of sealed vs. non-sealed joints on the performance of rigid pavements. In 1995 CDOT, working with the LTPP division of the FHWA, modified the SPS-4 experiment and added the joint geometry as one of the experimental factors. The focus of this paper is centered on evaluation of four different transverse joint configurations on US 287 near Campo in southeastern Colorado.

3.1 Project Objectives

The primary objectives of the Colorado SPS-4 were three-fold:

- Determine the optimized combination of joint sealant materials/joint configuration that performs best for the newly constructed jointed plain concrete pavement (JPCP).

- Determine the need for sealing transverse and longitudinal joints in JPCP, i.e., quantify the difference in pavement performance when joints are with and without joint sealants.

- Examine the adequacy and performance of single-cut joints.

3.2 Description of the Test Sections

The subject research site is located in the northbound lane of US 287 close to the Oklahoma-Colorado state line between mileposts 4.0 and 5.3. The average daily traffic (ADT) at this location is 3,000 vehicles, of which 55 percent are heavy trucks (primarily semi-trucks). Twenty test sections were installed, of which ten were replicates as shown below.

Table 3: SPS-4 Experiment In Colorado

Section Designation	Joint Width (in)	Sealant Materials
1A	1/8	Unsealed
2A	1/8	Silicone tooled
3A	1/8	Silicone S.L.
4A	1/4	Silicone tooled
5A	1/4	Silicone S.L.
6A	1/4	Compression seal
7A	3/8	Silicone tooled
8A	3/8	Silicone S.L.
9A	3/8	Compression seal
10A	3/8	Beveled tooled
Replicate Test sections		
1B	1/8	Unsealed
2B	1/8	Silicone tooled
3B	1/8	Silicone S.L.
4B	1/4	Silicone tooled
5B	1/4	Silicone S.L.
6B	1/4	Compression seal

7B	3/8	Silicone tooled
8B	3/8	Silicone S.L.
9B	3/8	Compression seal
10B	3/8	Beveled tooled

Four joint configurations were used as illustrated below. The initial cut for all joints were at one-forth of the slab thickness or approximately 2.5 inches.

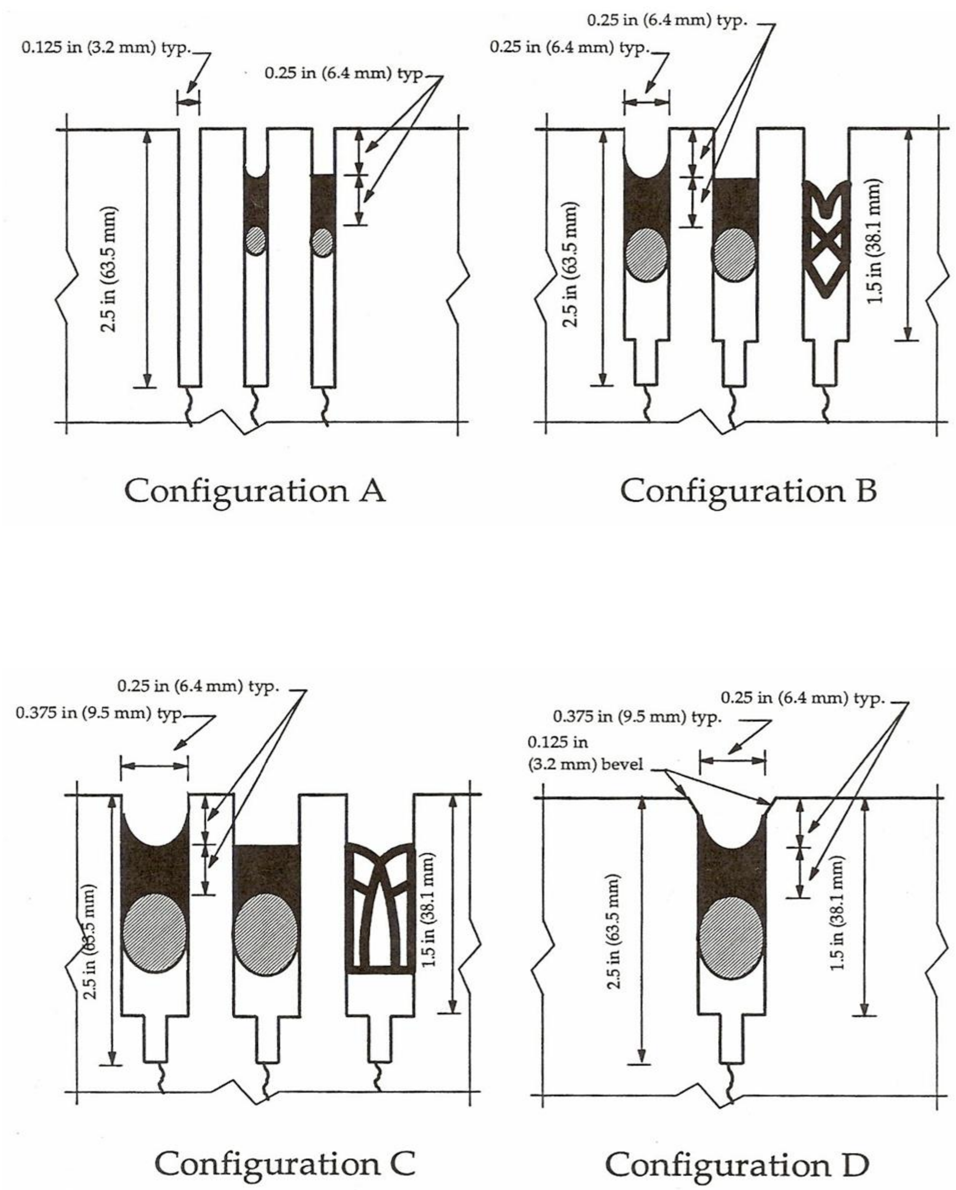


Figure 21: Joint Configuration Details

No additional sawcut was made for configuration A, which was used only for unsealed sections and sections containing silicone sealant. The design shape factor (SF = width/thickness) recommended by the manufacturer for this configuration is 1:2, resulting in thickness of .25 inches. For the rest of the silicone sealant test sections the shape factor was set at 1:1 ratio (17). The minimum recommended recess from the pavement surface was .25 inches.

3.3 Data Acquisition & Analysis

Data collection consisted of acquiring distress survey, joint sealant condition inspection including cohesion, adhesion and presence of incompressible in the joints, FWD and profile measurement. These measurements were taken by the Western Region of the LTPP, Nichols Consulting Engineers at various times between 1995 and 2003. The following criteria were used to rate individual test sections:

Rating	**Failure Level, %**
Very Good	0 to 10
Good	10.1 to 20
Fair	20.1 to 35
Poor	35.1 to 50
Very Poor (Failed)	> 50

3.4 Conclusions

- The results of this study revealed that the 1/8" single-cut joints were as effective as CDOT's standard 3/8" double-cut joints. The difference was that the narrower joints were less labor-intensive and required much less sealant materials.

- Based on a cost-benefit analysis, a saving of 57 cents per linear foot of joint was realized. This equates to approximately 1.7 million dollars per 100 miles of 2-lane concrete pavement. Since 1996, CDOT has been using this joint design on hundreds of miles of concrete pavements.

- Although, the impact of joint geometry on noise was not evaluated in this study, it was quite evident that 1/8" joints were much quieter than the wider joints. They virtually eliminated the objectionable thump-thump noises that are normally associated with the wider joints.

- The use of single-cut joints is strongly recommended.

4.0 Addressing Premature PCCP Longitudinal Cracking

This report presents the results of a research study titled, "Evaluation of Premature PCCP Longitudinal Cracking in Colorado," documenting the investigation of premature longitudinal cracking in several portland cement concrete pavements in CDOT's Region 1. Included in this report is an overview of the causes of the premature longitudinal cracking, a list of strategies to eliminate such occurrences, and descriptions of field and laboratory investigations.

Many factors are responsible for premature longitudinal cracking in portland cement concrete pavements. Cracking is primarily attributed to improper construction practices, followed by a combination of heavy load repetition and loss of foundation support due to heave caused by frost action and/or swelling soils. This study focused on distresses related to improper construction practices.

Possible construction related causes of premature longitudinal cracking include:

- Time of saw-cutting of the longitudinal joints at the shoulders and centerline.
- Depth of the longitudinal saw-cuts at the shoulder and centerline joints.
- Vibrator trails caused by malfunctioning vibrators on the paver.
- Improperly treated swelling soils with high plasticity index and lower R-value
- Inadequate compaction of the sub base soil.
- Misaligned dowel bars.

Design features such as slab thickness and width, base/subgrade type and stiffness, strength, and drainage can cause or have dramatic impact on the severity of premature longitudinal cracking. In addition, materials properties, including the mix constituents (aggregate type, cement type, admixtures, etc.) and their proportions may influence longitudinal cracking. Whatever the cause, premature longitudinal cracks have detrimental effects on the overall performance of portland cement concrete pavements. This study determined their causes and recommended ways to prevent or reduce their occurrence in future projects.

4.1 Project Objectives

The primary objectives of this study were two-fold:

1. To identify and confirm the causes of the premature longitudinal cracking observed at several locations in CDOT's Region 1.
2. To develop strategies to prevent such occurrences in the future.

4.2 Identifying the Causes of Longitudinal Cracking

The evaluation panel first identified possible contributing factors responsible for premature distresses and divided them into two general groups:

Group 1: Cracking with differential settlements related to high swell potential of the subgrade (high PI/lower R-value) and/or poor subgrade compaction.

Group 2: Longitudinal cracking without differential settlement, possibly related to design or construction practices, such as:

- Shallower depth of the saw-cut for the longitudinal joints at the shoulder.
- Malfunctioning or improper adjustment of the vibrators on the paving machine resulting in vibrator trails.
- Wider slab design (14' slabs).

This study primarily focuses on identifying and addressing group 2 distresses.

4.3 Data Acquisition & Analysis

Three sites with several test sections, all in Region 1, were selected and investigated. The investigation, which was conducted by the research team and the study panel members included: visual examination and distress survey of the cracked areas, extraction of cores for visual investigation and for laboratory evaluation, and photographic documentation of the distresses at each individual site.

Examination of cores from several locations on US-287 and I-70 revealed longitudinal joints with sawcut depth that were less than 1/3 of the thickness of the pavement, i.e., not deep enough to instigate the weakened plane cracking. As a result, longitudinal cracks developed to relieve the internal stresses in the concrete.   This discovery eliminated the 14-foot-wide slabs as a possible cause of these longitudinal cracks.

Figures 22 and 23: Longitudinal Cracks Due to Improper Depth of Saw Cut

Figure 24: Cores Showing Non-Working Joints

Figure 25: Vibrator Trails

Some of the longitudinal cracks on US-287 were assumed to be due to vibrator trails created by malfunctioning of paver vibrators. Laboratory testing revealed a definite relationship between improper vibration practices and longitudinal cracking in the path of the vibrators. Cores taken from three different locations on and next to the vibrator trails were sent to Construction Technology Laboratories (CTL) for petrographic analysis. Air-void system analysis was performed in accordance with the modified point-count method of ASTM C 457-98, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." The cores were cut longitudinally and one of the resulting surfaces was finely lapped (polished) and analyzed using a computerized apparatus.

The results showed the air content of the cores taken on the vibrator trails to be consistently lower (30-60 percent lower) than the air content of the cores taken next to the vibrator trails. Visual examination of the cores taken on the vibrator trails revealed non-uniform dispersion of the aggregate, indicating segregation of the mix caused by malfunctioning of the vibrators. High vibrator frequencies and/or prolonged vibrations at lower paver speed were determined to be the main factors that caused segregation and eventually longitudinal cracking along the vibrator trails.

Longitudinal cracks with differential settlement at I-70 near Agate were said to be attributed to improper treatment of swelling soils with high plasticity index and lower R-value. Undisturbed soil samples were taken in the Agate area where the concrete pavement had undergone differential settlement as shown in the following photo. The soil samples were sent to the CDOT Central Laboratory for testing. These test results confirmed the results of the previous soil survey and laboratory tests. The soil plasticity and the swelling potential are high (PI = 30-39) and fraction passing No. 200 sieve is very close to 100 %. Soils having that much swelling potential are very sensitive to moisture change and can undergo substantial movement with moisture penetration.

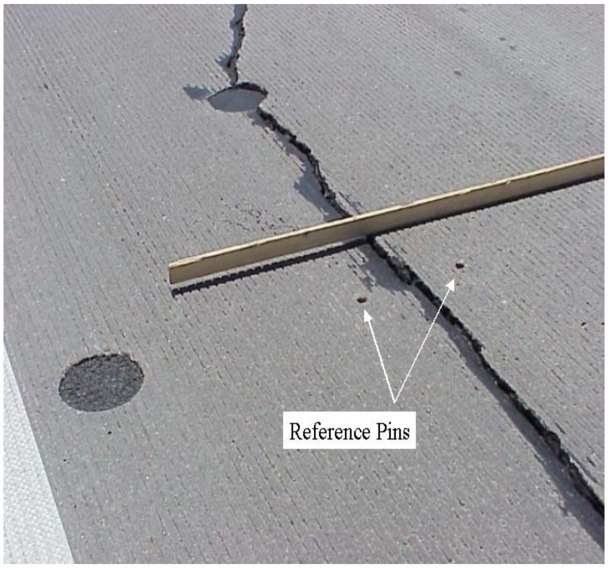


Figure 26: Differential Settlement

Figure 27: Cross Stitching

To alleviate the problem, slurry injection in conjunction with cross stitching was used to temporally seize the swelling. To properly address the problem of swelling soil, Region 1 is planning on removing the existing subsurface materials and replacing them with choice materials.

4.4 CONCLUSIONS AND RECOMENDATIONS

The conclusions and recommendations presented here are based on the results of visual observations and field and laboratory investigations of several concrete pavements in Region 1. CDOT, ACPA, and the concrete paving industry conducted this study as a joint effort.

4.1 Conclusions

- Untreated native soil with high swelling potential i.e., high plasticity index (PI), lower resistance to lateral movement (lower R-value), and poor compaction were identified as two main contributing factors in the development of premature longitudinal cracking. These types of distresses manifest themselves in the form of longitudinal cracks with differential settlements.
- The majority of the longitudinal cracks were attributed to a shallow saw-cut at the shoulder joints. In some cases the saw-cuts were only 50 percent of the recommended

depth. CDOT requires D/3 for standard 12-foot lanes and 0.4D for wider slabs (0.4D mimics the European specification for concrete pavements wider than 12 feet).

- This study found that the 14-foot-wide slab design was not among the causes of longitudinal cracking. CDOT adopted the14-foot slab design in 1996 based on the results of the LTPP SPS-2 experiment, and a supplemental study conducted by Dr. Michael Darter of ERES. The wider slab design is highly recommended for rural highways.
- This study also proved that malfunctioning or improperly adjusted paver vibrators could promote premature longitudinal cracking. Vibrators working at too high frequencies over-consolidate the concrete mix causing non-uniform dispersion of the aggregate and forming vibrator trails. Laboratory investigation of cores extracted on and adjacent to the vibrator trails clearly confirmed this phenomenon. The cores obtained on the vibrator trails had consistently lower air content than cores obtained 18 inches away - in the center of the lane.

4.2 Recommendations

- Premature longitudinal cracking due to improper depth of the longitudinal saw-cut can be prevented by adhering to CDOT's present specification, which requires saw-cut depth of D/3 for 12-foot slabs and 0.4D for 14-foot slabs. It is recommended that project engineers in the field measure saw-cut depth at intervals of 1 per 1/10 of a mile (528 feet). This specification has already been incorporated into CDOT's Field Materials Manual.
- It is strongly recommended that the paving contractors equip their paving machines with frequency monitoring devices for the vibrators. These monitoring devices provide the transportation agencies and the paving contractor a necessary tool to help achieve a quality concrete pavement that is long-lasting. CDOT has already adopted and fine tuned the Iowa DOT's specification for monitoring the frequencies of the vibrators. This specification was fully implemented at the completion of this study. To view this specification visit CDOT's website.

- Accurately recognizing and predicting the potential volume change of expansive soils and their treatment prior to construction plays a major role in overall longevity and performance of pavements. It is necessary to alleviate or eliminate the detrimental effects of expansive soils.

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