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Final Report

**MID-PANEL CRACKING OF PORTLAND
CEMENT CONCRETE PAVEMENTS IN INDIANA**

**Hung-Ming Chen
Yunus Dere
Elisa Sotelino
Graham Archer**

June 2002

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in Indiana**

By

Hung-Ming Chen
Graduate Research Assistant

Yunus Dere
Graduate Research Assistant

Elisa D. Sotelino
Associate Professor

Graham C. Archer
Assistant Professor

School of Civil Engineering
Purdue University

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16. Abstract <p>Portland cement concrete slabs are a common form of highway pavements in Indiana. As a result of their widespread use, the economic impact of their maintenance and life span is therefore tremendous. In Indiana, these types of pavements have been experiencing premature random transverse mid-panel cracking. This phenomenon has been observed under a variety of environmental and traffic conditions. Also, it has been found that the cracking occurs in conjunction with the opening of the lanes to traffic, within months of construction. In this project, a research synthesis was carried out to determine exactly what the current state of knowledge on random transverse mid-panel cracking of Portland cement concrete pavements. This was accomplished by means of a comprehensive literature review of published works and through a survey of other DOT's. In addition, preliminary analyses were carried out to help further understand and confirm the findings from the research synthesis.</p>					
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TABLE OF CONTENTS

Introduction	1
1. The Factors Affecting Transverse Cracking Occurrence in Jointed Plain Concrete Pavement	
1.1 Introduction	3
1.2 The Factors Cause the Transverse Cracking in JPCP	3
2. Finite Element Analysis of Concrete Pavement	
2.1 Introduction	16
2.2 The Early 2D Finite Element Analysis Programs For Rigid Pavement.....	17
2.3 Rigid Pavement Modeling Using 2D Finite Element Analysis Programs	19
2.4 Three-Dimensional Finite Element Analysis for Concrete Pavement	21
2.5 Recent Finite Element Software Developments for Concrete Pavement Analysis.....	29
3. The Analytical Solution Models Related to Mid Panel Cracking in JPCP	
3.1 Introduction	31
3.2 Mechanistic-Empirical Models	32
3.3 Other Closed-Form Solution Models	34
4. Design, Construction, and Rehabilitation Recommendations	
4.1 Introduction	36
4.2 JPCP Design and Construction Recommendation	36
4.3 Rigid Pavement Design Procedure Evaluation	39
4.4 Recommendations for the Rehabilitation or Reparation of Cracks.....	41

5. Survey of Departments of Transportation

5.1 Introduction	44
5.2 General Survey Data	45
5.3 Detailed Survey Data for States with Cracking Problems	48
5.4 Prevention and Rehabilitation Method Comments – States without Cracking Problems	49
5.5 Additional Comments – States with Cracking Problems	51
5.7 E-mail Comments.....	51

6. Preliminary Finite Element Analysis

6.1 Modeling of the Portland Cement Concrete (PCC) Pavements	56
6.2 Thermal Differential.....	64
6.3 The Effect of the Natural Soil Subgrade Stiffness	78
6.4 The Effect of the PCC Slab Thickness.....	81

7. Summary of Results, Conclusions, and Recommendations

7.1 Summary	86
7.2 Conclusions	90
7.3 Recommendations	90

List Of References	92
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Appendix 1: Survey Letter	102
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Appendix 2: Short Survey	103
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Appendix 3: Detailed Survey.....	106
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Appendix 4: Survey Summary	112
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INTRODUCTION

Portland cement concrete slabs are a common form of highway pavements in Indiana. As a result of their widespread use, the economic impact of their maintenance and life span is therefore tremendous. In Indiana, these types of pavements have been experiencing premature random transverse mid-panel cracking. This phenomenon has been observed under a variety of environmental and traffic conditions. Also, it has been found that the cracking occurs in conjunction with the opening of the lanes to traffic, within months of construction.

In the fall of 1997 INDOT, FHWA, and the Indiana Chapter of the American Concrete Pavement Association personnel participated in a field evaluation of random transverse mid-panel cracking of Portland cement concrete pavements in Indiana. This spawned an investigation by the INDOT Materials and Tests Division, which produced a report outlining several possible reasons for the random cracks. However, no clear cause(s) for this phenomenon was proposed.

Although, theories abound as to the causes for the random mid-panel cracking problem, such as usage (driving/passing lane) and sub-grade conditions, no repeatable experimental or analytical evidence has been developed. In an attempt to rectify the problem, INDOT made adjustments in the geometry of the concrete slabs. However, it was found that this change did not affect mid-panel cracking.

In this project, a research synthesis was carried out to determine exactly what the current state of knowledge on random transverse mid-panel cracking of Portland cement concrete pavements. This was accomplished by means of a comprehensive literature review of published works and through a survey of other DOT's. In addition, preliminary analyses were carried out to help further understand and confirm the findings from the research synthesis.

The organization of this report is as follows. A comprehensive literature review of existing published research in the area of mid-panel concrete pavement cracking is presented in Chapters 1 through 4. Chapter 1 presents the factors affecting the occurrence of transverse cracking, Chapter 2 contains the results from previous finite element analyses, Chapter 3 presents analytical models, and Chapter 4 summarizes design

recommendations found in the literature. Chapter 5 presents an analysis of the results of the DOT surveys -- the survey materials and survey summary are provided in Appendices 1 through 4. Chapter 6 contains the description of the developed finite element model and the results of the preliminary finite element analyses. The summary of results, conclusions, and recommendations are provided in Chapter 7.

CHAPTER 1. THE FACTORS AFFECTING TRANSVERSE CRACKING OCCURRENCE IN JOINTED PLAIN CONCRETE PAVEMENT

1.1 Introduction

Several researchers have tried to identify the causes of the transverse cracks in Jointed Plain Concrete Pavements (JPCP). In the literature, finite element analysis results, lab experiments, and long-term field test data are investigated. The results from this work are reviewed in this chapter and their conclusions are presented in the following section. These reviews indicate there is no one clear factor that can be identified as the major cause of transverse cracking of jointed plain concrete pavement. According to most researchers, the combined mechanisms of curling of the concrete slab due to temperature gradients, and fatigue due to repeated traffic loads, lead to the occurrence of the transverse cracks. In addition, the improper control of the shrinkage of the concrete in the early stages of construction is also cited as an important cause of cracking in JPCP.

1.2 The Factors That Cause Transverse Cracking in JPCP

1.2.1 Tayabii, S. D., et al. [49]

Tayabii and Colley (1983) report that excessive slab movements caused by temperature variations may result in lockups of doweled joints. This could result in midslab cracking and spalling of the concrete surrounding the dowels.

1.2.2 Sawan, J. S. and Darter, M. I. [45]

Sawan and Darter (1983) present a structural design procedure based on fatigue analysis that is intended to prevent cracking of the slabs on jointed plain concrete pavements. In results from highway field studies, for slabs of normal thickness (> 8 in.), cracking usually initiates at the slab edge and propagates transversely across the slab. These cracks are usually located in the center third of the slab.

1.2.3 Armaghani, J. M., et al.[3]

Armaghani, et al. (1987) present experimental data to describe the displacements of a concrete pavement slab associated with temperature variation and weather variation. At the Bureau of Materials and Research of the Florida Department of Transportation, a specially designed test road was constructed to simulate actual design features of Florida highways. For a period of three years, the pavement displacements and temperatures at specified time intervals were recorded and analyzed. The findings from this study are listed as follows:

1. Pavement slabs reach their minimum daily temperatures between 6:00 a.m. and 8:00 a.m., and their maximum temperature occurs between 12:00 noon and 2:00 p.m..
2. Maximum daily displacements were concurrent with maximum temperature differentials in the slab.
3. The average horizontal displacement at the doweled joint was only 45 percent of the displacement at the undoweled joint. This suggests that doweled joints offer resistance to slab movements, a condition that can induce stresses in the pavement.
4. Weather conditions significantly influenced temperature response of pavement. Clear, sunny weather characterized by wide variations of ambient temperature produced larger displacements in pavement slabs.

1.2.4 Janssen, D. J. [27]

Moisture gradients in concrete pavements cause differential shrinkage between the top and the bottom of the pavement. This research (1987) has led to the following conclusions, which apply to the effects of moisture gradients in concrete pavements:

1. Significant drying in a concrete pavement can be expected only at the top surface, to a depth of less than 2 in. The rest of the pavement remained at 80 percent saturation or higher;
2. The resulting moisture gradient leads to curling stresses in which the top of the pavement is in tension while the bottom is in compression.

Based on the typical moisture distribution determined as above, and using an aggregate content of 74 percent and an elastic modulus of 3.6×10^6 , a stress distribution was calculated. The tensile strength of the concrete would be exceeded down to a depth of approximately $\frac{3}{4}$ in. for the 4,000-psi concrete. This indicates that shallow hairline cracks can be expected to form by wetting the concrete surface and then allowing the water to evaporate.

1.2.5 Richardson, J. M. and Armaghani, J. M., et al.[42]

Richardson and Armaghani (1987) present a research program that was undertaken by the Florida Department of Transportation to determine the actual temperature gradient in a PCC pavement. For a period of 9 months, hourly temperatures were recorded from a 9-in thick test pavement in Gainesville, Florida. The temperature data was analyzed to determine the actual maximum compressive and tensile stresses caused by the nonlinearity of the temperature gradient. The results indicate that the nonlinearity of the temperature gradient in a PCC pavement did have a significant enough impact to cause a pavement to crack or fail. However, these results are only applicable to the conditions that obtained on the test road at Gainesville, Florida. Their extension to other climates,

thickness of pavements, coarse aggregates, and base materials is not advised until further research has been conducted.

1.2.6 Poblete, M., et al. [41]

Poblete, et al. (1991) present a predictive model of slab cracking developed by considering the actual behavior of Chile's Portland cement concrete pavements. The model incorporates realistic boundary conditions. Precise measures were carried out periodically, at 21 test sections have clearly shown the existence of an upward concavity in all slabs. The causes for this condition are related to the combined action of climatic features affecting pavement since construction.

- Daily temperature variations induce upward curling typically during the cooling period between 6:00 p.m. and 10:00 a.m..
- The internal moisture has wider variations near the surface, which is exposed to environmental conditions allowing evaporation. Therefore, the pavement slabs tend to be permanently upward warped.
- Another possible factor contributing to the upward concavity of the pavement slabs is related to the irreversible drying shrinkage of the concrete slab surface that occurs during the first hours of concrete hardening.

Yearly cyclic moisture warping and daily cyclic temperature curling data, obtained from measurements in the climatic zone of central Chile were collected. The approach used is a mechanistic-empirical one and is based on structural modeling of the jointed pavement using finite element program.

The analysis showed the maximum tensile stress is at the upper slab surface and toward the central portion of the slab when the loaded axle crosses the transverse joints. Tensile stresses are also high at the middle zone near the edge. These results are in good

agreement with the actual pattern of slab cracking, which usually starts at the middle of edges and progresses down and inward until the complete breakage of the slab.

1.2.7 Buch, N. and Zollinger, D. G. [7]

Buch and Zollinger (1993) report an experimental investigation that was designed to measure the relative humidity. The relative humidity and temperature changes within the body of the specimen were measured using humidity and temperature sensors; these sensors were connected to a continuous data-logging device. The humidity profile shows that drying in the surface layers is greater than in the interior concrete. Moisture content measurements indicate that the strength of concrete is dependent on the relative humidity. Hence, the drying at the surface of a slab has a definite effect on the performance of the concrete pavement. The moisture state in concrete should serve as a useful tool in the control of cracking of concrete pavement during construction operation.

1.2.8 Jenq, Yeou-Shang, et al. [28]

Jenq, et al. (1993) indicate that the major distress problems of concrete pavements generally start with crack formation caused by the combined effects of traffic load and service temperature. A cohesive crack model was used to study the effect of temperature on crack formation in concrete pavements and to demonstrate the feasibility of fracture mechanics analysis on concrete pavement systems. An Experimental study and a finite element numerical study are performed in this research.

It was found that the peak temperature differential that causes the formation of random cracks in the pavement is sensitive to the age of the pavement. To properly control the occurrence of random cracking, saw-cut grooves should be introduced at the earliest possible age of the concrete pavement. Results of crack control by the introduction of a saw-cut groove are dependent on the age of the concrete, the temperature differential, and

the depth of the groove. It can also be concluded that timing of the saw cut is actually more important than its depth.

1.2.9 Zollinger, D. G. et al. [56]

Zollinger, et al. (1994) also researched the sawcut depth for jointed concrete pavement using a fracture-mechanics analysis. Preliminary field results show that early-age saw-cutting, with appropriately determined joint spacing and depth, can be used for the positive control of cracking in jointed plain concrete pavements. Since the early 1950s, one-third of the pavement thickness ($d/3$) has been accepted as the necessary depth of cut to induce cracking. In this research, a modified linear elastic fracture mechanics analysis is employed to determine a sufficient sawcut depth to ensure controlled cracking. The appropriate sawcut depths and placement timing are estimated.

The authors concluded the theoretical sawcut depth, as determined by their fracture mechanics analysis, is significantly less than $d/3$ or $d/4$, where d is the slab thickness. Recent pavement surveys have verified this conclusion. They indicate that it is reasonable to use sawcut depth on the order of 1 in. at an early concrete age. The reduction of the sawcut depth can take advantage of the greater change in moisture and temperature in the concrete at the pavement surface to initiate a greater incidence of cracking at the sawcut notches.

1.2.10 Byrum, C. R. and Hansen, W. [9]

Byrum and Hansen (1994) present a technique for interactions between typical highway load and jointed concrete pavement by using influence functions technique, which can be used to estimate the minimum and maximum responses caused by moving wheel loads for any interested point on the slab. A parametric study of the model is presented showing the effects of various key input parameters, such as temperature gradients, load

magnitude, joint opening and dowel size, on the stress distributions in the slab. The traffic contributions were broken down into equivalent single axle loads per hour. Temperature and moisture gradient effects were estimated for a typical day. These factors were then reduced to obtain the daily fatigue loss.

The authors conclude that the influence function approach, developed at the University of Michigan Transportation Research Institute, is demonstrated to be a powerful tool for rigid pavement analysis. The results of this study indicate that the upward curled or nighttime temperature condition is prevalent and most severe. The peak tensile stresses being located in the top of the slab.

1.2.11 Bodocsi, A. et al. [6]

Bodocsi, et al. (1994) report research on monitoring the deflections of an experimental concrete pavement and analyzing the effect variables. This pavement was built in 1972 in Chillicothe, Ohio, by the Ohio Department of Transportation. The variables built into the pavement included two types of bases, different joint spacing, one section with skewed joints, joints with no dowels, standard dowels, and plastic-coated dowels. The magnitude of joint deflections in a concrete pavement caused by truck traffic is important because the larger the deflection, the larger the stress and the lower fatigue life of the pavement. The University of Cincinnati researchers have investigated this pavement for several years, first in the middle 1970s and then between 1989 and 1991. The following conclusion was made in this study:

1. The maximum measured deflection occurred in the fall in the morning and on granular base.
2. The overall average deflection of the joints in the morning was significantly greater than the overall average deflection in the afternoon. The temperature differential was the probable cause.

3. The joints on stabilized base deflected significantly less than the ones on granular base. This was because the stabilized base provides better support with less deflection. It also minimizes pumping and erosion.
4. There was no significant difference between the average joint deflections of doweled and undoweled joints on stabilized base.

1.2.12 Jenq, Y-S and Kim, S-C [29]

Jenq and Kim found that random crack formation in concrete pavements is mainly due to the development of tensile stress caused by temperature-induced volumetric change and shrinkage deformation at early age of concrete. To control random crack formation, current practice calls for a transverse sawcut of about 1/4 to 1/3 of the pavement thickness in an attempt to confine the random cracks to the sawcut location. In this paper (1994), it was found that,

1. Crack propagation in a concrete pavement without sawcut is unstable compared to that in a pavement with sawcut.
2. The introduction of sawcut drastically reduces the temperature differential needed to initiate and propagate a crack in the pavement.
3. In order for the sawcut to be effective, it was found the sawcut has to be introduced well before the occurrence of random cracks, that is, the timing of sawcut is very critical to success of crack control.

1.2.13 Marks, V. J. and Dubberke, W. G. [36]

Marks and Dubberke (1996) presented a new type of PCC pavement deterioration in Iowa. In 1990, cracking deterioration was identified on a 3-year-old US-20 pavement in central Iowa. The coarse aggregate was a crushed limestone with an excellent history of performance in PCC pavement. Examination of cores showed very few cracks through

the coarse aggregate particles. A high-resolution, low-vacuum scanning electron microscope with an energy dispersion detector was used to investigate the deterioration. Subsequent evaluation identified a very small concentration of silica gel (silicon) but substantial amounts of sulfur and aluminum (assumed to be ettringite) in the air voids. Some of these voids have cracks radiating from them leading to the conclusion that the ettringite-filled voids were centers of pressure causing the cracks. The research has indicated that the premature deterioration may be due to ettringite and may have been mistakenly identified as alkali-silica reactivity.

1.2.14 Moody, E.D. [38]

Moody (1998) performed a bivariate analysis on the transverse cracking in the joint plain concrete pavement. The joint spacing was considered the most significant variable that causes transverse cracking. Several other primary design variables and distress mechanisms that can cause transverse cracking were also presented. The Strategic Highway Research Program's Long-Term Pavement Performance (LTPP) was used in this research as a significant database to support this mechanics-based pavement research.

This paper provides evidence that either fatigue in the concrete surface layer or pumping of the base material is leading to transverse cracking over time. The extensive transverse cracking that has occurred in pavement sections with cement-treated bases (CTBs) suggests that either subgrade friction between the base and surface layer is excessively high or curling stresses on the hard CTB layer are leading to the occurrence of transverse cracking. The data show that of the 42 JPCP test sections constructed over CTBs, 33 percent are cracked. Fewer than 14 percent of the test sections constructed with other base types have resulted in transverse cracking.

1.2.15 Ahmed, I., et al. [1]

Ahmed, et al. (1998) investigate the causes of poor performance of plain cement concrete runway pavement at Zia International Airport. A review of various available documents supported by experimental and numerical investigations was presented. It is shown that improper spacing of the longitudinal and transverse joints and existence of high temperature stresses resulted in cracking even prior to application of any air traffic loading. The use of low strength concrete, large slab size, occurrence of high temperature induced stresses, and operation of aircraft of sizes larger than those considered in the design have all contributed to the poor performance of the pavement slab. Large slab panel dimensions were responsible for initial cracking.

1.2.16 Holt, E. E. and Janssen, D. J. [24]

The early age volume changes are presented in real pavements can contribute to the cracking behavior of the concrete at later age. However, volume changes can occur in concrete during the first 24 hours and are generally missed in laboratory shrinkage evaluations. Holt and Janssen (1998) showed the investigation results of volume changes in concrete during the first 24 hours under both drying and nondrying conditions.

1.2.17 Frabizzio, M. A., et al. [20]

Frabizzio, et al. (1999) indicate several mechanisms that can produce transverse cracking in jointed concrete pavements. Plastic shrinkage and drying shrinkage can cause transverse surface cracks early in the life of these pavements. These surface cracks can deteriorate over time due to traffic loads and climatic variations, thus leading to more severe cracks. Expansion/contraction of the slab, caused by variations in temperature and/or moisture conditions, can also cause transverse cracking. Such slab movements

induce interface friction between the slab and its support layer, which can lead to cracking.

Fatigue cracking, caused by repeated cycles of temperature curling and moisture warping combined with repeated applications of traffic loads at mid-slab edge location, is a major source of transverse cracks in Joint Concrete Pavements (JCPs). The mid-slab edge location is the critical load position for fatigue cracking for two main reasons. First, tensile stresses are greatest at this position because the load is located far from the joints, and the pavement thus does not benefit from the load transfer provided there by dowel bars. Second, placement of the load at a free edge results in the maximum bending stress. The combination of large tensile stresses induced by mid-slab edge loads and curling and warping stresses can eventually lead to fatigue cracking.

The objectives of this study were to determine the design parameters that significantly affect transverse cracking and to demonstrate methods available for evaluating cracked pavements. Field data were collected from in-service jointed concrete pavements located throughout southern Michigan to accomplish these objectives. Joint spacing, coarse aggregate type, shoulder type, and pavement temperature were found to have significant effects on transverse crack development and/or performance.

Several findings were made regarding the effects of JCP design parameters on transverse cracking:

1. Longer joint spacing leads to a greater number of transverse cracks per slab. This is due to the larger curling stresses associated with longer slabs.
2. Pavements containing slag or recycled concrete coarse aggregate appear to have more transverse cracks than those using natural gravel or carbonate aggregate.
3. Natural gravel pavements having tied concrete shoulders demonstrated significantly fewer transverse cracks than those having asphalt shoulders.

4. Recycled pavements having concrete shoulders with sympathy joints were found to have a significantly greater number of cracks than those having concrete shoulders without such joints.

1.2.18 Voigt, G. F. [53]

Voigt (2000) indicates many reasons that uncontrolled cracks occur, and it is usually a challenging task to isolate the causes. However, experience in examining projects has led to identification of some consistent characteristics.

1. Saw Timing. There is an optimum time to saw contraction joints in new concrete pavements, which is defined as the sawing window. The window begins when concrete strength is acceptable for joint sawing without excessive raveling along the cut.
2. Weather and Ambient Conditions. A sudden drop in surface temperature more than 9.5°C (15°F) can result in cracking from excessive surface contraction.
3. Subbase. Stabilized subbases may induce uncontrolled cracking because of the high friction and, in some cases bonding, between the subbase and concrete slab. The friction or bond restrains the concrete's volume change (shrinkage or contraction), inducing higher stresses that might occur in concrete pavement on granular subbases.
4. Joint Spacing. Pavement with long transverse joint spacing may crack due to tensile stresses from temperature curling.
5. Rapid Surface Moisture Evaporation. It is important not to confuse cracks from restraint of the concrete at early ages, to plastic shrinkage cracks. Plastic shrinkage cracking is a result of rapid drying at the concrete pavement surface.

1.2.19 William, G. and Shoukry, S. [54]

William and Shoukry (2000) developed a detail 3D Finite Element model to investigate the applicability of Westergaard's thermal stresses formulation to dowel joined concrete pavements. The basic assumption in Westergaard's formula is the change in temperature distribution through the slab thickness can be separated into a gradient only component and a uniform temperature component. It is found that the curling stresses due to temperature gradient in concrete slabs are small in comparison with the stresses due to uniform temperature change. Through the examination of the mechanism of dowel-concrete interaction, it is shown that uniform temperature changes play the major role in initiating transverse cracking in relatively long slabs. Due to built-in slab curling as well as temperature or moisture curling, the dowel bars bend, restricting the slab from free contraction due to uniform temperature changes. This gives rise to tensile stress sufficient to initiate transverse crack and correlates well with slab length. It was only through considering the actual temperature profile in a concrete slab, that the field observation of the relation between transverse cracking and slab length could be explained.

CHAPTER 2. FINITE ELEMENT ANALYSIS OF CONCRETE PAVEMENT

2.1 Introduction

The Finite Element Method currently is the most powerful and popular numerical method in the analysis of rigid pavements. Cheung and Zienkiewicz first developed finite element method for analyzing slabs on elastic foundations. In the 70s, several 2D finite element programs for rigid pavements analysis based on classical plate theory were developed. The famous programs include the ILLI-SLAB developed at the University of Illinois, KENSLABS by Huang and Wang and JSLAB developed by the Portland Cement Association.

Temperature effect is an important factor in the rigid pavement system. The early 2D finite element programs are limited to allow only linear temperature gradients through the slab thickness. In the real situation, the temperature distributions have been proven to be highly nonlinear. In order to improve the accuracy of modeling concrete pavement using these 2D finite element programs, several research projects were conducted to develop technique for modeling nonlinear temperature distributions using 2D programs.

In the 1990s, advances in computing technologies and the emergence of the general-purposed commercial finite element software, such as ABAQUS, make the detailed 3D modeling of rigid pavements possible. The high performance computing resources developed in recent years and powerful modeling capabilities provided by the software allow the researchers to perform 3D nonlinear dynamic analysis on rigid pavement system models using complex material constitutive models and advanced elements. Several research projects show the 3D finite element analysis provides the most realistic and detailed modeling of rigid pavement systems.

Although, the modern commercial finite element packages provide various and complete analysis algorithms, material models and element types to allow users to model and analyze different systems, these packages tend to be hard to learn due to their complexities. Some researchers also developed special finite element programs for rigid pavement analysis particularly to provide pavement engineers useful and friendly tools. The easy-to-use interfaces, minimal computer system requirements and special features used especially in pavement analysis make them attractive. They also have the ability for researchers to develop new elements or material models for pavement modeling.

2.2 The Early 2D Finite Element Analysis Programs For Rigid Pavement

2.2.1 Huang Y. H. and Wang, S. T. [25]

Huang and Wang (1974) developed a finite-element method program, named KENSLAB, for determining the stress and deflections in concrete pavements with partial subgrade contact. The partial contact may result from the pumping and plastic deformation of the subgrade in combination with the upward warping of the slab. The method presented is based on the classical theory of thin plates on Winkler foundation. The predictions of the stresses and deflections based on partial contact are more closely related to the experimental measurements from the AASHTO Road Test than with those based on full contact.

2.2.2 Tabatabaie, A. M. and Barenberg, E. J. [47] [48]

Tabatabaie and Barenberg (1978, 1980) developed a finite–element computer program called ILLI-SLAB. The procedure is based on the classical theory of a medium-thick plate on a Winkler foundation and can be used for the analysis of concrete pavements that have joints or cracks. The program can include consideration of various types of load-

transfer systems such as dowel bars, reinforcement steel, aggregate interlock, and keyways as linear-elastic spring elements. The model is also capable of handling the effects of stabilized bases or overlays on the stresses and deflections in concrete pavements and of traffic loadings on concrete shoulders that may or may not have tie bars, continuously reinforced concrete pavements, and slabs of varying thickness.

ILLI_SLAB is a static analysis program. Nasim et al. (1991) modified and extended it to be capable of handling dynamic analysis. The program is modified to generate influence functions, which are combined with the dynamic loads under the wheels of truck to predict the strain time histories at points of interest in the pavement. Experimental measurements of pavement response, demonstrate that the program is capable of predicting strains in a rigid pavement when the dynamic loads and pavement properties are known.

2.2.3 Tia, M., et al. [50]

Tia, et al. (1987) developed a computer program named FEACONS III (Finite Element Analysis of CONcrete Slabs) in response to a need for a suitable analytical model to analyze the behavior of concrete pavements effectively and realistically. The program has been used extensively in the analysis of existing concrete pavements and a test road in Florida. The analytical model and computational procedure used by FEACONS III are described in detail. The FEACONS III program was shown to be both versatile and effective in the analysis of concrete pavement response. The modeling of the edge stiffness and the linear joint stiffness and torsional joint stiffness produces fairly realistic analytical results. The program can be used to estimate pavement parameters and to compute the critical induced deflections and stresses caused by a combination of traffic loads and thermal conditions.

2.3 Rigid Pavement Modeling Using 2D Finite Element Analysis Programs

2.3.1 Harik, I. E. et al. [21]

Harik, et al. (1994) developed an analysis technique to be used in conjunction with packaged 2D finite-element programs for the study of rigid pavements subjected to temperature loading. The pavement is idealized as a thin isotropic plate resting on a Winkler-type elastic foundation. Since two-dimensional plate elements are limited to linear temperature distribution through the thickness, the advantage of the proposed method lies in its capability to superimpose the effect of the nonlinear temperature distribution on the finite-element solution. This obviates the need to use three-dimensional elements, which would significantly increase the input and execution time. Results of using this technique with 2D finite element program are presented and compared with those derived using 3D finite element analysis for both linear and nonlinear temperature variations. The results demonstrated that temperature effects should be considered in the analysis and design of rigid pavements. The assumption of linear temperature distribution cannot accurately predict the stresses. Nonlinear temperature gradient should be considered.

2.3.2 Choubane, B. and Tia, M. [12]

Choubane and Tia (1995) conducted an experimental and analytical study to develop an effective method for determining realistic thermal-load induced stresses in concrete pavements using FEACONS IV. Temperatures throughout the concrete slabs were measured over an extended time period. Resulting critical stresses were then analytically derived following the procedure developed in this study. To verify these analytical stresses, load-induced strains and deflections were recorded at numerous locations on the test slab at various time periods. The findings confirmed the importance and the need to account for the thermal gradient in the design and analysis of concrete pavements. The

temperature data indicated that the temperature distributions were mostly nonlinear and can be represented fairly well by a quadratic equation. The maximum tensile stresses computed using traditional linear temperature assumption tends to be higher for daytime condition and lower for nighttime condition in compared to the nonlinear temperature distribution modeling in this work. Finally, the measured strains were close to the computed ones, showing the appropriateness of the analytical model used in this study.

2.3.3 Roesler J. R. and Khazanovich, L. [44]

Roesler and Khazanovich (1997) used finite element to analyze concrete pavements with partial-depth cracks. To solve the problem of a partially cracked slab, fracture mechanics must be used. The existing static finite-element program, ILLI-SLAB, was modified (ILSL97) to analyze concrete pavements with partial-depth cracks. By using available fracture mechanics techniques, a relationship was derived between the amount of moment load transfer across a crack and the crack depth. To model a partial-depth crack, a special line spring element was used. The line spring element mimics the behavior of a crack by acting as a rotational hinge between two continuous slabs. The equations demonstrated how moments and normal forces are coupled in the analysis of cracked plates. This analytical solution was then used to formulate the element stiffness matrix for the line spring element. The displacements outputted by the finite element model were correct, but the stresses in the vicinity of the crack tip needed to be corrected to match the stress singularity zone present in front of cracks.

The proposed model was verified by running a series of cases. A practical example was analyzed a range of crack depths and pavement thicknesses. The results indicated that the maximum slab deflection increased with crack depth and was greater for thinner slabs. The stress intensity at crack tip also increased with crack depth. Thinner slabs were found to have higher stress intensity factors.

2.4 Three-Dimensional Finite Element Analysis for Concrete Pavement

2.4.1 Channakeshava, C. et al. [11]

Channakehava, et al. (1993) presented nonlinear finite element analysis of dowel-jointed concrete pavements. The material nonlinearities due to cracking and yielding of concrete under static loading, and geometric nonlinearities due to loss of support and temperature curling are considered.

Analyses of pavements, under different loading, support and dowel-concrete interface conditions, have given insights as follows:

1. The loss of subgrade support may lead to a rapid deterioration of pavement through fatigue, by increasing the tensile stress level in concrete.
2. The nighttime curling of slabs, because of a loss of support at the joints, leads to lifting up of the ends of slabs and increases the stresses. Daytime temperature curling is found to be less critical.
3. Softening of the dowel-concrete interface stiffness significantly affects the efficiency of the joint in transferring the loads.

2.4.2 Jenq, Y. et al. [28]

Jenq, et al. (1993) studied the effects of temperature on the early crack formation in the Portland Cement Concrete Pavement (PCCP) using fracture mechanics analysis. A fracture mechanics based cohesive crack model was developed to study the temperature effects and to demonstrate the feasibility of fracture mechanics analysis on concrete pavement systems. Both experimental study and finite element analysis are conducted in this research. In the fracture mechanic based finite element analysis, concrete pavement

with various slab thickness and a known temperature distribution were analyzed. ABAQUS finite element package was used in the finite element analysis.

It was found that the peak temperature differential that causes formation of random cracks in the pavement is sensitive to the age of the pavement. It can also be concluded that timing of the saw cut is actually more important than its depth.

2.4.3 Kuo, C. [33]

Kuo (1994) used the three-dimensional commercial finite element software, ABAQUS, to model and analysis the jointed plain concrete pavement (JPCP). The experimental crack development data in JPCP was recorded at the AASHTO Road Test. It showed that cracks in thin slab sections were first observed along the direction of the wheel path, then developing toward mid-slab edge. In thick slab sections, cracks most often developed from the edge at mid-slab.

ABAQUS was used to verify crack initiation in thin and thick slabs. The analysis reveals that the critical stresses in thin slab occur right under the wheel load; thus, the portions along the wheel path suffer the most severe fatigue damage. Contrary to thin slabs, the critical loading position of thick slabs (6.5 inches and greater) is mid-slab loading.

The contours of principal stresses on the tops and bottoms of slabs from ABAQUS not only explain the crack patterns of different slab thickness, but also reveal the cracking starting from top or bottom. . In thin slabs, the top stresses are significantly lower than bottom stresses. So, the cracks actually start from the bottom and propagate upward through the slab. However, in thick slabs, the critical stress at the bottom is only slightly higher than that at the top of the slab. Hence, it is possible to find some cracks initiating from the bottom and some form the top.

2.4.4 Mallela, J. and George, K. P. [34]

Mallela and George (1994) employed ABAQUS to analyze concrete pavement subjected to dynamic loading. The explicit time integration scheme is employed for impact- or impulse-load analysis. The finite element modeling results were verified using falling-weight deflectometer (FWD) deflections and those predicted by an elastodynamic solution. Then the model was employed for calculating deflection responses of factorially designed rigid pavements. The results indicated that static deflections were larger than their dynamic counterparts. Larger apparent deflection responses could result in overprediction of layer moduli in backcalculation algorithms.

The authors concluded the 3D finite element analysis could simulate moving or impulse loads and linear and nonlinear material properties. The static response analysis, traditionally employed in backcalculation algorithms, should be replaced with dynamic analysis routines. The 3D ABAQUS finite element program with its numerous features simulating real-world conditions is a powerful tool for analyzing the rigid pavement structure.

2.4.5 Chatti, K., et al. [10]

Chatti, et al. (1994) also employed the 3D dynamic finite element analysis to model the jointed concrete pavements subjected to moving transient loads using the dynamic finite element program, DYNA-SLAB. The important contribution of this study is a new analytical method for determining the stiffness and damping coefficients to be used in the Winkler foundation model. The accuracy of the modeling results is verified with the theoretical closed-formed solution, the dynamic soil-structure interaction program named SASSI and field data.

The author concluded that dynamic analysis is generally not needed for the design for rigid pavements and that it usually leads to decreased pavement responses. As far as the

response of the pavement is concerned, only the peak values of the wheel loads and the velocity with which the loads transverse the pavement are important, with the latter being significant only in determining the duration and rising times of an individual pavement response pulse. The detailed frequency content of the wheel loads appears to have little effect on the behavior of pavement. It appears that the results from quasistatic analysis, in which the time histories of wheel loads are treated as sequences of stationary static loads, is generally on the conservative side as far as the design is concerned.

2.4.6 Uddin, W. et al.[51]

Uddin, et al. (1994) used ABAQUS to investigate the effects of pavement discontinuities and dynamic analysis on the surface deflection response of a pavement-subgrade model under a standard falling-weight deflectometer (FWD). Typical discontinuities are cracks caused by fatigue or load repetitions, by environmental factors, or by the interaction of the two. Special gap elements are used to simulate pavement cracking and other discontinuities. The implicit scheme was used for dynamic analysis.

According to the analysis results, the maximum dynamic deflection for a severely distressed pavement with multiple transverse cracks is 22 percent higher than that for an uncracked pavement. This study demonstrated the usefulness of three-dimensional finite element simulation of pavement cracking and dynamic loads, simulation that is not possible using traditional layered elastic analysis and other finite element programs that do not allow crack simulation and dynamic analysis.

2.4.7 Uddin, W. et al. [52]

Uddin et al. (1995) also used the ABAQUS software to investigate the effects of pavement cracking and dynamic loading on the structural response of jointed plain concrete pavement. A 3D pavement-subgrade finite element model with appropriate boundary conditions was developed. Dynamic analysis was performed using the ABAQUS implicit approach. Since the interaction between the dowel bar and the concrete involves body-to-body contact, the transverse joints with dowel bars were modeled using gap and beam elements. The gap elements were used to specify the interaction between the dowel and the surrounding concrete medium. The gap elements are also used to model the contact between two faces of crack. A crack modeled by having two independent nodes on two free faces of the crack linked by special-purposed unidirectional gap elements to allow two surfaces to be in contact, or not in contact. The analysis results agreed with the falling-weight deflectometer (FWD) data measured in field. The authors conclude the 3D dynamic finite element analysis exhibited significant improvement of traditional multilayered linear elastic analyses that do not allow crack modeling and dynamic analysis.

2.4.8 Zaman, M. and Alvappillai, A. [55]

Zaman and Alvappillai (1995) developed a finite-element algorithm to analyze the dynamic response of multiple, jointed concrete slabs to moving aircraft loads. In the finite-element idealization, the pavement-subgrade system is idealized by thin-plate finite elements resting on a Winkler-type viscoelastic foundation represented by a series of distributed springs and dashpots. The dowel bars at the transverse joints are represented by plane frame elements. The dowel-pavement interaction effects are accounted for by employing contact elements between the pavement and the dowel bar. Keyed joint or aggregate interlock joint is assumed for the longitudinal joint and is represented by vertical spring elements. The dynamic aircraft-pavement interaction effects are considered in the analysis by modeling the aircraft by masses supported by spring-

dashpot systems representing the landing gear of the aircraft. The accuracy of the computer code developed was verified by the available experimental and analytical solutions. A parametric study was conducted to investigate the effects of various parameters on the dynamic response of pavements.

2.4.9 Masad, E. et al. [35]

Masad, et al. (1996) presented a finite element study of the effect of temperature variation on plain-jointed concrete pavements. Temperature variation causes curling and thermal-expansion stresses. Curling stresses result from temperature gradients through a slab depth. Thermal-expansion stresses are induced due to uniform changes in temperature that cause the slab to expand. The effects of different parameters were measured on constant and curling stresses separately. The 3D finite element model consists of four slabs separated by longitudinal and transverse joints. Interface elements are used to model the interaction between the ground and slab and the interaction at joints.

The results have shown reasonable agreement with the result from KENSLABS, ILLI-SLAB and JSLAB. Tensile curling stresses obtained by positive temperature gradients were about 85-90% of those values caused by negative temperature gradients of the same value. Curling stresses tended to increase with an increase in slab thickness. The maximum thermal-expansion stresses generally increased with an increase in the friction factor, an increase in uniform change in temperature and an increase in slab length. The arithmetic addition of positive curling stresses and thermal-expansion stresses were less than those obtained by superposition. Nonlinear temperature distributions caused higher tensile stresses than the linear temperature distributions.

2.4.10 Davids, W. G. [18]

Davids (2000) examines the effect of dowel looseness on the structural response of jointed concrete pavements. A technique for modeling dowels in 3D finite-element

analyses of rigid pavement systems is presented that relies on an embedded formulation of a quadratic beam element. The embedded bending element is extended to include a general bond-slip law, and the practical case of a Winkler foundation sandwiched between the dowel and slab is implemented. The results of parametric studies examining the significance of dowel looseness on the response of rigid jointed pavements to both axle and combined axle and thermal loadings are presented. These studies indicate that significant increases in both slab and soil stresses can be expected due to small gaps (less than 0.24 mm) between the dowels and the slabs.

The importance of explicitly modeling nonlinear load transfer arising from dowel looseness was also examined. The traditional modulus of dowel support approach to model dowel-slab interaction was compared with the explicit modeling of dowel looseness. Dowel looseness and the modulus of dowel support correlated to the equivalent load transfer efficiency (LTE) were shown to produce significantly different maximum tensile edge stresses in the same pavement system. It was shown that an equivalent, back-calculated dowel support modulus should be used with caution when dowel looseness exists.

2.4.11 William, G. and Shoukry, S. [54]

William and Shoukry (2000) developed a detail 3D Finite Element model to investigate the applicability of Westergaard's thermal stresses formulation to dowel joined concrete pavements. The transverse stress calculated using Westergaard's formula was found to be within less than ten percent of that computed using 3D Finite Element model. The analysis results also confirm Westergaard's finding that the slab curling stresses are independent of slab length. However, it should be noted that the range of slab length is not provided in this report. In comparison with the curling stresses, the stresses due to uniform temperature changes play the major role initiating transverse cracking in relatively long slab.

The author indicated the finite element modeling of concrete pavements should include detailed 3D modeling of dowel bars and its interfaces in addition to the capability of handling thermal effects. This implies that the finite element mesh should be fine, a requirement that increases the processing time, but ensures the accuracy of the results.

2.4.12 Davids, W. [19]

Davids (2000) examined load transfer at doweled joints in plain concrete pavement for both curled and flat slabs. The study employed 3D finite element models developed with EverFE. Recent extensions to EverFE's dowel modeling was outlined, with emphasis on modeling dowel/slab interaction. Parametric studies were completed that considered various degrees of dowel/slab interaction, realistic levels of slab curling, and two foundation models expected to bound realistic levels of response. Results indicated that foundation type and the presence of slab curling have a large effect on predicted shears and dowel/slab concrete bearing stresses.

2.4.13 Helwany, S. and Dyer, N. [22]

Helwany and Dyer (2000) evaluated the response parameters of a rigid pavement using the finite element method. The NIKE3D program, which is a static/dynamic (implicit) 3D commercial finite element program, was used in this research. It has a wide-ranging material library and sophisticated contact interface capabilities. The responses of pavements subjected to axle loads with different tire pressures, axle loads with different configurations, and axle loads traveling at different speeds were calculated. Simple material constitutive models such as linear elastic and nonlinear elastoplastic with hysteretic energy dissipation were employed in the analyses to describe the behavior of the pavement material. The method was able to qualitatively simulate the behavior of pavements subjected to axle loads with different tire pressure axle loads, with different configuration and axle loads traveling at different speeds.

2.5 Recent Finite Element Software Developments for Concrete Pavement Analysis

2.5.1 Davids, W. G., et al.[16]

Davids, et al. (1998) developed a new rigid pavement three-dimensional finite element analysis, EverFE, in the University of Washington. The use of 3D FE analysis has been hampered by (a) the difficulty of model generation and result interpretation, (b) the inability of many programs to adequately model joint shear transfer due to aggregate interlock and dowel action, and (c) large computational requirements of conventional solution techniques employed by available programs.

EverFE, which incorporates an intuitive windows-based interface, greatly simplifies model generation and result interpretation. The rational joint and contact modeling techniques employed by EverFE have also been examined. The aggregate interlock may be modeled using linear spring element or using two-phase model that rationally accounts for nonlinear joint response and the variation in shear transfer with joint opening. Dowel modeling is accomplished using a newly developed embedded bending element that permits independent meshing of the dowels and modeling of dowel looseness. The high-performance solution strategies employed by EverFE also allow realistic 3D models to be simulated on a desktop computer.

Davids and Mahoney (1999) verified the joint load transfer modeling capabilities of EverFE, a recently developed rigid pavement three-dimensional finite element analysis tool, through comparisons with available experimental data. Dowel joint load transfer is examined via comparison of displacements predicted by EverFE with results from laboratory tests of two small-scale doweled pavement systems, and dowel looseness is shown to be a probable cause for experimentally observed differential joint displacements. Results of finite element analyses using EverFE's nonlinear, two-phase aggregate interlock constitutive model are shown to agree well with available experimental data. A parametric study is performed that examines the effect of joint

opening on aggregate interlock load transfer and illustrates the importance of considering non-linearities in joint load transfer when predicting pavement response. The EverFE program currently permits only a linear temperature gradient. The effects of temperature and moisture induced slab curling should be considered in future studies.

2.5.2 Khazanovich, L., et al. [32]

Khazanovich, et al. (2000) presented the finite element program ISLAB2000, an extension of the plate-theory-based ILLI-SLAB. It retains all the positive features of ILLI-SLAB that made it the premier 2D program for rigid pavement analysis. It provides a variety of subgrade models, such as Winkler model, Pasternak model, and Kerr model. It has the ability to analyze separation between the pavement layers, and the effects of nonlinear temperature distribution throughout constructed layers.

In this paper, ISLAB2000 was demonstrated by examining the cracking problem on Interstate highway 80. The authors concluded that ISLAB2000 is an efficient and attractive alternative to more complex 3D models in many situations. However, ISLAB2000 is not a substitute for the 3D finite element analysis. For many important problems, such as analysis of stress distribution near dowel and analysis of friction between layers, only 3D models should be used.

CHAPTER 3. THE ANALYTICAL SOLUTION MODELS RELATED TO MID PANEL CRACKING IN JPCP

3.1 Introduction

In chapter 2, the reviews of the research into the numerical finite element modeling of the jointed plain concrete pavement system were presented. In this chapter, research into the mechanics-based analytical solutions related to the transverse cracking in JPCP are reviewed. These solutions range from simple closed form formulas to complex derivations for determining the stresses and deflections in rigid pavements. Unlike the finite element modeling, these solution models provide a clear and simple mechanism of the JPCP system. The parameters of these formulas indicate the major factors of the stresses occurrence in the JPCP. In addition, these formulas also serve as verifications of, or comparisons to, the detailed numerical analysis results.

Pavements are very complex structures, with performance depending on the interaction of such factors as climate, traffic conditions, support conditions, physical dimensions, and material properties. To predict long-term pavement performance, the Mechanistic-Empirical procedure is the solution most commonly used. M-E analysis and design methods evolved in the 1970s on the basis of engineering mechanics, material behavior, and the corresponding empirical performance of the pavement structure for all important combination of loading and environment conditions. Over the years, pavement engineers have attempted to develop rational mechanistic-empirical (M-E) methods for predicting pavement performance. In fact, the next version of AASHTO's *Guide for Design of Pavement* is planned to be mechanic-empirically based. Many M-E procedures have been developed on the basis of a combination of laboratory test data, theory, and limited field verification.

3.2 Mechanistic-Empirical Models

3.2.1 Darter, M. I., et al.[14] :

Darter, et al. (1991) developed field-calibrated mechanistic-empirical models for key performance indicators of jointed concrete pavements. Performance data from nearly 500 in-service pavements were used to calibrate mechanistic and empirical variables to develop improved prediction models for joint faulting, slab cracking, joint spalling, and present serviceability rating.

Transverse cracking in concrete slabs may occur for a number of reasons. Large temperature gradients through the slab, heavy-truck loadings, and shrinkage of the concrete immediately after placement can all produce stresses in the slab that can result in transverse cracking. The mechanism influencing the occurrence of transverse cracks in each pavement type is different. In jointed plain concrete pavements (JPCP), transverse cracks are usually caused by either thermal curling or truck loading (fatigue).

The transverse cracking model is developed on a fatigue-consumption approach. This concept theorizes that a concrete pavement has a finite life and can withstand a maximum allowable number of repetitions, N , of a given traffic loading until a critical portion of slabs is cracked. The model is given as follows:

$$P = \frac{1}{0.01 + 0.03 \times [20^{-\log(n/N)}]}$$

where P is the percent of slabs cracked and n is the actual number of 18-kips ESAL (equivalent single axle loading) application in the slab edge.

There are other factors currently not incorporated (e.g. thermal coefficient of expansion and friction from the base) that also are believed to contribute to cracking.

3.2.2 Bendana, L. J., et al.[5]

Bendana et al. (1994) developed a mechanic-empirical (M-E) design procedure for verifying the designs of rigid pavement thickness presented in the New York state design manual. A nondimensional fatigue model was established on the basis of New York's past pavement performance, environmental conditions, and traffic loading. The study then developed design curves for various pavement thicknesses. Finally, the M-E design curves are compared with the AASHTO equation.

The M-E developed in this study and AASHTO models predicted different performances for identical input values. In the present study, the M-E model predicts more ESALs (cumulative 18-kip equivalent single axle load) than AASHTO for pavement thicknesses under 275mm and fewer ESALs for thicker pavements.

3.2.3 Jiang, Y. J. and Tayabji, S. D. [31]

Jiang and Tayabji (1998) studied how well some of the existing M-E based distress prediction procedures performed when used in conjunction with the Long-Term Pavement Performance (LTPP) data. The transverse cracking data in the LTPP was obtain as follows:

$$\% \text{ slab cracked} = \text{total number of crack} * \frac{\text{average joint spacing}}{\text{section length}} * 100$$

This study shows that, the LTPP data can be used successfully to develop better insight into pavement behavior. However, the damage estimation was seriously handicapped by two primary factors: lack of adequate traffic data, and the many approximations that had to be made to establish concrete material parameters.

3.3 Other Closed-Form Solution Models

3.3.1 Ioannides, A. M. and Salsilli-Murua, R. A. [26]

Ioannides and Salsilli-Murua (1990) presented a closed-form solution to the problem of a slab-on-grade under combined temperature and wheel loading, derived on the basis of finite element results. This solution is in the form of a multiplication factor (function of the temperature difference) to be applied to the Westergaard equation to determine the maximum combined tensile stress in the slab under edge loading. In addition, a sound engineering approach to numerical, experimental, and field data interpretation was proposed, founded on the principles of dimensional analysis.

3.3.2 Mohamed, A. R. and Hansen, W. [37]

Mohamed and Hansen (1997) present a new closed form solution technique for calculating the stresses in a pavement slab due to nonlinear gradients. The temperature and moisture gradients can lead to significant tensile stresses at the slab top and bottom. The current technique for assessing the internal stresses due to such gradients is based on the assumption that temperature and moisture distributions through the slab thickness are linear. However, the actual distributions have been found to be highly nonlinear.

The analysis is separated into two parts. The first step consists of determining the self-equilibrated stress in a concrete slab satisfying equilibrium conditions and continuity of the strain within the cross section. In the second step, the stresses due to external restraint are calculated using an equivalent linear temperature gradient obtained from the first step and existing closed form solutions by Westergaard or Bradbury. The total internal stresses are obtained using a superposition principle. The methodology has been applied to field data from two studies and compared with predictions from Bradbury's standard

linear gradient solution. The results indicate that linear gradient analysis cannot accurately capture the curling stresses in a concrete pavement, especially during the evening and early morning hours.

3.3.3 Ramsamooj, D. V. et al. [43]

Ramsamooj, et al. (1998) employed the weight function method to determine the stress intensity factors for cracks and joints in highway and airport pavements. The relationship between the stress intensity factor and the deflection caused by a wheel load were then used to obtain the stresses in the pavement. The new method that combines the theory of elasticity and fracture mechanics is called EFM. The results from EFM for the deflection and bending stress at the midslab along the longitudinal edge were compared with the theoretical solution of Westergaard, solutions using the finite element method, and with the experimental data from AASHTO road test. There was good agreement in all cases.

The weight function method was simple and yields realistic results for the stress intensity factors. The analytical procedure EFM that combines the multi-layered elastic theory with theory of elasticity to obtain the stresses in rigid highway and airport pavements was much simpler than the finite element method and requires no arbitrary adjustment in the value of the coefficient of subgrade reaction for determining the edge stresses.

3.3.4 Bustos, M, et al. [8]

Bustos, et al. (1998) presented a methodology for calibrating performance models for jointed plain concrete pavement (JPCP); it was based on statistical analysis of data from the Long-Term Pavement Performance (LTPP) database. The methodology provided calibration factors to pavements in four climate regions (dry-freeze, dry-nonfreeze, wet freeze, and wet-nonfreeze) for JPCP performance models in joint faulting, transverse cracking, joint spalling, and roughness. No clear influence of climate zones existed in the

calibration factors obtained. So it was suggested that for large road networks, it could be more convenient to use global calibration factors instead of regional factors. The calibration factors were considerably influenced by the characteristics of the data used.

CHAPTER 4. DESIGN, CONSTRUCTION, AND REHABILITATION RECOMMENDATIONS

4.1 Introduction

In the previous chapters, the factors that affect the transverse cracking and the analyses of this problem have been reviewed. The ultimate goal of this research is to provide the optimal design and construction procedure standard for the jointed plain concrete pavement (JPCP) road system. In order to avoid or minimize the occurrence of the transverse cracks in the JPCP, the recommendations regarding the design and construction of JPCP were proposed in some research papers. These are first reviewed in section 4.2. In addition, several researchers also evaluated the current design procedures of some states in the United States. These are reviewed in section 4.3. Finally, some researchers provide recommendations for the rehabilitation of transverse cracking -- these are reviewed in section 4.4.

4.2 JPCP Design and Construction Recommendation

4.2.1 Peshin, D. G., et al. [40]

Peshin, et al. (1990) conducted a study as part of a major project to evaluate the performance and rehabilitation of rigid pavement in the United States. An experimental pavement project in Clare, Michigan, was the subject of a field survey and evaluation. Different pavement designs were evaluated, including jointed plain concrete pavement with aggregate, permeable asphalt-treated and dense-graded asphalt treated bases (ATB), and jointed reinforced concrete pavement with aggregate bases. Other variables included in this experiment were skewed joints and perpendicular joints, doweled and non-doweled sections, and sections with and without edge drains.

Regarding transverse cracking, the worst performing sections were those having a dense-graded ATB course, which trapped free water for long periods of time, and led to serious erosion of underside of slab. Good performance was exhibited by pavement sections having 9-in. JPCP doweled slab on aggregate base and the 9-in. nondoweled slab on permeable base course.

4.2.2 Zollinger, D. G., et al.[56]

An approach for estimating appropriate sawcut depths and placement timing for jointed concrete systems is suggested by Zollinger, et al. (1994). Preliminary field observations show that:

1. Early-age sawcutting with appropriately determined joint spacing and depth can be used for the positive control of cracking in jointed plain concrete pavements.
2. A shallow notch (1 in.) placed early in the pavement surface can help preventing the initiation of late-appearing cracks.
3. The reduction of the sawcut depth (less than $d/3$ or $d/4$, d is the slab thickness) at concrete joints by early-age sawcut can take advantage for the greater change in moisture and temperature in the vicinity of the concrete pavement surface (in comparison with the changes at $d/3$ or $d/4$), to initiate a greater amount of crack damage and subsequent incidence of cracking at the shallow surface notches than would otherwise be the case.

4.2.3 Aberdeen's Concrete Construction [2]

This study (1996) reveals that if recycled concrete aggregates (RCA) are substituted for virgin gravel in standard structural-concrete mix designs, the same performance results cannot be guaranteed. Because RCA concrete contains both new mortar and old mortar

from the recycled material, it has a higher coefficient of shrinkage. As a result, concrete pavement using recycled aggregates can develop wider transverse cracks.

4.2.4 Cuttell, G. D., et al. [13]

State highway agencies in Connecticut, Kansas, Minnesota, Wisconsin, and Wyoming have successfully designed and constructed rigid pavements containing recycled concrete aggregate (RCA). The field evaluation (1996) indicated that, because of the minimization of old mortar content in the RCA during recycling processes, comparable pavement performance between recycled and conventional PCC was especially common when there were similar amounts of natural aggregate in the PCC mixtures. It is hypothesized that total mortar content (recycled plus new) contributes to an increased amount of cracking. However, there was no clear correlation between mortar content and cracking distresses in field investigations since the recycled-to-control comparisons generally revealed a narrow range of differences between their mortar contents.

The authors recommended that RCA should be regarded as an engineered material and more research is needed to better assess the performance of pavements made using recycled PCC aggregate.

4.2.5 Shah, S.P., et al. [46]

In recent years, short, randomly distributed fibers have been used to reduce shrinkage cracking. This reinforcement does not influence the free shrinkage of concrete but it can keep cracks from widening. An alternate solution to prevent shrinkage cracking is to use a shrinkage-reducing admixture (SRA) in concrete. Shah, et al. (1997) reviewed the efficiency of SRA in controlling shrinkage cracking of concrete. The results of SRA concretes were compared with that of plain concrete with the same water-to-cement ratio.

The addition of SRA considerably reduces free shrinkage. The reductions in shrinkage ranged from 25 percent to 50 percent at 50 days, depending on the amount of SRA used. Moreover, concrete of SRA also takes advantage of the delay of cracking in restrained shrinkage tests. The first crack in plain concrete was observed between 10 and 14 days. Concrete with an SRA of 2 percent (by weight of cement) showed significantly improved cracking performance for up to 48 days.

4.2.6 Frabizzio, M. A., et al. [20]

Based on the research of Frabizzio et al. (1999), several findings were made regarding the effects of JCP design parameters on transverse cracking:

1. Longer joint spacing leads to a greater number of transverse cracks per slab. This is due to the larger curling stresses associated with longer slabs.
2. Pavements containing slag or recycled concrete coarse aggregate appear to have more transverse cracks than those using natural gravel or carbonate aggregate.
3. Natural gravel pavements having tied concrete shoulders demonstrated significantly fewer transverse cracks than those having asphalt shoulders.
4. Recycled pavements having concrete shoulders with sympathy joints were found to have a significantly greater number of cracks than those having concrete shoulders without such joints.

4.3 Rigid Pavement Design Procedure Evaluation

4.3.1 Darter, M. I., et al. [15]

Darter, et al. (1996) evaluated the original 1960 road test model and the extended 1986 AASHTO design model using data from the Long-Term Pavement Performance (LTPP)

database. The design models were evaluated by comparing the predicted cumulative 80-kN (18000-lb) equivalent single-axle loads (ESALs) using the design models to the actual ESALs (estimated from the traffic data) in the database. The conclusions are as follows:

1. The original AASHTO model generally overpredicted the KESALs required to cause a given loss in serviceability.
2. The extensions to the original AASHTO model significantly improved the performance prediction capability of the model.
3. The sensitivity analyses for the change in initial serviceability caused the 1986 AASHTO model to generally overpredict the number of ESALs. The predicted number of axle loads is very sensitive to the loss of serviceability.
4. The addition of the design reliability factor in the 1986 AASHTO model resulted in a conservative design.

4.3.2 Jiang, Y. et al. [30]

Jiang, et al. (1996) summarized and analyzed the current concrete pavement design practices and the key design features in the United States. The general design inputs were compared. The concrete slab thickness typically designed by the state highway agencies under different site conditions were compared and analyzed. The analysis indicated that significantly different slab thickness are used in different climatic regions for given traffic and subgrade conditions. However, at the high (5 to 10 million) traffic level, the design slab thicknesses are not significantly different across climatic regions.

Key rigid pavement design features, such as the base type and thickness, shoulder types, transverse and longitudinal joint design and material characterization were compared and summarized in this paper. No indication of which method is better was provided.

4.3.3 Hoerner, T. E., et al. [23]

Hoerner, et al. (1999) performed a field trial to evaluate a draft performance-related specification (PRS) sponsored by FHWA for jointed plain concrete pavement. The objectives were to verify the draft specification's effectiveness, identify potential problem areas and determine its reasonableness. The pavement performance is defined by four distress indicators. They are transverse cracking (fatigue), transverse joint faulting, transverse joint spalling, and pavement smoothness. As a result four recommendations were given. Fix the subplot length to one constant value, choose a practical subplot length, choose a minimum length between longitudinal sampling locations and consider placing practical limits on calculated pay factors.

4.4 Recommendations for the Rehabilitation or Repair of Cracks

4.4.1 Voigt, G. F. [53]

The AASHTO guide specification, Section 501.03 Q. *Repair of Defective Pavement Slabs*, provide a detailed specification for repairing uncontrolled cracking. The recommendations for mid-slab cracking are summarized as follow:

- Doing nothing to tight, uncontrolled cracks that only partially penetrate the full slab depth. The depth of the crack penetration will be determined by inspection of a core drilled at the Contractor's expense.
- Saw and seal any single, transverse uncontrolled crack that penetrates the full slab depth.
- Where a transverse uncontrolled crack parallels that planned contraction joint and is within a distance of 5 feet form the nearest contraction joint in the pavement, the joint and the crack shall be sealed.

- Remove the entire slab if it has more than one crack and is divided into three or more parts.

The clauses for repairing defective concrete pavement in the standard specification from Indiana and Kansas are also detailed, but deviate some from the repair recommendations in AASHTO guide specification. Table 1 provides this modified specification. A majority of state specifications are considerably less detailed and presumably prone to much debate whenever an uncontrolled cracking problem arises on a project.

Defect Type	Orientation	Location	Description	Recommended Repair
Plastic Shrinkage	Any	Anywhere	Only partially penetrates depth	Do nothing
Uncontrolled Crack	Transverse	Mid-slab	Full-depth	Saw & seal crack
Uncontrolled Crack	Transverse	Relatively parallel & w/in 1.5m of joint	Full-depth	Saw & seal crack; Seal joint
Saw cut or Uncontrolled Crack	Transverse	Anywhere	Spalled	Repair spall by partial-depth repair (PDR)*
Uncontrolled Crack	Multiple per slab	Anywhere	Two cracks dividing slab into 3 or more pieces	Remove & replace slab

- Saw around spall leaving 50 mm (2 in.) between spall and 50 mm (2 in.) deep perimeter saw cut. Chip concrete free, then clean any apply bondbreaker to patch area. Place a separating medium along any abutting joint or crack. Fill area with patching mixture.

Table 1. Recommended Repair of Defects in New Pavement

4.4.2 Bemanian, S. and Sebaaly, P. [4]

Bemanian and Sebaaly (1999) reported the evaluation of feasibility of several rehabilitation strategies for Portland cement concrete pavement. The four rehabilitation strategies/ rubblization, crack and seat, un-bonded concrete overlay, and reconstruction/ have been in service for 4 years. On the basis of this study, the following conclusions were reached regarding the I-80, Elko in Nevada, project:

1. The results of the study indicate the three options are viable.
2. The crack and seat project had the lowest initial cost.
3. After 4 years, the functional and structural performances of the pavements indicate both the cracked and seated and the rubblized sections are performing equally well.
4. Rubblization and crack and seat are effective methods for delaying reflective cracking if designed and constructed properly.
5. Empirical design procedures should be used to determine the initial overlay thickness. However, deflection measurements should be taken after the project is completed to verify the design assumptions.

Pavement performance monitoring is continuing in order to evaluate long-term performance and cost-effectiveness of each strategy.

CHAPTER 5. SURVEY OF DEPARTMENTS OF TRANSPORTATION

5.1 Introduction

Forty-five State Departments of Transportation received surveys (see Appendices) concerning Random Transverse Mid-Panel Cracking of Jointed Plain Concrete Pavements (JPCP). The remaining five states, Massachusetts, Connecticut, Rhode Island, Alabama, and South Dakota were not sent surveys due to their expressed lack of JPCP use. Of the forty-five states receiving the survey, thirty-three states responded.

An overwhelming majority of the states reporting problems with Mid-Panel Cracking of Jointed Plain Concrete Pavements are geographically east of the Mississippi River with three exceptions. The exceptions are California, Nevada, and the state of New Mexico. Since their percentage of current construction of JPCP is less than five percent, Nevada and New Mexico will be ignored in the data analysis.

Notably, cracking problems occur in states near the Great Lakes and extend on south as far as Florida, Mississippi, and Georgia. Kentucky and Tennessee are the only two states within this belt reporting no cracking problems in JPCP.

Case Studies were received from Florida, Georgia, Nebraska, New Mexico, North Carolina, Ohio, and Virginia. Florida, Illinois, Indiana, Michigan, North Carolina, and Wisconsin indicated in-house sponsored research projects relating to cracking of jointed plain concrete pavements.

5.2 General Survey Data

This section is an analysis of data taken from the survey responses. These survey questions appeared on both the shorter survey (Appendix 2), for the states showing no significant signs of random transverse mid-panel cracking, and the detailed survey (Appendix 3), for states with serious cracking problems.

The **percentage of current jointed plain concrete pavement construction** varied from zero to one hundred percent. Eighteen states use less than 10% of JPCP. Four states use between 11% and 40%. Two states use between 41% and 70%. Six states use between 71% and 100% with four responding states unknown. Three states did not respond to the question. The **performance** of much of the pavement across the United States is checked yearly. Several states check the performance every two years or as needed.

It is notable that the six states with the largest amount of jointed plain concrete pavement construction, Minnesota, Missouri, Arkansas, Oklahoma, New York, and Delaware were all states reporting no cracking problems. In contrast, the two states between 41% and 70% and three of the four states between 11% and 40% reported significant cracking problems. Nebraska was the one state within that range not reporting cracking.

Overall the panel dimensions used across the United States varies. The **typical transverse panel width** for JPCP ranged from twelve to fifteen feet with the majority of the states indicating a standard twelve-foot transverse width. Longitudinally, the majority of the states use a **panel length** of fifteen feet for jointed plain concrete pavements. Responses for longitudinal length varied between fifteen feet and twenty feet.

The **typical pavement thickness** ranged from eight to fourteen inches on average. Three states indicated a thirteen to fourteen inch typical pavement thickness. Four states indicated an eight to nine inch typical pavement thickness. Subsequently, the majority of the responding states indicated a ten to twelve inch typical pavement thickness.

For each state the **ratio of the panel length to thickness** (ft/in) was computed. The significantly larger ratios of Florida (2.2), Virginia (2.2), and especially North Carolina (3.3) may be a factor in their cracking problems. Georgia, New Mexico, and Ohio, three states also with cracking problems, have slightly larger length to thickness ratios compared to the other states. Of the ten states with cracking problems that responded to the question, six of those had ratios greater than or equal to 1.8. The remaining four states with cracking problems, Illinois, Indiana, Wisconsin, and California had ratios less than 1.5.

Comparing the remaining states within the belt of cracking to the exceptions, Tennessee and Kentucky, length to thickness ratios are nearly identical. Tennessee uses a ratio limit of 1.75 for open drainable bases and 2.0 for pavements on dense graded crushed stone. Unfortunately there appears to be no relationship between the panel dimensions and the states with cracking problems.

Typically the joints used for JPCP are **sawed joints**. The **joint depths** are typically T/3 or T/4 (T=thickness) with the exception of Georgia, Maryland, Nevada, and New Mexico, which typically use 1-1.25" joint. **Typical joint openings** included 1/8", 1/4", and 3/8". Numerous states did not respond to the question regarding joint opening. The **sealant** used for the joints included self-leveling silicone, compression seals, preformed seals, and hot poured joints, with the majority being silicone seals. No correlation can be established between the states with cracking problems and the typical joint type, depth, opening width, and sealant type.

In most cases epoxy coated **dowels** of diameter 1-1/4" to 1-1/2" by 18" long are used. The **dowel spacing** is generally 12" however Alaska uses an 18" spacing. Missouri starts with a 6" spacing at the ends and moves to a 12" spacing. **Dowel installation techniques** include baskets and mechanical inserters.

The **type of base commonly used** for jointed plain concrete pavements is almost 50% untreated base and 50% treated base for all responding states. Several states use both base types. Of the states reporting cracking problems, 46% use a treated base and 31% use and untreated base. The remaining percentage reported the use of both base types or did not respond.

Within the cracking region, Kentucky, Indiana, Ohio, Michigan, and Wisconsin use an untreated base. Notably, Kentucky was the only state without cracking problems using an untreated base, although the state uses less than 10% JPCP. Illinois, Tennessee, Mississippi, North Carolina, and Virginia are among the states within the cracking region using a treated base. Illinois is the only state using more than 10% JPCP. The specific treated base and specific untreated base types vary. No pattern resulted from comparing the base type for the jointed plain concrete pavement with the states with cracking problems.

Typically the **curing procedure** was a white-pigmented membrane-curing compound. Other procedures included curing blankets such as wet burlap. Florida suspects the cracking problems might be associated with ambient temperatures and curing methods. The exact curing methods vary greatly therefore no determination can be made from the data collected.

The **time elapsed before saw cutting** varied with the majority being cut as soon as possible. New York believes that timely saw cutting along with good construction practice helps eliminate mid-panel cracking problems. Tennessee and Arkansas also expressed the importance of timely saw cutting. From the responses, the **time of day of the saw cutting** varies depending on the contractor.

The **saw-cut depths** are typically T/4 and T/3 with T being the thickness of the panel. The state of Louisiana has reported that since increasing their saw-cut depth to T/3 about ten years ago, the problem has disappeared. No relationship is found between the states

with cracking problems and the curing procedure, time elapsed before saw-cutting, time of day of saw-cut, and the depth of the saw-cut.

5.3 Detailed Survey Data for States with Cracking Problems

This portion of the analysis consists of data obtained from the detailed portion of the survey. The detailed portion was filled out by states showing random transverse mid-panel cracking of jointed plain concrete pavements.

Cracking occurred under several **environmental conditions** including wet subgrade/freeze regions, wet subgrade/no freeze regions, dry subgrade/no freeze regions, and dry regions. Illinois, Ohio, and Wisconsin reporting cracking under a Wet/Freeze condition. Under a Wet/No freeze condition, cracking occurred in California and Mississippi. The environmental conditions reported by Florida and New Mexico were Dry/No Freeze and Dry. Six states (Georgia, Indiana, Michigan, Nevada, North Carolina, Virginia) replied that there was no discernable environmental pattern under which cracking occurred.

The **traffic condition cracking most often occurred** under was heavy loads. In some cases cracking was reported to occur prior to opening to traffic. Other states have shown a combination of cracking immediately after opening, several months after opening, and several years after opening to traffic.

The **orientation of the cracking** in JPCP ranged from transverse and longitudinal cracks in both the driving and passing lanes. Five states indicated cracking in the driving lane only while five different states reported cracking in both lanes. Illinois, a state with 44% JPCP, was the only state to report cracking problems in the passing lane only. Ohio and New Mexico did not respond to the question. Transverse cracking was most prevalent with nine out of the thirteen states that reported cracking. Mississippi and Nevada

reported having both transverse and longitudinal cracking. Illinois and Ohio did not report the direction orientation of their cracking problems.

5.4 Prevention and Rehabilitation Method Comments – States without Cracking Problems

This section contains direct quotes from surveys of states without random transverse mid-panel cracking problems. The quotes are from a comment section concerning prevention and rehabilitation methods for cracking.

Alaska

Crack sealants to repair. Design thickness is for infinite life.

Arizona

Good base construction, relatively thick pavements 10"-14", dowel bars, tie bars, relatively close transverse joint spacing (15'). Tied concrete shoulders at same thickness.

Arkansas

Early sawing of joints.

Delaware

By lowering the joint spacing to 20' we have reduced mid-slab cracking.

Idaho

Mid-panel cracking does not seem to be a problem in Idaho. Use drainable bases to avoid pumping problems. Rehab techniques consist of sealing joints and cracks and grinding.

Kansas

Limit strength of treated subbase to 600-1200psi. Attempt to prevent the bond by using prime of asphalt cement. Keep joint spacing less than twenty-five times the pavement thickness. Keep the length to width dimensions less than 1.25.

Louisiana

Haven't had problems with mid-panel cracking since depth of saw cut was increased to D/3 (or T/3) about ten years ago. If some cracks occur, repairs are made by full depth patch.

Missouri

Driving lane is paved 14' with 2' over on shoulder side to reduce edge stresses. Have been experimenting with lightweight early entry saws.

Nebraska

Stitch any random cracks of new pavement.

New York

Timely saw-cutting and good construction practices help eliminate mid-panel cracks.

Oklahoma

Use of dowels to prevent erosion of support at joints (pumping) has stopped cracking.

Washington

Short joint spacing contributes to minimal mid-panel cracking in Washington. Most mid-panel cracking is related to late sawing or fatigue.

Wisconsin

Opinion- shorten joint spacing to prevent cracking.

Wyoming

Do not permit soft-cut saw-cutting. For rehab either route and seal, dowel bar retrofit and seal, or slab replacement.

5.5 Additional Comments – States with Cracking Problems

This section contains direct quotes from surveys of states with random transverse mid-panel cracking problems. The quotes are from an additional comments section.

Indiana

INDOT could not isolate the problem. There appeared to be a variety of problems that occurred at each location. The factor common at each evaluation location was poor construction practice.

New Mexico

New Mexico has a historical problem with ASR. This is one of the reasons PCCP is utilized as little as it is.

North Carolina

Most of our JCP transverse cracks show up when JCP is over 25 or 30 years old.

5.6 E-mail Comments

Connecticut

From: "Gardon, Charles V." <Charles.Gardon@po.state.ct.us>

Date: Fri, 8 Sep 2000 12:27:52 -0400

In 1998 several CTDOT employees and I attended an **AASHTO/FHWA Industry Joint Training for the Construction of Portland Cement Concrete Pavements**. This 2 1/2

day training course was developed to provide contractor and agency personnel with a general working knowledge of field operations **including sawing and sealing operations to prevent random cracking**. The participant's manual for this course may provide some of the information you are seeking. (NHI Course No. 13133-Publication No. FHWA HI-96-027, Oct.1996)

American Concrete Pavement Association
3800 North Wilke Rd. Suite 490
Arlington Heights, ILL 60004

Department of Transportation
Federal Highway Administration
400 Seventh St.,S.W., Room 4410
Washington, D.C. 20590

Florida

From: Bruce Dietrich <Bruce.Dietrich@dot.state.fl.us>

Date: Thu, 14 Sep 2000 14:27:00 -0400

We have also experienced transverse cracking on some of our JPCP pavements in Florida and don't have a full explanation of why some projects crack and others don't, so your research will be of interest. I would like to caution you that **I suspect the cause may be due to ambient temperatures and curing methods used during construction**, and our historical construction data is very limited or difficult to obtain for older projects.

Bruce Dietrich
State Pavement Design Engineer
(850) 414-4371

Tennessee

From: "Samir Hindieh" <shindieh@mail.state.tn.us>

Date: Thu, 14 Sep 2000 11:39:54 -0500

Subject: Fwd: Mid-panel cracking

I hope that the attached would help you in your research.

Samir Hindieh

TDOT

(615)741-5004

From: JNorris466@aol.com

To: shindieh@mail.state.tn.us

Date: Thu, 14 Sep 2000 12:04:14 EDT

Samir:

There are several factors that could affect mid-panel cracking.

1. The type of **base** the concrete is placed upon crushed stone, bituminous drainable, cement drainable, cement treated base.
2. The **joint spacing**
Depending upon the type of base for open drainable bases, the joint spacing in feet should be no more than 1.75 times the thickness of the pavement in inches ie, a 10 inch pavement should have a maximum joint spacing of 17.5 feet. For pavements on dense graded crushed stone the joint spacing should be no more than 2.0 times the thickness in inches or a 10 inch pavement should have joints every 20 feet.
3. The design of the **joint depth**. Should always be $t/3$. Where t is the thickness in inches. This would apply to transverse and longitudinal joints. In tennessee we still allow $t/4$ and that needs to be changed on our standard drawings.

4. The **timing of the sawing** is very critical. Especially during hot windy days, or when severe changes in temperature occur. Joints should be sawed as soon as equipment can get on the pavement, and the blades do not cause raveling.
5. I think Indiana uses a **non-bound drainable base**, and they have had lots of trouble with mid-panel cracking. We in Tennessee have never utilized that type of base.

Louisiana

From: GaryDoyle@dotd.state.la.us

Date: Fri, 15 Sep 2000 13:07:56 -0500

We too have had a great deal of problems with random transverse mid-panel cracking of unreinforced jointed concrete pavements. **We have done a great deal of investigating and have made changes. We don't seem to have the problem any more.** Truthfully, we will not be able to say exactly what the problem was, and that the problem won't mysteriously resurface one day. We look forward to your findings.

Pennsylvania

From: "Ron Blauch" <etsect@hotmail.com>

Date: Fri, 22 Sep 2000 16:55:17 GMT

Pennsylvania DOT has experienced mid-slab cracking of jointed plain cement concrete pavements. **A Task Force was organized to review this problem.** The Task Force would be the primary contact for your survey. A Task Force member from Pennsylvania DOT's Materials and Testing Lab is as follows:

Mr. Paul M. Ingram, P.E.

Pennsylvania Dept. of Transportation

Bureau of Construction and Materials

P.O. Box 2926
Harrisburg, PA 17105

From: Dan Dawood <dadawood@netscape.net>

Date: 27 Sep 00 12:37:46 PDT

I'm sorry that we took so long to get back to you, however, there is a lot of information pertaining to your request that we can provide from Pennsylvania's perspective. **We have had some serious premature concrete pavement failure of our own on one of our most traveled interstates highways.** Therefore, please contact me at the following to discuss:

Dan Dawood, PE
Chief Pavement Engineer
Bureau of Maintenance and Operations
7th Floor Forum Place Bldg.
555 Walnut Street,
Harrisburg, PA 17101

PH: 717-787-4246

email: dadawood@netscape.net

CHAPTER 6. PRELIMINARY FINITE ELEMENT ANALYSIS

6.1 Modeling of the Portland Cement Concrete (PCC) Pavements

A typical PCC pavement consists of three layers of material: the concrete slab, the treated granular base (subbase) and the natural soil subgrade. PCC pavements are constructed in certain segments to allow expansion of the concrete, and, thus preventing thermal cracking. Dowel bars are placed at the transverse joints of the PCC slabs to avoid joint failure. In Figure 6.1 a typical PCC pavement is shown.

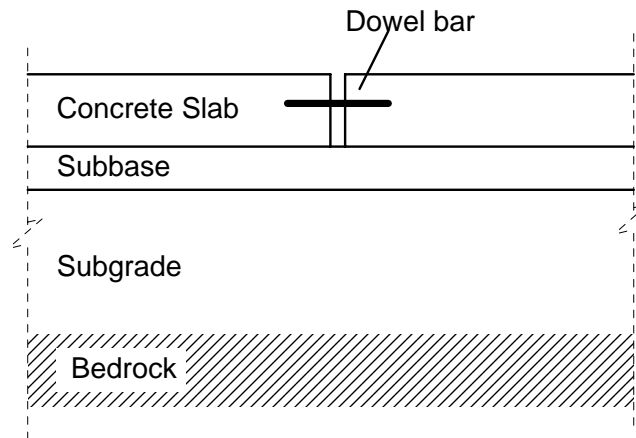


Figure 6.1. A typical PCC pavement

In general, two-dimensional (2D) finite element models are used in the analysis of PCC pavements. Many 2D finite element analysis programs have been developed and used for analysis and design of PCC pavements. However, in order to model the complex behavior of the concrete and three-dimensional (3D) effects, such as curling due to temperature differentials, 3D finite element models have been developed and analyzed by researchers. 3D models allow modeling of vertical separation between concrete and subbase, of nonlinear temperature differentials through the slab and of the friction at the interface layers.

In this preliminary 3D finite element analysis of PCC slabs, fully elastic behavior has been assumed although the materials in a real pavement have inelastic and temperature dependent properties. Modeling of PCC pavement joints (dowel bars) is not addressed in the present study. Furthermore, the dimensions of the model are kept constant throughout the analysis except for the slab thickness. The effect of slab thickness is discussed in Section 6.3. The 3D finite element models of PCC are developed and analyzed using the ANSYS general-purpose finite element software.

6.1.1 Finite Element Mesh

In the development of the finite element mesh to model PCC pavements, a number of issues were addressed. First the selection of appropriate finite elements was addressed. Initially, shell elements were considered for the modeling of the slab and simple spring elements were used to simulate the subbase/subgrade layer. However, a mesh of shell element does not lend itself to the application of nonlinear temperature gradients. In lieu of this, it was decided to use 3D brick elements. The issue related to the modeling of the subbase/subgrade was addressed next. Initially, as mentioned above, the use of simple spring elements was attempted. However, it was verified through a number of simulations that the stress distribution in the subgrade was not constant, i.e., the stress bulb propagated well within the subgrade layer. This led to further studies to determine the final depth of soil needed to accurately account for these varying stresses. The depth of subbase and subgrade adopted are 8” and 80”, respectively. Finally, the appropriate mesh refinement was studied. The coarsest mesh that provides accurate results was selected as the final mesh for the current analyses.

Three-dimensional elastic 8-node and 20-node brick solid elements with three translational degree of freedom per node have been considered in the modeling of concrete and soil layers. The 20-node brick element (Figure 6.2) is chosen in the present study. The reason for this choice is that this element has mid-nodes, which allows the accurate application of nonlinear temperature gradients (i.e., this element type is capable of quadratic interpolation).

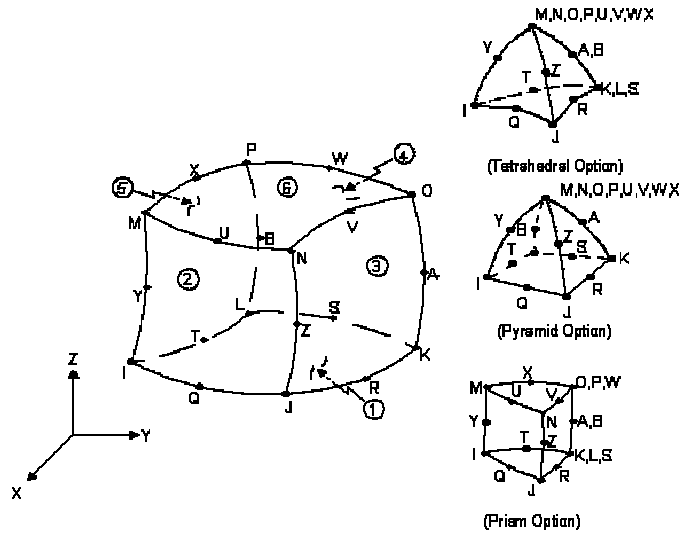


Figure 6.2 The selected 20-node brick element

For the modeling of the interface between the PCC slab and the subbase, so called contact elements are used. Contact elements allow the simulation of the separation between the concrete slab and subbase, to which they are connected. They also allow for the simulation of friction, sliding and bonding at the interface. In ANSYS, the contact can be modeled as either point-to-point (Figure 6.3a) or surface (Figure 6.3b).

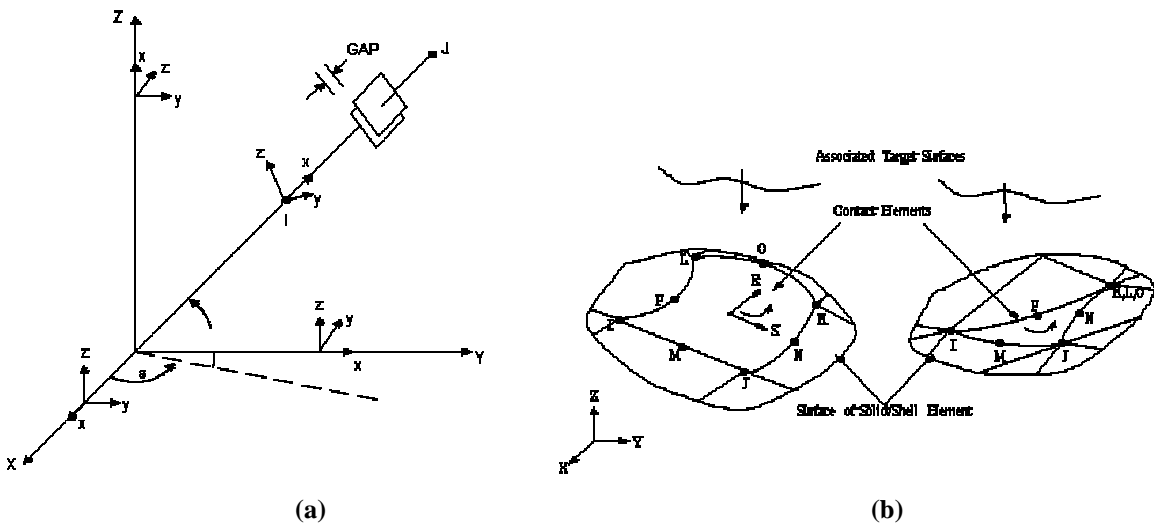


Figure 6.3 (a) 3D Point-to-point type contact (b) 3D Surface-to-surface type contact

ANSYS does not recommend using point-to-point type contact elements between the elements with mid-nodes. Therefore, surface-to-surface type contact elements with 8

nodes with 3 translational degrees of freedom per node are selected. These elements are overlaid at the bottom of the PCC slab.

Contact elements are associated with target elements. These target elements (Figure 6.4) are overlaid on top of the subbase to complete the modeling of the interface.

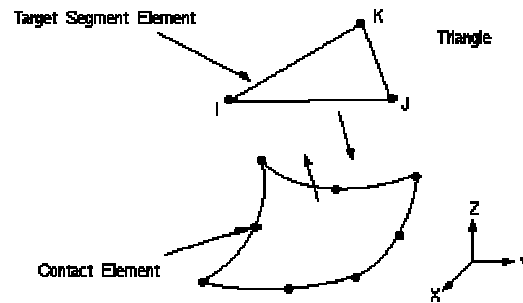


Figure 6.4 3D Target Elements

The contact and target elements are nonlinear elements. It is found in this study that the convergence of the analysis is highly sensitive to the parameters that define the contact behavior. The surface contact may be defined to occur at the nodes or at the gauss points at the elements. In most of the cases studied here, contact at gauss points is found to be the only choice for the convergence of the pavement analysis. Another parameter defines the penetration at the contact interface. This parameter is also found to affect the convergence of the analysis. Appropriate values for the penetration parameter are chosen for the cases studied in order to achieve better convergence.

6.1.2 Friction Model

Many researchers have studied the friction factors that affect the sliding of the concrete slab. Timms (1964) has conducted sliding tests and evaluated the test results. The friction factor is defined as the ration between horizontal force and the weight of the concrete slab and/or vertical load. The friction factors and the horizontal displacements obtained from the tests are shown in Figure 6.5.

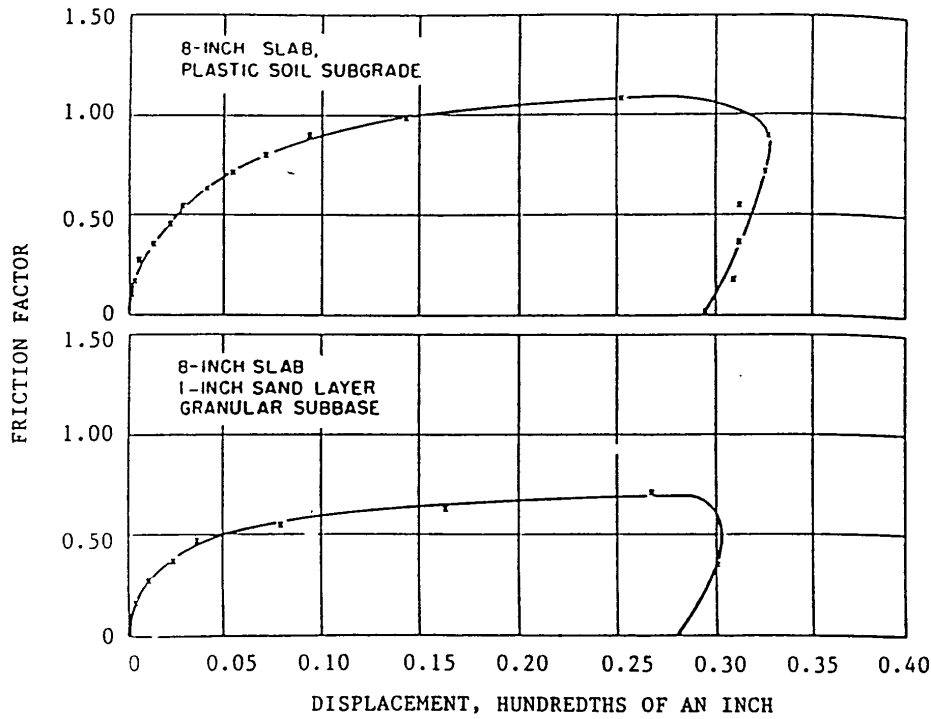


Figure 6.5 Typical friction factors versus displacement curves (Timms, 1964)

The friction factor in Figure 6.5 is the same as the Coulomb's friction coefficient, μ . Clearly, the friction coefficient depends on the thickness of the slab, i.e., the weight of the slab. Its value decreases with slab thickness. The friction coefficient is also dependent on the material and the texture of the subbase as well as the moisture level inside the subbase.

In the present analysis of PCC slabs, a typical value of 0.9 is selected for all of the test models. Two contacting surfaces can carry shear stresses up to a certain magnitude across their interface before they start sliding relative to each other. This phenomenon is known as sticking. The friction model used in the contact elements adopted in the present study is shown in the Figure 6.6.

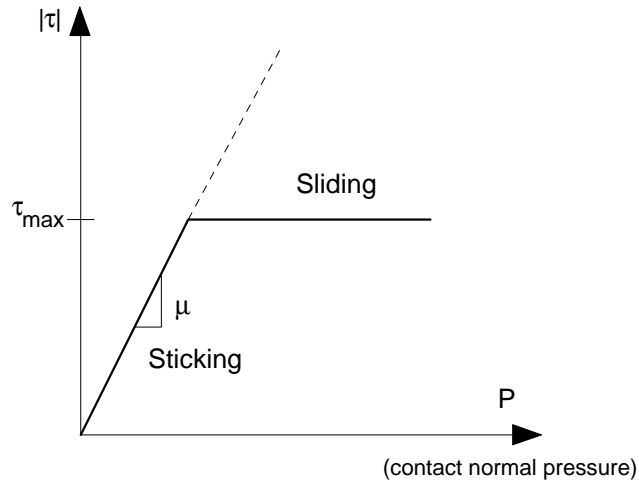


Figure 6.6 The friction model in the contact elements

6.1.3 Mesh Refinement

Performing a simulation with a 3D model with thousands of nodes and many degrees of freedoms would take too much of a computer time and storage. Therefore, the size of the finite element mesh must be determined so that enough accuracy with acceptable analysis durations can be achieved. After trying three different meshes for the pavement structure, the mesh, which satisfies the above considerations best, is chosen for the analyses and it is shown in Figure 6.7.

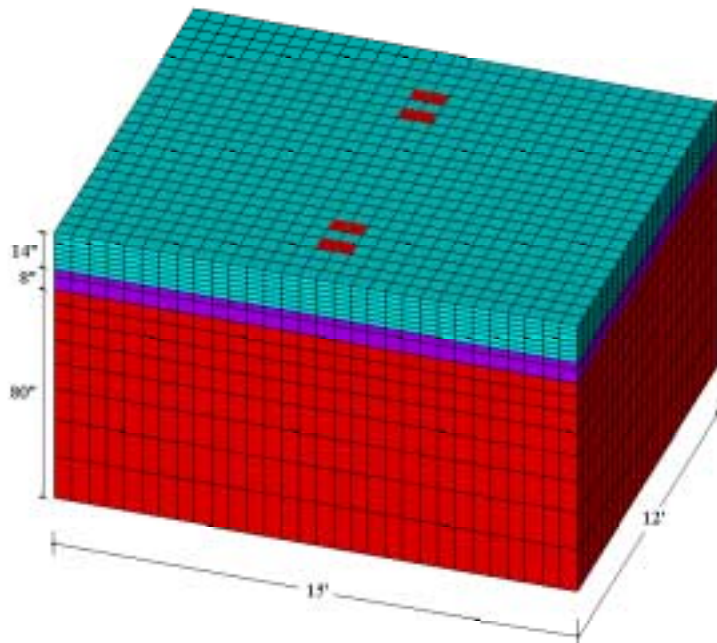


Figure 6.7 The 3D finite element mesh of the pavement model.

6.1.4 Model Data

15'x12' PCC slabs with 12", 14" and 15" thickness values are analyzed. Unless specified, the slab thickness is assumed to be 14". The assumed subbase and subgrade thickness values are 8" and 80", respectively. The material properties used in the models are given in Table 6.1.

Table 6.1 Material properties

Location	Material	E (psi)	ν	γ (lb/in ³)	α (1/°F)
Slab	Concrete	4.0E6	0.15	0.082	5.5E-6
Sub-base	Crushed Stone	35,000	0.35	0.081	7.5E-6
Sub-grade	Soft Clay	2,000	0.40	0.064	9.0E-6
	Medium Clay	10,000			
	Stiff Clay	17,000			

where,

E: Young's Modulus

ν : Poisson's ratio

γ : Unit Weight

α : Coefficient of thermal expansion.

Three different material property sets are used to study the effect of soil stiffness. This is accomplished by changing only the subgrade material properties. In the material set 1, 2 and 3; soft, medium and stiff clay is used respectively.

The wheel-loading configuration used for the analyses is shown in the Figure 6.8. The wheel loads are converted to pressure loads and they are applied at the corresponding element surfaces as pressure loads. A rectangular tire print shape is adopted for simplicity. In Figure 6.8, the dimensions of the tire print are also shown. The wheel load is assumed to be 4800lb, or 66.67psi over the tire print surface. The location of the tire prints on the finite element mesh is shown in the Figure 6.7.

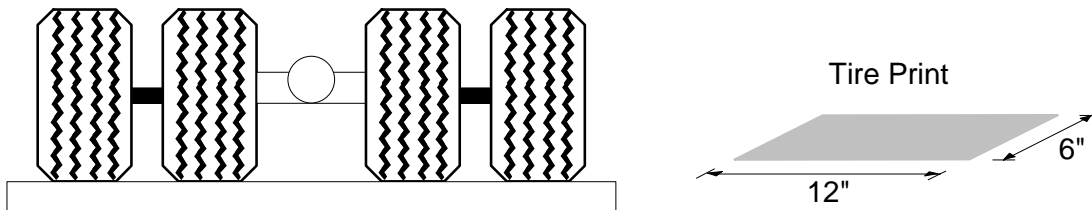


Figure 6.8. Assumed tire loading configuration and the tire print sizes.

6.1.5 Boundary conditions

The PCC slab is allowed to move in any direction. The subbase and subgrade boundaries are constrained against the horizontal movement (u_x and u_z), However, the upper nodes of the subbase elements which are located at the slab boundary are not constrained against u_x and u_z . Therefore the surface of the subbase is allowed to move together with (and relative to) the expanding or contracting PCC slab. The model is fixed at the bottom of the subgrade simulating the existence of bedrock.

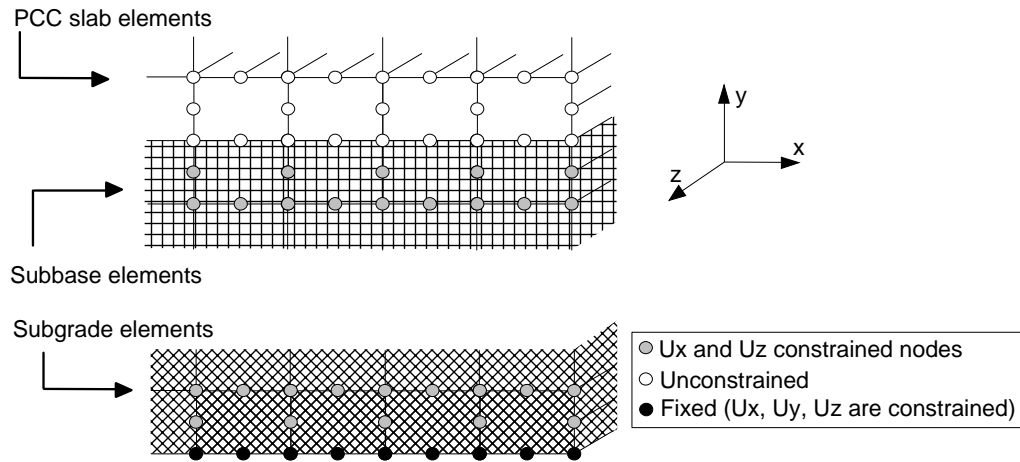


Figure 6.9 Setting the boundary conditions

In Figure 6.9 the boundary conditions and the global coordinate system are illustrated. Since the loading and geometry of the pavement is symmetric, only half of the pavement has been modeled and analyzed. Therefore, in addition to the boundary conditions given above, symmetry boundary conditions are applied along the transverse centerline of the pavement structure. The solid elements used have only translational degree of freedoms, therefore only u_x is constrained (symmetry boundary condition) at every node in the symmetry plane.

6.2 Thermal Differential

Curling due to temperature differentials is an important issue in the PCC pavement design. Many two dimensional finite element programs can do approximate analysis of the stresses caused by the temperature differentials and wheel loads, however the separation that occurs between the concrete slab and the subbase can only be modeled by three dimensional models. The 2D analysis cannot handle the nonlinear temperature distribution, which is present in all PCC pavements. The errors due to the linear approximations to the temperature profile are discussed and two different temperature-loading cases are compared in the following subsections.

In this work, the temperature gradient that causes the slab surface to cool is called the negative (nighttime) temperature gradient. Similarly, the temperature gradient that causes the slab surface to warm is called positive (daytime) temperature gradient. Negative temperature differentials may cause the slab corners to curl upward (a concave deformed shape) creating tensile stresses at the slab surface and compressive stresses at the bottom of the surface (Figure 6.10a). However, there can be tension zones around the slab edges. Positive temperature gradients may cause the slab edges to curl downward (a convex deformed shape) (Figure 6.10b). In this case, the concrete slab is mainly supported by the edges on the supporting layer. Due to the positive temperature gradient the top of the concrete slab is in compression while the bottom is in tension.

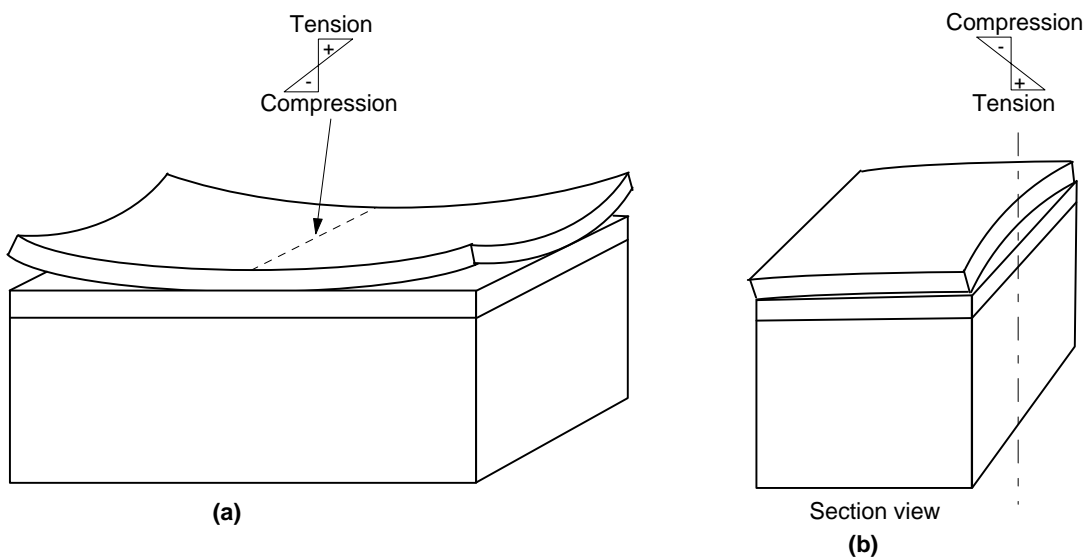


Figure 6.10 The curling of the concrete slab edges:

(a) Negative temperature gradient case (b) Positive temperature gradient case

The temperature change in the supporting layers is very small (Thompson et al. 1987) , therefore the temperature in the supporting layers is assumed to be constant. A temperature differential of ($\pm 42^{\circ}\text{F}$) is adopted in the analyses. For a thorough study of the effect of temperature, various temperature differentials as well as various temperature distribution profiles are analyzed. Mohamed & Hansen (1997) have shown that PCC

pavements are subjected to nonlinear temperature gradients associated with daily and seasonal variations in environmental temperature. In their work, the temperature profiles are approximated using a third degree polynomial that has a general form of

$$T = A + Bz + Cz^2 + Dz^3 \quad (6.1)$$

where the constants A, B, C and D are given in Table 6.2 for temperatures at six times during a 24-hour period.

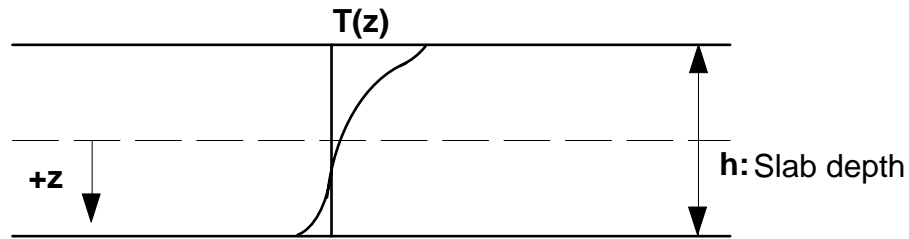


Figure 6.11 Temperature distribution through thickness (Mohamed & Hansen, 1997)

The coefficients given in Table 6.2 were derived using the field measurements data in a 9-inch PCC slab during April in Urbana, Illinois. For the 14-inch slab used in the current analyses, the same curve fitting constants are used and the curves resulting from these coefficients are shown in the Figure 6.13. Although to use of the same coefficients may not be realistic, they are use in this preliminary analysis.

Table 6.2. Curve-Fitting Coefficients for Temperature Data (Ivindra et al. 1998)

Time		2:00am	6:00am	10:00am	3:00pm	7:00pm	11:00pm
Polynomial Coefficient	A	2.6905	1.881	1.12143	1.4762	2.9286	3.3214
	B	-0.4947	0.09127	0.1720	-0.5291	-1.3717	-0.8723
	C	-0.16402	-0.16931	0.07937	0.26852	0.07937	-0.11905
	D	0.03292	0.01294	-0.04115	-0.0514	0.02056	0.03479

In the literature, a bi-linear approximation has been made to this nonlinear distribution (Kim, 2000) as well as many linear approximations. For a 3-D analysis, neither a linear nor a bi-linear approximation needs to be assumed, as long as there are enough number of

nodes through the thickness at which the temperature values can be applied as body forces. Example temperature distribution profiles are shown in Figure 6.12. Figure 6.13 shows the third-order polynomial approximation of temperature changes (Mohamed & Hansen 1997) for the 14-inch PCC slab.

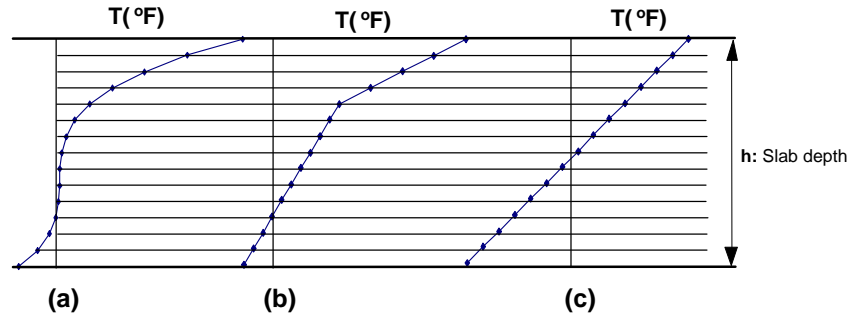


Figure 6.12 Temperature distribution profiles: (a) Nonlinear, (b) Bi-linear, (c) Linear

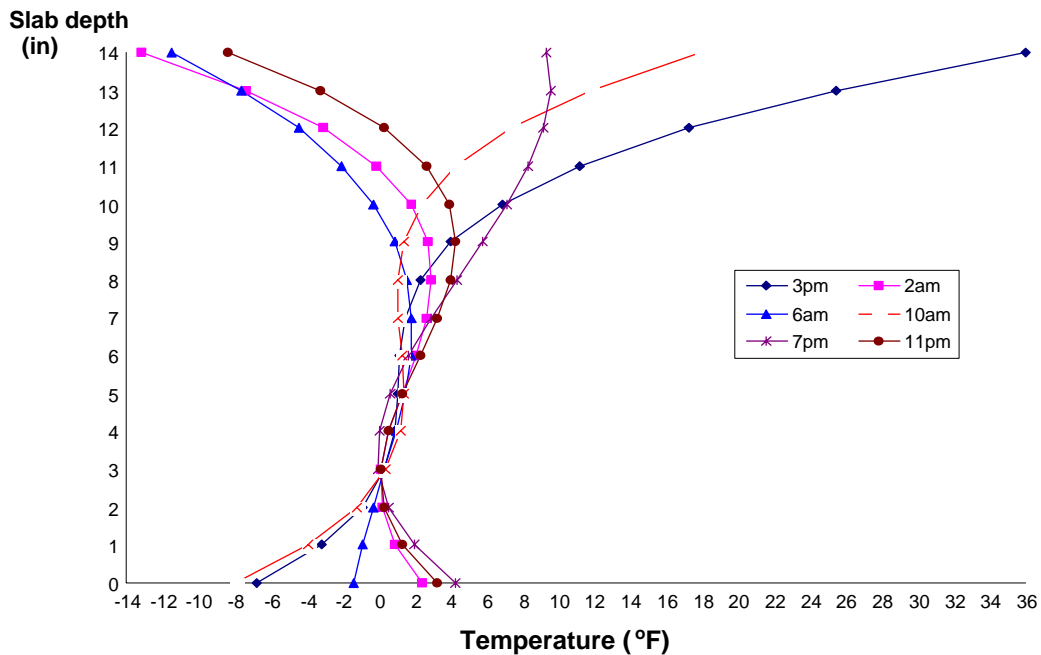


Figure 6.13 Temperature changes for a 14-inch PCC slab obtained from the third-order polynomial approximation

6.2.1. Comparison of Linear and Nonlinear Temperature Distributions

In this section, four different temperature distributions (Figure 6.14) have been analyzed to study the effects of the approximation of nonlinear temperature differentials with linear

distributions. The results obtained from linear and nonlinear temperature differential loadings for negative and positive temperature differentials are compared.

In the analysis the material set 2 (see Table 6.1) has been adopted. The nonlinear positive temperature differential corresponds to the 3pm curve of Figure 6.13. The same curve is also used for negative temperature loading, although this may not be quite appropriate. The linear distributions are obtained by connecting the top and bottom temperature values taken from the actual nonlinear temperature distributions.

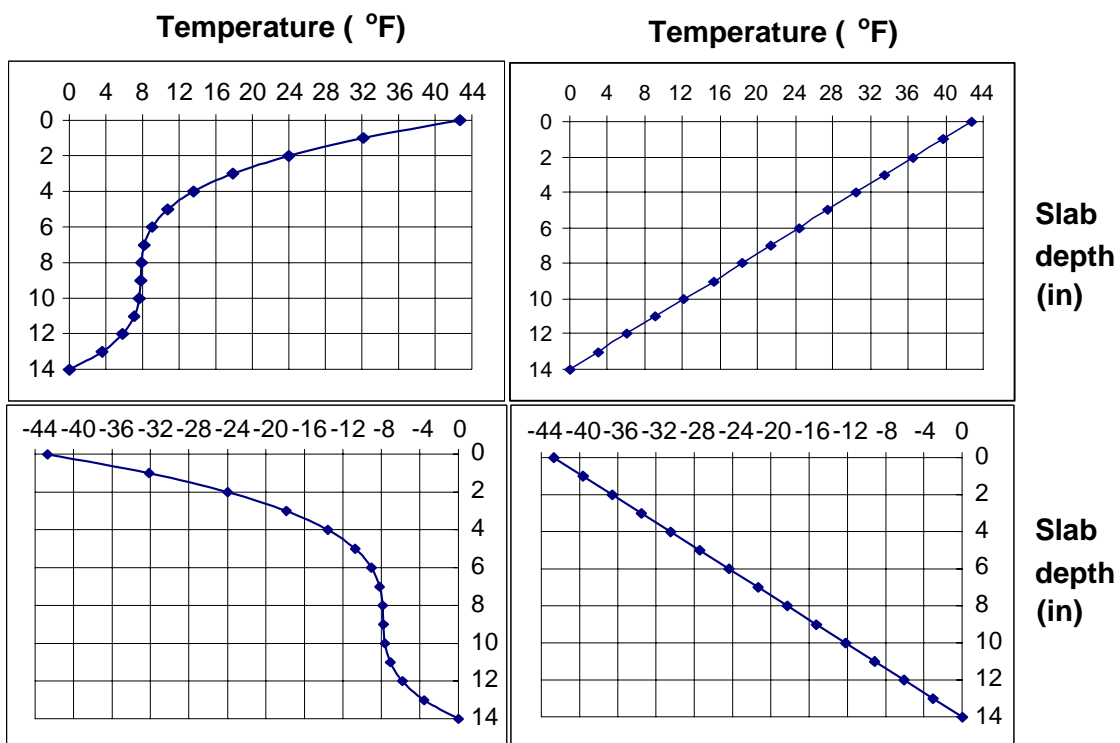


Figure 6.14 Positive and negative temperature differentials used in the analyses

6.2.1.1. Negative Temperature Loading

Negative temperature loading causes curling at the edges of the PCC pavement. In this case, the maximum opening between the PCC slab and the subbase occurs at the corners. The maximum opening due to linear temperature differential is found to be around 70%

larger than that of the nonlinear temperature differential. Table 6.3 provides the comparisons between these two cases. In this table, σ_x refers to the normal stress in the x-direction and Δu_y refers to the difference between the vertical displacements of the concrete slab and the subbase (i.e., the opening).

Table 6.3 Comparison of extreme stress and deformations

Temperature profile	Max. σ_x (Tension) (psi)	Min. σ_x (Compression) (psi)	Max. Δu_y
Linear	107	-112	0.077"
Nonlinear	491	-141	0.046"

The maximum normal tensile stress occurs at the center of the slab. In Figure 6.15, the stress profiles at the slab center are given for both linear and nonlinear temperature gradients. The shape of the stress profile is similar to the applied temperature loading. As it is seen from the figure, the maximum tension stress occurs at the upper layer of the concrete slab for the nonlinear case. The maximum normal tensile stress for nonlinear case is more than four times larger than the tensile stress for the linear case.

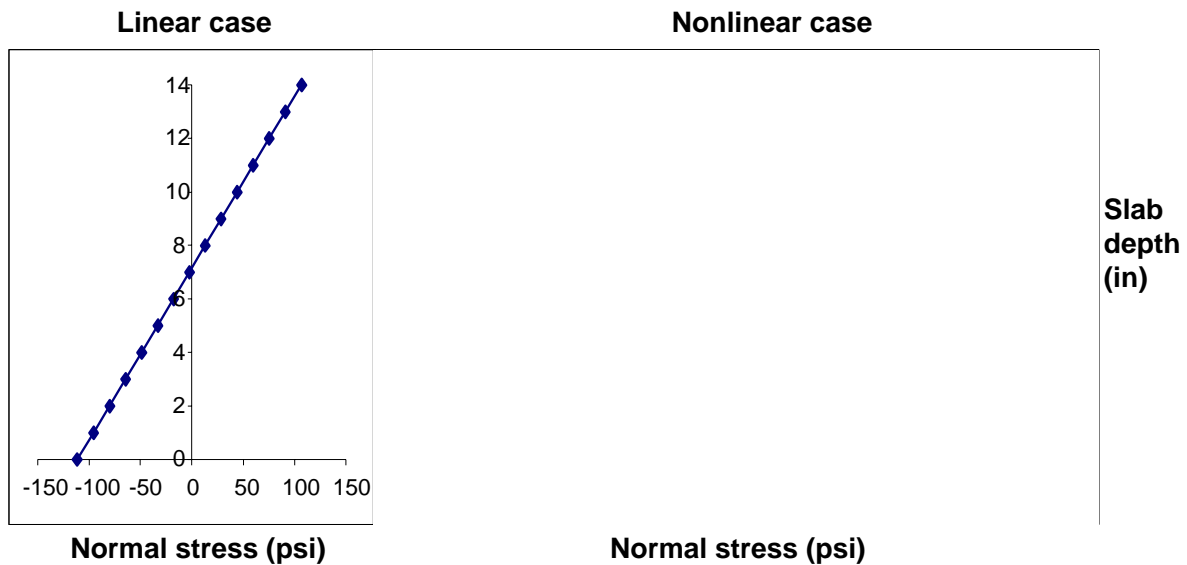


Figure 6.15. The stress profiles at the maximum tension sections

In Figures 6.16 and 6.17, normal stress distributions are shown along the longitudinal and transverse centerlines of the slab respectively. These figures show that the linear distribution is not able to capture the actual behavior of the concrete slab. There are significantly large differences in the tensile stress distributions as well as in the compressive stress distributions. Therefore linear approximation is found to be inappropriate for PCC pavement analysis.

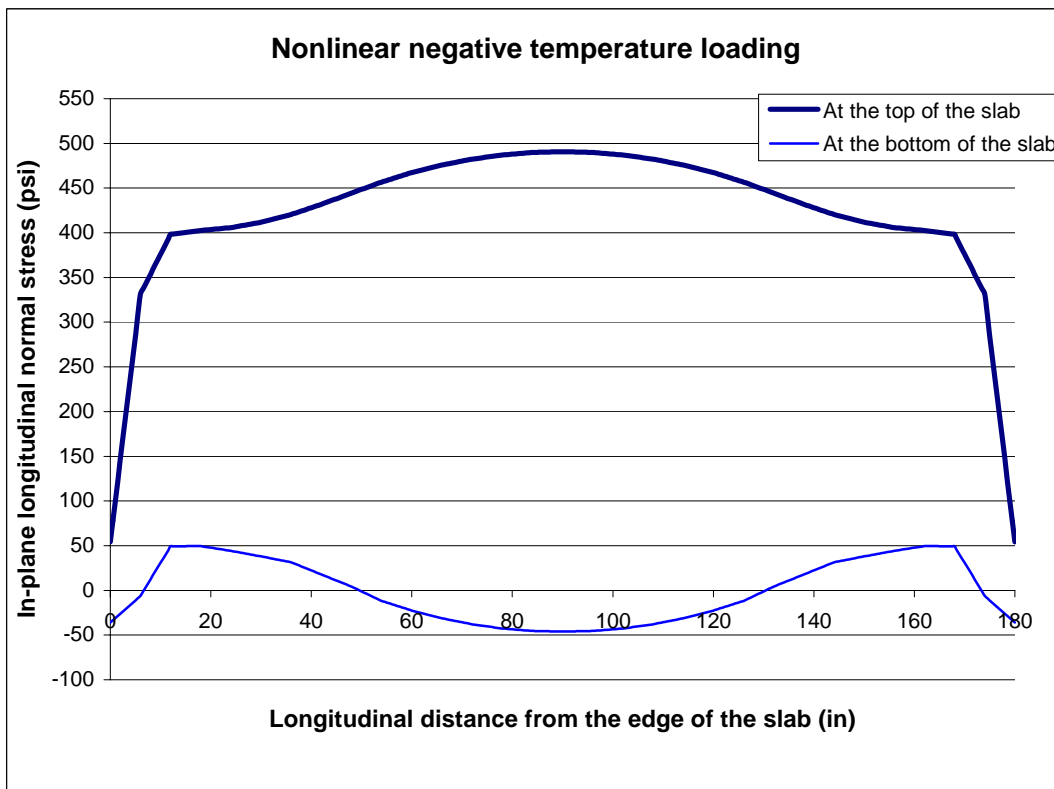
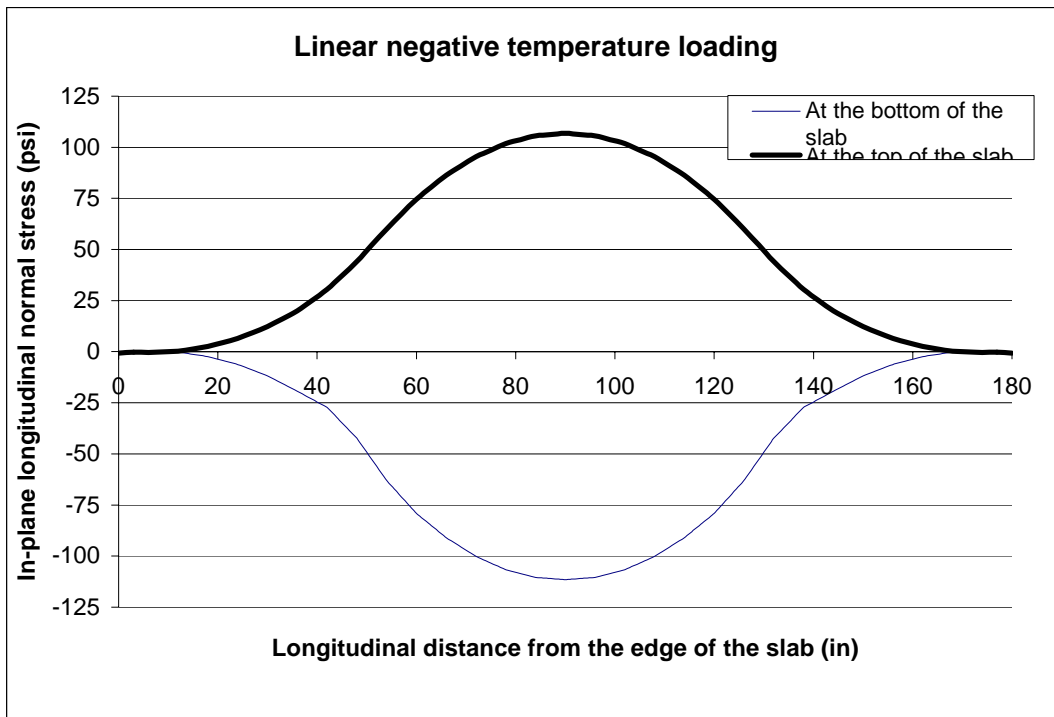


Figure 6.16 Normal stress distribution along the longitudinal center line of the PCC slab

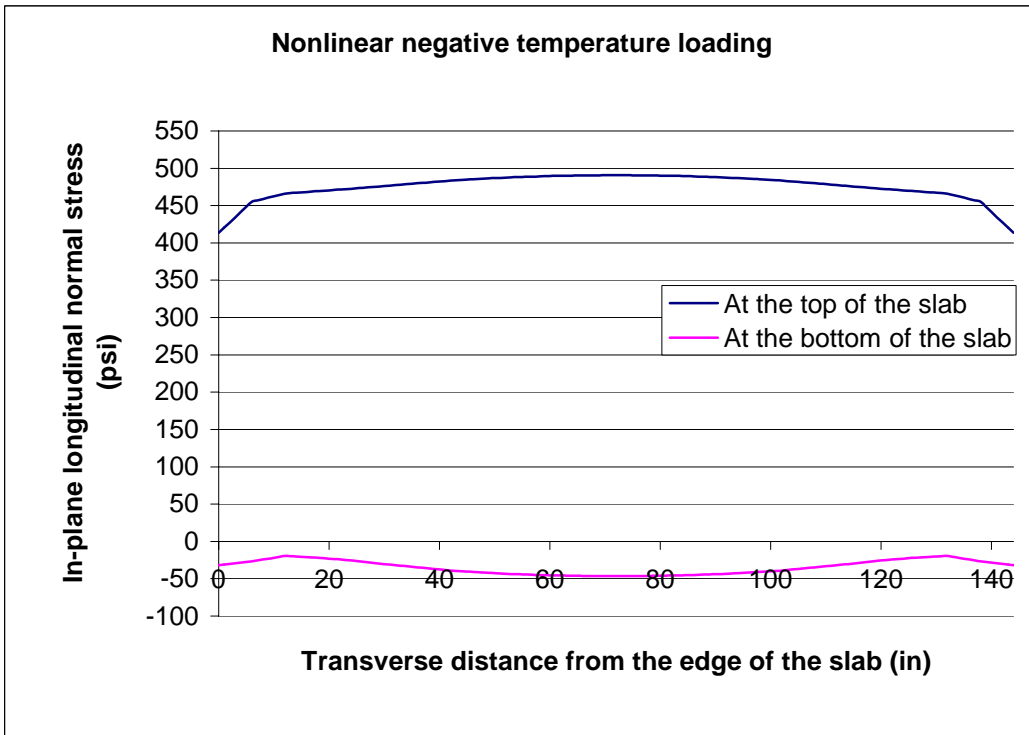
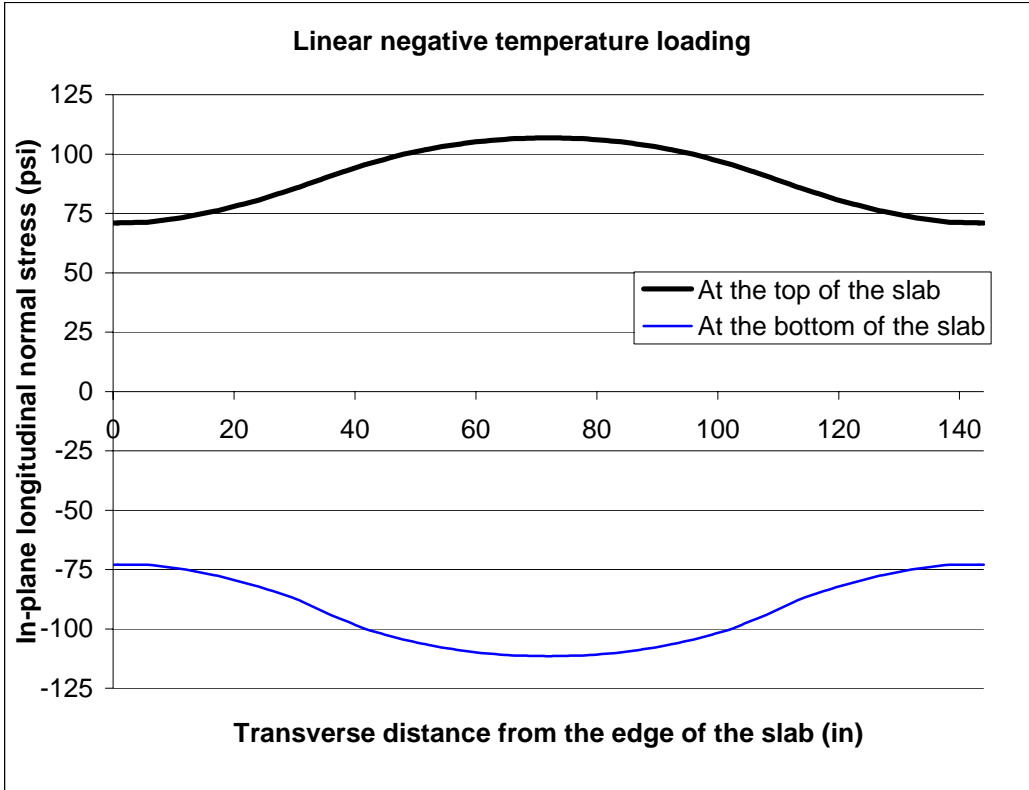


Figure 6.17 Normal stress distribution along the transverse centerline of the slab

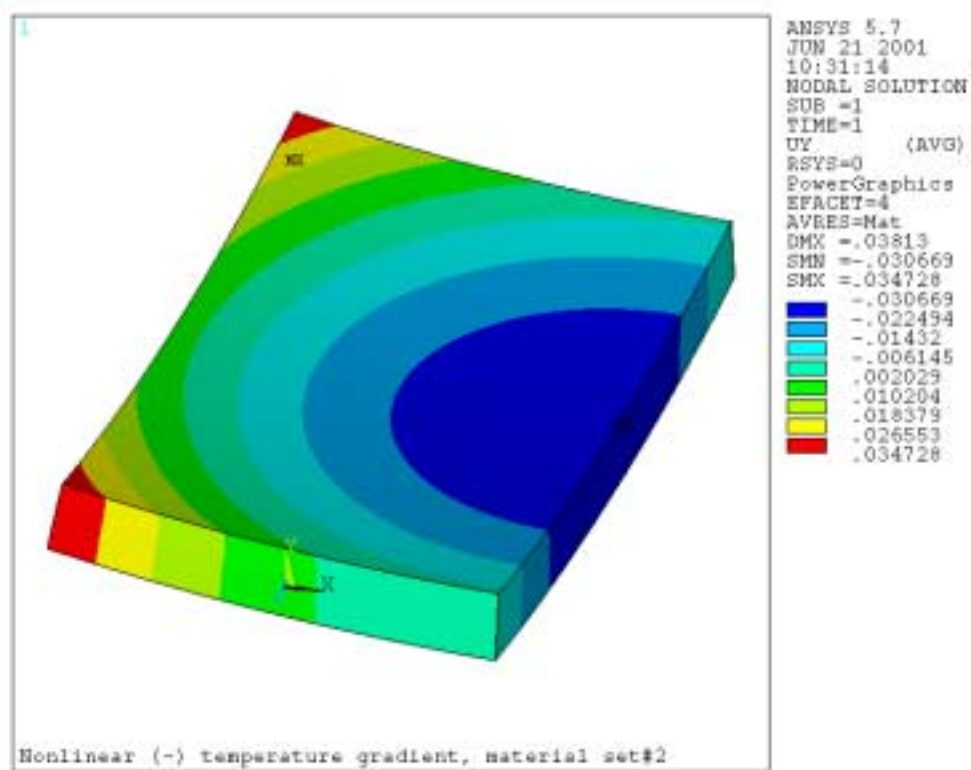


Figure 6.18 The vertical displacement contours for the nonlinear negative temperature loading

In Figure 6.18 the vertical displacement contour graph is given to show the curling of the slab corners under the nonlinear negative temperature loading. It should be noted that only the slab is depicted in this figure.

6.2.1.2 Positive Temperature Loading

Under the positive temperature loading, the center of the slab loses contact with the subbase and it deforms in a convex shape (the edges curled down). For the linear temperature distribution case the maximum normal tensile stress occurs at the edges of the slab along the centerline whereas for the nonlinear temperature distribution, the location of the maximum stress is at the center of the slab. The stress distribution at these locations is given in the Figure 6.19. For the linear case, the bottom layer of the concrete

is in tension, while for the nonlinear case tensile stress occurs somewhere between the bottom and the top layers of the slab.

Table 6.4 provides the maximum and the minimum values of the stresses and the magnitude of the opening. The maximum compressive stress value for the nonlinear case is about 3.8 times larger than that for the linear case. The maximum tensile stress value, on the other hand, is not affected considerably. Similar to the case of the negative temperature loading, the maximum opening between the concrete slab and the subbase for the case of nonlinear temperature loading is about half of the linear temperature loading. In Figures 6.20 and 6.21, the normal stress distributions along the longitudinal and transverse centerlines are shown. For the case of linear temperature loading (Figure 6.20) the normal stress distribution along the longitudinal edge of the concrete slab is also shown since the maximum tensile stress did not occur at the center of the slab, as is the case for the nonlinear temperature loading.

Table 6.4 Comparison of extreme stress and deformations

Temperature profile	Max. σ_x (Tension) (psi)	Min. σ_x (Compression) (psi)	Max. Δu_y
Linear	131	-132	0.044"
Nonlinear	136	-509	0.022"

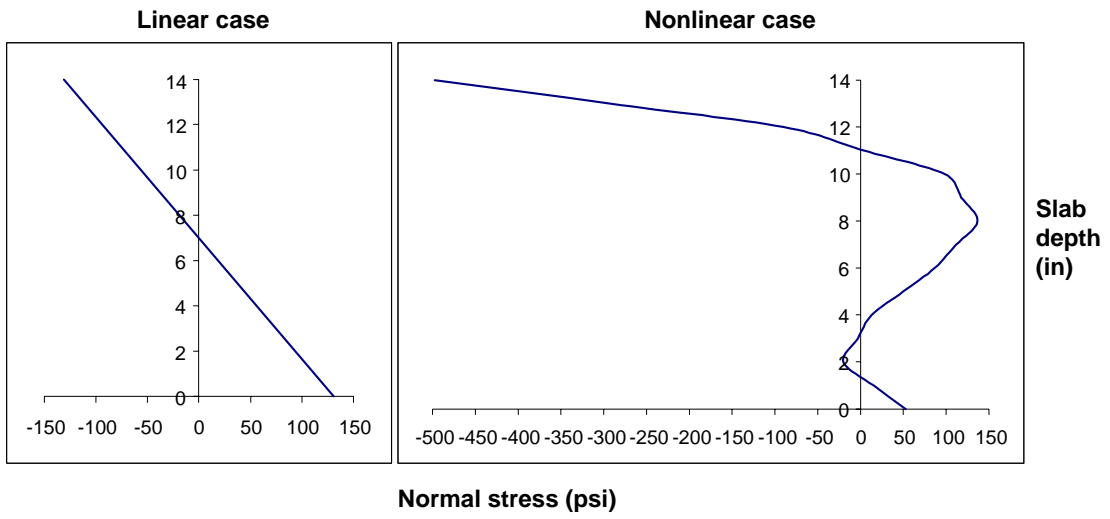


Figure 6.19 The stress profiles at the maximum tension sections

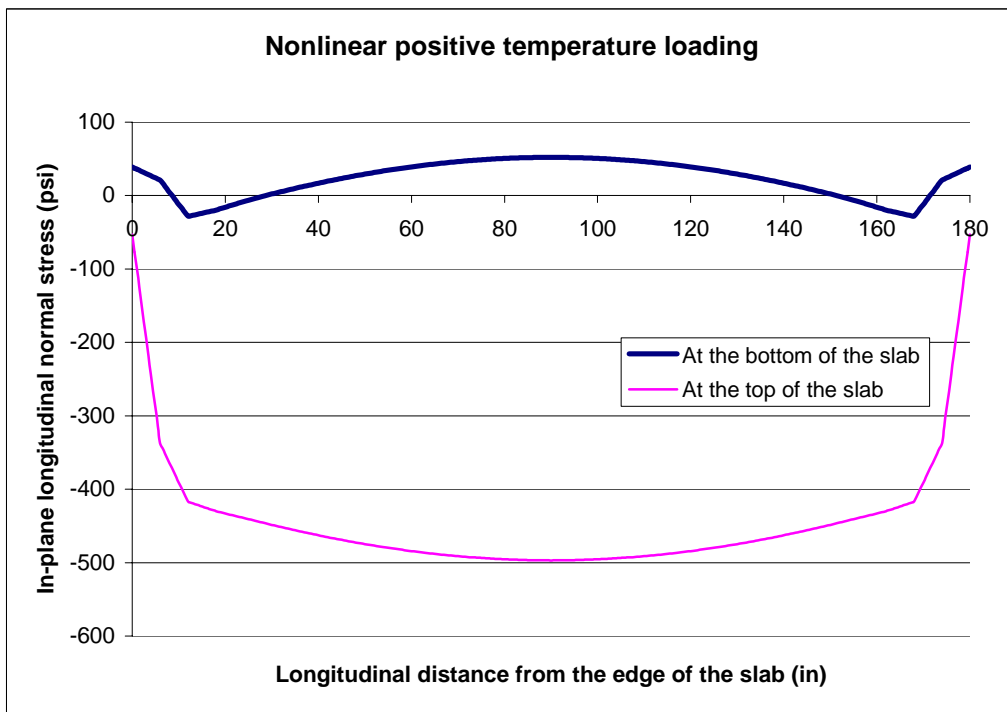
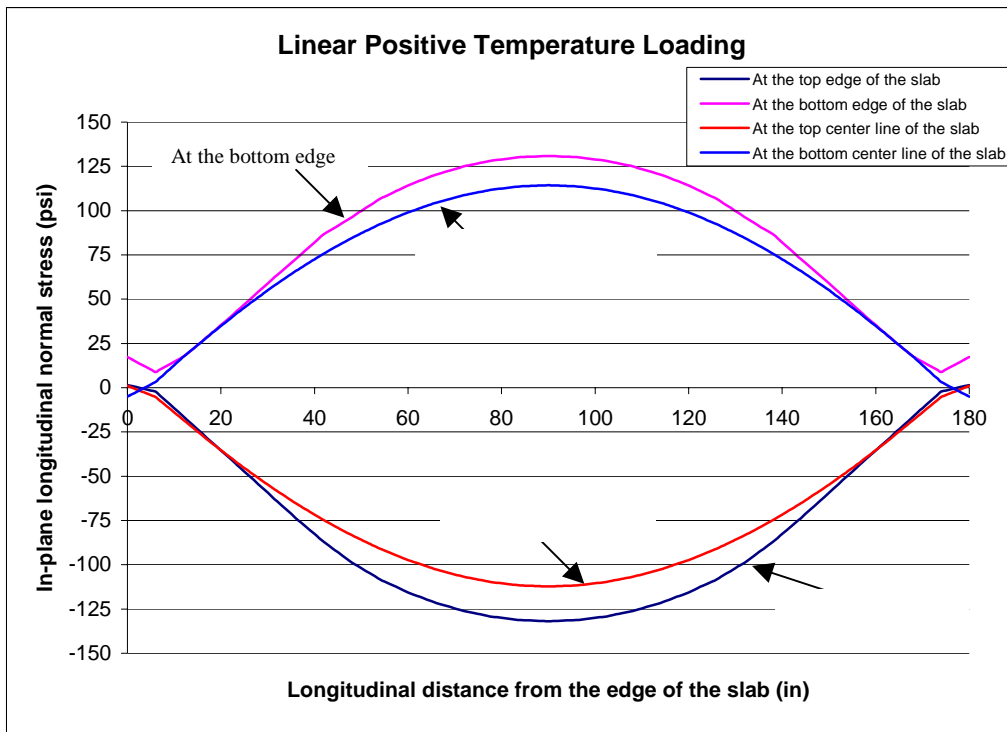


Figure 6.20 Normal stress distribution along the longitudinal centerline of the PCC slab

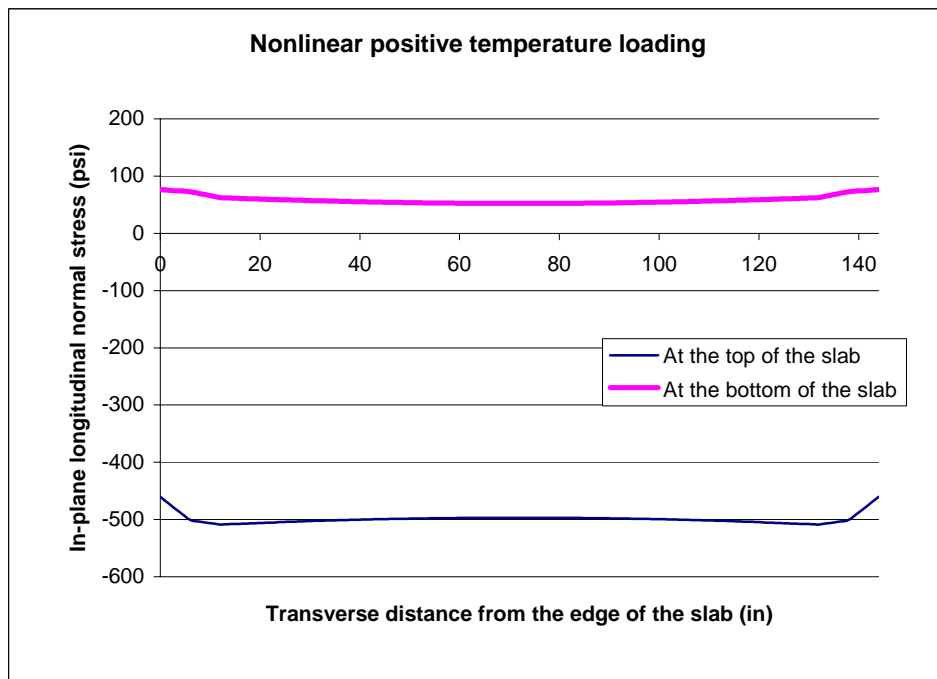
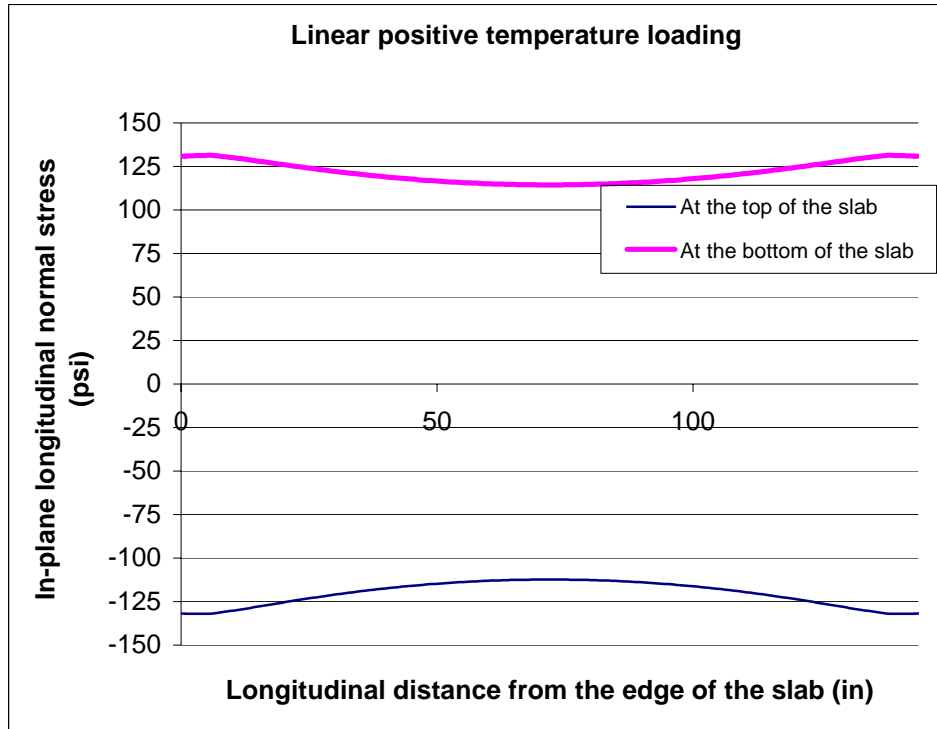


Figure 6.21 Normal stress distribution along the transverse center line of the PCC slab

6.3 The Effect of the Natural Soil Subgrade Stiffness

In this section four different load cases are solved using three different subgrade materials. The soil properties for these three material sets are given in the Table 1. The load cases considered are the following:

- 1- Gravity loading only
- 2- Wheel loading (includes gravity)
- 3- Negative temperature loading (includes gravity)
- 4- Negative temperature+wheel loading (includes gravity)

The temperature differential profile used in this section is shown in the Figure 6.22. The bilinear variation is chosen as an approximation to the actual nonlinear temperature variation.

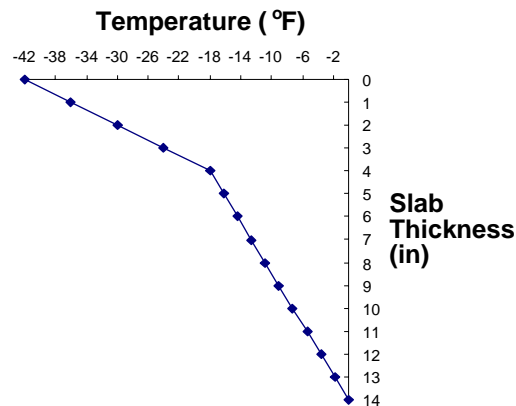


Figure 6.22 The bi-linear temperature profile that is used in the analyses

6.3.1 Gravity loading only

For the gravity loading case, it is found that increasing the subgrade material stiffness reduces the maximum vertical displacement (downward). The reduction ratio is almost of the same magnitude as the ratio of stiffness increase. However, the bending stresses are not affected noticeably.

6.3.2 Wheel loading case

For the wheel loading case, the maximum vertical displacement (downward) decreases with the increase in subgrade stiffness, as it is the case for gravity loading. The maximum and minimum in-plane normal stresses decrease with the increase in subgrade material stiffness. Therefore, the stiffer the subgrade is, the lesser the maximum normal stresses (tension and compression). The location of the maximum stresses is not affected by the stiffness change. The change in the stiffness causes very little effect on the shear stresses between the slab and the subbase.

6.3.3. Negative temperature loading case

For the negative temperature loading case, the increase in the stiffness causes the maximum downward displacement to decrease and the maximum opening at the corners to increase. The maximum tensile bending stress in the PCC slab is considerably greater for the stiffer subgrade material set, whereas there is little decrease in the maximum compressive bending stress. For example, there is around 17% difference between the tensile bending stress for material set 1 and that for material set 2. The maximum and minimum bending stresses occurs at the same nodes for each case.

6.3.4 Negative temperature + wheel loading case

For the case in which negative temperature and wheel loading combined, it is found that the negative temperature loading dominates. Therefore, the tensile bending stress increases with the increase in material stiffness. Conversely, the maximum compressive bending stress decreases with the increase in material stiffness for both wheel and negative temperature loading cases. However, a faster decrease is observed for the combined loading. The shear stresses between the slab and the subbase surfaces are not affected much by the increase in the subgrade material stiffness.

In Table 6.5 the extreme stress results are given for the four loading cases using the three material sets. Figure 6.23 shows the vertical normal stress contours at the transverse centerline section.

Table 6.5 Comparison of extreme stress and deformations

Loading	Max. σ_x (Tension) (psi)			Min. σ_x (Compression) (psi)		
	Mat#1	Mat#2	Mat#3	Mat#1	Mat#2	Mat#3
Gravity	0.3	0.3	0.3	-4.6	-4.6	-4.6
Wheel	86	73.4	67.2	-113.5	-100.1	-93.5
Negative Temperature	279.7	317	327.1	-109.5	-100.9	-99.4
Negative Temperature+Wheel	248.9	292.4	308.5	-140.2	-120.4	-117.3

(For material set definitions, see Table 6.1)

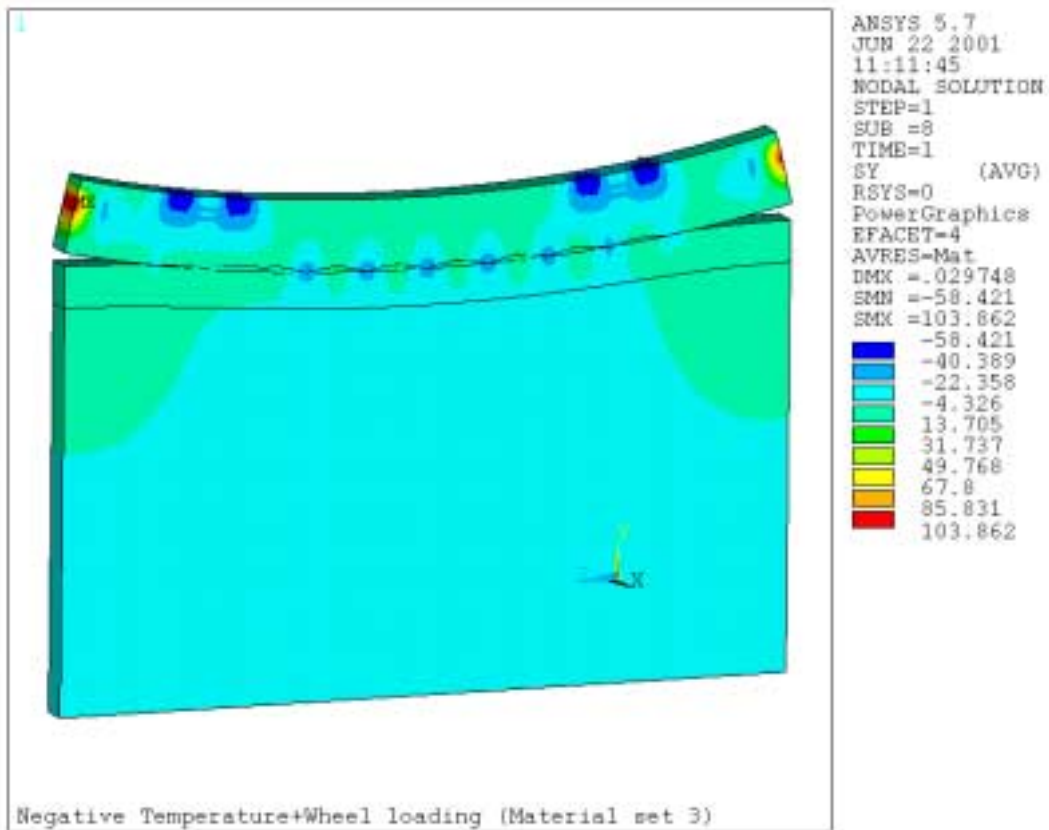


Figure 6.23 Vertical normal stress contours at the transverse centerline section

6.4 The Effect of the PCC Slab Thickness

The effect of slab thickness has been investigated for three different slab thicknesses : 12", 14" and 15" slabs using material set 2. For the temperature loading the positive temperature profile from the Figure 6.14 is considered. This case was considered because for wheel loads in the middle of the slab, this is the critical case. The loading cases analyzed are the following:

- 1- Wheel loading
- 2- Positive temperature loading
- 3- Positive temperature+wheel loading

Table 6.6 Comparison of extreme stress and deformations

Loading	Max. σ_x (Tension) (psi)			Min. σ_x (Compression) (psi)		
	12"	14"	15"	12"	14"	15"
Wheel	91.9	73.3	65.9	-117.5	-100.1	-93.26
Positive Temperature	132.7	136	137.5	-536.8	-509	-497.7
Positive Temperature+Wheel	228	173.1	151.3	-700.5	-644.3	-622.2

6.4.1 Wheel loading

For the case of wheel loading, the maximum and minimum normal bending stresses decrease with the increase in concrete slab thickness. This can be explained because it is more difficult to deform a slab with a higher thickness, thus causing the bending stress to decrease. As it is can be seen from Table 6.6, the reduction in the maximum normal bending stress value is around 26% for a 2" thickness increase. In Figure 6.24 the normal bending stress contours for the slab with 12" thickness are shown. The stress contour

values are given in psi. The maximum and minimum values of the stresses occur under the wheel loading closer to the edge of the slab.

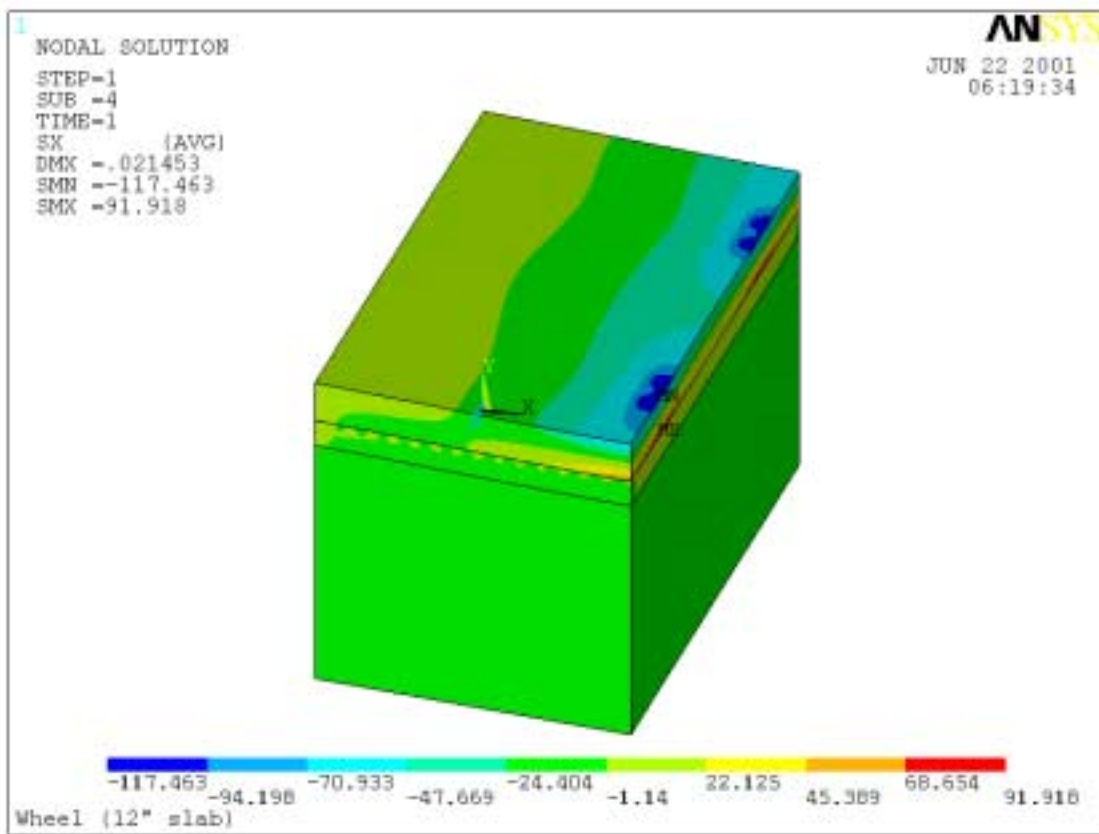


Figure 6.24 The normal bending stress contours for the 12” slab (only one symmetric half of the pavement is shown)

6.4.2. Positive temperature loading

For positive temperature distribution, there is little increase in the maximum bending stress value with the increase in concrete slab thickness. However, the maximum compressive stress value decreases. Once again, this can be explained, since the thicker the slab, the heavier it is and the gravity effect reduces the opening between the concrete slab and the subbase.

6.4.3 Positive temperature + wheel loading

For the positive temperature + wheel loading case, the wheel loading dominates. This is because, as discussed above, the positive temperature loading causes a very little increase in the maximum bending stress, while the gravity loading causes a more significant decrease with the increase in concrete slab thickness. Therefore, the maximum bending stress decreases when the concrete slab thickness is increased. When the thickness of the concrete slab is smaller, the opening between the concrete slab and the subbase is higher. The wheel loading, in this case, causes more bending stress; therefore the highest bending stress occurred for the 12" slab configuration. In Figure 6.25 the opening along the transverse centerline of the concrete slab is shown for the three thickness values. Figure 6.26 shows the bending stress profiles along the transverse centerline of the pavement at the locations of maximum bending stress value.

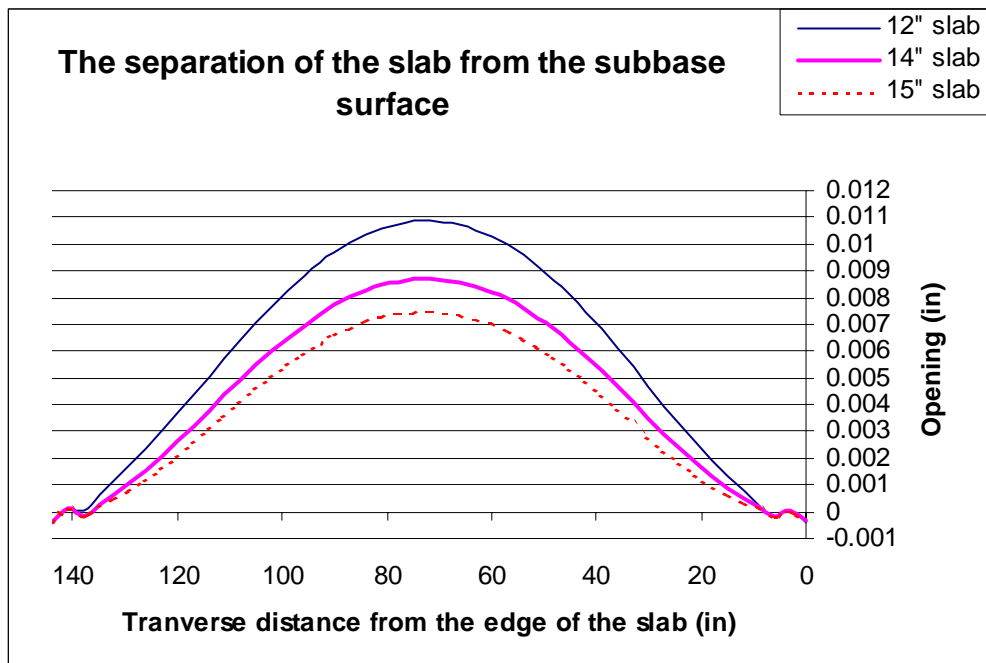


Figure 6.25 The opening along the transverse centerline for positive temperature +wheel loading case.

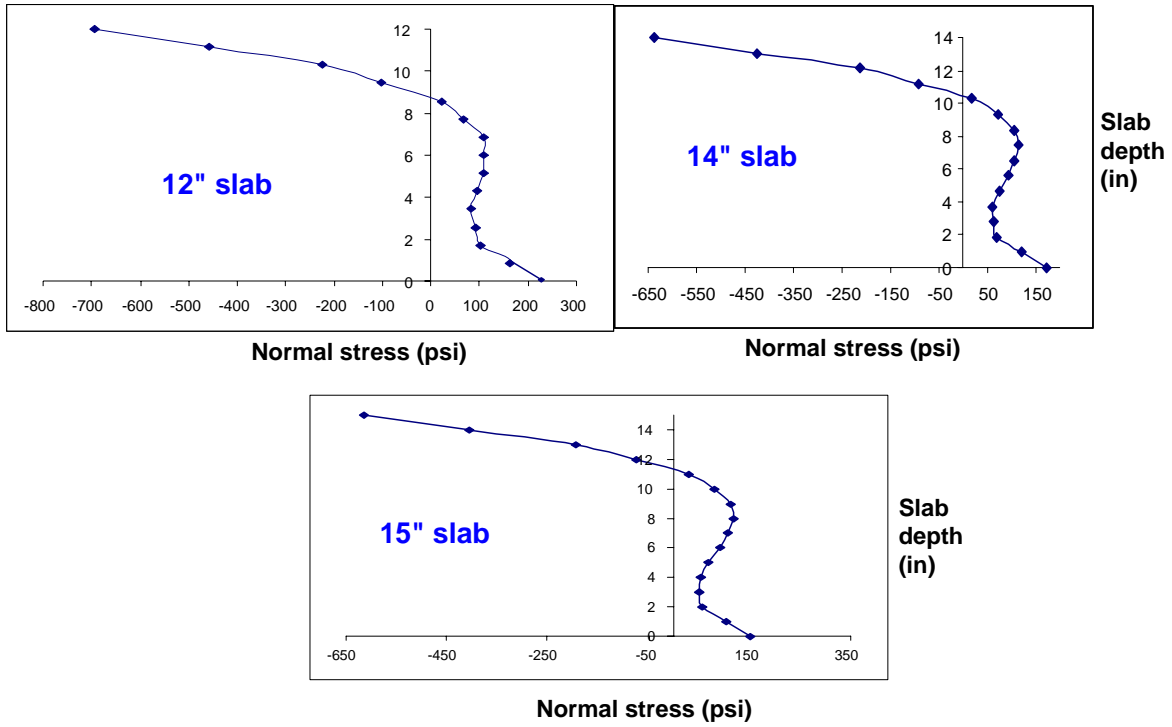


Figure 6.26 Bending stress profiles at the maximum tension stress occurring points

In Figure 6.27, the normal bending stress distributions along the transverse centerline of the PCC slab are shown for upper and lower layers of the slab. It is evident from this figure that for the top layers of the slab that there are sudden increases in the compressive stresses at the wheel locations. Again, right under the wheels, the tension stress increases due to the opening. Therefore, when there is positive temperature differential, the wheels at the center of the slab causes the highest tension stress configuration.

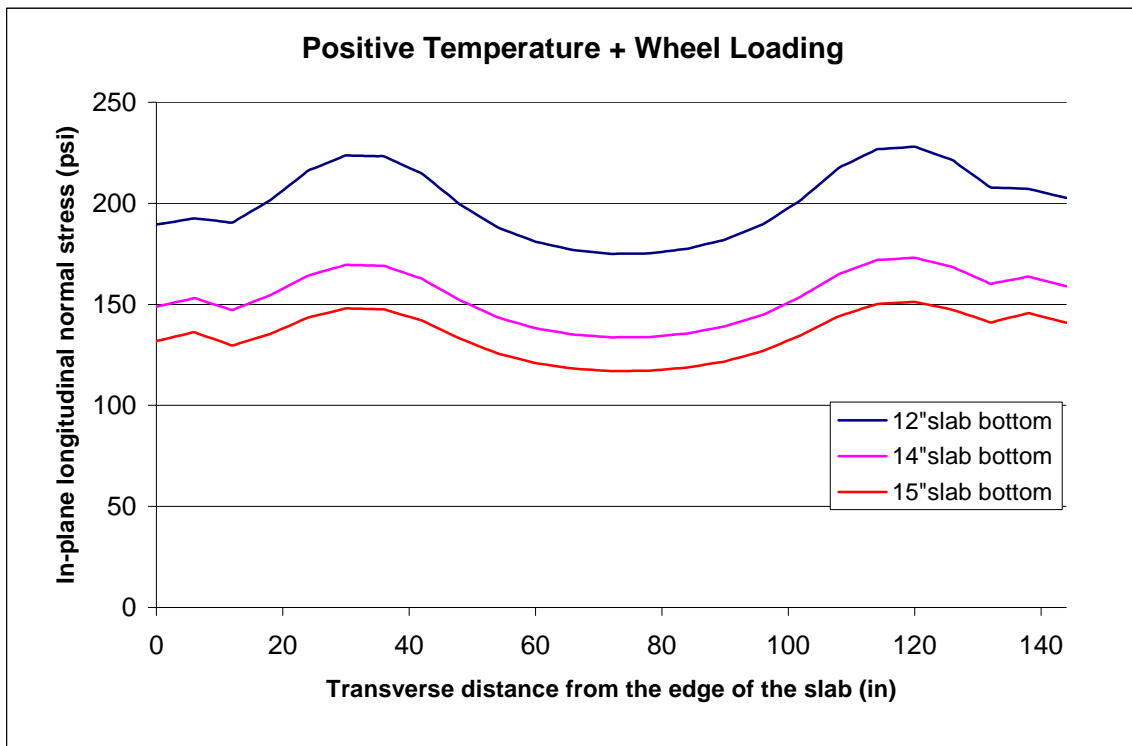
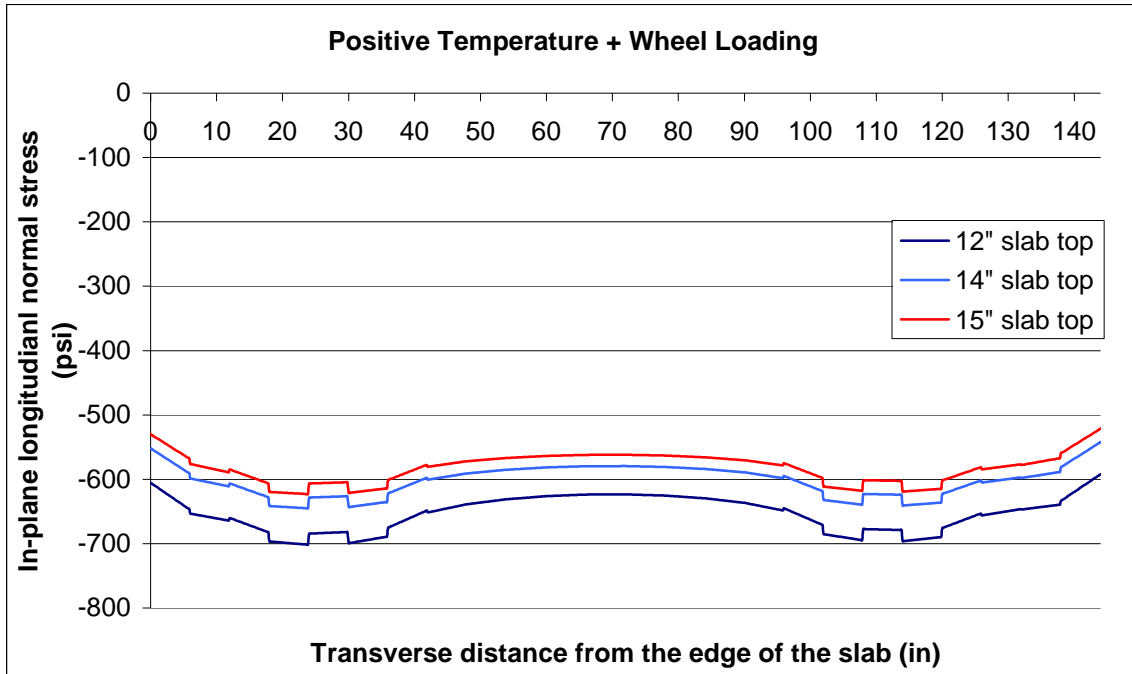


Figure 6.27 The normal stress distribution along the transverse center line of the PCC slab

CHAPTER 7. SUMMARY OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

The primary objective of this research was to provide INDOT with the current state of knowledge on mid-panel cracking in Jointed Plain Concrete Pavements (JPCP). This was accomplished by means of a synthesis study of the existing literature, a written survey of other state DOT's experiences, and preliminary finite element analyses.

7.1.1 Synthesis Study Summary

The results from the literature review indicate there is no one clear factor that can be identified as the major cause of transverse cracking of jointed plain concrete pavement. According to most researchers, the combined mechanisms of curling of the concrete slab due to temperature gradients, and fatigue due to repeated traffic loads, lead to the occurrence of the transverse cracks. In addition, the improper control of the shrinkage of the concrete in the early stages of construction is also cited as an important cause of cracking in JPCP. The following is a list of factors affecting mid-panel cracking of JPCP that were identified in the literature:

- Thermal changes and gradients through the thickness of the slabs [1, 42, 41, 6, 29, 1, 21, 11, 32, 14].
- Temperature variations leading to a lockup of the dowel bars [49, 3, 54].
- Plastic or drying shrinkage of the concrete [27, 41, 29, 24, 20, 53, 14].
- Nonlinear temperature gradient [42, 21, 35].
- Yearly cyclic moisture warping [41, 7].
- Concrete fatigue from a variety of effects [45, 28, 20].
- Saw cut timing and depth [28, 56, 29, 53, 28].
- Traffic loadings [9, 14, 5, 31, 15].
- Use of a non-stabilized granular base [6, 53].

- Voids in the concrete producing raised stress levels [36].
- Joint spacing [38, 1, 20, 53].
- Pumping of the granular base [38].
- Subgrade friction [38, 53].
- Slab thickness [44, 33].
- General subgrade issues (base type, thickness, etc.) [11, 19, 40, 2, 30].
- Dowel looseness [18, 11].
- Mix design issues [46].

7.1.2 Summary of Survey of State DOTs

All states that used JPCP were surveyed -- thirty-three states responded. In addition, case studies were received from Florida, Georgia, Nebraska, New Mexico, North Carolina, Ohio, and Virginia. Florida, Illinois, Indiana, Michigan, North Carolina, and Wisconsin indicated in-house sponsored research projects relating to cracking of JPCP. The survey responses indicate there is no one clear factor that can be identified as the major cause of transverse cracking of jointed plain concrete pavement.

An overwhelming majority of the states reporting problems with Mid-Panel Cracking of Jointed Plain Concrete Pavements are geographically east of the Mississippi River with three exceptions. Notably, cracking problems occur in states near the Great Lakes and extend on south as far as Florida, Mississippi, and Georgia. Kentucky and Tennessee are the only two states within this belt reporting no cracking problems in JPCP. Although no response was received, Pennsylvania and Virginia are reported to have cracking problems.

The typical pavement thickness ranged from eight to fourteen inches on average. Cracking was observed in states using thinner (8"-9") pavements, notably Ohio, Virginia, North Carolina, and Florida. However, cracking was also observed in thicker pavements (10-14"), such as Indiana, Michigan, Illinois, Wisconsin, Georgia. Similarly, cracking was reported by states using both short (e.g., Illinois and Ohio) and long (e.g., Indiana,

Wisconsin, and Florida) joint spacing. In addition, the ratio of the panel length to thickness (ft/in) also does not appear to affect the occurrence of cracking. States with high ratios, such as Virginia and North Carolina, and states with low ratios, such as California and Illinois, have reported cracking.

The type of base commonly used for jointed plain concrete pavements is almost 50% untreated base and 50% treated base for all responding states. Of the states reporting cracking problems, 46% uses a treated base and 31% use and untreated base. The remaining percentage reported the use of both base types or did not respond. Thus, no pattern resulted from comparing the base type for the jointed plain concrete pavement with the states with cracking problems.

Cracking occurred under several environmental conditions including wet subgrade/freeze regions, wet subgrade/no freeze regions, dry subgrade/no freeze regions, and dry regions. There was no discernable environmental pattern under which cracking occurred.

In some cases cracking was reported to occur prior to opening to traffic. Other states have shown a combination of cracking immediately after opening, several months after opening, and several years after opening to traffic. The orientation of the cracking in JPCP ranged from transverse and longitudinal cracks in both the driving and passing lanes. Five states indicated cracking in the driving lane only while five different states reported cracking in both lanes.

7.1.3 Summary of Preliminary Finite Element Analyses

Preliminary finite element analyses were carried out to study the effects of some of the factors that may be responsible for mid-panel cracking of JPCP. Based on the synthesis study it was found that thermal variations, subgrade conditions, and slab thickness are primary factors that affect JPCP performance. A three-dimensional (3D) model was adopted in order to capture the complex behavior of JPCP, such as the three-

dimensional (3D) effects caused by the curling due to temperature differentials. This 3D model is also capable of capturing the vertical separation between concrete and subbase, nonlinear temperature differentials through the slab, and friction at the interface layers. The developed model assumes fully elastic behavior. Modeling of JPCP joints (dowel bars) was not addressed in the present study. The 3D finite element models of JPCP were developed and analyzed using the ANSYS general-purpose finite element software.

Three factors that may affect the mid-panel cracking of JPCP have been studied in detail. The first is the effect of the assumption of a nonlinear versus a linear temperature distribution over the concrete slab depth. The second is the effect of the stiffness of the soil subgrade, and the third is the effect of slab thickness. It has been found that the temperature distribution assumption has a major impact on the stress distributions in JPCP. The highlights of these findings can be summarized as:

- The assumption of linear versus nonlinear temperature distribution throughout the PCC slab was studied. It was found that the linear assumption is inappropriate for PCC pavement analysis. Significantly different results were found when comparing the results obtained with a more realistic nonlinear temperature distribution with those from the linear case. For example, for the negative temperature loading case the maximum tensile stress at the center of the slab is more than four times larger for the nonlinear case than that for the linear case, while the maximum opening due to linear temperature differential is found to be around 70% larger than that of the nonlinear temperature differential.
- The effect of the stiffness of the soil subgrade was studied. Four different load cases were studied using three different subgrade materials. A bilinear temperature differential profile was used as an approximation to the actual nonlinear temperature variation. It was found that the stiffness of the soil subgrade has a moderate effect on the stress distribution in the JPCP slab. For example, for the gravity loading case and for the wheel loading case, it is found that increasing the subgrade material stiffness reduces the maximum vertical displacement by a ratio of the same magnitude as the ratio of stiffness increase. In particular, for the negative temperature loading case, the

maximum tensile bending stress in the JPCP slab is around 17% larger for material set 1 ($E = 2,000$ psi) than that for material set 2 ($E = 10,000$ psi).

- Three slab thickness values (12", 14" and 15") under three loading conditions were investigated. It was found that the slab thickness has a moderate effect in the maximum normal bending stresses. For example, the reduction in maximum normal bending stress with an increase of 2" in slab thickness is about 26%.

7.2 Conclusions

The results from the literature review, DOT survey, and the preliminary finite element analyses indicate there is no one clear factor that can be identified as the major cause of transverse cracking of jointed plain concrete pavement. As reported in the literature and confirmed by the finite element simulations, the thermal variations, wheel loadings, and adverse subbase conditions greatly stress the pavements. However, no one cause or combination of causes was found to be enough to cause the cracking. Hence, it seems evident that it is the cumulative damage from many sources of distress that causes the observed cracking.

7.3 Recommendations

Although the state-of-the-art in pavement research and practice cannot conclusively predict the lifespan of a particular pavement, INDOT must be able to provide estimates for design and rehabilitation schedules based on predicted cumulative damage analyses. Therefore, INDOT requires the ability to perform accurate finite element analysis of JPCP subjected to a wide variety of wheel loads, subbase/subgrade conditions, environmental conditions, and dowel bar interactions. The cumulative damage caused by these various effects need to be blended into a tool that provides a quick and accurate estimate for pavement life expectancy. The available tools do not fulfill this requirement. Thus, it is recommended that such a tool be developed.

Cumulative damage models for plain concrete pavements exist. It is recommended that a review of the literature be synthesized and that an appropriate damage model for pavements in Indiana be selected. In addition, excellent general-purpose nonlinear finite element software exists. It is recommended that this tool simply interface to such software (likely candidates are ANSYS and ABAQUS). This interface will allow INDOT to completely describe the complex three-dimensional models necessary for accurate analysis with only a minimum of input parameters.

In summary, this recommendation will produce a calibrated, working tool for estimating the life of plain Portland cement concrete pavements in Indiana. This will not only aid in producing more economical concrete pavement designs in the future, but it will also be useful for predicting the remaining life of existing pavements. With such a tool, INDOT will be better equipped to rationally decide which pavements require closer monitoring. The tool will also help simplify the task of anticipating pavement repairs and facilitate the long-term planning of these activities. Furthermore, it will provide a sound model for predicting the shortening of the life of a pavement due to overloads.

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APPENDICES

APPENDIX 1: SURVEY LETTER

MID-PANEL CRACKING OF JOINTED PLAIN CONCRETE PAVEMENT

September 20, 2000

Attn: Department of Transportation

The Civil Engineering Department of Purdue University is conducting a research project on behalf of the Indiana Department of Transportation to determine the cause of random transverse mid-panel cracking of jointed unreinforced portland cement concrete pavements. Our concern lies with cracks not stemming from the joints between the unreinforced concrete panels.

In efforts to gain your current state of knowledge, we ask that you please take the time to complete our short survey. If you are not a person within the Department of Transportation specializing in the area of concrete pavements, we ask that you please direct the survey to the appropriate person.

Thank you,

Graham C. Archer
Principal Investigator

Elisa D. Sotelino
Principal Investigator

APPENDIX 2: SHORT SURVEY

PLEASE START HERE

Purdue University Survey:

Random Transverse Mid-Panel Cracking of Jointed Plain Concrete Pavements (JPCP)

Name:

Address:

Telephone No.: ()

E-mail Address:

1. What percentage of current construction is jointed plain concrete pavements (JPCP)?
 _____ %

2. If your D.O.T. uses JPCP, have you observed any problems with mid-panel transverse cracking not associated with the joints? (If yes, please skip to the detailed survey)
 Yes No

3. How often do you check pavement performance?
 Once a year
 Once in two years
 Other: _____

4. What is the typical panel width, length, and thickness used in your state?

Transverse Longitudinal Thickness:
Width: _____ Length: _____

5. Please provide relevant material concerning your concrete properties (ie. flexural strength, mix design, type of aggregate and additives, etc.):

6. What joint type, depth, opening, and sealant are commonly used in your state for JPCP?

7. What type of dowels are used for JPCP? What is the dowel spacing, placement, and installation technique used?

8. What type of base is commonly used in your state for JPC pavements?

- Treated base (lean concrete or permeable asphalt)
- Untreated base (aggregate)

9. If a treated base is used, please describe the treatment type. If an untreated base is used, please describe the placement method, aggregate size, etc.

10. Please describe your curing procedure. What is the time elapsed (after curing) before saw-cutting, the time of day of saw-cutting, and the depth of the saw-cut?

11. Do you have prevention or rehabilitation methods for avoiding mid-panel cracking?

WOULD LIKE TO BE CONTACTED WHEN THE RESULTS ARE POSTED VIA THE WEB?

- Yes** **No**

APPENDIX 3: DETAILED SURVEY

PLEASE ANSWER THE OTHER SURVEY FIRST

DETAILED SURVEY:

Random Transverse Mid-Panel Cracking of Jointed Plain Concrete Pavements (JPCP)

Name:

Address:

Telephone No.: ()

E-mail Address:

PART I:

1. How often do you check the pavement performance?

- Once a year
- Once every two years
- Other: _____

2. Under what environmental conditions does the cracking most often occur? (Check all that apply)

- Dry (subgrade)
- No freeze region
- No discernable pattern

- Wet (subgrade)
- Freeze region

3. Under what traffic conditions does the cracking most often occur? (Check all that apply)

- Heavy Loads AADT: _____ % of Trucks: _____
- ESAL: _____

4. Under what traffic conditions does the cracking most often occur? (Check all that apply)

- Prior to opening to traffic.
- Immediately after opening to traffic.
- Several months after opening to traffic.
- Several years after opening to traffic.

5. Location and orientation of typical midpanel cracks (non-joint related)? (Check all that apply)

- Passing Lane Transverse Other: _____
- Driving Lane Longitudinal

6. Please provide relevant material concerning your concrete properties (ie. flexural strength, mix design, type of aggregate and additives, etc.):

7. What joint type, depth, opening, and sealant are commonly used in your state for JPCP?

8. What type of dowels are used for JPCP? What is the dowel spacing, placement, and installation technique used?

9. What type of base is commonly used in your state for JPC pavements?

- Treated base (lean concrete or permeable asphalt)
- Untreated base (aggregate)

10. If a treated base is used, please describe the treatment type. If an untreated base is used, please describe the placement method, aggregate size, etc.

11. Please describe your curing procedure. What is the time elapsed (after curing) before saw-cutting, the time of day of saw-cutting, and the depth of the saw-cut?

12. Please describe your state's construction methodology of JPC pavements:

13. Has your D.O.T. conducted any in-house or sponsored research projects regarding random transverse cracking in unreinforced concrete pavements?

- Yes No

14. Please provide us with any additional comments or suggestions:

15. Would you like to be contacted when the results are posted via the web?

- Yes No

PART II:

Case Studies: Please refer to a specific case in which random transverse mid-panel cracking occurred in jointed plain concrete pavement and answer as

many questions below as possible. Feel free to make additional copies of this form for other case studies.

Project Location and Description: _____

Time/Date of Construction (month, etc): _____

Has this site been rehabilitated? If so, what method was used?

Slab Width: _____	Saw Cut depth: _____
Slab Length: _____	Time of Saw Cut: _____
Slab Thickness: _____	Joint Type: _____
Concrete Strength: _____	Joint Depth: _____

What type of base was used (dense aggregate, bituminous or cement-treated drainable, etc.)?

What was the subgrade for the JPC pavement? (sand, silt, clay, etc.)?

Please describe the concrete properties used: (type, flexural strength, mix design, curing procedure, water content, admixtures, type and percentage of aggregate, etc.)

What was the type and spacing of the dowel bars (spacing, size, length, sleeves, etc.)?

Under what environmental conditions did the cracking occur? (Check all that apply)

- Wet
- No freeze region
- No discernable pattern
- Dry
- Freeze region

Under what traffic conditions did the cracking occur? (Check all that apply)

- Prior to opening to traffic.
- Immediately after opening to traffic.
- Several months after opening to traffic.
- Several years after opening to traffic.

Location and orientation of midpanel cracks? (non-joint related cracks)

- Passing Lane
- Transverse
- Driving Lane
- Longitudinal

Specific Crack Description:

What technique was used to repair the cracked JPC pavement?

Please provide any other relevant material about your case (include additional sheets if necessary):

APPENDIX 4: SUMMARY OF SURVEY DATA

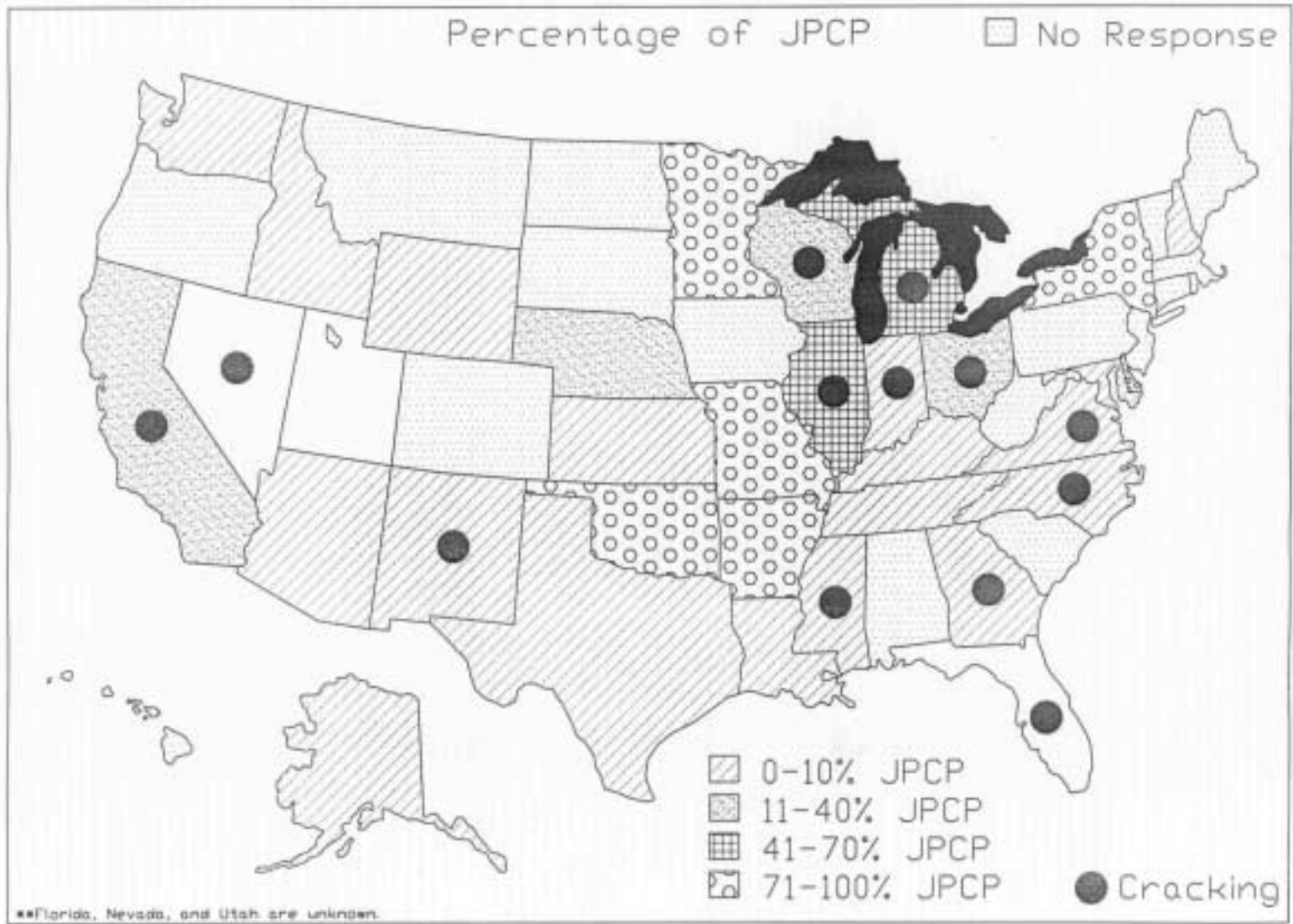
Mid-panel Cracking of Portland Cement Concrete Pavements



**Massachusetts, Connecticut, Rhode Island, Alabama, South Dakota - Not responding due to very little or no use of JPCP.

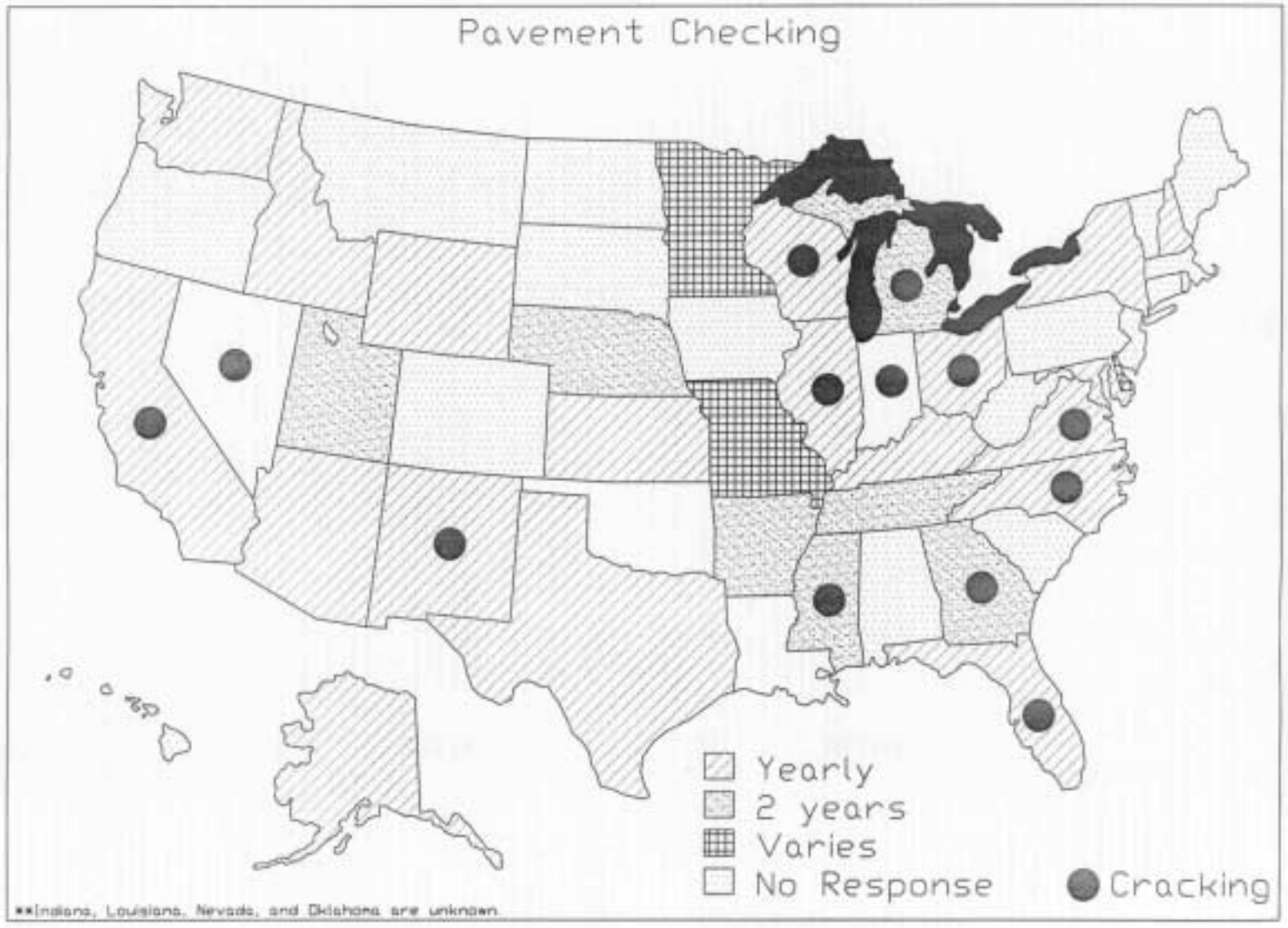
Percentage of JPCP

☐ No Response

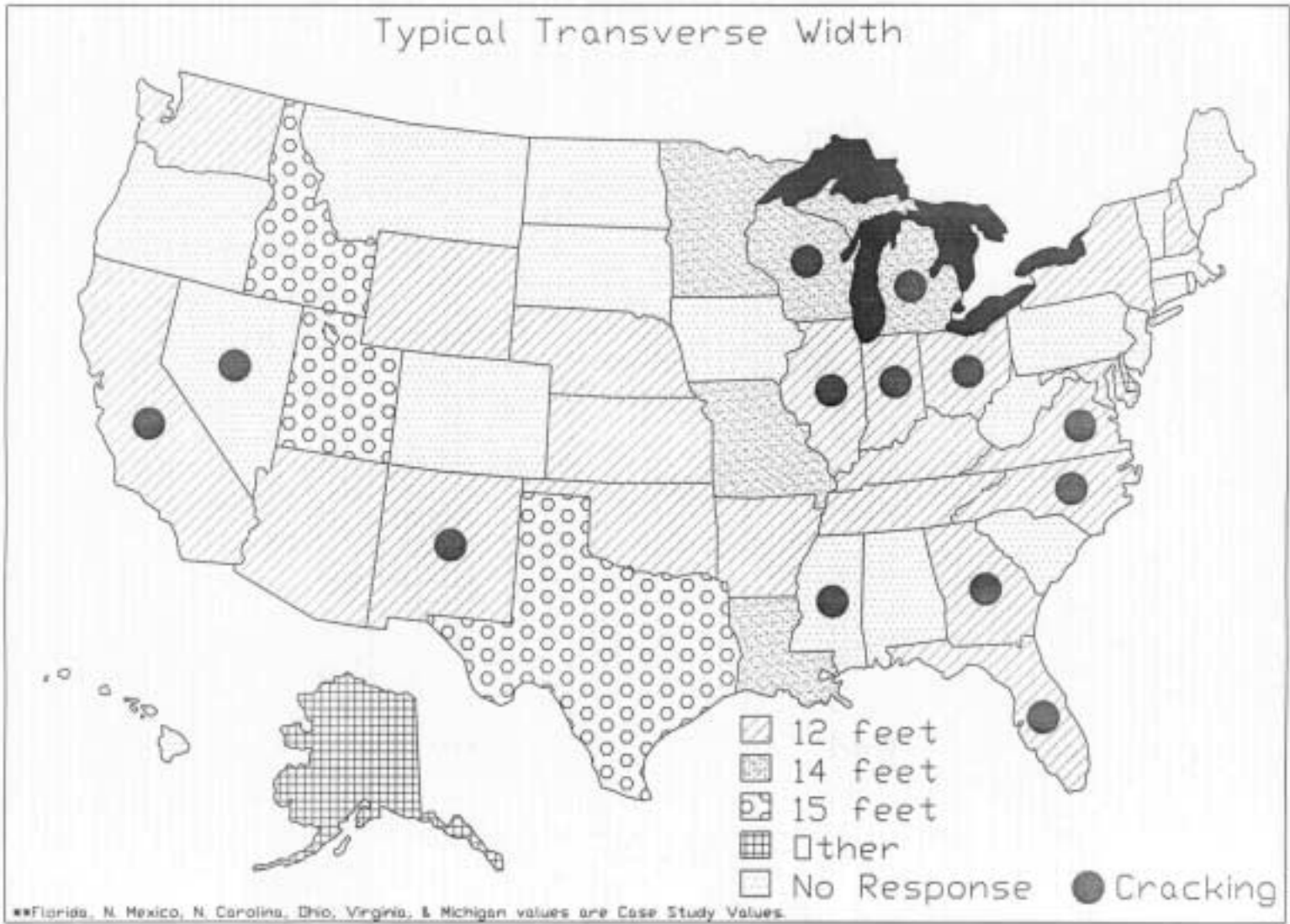


**Florida, Nevada, and Utah are unknown.

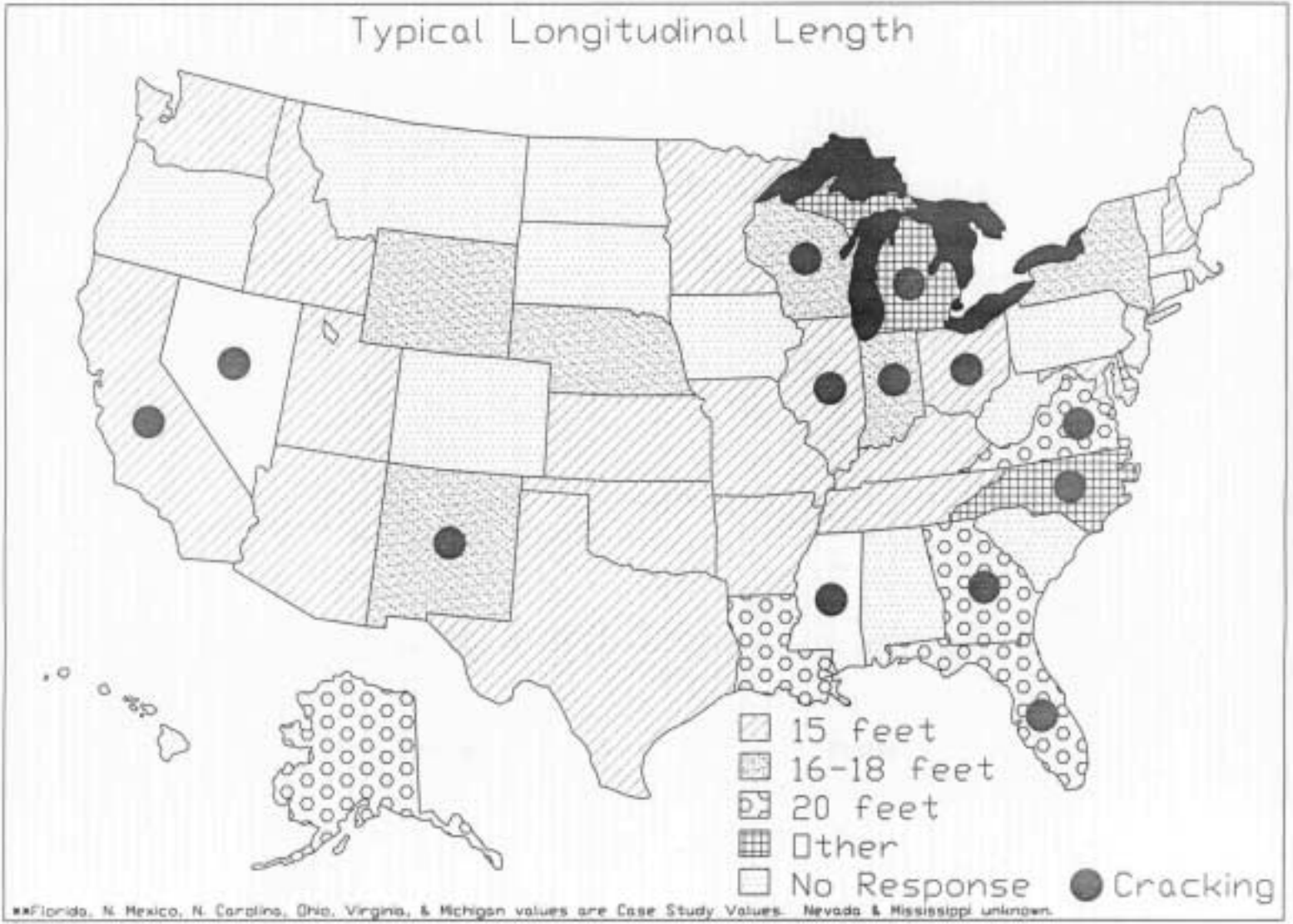
Pavement Checking



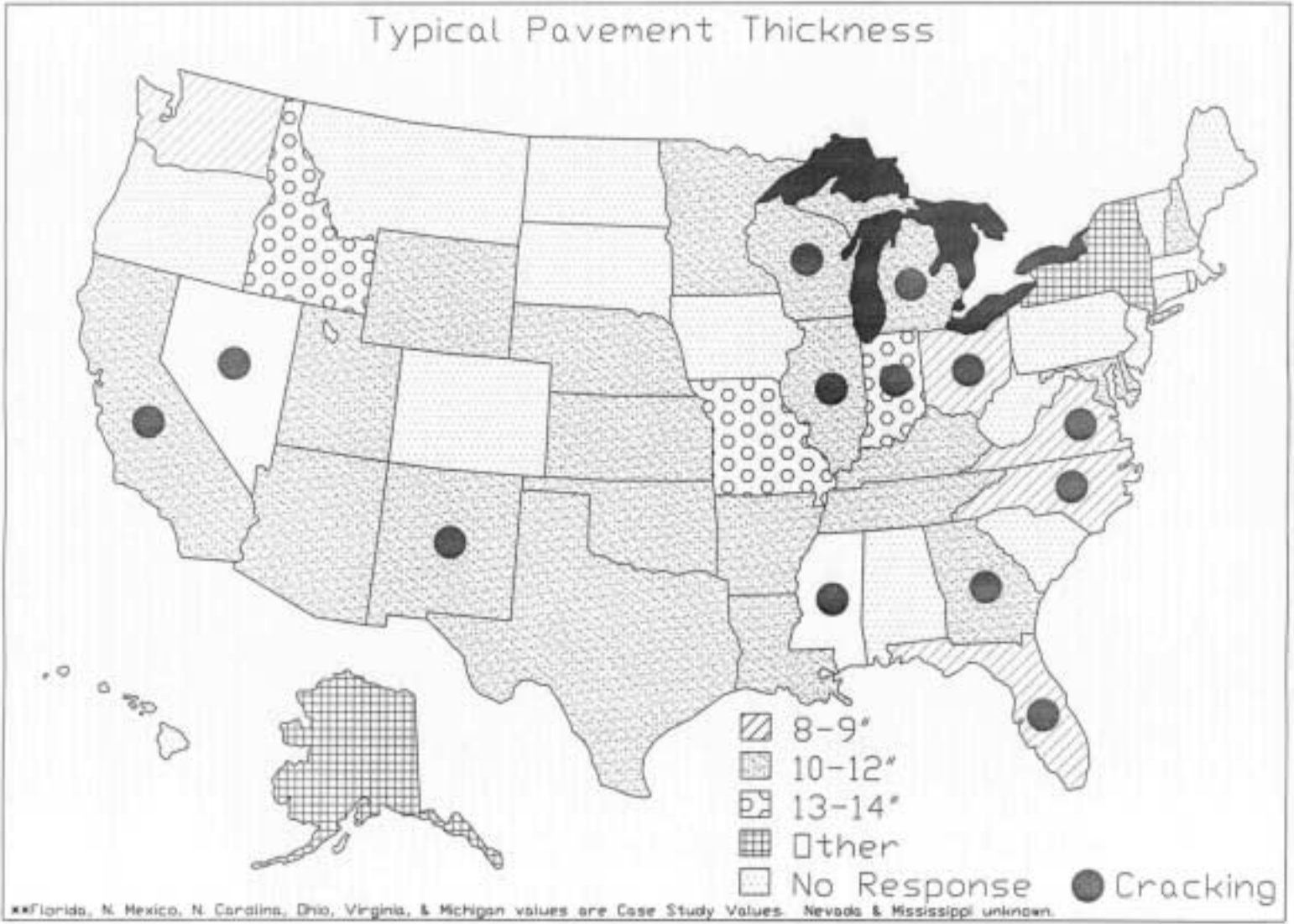
Typical Transverse Width



Typical Longitudinal Length

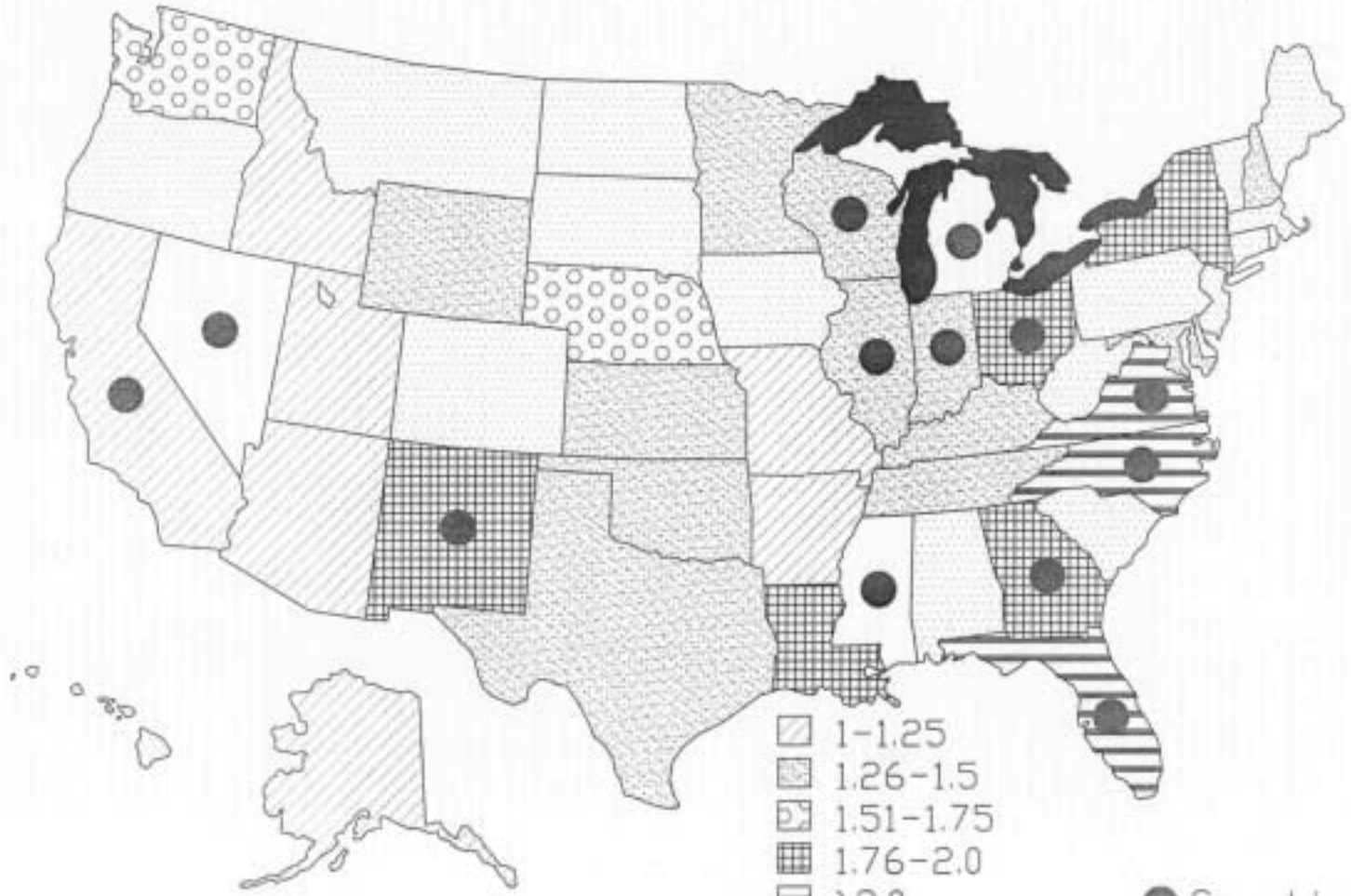


Typical Pavement Thickness



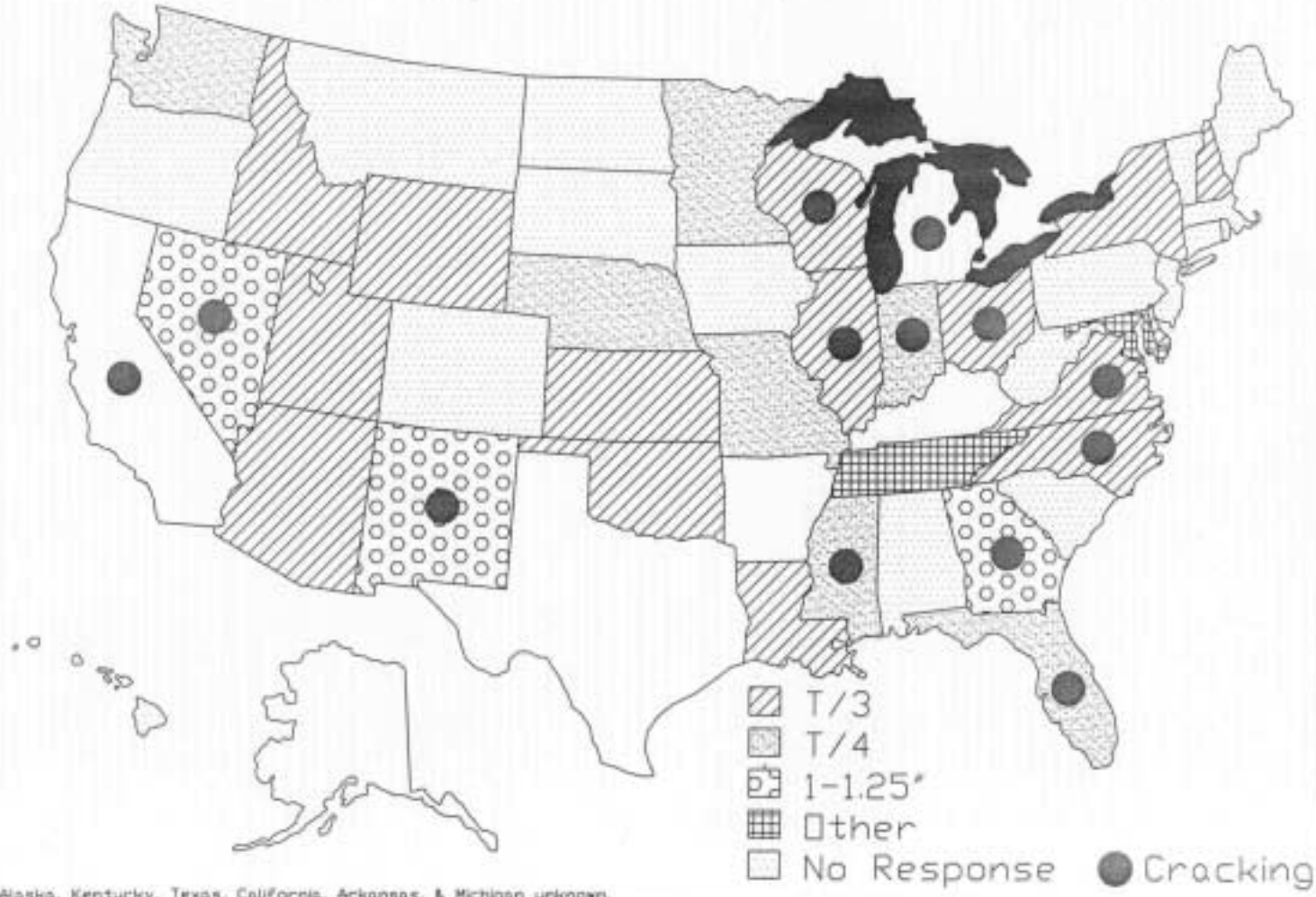
Panel Length vs. Thickness Ratios

☐ No Response

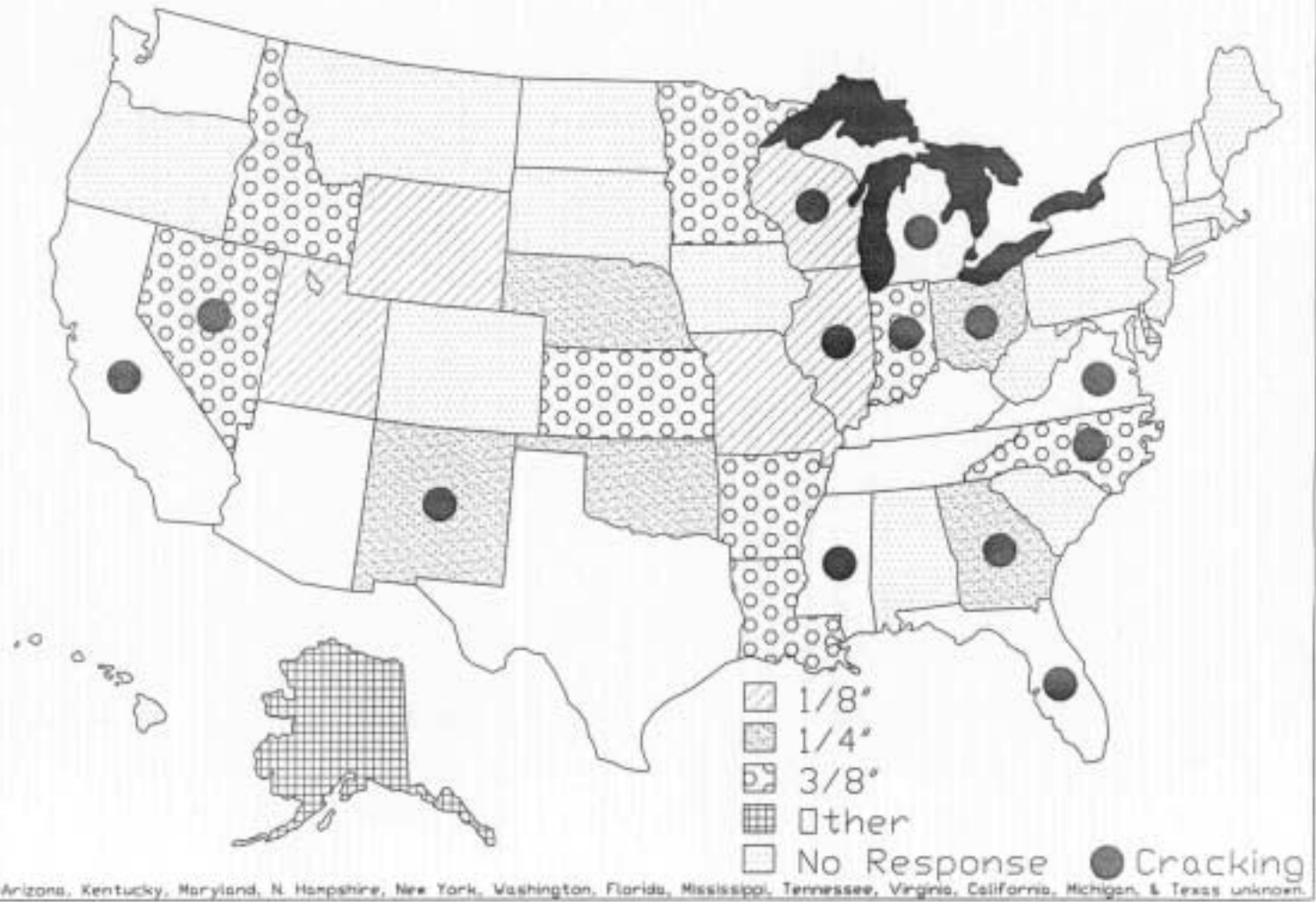


***Michigan, Mississippi, & Nevada unknown.

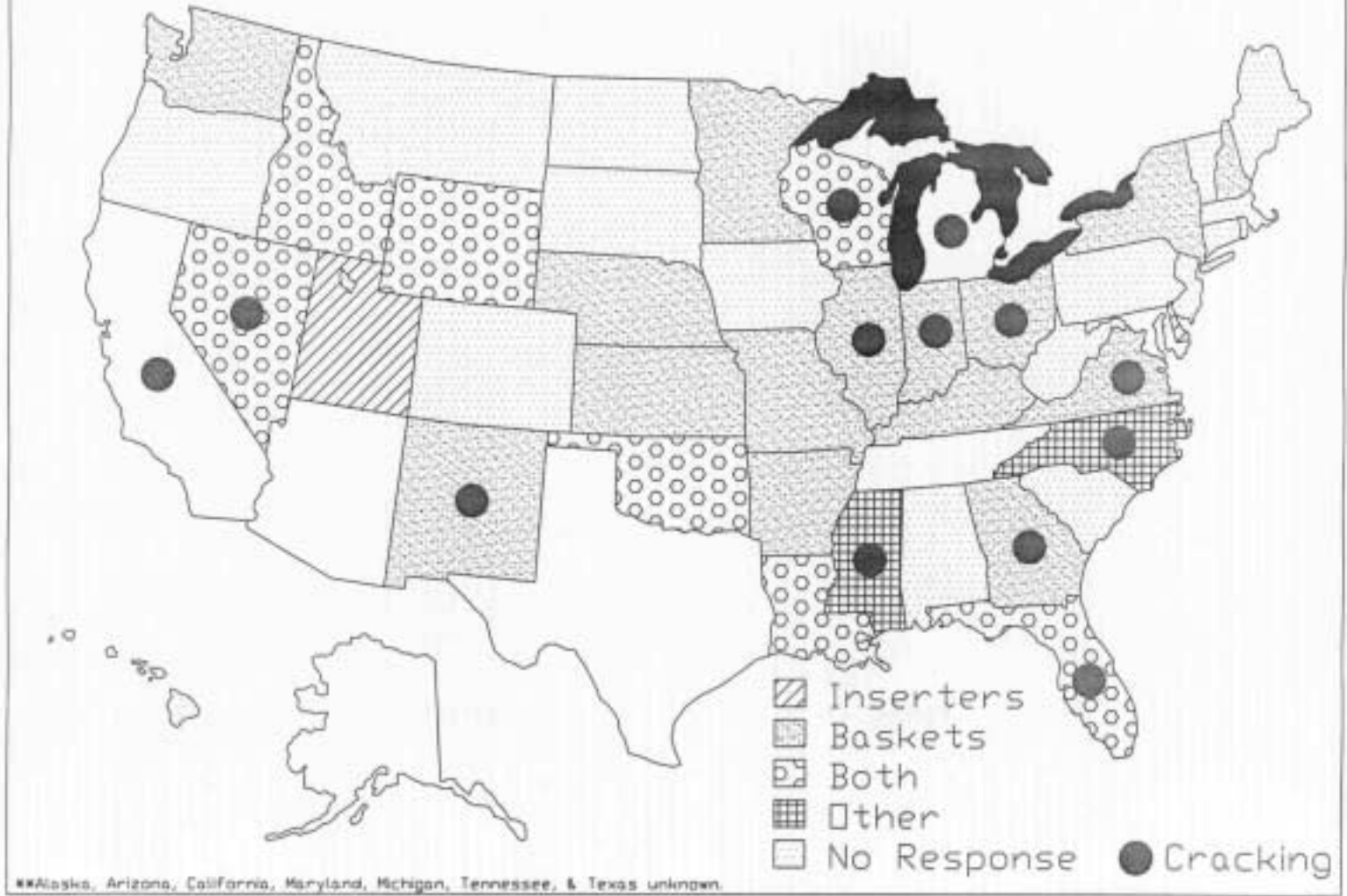
Typical Joint Depth



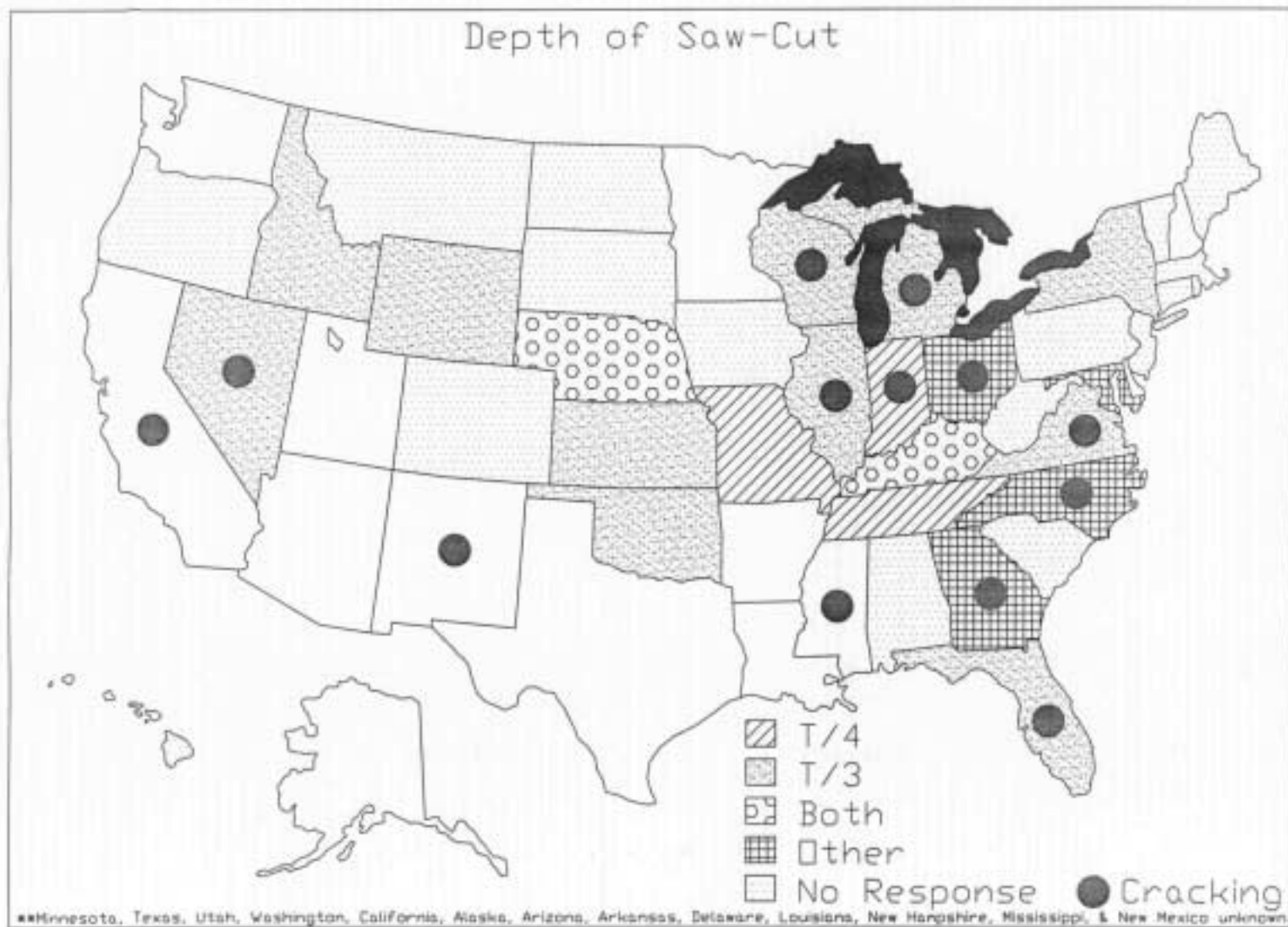
Typical Joint Opening



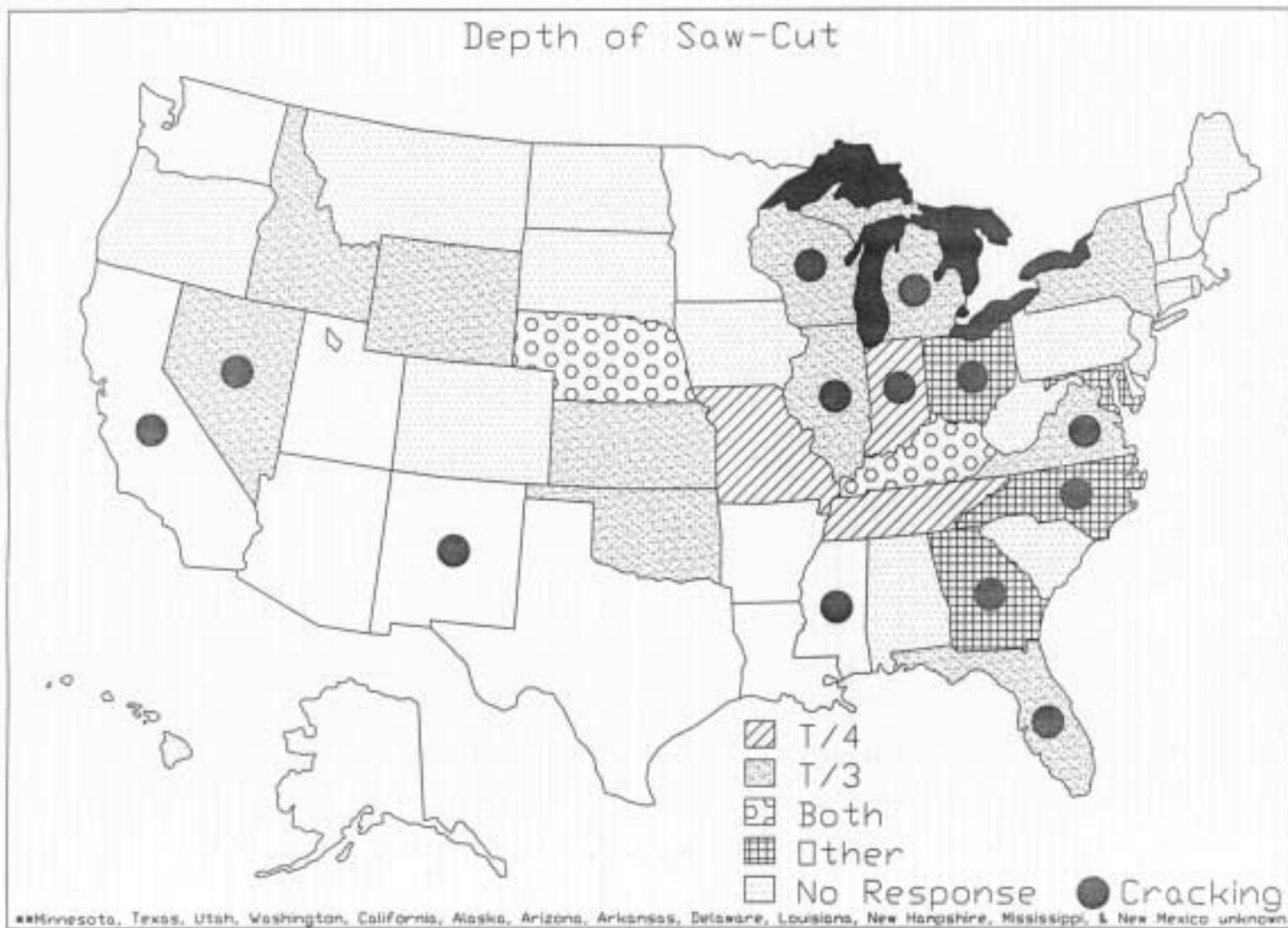
Dowel Installation Technique



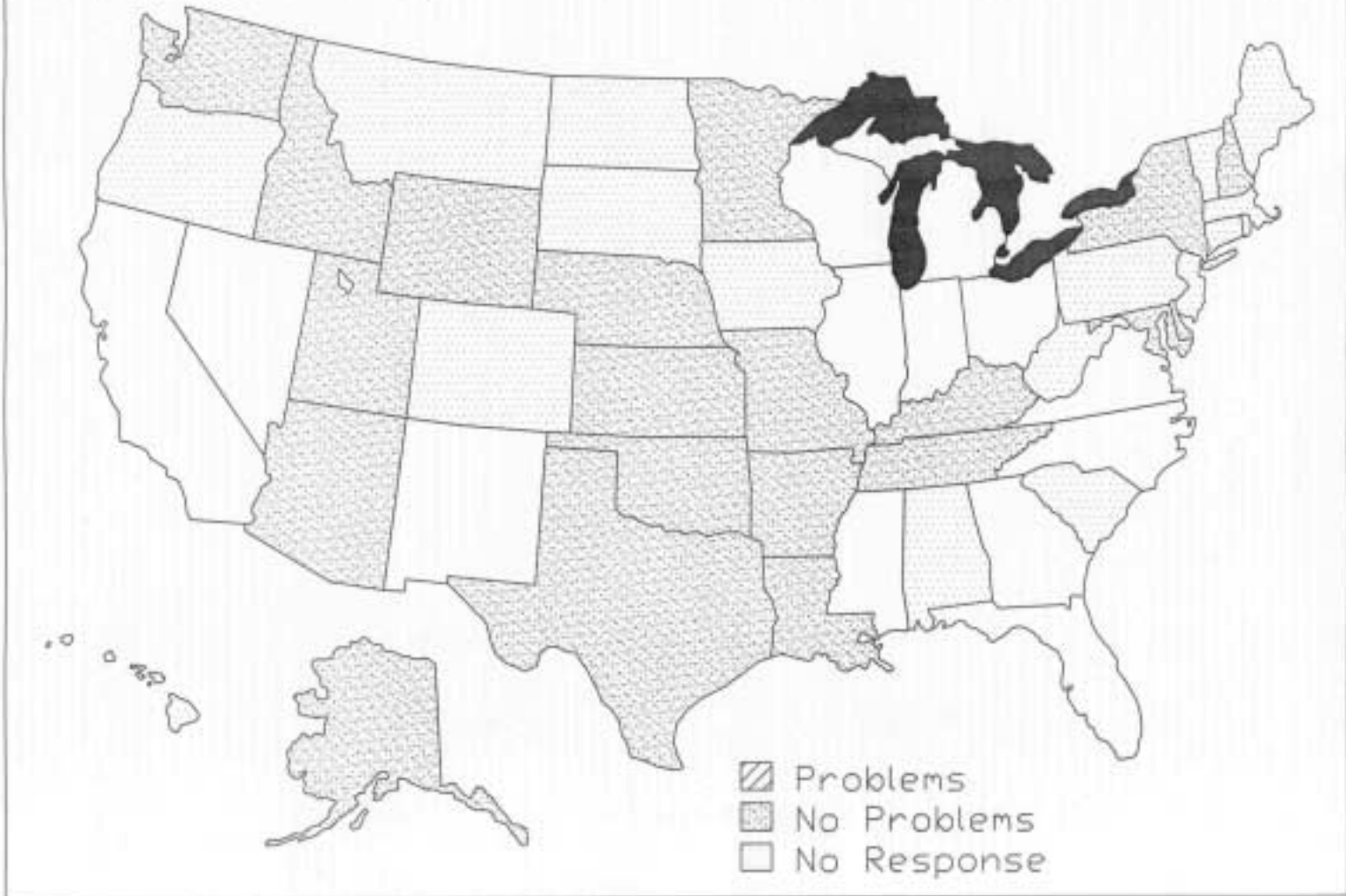
Depth of Saw-Cut



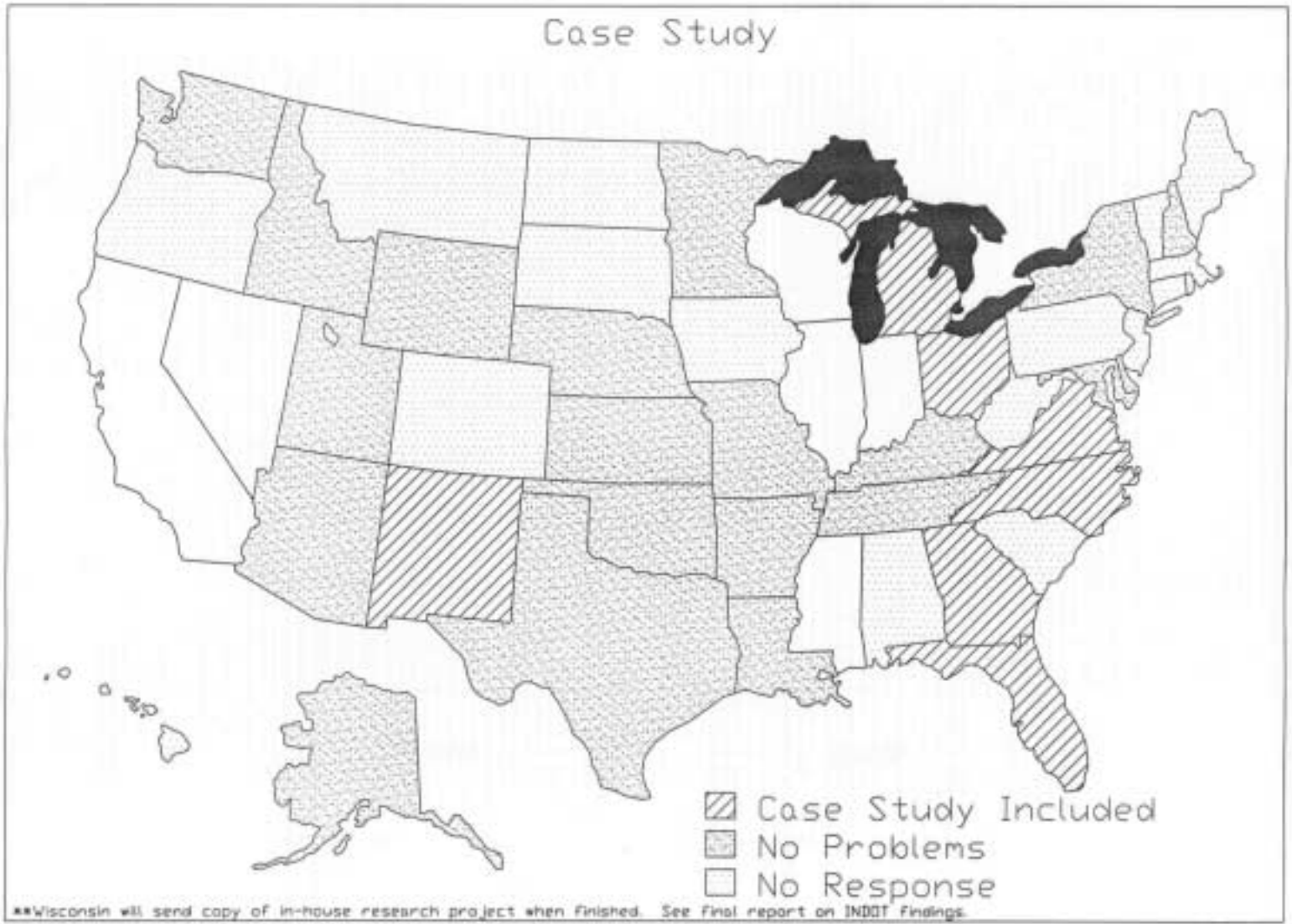
Depth of Saw-Cut



Mid-panel Cracking of Portland Cement Concrete Pavements



Case Study



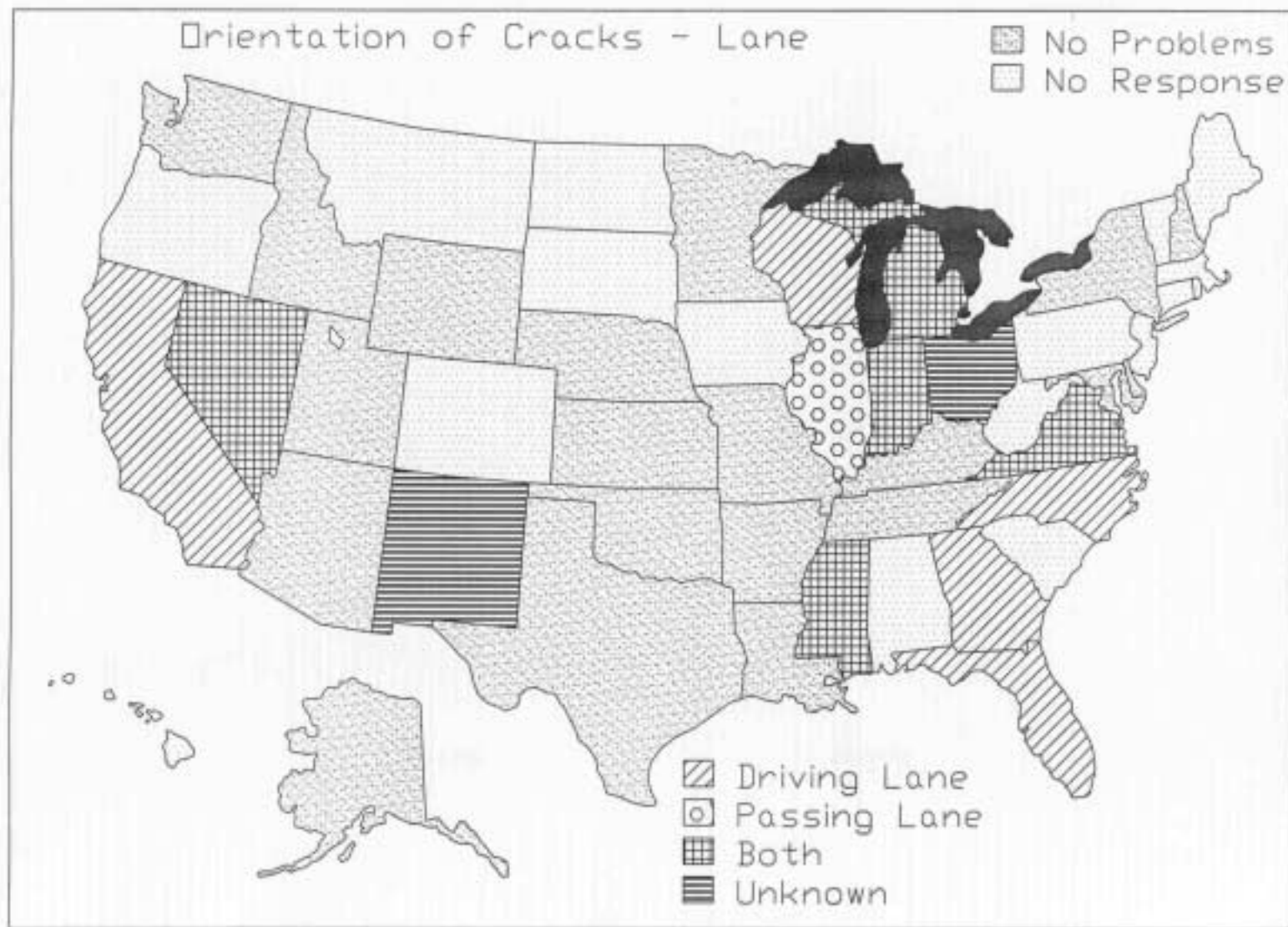
Time After Opening Cracking Occurs

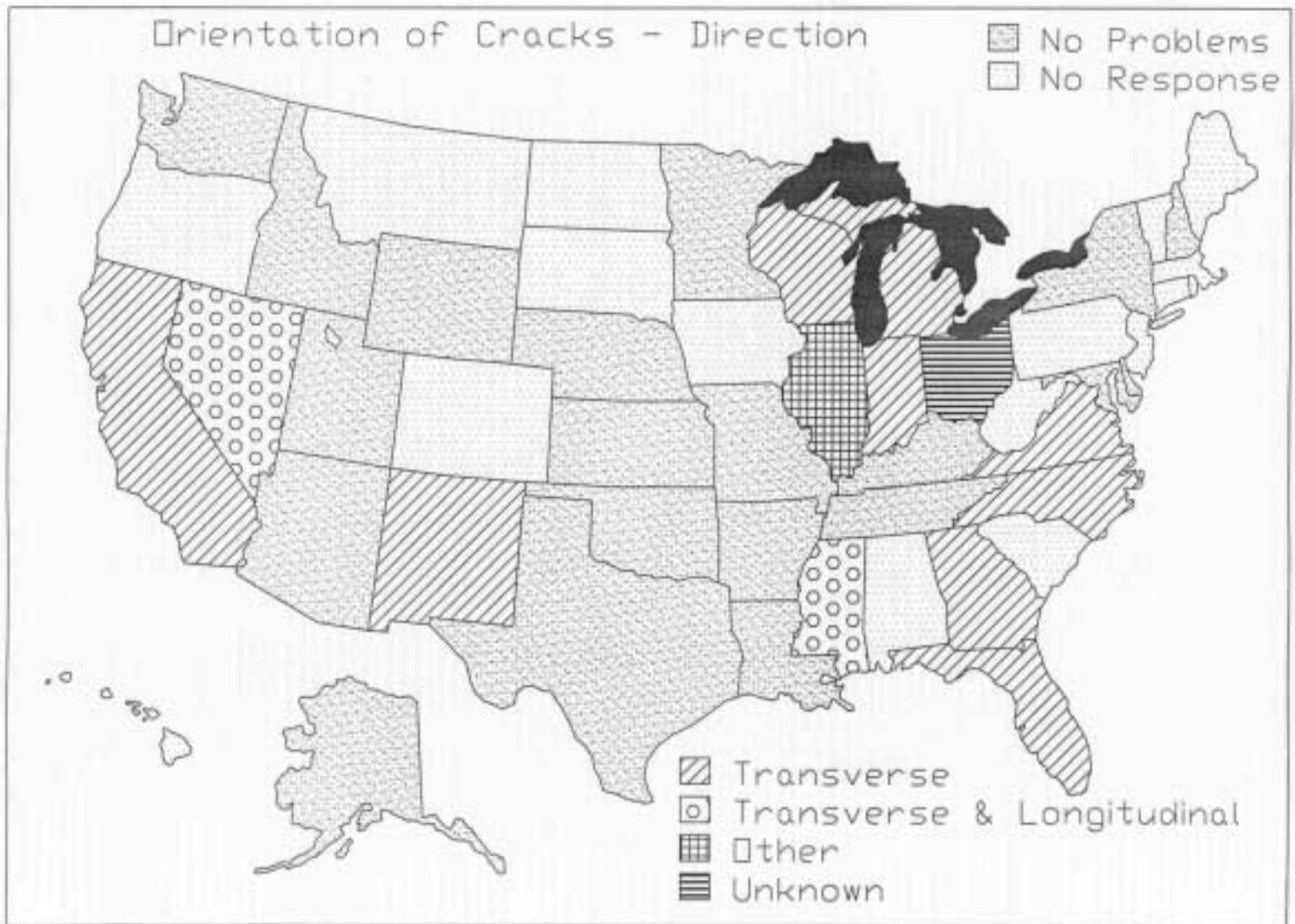
- No Problems
- No Response



- Prior to Opening
- Years Later
- Combination (prior, months, years)
- Unknown

Orientation of Cracks - Lane





In-house Sponsored Research Projects

