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Rehabilitation of Concrete Pavements

Volume II: Overlay Rehabilitation Techniques

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report is one volume of a four-volume set presenting the results of a research study to develop improved evaluation procedures and rehabilitation techniques for concrete pavements. Each report includes the Table of Contents for all four volumes. Eight rehabilitation techniques were selected for detailed investigation by field inspection and analytical study. These eight techniques are diamond grinding, load transfer restoration, edge support, full-depth repair, partial-depth repair, bonded concrete overlays, unbonded concrete overlays, and crack-and-seat with AC overlay. Based on analysis of the field data, a series of distress models were developed to predict the performance of the various rehabilitation techniques under a variety of conditions. These models and other information were then used to develop a comprehensive prototype system for jointed plain, jointed reinforced, and continuously reinforced pavement evaluation and rehabilitation.

This report will be of interest to engineers involved in planning, designing, or performing rehabilitation of concrete pavements.

Sufficient copies of this report are being distributed by FHWA memorandum to provide one copy to each FHWA Region and Division and two copies to each State highway agency. Direct distribution is being made to the division offices. Additional copies for the public are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Thomas J Pasko Jr

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and Highway Operations
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NOTICE

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16. Abstract

Extensive field, laboratory and analytical studies were conducted into the evaluation and rehabilitation of concrete pavements. Field studies included over 350 rehabilitated pavement sections throughout the U. S., and the construction of two field experiments. A laboratory study was conducted on anchoring dowels in full-depth repairs. Analyses of field and laboratory data identified performance characteristics, improved design and construction procedures, and provided deterioration models for rehabilitated pavements. A concrete pavement advisory system was developed to assist engineers in project level evaluation and rehabilitation.

The overlay techniques in Volume II include bonded concrete, unbonded concrete and crack and seat with an asphalt concrete overlay.

This volume is the second in a series. The others in the series are:

FHWA NO.	Vol. No.	Title
RD-88-071	I	Repair Rehabilitation Techniques
RD-88-073	III	Conc. Pvt. Eval. and Reh. System
RD-88-074	IV	Appendixes

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2

VOLUME

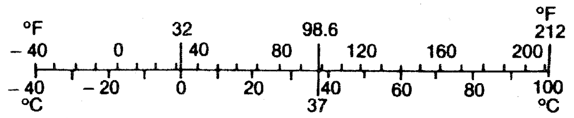
Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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CHAPTER 1

INTRODUCTION

1.0 STUDY OBJECTIVE

The overall objective of this study was to develop improved evaluation procedures and rehabilitation techniques for concrete pavements. This objective was accomplished through extensive field, laboratory and analytical studies that have provided new knowledge and understanding of the performance of rehabilitated concrete pavements. New and unique evaluation and rehabilitation procedures and techniques were developed that will be very useful to practicing pavement engineers.

This final report, presented in four volumes, documents all of the results developed under the contract, "Determination of Rehabilitation Methods For Rigid Pavements", conducted for the Federal Highway Administration. This volume documents the results of the study on Overlay Rehabilitation Techniques.

1.1 FIELD STUDIES

The field studies involved a large and extensive field survey of 361 rehabilitation sections of jointed plain and reinforced concrete pavement. These sections were located in 24 States as shown in figure 1 and table 1. Eight rehabilitation techniques were selected for detailed study:

- Diamond grinding.
- Load transfer restoration.
- Edge support.
- Full-depth repair.
- Partial-depth repair.
- Bonded concrete overlays.
- Unbonded concrete overlays.
- Crack and seat and AC overlay.

The extent of the pavement surveys is more fully summarized in table 2, which shows the number of database records and the contents of each record for each of the rehabilitation techniques. Considering full-depth repairs for example, there were 96 different projects located in 22 States, these consisted of 233 different repair designs, for a total of 2001 actual full-depth repairs surveyed.

There were five basic data types that were deemed necessary for the development of performance prediction models and the development and improvement of design and construction procedures. These include:

- Field condition data.

- Original pavement structural design, in situ conditions, and historical improvement data.

- Rehabilitation design data.

- Historical traffic volumes, vehicle classifications and accumulated 18-kip [80 kN] equivalent single-axle loadings.

- Environmental data.

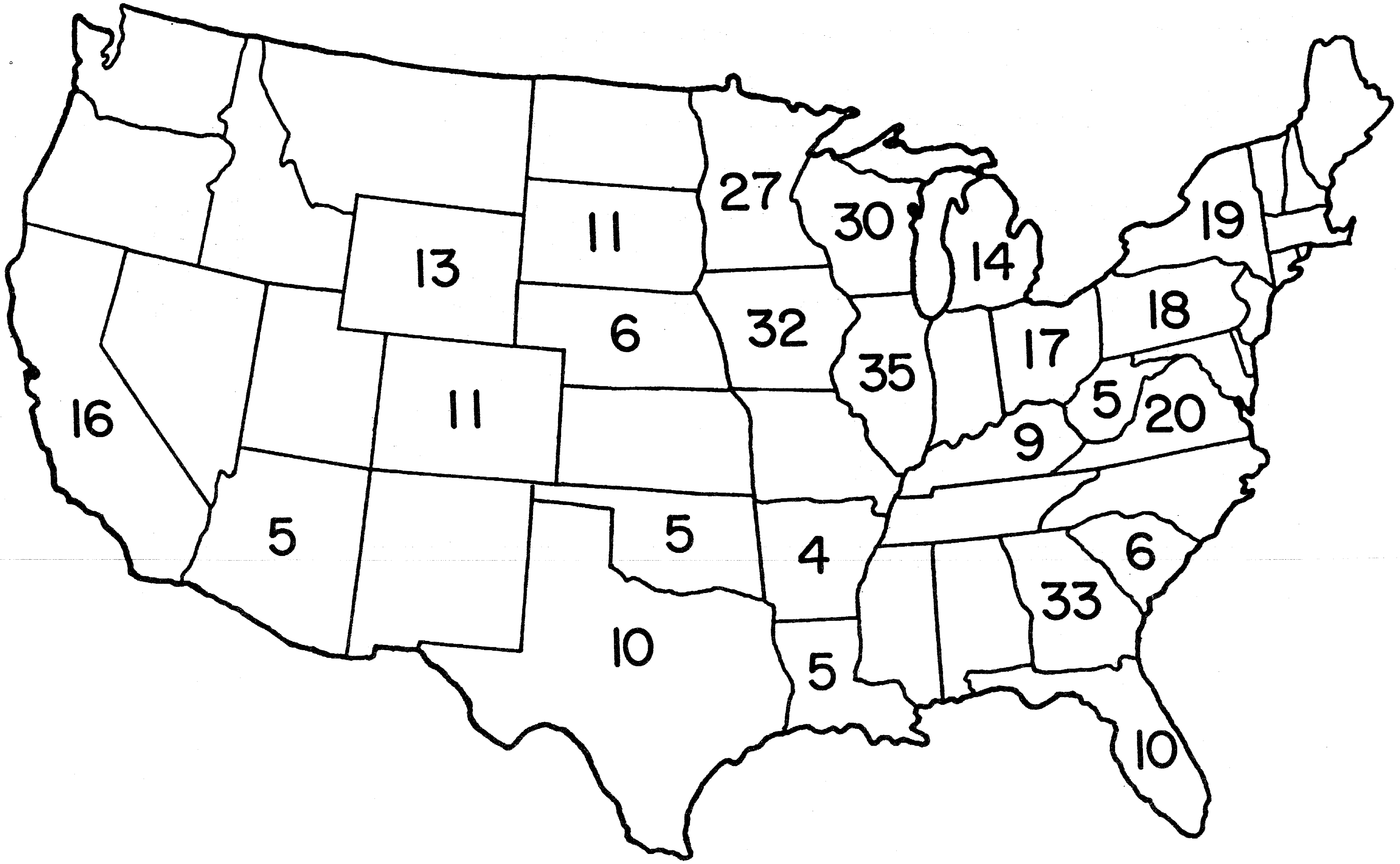

Figure 1. General locations of all rehabilitation projects surveyed.

Table 1. Breakdown of rehabilitation techniques by State.

STATE	FDR	PDR	DGD	LTR	CAS	UNBOL	BOL	ES	TOTAL
Arizona	1	1	3	0	0	0	0	0	5
Arkansas	1	0	1	0	1	0	0	1	4
California	3	0	7	0	6	0	0	0	16
Colorado	2	0	1	1	2	3	0	2	11
Florida	3	0	2	0	5	0	0	0	10
Georgia	5	6	16	2	0	2	0	0	31
Illinois	11	1	6	2	12	2	0	1	35
Iowa	5	0	2	0	0	0	25	0	32
Kentucky	0	0	0	0	9	0	0	0	9
Louisiana	1	1	1	1	0	0	1	0	5
Michigan	8	1	0	0	0	2	0	2	13
Minnesota	7	5	7	0	2	0	0	1	22
Nebraska	6	3	0	0	0	0	0	0	9
New York	1	1	2	2	10	0	2	0	18
Ohio	6	1	6	1	0	3	0	1	18
Oklahoma	1	0	2	2	0	0	0	0	5
Pennsylvania	5	2	3	1	2	2	0	2	17
South Carolina	2	1	2	0	0	0	0	1	6
South Dakota	0	3	3	0	3	0	1	0	10
Texas	6	3	0	0	0	0	0	0	9
Virginia	10	5	2	1	0	0	0	0	18
West Virginia	2	0	0	0	3	0	0	0	5
Wisconsin	8	1	5	0	15	0	0	0	29
Wyoming	2	1	5	0	0	0	2	2	12
Total	96	36	76	13	70	14	31	13	349

NOTE: FDR = full-depth repair
PDR = partial-depth repair
DGD = diamond grinding
LTR = load transfer restoration
CAS = crack and seat and AC overlay
UNBOL = unbonded concrete overlay
BOL = bonded concrete overlay
ES = edge support (tied PCC shoulder or edge beam)

* Represents the number of different uniform sections in the database. In addition, there are typically two replicate sample units for each different design.

Table 2. Summary of monitoring and design data for each rehabilitation technique.

DATABASE TYPE: MONITORING DATA

DATABASE	CONTENTS OF EACH RECORD	NUMBER OF RECORDS
FULL-DEPTH REPAIR	INDIVIDUAL PATCH DISTRESSES	2001
PARTIAL-DEPTH REPAIR	INDIVIDUAL PATCH DISTRESSES	1296
DIAMOND GRINDING	SAMPLE UNIT DISTRESSES	134
CRACK AND SEAT	SAMPLE UNIT DISTRESSES	120
BONDED OVERLAYS	SAMPLE UNIT DISTRESSES	50
UNBONDED OVERLAYS	SAMPLE UNIT DISTRESSES	21
EDGE SUPPORT	SAMPLE UNIT DISTRESSES	24
LOAD TRANSFER REST.	INDIVIDUAL JOINT AND CRACK DISTRESSES	421

DATABASE TYPE: DESIGN DATA

DATABASE	CONTENTS OF EACH RECORD	NUMBER OF RECORDS
FULL-DEPTH REPAIR	INDIVIDUAL PATCH DESIGN	233
PARTIAL-DEPTH REPAIR	INDIVIDUAL PATCH DESIGN	87
DIAMOND GRINDING	GRINDING TECHNIQUE DESIGN	105
CRACK AND SEAT	CRACK AND SEAT DESIGN	114
BONDED OVERLAYS	OVERLAY DESIGN	39
UNBONDED OVERLAYS	OVERLAY DESIGN	19
EDGE SUPPORT	SHOULDER/EDGE BEAM DESIGN	17
LOAD TRANSFER REST.	LOAD TRANSFER DESIGN	36
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The data sources and collection procedures used in this research study are described below.

1.1.1 Field Condition Surveys

A standard field condition survey was performed on each project or uniform section. The procedures used in the collection of condition data closely follow those described in NCHRP Project 1-19 (COPES) study for field data collection.(1) The distress identification manual developed for the COPES study was used as a standard for the identification and measurement of distresses and their severity levels.

The term "uniform section" was defined in the COPES study as a section of pavement with "uniform characteristics along its length including structural design, joint design and spacing, reinforcement, truck traffic, subgrade conditions, and distress".(2) To properly incorporate rehabilitation technique variation (e.g., different full-depth repair designs, different overlay thicknesses, etc.) into the uniform section concept, it was necessary to expand the definition of a uniform section to include uniformity of rehabilitation design.

Preliminary Work

The first step in project selection was to contact State department of transportation personnel to determine their interest in participating in the study. Project description forms were then sent to those States who were interested and willing to participate. The State personnel then selected representative rehabilitation projects that included one or more of the eight techniques, and filled out a project description form for each section.

The project description forms from all over the country were reviewed by the University of Illinois staff, any inappropriate sections excluded (where one or more of the eight rehabilitation techniques were not included for example), and detailed data collection forms were sent to the State personnel for the selected projects in their State. Upon completion of these data collection forms, data entry into the database was begun. If important data items were missing, an additional written request was sent to the State personnel for this information. In some cases, this information was retrieved in person through a trip to the State department of transportation office.

In preparation for the field work, the beginning and ending markers (stations, mileposts, landmarks) of the project were determined as best as possible in the office by verbal communication with State department of transportation personnel, prior to the commencement of surveying procedures. These steps ensured that any changes in uniform section pertaining to variations in the design of the original pavement or rehabilitation design would not be overlooked.

Field Work

After the preliminary identification of the uniform sections to be surveyed, the following procedures were used in the field data collection process.

- A two-person trained survey crew made at least one pass over the project areas at the posted speed. During the pass, changes in the pavement condition, in situ foundation conditions (cut/fill) and drainage were noted. This pass was used to determine whether one or more uniform sections were necessary on the basis of pavement distress, grade or drainage variation.

- The uniform sections were surveyed by representative sampling. Usually two 1000-ft [305 m] sample units were surveyed per uniform section. If the section was of considerable length (greater than 10 miles [16.1 km]), a third sample unit was taken to ensure reasonable coverage. The location of the sample units was selected randomly; however, sample units were selected such that grade conditions (cut/fill) along their lengths were as uniform as possible. Also, in consideration of the fact that a project or sample unit might require additional evaluation at some future date, many of the sample units were located at milepost markers for easier future identification.

- A very comprehensive distress survey was conducted along each sample unit. The condition of both lanes was measured where traffic or other conditions did not pose a serious safety hazard to the survey crew. The outer lane survey was conducted from the outer shoulder of the pavement and, likewise, the inner lane survey was conducted from the inner shoulder. Measurements of faulting and joint widths were taken 1 foot [0.3 m] from the PCC slab lane edge. Also, photographs of the pavement, general topography and other distresses were recorded.

- The presence of subsurface drainage and the condition of subsurface drainage facilities were noted.

1.1.2 Original Pavement and Rehabilitation Design Factors

For the collection of this data, the as-built original construction and rehabilitation construction plans, as well as special provisions for the rehabilitation projects, were obtained for each project. Much of the required data was obtained from these records; however, consultation with State department of transportation personnel was also necessary to collect additional information. Finally, data from other sources such as published reports was also used.

A detailed listing of the variables collected under this study pertaining to original pavement and rehabilitation design and rehabilitation field monitoring is included in volume IV.

1.1.3 Traffic Data

Values for the average annual daily traffic and percent heavy commercial truck traffic were also collected from the State department of transportation records. Historical information was collected where the data was available; however, in some instances only current traffic levels were obtained. For the determination of the number of equivalent 18-kip [80 kN] single-axle loadings (ESALs) accumulated on each project, Federal Highway Administration W-4 truck axle load distribution data were utilized to compute the truck factors over the life of the pavements. The number of accumulated axle loads from the time of original pavement construction until the time each rehabilitation technique was applied, and from then until the time of survey, was calculated for each project.

1.1.4 Environmental Data

The average monthly precipitation and average daily minimum, maximum and mean temperatures were taken from National Oceanic and Atmospheric Administration data. The nearest weather station was assumed to be representative of the conditions at the project site. The mean Freezing Index was interpolated from the contour map developed by the Corps of Engineers for the continental United States.(2) The climatic zone as classified by Carpenter was also determined for each site.(2)

1.2 LABORATORY STUDIES

Laboratory studies included the first comprehensive testing of dowel anchoring procedures and designs. Full scale repeated shear loading of dowels was conducted for up to one million load repetitions using slabs cut from I-70 in Illinois. Many different design, material and construction variables were considered in a factorial type experimental design.

1.3 ANALYTICAL STUDIES

Analytical studies were accomplished primarily to develop prediction models for rehabilitated pavement deterioration so that the service life of different rehabilitation techniques could be estimated. Twelve distress models were developed including reflective cracking, faulting, rutting, and serviceability for most of the above rehabilitation techniques. These models were incorporated into the evaluation and rehabilitation system.

1.4 EVALUATION AND REHABILITATION SYSTEM

A comprehensive concrete pavement evaluation and rehabilitation system was developed for jointed plain, jointed reinforced and continuously reinforced concrete pavements. This system is intended to assist the design engineer in the following rehabilitation project design activities:

- Project data collection.
- Evaluation of present condition.
- Prediction of future condition without rehabilitation.
- Physical testing recommendations.
- Selection of feasible rehabilitation approaches.
- Development of detailed rehabilitation recommendations.
- Prediction of performance of the rehabilitation strategy.
- Cost analysis and selection of the preferred rehabilitation alternative.

The results of this research are published in four volumes:

●	Volume I	Repair Rehabilitation Techniques
●	Volume II	Overlay Rehabilitation Techniques
●	Volume III	Concrete Pavement Evaluation/Rehabilitation System
●	Volume IV	Appendixes

Each of these volumes are stand alone volumes that present the data, analyses and conclusions for each of the rehabilitation techniques and the evaluation and rehabilitation system.

CHAPTER 2

BONDED PORTLAND CEMENT CONCRETE OVERLAYS

2.0 RESEARCH APPROACH

Portland cement concrete (PCC) bonded overlays are designed to achieve a total permanent bond of the new overlay to the existing concrete. This type of overlay has been used as part of experimental and routine resurfacing for many years, particularly on airports. However, within about the last 10 years, the practice of overlaying existing concrete pavements with bonded PCC has increased.

To date there has been no nationwide documentation of the performance of this overlay technique, nor has a uniformly recognized standard for construction procedures been developed. A few procedures exist for the design of bonded concrete overlays, but none have been verified with field performance.

Many references were reviewed for bonded concrete overlays. Several new publications have recently become available that have added considerable knowledge to the design, construction and performance of bonded concrete overlays.(7,9,21,25,27,52,59,60,61,62,63,64,65,66,67) An excellent report entitled "Status Of Thin-Bonded Concrete Overlays" provides a description of several newly constructed bonded overlays.(61)

The development of an extensive database containing information on the original pavement design, concrete overlay design, traffic, environmental conditions and performance of existing overlays was required. The database was developed in order to allow analysis to include the consideration of many factors which might affect performance. To obtain all of the necessary database elements the following methods and sources were utilized:

- Extensive field surveys including mapping of cracks, physical measurements and subjective ratings were conducted on each project to document the current condition of the overlay.

- The design of the original pavement structure was determined from "as-built" plans and verbal communication with State DOT personnel.

- The design of the overlay was determined through the analysis of special rehabilitation construction provisions, "as-built" plans and verbal communication with State DOT personnel.

- Environmental data was taken from documentation of the monthly normal temperature, precipitation, and heating and cooling degree days by the National Oceanic and Atmospheric Administration.

- Traffic estimates, including average daily traffic and percent commercial trucks, were obtained from the State DOT's. For the calculation of accumulated axle-loads on each project, Federal Highway Administration historical W-4 tables on axle load distributions for respective States and pavement classifications were used.

Physical test data were not collected. This data would have greatly increased the ability to analyze and interpret the pavement deterioration identified from visual surveys. The most useful tests would include heavy load deflection testing and coring (plus laboratory testing). An understanding of the physical properties of the pavement layers, loss of support, load transfer and gradations (of the base) would have made it possible to conduct structural, material and drainability evaluations.

2.1 DATABASE AND DATA COLLECTION

A total of 32 bonded concrete overlay sections obtained from 19 different designs were included in the database (those located on two-lane highways were considered as two sections, one for each direction of travel). Two sample units having a length of about 1000 ft [305 m] were obtained from each of the sections where possible (50 total). The projects included in the database represent most of the bonded concrete overlay highway pavements in the United States constructed after 1973. These pavements were field surveyed between June 1985 and July 1986. Figure 2 shows the general location of the bonded overlays. Most of the bonded overlays are located in wet-freeze areas where this rehabilitation technique was pioneered by Iowa.

A detailed description of the field and office data collection procedures is given in volume IV. Five basic data types were necessary for the development of life prediction models and for analysis aimed towards the development and improvement of design and construction procedures. These include:

- Field condition data.
- Original pavement structural design, in-situ conditions, and historical improvement data.
- Rehabilitation design factors.
- Historical traffic values, classifications and accumulated 18-kip [80 kN] equivalent single-axle loadings.
- Environmental data.

A complete list of all of the variables considered in the field surveys is given in table 3. The design variables for the original pavement which are contained in the database are given in table 4. Variables for the bonded overlay construction and design are given in table 5.

The database is comprehensive containing as many projects as were available, or that could be included with available resources. This was done to provide a wide range of data to facilitate regression analysis for the development of performance models.

Figures 3 and 4 give the overlay age and thickness distribution. The age distribution indicates the relative newness of the bonded concrete overlay technique (1 to 12 years). The thickness distribution shows 2 to 5 in [5.1 to 12.7 cm] of bonded concrete.

Key overlay construction and design variables are included in table 6 for each section. Key variables that may affect performance, such as bonding materials, surface preparation techniques and construction date are included.

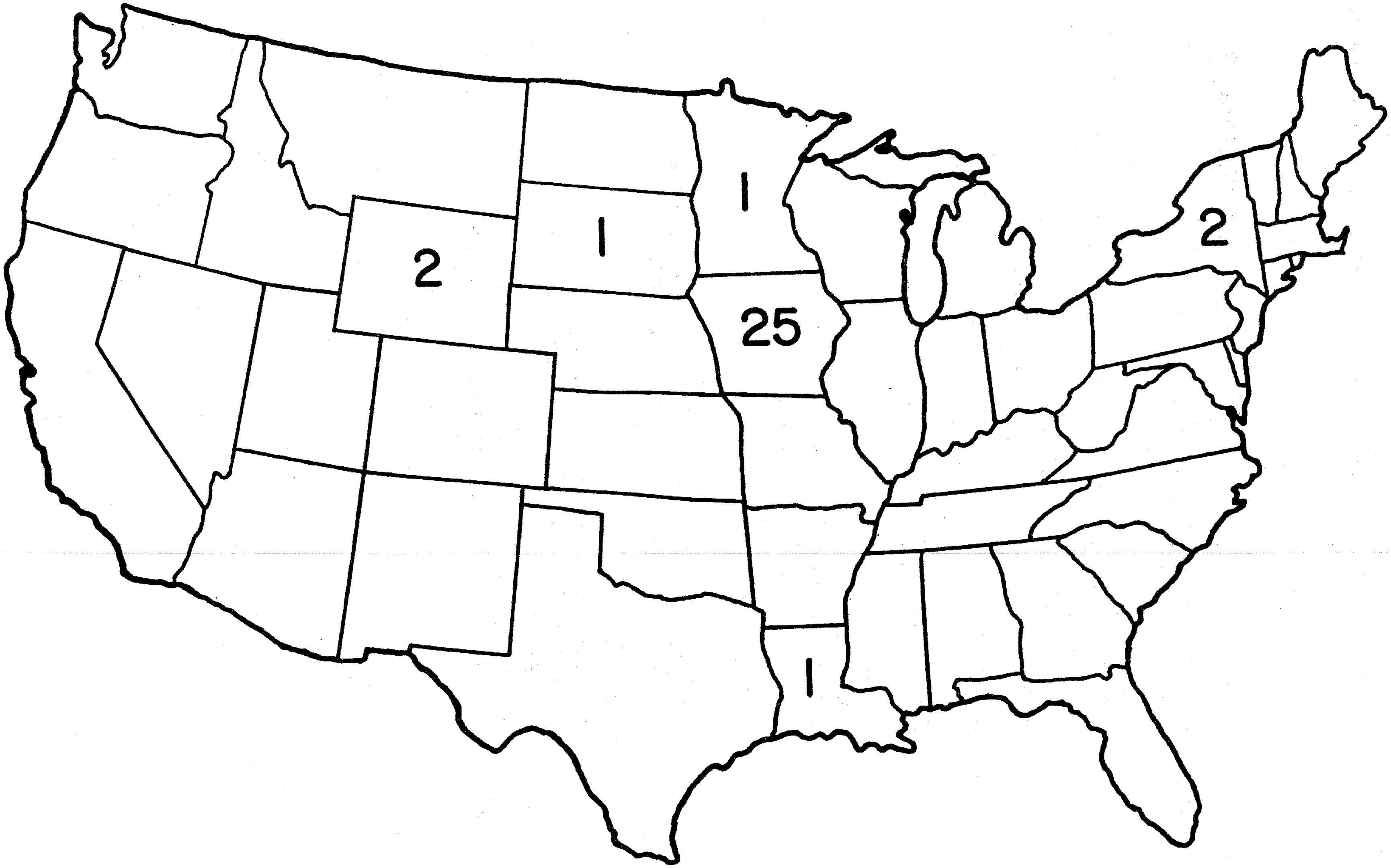


Figure 2. General locations of bonded PCC overlays.

Table 3. Pavement condition variables collected in the field surveys.

FIELD SURVEY PAVEMENT CONDITION VARIABLES

FIELD DATA GENERAL VARIABLES

- Sample Unit Length.
- Foundation of Sample Unit.
- Condition of Drainage Ditches.
- Subsurface Drainage Present and Functional.
- Number of Transverse Joints on the Sample Unit.

FIELD DATA DISTRESS VARIABLES

- Transverse Cracking.
- Transverse "D" Cracking.
- Longitudinal Cracking.
- Longitudinal "D" Cracking.
- Longitudinal Joint Spalling.
- Scaling, Crazing, Map Cracking.

JOINT DISTRESS SUMMARY

- Spalling Transverse Joint (approach side, leave side).
- Corner Spalling (approach side, leave side).
- Pumping.
- Mean Joint Faulting over Sample Unit.
- Mean Joint Width over Sample Unit.
- Corner Breaks (approach side, leave side).
- "D" Cracking Along Joint.
- Reactive Aggregate Distress.
- Sealant Conditions and Incompressibles in Joint.

Table 4. Original pavement construction and design variables.

ORIGINAL PAVEMENT DESIGN VARIABLES

GENERAL PROJECT VARIABLES

- Identification Number (State Code, Highway #, Milepost, Direction).
- Beginning & Ending Mile Marker (Station).
- Number of Through Lanes.
- Type of Original Pavement (JPCP, JRCP).
- Layer Descriptions, Thicknesses, Material Types.
- Date of Original Pavement Construction.
- Dates and Description of Major Pavement Improvements.

JOINTS AND REINFORCING VARIABLES

- Average Contraction Joint Spacing.
- Skewness of Joints.
- Expansion Joint Spacing.
- Transverse Contraction Joint Load Transfer System.
- Dowel Diameter and Length.
- Type of Slab Reinforcing (Welded Wire Fabric, Deformed Bars).
- Longitudinal Bar/Wire Diameter and Spacing.

SUBGRADE, SHOULDER AND DRAINAGE VARIABLES

- Type of Subgrade Soil (Fine Grained, Coarse Grained).
- Outer Shoulder Surface Type.
- Original Subsurface Drainage Type.
- Original Subsurface Drainage Location (Continuous, Intermittant).

Table 5. Overlay construction and design variables.

CONCRETE OVERLAY DESIGN VARIABLES

GENERAL OVERLAY PROJECT VARIABLES

- Type of Concrete Overlay (JPCP, JRCP) .
- Bonding Condition of Overlay (Bonded, Unbonded, Partially Bonded).
- Initial Surface Preparation .
- Final Surface Preparation.
- Type of Grout Used for Bonding Overlays .
- Type of Debonding Material Used .

JOINTS AND SLAB REINFORCEMENT VARIABLES

- Overlay Jointing Arrangement .
- Average Overlay Contraction Joint Spacing .
- Expansion Joint Spacing .
- Skewness of Joints .
- Contraction Joint Load Transfer System (Dowels, Aggregate Interlock).
- Dowel Diameter, Spacing and Length .
- Method used to Form Transverse Joints (sawing, inserts) .
- Type of Overlay Slab Reinforcement (wire fabric, deformed bars).
- Longitudinal Bar Diameter and Spacing .

SHOULDER VARIABLES

- Outer Shoulder Surface Type .
- Lane/Shoulder Tie Bar Diameter, Spacing and Length .

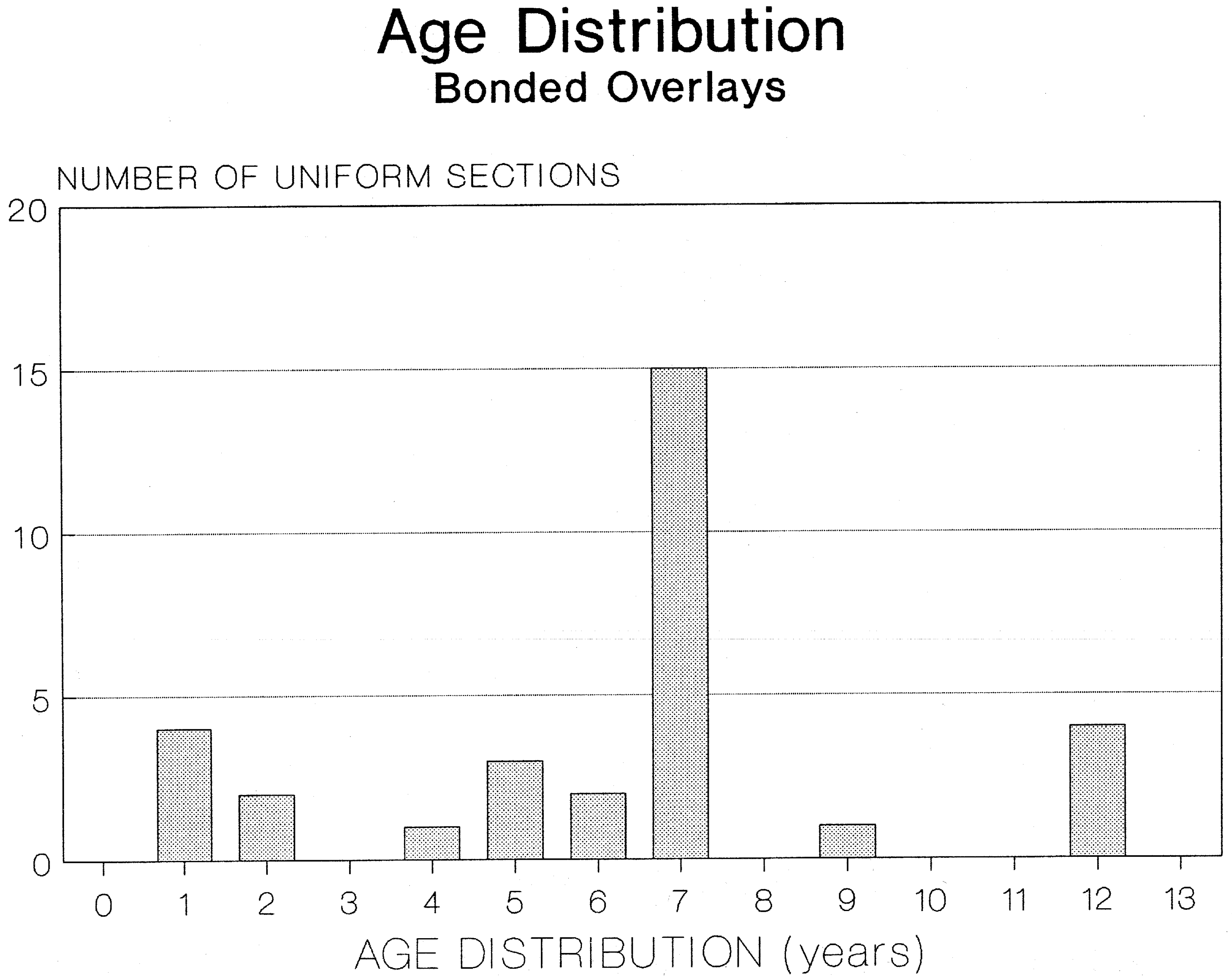


Figure 3. Age distribution of bonded concrete overlays.

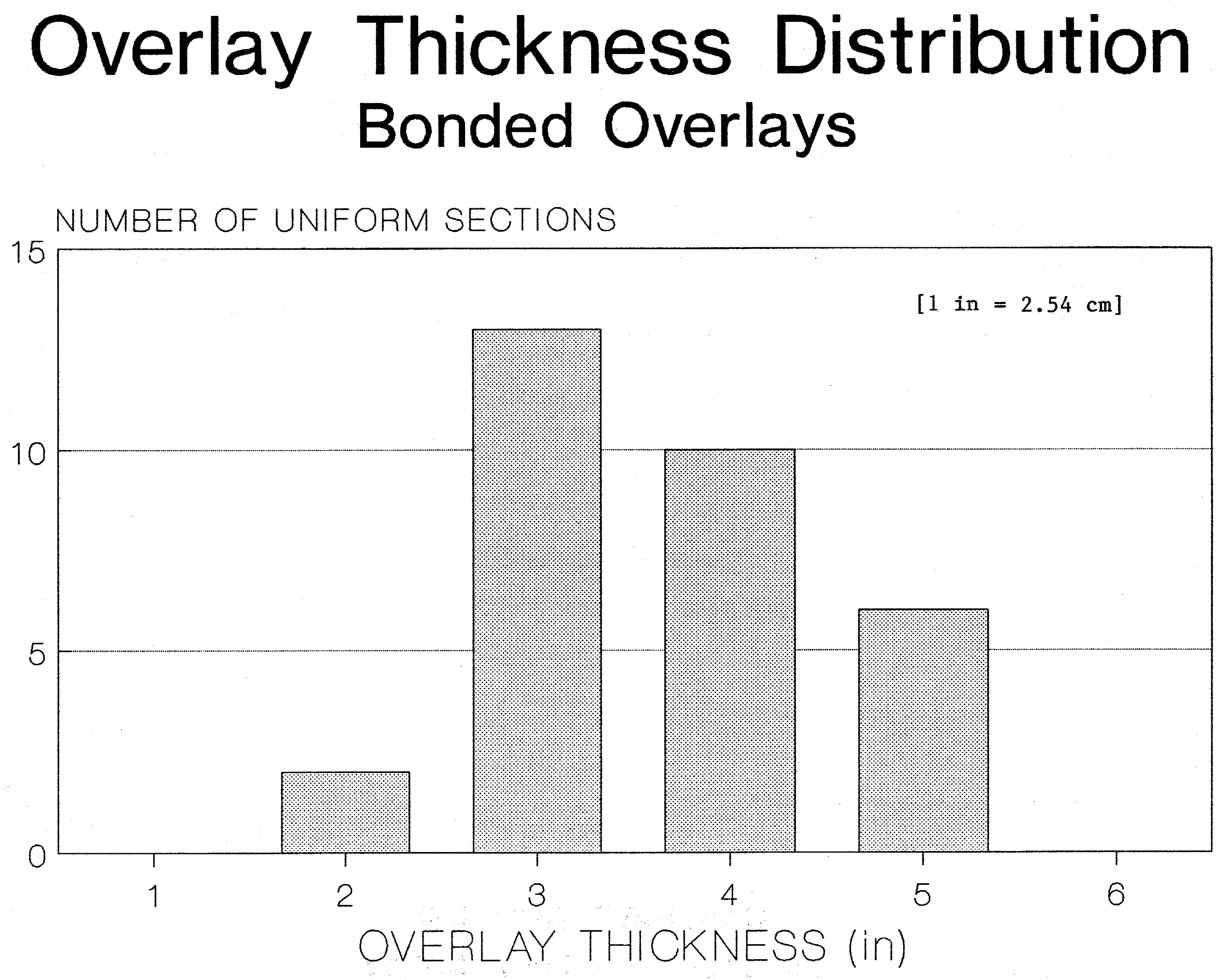


Figure 4. Distribution of the overlay thickness of bonded concrete overlays.

Table 6. Design and construction data for bonded concrete overlays.

PROJECT	DESCRIPTION	SURFACE PREPARATION	OVERLAY THICKNESS (inch)	OVERLAY TYPE	YEAR OF OVERLAY CONSTR.
A(1) *	IA Clayton county	Sand Blast	3	PLAIN	1978
A(2) *	IA Clayton county	Sand Blast	3	REINF	1978
A(3) *	IA Clayton county	Cold Mill	5	PLAIN	1978
A(4) *	IA Clayton county	Cold Mill	5	REINF	1978
A(5) *	IA Clayton county	Sand Blast	4	PLAIN	1978
A(6) *	IA Clayton county	Cold Mill	4	REINF	1978
A(7) *	IA Clayton county	Sand Blast	2	PLAIN	1978
B	IA I-80 Grinnel	Cold Mill Sand Blast	4	PLAIN	1984
C	IA I-80 Avoca	Cold Mill Sand Blast	4	PLAIN	1979
D	IA US-20 Waterloo	Cold Mill Sand Blast	3	PLAIN	1976
E	IA US-141 Perry	Cold Mill Sand Blast	3	PLAIN	1983
F	IA SR-12 Souix City	Cold Mill Sand Blast	3	PLAIN	1978
G(1) *	IA Greene County	Sweeping	5	REINF	1973
G(2) *	IA Greene County	Sweeping	4	REINF	1973
H	LA US-61 Baton Rouge	Shot Blast Air Blast	4	PLAIN	1981
I	NY I-81 Syracuse	Cold Mill Sand Blast Air Blast	3	PLAIN	1981
J	SD SR-38A Souix Fall	Cold Mill	3	PLAIN	1985
K(1)	WY I-25 Douglas	Cold Mill Air Blast	3	PLAIN	1983
K(2)	WY I-25 Douglas	Cold Mill Air Blast	3	PLAIN	1983

* Indicates projects which are two lane highways. Both lanes are considered "drive" lanes for analysis of performance data.

Note: 1 in = 2.54 cm

Detailed descriptions of representative overlay projects are given in volume II, appendix A. For each project in the appendix, the following is provided:

- Project location.
- Original pavement design.
- Concrete overlay design.
- Traffic estimates.
- Environmental factors.
- Field performance.

This information is included to provide a concise reference and documentation of projects specifically included in the development of performance models and improved construction guidelines.

2.2 FIELD PERFORMANCE AND EVALUATION

Bonded concrete overlays can be designed to improve the structural capacity of the pavement, while also improving the rideability of the pavement through the provision of a new surface. An evaluation of distresses which may impede the structural capacity or rideability of the overlaid pavements is presented to determine improvements needed in design and construction to increase the reliability of the techniques.

The distresses that have been identified that may directly affect the structural integrity of the overlayed pavement are transverse and longitudinal cracking, joint faulting and pumping, corner breaks, shrinkage cracking and "D" cracking. Rideability of the overlay may be directly affected by most of the aforementioned distresses.

Further problems for consideration are from delamination of the overlay concrete near the slab corners and edges and secondary joint cracking, which may cause spalling and delamination at the joints.(2,3,4,30) For these debonding problems and for each of the observed distresses, a description of the development and extent of occurrence is given. Table 7 gives a summary of distresses, normalized to 1000 ft [305 m] of outer lane, found for each bonded overlay uniform section.

The severity levels employed in describing distresses are those defined in NCHRP Project 1-19 (COPES) distress manual.(1) For example, low severity cracking describes hairline cracking, medium severity describes working cracks and high severity a badly spalled and faulted crack needing immediate repair.

2.2.1 Transverse (Reflective) Cracking

<u>Field Observation</u>

Data on the condition of the existing pavements prior to the placement of the overlays was not available for most sections. Therefore a mapping process to discern the development of reflection cracking could not be conducted, except in Clayton County, Iowa. Field surveys on this project in 1979 (after 2 years of service) confirmed that all cracks that were in the existing slab had reflected through the overlay regardless of overlay thickness.(3)

The distribution of the severity of transverse cracking in the truck lane for bonded overlays is depicted in figure 5. Practically all uniform sections contained some low and medium severity transverse cracking. Only one project exhibited no transverse reflective cracking. This overlay section was built in South Dakota on

Table 7. Summary of bonded concrete overlay faulting and cracking observed on each uniform section surveyed.

* FOR TWO LANE ROADS, DATA FOR BOTH DRIVE LANES ARE SHOWN (ie. ** / **)

PROJECT	AGE (yr)	ADT	% TRUCKS	ACCUM. 18 k ESA (millions)	MEAN FAULTING (in)	LOW SEVERITY TRAN. CRACK (ft / 1000 ft)	MED SEVERITY TRAN. CRACK (ft / 1000 ft)	HIGH SEVERITY TRAN. CRACK (ft / 1000 ft)	LOW SEVERITY LONG. CRACK (ft / 1000 ft)	MED SEVERITY LONG. CRACK (ft / 1000 ft)	HIGH SEVERITY LONG. CRACK (ft / 1000 ft)
A(1) *	7	651	43	1.2 / .30	.07 /.06	127 / 43	428 / 325	35 / 25	5 / 0	51 / 10	0 / 0
A(2) *	7	651	43	1.2 / .30	.09 /.02	24 / 124	625 / 525	0 / 0	0 / 0	100 / 48	0 / 0
A(3) *	7	651	43	1.2 / .30	.07 /.03	0 / 0	720 / 360	0 / 0	0 / 0	8 / 0	0 / 0
A(4) *	7	651	43	1.2 / .30	.05 /.10	300 / 520	720 / 160	120 / 0	45 / 0	0 / 95	0 / 0
A(5) *	7	651	43	1.2 / .30	.09 /.07	0 / 0	300 / 180	0 / 0	55 / 17	40 / 0	0 / 0
A(6) *	7	651	43	1.2 / .30	.01 /.04	137 / 149	54 / 54	0 / 0	5 / 0	0 / 10	0 / 0
A(7) *	7	651	43	1.2 / .30	.10 /.02	560 / 240	180 / 70	0 / 0	40 / 53	20 / 20	0 / 0
B	1	14100	33	0.086	.05	504	24	0	4	0	0
C	6	10800	38	4.518	.06	372	60	0	10	0	0
D	9	7500	11	0.612	.07	90	490	0	41	0	0
E	2	4300	17	0.116	.02	215	12	0	5	0	0
F	7	21100	8	0.462	.04	9	30	0	7	16	0
G(1) *	12	1100	4	.96 /.96	.06 /.07	47 / 62	277 / 565	0 / 0	4 / 18	70 / 75	0 / 0
G(2) *	12	1100	4	.96 /.96	.06 /.04	120 / 23	524 / 518	0 / 0	25 / 10	85 / 22	0 / 0
H	5	11860	15	1.352	.02	35	0	0	0	0	0
I	5	23000	8	1.207	.05	526	12	0	0	0	0
J	4	4412	3	0.066	.02	0	0	0	0	0	0
K(1)	1	4390	27	0.162	0.01	48	0	0	8	0	0
k(2)	1	4390	27	0.162	0.01	168	0	0	240	0	0

Note: 1 in = 2.54 cm, 1 ft/1000 ft = 1 m/km

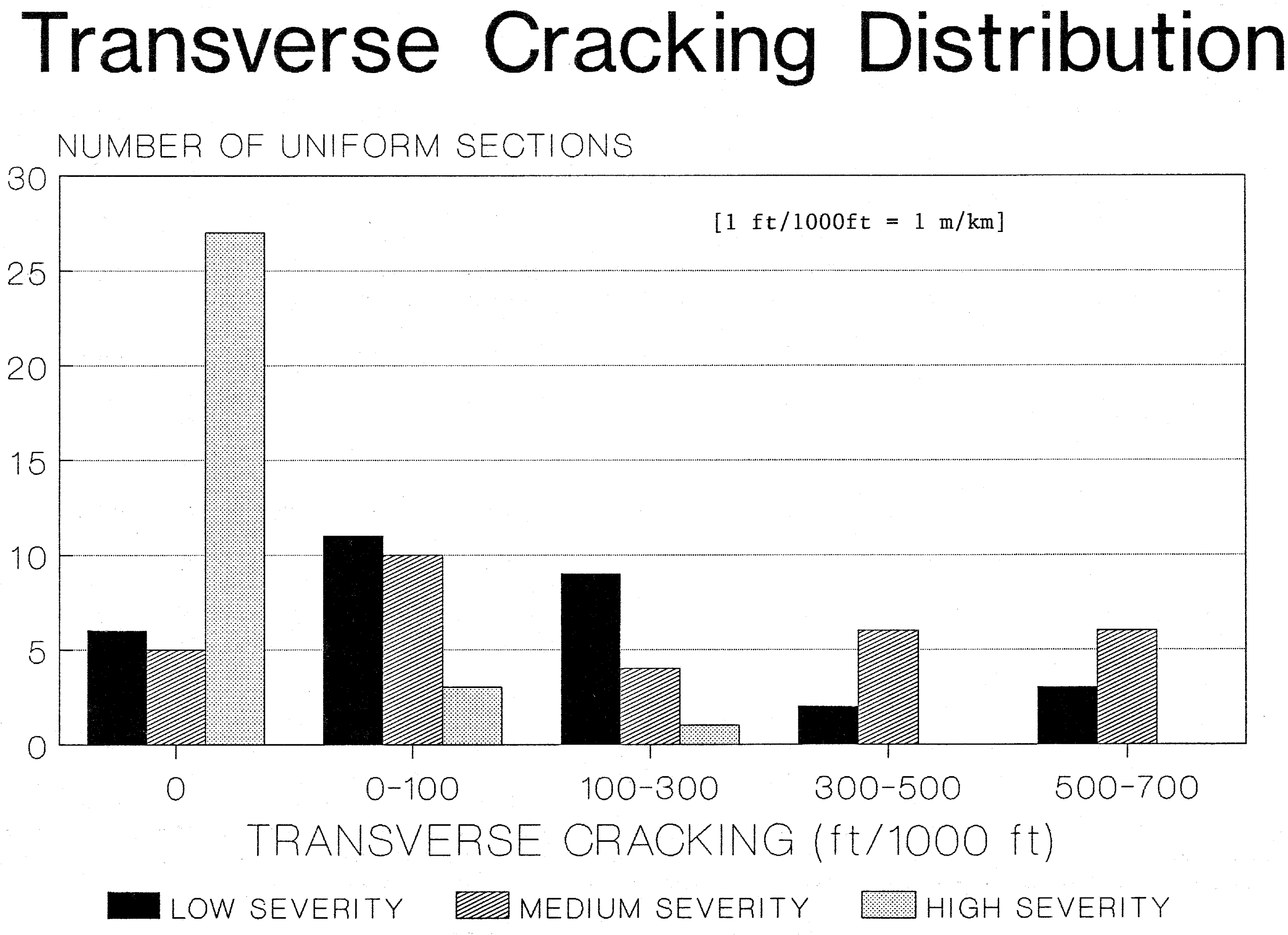


Figure 5. Distribution of severity of transverse cracking in the outer lane on bonded concrete overlays.

route 38A in 1985. The overlay was in service only 1 year at the time of survey. Deteriorated areas of the existing pavement were full-depth repaired with dowels prior to construction.

Of the 24 projects that exhibited some medium severity cracking, 50 percent contained less than 200 ft [61 m] of medium severity cracking per 1000 ft [305 m] of drive lane. This is an average of one transverse medium severity crack every 60 ft [18.3 m].

There was very little deterioration of the reflective cracking observed on a nationwide basis. Only 3 of the 31 sections contained high severity cracking. These were found on the sections with 3-in and 5-in [7.6 and 12.7 cm] overlay thicknesses at Clayton County, Iowa. Although reinforcement was used in the 5-in [12.7 cm] section, full-depth replacement at cracked areas in the existing slab was not performed. Other sections along the same research project were constructed in areas of little existing deterioration with a 2-in [5.1 cm] overlay thickness and these contained no high severity reflection cracking.

Thus, it is believed that the cracking developed in a bonded PCC overlay will very quickly reach the severity level of the underlying crack. If the original crack is of low severity (e.g., nonworking), the reflection crack will not deteriorate rapidly.

Development

Transverse cracking observed at the surface of bonded overlays is largely caused from the reflection of cracks that existed in the pavement prior to overlay.(2,3,4) Some cracks develop in the overlay due to shrinkage or debonding. A description of these cracking mechanisms will be presented later.

The existence of reflective cracking is inevitable in any bonded overlay that is built over a pavement exhibiting working transverse cracks.(3) Because of the physical bond between the layers, there can be no stress relief at the bonding interface. Fine low severity cracks will normally not create any problems. Any existing working cracks, however, must be repaired prior to placing the overlay. The most effective technique is to replace the medium to high severity working cracks with full-depth repairs, and to form joints in the overlay.(2,3,25) Without some form of repair, however, reflection of existing working cracks through the overlay will result in subsequent deterioration similar to that in the existing slab prior to overlay.

There are three mechanisms that may initialize and contribute to reflective cracking formation. These are:

- Thermal contraction of the monolithic slab at low temperatures (see figure 6).
- Vertical differential deflection from traffic loadings (see figure 7).(2,3,4)
- Bending stress in the bonded concrete overlay directly above the crack (see figure 7).

The crack will likely initiate as a result of the horizontal movement of the existing slabs from thermal contraction during a temperature drop. Tensile stress will also develop in the PCC overlay from the temperature drop. This movement will result in a high tensile stress across the crack opening as shown, which will likely cause cracking in the PCC overlay.(2)

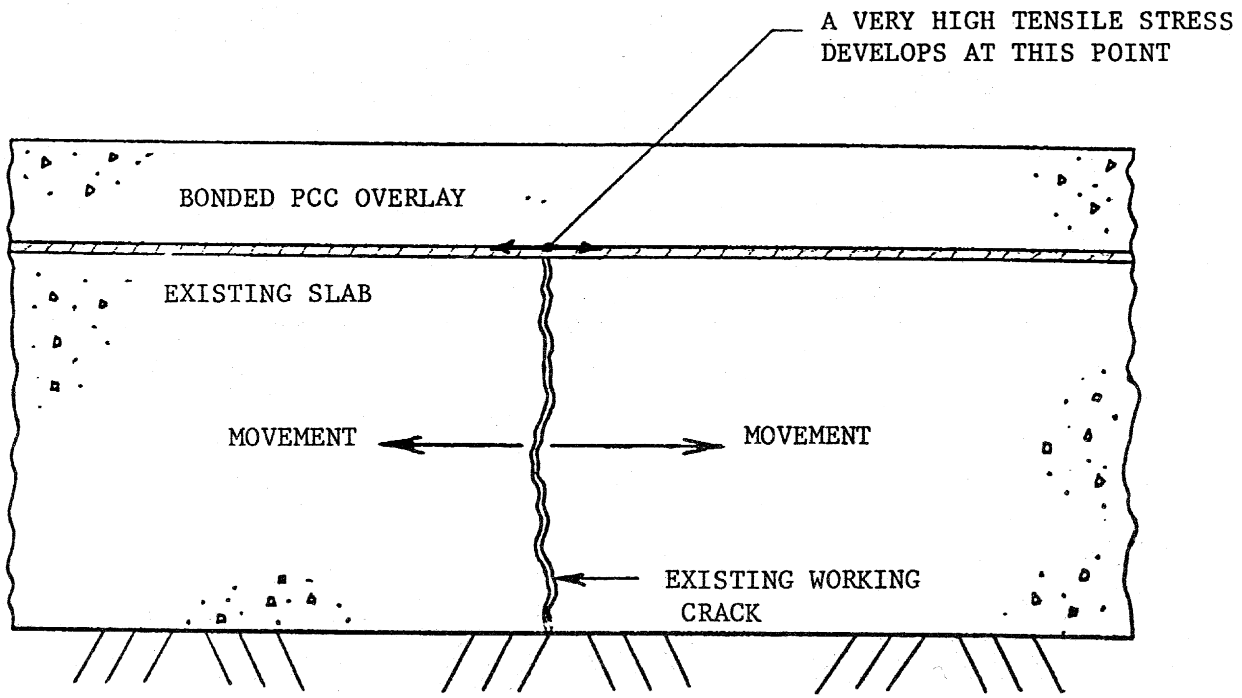


Figure 6. Development of reflective transverse cracking in bonded concrete overlays from thermal contraction at low temperatures.

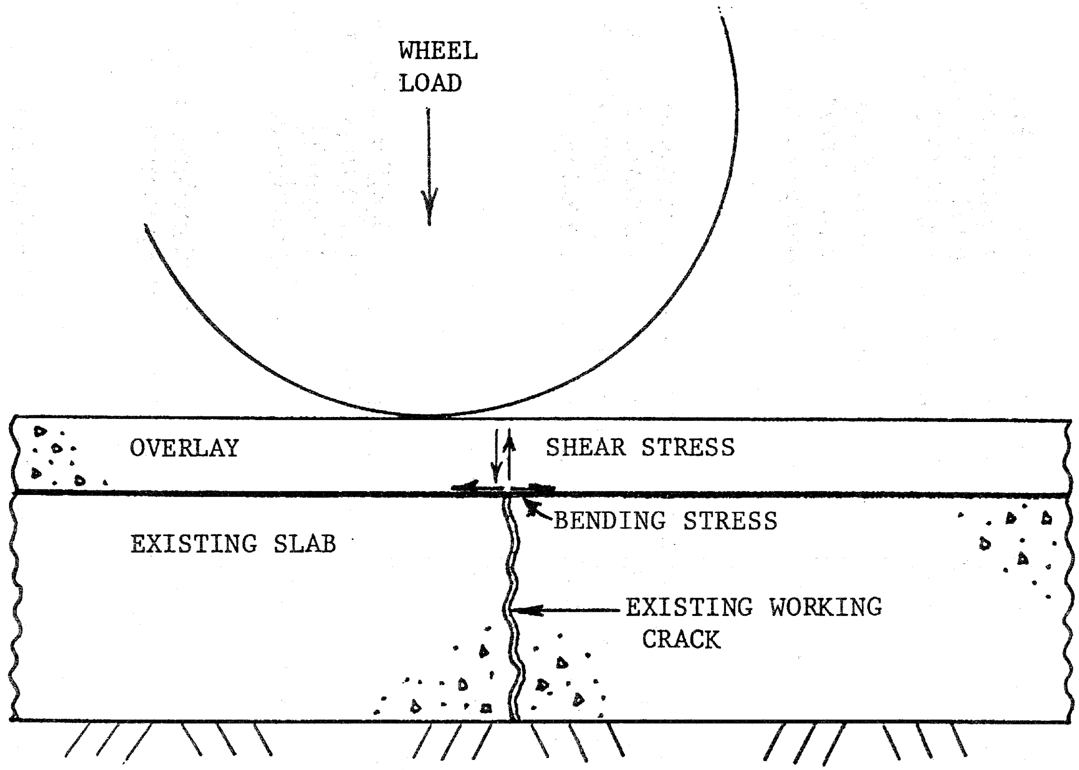


Figure 7. Development and deterioration of reflective transverse cracking in bonded concrete overlays from shearing stresses and bending stresses created by traffic loadings.

Traffic loadings will produce vertical deflections over the crack. The magnitude of these deflections is dependent on the weight of the load, the foundation support and the load transfer efficiency across the crack.(1,2) The result of these deflections is to put a shearing stress through the overlay concrete and also a bending stress at the tip of the existing crack. The shear stress will also contribute to the deterioration of an already initiated crack into a medium and high severity.

2.2.2 Longitudinal (Reflective) Cracking

Field Observation

Figure 8 is a histogram of the severity of longitudinal cracking on the 31 bonded overlay performance sections. Very few uniform sections contained more than 50 ft [15.2 m] of longitudinal reflective cracking (per 1000 ft [305 m]), and only two sections contained more than 100 ft [30.5 m] (per 1000 ft [305 m]).

Interestingly, most sections contained a majority of cracking of a uniform severity, either low or medium. This result leads to the conclusion that reflective cracking will reflect to the similar severity of the underlying crack, and then deteriorate very slowly.

Development

Longitudinal cracking, similar to transverse cracking, is generally caused from the reflection of cracks that had developed in the existing pavement prior to overlay construction. As with transverse cracking, it is inevitable that existing working longitudinal cracks will propagate through the overlay.(3) The question of severity again becomes the critical factor.

2.2.3 Joint/Crack Faulting And Pumping

Field Observation

None of the 31 performance sections contained a significant faulting problem. The average faulting in the drive lane ranged from 0.01 to 0.10 in [0.025 to 0.25 cm]. Faulting becomes detrimental when it exceeds 0.13 in [0.33 cm] for jointed plain concrete pavements (JPCP) or 0.26 in for jointed reinforced concrete pavements (JRCP).(95)

Although some pumping was observed on several projects, no significant problem was noted. When significant visual pumping exists, the potential for faulting of the slab increases.

Development

Faulting and pumping in any pavement system develops from the combination of four factors:

- The movement of heavy wheel loads across the joint or crack.
- The presence of free moisture in the pavement subbase and/or subgrade.
- A subbase or subgrade material that is erodible (contains many fines).
- A deficiency in load transfer across the joint.(2)

If these factors exist, the subbase and/or subgrade materials have the potential to pump beneath the approach joint with traffic loadings. Pumping generally will force water and fines from under the leave side and either deposit the fines under the approach side of the joint or force the fines out from beneath the slab through the longitudinal joint. This action is dependant on the deflection of the slabs, and will be more severe on pavements that exhibit poor load transfer. The movement

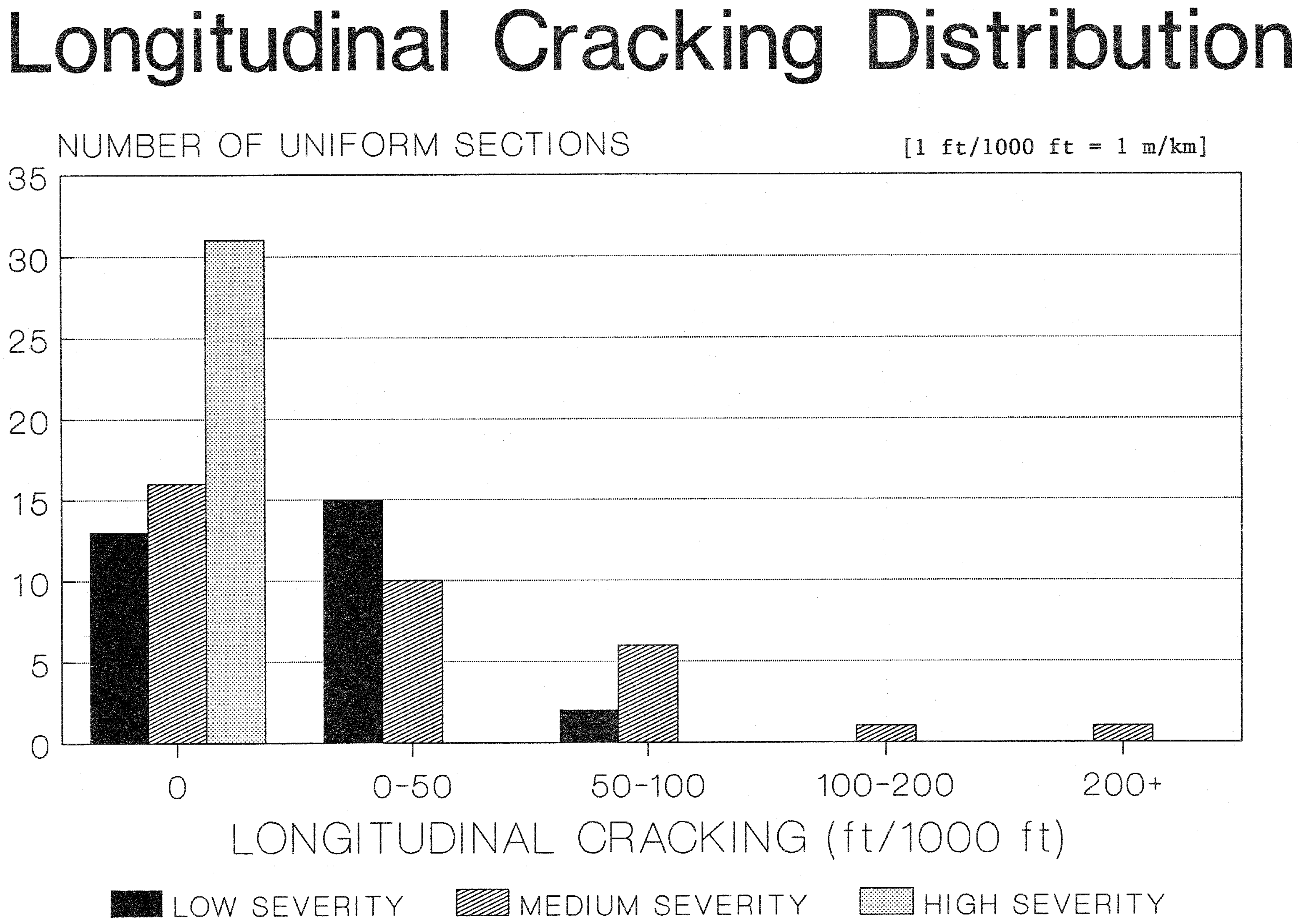


Figure 8. Distribution of severity of longitudinal cracking in the outer lane on bonded concrete overlays.

of fines will normally lift the approach side and leave a void under the leave side of the joint and lead to a differential in elevation from approach to leave side causing the faulting step-off.(8)

The placement of a bonded overlay will have little effect on the pumping/faulting of the pavement. The overlay does not provide an increase in load transfer, because bonded overlay joints need to be sawed fully through the overlay thickness. Therefore, once the overlay is in place, the pavement may take on nearly the same rate of development of pumping/faulting that existed prior to overlay. The only improvement is a decrease (e.g. approximately 20 percent decrease in free corner deflection for a 5-in [12.7 cm] bonded overlay) in deflection due to the thicker monolithic slab. Pumping can be slowed by sealing joints, restoring support by subsealing, and installing a subdrainage system.

2.2.4 Secondary Joint Cracking

Field Observation

Secondary joint cracking of low severity was found to some extent on approximately one-half of the sections (usually only a small percentage of joints for each section, except Clayton Co.).

It should be noted however that the presence of the secondary joint crack poses no significant rideability problems unless the thin sections between the sawed overlay joint and the secondary joint crack debond and break loose. Once this happens maintenance patching is needed or the rideability of the overlay will decrease significantly, because the pieces will tend to dislodge from traffic action.

Deterioration of the secondary joint crack was found on two of the overlay uniform sections. At Clayton County, Iowa, secondary joint cracking developed along approximately 25 percent of the transverse sawed joints. Of this 25 percent, only about 10 percent had broken loose.

Development

Secondary joint cracking is a problem unique to bonded concrete overlays. The cause of secondary joint cracking has not been proven, however there are some theories for its development. Darter and Barenberg hypothesized that either the cracking initiates before saw cuts are made or that the joint forms at a joint-spall crack not coinciding with the existing joint location.(3) It could also occur if the joint in the overlay was simply not sawed over the existing joint, and a crack formed over that existing joint.

According to the first theory, cracking starts at the approximate location of the existing joint very soon after placement of the overlay, and will propagate to the surface at random angles as time passes.(3) It was observed that this distress occurred more readily on thinner overlays, because the distance the crack must propagate is less. If the crack has not propagated far at the time that the joints in the overlay are sawed, the crack can reroute itself to meet the saw cut.(3) If the sawing operation is performed too late, the crack cannot adjust itself to meet the saw cut and a secondary crack along the joint will result.(3) Figure 9 illustrates secondary joint cracking development.

In the second theory, the development of the secondary joint crack is dependent on the amount of spalling present on the existing joint. The crack may initiate at a joint-spall crack several inches away from the original joint location.(3) If the

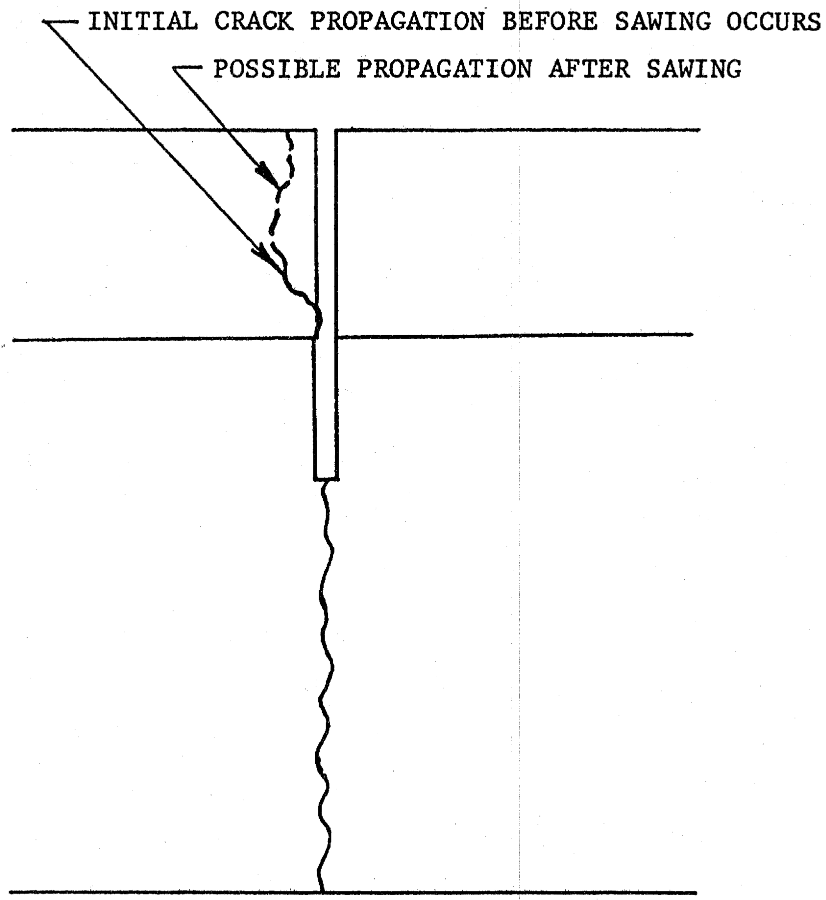


Figure 9. Development of secondary joint cracking in bonded concrete overlays when the overlay joint is not sawed prior to crack propagation past the adjustment point.

crack initiation occurs a significant distance from the existing pavement joint, a secondary crack may develop regardless of the overlay thickness. Figure 10 illustrates the development of secondary joint cracking under this theory.

2.2.5 Shrinkage Cracking

Field Observation

Twenty-six percent of the sections exhibited some shrinkage cracking. Shrinkage cracking did not affect the rideability of the bonded overlay sections observed, because in all instances the cracks were low severity, tight-hairline cracks. It is possible that water infiltration into the cracks may eventually cause problems at the bonding interface.

Development

Shrinkage cracking forms from tensile forces that develop from excessive contraction in the overlay concrete prior to strength development. Typical shrinkage cracking appears like map cracking. The tight hairline cracks are spaced at close intervals of 1 to 3 ft [0.3 to 0.9 m]. The unique aspect in the appearance of shrinkage cracking in bonded PCC is that the cracks run in only the transverse direction. This distress can be attributed to one or more of the following:

- Inadequate curing procedures.
- A high water/cement ratio.
- High air temperatures at the time of placement of the overlay.
- High wind velocity at the time of placement of the overlay.

If highly efficient curing techniques are not used when these conditions exist, shrinkage cracking will result. Due to the large proportion of sections containing shrinkage cracking, bonded concrete overlays appear to require special curing techniques to prevent shrinkage cracking. This may require moist curing for as much as 72 hours, as required by the Corps of Engineers, followed by additional cure with polypropylene sheeting.(4) These same techniques are also needed to prevent delamination as presented in the next section.

2.2.6 Overlay Delamination

Field Observation

There was no concentrated effort during the field surveys to perform delamination sounding testing of the bonded overlay projects. Therefore, the only indications that delamination had occurred would be from cracking observations and previous reports from the State agencies.

Delamination along the joints was observed on two projects, of which one (Clayton County, Iowa) was linked to secondary joint cracking and is described in section 2.2.4 "Secondary Joint Cracking Field Observation." Some delamination also occurred on those sections in which waterblasting was used as the surface preparation technique.(3,5)

The other project was US Route 61 in Louisiana. The delamination occurred near the transverse joints. A complete disbondment survey indicated that 36 percent of the joints experienced some form of disbondment, which is 0.3 percent of the total surface area.(7) About half of the delamination occured in the first year, with the other half occuring slowly over the succeding 4 years. The causes were identified as inadequate bond obtained during construction by either the grout drying out prior

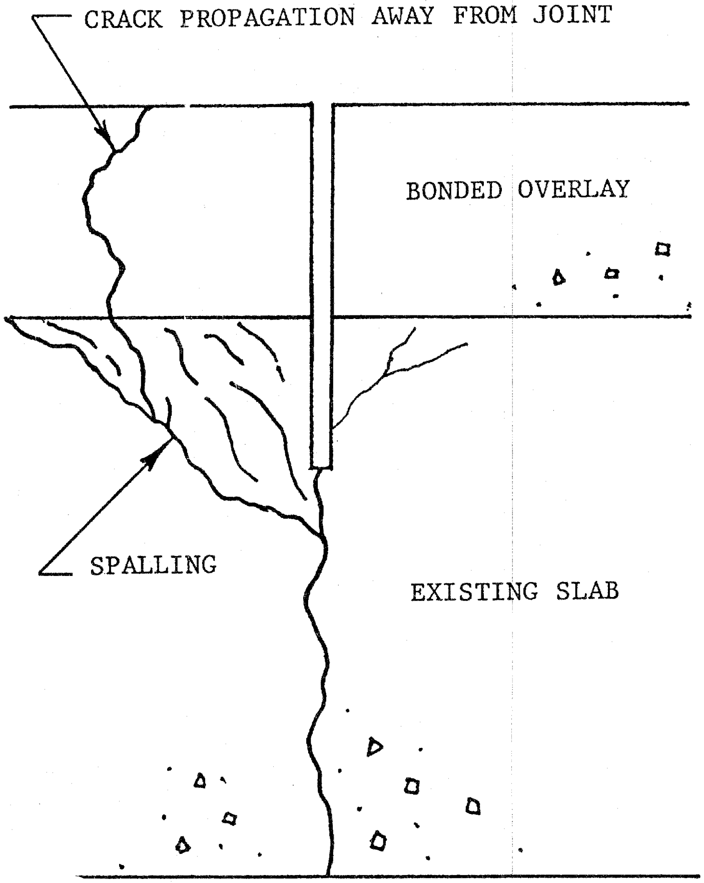


Figure 10. Development of secondary joint cracking in bonded concrete overlays from the propagation at a location away from the underlying pavement joint.

to overlay and/or excessive air content in the concrete mix.(7) These areas were rebonded to the existing slab with an injection of epoxy cementing material.

Another bonded concrete overlay project constructed in California on I-80 near Donner's Summit debonded extensively within a few days after construction.(58) This was attributed to large temperature changes, in September, in a high elevation area.

Another project included I-25 in Wyoming where some minor debonding has occurred at the intersection of the longitudinal and transverse joints. About a dozen small corner breaks with accompanying debonding have been noted for the project.(68,69)

Development

The delamination of a bonded concrete overlay will lead to rapid failure. Delamination is most critical and most likely to occur at the slab corners.(10,30) This problem is very complex and has been attributed to excessive drying shrinkage of the bonded overlay, drying of the grout before the overlay is placed, large temperature differentials between the overlay and underlying concrete and secondary joint cracking.(30) Another concern is differential curling of the overlay and the underlying slab.

Felt and others, have indicated that laboratory and field tests identify 200 psi [1.4 MPa] as the minimum acceptable bond strength at the overlay interface.(2,10,30) According to Domenichini, satisfactory field results have been obtained in Europe with bond strengths of 400 psi [2.8 MPa].(30) Domenichini studied the shear stresses developed at the interface of a thin bonded overlay and existing slab as presented in figure 11.(30) Note that at some distance away from the slab edge, the stress becomes negligible. Domenichini computed shear stresses acting along the bond interface as a function of drying shrinkage taking into account relative air humidity, water-cement ratio (overlay PCC), overlay thickness and the exposed surface area for a 1-in [2.5 cm] overlay.(30)

Shrinkage induced shear stresses at the interface quickly reduces to zero at a given distance from the slab edge.(30) This effect is illustrated in figure 12 for a 1-in [2.5 cm] thick overlay. Therefore, concern for bond strength must be focussed at the slab edges and corners.

The effect of relative air humidity is shown in figure 13. The shear stress can only be kept below the maximum bond strength values (about 450 psi [3.1 MPa] from field tests), if the curing procedure can produce a condition similar to that at 90 percent ambient relative humidity.(30) If the curing compound or other technique cannot produce these conditions, the shear stresses may exceed tolerable levels. For example, at conditions equivalent to 70 percent relative humidity, the shear stresses induced by shrinkage will be about 550 psi [3.8 MPa].

The above values are based on a 1-in thick overlay. The effects on thicker bonded concrete overlays is somewhat less, as shown in figure 14. The effect of water-cement ratio is also shown in figure 14 where it can be seen that the lower the water-cement ratios, the lower will be the induced shear stresses.

Temperature drops were also used to compute shear stresses due to temperature variation through the pavement. Large temperature differentials between the overlay and existing concrete can also result in debonding.(30) Figure 15 shows the temperature profile through a standard bonded overlay cross-section. This graph was developed for May which is considered to be a critical month (in most regions) for overall pavement temperature variation. The program used to develop this

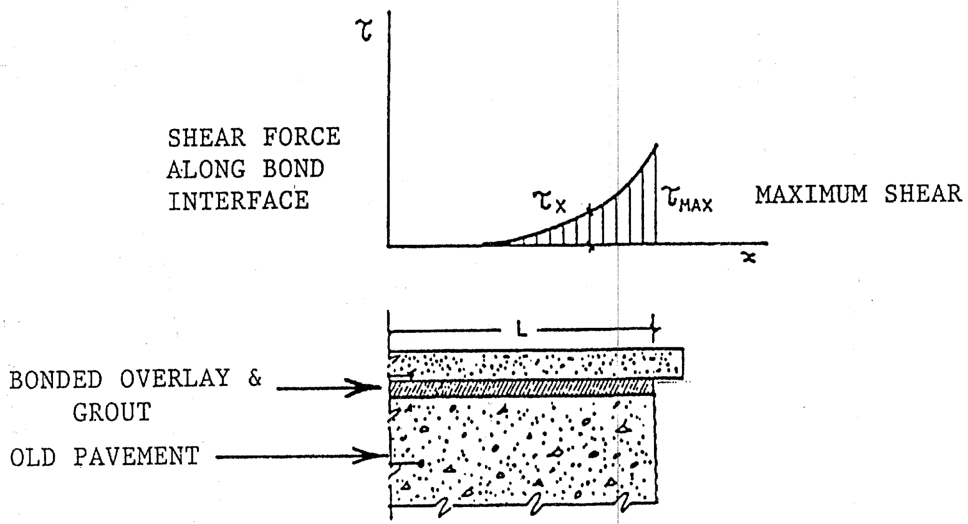


Figure 11. Shear stress distribution at the slab edge. (30)

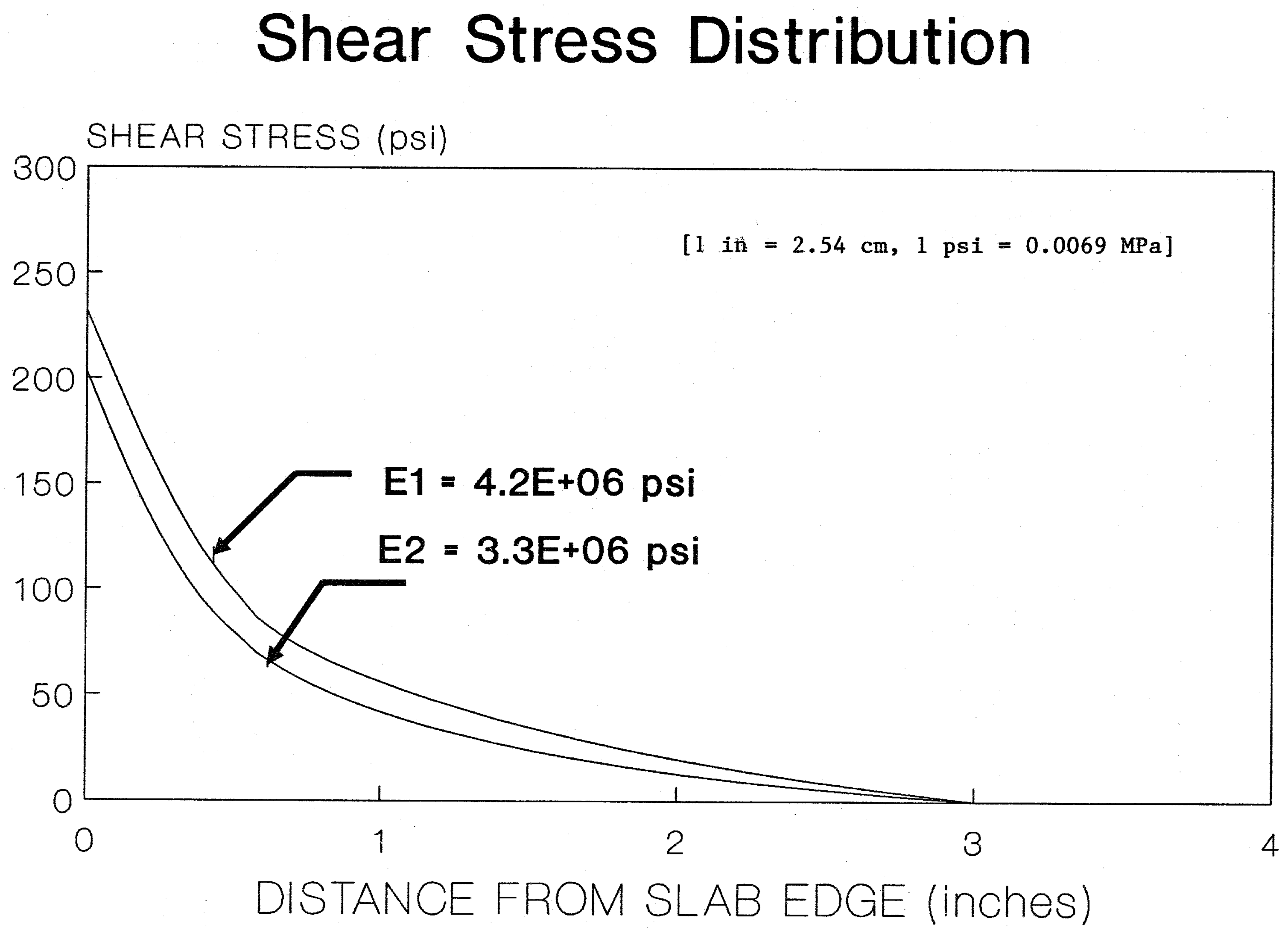


Figure 12. Shear stress distribution for a 1-in bonded concrete overlay from drying shrinkage effects. (30)

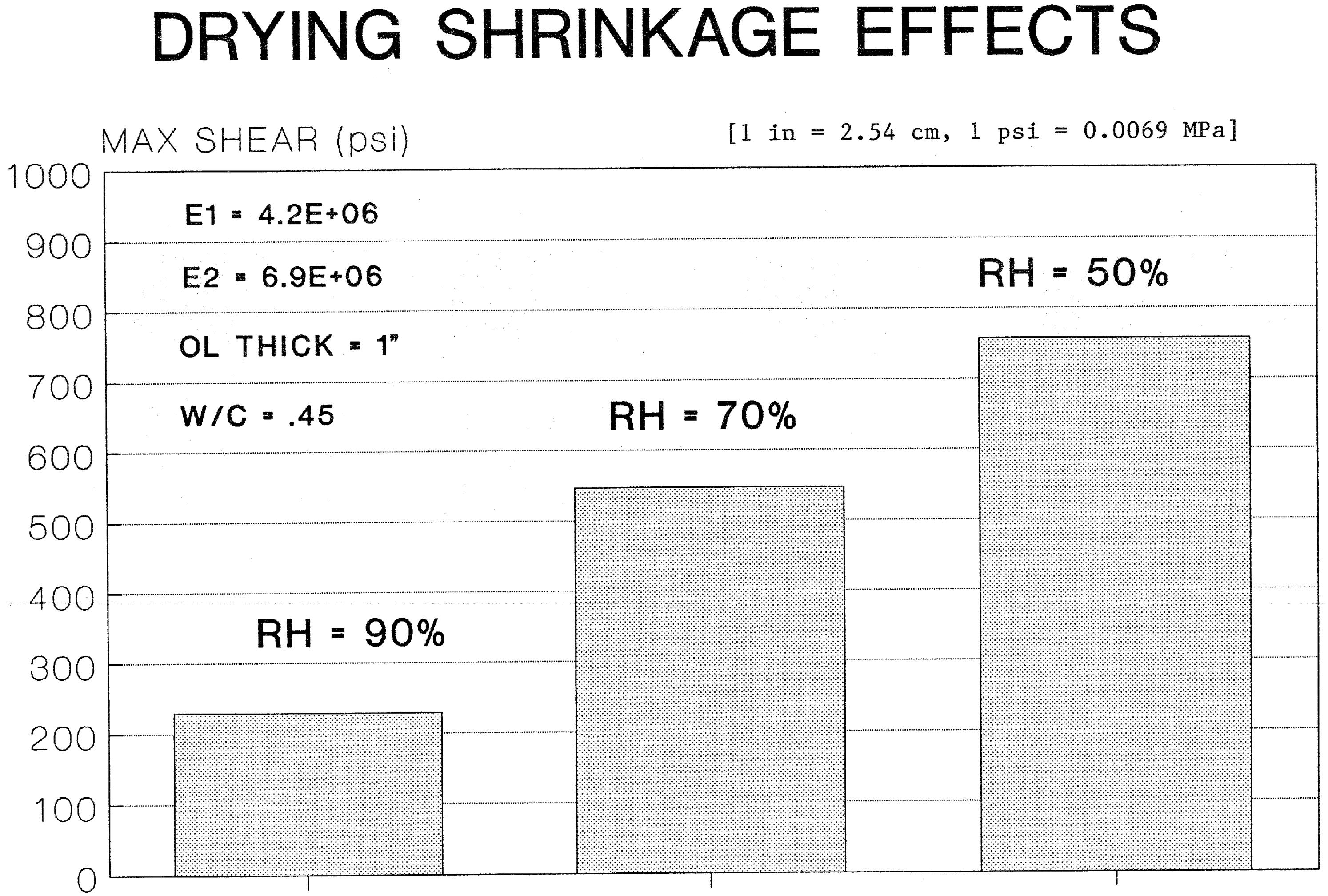


Figure 13. Shear stress induced by drying shrinkage of the bonded overlay at various ambient relative humidity levels. (30)

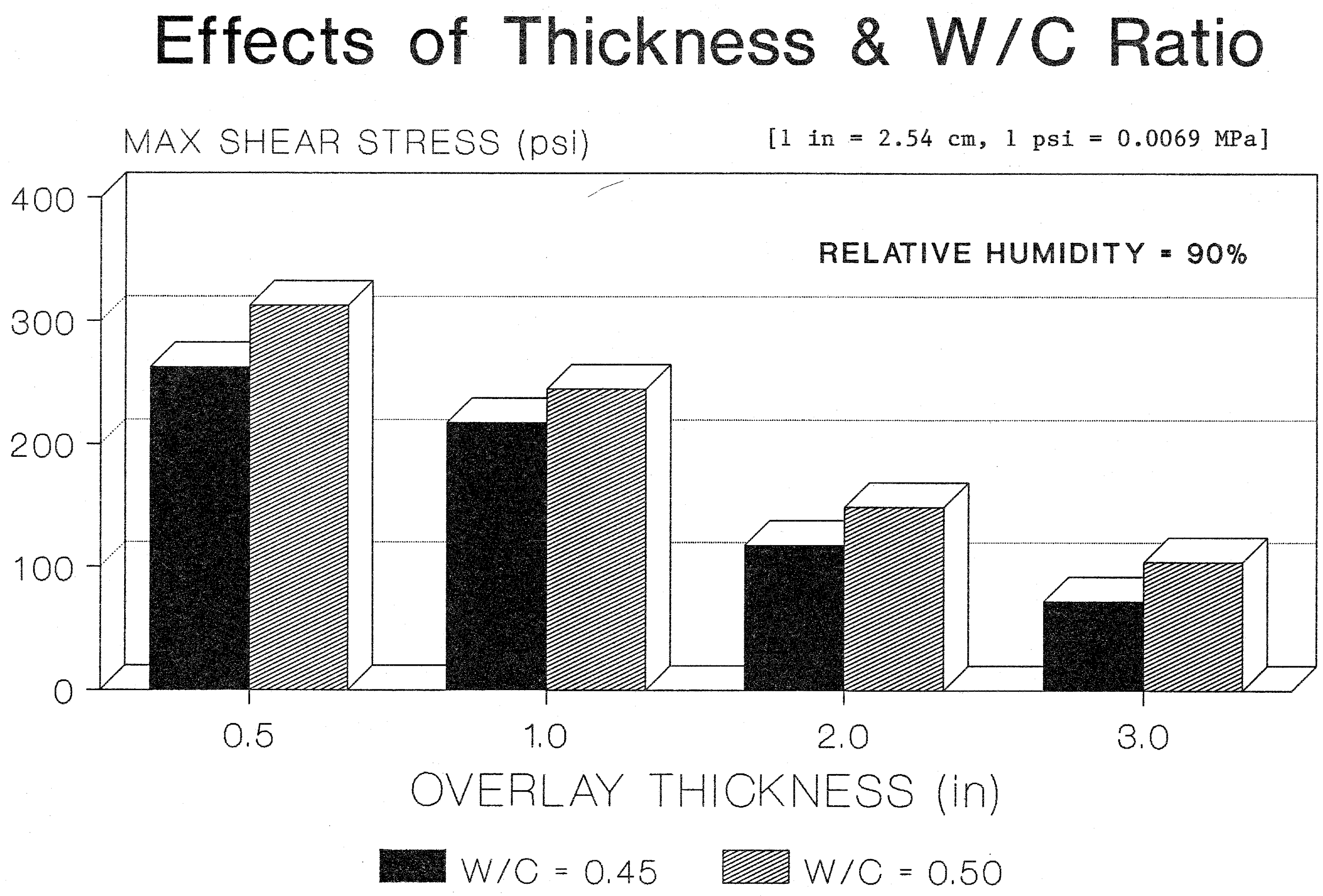


Figure 14. Maximum shear stresses due to drying shrinkage versus the overlay thickness for various water-cement ratios. (30)

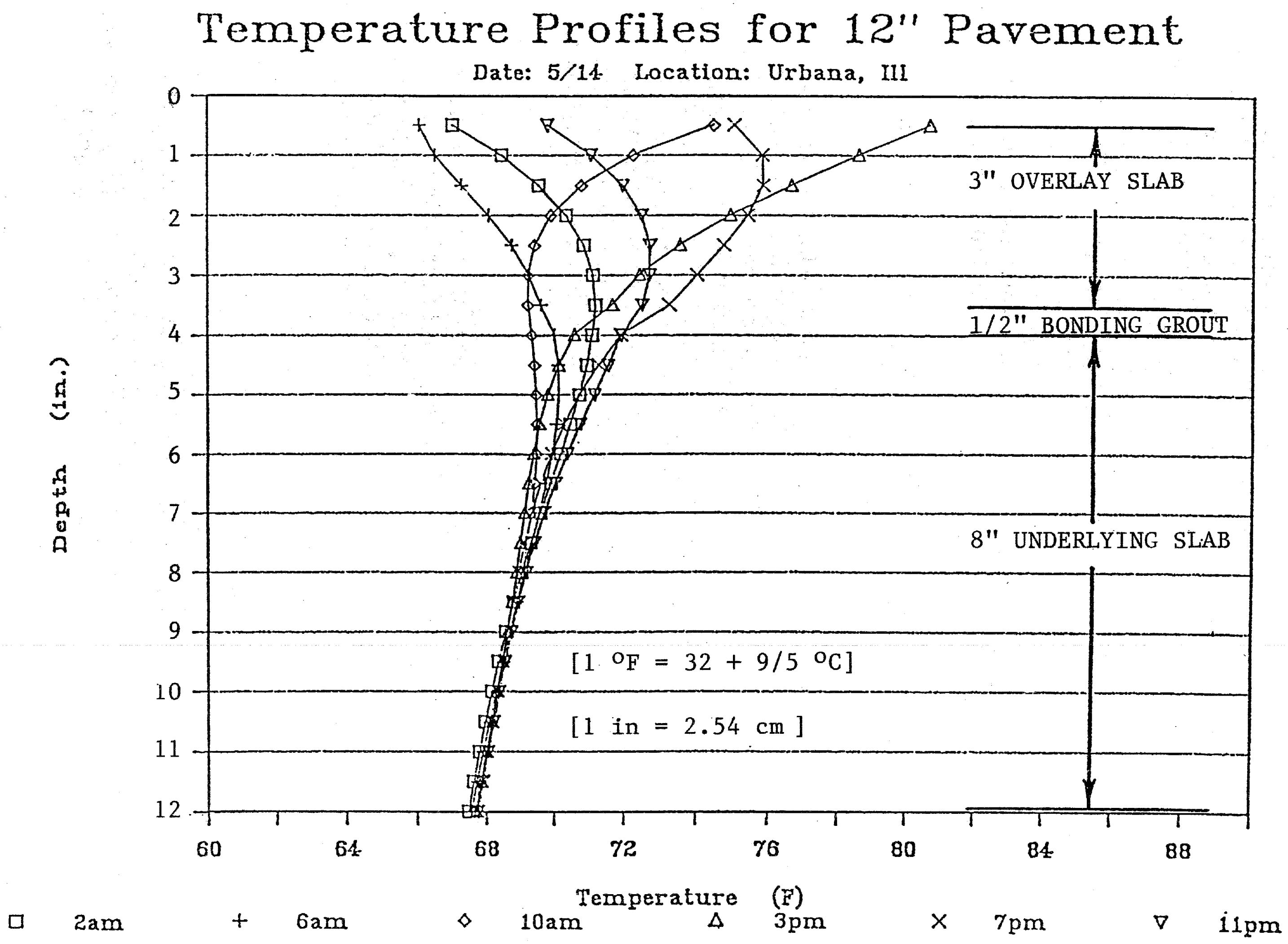


Figure 15. Temperature profile through a concrete slab (mid-May).

relationship is CMS.(28) The graph illustrates the insulation effect that the overlay has on the underlying slab, and the resultant temperature differential. The predicted maximum differential ranges between about 10 ^{O}F [5.5 ^{O}C] at 3 PM during the daytime part of the cycle when the overlay is in compression to 4 ^{O}F [2.2 ^{O}C] at 6 AM when the overlay is in tension.

Figure 16 illustrates the maximum shear stresses due to shrinkage and temperature versus various overlay thicknesses.(30) As can be seen, temperatures differences greater than about 5 ^{O}F [3 ^{O}C] will result in shear stresses above the tolerable maximum. When considering the 10 degree difference illustrated in figure 15, this effect becomes critical. It is also interesting to note that above the tolerable levels, the overlay thickness begins to have an adverse effect on the shear stress. This is a result of the increased insulation provided the thicker layer, which further increases the temperature differential.

In summary, critical concerns in preventing delamination of the bonded overlay are the initial bonding and curing procedures employed and the temperature characteristics during and after placement.

2.2.7 "D" Cracking

Field Observation

Though it is likely that some of the original sections over which the overlays were built contained some "D" cracking at joints and cracks, such as Iowa I-80 at Grinnel and US 20 in Waterloo, Iowa, only one section experienced this problem in the overlay. This project was the 9-year-old section on US 20 in Waterloo, Iowa. Approximately 90 percent of the overlay joints per 1000 feet [305 m] of roadway experienced medium severity "D" cracking. It is known that the existing pavement contained badly "D" cracked joints.(3) Either "D" cracking susceptible materials were used in the new overlay concrete, or it has reflected from the "D" cracking in the underlying concrete. The apparent "D" cracking observed on the overlay is not yet severe.

Development

"D" Cracking is a durability problem of the aggregates used in the concrete mix. It is caused by the freeze-thaw expansive pressures of certain coarse aggregates.(8) The pressures developed in the concrete tend to cause fine hairline cracks near joints and cracks. The development of this distress in the bonded overlay indicates that either a "D" cracking aggregate is used in the overlay mix, or the "D" cracks have propagated through the overlay.

2.3 PERFORMANCE MODELS

2.3.1 Model Development

Regression analysis was performed on the database for bonded overlays. Predictive models were developed for significant distresses using nonlinear regression techniques as included in the SHAZAM statistical package.(55) Models for faulting and reflective cracking were developed from the database for bonded concrete overlays.

In terms of other performance indicators, such as joint deterioration and present serviceability, sufficient data was not available to develop models. However, performance of concrete overlay pavements in terms of these parameters is thought to be similar to that of standard concrete sections as modelled in the NCHRP Project 1-19 (COPES) study.(1)

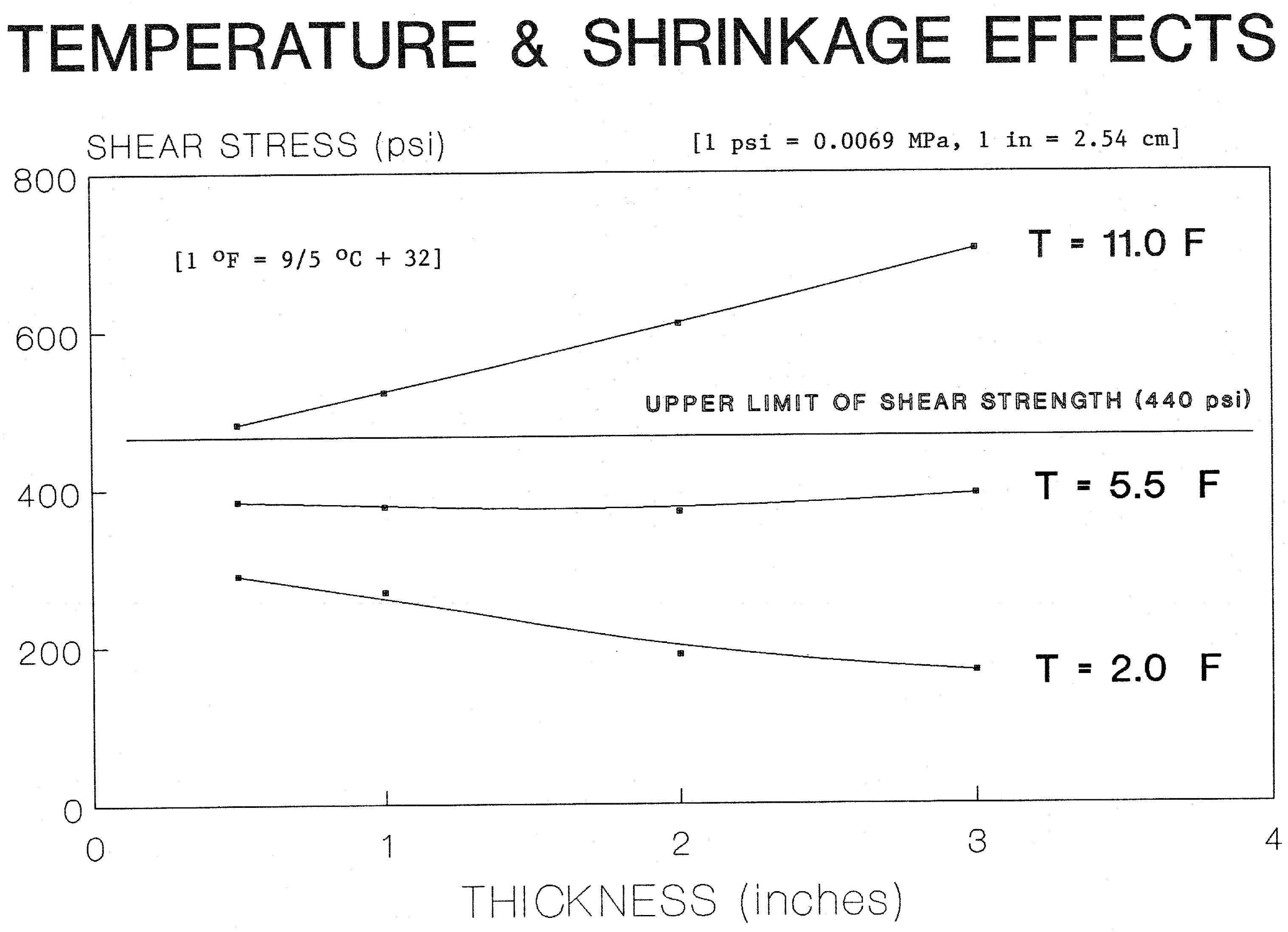


Figure 16. Maximum shear stresses due to shrinkage and differential temperature effects. (30)

As a first step in analyzing the data, all independent variables that were considered to have meaningful and significant influence on the performance of the bonded overlays were identified. These variables were then considered in the development of the models with nonlinear regression.

Extensive time was spent refining the models, however, they should be considered tentative/initial models because of the limited nature of the database. As concrete overlay techniques are applied in more States with differing climates and designs, these initial models can be revised to include more variables and wider ranges of applicability. The nature of the available design and performance data posed certain limitations. The variables that entered the predictive models included:

- 18-kip [80 kN] ESAL accumulated on the overlay in the outer truck lane.
- Type of subbase (stabilized or untreated granular).
- Freezing Index, mean degree days below freezing.
- Diameter of dowels (in existing pavement).
- Age of the overlay, years.
- An index of the amount of existing cracking prior to overlay.

As can be seen upon examination of the models, there are several important variables missing. These variables were either determined to be insignificant in characterizing the performance of the overlays, or were not sufficiently available in the database so as to show their actual effect. Future refinement of the models should attempt the inclusion of the following:

- Thickness (existing slab and overlay).

- Joint spacing.

- Preoverlay repair techniques employed.

- Additional climates (dry-no-freeze, dry-freeze).

- Mechanistic data (e.g., elastic moduli from deflection testing, subgrade support).

- Overlay concrete properties.

- Drainage characteristics.

It should be kept in mind that each model was based on the data as was available in the database, and thus should not be applied or used beyond the ranges under which they were developed. The range of applicability for each model variable is provided.

Two models were developed from the database for bonded concrete overlays. These models were developed for both joint faulting and reflective cracking.

2.3.2 Joint Faulting

The faulting model for bonded concrete overlays is as follows:

$$\begin{aligned} \text{FAULT} = {} & 0.0015897\ \text{ESAL}^{.233}\ [\,-10.942 - 30.657\ \text{BASE} \\ & + 0.0005652\ (\text{FI} + 1)^{2.299} + 33.322\ (\text{DIA} + 1)^{-.8477}\,] \end{aligned}$$

where:

FAULT = Mean faulting across the transverse overlay joints, inches

ESAL = Equivalent single-axle loads accumulated on the overlay, in outer traffic lane, millions

BASE = 0, if granular base type
1, if stabilized base (asphalt, concrete, etc.)

FI = Freezing Index, mean degree days below freezing

DIA = Diameter of dowel bars in the original pavement, inches (0 if no dowel bars exist in the original pavement)

Note: all dowel bar spacing was 12 in [30.5 cm] on center

Statistics:

R^2 = 0.54
SEE = 0.02 in [0.05 cm] (standard error of estimate)
n = 27 (number of data points)

Equation Range of Applicability:

ESAL	Equivalent single-axle load data ranged from 0.03 million to 5.4 million accumulated on the overlay.
FI	The Freezing Index ranged from 0 in Louisiana to 1250 in South Dakota, but the majority of the data fell in the range between 700 and 1000.
DIA	The diameter of the dowel bars in the existing pavement ranged between 0 (no dowels) and 1.25 in [3.2 cm].

It should be noted that the model is only valid for thin bonded overlays of thickness between 2 and 5 in [5.1 and 12.7 cm]. The joint spacing ranged between 12 and 76.5 ft [3.6 and 23.3 m].

Sensitivity plots of the faulting model are shown on figures 17 and 18. These plots indicate the relationship between faulting of a bonded concrete overlay and the variables in the faulting model. The functional form of the model is very similar to that obtained from a much larger database of original jointed plain and jointed reinforced pavements in NCHRP Project 1-19 (COPES).(1) Faulting starts out rapidly and then levels off, probably due to initial pumping action and dowel looseness. The results show important effects of the model parameters.

The type of subbase layer has a profound effect on the development of faulting. When a bonded overlay is placed over a pavement with a stabilized base, the potential for developing faulting is greatly decreased due to reduced erodability. Stabilized base layers will effectively decrease faulting by about 50 percent where the Freezing Index is high (FI = 1000), and show very little potential for faulting where the Freezing Index is lower (FI = 500). Stabilized layers were found to have a similar effect on new pavements.(1)

Significant influence is shown by the Freezing Index, where the expected faulting is reduced by as much as 30 percent for an existing pavement with a granular subbase when changing from 1000 to 500 (a warmer climate). The model

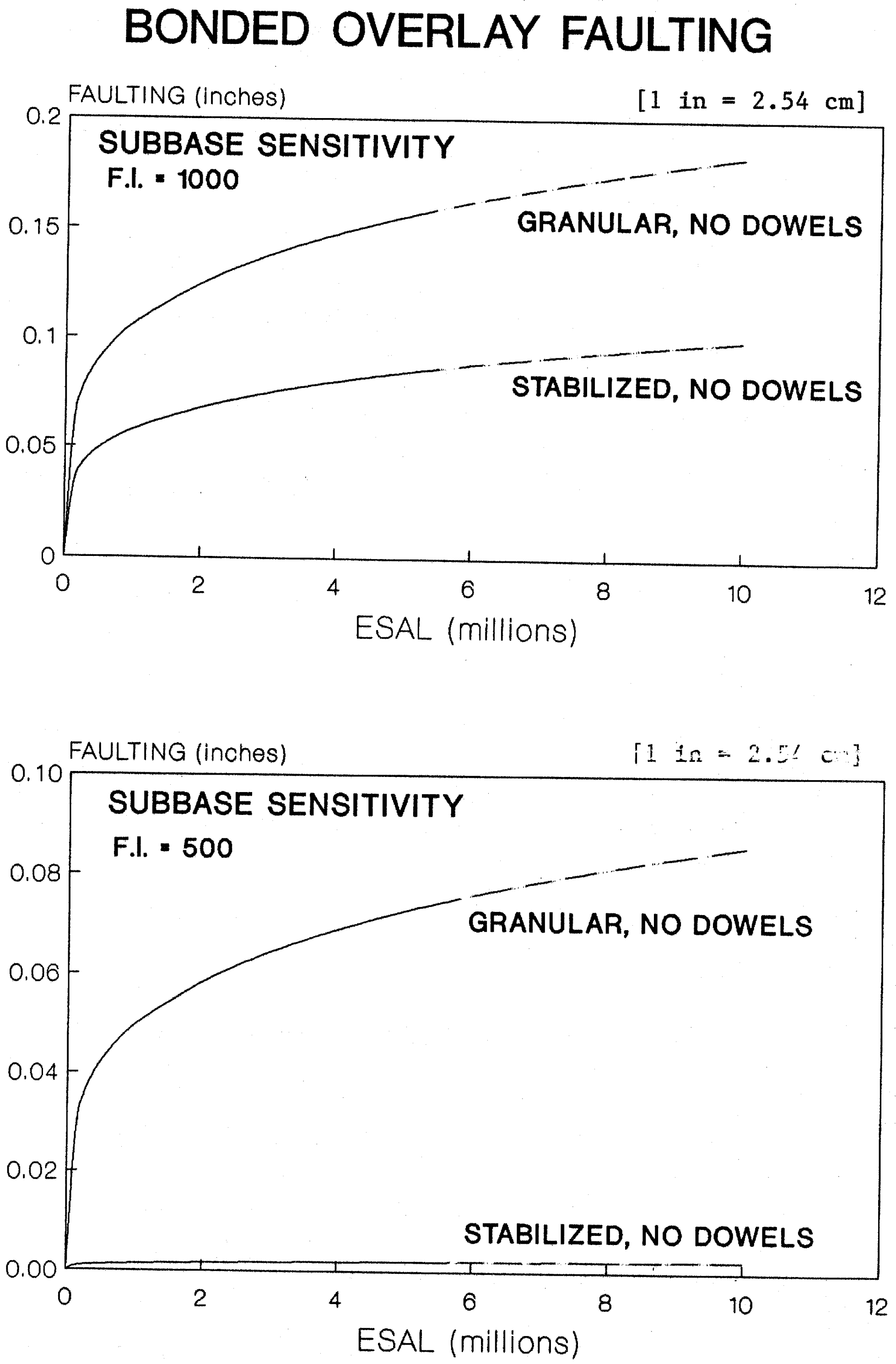


Figure 17. Sensitivity of bonded overlay faulting model to subbase type and freezing index.

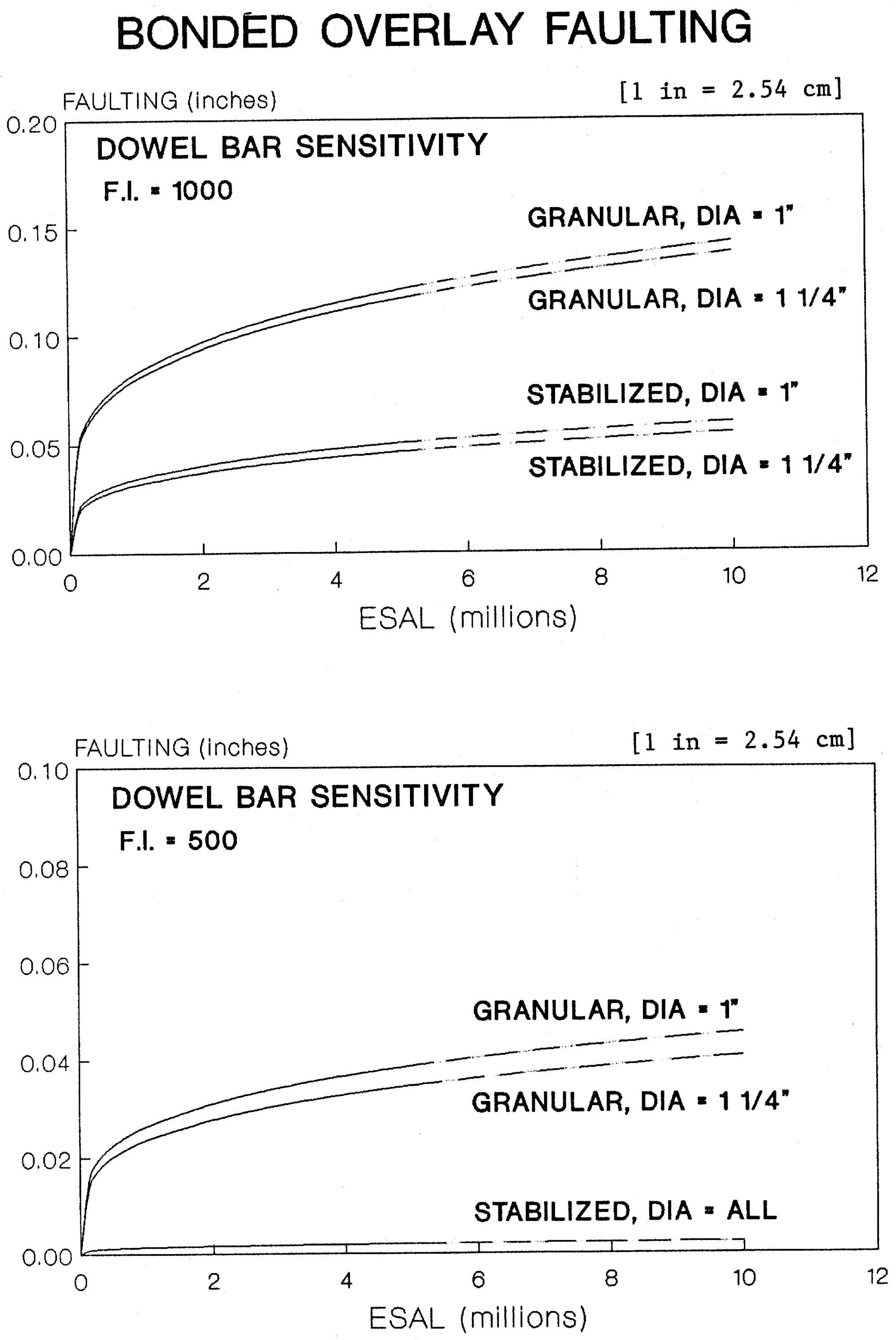


Figure 18. Sensitivity of bonded overlay faulting model to dowel diameter and freezing index.

indicates very little potential for faulting on overlay pavements in the south where Freezing Index is low. In practical terms, the Freezing index is a parameter that relates to the seasonal joint opening at the contraction joints.(1) Where joint openings are wider (Freezing Index is higher) there is both less aggregate interlock and if dowels are present, greater bearing stresses induced on the dowel bars in the existing pavement. Both of these phenomena lead to increased faulting.

The presence of dowel bars in the existing pavement influences the faulting developed in the overlay. As can be seen by comparing figures 17 and 18, the overall faulting can be decreased by about 25 percent when the overlay is placed on an existing pavement containing dowel bars with a diameter of 1.25 in [3.2 cm]. The effects are not as great as was found to exist in original concrete pavement sections.(1) In original concrete pavement sections, the presence of 1.25-in [3.2 cm] dowels was found to decrease expected faulting by about 50 percent.(1)

The smaller influence that dowels have on bonded overlay pavements may be attributed to the problem that the existing dowels may be loose in their holes which would reduce their effectiveness after the overlay is placed. Some reduction may also be attributed to the increased slab thickness with the addition of the overlay. Increased thickness reduces overall vertical deflection from traffic loadings at the joint, thereby decreasing the <u>overall</u> potential for pumping and faulting.

Figure 19 shows the comparison of predicted faulting on bonded overlays to the predicted faulting on new pavement sections from the NCHRP Project 1-19 for similar inputs.(1) This plot shows some interesting results. The functional form of the models are identical. There is little difference between faulting of bonded overlays and new pavements where no dowels exist (curves #1 and #2). Therefore, the expected pumping problems should be very similar for either a bonded overlay or an original pavement when no dowels exist.

There is much greater difference between faulting of bonded overlays and new pavements where dowels exist in the original pavement slabs beneath the overlay. From figure 19 the predicted new pavement faulting is 22 percent lower than predicted faulting on the bonded overlay. The looseness of the dowel bars in the underlying slabs after many years of service may be a major contributor to the increased faulting exhibited by the bonded overlays.

2.3.3 Reflective Cracking

The model for reflective cracking in bonded concrete overlays is as follows:

$$\begin{aligned} \text{CRACK} = {} & 11.328\ \text{ESAL}^{.07546}\ [\ 21.426\ (\text{AGE}\ (\text{FI}+1)/1000)^{.66876}\ ] \\ & + \text{ESAL}^{.002}\ [\ 378.5\ \text{INDEXM} + 1257.1\ \text{INDEXH}\ ] \end{aligned}$$

where:

CRACK = Total length of medium- and high-severity deteriorated reflective cracks, ft/mile

ESAL = Equivalent single-axle loads accumulated on the overlay, outer truck lane, millions

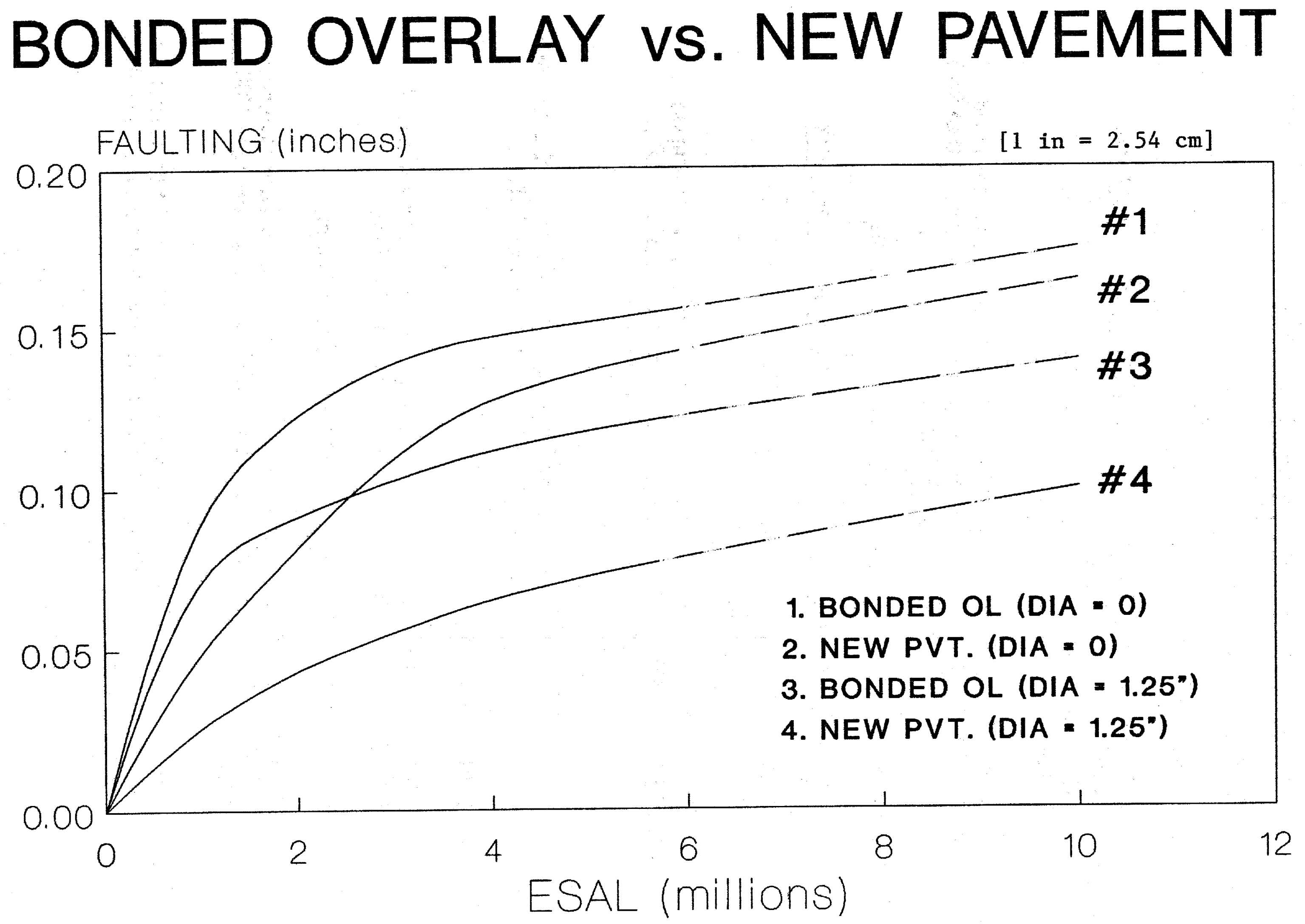


Figure 19. Comparison of predicted faulting on bonded overlays to predicted new pavement faulting.

AGE = Time since construction of the overlay, years (Indicator of the number of temperature cycles affecting shrinkage and expansion of concrete layers.)

FI = Freezing Index, mean degree days below freezing.

INDEXM and INDEXH VALUES

If original pavement was JPCP:

EXISTING CRACKING*		INDEXM	INDEXH
LOW	0 to 100	0	0
MEDIUM	101 to 500	1	0
HIGH	> 500	0	1

* total linear feet per mile of medium- and high-severity cracking on existing pavement prior to overlay placement [or 0 to 18.9, 19.0 to 94.7, and >94.7 total linear meters per kilometer].

If original pavement was JRCP:

EXISTING CRACKING*		INDEXM	INDEXH
LOW	0 to 200	0	0
MEDIUM	201 to 1000	1	0
HIGH	> 1000	0	1

* total linear feet per mile of medium- and high-severity cracking on existing pavement prior to overlay placement [or 0 to 37.9, 38.0 to 189.4, and >189.4 total linear meters per kilometer].

Statistics:

R^2 = 0.75
SEE = 326 ft/mile [61.7 m/km] (standard error of estimate)
n = 13 (Clayton County sections not included)

Equation Range of Applicability:

ESAL	Equivalent single-axle load data ranged from 0.03 million to 5.4 million accumulated on the overlay, outer traffic lane.
AGE	Age of the pavements ranged between 0.5 to 12 years.
FI	Mean Freezing Index ranged from 0 in Louisiana to 1250 in South Dakota, but the majority of the data fell in the range between 700 and 1000.
INDEX(x)	The level of cracking existing on the pavement prior to placement of the overlay (not repaired). The database included pavements within all three cracking index levels.

It should be noted that Low Cracking Index is not a variable found in the model, but is reflected when the dummy variables INDEXM and INDEXH are equal to zero. Also, the determination of the cracking index for each individual project was based on available literature which described existing cracking prior to overlay. It is highly recommended that in the future, thorough cracking surveys be conducted and reported for each bonded overlay project, since this variable (when it is not full-depth repaired) is critical to the performance of the overlay.

Sensitivity plots of the cracking equation are given in figures 20 and 21. It is very interesting to note the influence of the existing preoverlay cracking index on the amount and occurrence of reflective cracking. As would be expected, the existing pavement cracks reflect through the overlay very rapidly after placement, within the first year as predicted by the model and observed in the field. The amount of cracking exhibited on the overlay is almost entirely governed by the index (amount) of existing cracking (of medium or high severity level).

Although traffic does have a slight effect on the model, the influence is on the deterioration of initialized reflective cracking over existing cracks, and not on the development or initialization of new structural fatigue cracks from repeated loading. Typical structural cracking for new pavements develops as shown in figure 22.(1) Bonded overlays increase the slab thickness typically over 10 in [25.4 cm], which requires a large number of axle loads to cause fatigue cracking. Fatigue damage in the existing slab may cause some increase in fatigue cracking over that of a new pavement slab however. The minor effect of traffic on fatigue cracking is more obvious when examining the slopes of the sensitivity plots for high and moderate traffic levels in figures 20 and 21.

The Freezing Index also has an effect on the development of reflective cracking in the overlay. Where the Freezing Index is relatively low (FI=500), and the existing pavement exhibited a low cracking index prior to overlay placement, reflective cracking will develop at only about 68 percent of the rate when the overlay is placed in a region with a high Freezing Index (FI=1000). This may be the result of the smaller expansion and contraction movements of the pavement from seasonal temperature variations, which would reduce the tensile stresses in the overlay concrete across cracks in the underlying slabs.

2.3.4 Joint Deterioration

The database did not contain a sufficient number of deteriorated joints on the uniform sections to develop a model of joint deterioration.

Joint deterioration does not include secondary joint cracking or debonding at the overlay joints, because these are construction related problems, that with proper techniques and conditions can be eliminated. Joint deterioration is, however, defined by the broad definition, which is joint spalling of medium and high severities, blowups and load transfer related distress.

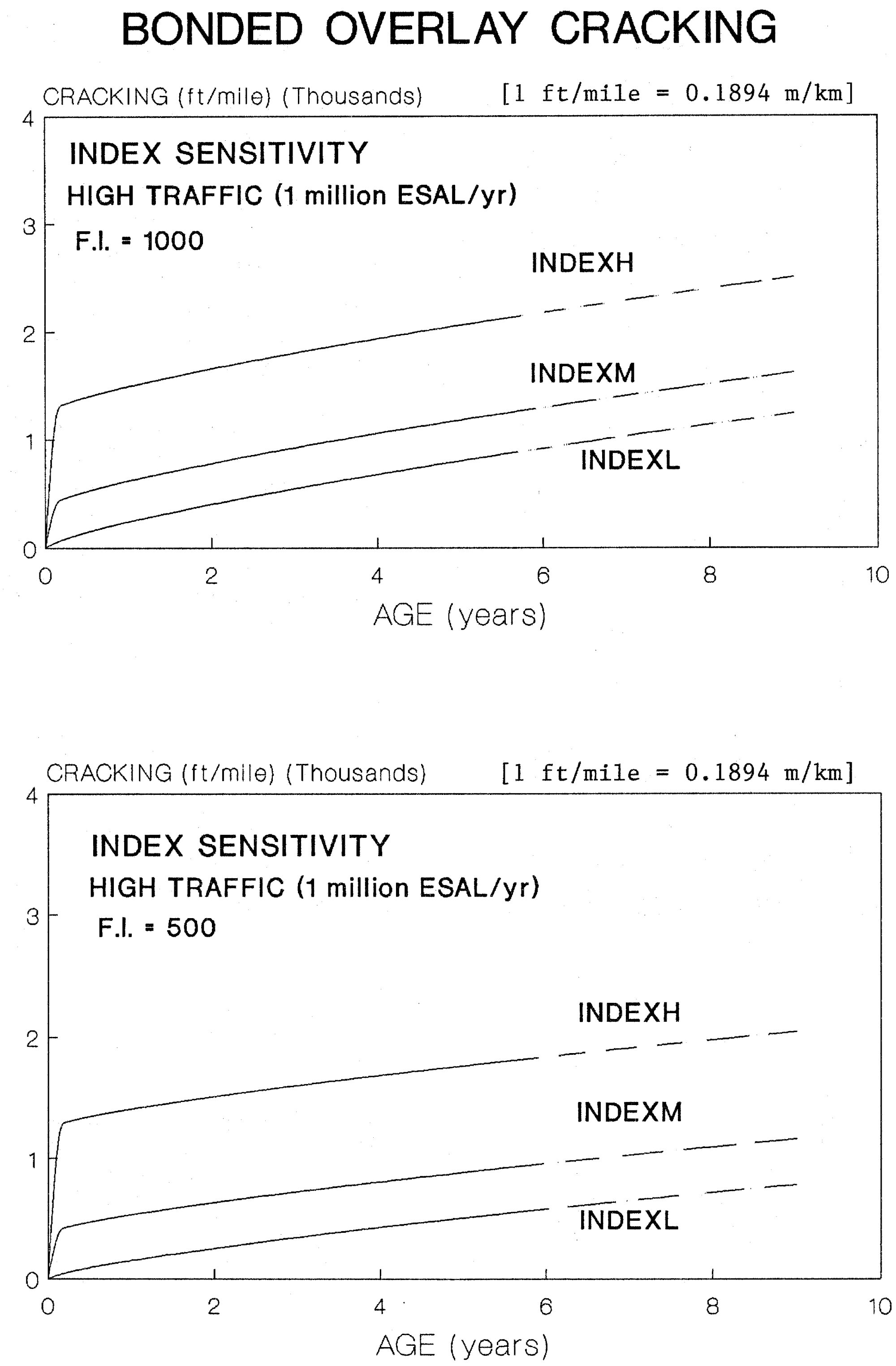


Figure 20. Sensitivity of bonded overlay cracking model to Cracking Index and Freezing Index, at high traffic (1 million ESAL/yr).

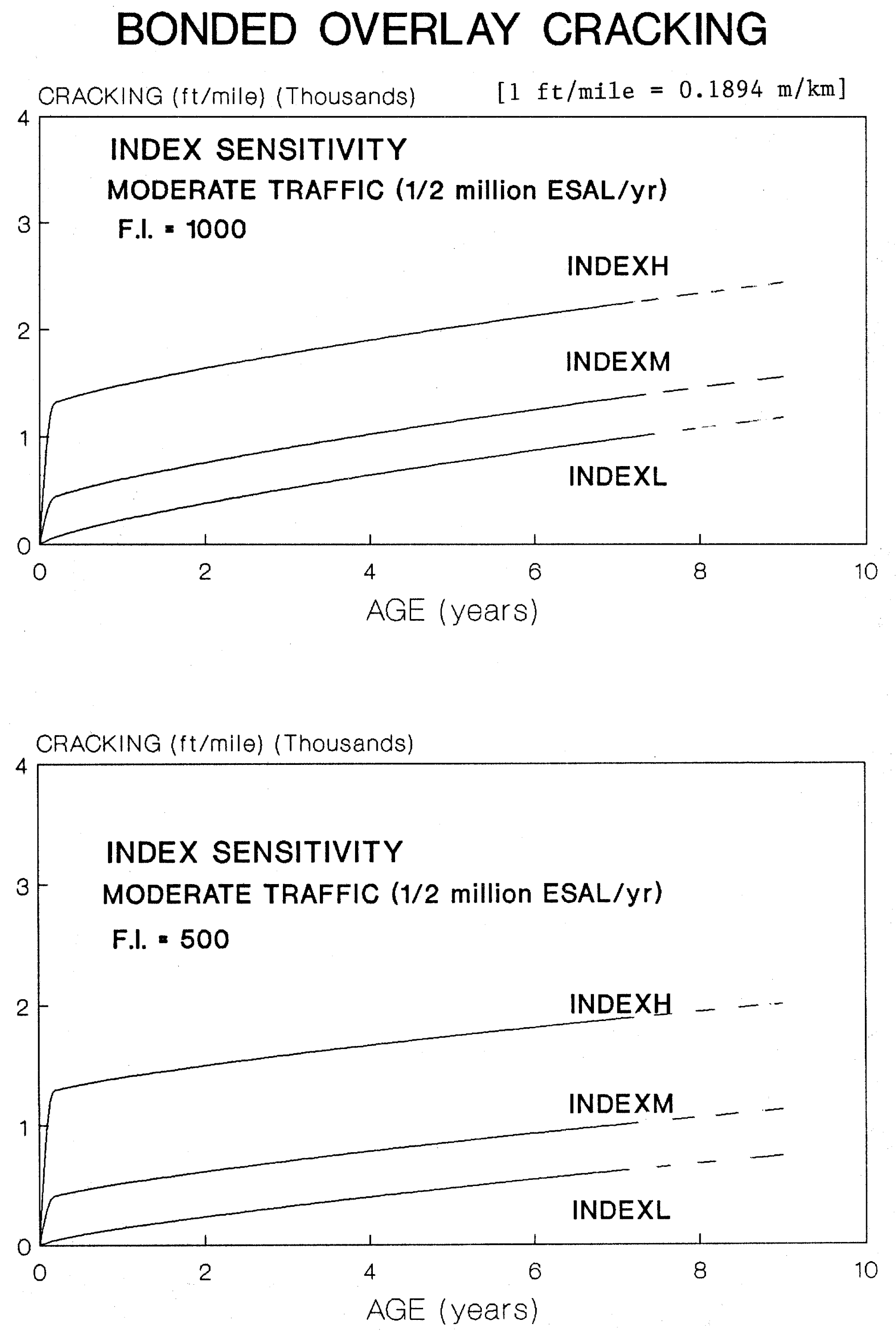


Figure 21. Sensitivity of bonded overlay cracking model to Cracking Index and Freezing Index, at moderate traffic (1/2 million ESAL/yr).

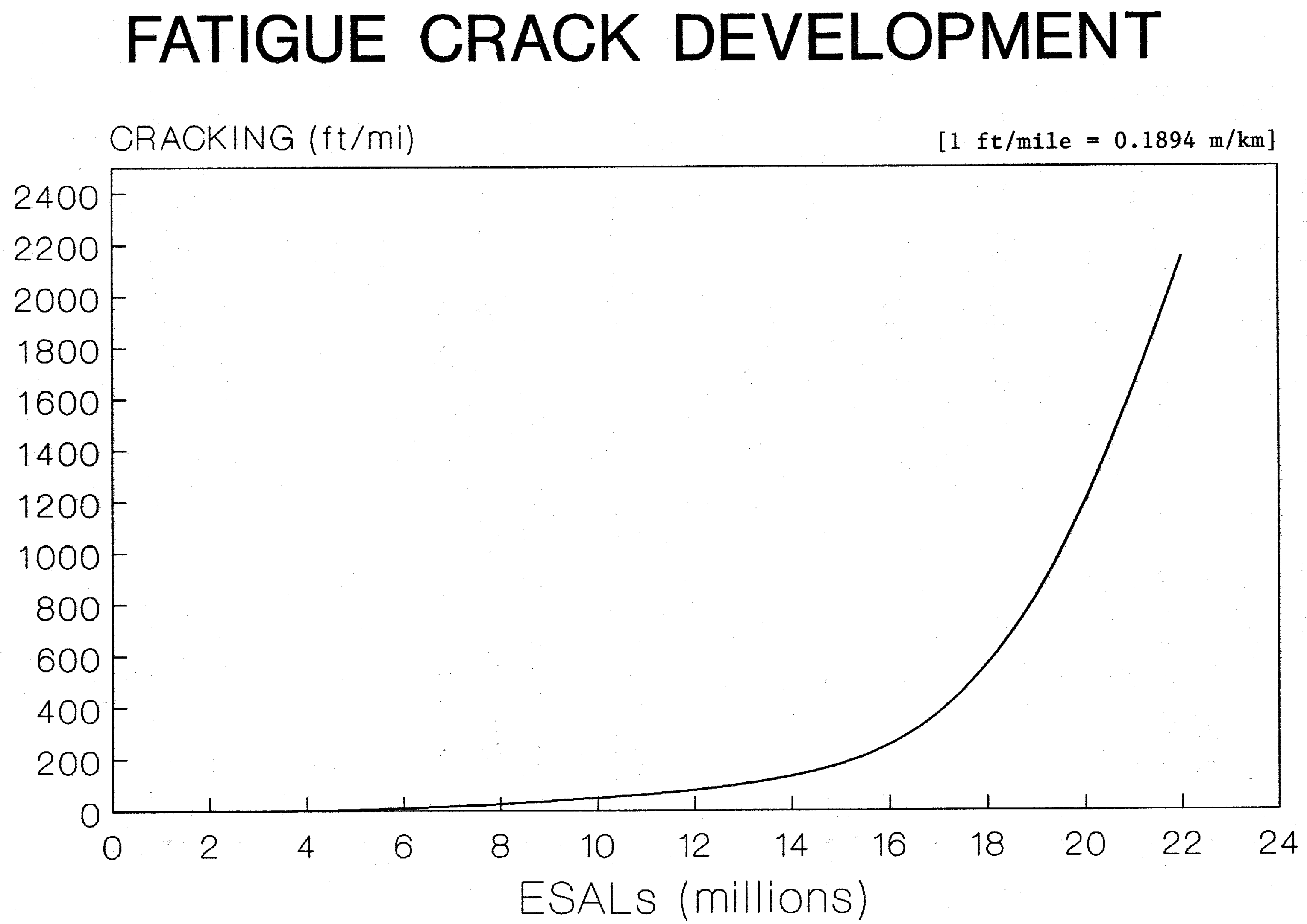


Figure 22. Typical fatigue cracking development curve.

2.4 DESIGN AND CONSTRUCTION GUIDELINES -- BONDED CONCRETE OVERLAYS

2.4.1 Introduction

This chapter provides a comprehensive summary of the design and construction of bonded concrete overlays. The information is a synthesis of that obtained from past research studies, published design procedures, field performance results from the database and staff experience. The guidelines are presented in a format intended to facilitate usage by practicing engineers.

The following guidelines cover the overlay of existing jointed portland cement concrete (PCC) pavements with a bonded jointed concrete overlay. This overlay method involves the placement of a thin layer of PCC on top of the existing surface to form a monolithic system.

Need For Bonded Concrete Overlays

Bonded concrete overlays can be used to upgrade existing PCC pavements that are not significantly deteriorated and are in need of structural and/or rideability improvements. Some specific guidelines include:

- No concrete durability problems such as "D" cracking or reactive aggregates.
- Doweled full-depth repairs at all medium-high spalls and cracks and the repair joints included in the bonded overlay (the bonded overlay may not be cost-effective if more than 10 percent area must be repaired).

This overlay alternative may be particularly cost effective for pavements which need structural improvements. One particular cause of the need for structural improvement is from a projected increase in the amount of heavy truck traffic. Truck traffic in excess of that for which the pavement was designed will cause significant fatigue damage in the existing pavement and reduce its life considerably.

Figure 23 shows the reduction in edge stress and corner deflection under an 18-kip [80 kN] axle load for varying thicknesses of bonded concrete overlays. The effectiveness of bonded concrete overlays versus equivalent thicknesses of asphalt concrete is shown in figure 24. Edge load stresses are approximately 35 percent lower for equivalent thicknesses of bonded concrete overlay.

Structural distress indicating that structural improvements are needed include corner breaks, transverse cracking for JPCP (and deteriorated transverse cracks for JRCP) and shattered slabs. The presence of these distresses in significant amounts indicates that the structural capacity of the pavement is being exceeded.

Another important need is for an improved riding surface from both comfort and safety aspects. Severe concrete scaling from concrete mix deficiencies or poor surface finishing, spalling from "D" cracking or reactive aggregate deterioration, wheel path polishing or "rutting" (by studded tires) and joint faulting are major indicators of this need.

Effectiveness

The addition of a few inches of portland cement concrete bonded to the existing slab thickness results in reduced critical stresses and deflections in the slab system. Typically, the critical tensile stress is located along the outside edge at the bottom of the existing slab under an edge wheel load. It is highly advantageous when both the old and new overlay concrete act together as one monolithic

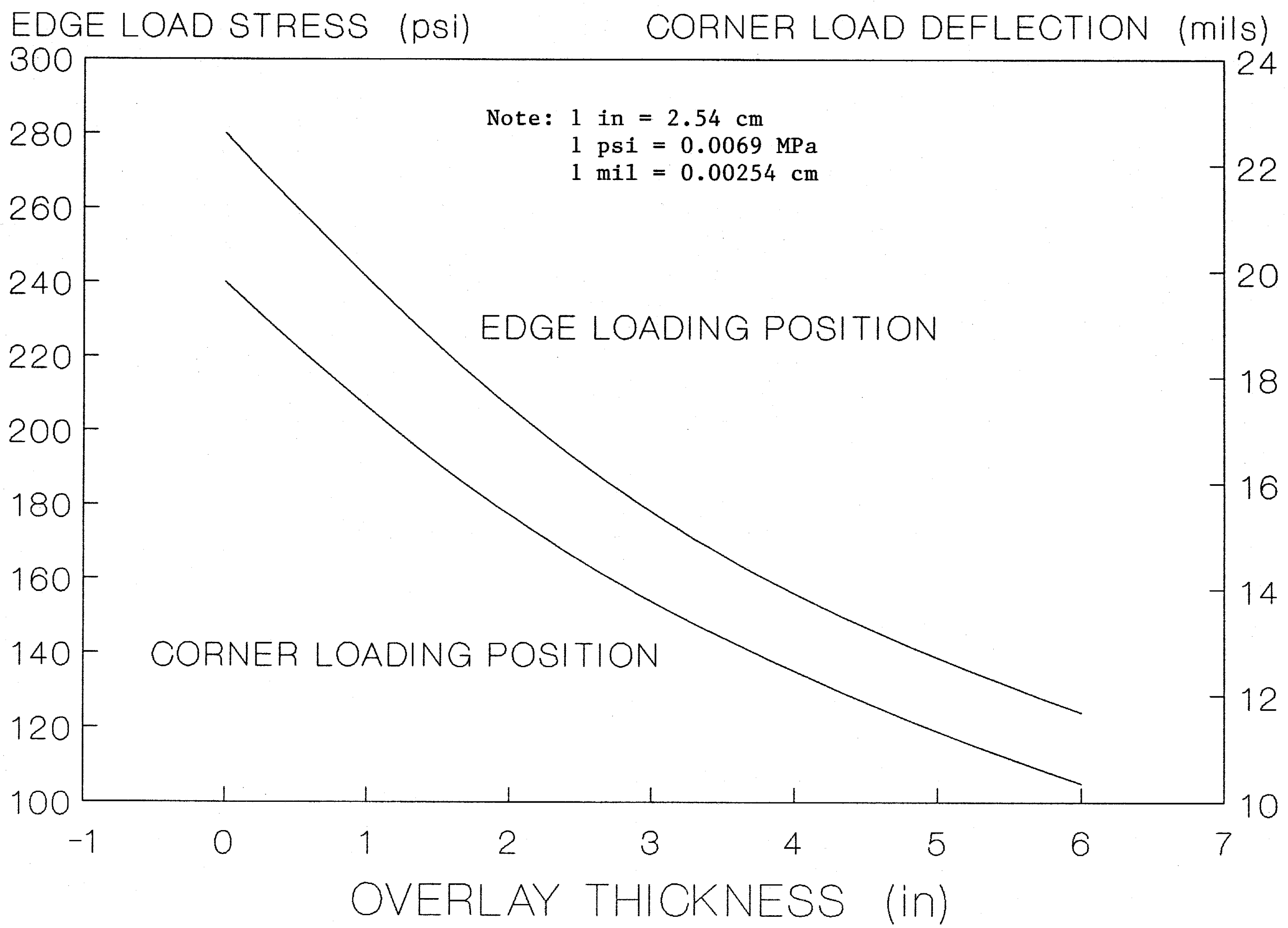


Figure 23. Edge load stress and corner deflection versus overlay thickness on a standard 9-in concrete pavement. (Developed by ILLI-SLAB modelling of a 9 kip wheel load [tire pressure = 75 psi] positioned at free edge and corner.)

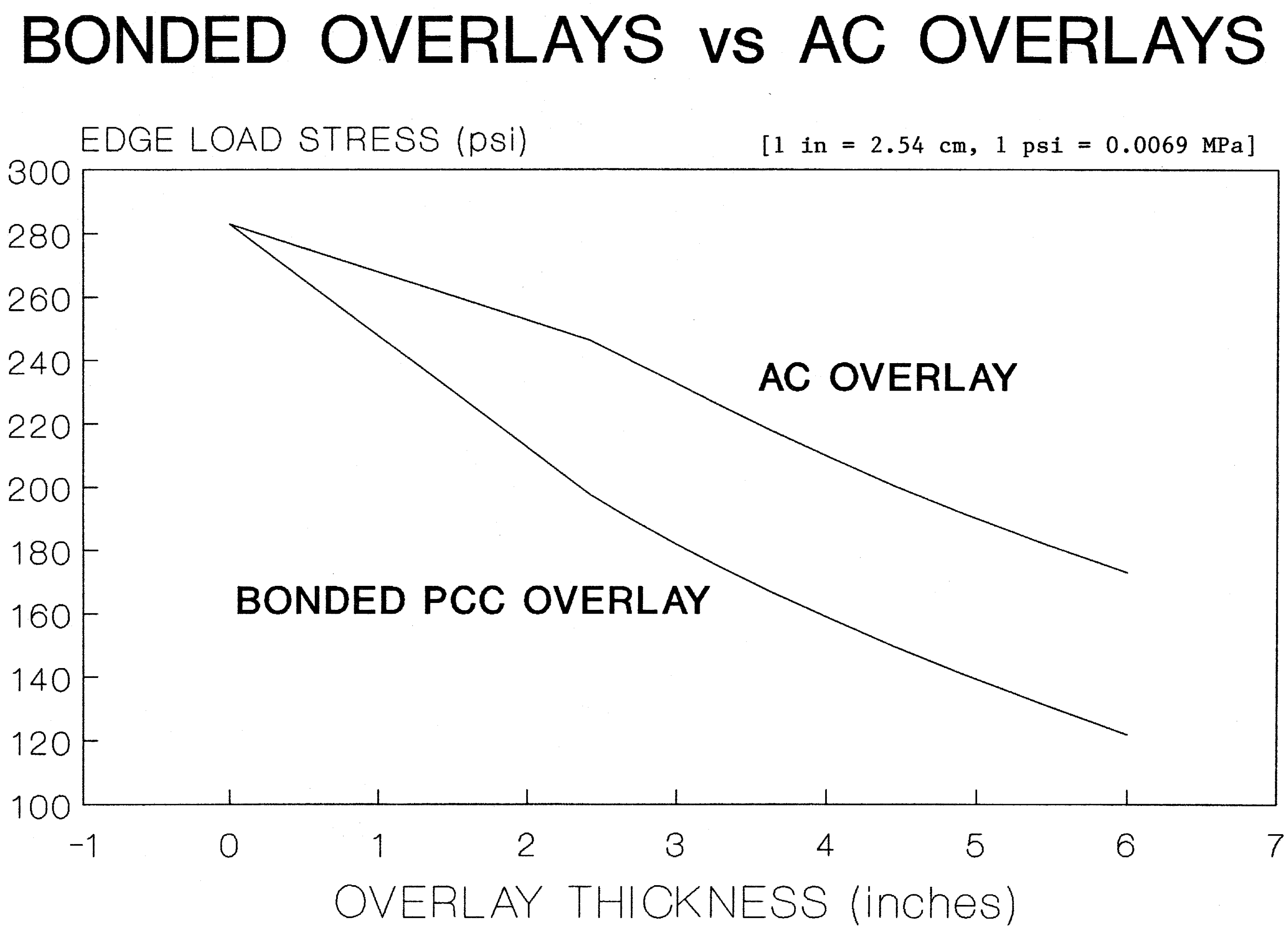


Figure 24. Comparison of free edge stress for bonded concrete overlay, to equivalent thickness of asphalt concrete overlay (Computed by ILLI-SLAB finite element program for 12x20 ft slab with 18 kip single-axle load at edge).

slab under load, because it is this effect that tends to produce a large reduction in the tensile stresses from which slab cracking develops. When the overlayed pavement is subjected to load, reduced tensile stresses mean reduced fatigue damage per load application which consequently prolongs pavement life. This will result in a many-fold increase of load applications before slab cracking occurs. In fact, increasing the total monolithic slab thickness beyond approximately 11 in [27.9 cm] may practically eliminate cracking due to fatigue damage (except under very heavy traffic conditions).

The life of bonded overlays, when proper construction procedures are employed and a permanent bond is achieved between the layers, should meet the projected design life. The reliability of the design life is largely governed by the following factors:

- Bonded overlay thickness.
- Construction procedures used and the bond achieved.
- Condition of the existing pavement and the amount of preoverlay repair accomplished.
- Adequacy of subdrainage.

Limitations

The cost effectiveness of bonded concrete overlays is dependent on the preoverlay repair required, surface preparation techniques used, thickness of overlay required, traffic control measures necessary during construction and the design life of the overlay.

The performance of bonded concrete overlays has been good on many projects.(4,61) However, when applied to existing pavements with significant amounts of slab cracking, the performance has been poor, because all working cracks in the existing pavement will reflect through the overlay, usually within the first two years of service. When a bonded overlay is used on an existing pavement where there are many working cracks and they are not repaired, the overlay will deteriorate at an accelerated rate.

Another potentially serious problem is delamination of the overlay from the existing slab which has occurred on a few projects due to poor construction or thermal conditions.(7,58) Other deterioration problems are secondary joint cracking and shrinkage cracking.(2,3) These problems are the result of poor construction techniques and can be prevented by following recommended procedures.

Bonded concrete overlays should not be placed on pavements with extensive "D" cracking or reactive aggregate problems. These problems may hamper the ability to achieve a permanent bond, as well as the possibility of the deterioration reflecting through the thin bonded overlay. If only low-severity aggregate durability problems exist, experience with bonded overlays has been good, however.

2.4.2 Concurrent Work

When applying a bonded concrete overlay, a variety of preoverlay repairs and other needed rehabilitation is normally required.

Preoverlay Repair

Preoverlay repairs are necessary to bring the existing pavement to a condition adequate for a bonded overlay to perform adequately over its design life. The major work items include the following:

- Full depth repairs or slab replacements of deteriorated joints and cracks and slabs.
- Partial depth patching of spalls.
- Subsealing to restore loss of support.
- Subdrainage to improve rapid drainage of the pavement structure.
- Resealing of existing joints, if they are open and significant incompressibles from the cleaning, grouting or paving operation could infiltrate.
- Slab jacking of high severity settlements.
- Retrofiting dowels and cross-stitiching (with deformed rebars) at working cracks.(2,70)

Other Concurrent Rehabilitation Work

The major item is the provision of shoulders that match the new concrete overlay surface alignment. If the existing shoulders are in good condition, a simple overlay of asphalt concrete to match the thickness of the overlay would be cost-effective. If the existing shoulders are deteriorated it might be cheaper to remove some of the deteriorated material, rework and compact the surface, and place a concrete shoulder that is tied into the traffic lane slab.

2.4.3 Design And Construction

Design Procedures

The design procedures employed in determining the thickness of the bonded overlay should include the following items:

- Visual survey of the existing pavement to identify needed repairs.
- Structural evaluation (using deflection testing) to determine:
    a. Elastic modulus of the existing slab, base and subgrade (or an effective k-value of the base and subgrade).

    b. Transverse joint load transfer.
- Detection of loss of support beneath the slab corners using deflection testing.
- Cores from the existing slab to estimate strength of the concrete.
- Analysis of past fatigue damage from past traffic (to provide an estimate of the remaining life of the existing slab).
- Prediction of realistic future traffic loadings for the overlay design period.(2,53)

The use of heavy load deflection testing, such as a Falling Weight Deflectometer, and the back-calculation of the slab and foundation modulus values and joint load transfer efficiency is extremely valuable to the structural evaluation of the pavement and the design of the bonded concrete overlay.(2,26,27,52,53)

The design procedure developed by Tayabji and Okamoto utilizes key inputs and provides reasonable results for bonded concrete overlays.(52) Examples of application of the procedure for designing Iowa bonded concrete overlays is given in reference 66. A detailed evaluation of overlay design procedures is provided in reference 27.

It is very important that after the overlay thickness has been determined using a given design procedure, the results be checked using another procedure. The predictive models given in section 2.3 can be used to estimate the amount of faulting and reflective cracking that will develop over the design period. These models are based on limited data, but provide a valuable tool for determining the adequacy of the design.

Materials

The portland cement concrete used for the bonded overlay should ideally have a low water cement ratio, low slump and yet be workable for placement.(13,18,21,25) The specifications for the portland cement concrete material will be governed by the specifying agency. Both Type I and high early strength (Type III for early opening to traffic) cement can be used. Aggregate materials should meet the gradation and durability requirements of the specifying agency. The mix design specifications that are used for new construction should be used in specifying the concrete mix for the overlay. Where Type III cement is employed, adjustments in the mix design and precautions in the curing process are mandatory.(21)

When workability of the concrete is a concern, a water reducing admixture meeting the requirements of ASTM can be specified.(25) If this alternative is chosen, the mix design should be adjusted according to the requirements of the specifying agency. Admixtures that will increase the strength gain of a Type I cement concrete mix, such as calcium chloride can be used where particular concern is made for reopening the lanes to traffic in short periods of time. Particular attention must be paid to achieve highly efficient curing, however, because debonding and shrinkage cracking must be prevented at all costs.(21)

A portland cement based grout material for bonding the overlay to the existing prepared slab surface can normally generate the required bond strength. Past data has indicated that a direct shear strength of 200 psi [1.4 MPa] is sufficient to withstand shearing forces.(2,10,30) Satisfactory results have been obtained with grouts using sand-cement-water or just cement-water. Direct shear test data from Iowa shown below indicate expected bond strengths for various application techniques and grout materials.(18)

TREATMENT AT INTERFACE	BONDING STRENGTH, psi
1:1 Sand-Cement-Water	450 [3.1 MPa]

Water-Cement at 0.70 lb/lb Brushed on	640 [4.4 MPa]
Water-Cement at 0.70 lb/lb Sprayed on	490 [3.4 MPa]
Water-Cement at 0.62 lb/lb Brushed on	390 [2.7 MPa]
Water-Cement at 0.62 lb/lb Sprayed on	610 [4.2 MPa]

The tests were performed on cores that were prepared with a simulated scarification and cured for 23 days under moist conditions. Results are based on three cores tested for each interface condition.

Based on these results and past experience, the water/cement ratio should not exceed 0.62 (7 gallons [26.5 l] of water per bag of cement).(18) The grout should have a creamy consistency. Care should be used with the grout material. The grout should be stir-agitated from the time of mixing to the time of application. All grout material should be used within 90 minutes from the time of mixing.(7,11,18,25,42) Most recent projects have utilized only cement-water bonding material, which has worked well.

Recent coring of several projects in Iowa after several years of service showed the interface bond strength to range from 370 to 550 psi [2.6 to 3.8 MPa].(66)

It is recommended that lab testing of the compatibility of the grouting material and existing pavement be performed for verification of the bonding procedures. Testing should be performed on a portion of the existing slab that was removed from the field, prepared as closely to the field procedures as possible, and overlayed with similar material and under climatic conditions as expected in the field. The same material and surface removal/cleaning methods should be used, as well as curing at conditions equivalent to the weather conditions expected at the time of placement. After curing, cores should be cut and tested for shear strength across the bonding interface.

Liquid epoxy resins have recently been used for the bonding material. Research at Caltrans has shown much better bonding than with grout.(58) Caltrans experience has been with pressure spraying application of low viscosity epoxy material over the entire surface of the existing slabs.

The best results have been obtained when the liquid epoxy resin is applied at a high coverage rate, about 40 square feet per gallon [0.98 sq m/l].(58) This will ensure a relatively thick (1/10-in [0.25 cm]) layer, which helps promote a uniform bond. An epoxy bonded overlay was placed on I-80 near Donner's Summit in California in 1984.

Some recent results from three States have indicated good initial bond strengths without the use of a bonding agent.(61,67) The long-term effect of using no bonding material has not been established, however.

Preoverlay Repair

The performance of a bonded concrete overlay depends largely on the condition of the pavement on which it is placed. If a bonded overlay is to perform well, the existing pavement must be brought to an adequate condition level. This involves preoverlay repair to upgrade the existing pavement as presented in section 2.4.2. The following guidelines describe the conditions under which preoverlay repairs are required.

Pumping And Loss of Support - Loss of support typically exists when visual pumping occurs. Loss of support can be verified by deflection testing utilizing procedures in reference 26. Joints having loss of support must be identified and subsealed to fill the voids created by the eroded subbase or subgrade materials. This will ensure full support beneath the existing slabs and overlay. A subdrainage evaluation must also be conducted to determine if edge drains would be effective in removing free moisture rapidly and reducing the pumping activity.(2)

Faulting - Faulted joints will be somewhat smoothed during the surface preparation and paving operations. Where faulting is a major problem on an existing pavement to be overlayed, the pavement should be evaluated for pumping and loss of support beneath the slab corners. The bonded concrete overlay will fill in the faulted areas and grinding is not required.

Cracked Slabs - Shattered slabs in the existing pavement should be replaced full depth with portland cement concrete. Full-depth repairs should also be employed to repair working transverse or longitudinal cracks. The joints from the repairs will become joints in the bonded overlay, and, thus, they should be doweled if truck traffic is substantial.

Another possibility for repairing transverse cracks is the retrofiting of dowels across the crack to improve load transfer.(2) This procedure is described in volume I of this report. It provides good load transfer across the joint and reduces faulting and deflections. The joint in the overlay must be sawed above the retrofit crack.

Longitudinal cracks could be repaired by cross-stitching with deformed rebars to help hold the crack tight. This technique has been used on newer pavements with success.(70)

Joint Deterioration - Serious joint deterioration problems, such as corner breaks, major spalling, or blowups, should be repaired with full-depth concrete repairs. If partial depth joint spalling problems exists, these areas should be either sawed or milled partial-depth to sound concrete. The shallow depressed areas left by the removed concrete can be filled during the paving operation. However, it is recommended that if removal is made to a depth exceeding 2 inches, the repair should be filled and cured prior to paving to ensure a uniform surface on which to place the overlay.(21,26) The joints must be maintained with fillers in the partial depth patch areas to prevent fresh concrete from entering the joint.

Unsealed Joints - Existing pavement joints must be sealed to keep the bonding agent, overlay concrete and other incompressibles from the surface preparation operations, from penetrating unsealed joint reservoirs and causing compressive stress problems upon thermal expansion.

Surface Preparation

The pavement must be thoroughly cleaned so that all foreign matter and surface contaminants are removed.(2,3,4,13,18,25) The procedures employed must use equipment which is capable of removing paint, oil, rubber, rust and loose concrete and yet not damage the surface or create environmental hazards. There is different equipment that can be used in this process. For best results, a concrete surface removal procedure should be followed by a secondary cleaning operation. Shot blasting and cold milling have both been successfully used to clean the surface.(2,3,4,7,9) Shot blasting may be more economical in some instances and does not damage the joints as much as cold milling, however, cold milling is more effective in removing extensive surface contaminants.

Shot Blasting - Shot blasting is performed by a self contained mechanical unit that will cause no dust or particulate problems. The machine is capable of removing all surface contaminants, except asphalt concrete or asphalt cement.(25) The machine throws abrasive metal shot at the surface in a contained cleaning head. The shot are reused as they are picked up by magnetic action and recycled to the blast wheel.(7,11,25) The particulate matter and dust created by the operation are also picked up and discharged. The average depth of removal for this equipment is about 1/8 in [0.32 cm].(7)

Care should be employed when using this equipment, as the shot can penetrate the joint reservoirs where they will not be recycled. It is recommended that a backer rod be installed in all open transverse joint reservoirs prior to the shot blasting operation. Depending on the efficiency of the vacuum attachment on the equipment, secondary cleaning may not be necessary after this procedure, but is highly recommended.

Cold Milling (Scarifying) - Cold-milling of the existing surface should remove all contaminants and loose material. The equipment should be capable of removing the old surface to depths necessary to provide a uniform profile, cross-slope and surface texture. A depth of approximately 1/4 in [0.64 cm] has proven to be adequate for bonded overlay projects.(11,25) Milling machines are usually equipped with dust abatement and means of protection from particulate matter created by the cutting action.

When cold-milling is used, a secondary cleaning must follow to ensure the removal of dust and particulate material from the milling operation. Secondary cleaning can be accomplished through sandblasting or waterblasting, which should be followed by a pass with a mechanical sweeper or airblowing operation immediately prior to applying the bonding grout.

Secondary cleaning of the shot blasted or milled surface is accomplished using one of the following two techniques:

Sandblasting - This is recommended as a secondary cleaning operation only. Sandblasting will normally remove any additional deteriorated material about 1/32 to 1/16 in [0.08 to 0.16 cm] from the surface.(11,25) When proper procedures are employed, the aggregates should be exposed to the extent that the colors are easily detected. There may be some dust problems from a sandblasting operation; the determination of whether dust abatement is necessary is left to the approval of the engineer.

Waterblasting - If waterblasting is chosen as the secondary cleaning means, the equipment used should generate enough pressure to remove all remnants from the surface preparation operation.(11,25) When used, extra time must be scheduled to allow for the complete drying of the prepared surface before paving can begin.

Airblasting - Airblasting is employed to thoroughly blow the exposed concrete free of debris caused by the milling or sandblasting operation. The debris should be blown to the nearest shoulder to avoid resettling of the debris on adjacent lanes. Airblasting equipment should be equipped with filters to prevent the spraying of compressor oil on the freshly cleaned surface.(25)

Placement of Bonding Grout

Under no circumstances should the grout be applied to a wet, moist or unprepared surface. Specifications should require a completely dry, clean prepared surface before paving operations can begin. Both a sand-cement-water grout and a cement-water grout have been used successfully.(2,3,4,11,18) Epoxy resin material has also been used successfully.(58)

Sand-cement bonding grout can be applied with a stiff brush or broom in a thin, even coating. When this procedure is used, it is emphasized that the grout should not run or puddle in depressions or low spots. The coating should be about 1/16 to 1/4 in [0.16 to 0.64 cm] thick.(4,13,25) The grout should be placed just far enough ahead of the paving operation, to avoid delaying the paver. If there are problems with the grout drying, a thin fogging of water should be applied ahead of the grout application at a distance that will allow the pavement surface to be dry prior to applying the grout. Paving should not be continued over dried grout; should the surface of the grout appear whitish dry, additional grout should be applied before continuation of the overlay placement.(11,42) Removal and replacement of thoroughly dried grout is mandatory. The determination of the need and equipment used is subject to the approval of the engineer. Equipment used in the operation should meet the standards required for the surface preparation procedures.

Applying neat-cement grout through a mechanical spraying device can give an excellent uniform coat. Mechanical spraying devices can apply the grout at a minimal distance ahead of the paving operation. An 8-ft [2.4 m] margin between the grout application and the slip-form paver should be sufficient.(42) When using this equipment, neat-cement (cement/water) must be specified. By using this application technique, the drying problems encountered when applying the grout with a brush should be avoided. If problems do exist, the same procedures for removal or application of additional grout apply.

Epoxy resin materials are new in bonded overlay applications. Therefore it is recommended that thorough testing procedures be employed to determine the compatibility of the epoxy, and existing and overlay concrete. The specimens should be prepared in a manner depicting field environment. Direct shear tests or slant shear tests can be used to evaluate bond strengths.

The epoxy specified should have a liquid (low viscosity) consistency that is capable of being applied through pressure spraying equipment. Laboratory bond strength values for liquid epoxy materials have been rated at over 5000 psi [34.5 MPa] from slant shear tests. This strength value indicates failure of the concrete before failure along the bond interface.(58) These values are very adequate for bonded overlay applications. Other benefits of epoxy materials are that they have a moderate working life in hot environments, and thus the construction problems encountered with early grout drying can be avoided.

Placing and Finishing Concrete

The placing and finishing of the bonded PCC overlay consists of all operations to place, finish, texture and cure the overlay. Placing the overlay concrete should be to the thickness as shown on the standard plans. Any deviation from this thickness, for filling partial depth repairs from milling or otherwise, should be to thicknesses greater than those on the plans and included in the placing of the overlay concrete. It is extremely important that every precaution available be taken to ensure a smooth riding surface of the overlay. This means good coordination between the contractor and the engineer on activities and inspection.

Texturing the pavement should be performed to produce good friction characteristics.(25) The normal procedures applied by the specifying agency should govern.

Curing of the bonded concrete overlay is a most critical aspect of the work. Shrinkage of the overlay concrete during the early curing stage is very critical. High shear stresses at the interface can result in failure of the bond as described. It can be reduced to acceptable levels through a low water cement ratio and highly efficient curing procedures.

Bonded resurfacing is best done during the cooler portions of the year. Under fairly cool weather conditions, good results have been obtained when temperatures are cool with a curing compound applied at rates of between 1.5 to 2.0 the normal rate.(25) It may be necessary to apply this in two passes to avoid running and puddling of the compound.

Placement of thin bonded overlays is not recommended during extremely hot weather (greater than 90 ^{O}F [32.2 ^{O}C]) due to accelerated moisture loss.(25) If hot drying conditions exist (e.g., high ambient temperatures, low humidity, drying winds, direct sun), it is necessary to require more effective curing procedures such as wet burlap that is placed immediately after texturing is completed. The burlap must be kept wet for at least 72 hours to prevent excessive moisture loss. After removal, the surface should still be sprayed with a curing compound. Failure to cure the bonded concrete overlay adequately will result in debonding of the overlay and shrinkage cracks.

If high early strength concrete is used, a thermal curing blanket should be placed directly after the joints are sawed (about 3 to 4 hours after paving).(21) The thermal blanket is used to keep the concrete temperature at a higher level to promote hydration of the cement. The blanket is not placed immediately after texturing because it is thought that the high temperatures in the overlay would cause the existing slab to expand at the joints resulting in the debonding of the overlay.

Jointing The Bonded Concrete Overlay

Joints must be cut or formed as soon as possible after the overlay is placed. Prior to applying the bonding grout, the contractor should carefully mark all existing pavement joints, including those formed by preoverlay full-depth repairs and repairs from rehabilitation at other times during the life of the pavement. A tolerance of plus or minus 1 in [2.5 cm] to either side of the existing joint is acceptable. This tolerance is provided to allow for the adjustment to a crack that has initiated prior to joint forming, which will help avoid the development of secondary joint cracking and eventual delamination of the overlay at the joint.(3) The best results are obtained when a sawing operation is used.

It is essential that for overlay thicknesses of 4 in [10.2 cm] or less, joints in the overlay must be sawed completely through the thickness of the overlay plus another 1/2-in [1.3 cm] to ensure that the full thickness is cut.(71) For thicknesses in excess of 4 in [10.2 cm], the depth of saw cut can be less than the depth of the overlay, but should be at least 3 inches [7.6 cm] in depth.

Expansion joints in the existing pavement should be specially marked, and reformed as expansion joints in the overlay.(2,7,25) Any especially wide joint in the existing slab should also be cut wider in the overlay to avoid any potential for point to point contact in the overlay.

Longitudinal joint sawing should also be performed; the depth of saw cut used and location should be governed by the same recommendations given for transverse joints.

2.4.4 Preparation of Plans and Specifications

It is recommended that a complete list and location of all preoverlay repair areas be included on the plans. Reference should be made to pavement stationing or other markings to define the size and type of repair warranted at each location. As-built changes in these plans should be noted. Joints must be cut over the full depth repairs, thus, they must be marked carefully.

Existing profile grades and the necessary changes of this grade to be completed during a milling or other surface removal operation or during the paving operation should be clearly noted on the plans.

The concept of "fast tracking" a bonded concrete overlay has been recently developed where the project is opened to traffic in 24 hours.(21)

2.5 BONDED OVERLAYS ON CRCP

Three bonded concrete overlays have been placed over existing continuously reinforced concrete pavements (CRCP). These were surveyed in Minnesota, Iowa and Texas. Surveys performed on these projects in 1985-86 showed them to be in good condition. Hairline transverse cracking had formed in the bonded CRCP overlays, but no significant crack deterioration was found. Cores taken in 1986 from the Iowa I-80 project determined the mean interface shear strength was 370 psi [2.6 MPa] (7 years age and heavy traffic).(66)

2.6 CONCLUSIONS AND RECOMMENDATIONS

Bonded concrete overlays can be an effective rehabilitation technique for pavements that are in need of structural improvements or improved rideability. The performance of many of the 31 uniform sections of bonded concrete overlays was good. However, the performance of several sections was poor, mainly due to the deteriorated condition of the existing pavement prior to overlay.

The design and construction of bonded concrete overlays requires special considerations to promote both good bonding of the overlay and to minimize distress over the life of the overlaid pavement. Detailed recommendations for the design and construction of bonded overlays are given in section 2.4. Overall conclusions and recommendations from this research study are as follows:

1. Cracking in the existing pavement should be expected to reflect through the overlay during the very early stages of the life of the overlay. Working cracks will reflect through to about the same severity as that of the crack in the existing pavement. However, the thicker the overlay, the less severe the reflected crack will tend to be in comparison to that of the existing crack (e.g. 5 in vs. 3 in [12.7 vs. 7.6 cm]). Bonded overlays, however, should not be placed on pavements with significant lineal feet of working cracks (greater than 100 ft/mile [18.9 m/km] if jointed plain, or greater than 200 feet/mile [37.9 m/km] if jointed reinforced), unless the cracks are repaired with full depth repair and joints are formed in the overlay at the repair joints.

2. Increased slab cracking from structural fatigue was not identified on any of the projects, except Clayton County, Iowa, where thinner original pavement slabs existed (6 in [15.2 cm]) and traffic levels varied in each direction. Bonded overlays will normally increase slab thickness beyond the point where normal traffic load fatigue can cause appreciable damage.

3. Only one bonded overlay exhibited "D" cracking. The existing pavement had severe "D" cracking and it appears that either this cracking reflected through the overlay after 9 years, or the overlay concrete contained a "D" cracking aggregate.

4. Secondary joint cracking is a significant distress on bonded concrete overlays. Because there were many projects that had no secondary joint cracking, it is obvious that good construction techniques are available to eliminate this problem. The critical item is sawing the overlay joint as soon as possible before a crack forms from contraction of the base slab. It is recommended that joints be sawed completely through the overlay as soon as possible after placement.

5. Faulting of transverse joints of the overlays has not been a significant problem. The maximum average faulting measured was at 0.10 in [0.25 cm]. Faulting increase with traffic is rapid at first, then leveling out, similar to faulting of new pavements. The development of faulting in bonded concrete overlays will be similar to the development of faulting of the existing pavement when it was opened to traffic. This is because, other than a reduction in deflection due to a thicker slab, the overlay provides no preventative measures against faulting. Thus, subdrainage and/or reducing water infiltration are needed if the existing pavement has faulted considerably (e.g., mean faulting greater than 0.15 in [0.38 cm]).

6. Visual pumping was not observed and was not a problem on bonded overlays for the traffic levels applied. However, the fact that faulting is occurring indicates that pumping is going on beneath the slabs. The decreased deflections from thick monolithic slabs has some effect on reducing pumping.

7. A substantial amount of shrinkage cracking was found on the bonded overlays. Very little shrinkage occurs on regular concrete pavements.(1) This indicates that either curing of the overlay concrete was not adequate, or the mix design was inadequate. However, less than ideal weather conditions, (e.g., higher temperatures (above 90 ^{O}F [32.2 ^{O}C]) and wind velocity) at the time of construction of the overlay may require upgraded curing techniques to prevent shrinkage cracking and debonding. Prevention of the problem may warrant the application of wet burlap and curing compound at twice the normal rate for most projects.

8. Some occurrences of debonding of the overlay at corners indicate the need for improved techniques to achieve bond. Analytical results show that horizontal shear stresses are highest at edges and can become high enough to cause debonding if efficient curing and low water/cement ratios are not used. The use of a low water/cement ratio and highly efficient curing may be the most economical way of assuring adequate bond is achieved. The use of liquid low viscosity epoxy resin material has shown promise of providing improved bonding in California.

9. Steel reinforcement was not very effective on one project where it was used to limit or prevent reflective cracking for a thin bonded overlay. Better results are obtained when the existing pavement is repaired full-depth prior to overlay and the transverse joint formed in the bonded overlay.

10. Applying the bonding grout with a pressure spraying device just ahead of the paving operation provided a uniform application of material. The use of an epoxy resin as an improved bonding agent was used in California. Further testing is recommended.

11. Predictive models for joint faulting and cracking were developed using the database. These models can be used to approximately estimate distress and for approximate design checks for bonded concrete overlay designs.

CHAPTER 3

UNBONDED PORTLAND CEMENT CONCRETE OVERLAYS

3.0 RESEARCH APPROACH

Portland cement concrete (PCC) unbonded overlays are designed to achieve a separation between the new overlay and the existing slab to eliminate reflection cracking. This type of overlay has been used as part of routine resurfacing for many years.(4)

To date there has been no nationwide documentation of the performance of this overlay technique. A few procedures exist for the design of unbonded concrete overlays, but none have been verified with field performance.

Many references were reviewed for unbonded concrete overlays as provided at the end of this volume. Several new publications have recently become available that have added considerable knowledge to the design, construction and performance of concrete overlays.(4,20,23,25,27,31,45,52,72,73,74,75)

The development of a database containing information on the original pavement design, concrete overlay design, traffic, environmental conditions and performance of existing unbonded overlays was required. The database was developed in order to allow analysis to include the consideration of many factors which might affect performance. To obtain all of the necessary database elements the following methods and sources were utilized:

- Extensive field surveys including mapping of cracks, physical measurements and subjective ratings were conducted on each project to document the current condition of the overlay.
- The design of the original pavement structure was determined from "as-built" plans and verbal communication with State DOT personnel.
- The design of the overlay was determined through the analysis of special rehabilitation construction provisions, "as-built" plans and verbal communication with State DOT personnel.
- Environmental data was taken from documentation of the monthly normal of temperature, precipitation, and heating and cooling degree days by the National Oceanic and Atmospheric Administration.
- Traffic estimates, including average daily traffic and percent commercial trucks, were obtained from the State DOT's. For the calculation of accumulated axle-loads on each project, Federal Highway Administration historical W-4 tables on axle load distributions for respective States and pavement classifications were used.

Physical test data were not collected. This data would have greatly increased the ability to analyze and interpret the pavement deterioration identified from visual surveys. The most useful tests would include heavy load deflection testing and coring (plus laboratory testing). An understanding of the physical properties of the pavement layers, loss of support, load transfer and gradations (of the base) would of made it possible to conduct structural, material and drainability evaluations.

3.1 DATABASE AND DATA COLLECTION

A total of 14 unbonded concrete overlay sections obtained from 7 different sites (design factors varied between sections at some sites) were included in the database. Two sample units having a length of about 1000 ft [305 m] were obtained from each of the sections where possible (23 total sample units were measured, most in opposing directions of traffic at a given project site). The projects included in the database represent some of the newer unbonded concrete overlays in the United States constructed after 1975. These pavements were field surveyed between June 1985 and July 1986. Figure 25 shows the general location of the unbonded overlays. Most of the unbonded overlays are located in wet-freeze areas.

A detailed description of the field and office data collection procedures is given in volume IV. There were five basic data types that were necessary for the development of life prediction models and for analysis aimed towards the development and improvement of design and construction procedures. These are:

- Field condition data.
- Original pavement structural design, insitu conditions, and historical improvement data.
- Rehabilitation design factors.
- Historical traffic values, classifications and accumulated 18-kip [80 kN] equivalent single-axle loadings.
- Environmental data.

A complete list of all of the variables considered in the field surveys is given in table 3 (see chapter 2). The design variables for the original pavement which are contained in the database are given in table 4 (see chapter 2). Variables for the unbonded overlay construction and design are given in table 5 (see chapter 2).

The database is comprehensive, containing as many projects as were available or that could be included within available resources. This was done to provide a wide range of data to facilitate regression analysis for the development of performance models.

Figures 26 and 27 give the age and thickness distribution. The age distribution indicates the relative newness of the unbonded concrete overlay sections (1 to 10 years). The thickness distribution shows 6 to 10 in [15.2 to 25.4 cm] of unbonded concrete.

Key overlay construction and design variables are included in table 8 for each section. Key variables that may affect performance are included, such as separation material and thickness, overlay type (both JPCP and JRCP), joint spacing and whether or not the joints were matched or mismatched.

Detailed descriptions of representative unbonded concrete overlay projects are given in volume II, appendix A. For each project in the appendix, the following is provided:

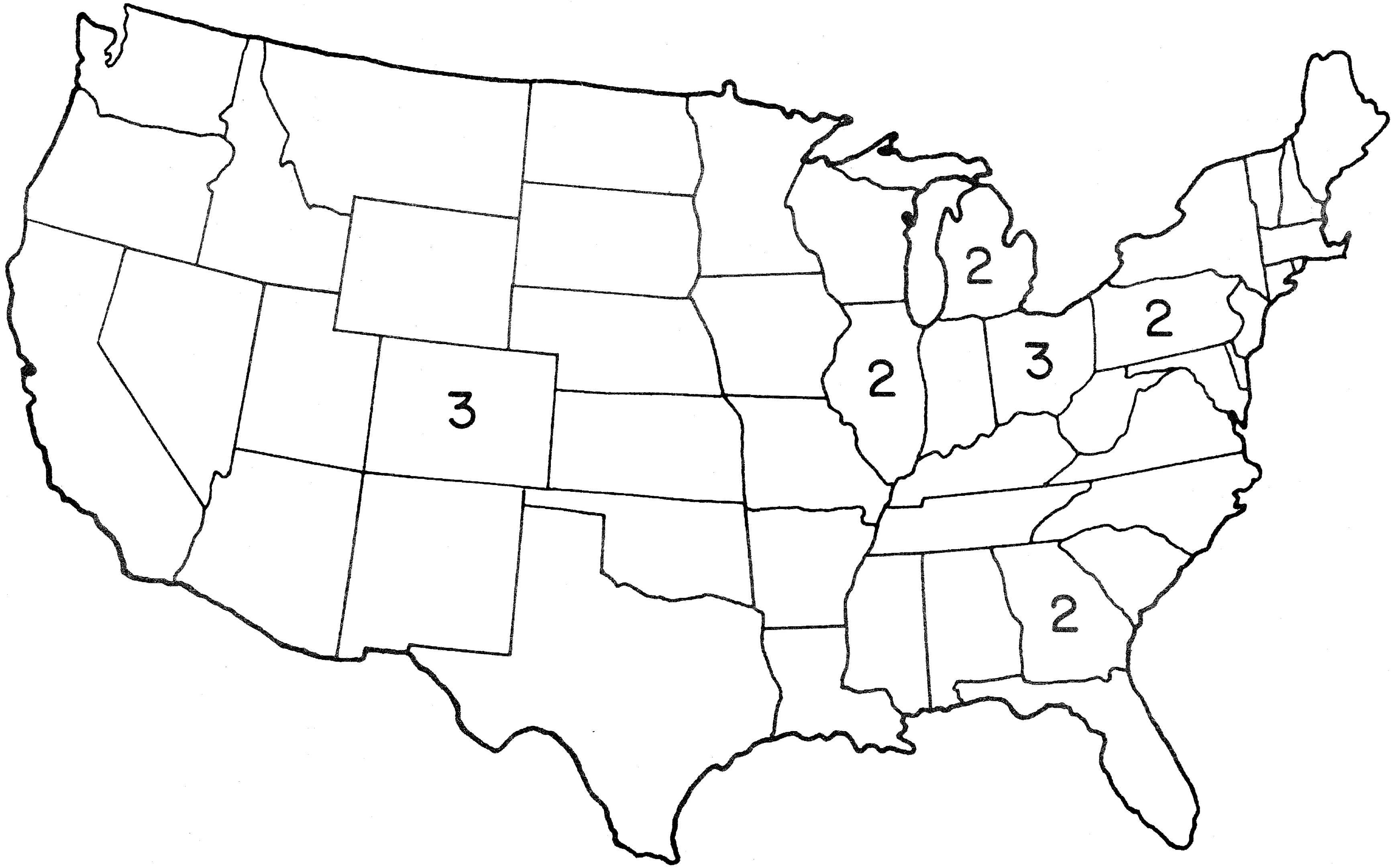


Figure 25. General locations of unbonded PCC overlays.

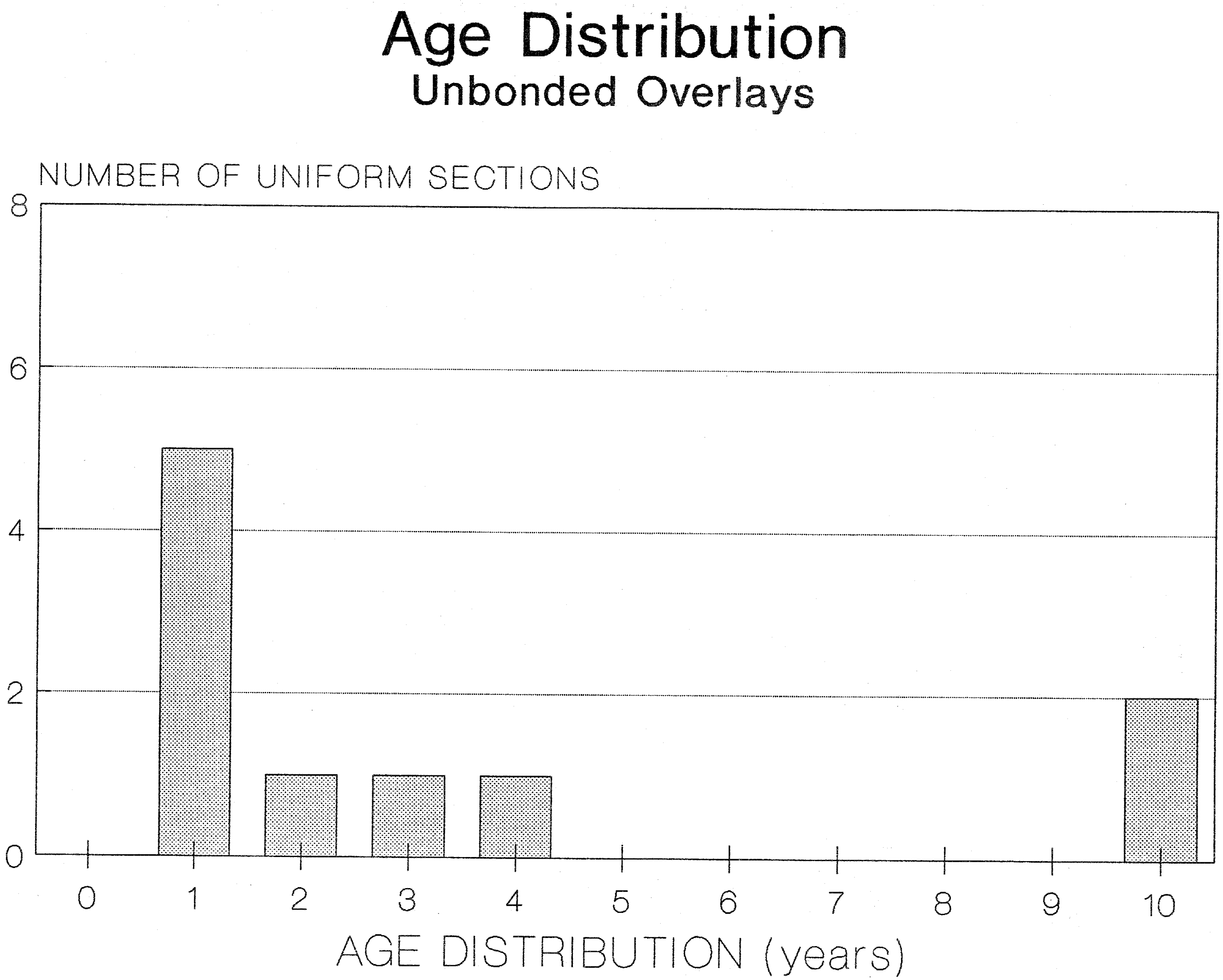


Figure 26. Age distribution of unbonded concrete overlays.

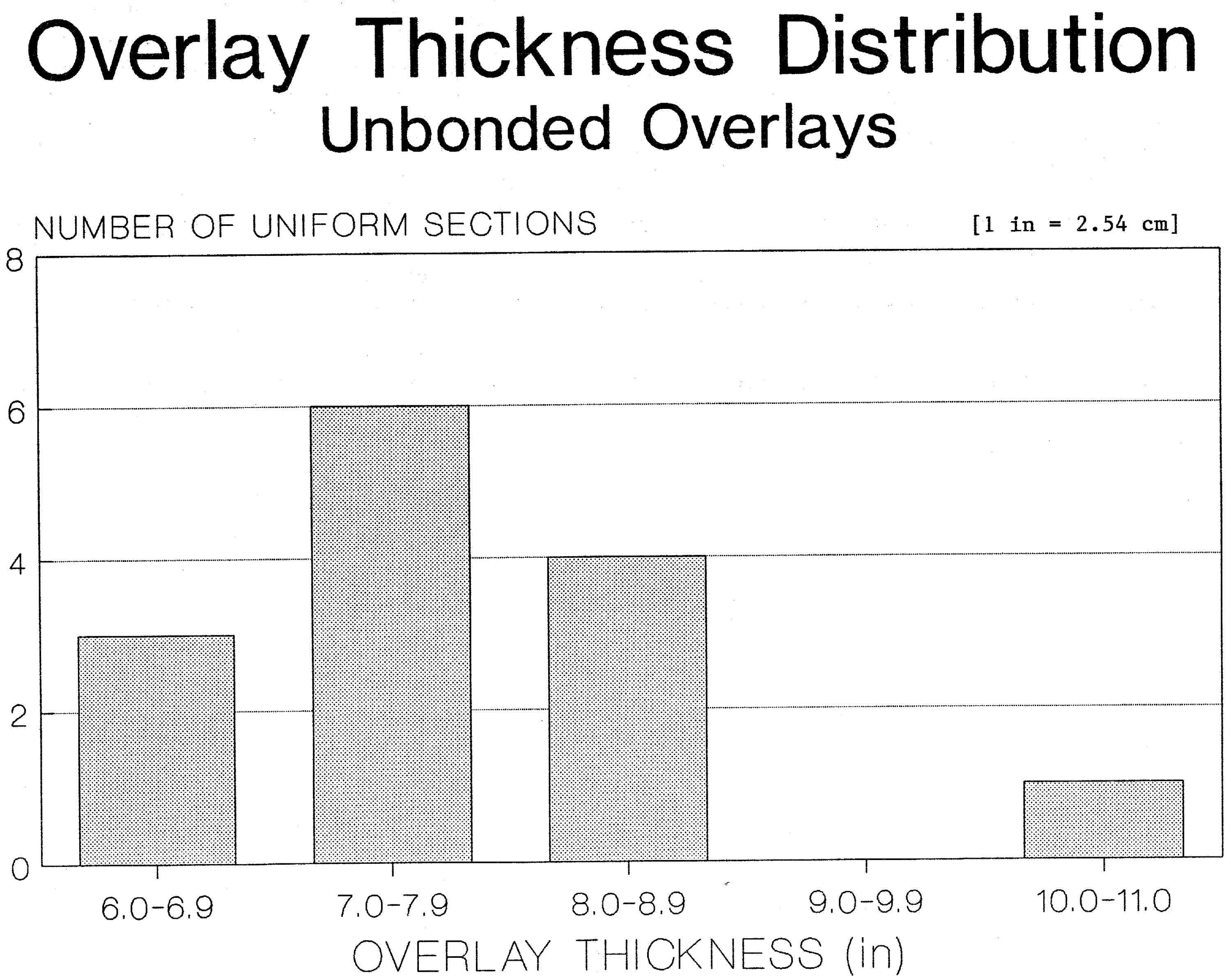


Figure 27. Distribution of the overlay thickness for unbonded concrete overlays.

Table 8. Design and construction data for unbonded concrete overlays.

PROJECT	DESCRIPTION	DEBONDING MATERIAL	LAYER THICKNESS (inches)	OVERLAY THICKNESS (inches)	OVERLAY TYPE	JOINT SPACING (feet)	JOINTING ARRANGEMENT	YEAR OF OVERLAY CONSTR.
A	IL East-West Tollway	SAND-ASPHALT	0.5	8.0	PLAIN	14.5 (random)	MISMATCHED	1981
B(1)	GA I-85 Braselton	CURING COMPOUND	0.2	6.0	PLAIN	30	MATCHED	1975
B(2)	GA I-85 Braselton	CURING COMPOUND	0.2	6.0	PLAIN	15	MATCHED	1975
C	MI US 23 Dundee	HOT-MIX ASPHALT	0.75	7.0	REINF	41	MISMATCHED	1984
D	PN I-376 Pittsburg	HOT-MIX ASPHALT	1.0	8.0	REINF	30.75	MISMATCHED	1983
E	OH I-70 Springfield	HOT-MIX ASPHALT	1.0	10.0	REINF	60	MISMATCHED	1984
F	OH US 33 Russels Point	HOT-MIX ASPHALT	0.75	7.0	PLAIN	13.5 (random)	MISMATCHED	1982
G(1)	CO I-25 Mead	THIN AC WITH SAND COAT	0.25	6.25	PLAIN	14.5 (random)	MISMATCHED	1985
G(2)	CO I-25 Mead	THIN AC WITH SAND COAT	0.25	7.75	PLAIN	14.5 (random)	MISMATCHED	1985
G(3)	CO I-25 Mead	THIN AC WITH SAND COAT	0.25	7.75	PLAIN	14.5 (random)	MISMATCHED	1985

* Indicates projects which are two lane highways. Both lanes are considered "drive" lanes for analysis of performance data.

Note: 1 in = 2.54 cm, 1 ft = 0.3048 m

- Project location.
- Original pavement design.
- Concrete overlay design.
- Traffic estimates.
- Environmental factors.
- Field performance.

3.2 FIELD PERFORMANCE AND EVALUATION

Unbonded concrete overlays can be designed to improve the structural capacity of the pavement, while also improving the rideability of the pavement through the provision of a new surface. Unbonded concrete overlays are constructed similar to new construction portland cement concrete pavements. There are no known unusual distresses that develop because of construction techniques for unbonded concrete overlays.

There are some distress types that were identified on the unbonded concrete overlays surveyed. These include transverse cracking, longitudinal cracking, joint faulting and pumping. A description of the development and observed field conditions related to each distress observed is given. Table 9 gives a summary of unbonded concrete overlay distress observed on each uniform section, normalized to 1000 ft [305 m] of outer lane, found for each unbonded overlay uniform section.

The severity levels employed in describing distresses are those defined in NCHRP Project 1-19 (COPES) distress manual.(1) For example, low severity cracking describes hairline cracking, medium severity describes working cracks and high severity a badly spalled and faulted crack needing immediate repair.

3.2.1 Transverse Cracking

Field Observation

Only two of the 14 unbonded overlay uniform sections contained deteriorated transverse cracking. These sections are located on the two Georgia I-85 JPCP overlays and consisted of 12 and 24 ft per thousand feet [3.6 and 7.3 m per 305 m] of traffic lane. One of these sections had a 30-ft [9.1 m] joint spacing and the other 15 ft [4.6 m] placed over a 30-ft [9.1 m] existing JPCP. These overlays do not have an AC separation layer. Figure 28 shows the distribution of all severities of transverse cracking for each unbonded overlay surveyed. In each case, the majority of cracking was located in the center 1/3 area of the slab.

Development

Transverse cracking on unbonded overlays can develop from at least three major causes (or a combination of these): reflection cracks, thermal curling and traffic load fatigue damage.(2)

Reflection cracking could result if the overlay is built over a very thin or extremely stiff separation material and the material is not performing adequately.(2,4) However, unbonded overlays are designed against the development of reflection cracking and in most cases this distress should not occur. There was no evidence that any of the transverse cracks were reflection cracks.

The most common separation material used is hot mixed asphalt concrete. This material is known to have a relatively high friction factor (perhaps over 3.0 as per reference 79). Thus, there is likely to be considerable friction between the overlay slab and the AC separation layer. A more detailed discussion of this is given in section 3.4.

Table 9. Summary of unbonded concrete overlay faulting and cracking observed on each uniform section surveyed.

PROJECT	AGE (yr)	ADT	% TRUCKS	ACCUM. 18 k ESAL (millions)	MEAN FAULTING (in)	LOW SEVERITY TRAN. CRACK (ft / 1000 ft)	MED SEVERITY TRAN. CRACK (ft / 1000 ft)	HIGH SEVERITY TRAN. CRACK (ft / 1000 ft)	LOW SEVERITY LONG. CRACK (ft / 1000 ft)	MED SEVERITY LONG. CRACK (ft / 1000 ft)	HIGH SEVERITY LONG. CRACK (ft / 1000 ft)
A *	4	30500	24	4.516	.05 /.08	0 / 0	0 / 0	0 / 0	0 / 77	0 / 0	0 / 0
B(1)	10	10922	25	6.736	.03	429	24	0	261	0 / 0	0 / 0
B(2)	10	10922	25	6.736	.03	189	12	0	101	0 / 0	0 / 0
C *	1	19400	17	0.380	.02 /.01	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
D *	2	67092	8	1.822	.04 /.04	162 / 247	0 / 0	0 / 0	0 / 4	0 / 0	0 / 0
E	1	26900	26	1.321	.005	119	0	0	0	0 / 0	0 / 0
F *	3	5470	19	0.732	.02 /.03	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
G(1)	1	25100	16	0.920	.00	0	0	0	0	0	0
G(2)	1	25100	16	0.920	.01	0	0	0	0	0	0
G(3)	1	25100	16	0.920	.01	0	0	0	0	0	0

* FOR TWO AND FOUR LANE ROADS, DATA FOR BOTH DRIVE LANES (DIRECTIONS) ARE SHOWN (ie. ** / **)

Note: 1 in = 2.54 cm, 1 ft/100 ft = 1 m/km

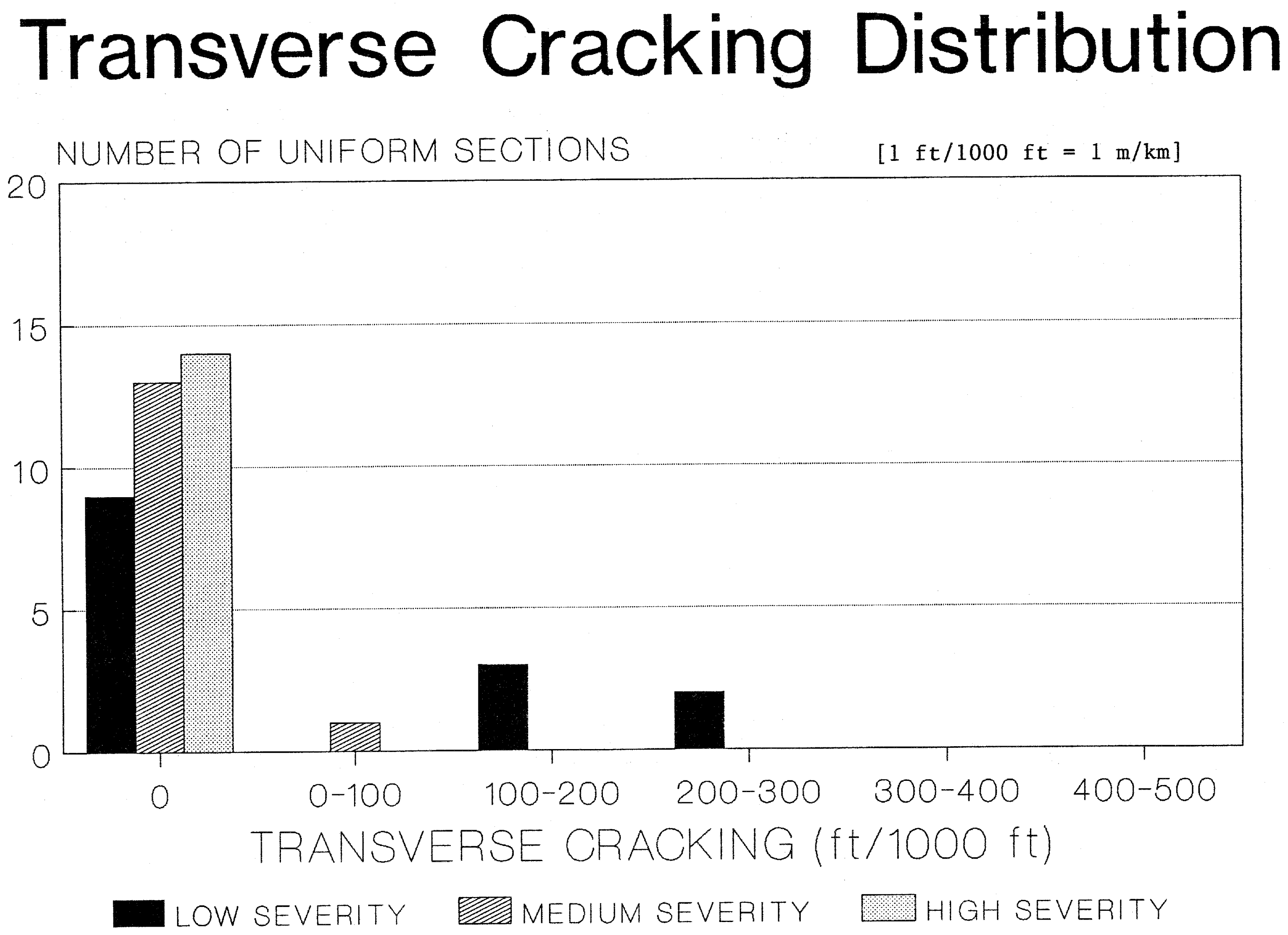


Figure 28. Distribution of severity of transverse cracking in the outer lane on unbonded concrete overlays.

The thermal curling is a potentially severe problem for unbonded concrete overlays. Figure 29 illustrates the temperature differential through a standard unbonded overlay section.(28) A large temperature gradient occurs through the unbonded overlay and separation material, but very little gradient through the underlying slab. Thus, the overlay slabs, which will experience a temperature differential through their thickness, will tend to curl over the stiff existing slabs.

The curling action of the unbonded overlay slab is probably not restrained much at the interface, therefore the overlay slab will actually lift off the underlying slab when a temperature gradient exists. The lifting will cause a void between the overlay slab and existing pavement surface which is illustrated in figure 30. When this void develops from curling during the daytime, the void will be at the center region of the slab. Tensile stresses at the bottom of the overlay will occur from the curl (due to the weight of the slab pulling down), and stresses caused by truck loads will add to this tensile stress (even more than normal due to the loss of support beneath the slab) to create a critical stress location.(78)

The other factor that contributes greatly to the curling problem is the increased effective k-value beneath the overlay slab. This will result in much greater curling stresses.(78)

There are two critical locations where cracking could initiate; the longitudinal outer slab edge and near the slab corner. This would result in edge cracks and corner breaks. Several transverse cracks were identified on the sections surveyed. No corner breaks were found however.

Transverse cracking is more likely to occur on overlay slabs that have long joint spacing due to the increase in curl stresses with increase in slab length.(78) This is particularly critical with the extremely high effective k-value.(78) The effect of joint spacing was seen on the Georgia I-85 sections where the original pavement had a 30-ft [9.1 m] joint spacing. One section of the jointed concrete overlay had matched joints at the 30 ft [9.1 m] interval. Another section had intermediate joints cut creating a 15 ft [4.6 m] joint spacing. The unbonded overlay cracked in the middle region of many of the 30-ft [9.1 m] slabs. Where the 15-ft [4.6 m] joint spacing was used, there were no cracks in the overlay.(22)

There are two solutions to this problem: reduce the length of the overlay slabs, or heavily reinforce the slabs to hold the cracks tight. Both of these solutions are discussed in section 3.4, Design and Construction Guidelines.

3.2.2 Longitudinal Cracking

<u>Field Observation</u>

Only two projects contained a significant amount of longitudinal cracking, and even those were all at low severity. Figure 31 shows the longitudinal cracking distribution for the unbonded overlay sections contained in the database.

The Georgia I-85 6-in [15.2 cm] thick overlay contained on average nearly 310 ft [94.5 m] of outer lane longitudinal cracking per 1000 ft [305 m] of roadway. All of this was low severity, tight-hairline cracking. Georgia used a curing compound as a separation material. Georgia reported that curing compound is not an effective separation material.(22) Likely causes of the cracking include late sawing of the longitudinal joint, inadequate joint sawed depth or use of a plastic insert to form the joint.

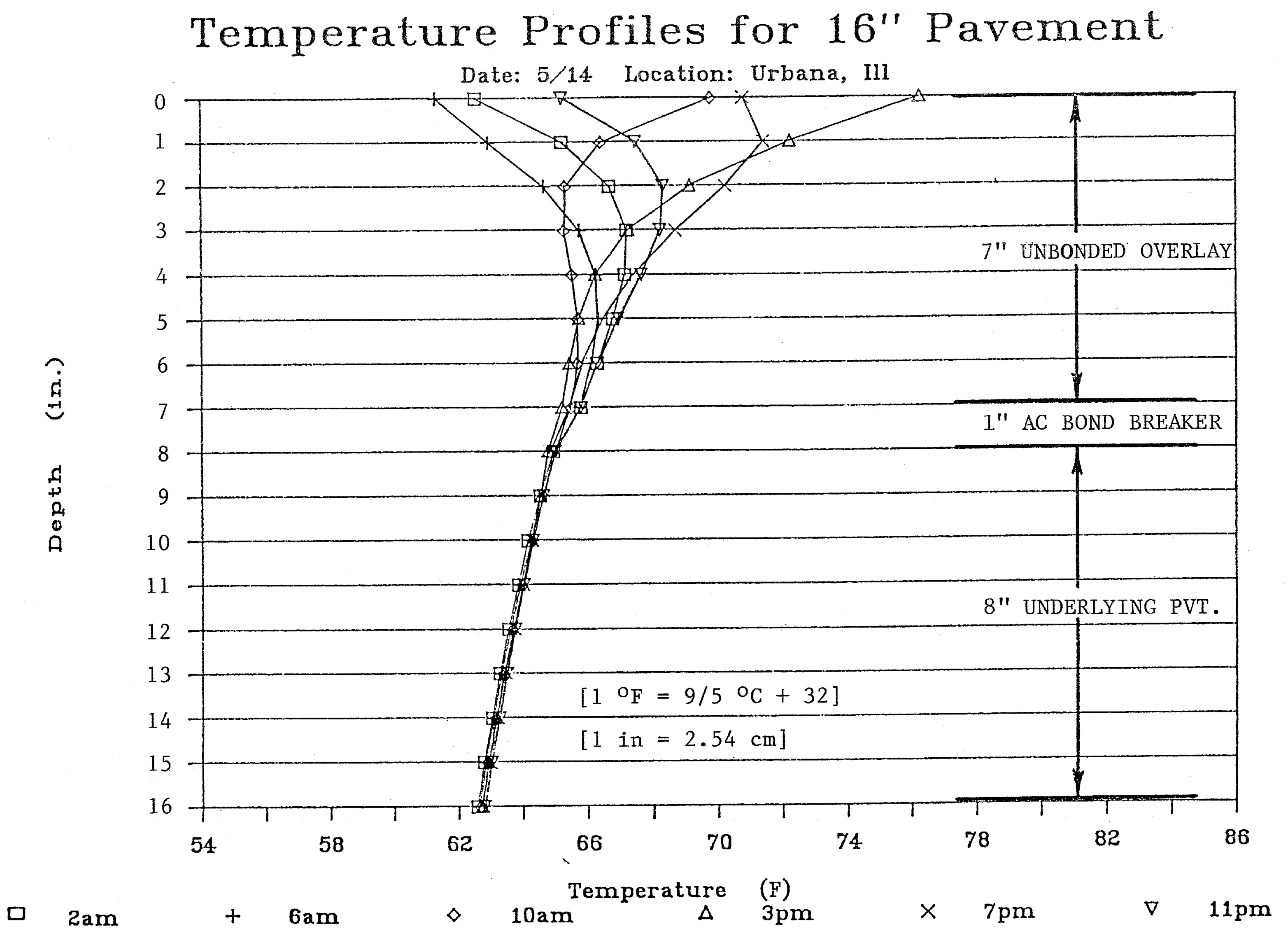
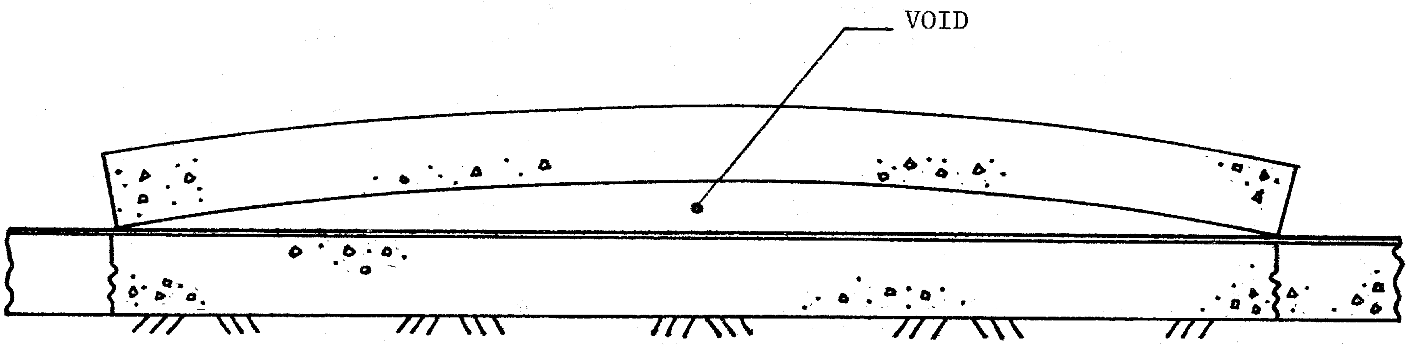
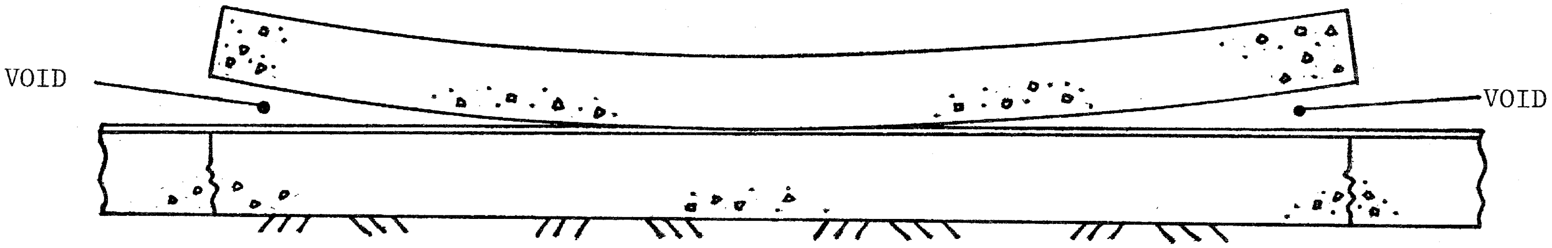


Figure 29. Temperature profile (for mid-May) through an unbonded overlay cross-section.



DAYTIME CURLING



NIGHTTIME CURLING

Figure 30. Development of the void under unbonded concrete pavements from the differential curling phenomena.

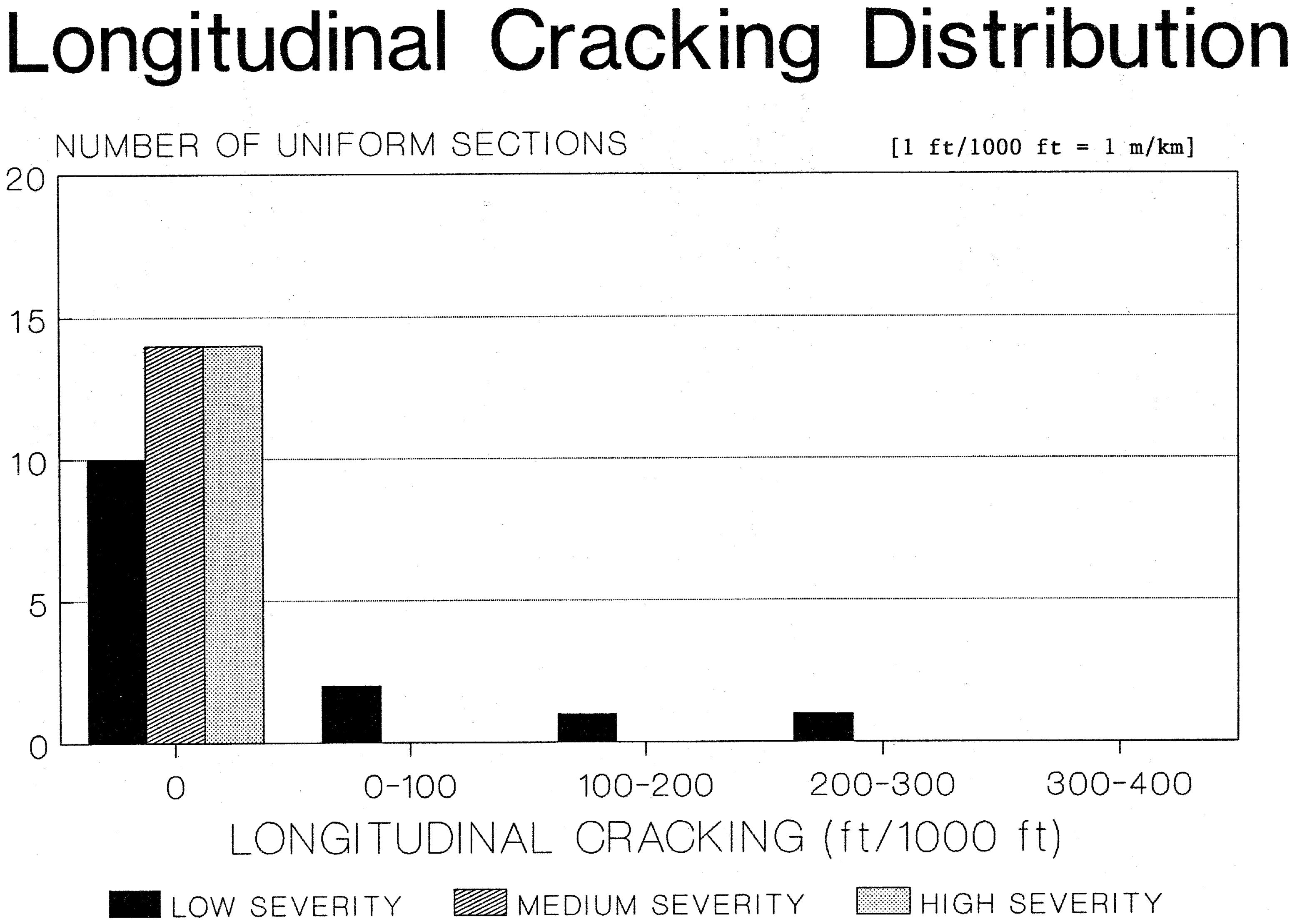


Figure 31. Distribution of severity of longitudinal cracking in the outer lane on unbonded concrete overlays.

The Illinois East-West Tollway (I-88) also contained longitudinal cracking in the west bound direction. This cracking was attributed to late sawing of the longitudinal joint.(23)

Development

The development of longitudinal cracking on unbonded overlays can be attributed to curling stresses, reflection cracking, and late sawing of the joints.

The thermal curling problem, described in section 3.2.1, could possibly contribute to the development of longitudinal cracks. However, the development is less likely because the effective slab width is only the 12-ft [3.7 m] lane width, which may not be enough to develop large curling stresses.

Longitudinal cracks in the existing pavement will reflect through the overlay if the separation material is not adequate. The movements of the overlay and existing pavements must be separated by the separation material for proper performance of the overlay when working cracks exist in the existing slab.

3.2.3 Faulting And Pumping

Field Observation

There was no significant faulting measured on any of the uniform sections. The section mean high was 0.08 in [0.2 cm] and the low was 0.0 in while the average faulting for all projects was just 0.03 in [0.08 cm]. All sections were constructed with mismatched joints except the Georgia I-85 section. This pavement was constructed with a 30-ft [9.1 m] joint spacing and faulting averaged just at the overall average of 0.03 in [0.08 cm] (this section had dowel bars). There was no visual pumping problem found on any uniform section surveyed, which correlates with the low amount of faulting.

Development

Faulting and pumping in unbonded overlays is reduced by several factors:

- Highly nonerodible layers (existing PCC slabs and AC bondbreaker material) beneath the overlay slabs.
- Dowels providing load transfer in some of the overlays.
- The mismatching of the overlay joints.

The deflection in the existing slab at the depths at which the erodible subbase or base materials exist are much reduced from prior to the overlay. This limits the potential for pumping erosion to create the voids and loss of support which cause faulting development.

It has also been observed that mismatched joints provide improved load transfer through support from the base slab. Most of the unbonded overlays had mismatched joints. There was no apparent cracking caused by this design. Figure 32 illustrates the effectiveness of the mismatched joint arrangement.

Other deterioration may very well develop in unbonded overlays such as joint deterioration, "D" cracking and reactive aggregate deterioration. Joint deterioration may be reduced due to the shorter joint spacing of many of the unbonded concrete overlays.(1)

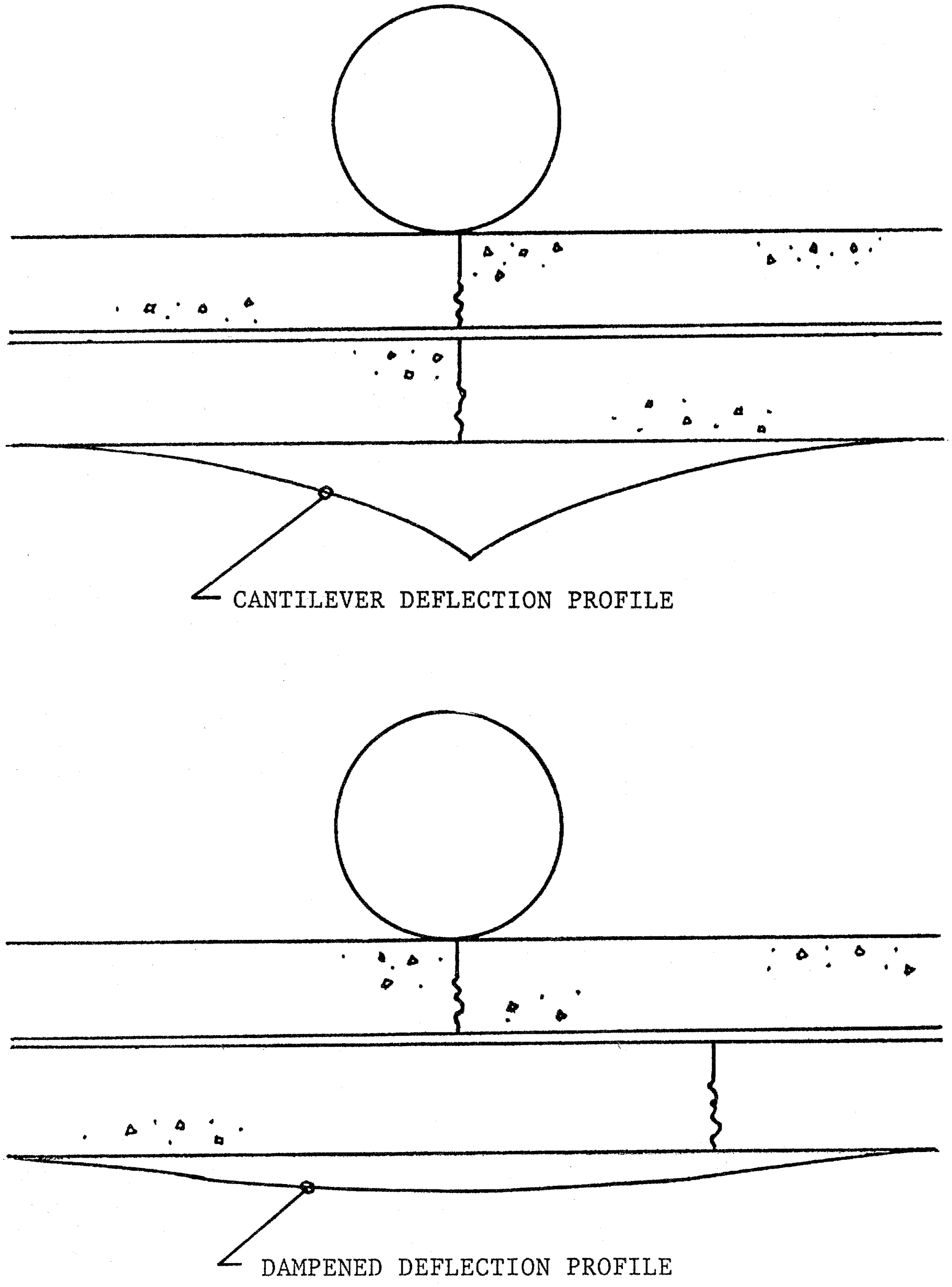


Figure 32. The effectiveness of mismatched joints in inhibiting the development of faulting and pumping.

3.3 PERFORMANCE MODELS

Although considerable analysis on the database for unbonded concrete overlays was conducted, only one model (joint faulting) could be developed from the data. The analysis on other performance indicators was limited by the small number of occurrences of these problems.

3.3.1 Joint Faulting

The model developed for joint faulting in unbonded concrete overlays is as follows:

$$\text{FAULT} = 0.28615\ \text{ESAL}^{.39654}\ [\ 0.0987\ (1 + \text{DOWEL})^{-.51083}\ ]$$

where:

FAULT = The mean faulting across the overlay joints, inches.

ESAL = Equivalent single-axle loads accumulated on the overlay, millions.

DOWEL = Diameter of dowel bars placed in the overlay, inches.
(0 if no dowel bars were used in the overlay)
Note: all dowel bar spacing was 12 in [30.5 cm] on centers.

Statistics:
R^2 = 0.51
SEE = 0.02 in [0.05 cm] (standard error of estimate)
n = 23

Equation Range of Applicability:

ESAL	Equivalent single-axle load data ranged from 0.73 million to 7.0 million accumulated on the overlay.
DOWEL	The diameter of the dowel bars in the existing pavement ranged between 0 (no dowels) and 1.625 in [4.1 cm].

A sensitivity plot for the faulting equation is given in figure 33. It is evident that faulting in unbonded overlays is not a significant problem. Faulting typically becomes detrimental when over 0.13 in [0.33 cm] for JPCP or 0.26 [0.66 cm] for JRCP.(95) After 10 million equivalent single-axle loads, the predicted faulting, with undowelled joints, is just 54 percent of the JPCP critical value. When the overlay joints are dowelled the predicted faulting at 10 million ESAL's becomes just 35 percent of the critical JPCP value.

An interesting point arises when considering the difference between dowel diameters. As was also discovered with bonded overlays, the effects of dowel diameter is also not as great on unbonded overlays as on new pavement sections. This may be attributable to the increased slab support from the underlying slab, and the more erosion resistant AC and PCC beneath the the overlay. Figure 34 shows the comparison of new pavement faulting predicted with the COPES model, to faulting modelled by the unbonded overlay model. Without dowels, newly constructed pavements fault far more than unbonded overlays, however, with dowels the predicted faulting is very similar for both.

These overlays have received from 0.7 to 7.0 million 18-kip [80 kN] equivalent single-axle loads. Faulting normally begins early in the life of a pavement as shown in figure 33. Higher load applications may result in increased faulting.

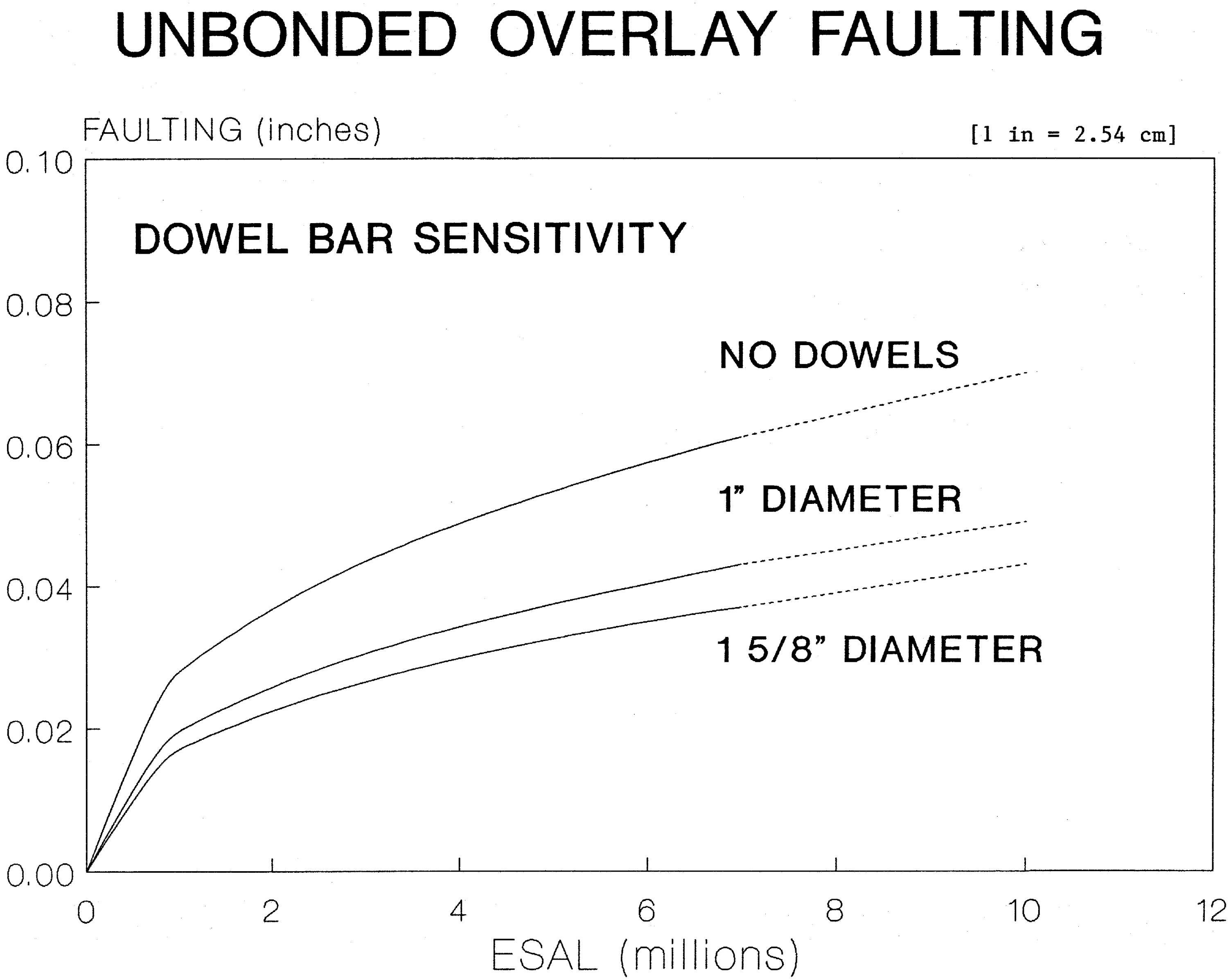


Figure 33. Sensitivity of the unbonded overlay faulting model to dowel bar diameter.

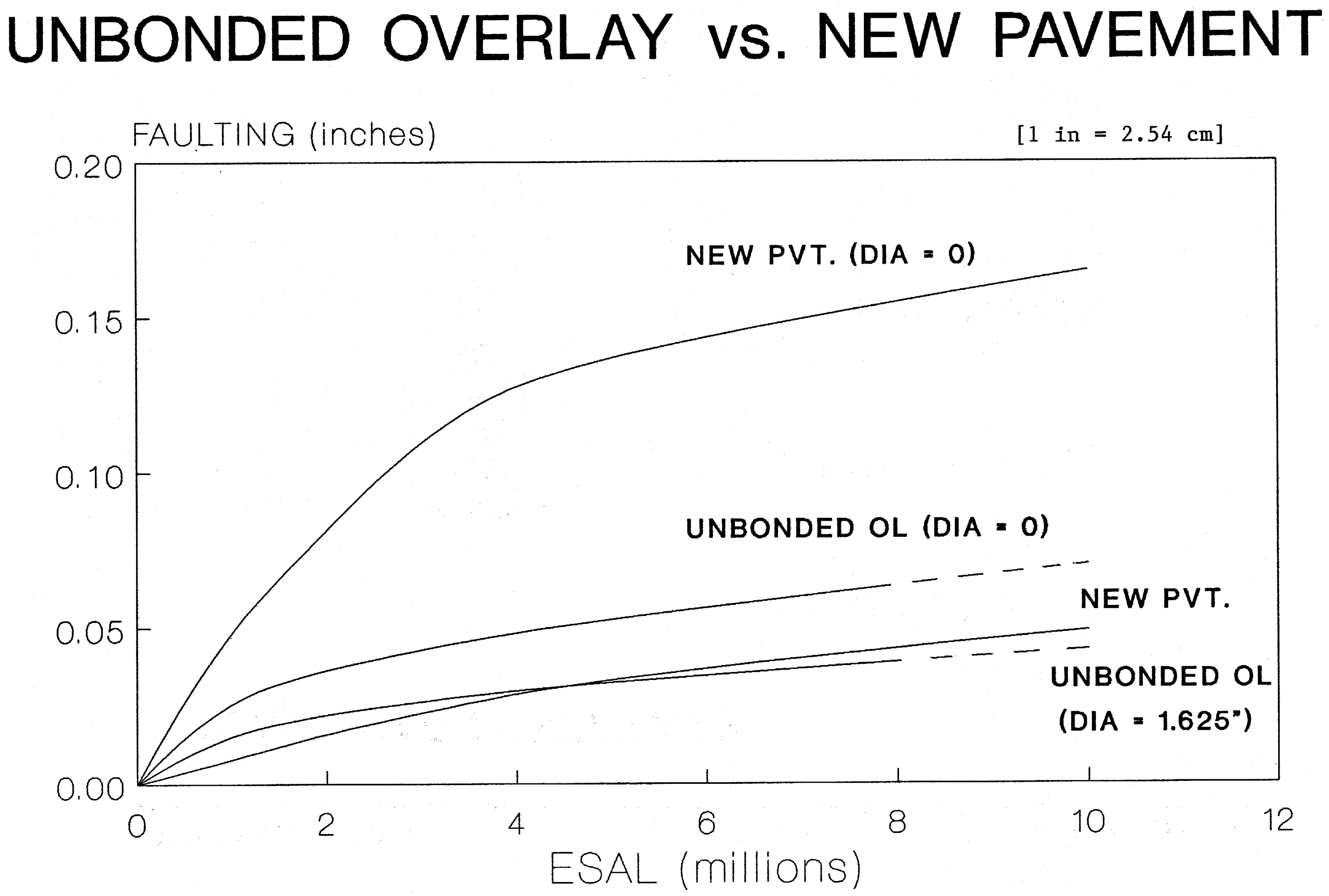


Figure 34. Comparison of predicted faulting on unbonded overlays to predicted new pavement faulting (similar design conditions).

3.3.2 Other Distress Models

Although considerable analysis of the database for unbonded concrete overlays was conducted, only one model (joint faulting) could be developed from the data. The analysis on other performance indicators was limited by the small number of occurrences of these problems.

The database did not show a significant pumping problem and the development of pumping in unbonded overlays appears to be minimal.

3.4 DESIGN AND CONSTRUCTION GUIDELINES -- UNBONDED CONCRETE OVERLAYS

3.4.1 Introduction

This section provides a comprehensive summary of the design and construction of unbonded concrete overlays. The information is a synthesis of that obtained from past research studies, published design procedures, field performance results from the database and staff experience. The guidelines are presented in a format similar to NCHRP Project 1-21 and the FHWA Rehabilitation Manual and are intended to facilitate usage by practicing engineers.(26,76)

The following guidelines cover the overlay of existing jointed portland cement concrete (PCC) pavements with an unbonded concrete overlay. This overlay method involves the placement of a separation material/leveling course and construction of a jointed concrete pavement above the existing surface.

Need For Unbonded Concrete Overlays

Unbonded concrete overlays can be used to correct many deficiencies in concrete pavements. This technique may be cost-effective when the condition of the existing pavement is structurally deficient or deteriorated past the point of economical restoration, when overhead clearance is not critical (or can be handled economically by reconstructing the pavement under bridges), or when it is not economical to match joints in the overlay with those of the existing pavement.(2,4)

This overlay technique can provide a substantial increase in the load carrying capacity of the pavement if properly designed. When applied, the overlay will react structurally as a new pavement built on a very high modulus base (e.g., concrete). The beneficial effect this will have on the overlay is to impede the development of load induced distresses such as loss of support, pumping, faulting and cracking. A potential problem exists due to high thermal curling stresses in the unbonded overlay, but this can be handled as subsequently presented.

In addition, the separation material layer inherent in unbonded overlays can also retard or arrest the development of reflective cracking in the overlay concrete.(4,22,23) This is a major advantage of this type of overlay. By limiting the development of reflective cracking, the separation material will increase the life expectancy of the overlay and consequently produce a more cost-effective long-lasting alternative.

Effectiveness

The concept of applying a concrete overlay with a separation material separating the old and new concrete is based on producing a cost-effective rehabilitation of an extensively deteriorated pavement. If the existing pavement is not extensively deteriorated, there are probably more cost-effective overlay types available, although there are exceptions to this (e.g. exceptionally heavy traffic requires a large increase in structural capacity or failure will occur rapidly in the existing pavement). Although unbonded overlays have not been extensively used in the past, the available performance data including the field data collected under this FHWA contract has indicated that this technique has provided excellent service.(4,15,20,31)

Unbonded overlays require only conventional construction procedures.(25) The overlay is constructed in the same fashion as a new mainline pavement over a base course. Special construction equipment or materials are not needed. This results in a relatively good assurance of a well constructed pavement, and eliminates potential distresses from construction induced problems that have developed in other overlay types.

The reliability of the design procedure used to specify the overlay thickness and joint spacing is very important because of the critical tensile stresses that will develop in the overlay concrete. If the thickness of the overlay is not sufficient to support the expected traffic over the design life, the overlay will prematurely fail from fatigue cracking. If the joint spacing is inadequate, transverse cracking will develop prematurely. Thermal curling stresses must also be considered in design in order to ensure an overlay joint spacing and thickness combination that will not crack from extensive curling and traffic induced stresses. The procedures used must accurately characterize the remaining life of the existing pavement, and then use this in evaluation of the structural support the existing pavement will provide in the overlaid pavement structure.(52,53) If proper evaluation is made and applied, the overlay should provide good service over the design life.

Limitations

The cost-effectiveness of unbonded concrete overlays is dependant on the separation material employed, the thickness of the required overlay and additional costs generated from the increased elevation of the pavement surface (e.g., bridge clearances, thickened shoulders). In addition, joint sawing and lane closure time influence costs also.

Poor performance of some unbonded overlays has primarily been linked to the type of separation material used.(4) When a material which is incapable of isolating the movements of existing and new concrete is used as separation material, cracking in the overlay is accelerated.(22) Reflective cracking will propagate from an inadequate separation layer.

Differential curling stresses can also create a cracking problem in the overlay concrete. The overlay concrete slabs will be exposed to much greater temperature gradients than the underlying slabs. This will induce greater curling stresses in the overlay. When combined with traffic induced stresses and the extremely stiff foundation created by the underlying slab, the curling phenomena can produce very high stresses in the overlay concrete. This problem can be prevented by using a shorter overlay joint spacing, usually below 15 ft [4.6 m], or heavy reinforcement to hold the cracks tight.

3.4.2 Concurrent Work

Preoverlay Repair

When applying an unbonded overlay, usually very little preoverlay repair is necessary. Normally only serious types of deterioration are considered.(25) The use of any form of preoverlay repair of distressed areas should be based on their possible effect on the overlay performance. The following distresses should be considered when an unbonded overlay is to be placed:

- Joint Deterioration: High severity spalling at existing pavement joints should be filled and compacted with an asphalt concrete patching mix.

- Broken Slabs: In areas where the pavement slabs are shattered and experiencing excessive deterioration, or where slabs have lost support and are deflecting, the pavement should be repaired.(25) The repair should be full-depth replacement or, where economical, stabilized with subsealing. This will ensure that the overlay will have full support at these locations.

- Faulting: Faulting of the transverse joints should present no problems when an AC separation layer is used.

3.4.3 Design and Construction

Design Procedures

The design procedures employed in determining the thickness of the unbonded overlay should include the following items:

- Visual survey of the existing pavement to identify needed repairs.

- Structural evaluation (using heavy load deflection testing) to determine
  a. Elastic modulus of the existing slab, base and subgrade (or effective k-value of the base and subgrade).

  b. Transverse joint load transfer.

- Detection of loss of support beneath the slab corners using deflection testing.

- Cores from the existing slab to estimate strength of the concrete.

- Analysis of past fatigue damage from past traffic (to provide an estimate of the remaining life of the existing slab).

- Prediction of realistic future traffic loadings for the overlay design period.

- Direct consideration of the friction factor between the separation material and the unbonded concrete overlay.

The use of heavy load deflection testing, such as a Falling Weight Deflectometer, and back calculation of the slab and foundation modulus values and existing joint load transfer efficiency is valuable to the structural evaluation of the pavement.(2,26,52,53)

The friction factor actually achieved between the separation material and the unbonded concrete overlay has an important effect on the performance of the overlay. Asphalt concrete is known to have a friction factor of at least 3.0, polyethylene sheeting about 0.5 and cement treated material about 8 to 51.(79,81)

A low friction factor can cause problems. For example, one agency recently used a lime slurry on the AC layer to reduce the temperature of the AC layer and also to break the bond. This resulted in the 7-in [17.8 cm] overlay cracking only through the joints spaced at about 100-ft [30.5 m] intervals (actual joint spacing was 27 ft [8.2 m]). Using a separation layer with this low of a friction factor is not recommended.

A very high friction factor may result in transverse and longitudinal crack deterioration problems for a JRCP overlay if the reinforcement is not adequate to hold the cracks together. Thus, the design of reinforcement must use a realistic friction factor, consider the type of steel (smooth wire, deformed wire, or reinforcing bars), and consider the temperature extremes expected for the concrete and steel during the design life. Use of a shorter joint spacing (20 to 30 ft [6.1 to 9.1 m]) is another design alternative to reduce cracking.

Joint design for unbonded concrete overlays is also very important and critical. In general, for JPCP overlays the joint spacing should be very short to minimize the effect of high thermal curling stresses and high friction factor between the overlay and the separation material. A maximum joint spacing depends somewhat on the slab thickness, with a 10-in [25.4 cm] overlay having longer spacing than a 6-in [15.2 cm] overlay (due to reduced thermal curling in the thicker slab). A general rule of thumb is the maximum joint spacing (in feet) be not greater than 1.5 to 1.75 times the slab thickness (in inches). Thus, the following results would be obtained:

6-in [15.2 cm] unbonded concrete overlay: 10.5 ft [3.2 m] maxium joint spacing.

10-in [25.4 cm] unbonded concrete overlay: 17.5 ft [5.3 m] maximum joint spacing.

The longitudinal joint should be sawed at least 1/3 the depth of the slab within 24 hours after placement. Transverse joints should also be sawed at least 1/4 the depth of the slab within 24 hours after placement.

Another design concept for unbonded overlays is to breakup the existing slab into small pieces (rubble, or to an aggregate base) before placing the overlay. The States of Wisconsin, Minnesota and New York have experimented with this technique recently. This may be cost effective for pavements that are severely "D" cracked or badly cracked and distorted.

Design concepts as described in the Portland Cement Association (PCA) method are recommended.(52) These procedures should be employed in conjunction with the portland cement concrete pavement design procedures of the specifying agency.

It is very important that after the overlay thickness has been determined using a given design procedure, the results be checked using another procedure. The predictive faulting model given in section 2.3 can be used to estimate the amount of faulting that will develop over the design period. This model is based on limited data, but provides a valuable tool for determining the adequacy of the design.

<u>Materials</u>

1. Portland cement concrete: The specifications for the portland cement concrete material will be governed by the specifying agency. Aggregate materials should meet the gradation and durability requirements of the specifying agency. The mix design specifications that are used for new construction should be employed in specifying the concrete mix for the overlay.

2. Separation material: The separation material can be constructed out of several materials. Hot-mix asphalt is very widely used, and should be constructed to a minimum thickness of 1 in. The material should meet the mix design

specifications of the specifying agency and can employ conventionally graded aggregates with a maximum aggregate size dependent on minimum thickness of the separation material.(25) A uniformly graded sand has also been used successfully in hot-mix separation interlayers. Hot-mix asphaltic material has proven to be the best alternative for isolation of the overlay and underlying slabs and also as a leveling course to smooth undulations and surface roughness for the paving operation. It is recommended that this alternative be applied where the underlying pavement has numerous cracks, faulting greater than 0.2 in [0.51 cm] at the joints and is in need of a leveling course.

Bituminous surface treatment type materials have also been used. These materials are:

- A slurry seal to a required depth of 1/8 in [0.32 cm].
- MC-250 cutback asphalt with a sand cover.(25)

The use of thin-layer separation materials can be effective when surface roughness, such as that which is due to faulting, is either not present in the existing pavement or has been eliminated with other repair techniques.(22) These materials are not recommended on pavements in which joint and/or crack faulting exceeded 0.2 in [0.51 cm], or signs of loss of support under the slabs existed prior to preoverlay repair.

Other materials that have been suggested for use as separation materials are lean concrete, heavy roofing paper and polyethylene sheeting. Lean concrete has been suggested for use as a leveling course over the existing pavement. It is currently being used in West Germany as standard practice. A 4-in [10.2 cm] minimum thickness is used. This layer is also used to provide an increased cross-slope. Using lean concrete as a leveling course requires membrane curing compound for use as the separation material. The use of lean concrete must be carefully considered, because it may act as a bonded concrete overlay and reflect all cracks in the underlying slab through to the bottom of the unbonded overlay. These cracks may eventually reflect through the overlay. Studies have shown that the use of membrane curing compound as a separation material may not be effective.(22)

If roofing paper is to be used as a separation layer, it is suggested that the paper be heavy, weighing about 15 pounds per 100 square feet [0.73 sq m].(25) Polyethylene sheeting of thickness greater than 6 mils [0.015 cm] has also been suggested for placement over the area to be paved. This material provides a very low friction factor, and as described in section 3.4.3--Design Procedures, has resulted in problems on unbonded concrete overlays. Considerable problems were attributed during construction to the use of a polyethylene sheeting bondbreaker for a CRCP overlay in Wisconsin.(77) These problems were experienced on sections with grades of 2-4 percent. The contractor had a difficult time keeping the longitudinal steel and concrete in place. Also, since the concrete had a tendency to slide and dam on the 4-ft [1.2 m] spaced transverse bar chairs, concrete fineshing was difficult. Ride over the CRCP overlay sections with the polyethylene bondbreaker on 2-4 percent grades revealed a definite pavement chatter. Profilogram readings also revealed definite sinusoidal surface pavement waves about 4 ft apart.

Another possible separation layer would be a permeable asphalt-treated or cement-treated material. This material would also assist in minimizing pumping of the overlay by providing a porous interlayer to remove water that infiltrates through the overlay. This has not been used for unbonded concrete overlays, but has for regular new construction with good success.

Procedures

The performance of unbonded concrete overlays relies on the performance of the separation material in isolating the existing and overlay layers, and for the existing pavement to provide uniform support for the overlay. This may involve preoverlay repair to upgrade failed areas in the existing pavement and construction of a leveling course.

1. Joint resealing: Final preparation of the existing pavement prior to placement of the separation material is to reseal all pavement joints and remove loose materials on the surface. Resealing the joints is recommended in order to help prevent moisture from penetrating the subbase of the existing pavement causing loss of support problems for the overlay.(25) A liquid asphalt sealant should be employed. After installing the sealant, the pavement should be cleaned with a mechanical sweeper or air blowing procedure.(25)

2. Leveling Course and Separation Layer: A leveling course should be placed on all pavements exhibiting settlements or heaves. It is recommended that the leveling course be constructed with hot-mix asphalt to a minimum depth of 1 in [2.5 cm]. Greater depths should be employed to ensure removal of undulations.

3. Placing and Finishing Concrete: Construction of the overlay will require no special techniques. The basic procedures that are employed for new pavement construction should be specified by the contracting agency.

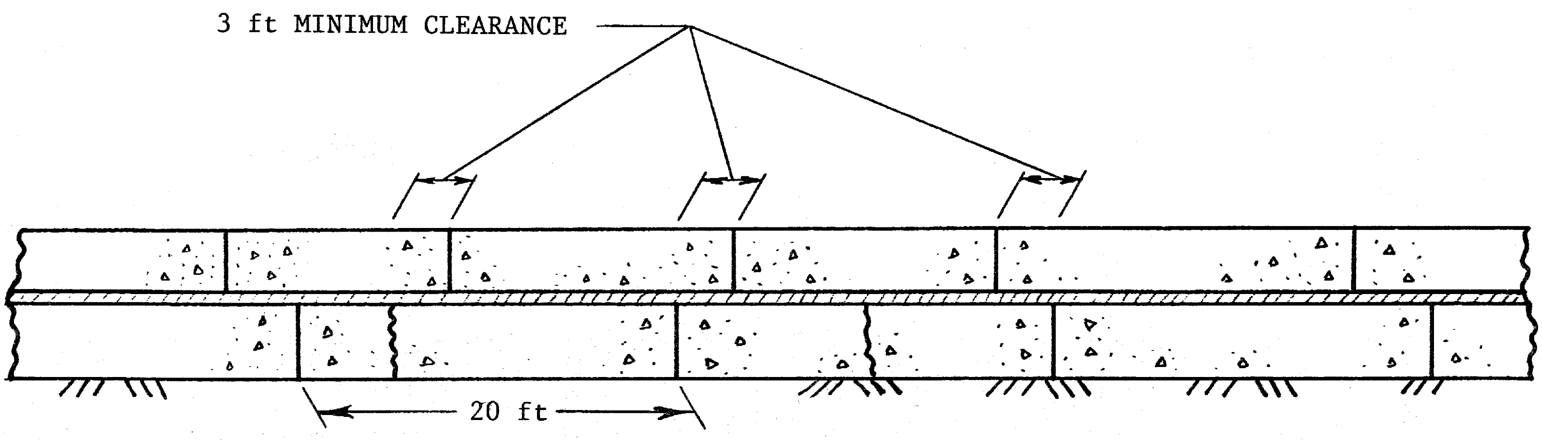
The placing and finishing of the unbonded PCC overlay will consist of all operations to place, finish, texture, cure, joint and seal the overlay. The overlay concrete should be placed to a thickness as shown on the standard plans.

Matching of joints in unbonded overlays with the joints in the existing pavement is not recommended. Depending on the specifications of the contracting agency, the placement of joints in the overlay should be mismatched from existing joints and working cracks by at least 3 ft [0.9 m].(45) Mismatching will help ensure that good load transfer is maintained on the overlay joint, because each joint will be placed over continuous concrete which will act as a sleeper slab beneath the joint. Figure 35 illustrates the joint placement.

Results from the field survey of unbonded concrete overlays showed very little transverse joint faulting when no dowels were used. It is recommended that longer jointed JRCP should be doweled as per regular design for JRCP due to the large joint openings. The predictive model for unbonded overlays can be used to determine the amount of faulting for the design traffic. The dowel design should be similar to that of new pavements with the same slab thickness.

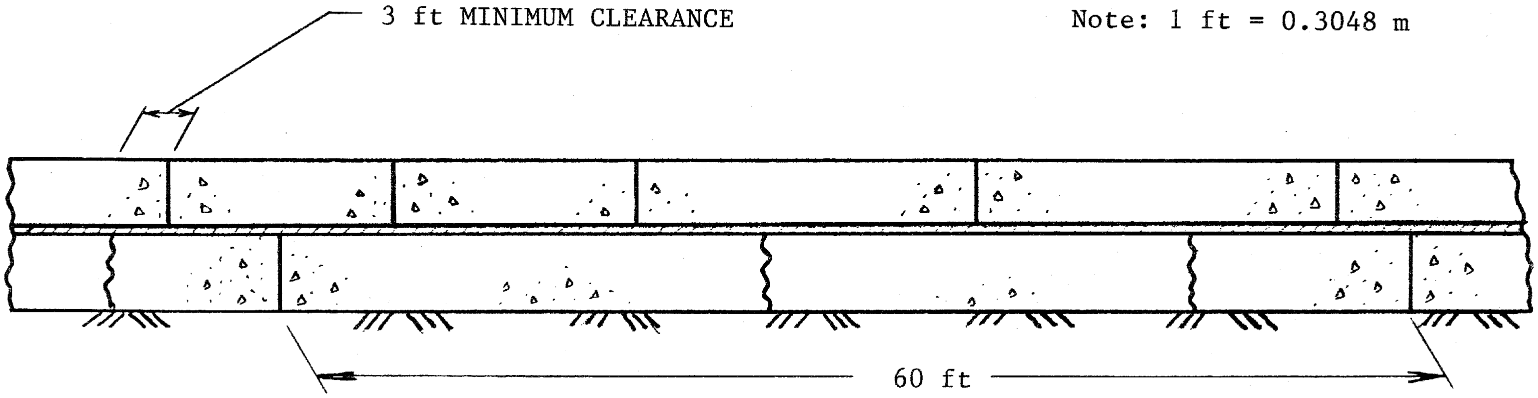
Joints should be sealed using an approved sealant. The procedures and materials normally specified by the contracting agency should apply. Texturing the pavement should be performed to provide adequate friction. The normal procedures applied by the specifying agency should govern.

Curing compound should be applied at the rate normally specified by the contracting agency. This compound is to be applied immediately following the texturing operations to avoid moisture loss and development of shrinkage cracking in the newly placed concrete.



A. Placement of Overlay Joints over Existing 20 ft JPCP Pavement.

Note: 1 ft = 0.3048 m



B. Placement of Overlay Joints over Existing 60 ft JRCP Pavement.

Figure 35. Details for mismatching of overlay joints with joints in the existing pavement.

3.4.4 Preparation Of Plans And Specifications

It is recommended that a thorough list of all preoverlay repair areas be included on the plans. Reference should be made to pavement stationing or other markings to define the size and type of repair warranted at each location.

Thicknesses and cross-slopes to be developed by the leveling course should be clearly specified in the plans.

3.5 CONCLUSIONS AND RECOMMENDATIONS

Unbonded concrete overlays have been used successfully to resurface existing concrete pavements with extensive deterioration. The performance of practically all of the 14 uniform sections of unbonded concrete overlays was very good, with no significant deterioration. No special construction techniques are needed in the construction of unbonded overlays. Detailed guidelines for the design and construction of this technique are given in section 3.4. The following overall conclusions and recommendations are as follows:

1. Thermal curling stresses are critical in unbonded concrete overlays because the temperature gradient through the overlay becomes large during many days and nights of the year, and because of the very stiff support from the existing slab. At these times curling may cause the overlay slab to lift from the underlying slab and create voids between the slabs, which when combined with traffic load stresses and the stiff foundation of the underlying slab, can cause increased fatigue cracking. It is highly recommended that the overlay joint spacing be kept short (less than 15 ft [4.6 m]), or if longer slabs are used, heavy reinforcement must be included to keep the cracks tight.

2. Where a separation material is not efficient in separating the overlay from the existing slab, reflective cracking may result. This is due to inadequate materials and insufficient separation material layer thickness. It is recommended that a minimum of 1 in [2.5 cm] of hot-mix asphalt concrete be used as the separation material. A realistic friction factor must be used in designing the reinforcement in a JRCP and/or CRCP overlay. Another possibility for a separation layer is to use a porous asphalt or cement treated granular material to provide drainage beneath the overlay. The use of polyethylene sheeting is not recommended due to its too low friction factor.

3. Unbonded overlays without dowels fault very little (maximum measured was 0.04 in [0.10 cm]), which is far less than new pavements without dowels for the same number of ESAL's. However, with dowels the predicted faulting is similar for both. The development of faulting in unbonded overlays is not reduced much by the use of dowels in the transverse joints. This has been attributed to fairly non-erodable and stiff foundation support from the underlying slab and mismatched joint locations. It is recommended that under normal traffic conditions (less than 0.5 million 18-kip [80 kN] ESAL per year) that dowels are not needed in the transverse overlay joints for JPCP. They should be placed in transverse joints of JRCP, however. The predictive model for faulting can be used to predict faulting for the recommended overlay design to determine if substantial faulting will occur.

4. Visual pumping was not observed in the field distress surveys. This is attributed to lack of erodible materials beneath the overlay slab, greatly reduced deflections of the slabs, and mismatched joints which alter the deflection basin developed under load. With these effects, there is very little potential for pumping in unbonded overlays.

5. Although matching the overlay joints to the existing pavement joints is not recommended, joint placement is not a critical concern in unbonded overlays. It is recommended that the joints be placed at least 3 ft [0.9 m] from existing transverse joints or working cracks. This will ensure the load transfer benefits mentioned.

6. A predictive model was developed for joint faulting. This model can be used as a design check for a given unbonded overlay design. Other predictive models such as cracking could not be obtained due to the lack of cracking, pumping and joint deterioration occurrence for the unbonded overlays.

CHAPTER 4

CRACK AND SEAT AND ASPHALT CONCRETE OVERLAYS

4.0 RESEARCH APPROACH

Crack and seat rehabilitation on concrete pavements is the process wherein the existing concrete pavement is cracked to destroy the integrity of the slab. This cracking reduces the slab length which reduces the thermal affect on joint movement, a major factor in the occurrence and progression of reflection cracking. The seating operation is required to ensure that the pieces of slab are firmly seated into the underlying foundation material to eliminate vertical movement, a contributing factor in reflection cracking at a pavement discontinuity. The reduction in the amount and severity of reflection cracking in an asphalt concrete overlay is the sole design requirement of the crack and seat procedure on a rigid pavement.

To date there has been one nationwide documentation of the performance of this overlay technique.(83) However, a uniformly recognized standard for construction procedures has not been developed. General guidelines have been proposed by several agencies, relying on their local experience, but they have not been verified with a comprehensive field survey. The National Asphalt Pavement Association has published two reports on the performance of crack and seat projects in the Midwest.(82,89) Recently the Federal Highway Administration released the results of their survey of crack and seat projects in the United States which provides some indications of performance variables, but with no specific recommendations concerning design procedures.(83)

To obtain specific indications regarding design of crack and seat rehabilitation projects, the development of an extensive database containing information on the original pavement design, asphalt concrete overlay design, traffic, environmental conditions and performance of existing overlays was required. This database allows analyses to be performed which include consideration of the many factors which might affect performance. To obtain the necessary database elements to allow such an analysis to be performed, the following methods and sources were utilized:

- Extensive field surveys including mapping of cracks, physical measurements, and subjective ratings, were conducted on each project to document the current condition of the overlay.

- The design of the original pavement structure was determined from "as-built" plans and verbal communication with State DOT personnel.

- The design of the overlay was determined through the analysis of special rehabilitation construction provisions, "as-built" plans and verbal communication with State DOT personnel.

- Environmental data was taken from documentation of the monthly normals of temperature, precipitation, and heating and cooling degree days by the National Oceanic and Atmospheric Administration.

- Traffic estimates, including average daily traffic and percent commercial trucks, were obtained from the State DOT's. Federal Highway Administration historical W-4 tables on axle load distributions for the State's pavement classifications were used for the calculation of accumulated axle-loads on each project.

4.1 DATABASE AND DATA COLLECTION

The projects surveyed for inclusion in the database represent a cross-section of the crack and seat projects in the United States. These pavements were field surveyed between June 1985 and July 1986.

A detailed description of the field and office data collection procedures is given in volume IV. There are five basic data types necessary for the development of life prediction models and for analysis to develop and improve design and construction procedures. These include:

- Field condition data.
- Original pavement structural design, in-situ conditions, and historical improvement data.
- Rehabilitation design factors.
- Historical traffic values, classifications and accumulated 18-kip [80 kN] equivalent single-axle loadings.
- Environmental data.

A complete list of all of the variables considered in the field surveys was shown in figure 3 (see chapter 2). The design variables for the original pavement which are contained in the database were given in figure 4 (see chapter 2). Variables for the overlay design are given in table 10.

Extent Of The Database

The database contains as many projects as were available or that could be included, given available resources, to provide a valid range of design parameters. This was necessary to provide a wide range of data to facilitate regression analysis for the development of performance models.

Figure 36 shows the general location of the crack and seat and asphalt concrete overlay projects. The distribution of projects across the United States provides for a comprehensive inclusion of the variety of environmental zones. The performance of asphalt overlays on concrete pavements has long been felt to be related to the severity of environment and temperature variations.

Figure 37 and 38 show the distribution of age and thickness for the crack and seat projects in the database, and show the presence of very young to relatively old projects available for analysis. These parameters are shown broken down based on the original slab characteristics, whether the concrete was plain or reinforced. The presence of reinforcing steel has long been felt to be a major factor influencing the performance of crack and seat rehabilitation. It is apparent from the figures that the reinforced pavements have received thicker overlays, and are generally not much older than the plain pavements.

There are no "overlay design" variables for crack and seat as there is no design procedure for this rehabilitation strategy outside of assuming a structural layer coefficient for the cracked concrete slab and designing the overlay based on this coefficient. Variables which are felt to be significant to the performance of a crack and seat project are listed in table 10. Key variables which might affect performance, such as cracking pattern, roller characteristics, and construction data are included.

Table 10. Crack and seat overlay design variables.

CRACK AND SEAT AND ASPHALT CONCRETE OVERLAY

DATABASE DESIGN VARIABLES

- Project Identification Number.
- Sample Unit.
- Presence of "D" Cracking on Existing Pavement.
- Original Slab Repair.
- Pavement Breaker Type.
- Average PCC Breakage Size -- Width.
- Average PCC Breakage Size -- Length.
- Wire Mesh Cut or Broken.
- Seating Roller Type.
- Seating Roller Weight.
- Broken Pavement Exposure to Traffic.

DATABASE PERFORMANCE VARIABLES

General Data

- Project Identification Number.
- Sample Unit Number and Length.
- Present Serviceability Rating.
- Foundation of Sample Unit (cut/fill).
- Condition of Drainage Ditches.
- Subsurface Drainage Functional.

Distress Data (Inner and Outer Lanes)

- Centerline Longitudinal Cracking.
- Transverse Cracking.
- Joint Reflective Cracking.
- Longitudinal Cracking.
- Lane Edge Cracking.
- Alligator Cracking.
- Block Cracking.
- Raveling/Weathering.
- Pumping.
- Bleeding.
- Potholes.
- Rutting (inner and outer wheelpaths).

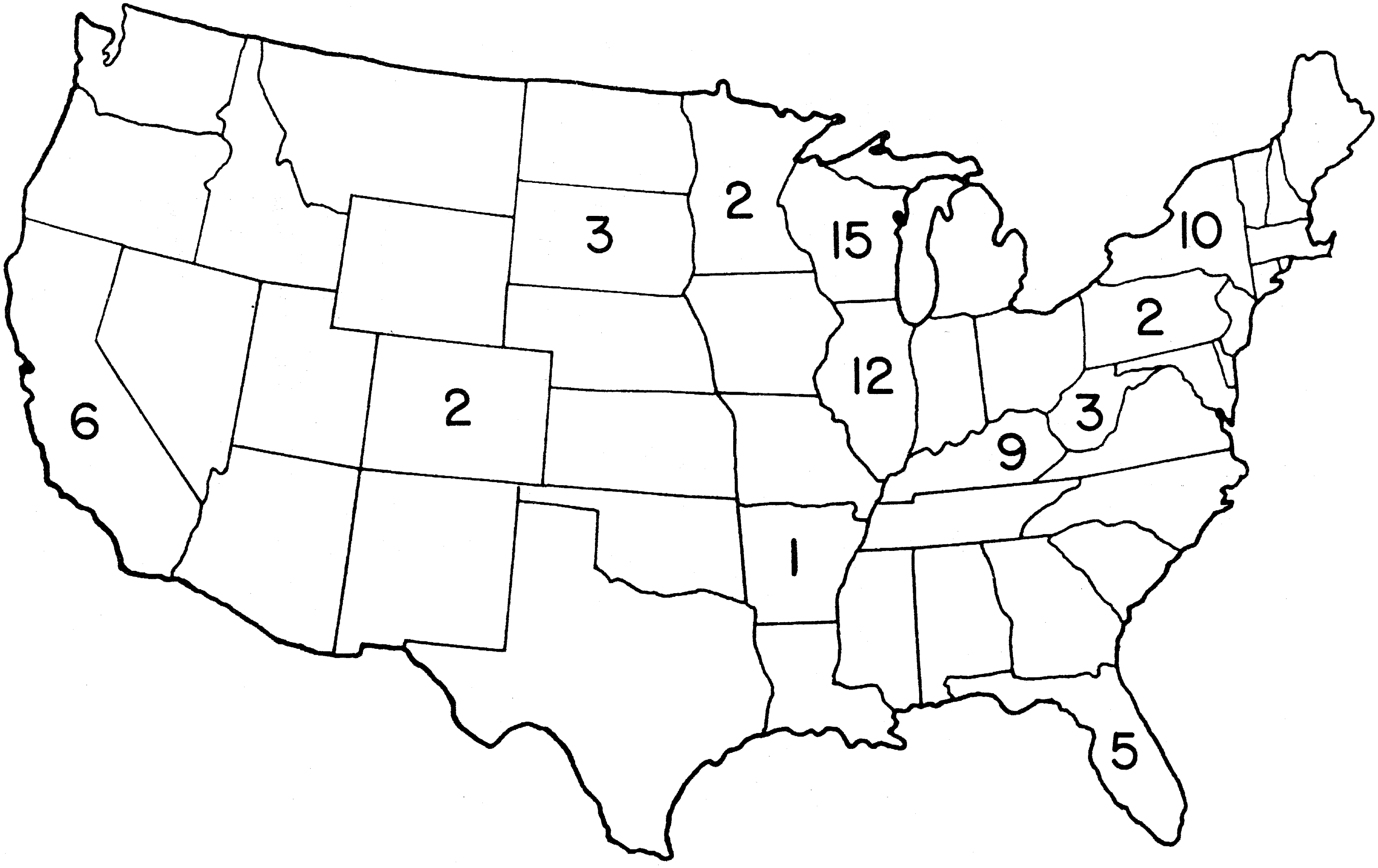


Figure 36. Distribution of crack and seat projects in the database.

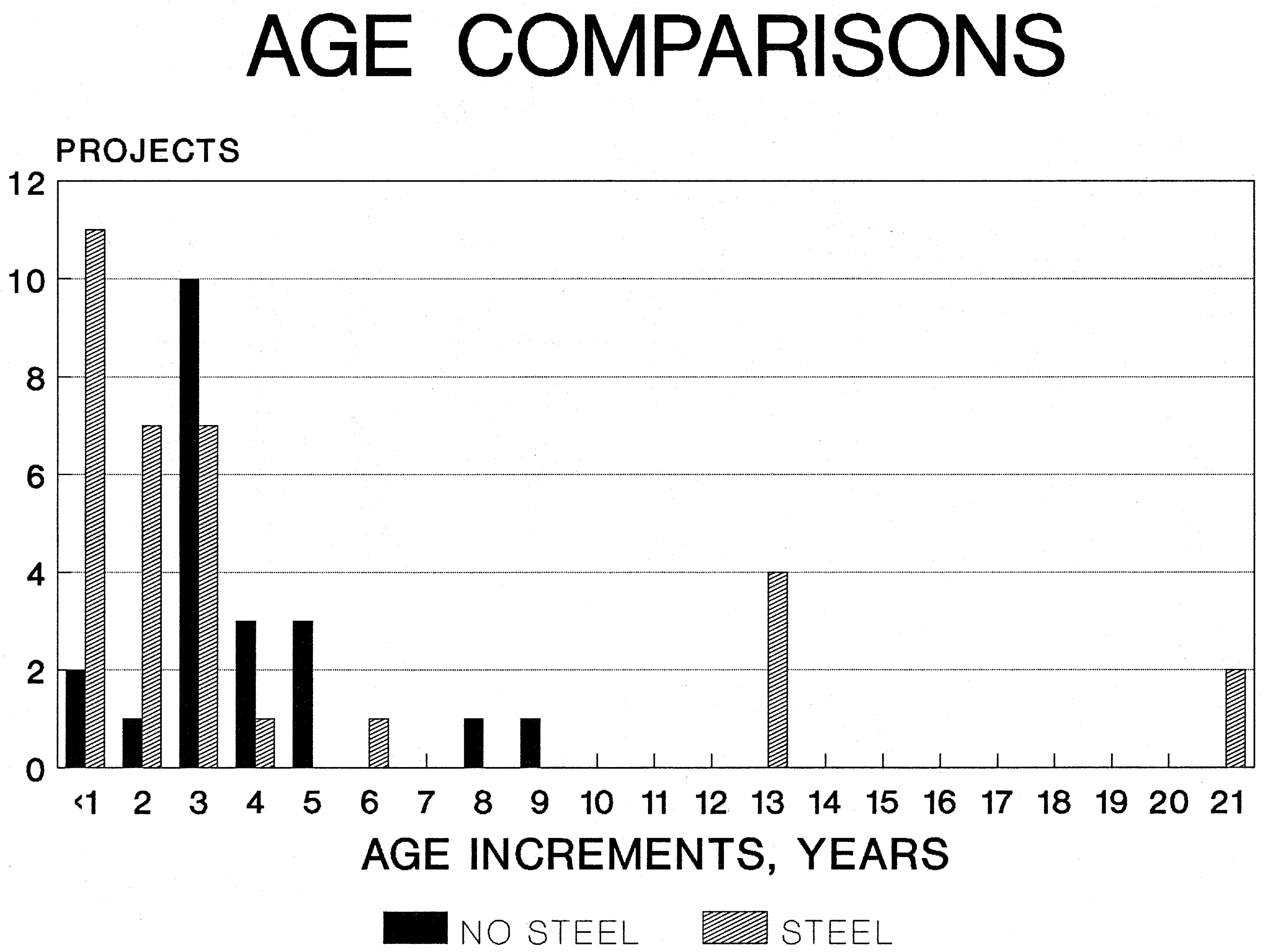


Figure 37. Age comparisons for the crack and seat projects in the database.

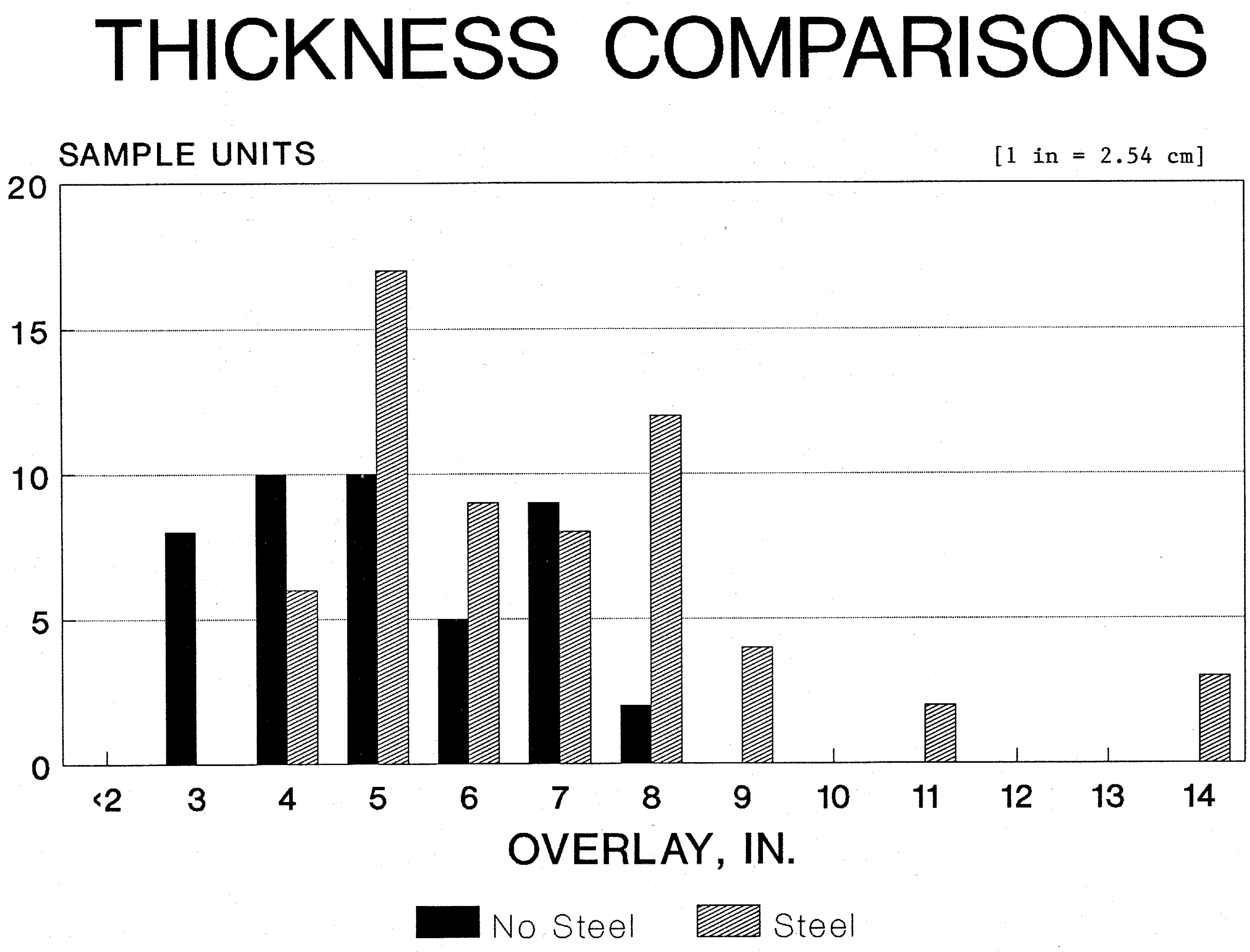


Figure 38. Thickness comparisons for crack and seat projects in the database.

Detailed descriptions of representative overlay projects are given in appendix A. For each project in the appendix the following is provided:

- Project location.
- Original pavement design.
- Asphalt concrete overlay design.
- Traffic estimates.
- Environmental factors.
- Field performance.

This information is included to provide a concise reference and documentation of projects specifically included in the development of performance models and improved design and construction guidelines.

4.2 FIELD PERFORMANCE AND EVALUATION

Crack and seat rehabilitation is a procedure to improve the performance of the asphalt concrete overlay in resisting reflection cracking. The desired effect of this rehabilitation is to reduce the incidence of reflection cracking, or the severity of any resulting cracks. From a structural design consideration, the cracked concrete slab is typically assumed to approach a high quality crushed stone base, and the overlay thickness required is typically selected by designing an asphalt surface over a very high quality crushed stone base. A cracked concrete slab is going to be significantly better than a base material, and the resulting overlay thickness should be conservative from a structural traffic standpoint. However, reflection cracking is not related strictly to the structural section and the traffic handling characteristics of the asphalt surface. New design procedures which attempt to account for the influence of cracks in the concrete slab on reflection cracking in the overlay have only recently been developed, and are undergoing field validation.(94)

Reflection cracking is the major distress in an asphalt concrete overlay of a concrete pavement. Rutting is a major distress in any asphalt concrete construction, and should be investigated to determine whether the crack and seat process produces any difference in rutting potential from a conventional overlay. Because the crack and seat process produces a more "flexible" base layer as compared to a concrete slab, the development of fatigue cracking may be a distress that develops in the asphalt concrete overlay, which never develops in an asphalt concrete overlay of an uncracked concrete slab. Table 11 gives a summary of distresses, normalized to 1000 ft [305 m] of outer lane, found for each crack and seat uniform section.

The severity levels employed in describing distresses are those defined in the FHWA distress manual.(8) For example, low severity cracking describes hairline cracking, medium severity describes working cracks and high severity a badly spalled and faulted crack needing immediate repair.

4.2.1 Transverse (Reflective) Cracking

__Field Observation__

Data on the condition of the existing pavements prior to the crack and seat rehabilitation was not available for the projects. Therefore a mapping process to illustrate the time development of reflection cracking on each project could not be conducted, and the distress data represents a one time sequence data point.

Table 11. Distresses in each sample unit in the database.
[1 in = 2.54 cm, 1 ft/1000ft = 1 m/km].

PROJ ID	ESAL	AGE	RFL CRK,	FT/1000FT			RUT DEPTH
	MILLIONS	YEARS	LOW	MED	HIGH	TOTAL	IN X 100
4810800004	3.442	3	0	0	0	0	18.18
4810800004	3.442	3	0	0	0	0	24.77
4810800003	3.442	3	0	0	0	0	12.27
4810800003	3.442	3	0	0	0	0	9.545
4810050432	2.081	1	0	0	0	0	14.09
4810050431	2.081	1	0	0	0	0	14.32
4110703054	1.382	3	792	0	0	792	23.64
4110703054	1.382	3	798	0	0	798	22.95
4110703053	1.382	3	310	0	0	310	33.41
4110703053	1.382	3	492	0	0	492	39.55
3810300564	2.351	1	0	0	0	0	14.55
3810300564	2.351	1	5	110	0	115	23.64
3349999034	.0336	2	0	28	0	28	8.75
3349999033	.0336	2	12	53	0	65	3.75
3349999024	.0079	1	138	0	0	138	1.818
3349999023	.0079	1	110	0	0	110	3.864
3349999014	.264	4	42	48	0	90	4.091
3349999013	.264	4	47	48	0	95	7.045
3331016254	.1064	2	0	0	0	0	14.32
3331016254	.1064	2	0	0	0	0	20.45
3331016253	.1064	2	0	0	0	0	14.32
3331016253	.1064	2	0	0	0	0	10.91
3330978952	.1952	1	111	59	0	170	1.818
3330978952	.1952	1	106	84	0	190	.25
3330978951	.1952	1	146	50	0	196	2.25
3330978951	.1952	1	125	12	0	137	1.364
3330978562	.1952	1	0	0	0	0	.2273
3330978562	.1952	1	0	0	0	0	.2273
3330978561	.1952	1	0	0	0	0	1.591
3330978561	.1952	1	0	0	0	0	1.591
3030504164	.183	5	108	0	0	108	25
3030504164	.183	5	183	0	0	183	22.5
3030504084	.3469	6	12	336	0	348	32.5
3030504084	.3469	6	18	327	0	345	35
3020143334	.058	.25	0	0	0	0	22.5
3020143334	.058	.25	0	0	0	0	31.25
2921690902	1.549	2	518	82	0	600	15
2921690902	1.549	2	427	156	0	583	23.18
2920711152	.5816	8	235	24	0	259	24
2920711152	.5816	8	325	12	0	337	13.18
2831409012	.2589	3	24	0	0	24	19.09
2831409012	.2589	3	12	0	0	12	12.95
2831409011	.2589	3	12	0	0	12	13.41
2831409011	.2589	3	14	0	0	14	14.55
2830809012	.5753	4	37	36	0	73	18.64
2830809012	.5753	4	62	36	0	98	10.23
2830809012	.5753	4	0	24	0	24	16.36
2830809011	.5753	4	24	0	0	24	15.91
2830809011	.5753	4	24	0	0	24	9.318
2830809011	.5753	4	28	0	0	28	20.68
2820539012	.1506	3	103	12	0	115	15.45
2820539012	.1506	3	36	36	0	72	15
2820539011	.1506	3	36	36	0	72	15

Table 11. Distresses in each sample unit in the database (cont'd).
[1 in = 2.54 cm, 1 ft/1000ft = 1 m/km].

PROJ ID	ESAL	AGE	RFL CRK, FT/1000FT				RUT DEPTH
	MILLIONS	YEARS	LOW	MED	HIGH	TOTAL	IN X 100
2820539011	.1506	3	87	12	0	99	18.18
2820149024	.896	5	24	0	0	24	21.14
2820149024	.896	5	96	132	0	228	23.86
2820149023	.896	5	107	120	0	227	19.09
2820149023	.896	5	24	0	0	24	22.27
2820149014	1.269	3	0	0	0	0	14.55
2820149014	1.269	3	18	0	0	18	13.41
2820149013	1.269	3	24	0	0	24	11.59
2820149013	1.269	3	0	0	0	0	11.59
2810940793	2.515	3	72	0	0	72	24.09
2810940783	2.515	3	24	0	0	24	30
2810940773	2.515	3	48	0	0	48	24.09
2810940724	1.936	2	84	0	0	84	16
2810940723	1.936	2	24	12	0	36	24.55
2310710602	8.305	3	0	0	0	0	27.5
2310710592	8.305	3	0	0	0	0	30
2310710582	8.305	3	0	0	0	0	23.75
2310710372	4.879	1	72	0	0	72	7.5
2310640303	5.904	2	0	0	0	0	-22
2310640243	5.904	2	0	0	0	0	-22
2310640223	5.904	2	0	0	0	0	-22
2310640203	5.904	2	0	0	0	0	-22
2310640193	5.904	2	0	0	0	0	10
1930240071	2.519	10	10	0	0	10	19.09
1930240071	2.519	10	0	0	0	0	19.09
1920900003	3	3	0	0	0	0	-22
1920900003	3	3	0	0	0	0	-22
1920010041	3	3	0	0	0	0	-22
1920010041	3	3	0	0	0	0	-22
1920010001	.2231	11	26	0	0	26	5.426
1920010001	.2231	11	29	0	0	29	5.398
1510771151	1.578	1	183	0	0	183	10
1510771151	1.578	1	168	0	0	168	5
1510640083	2.656	1	144	0	0	144	5
1510640083	2.656	1	84	0	0	84	5
1010900354	2.491	3	0	0	0	0	3.182
1010900353	2.491	3	0	0	0	0	8.864
1010900353	2.491	3	0	0	0	0	9.091
930609012	.1675	1	12	12	0	24	4.091
930609012	.1675	1	0	0	0	0	.9091
930609011	.1675	1	12	12	0	24	1.818
930609011	.1675	1	0	0	0	0	3.636
930229012	.3328	13	3	66	0	69	10.68
930229012	.3328	13	0	120	0	120	11.59
930229011	.3328	13	4	66	0	70	12.5
930229011	.3328	13	12	108	0	120	11.82
922029014	2.431	13	12	96	24	132	15.91
922029014	2.431	13	21	65	4	90	15.91
922029013	2.431	13	5	96	24	125	16.59
922029013	2.431	13	61	91	11	163	16.59
920209024	2.799	21	2	12	0	14	33.41
920209023	2.799	21	27	0	0	27	32.95
920209014	2.799	21	16	12	0	28	40.45
920209013	2.799	21	18	12	0	30	40.68

The percentage of projects containing lengths of cracking (ft/1000 ft [m / km]) of low medium and high severity cracking are shown in figures 39 and 40. For example, 100 percent of the projects exhibited zero cracking of high severity for the plain pavements, while only 96 percent of the reinforced pavements had no high severity cracking. These figures have been separated based on the presence of reinforcing steel in the concrete slab because this is felt to be a significant variable in the performance of crack and seat rehabilitation.

From a preliminary comparison of the two figures, it appears that the reinforced pavements develop more high and medium severity cracking of short length than the plain pavements. The plain pavements exhibit much more low severity cracking as demonstrated by the greater length of cracking found on the plain sections. The plain pavements do indeed have a much greater occurrence of low severity cracking. However, as will be discussed later, this is may not be directly related only to the type of concrete pavement.

There is not a great amount of high severity reflection cracking in any of the sections even though some of these projects are quite old. The development of medium to high severity reflection cracking on the crack and seat projects should be compared to conventional overlay projects to determine if the rehabilitation reduces the severity and/or amount of the reflection cracking. The occurrence of the high and medium severity cracking only on the reinforced pavements may indicate that that the severity is being reduced, although the age and traffic volume may be other factors that should be included in the comparison.

Overlay Thickness

The thickness of the overlay has a critical role in the development of reflection cracking, particularly when the overlay is less than 6 in thick. Figure 38 showed the distribution of overlay thicknesses broken out by pavement type. The reinforced pavements clearly received a thicker overlay. The average overlay thickness for the plain pavements was 4.25 in [10.8 cm], while the average overlay thickness for the reinforced pavements was 6.25 in [15.9 cm]. Thicker overlays retard the appearance of reflection cracking, and should produce a low severity crack and significantly less high severity cracking. The thicker overlays are indicating a higher potential for medium and high severity reflection cracking which may indicate that the presence of reinforcing steel may be a significant factor in the performance of the overlay.

Age and Traffic

The average age of the reinforced pavements examined was 4.7 years while the age for the plain pavement sections was 4.0 years. The thicker overlays have been in place longer and they have been subjected to more traffic. The accumulated 18-kip [80 kN] Equivalent Single Axles since overlay (ESAL) for the plain pavements is 1.3, while for the reinforced pavements it is 1.9 million ESALs. The percentage of trucks in the traffic stream was also higher for the reinforced pavements (24 percent) compared to the plain pavements (18 percent). The actual values of ESALs varied from approximately 0.08 to 8.3 million ESALs for all projects.

These differences indicate that the performance of plain and reinforced pavements cannot be made on a direct comparison of visual survey data taken from a distress survey, without knowing the causative factors which may produce different levels of cracking on the surface. In this case, similar performance has developed on projects with very different design considerations of thickness, age, and traffic which indicate that one set of overlays, those over crack and seated reinforced pavements, are not performing as well as those over plain pavements.

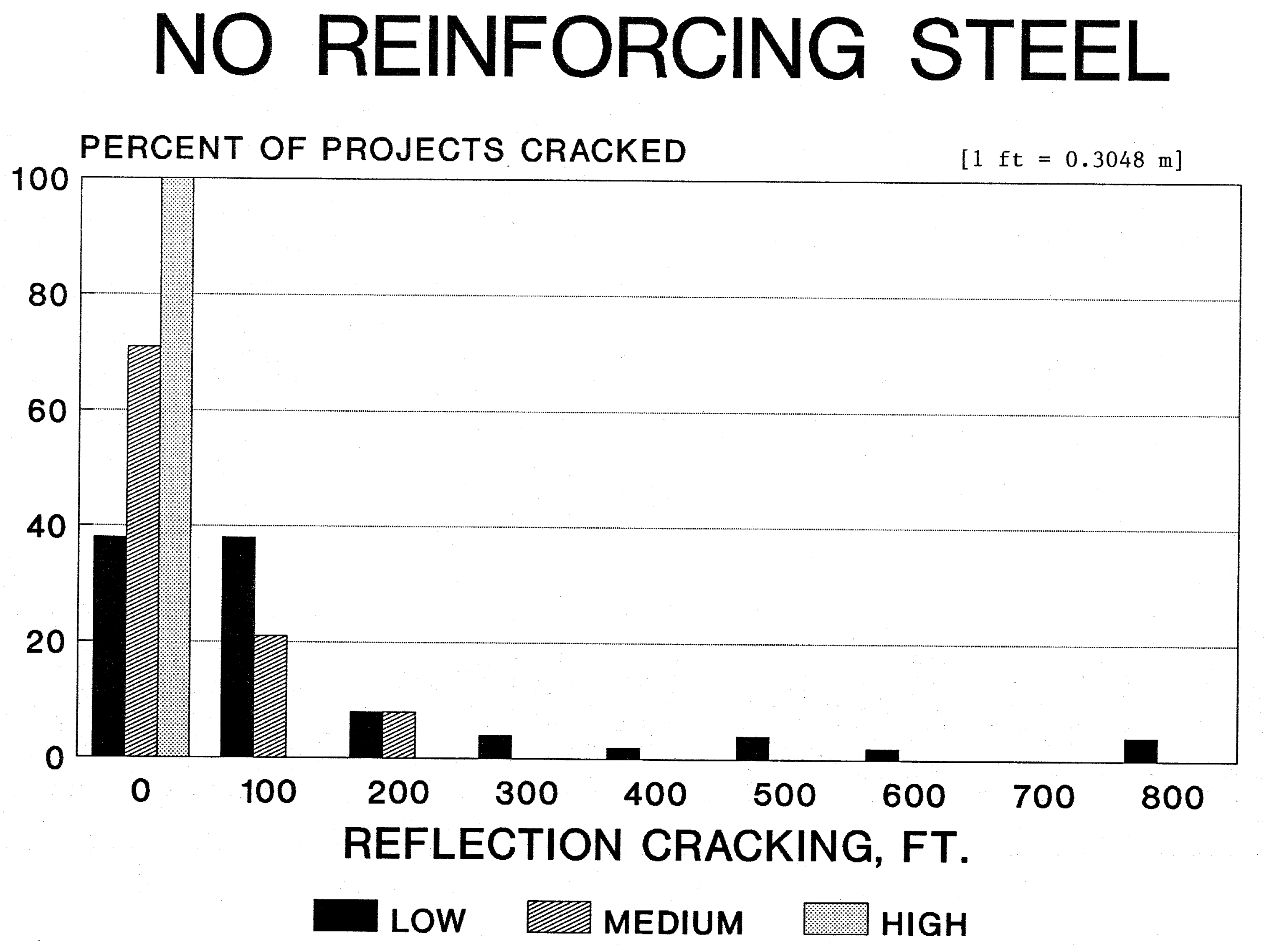


Figure 39. Amount and severity of reflection cracking present on crack and seat projects (JPCP).

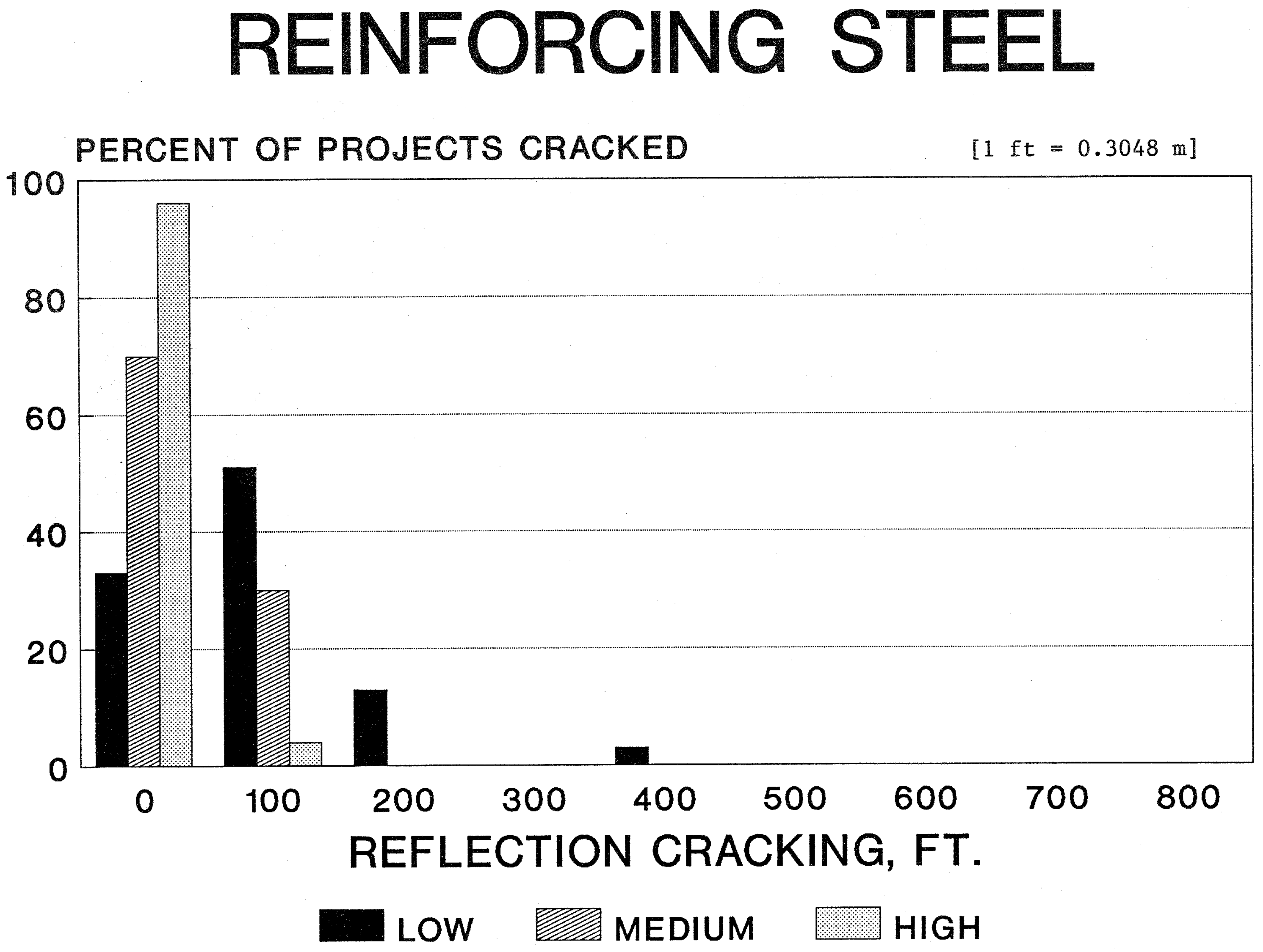


Figure 40. Amount and severity of reflection cracking present on crack and seat projects (JRCP).

4.2.2 Serviceability

Present Serviceability Rating information was available from a small cross section of the crack and seat projects (27 projects). The PSR curve for the crack and seat sections is shown in figure 41. There is no tendency for the better performing pavements to have thicker overlays. The best performing projects were in the milder climates (California and Florida with relatively thin overlays and mixed traffic levels). The data indicate that crack and seat projects begin to lose serviceability after three million load applications.

This serviceability loss can be attributed to cracking, rutting, and possibly roughness induced by slab motion under traffic. The average rut depth for these projects was only 0.15 in [0.38 cm], with the maximum rut depth measured at 0.42 in [1.07 cm], which may contribute to roughness on a few of the sections. In general, the higher rutting did not occur on the projects with lower PSR values, indicating that some design variable in the crack and seat procedure is contributing to the development of the roughness. Similar correlations with the various forms of cracking also showed no direct relationship between the severity or amount of cracking and roughness, further lending credence to the feeling that a design variable in the crack and seat process may be responsible.

Development

The development of transverse reflection cracking in a crack and seat rehabilitation project is exactly the same as for an asphalt concrete overlay of a conventional concrete pavement. Temperature variation producing slab movements at the joint will propagate a crack. The cracking process is designed specifically to reduce the magnitude of this movement. The traffic produces vertical differential movement at the joint, which the seating operation is designed to minimize. Improper cracking will not reduce the temperature related movement. Improper seating of the cracked pieces will produce more discontinuities which may have a greater vertical differential movement under traffic which could result in more cracks in the overlay than there are joints in the original pavement.

4.2.3 Rutting

Field Observation

None of the uniform sections showed a significant rutting problem, with only two sections developing rutting near a level that would receive attention in potential rehabilitation considerations. The average rutting in the driving lane ranged from 0.0 to 0.42 in [1.07 cm] with the distribution among the sample units being as shown in figure 42. Rutting generally begins to become a problem at 0.25 in [0.64 cm] with hydroplaning, and becomes a safety and handling problem when it reaches an average of 0.5 in [1.27 cm]. There does not appear to be a difference in the rutting performance of the overlays on crack and seated pavements compared to conventional pavements.

Development

The development of rutting in an asphalt concrete overlay is the same for conventional overlay as it is for crack and seat rehabilitation, and is primarily a function of mix quality, traffic level, and temperature. The most influential parameter is generally the number of load repetitions on any one mixture, as illustrated in figure 43 which shows the relationship between the average number of ESALs on the sample units with rut depths within the increments indicated.

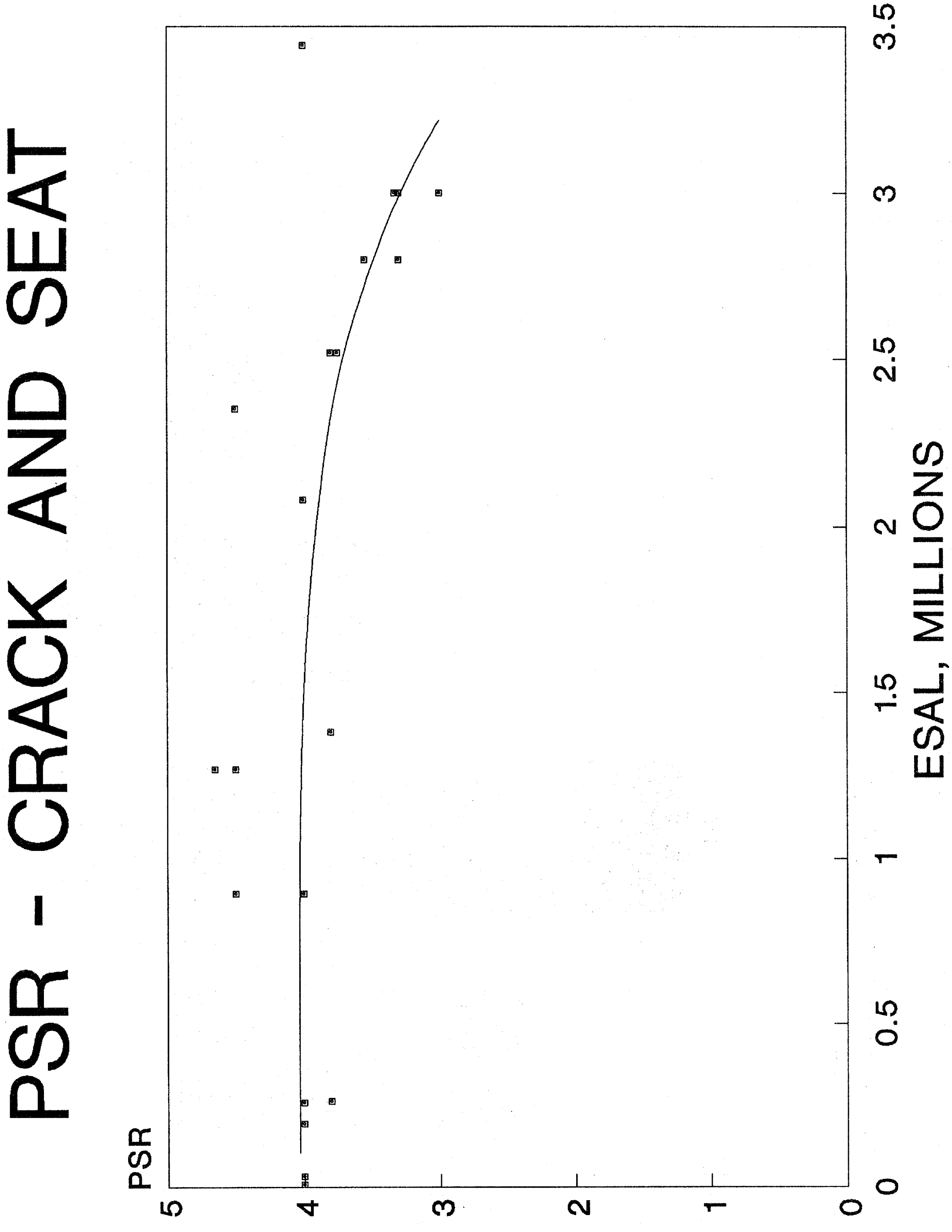


Figure 41. Present serviceability rating (PSR) for the crack and seat projects.

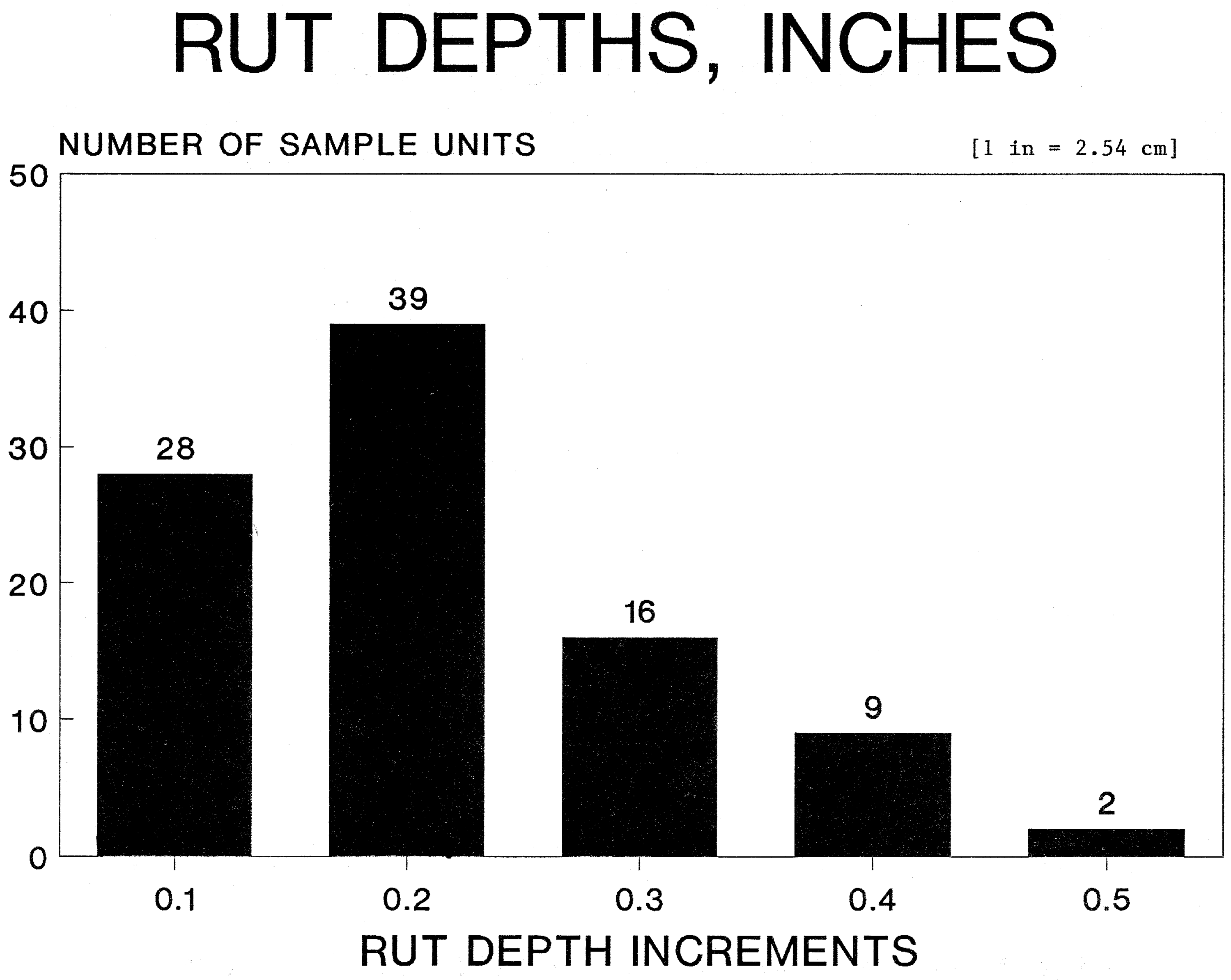


Figure 42. Distribution of rut depths in the database.

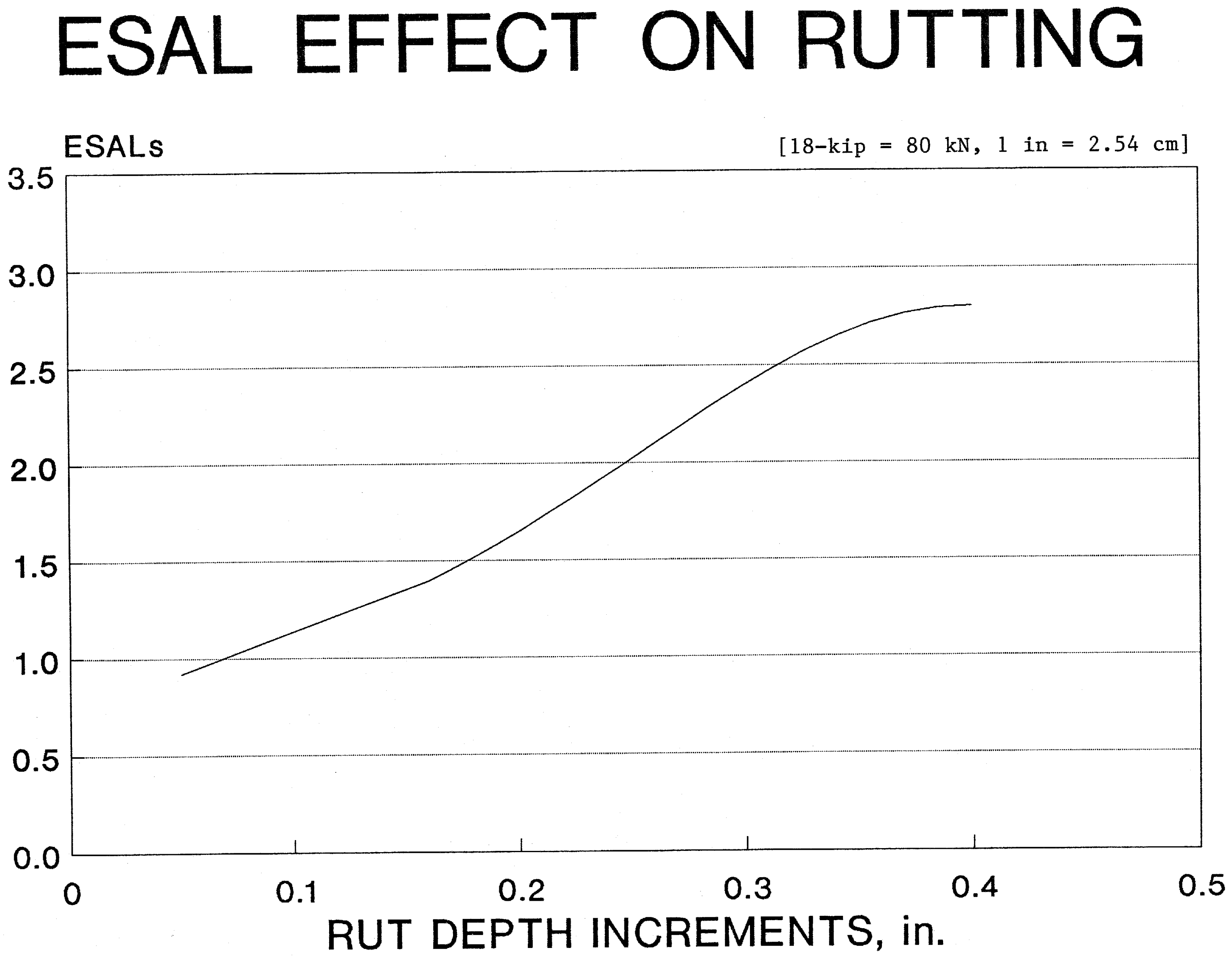


Figure 43. Relationship between rut depth and number of 18-kip ESALs on the overlay.

4.3 PERFORMANCE MODELS

4.3.1 Model Development

Regression analysis was performed on the database for crack and seat overlays. Predictive models were developed for significant distress variables using the regression techniques as included in the SHAZAM statistical package.(55) Models for rutting and reflective cracking were developed from the database.

As a first step in analyzing the data, all independent variables that were considered to have meaningful and significant influence on the performance of the crack and seat overlays were identified. These variables were then considered in the development of the models with linear regression.

Although extensive time was spent refining the models and examining variable interactions, they should be considered tentative models because of the limited nature of the database. As crack and seat projects are applied in more States with differing climates and designs, these initial models can be revised to include more variables and wider ranges of applicability to overcome some of the limitations of the database mentioned earlier.

The variables that entered the predictive models include:

- 18-kip [80 kN] ESAL accumulated on the overlay.
- Type of subgrade soil (granular or fine grained).
- Freezing Index, mean degree days below freezing.
- Seating roller weight, tons.
- Age of the overlay.
- Thickness of the original concrete slab.
- Width of the crack pattern.
- Length of the crack pattern.
- Area of the crack pattern.
- Slab length.
- Annual average temperature, $^{\circ}$F.
- Annual average precipitation, in.
- Annual average monthly temperature range, $^{\circ}$F.

As can be seen upon examination of the models, there are several variables missing which many have intuitively felt should be influential on the performance of crack and seat and overlay rehabilitation. These variables were either determined to be statistically insignificant in characterizing the performance of the overlays, or were not present with sufficient variability in the database to allow a true indication of their actual effect. Future refinement of the models as the database is expanded should address the proper inclusion of the following:

- Thickness of the overlay.
- Pre crack and seat and overlay repair techniques employed.
- Reinforced vs plain jointed concrete.
- Mechanistic data (e.g., elastic moduli from FWD deflection testing).
- Overlay asphalt mixture properties.

It should be kept in mind that each model was based on the data that was available in the database, and thus should not be applied or used beyond the ranges under which they were developed. The range of applicability for each variable is provided in the appropriate section dealing with application. The crack and seat database has some peculiar combinations of data which entered into the model development which must be fully understood before the models are applied.

4.3.2 Reflection Cracking

Separate models were developed for each severity level, Low, Medium, and High reflection cracking. Those models should not be used to predict cracking, this was done to illustrate the different factors which are shown to be important in the development of cracking, and the progression of cracking from low to medium and high. The models are not used to predict overall performance primarily due to the lack of sample units in certain distress categories. The models showed some interesting relationships with the different variables which entered each equation. These first three models are provided only for informative purposes only.

High Severity

There were only 4 sample units exhibiting high severity cracking, all of them on sections over reinforced pavement. The model for the high severity cracking developed using all samples in the database was:

$$\begin{aligned} \mathrm{RFLCH} = {} & 1491.4 - 17.306\,(\mathrm{YR}) - 19.9\,(\mathrm{AGE}) + 0.00378\,(\mathrm{FI}) \\ & + 0.40355\,(\mathrm{WDT}) + 0.86455\,(\mathrm{AVGTMP}) - 1.9469\,(\mathrm{AVGMAXT}) \\ & + 1.1472\,(\mathrm{ANNPREC}) + [\,0.14263\,(\mathrm{AVGTMP}) \\ & - 0.12123\,(\mathrm{ANNPREC}) + 0.1955\,(\mathrm{ANNRNG}) - 5.953\,] \\ & \times [\,6.2323 - (\mathrm{AGE})(\mathrm{FI}+1)\,] \end{aligned}$$

Statistics:
R^2 = 0.42
SEE = 0.27
N = 107

where:
RFLCH = High Severity reflection cracking, ft/1000 ft
YR = Year of overlay (e.g. 83)
AGE = Age of overlay in years
FI = Freezing Index
WDT = Width of crack pattern, ft
AVGTEMP= Average annual Temperature, $^{\circ}$F
AVGMAXT= Average maximum monthly temperature, $^{\circ}$F
ANNPREC= Annual precipitation, in
ANNRNG = Average Monthly Temperature Range

Medium Severity

There were 40 sample units with some medium severity reflection cracking. The model developed was:

$$\begin{aligned} \mathrm{RFLCM} = {} & 22.117 + 2.503\,(\mathrm{AGE}) + 0.03866\,(\mathrm{FI}) - 10.614\,(\mathrm{TPCC}) \\ & - 0.5451\,(\mathrm{SWR}) - 13.805\,(\mathrm{WDT}) + 3.2302\,(\mathrm{AREA}) \\ & + 2.0178\,(\mathrm{ANNPREC}) - 0.003395\,[\,0.14263\,(\mathrm{AVGTMP}) \\ & - 0.12123\,(\mathrm{ANNPREC}) + 0.1955\,(\mathrm{ANNRNG}) - 5.9531\,] \end{aligned}$$

Statistics: $R^2 = 0.69$
SEE = 22.1
N = 107

Where the variables are as previously defined with the following additions:

SWR = Seating weight of roller, tons
TPCC = Thickness of original slab, inches
AREA = Area of the cracked slab pattern, square feet

Low Severity

There were 71 sample units with some amount of low severity reflection cracking, indicating the widespread occurrence of the low severity form of this distress. The model developed for low severity distress is:

$$\begin{aligned} \text{RFLCL} = \; & 87.396 - 1.7074\,(\text{JTS}) + 3.3215\,(\text{SWR}) + 33.596\,(\text{LT}) \\ & - 1.5298\,(\text{AREA}) - 47.438\,(\text{SOIL}) - 4.6739\,(\text{ANNPREC}) \\ & + 2.5865\,[\,(\text{ESAL})\,(0.14263\,(\text{ANNAVGT}) \\ & - 0.12123\,(\text{ANNPREC}) + 0.1955\,(\text{AVGRNG}) - 5.9531\,] \end{aligned}$$

Statistic: $R^2 = 0.41$
SEE = 111.2
N = 107

Where the variables are as previously defined with the addition of:

LT = Length of cracked pieces (longitudinal along traffic lane), feet
SOIL = Subgrade soil type, 1 - Coarse, 0 - Fine grained

These three individual models provide insight into potential areas where performance of crack and seat rehabilitation projects can be altered. The rate at which medium severity cracking develops is more affected by the age and environment, variables which are slightly less influential in the development of low severity cracking. The original pavement variables and construction procedures are more highly related to the development of low severity cracking, and not highly significant for the development of medium or high severity, with the exception of cracking pattern and thickness of the original pavement slab.

The analysis of these individual equations tends to indicate that low severity cracking will occur regardless of environment and traffic, and that construction variables influence the amount of low severity reflection cracking and its progression. The progression of low severity cracking into medium and high severity cracking is more dependent on the environment in which the project is constructed, and the traffic levels on the project. To predict the development of reflection cracking, two models were used. One for medium plus high severity cracking, and the previously shown equation for low severity cracking.

Medium and High

To provide a model based on a suitable number of distressed sample units, the medium and high reflection cracking were added and analyzed to produce one equation, as follows:

$$\begin{aligned}\mathrm{RFLCMH} = {} & 14.0523 + 2.928\,(\mathrm{AGE}) + 0.04158\,(\mathrm{FI}) - 10.677\,(\mathrm{TPCC}) \\ & - 0.5853\,(\mathrm{SWR}) - 13.583\,(\mathrm{WDT}) - 6.555\,(\mathrm{LT}) \\ & + 3.236\,(\mathrm{AREA}) + 2.1345\,(\mathrm{ANNPREC}) \\ & - 0.003928\,[\,0.14263\,(\mathrm{ANNAVGT}) - 0.12123\,(\mathrm{ANNPREC}) \\ & + 0.1955\,(\mathrm{ANNRNG}) - 5.9531\,]\,(\mathrm{ESAL})\end{aligned}$$

Statistics:
$R^2 = 0.61$
$SEE = 32.7$
$N = 107$

Where the variables are as previously defined.

The two equations for low and medium plus high can be used more accurately than one equation for the combination of low medium and high severity cracking because the variables entering each level of severity are so different. The summation of the two equations can be used in establishing limits of cracking which trigger the need to perform rehabilitation on the crack and seat installation. This summation is used in the reaminder of this report for reflection cracking in crack and seat overlay rehabilitation.

Application Limits

The variables in the equations were developed from data falling into specific ranges. The use of data outside those present in the database has the potential to produce predicted amounts of reflection cracking that are not typical of a pavement with the variables chosen. Further, there are certain combinations of variables that should be noted and not used because they were not present in the database, and may or may not be present in another pavement not included in this analysis. These combinations and ranges are outlined here:

• ESAL	The total applications of 18 kip equivalent single-axle loads varied from 0.1 to 9 million.
• SOIL	This variable is an indicator, 0 -for a fine grained subgrade soil (A-5 to A-7), and 1 -for a coarse grained soil (A-1 to A-2).
• FI	Freezing index, cumulative time below freezing varied from 0 to 1750.
• SWR	The seating weight of the roller used in the crack and seat operation varied from 3 to 60 tons [2724 to 54480 kg]. The smaller rollers were used only on short joint spacings, reinforced and plain, while the heavier rollers of 50 tons [45400 kg] were used on all pavement types.
• AGE	The time in years since the overlay was placed varied from 0.25 years to 21 years, with a practical upper limit of 13 years.
• TPCC	The thickness of the original concrete slab varied from 6 to 10 in [15.2 to 25.4 cm].
• WDT	The width of the cracking pattern varied from 1 to 20 ft [0.3 to 6.1 m], with a practical upper limit being 6 ft [1.8 m].

LT	The length of the cracking pattern varied from 1 to 10 ft [0.3 to 3.1 m].
AREA	The area of each block in the cracking pattern varied from 1 to 200 sq ft [0.09 to 18.6 sq m] with a practical upper limit of 60 sq ft [5.57 sq m].
JTS	The joint spacing varied from 15 to 90 ft [4.6 to 27.4 m].
ANNAVGT	The annual average temperature varied from 44 to 70 $^{\circ}$F [6.7 to 21.1 $^{\circ}$C].
ANNPREC	The total annual precipitation varied from 19 to 47 in [48.3 to 119.4 cm].
ANNRNGT	The average monthly temperature range varied from 17 to 31 $^{\circ}$F [10 to 17 $^{\circ}$C].

The selection of the last three climatic parameters must be done in a combination representative of the actual values common to an area. A check is to use the following equation. The result <u>must</u> be between 0.5 and 9.5, preferably between 1 and 9.

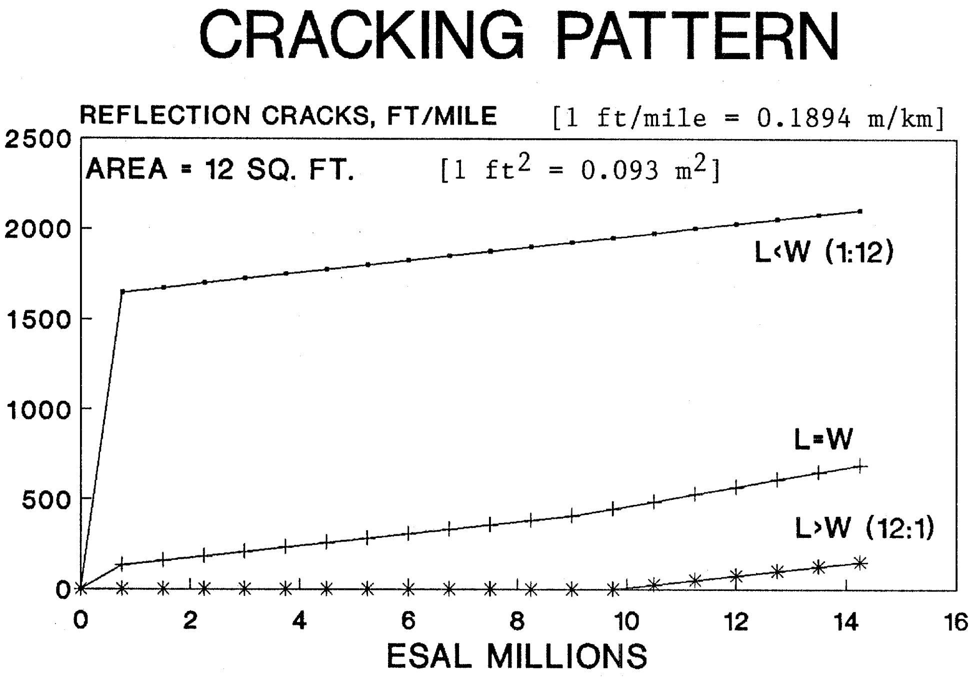
$$\text{ZONE} = [\ 0.14263\ (\text{AVGTMP}) - 0.12123\ (\text{ANNPREC}) + 0.1955\ (\text{ANNRNG}) - 5.9531\ ]$$

When this equation calculates outside the limits, the combination is not representative of a naturally occurring climatic area of the country, and the input variables should be examined.

Sensitivity comparisons are given in figures 44 through 50. The two separate straight line portions of each graph show the separate influence of low and the medium-high equations which make up the total reflection cracking. Analysis of the area of the cracked sections shows that large areas should be avoided. The area is calculated from length and width. The length to width ratio of the cracking pattern also influences the development of reflection cracking. More total reflection cracking can be expected in areas with higher Freezing Index values up to a certain age. The Freezing Index value relates directly to the amount of thermal activity which produces movement in the joint, propagating the reflection crack.

The thickness of the original PCC slab effects medium and high severity cracking, but does not alter the development of low severity cracking. Heavier rollers to seat the cracked sections will produce more low severity reflection cracking, while it reduces the development of the medium and high severity cracking. The use of heavy rollers may alter the cracking effectiveness and change the development of low severity cracking. The effectiveness of the cracking is a critical element in the performance of crack and seat, and it cannot be evaluated from distress surveys and thus cannot be included in this analysis. The use of the heavier roller to seat the cracked sections delays the progression from low to medium or high severity, and may be beneficial with this in mind.

The presence of a coarse grained subgrade soil greatly reduces the amount of low severity cracking, but has no effect on the development of medium or high severity cracking. The same holds for the joint spacing of the original pavement. Longer joint spacings produce less total length of cracking in the overlay than short joint



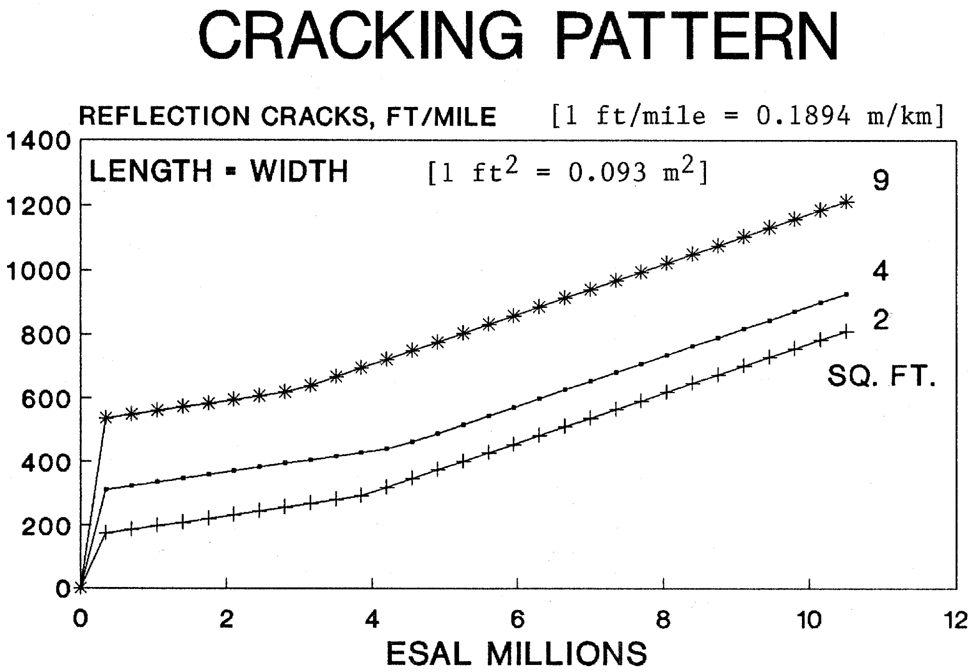


Figure 44. Influence of cracking pattern on reflection cracking.

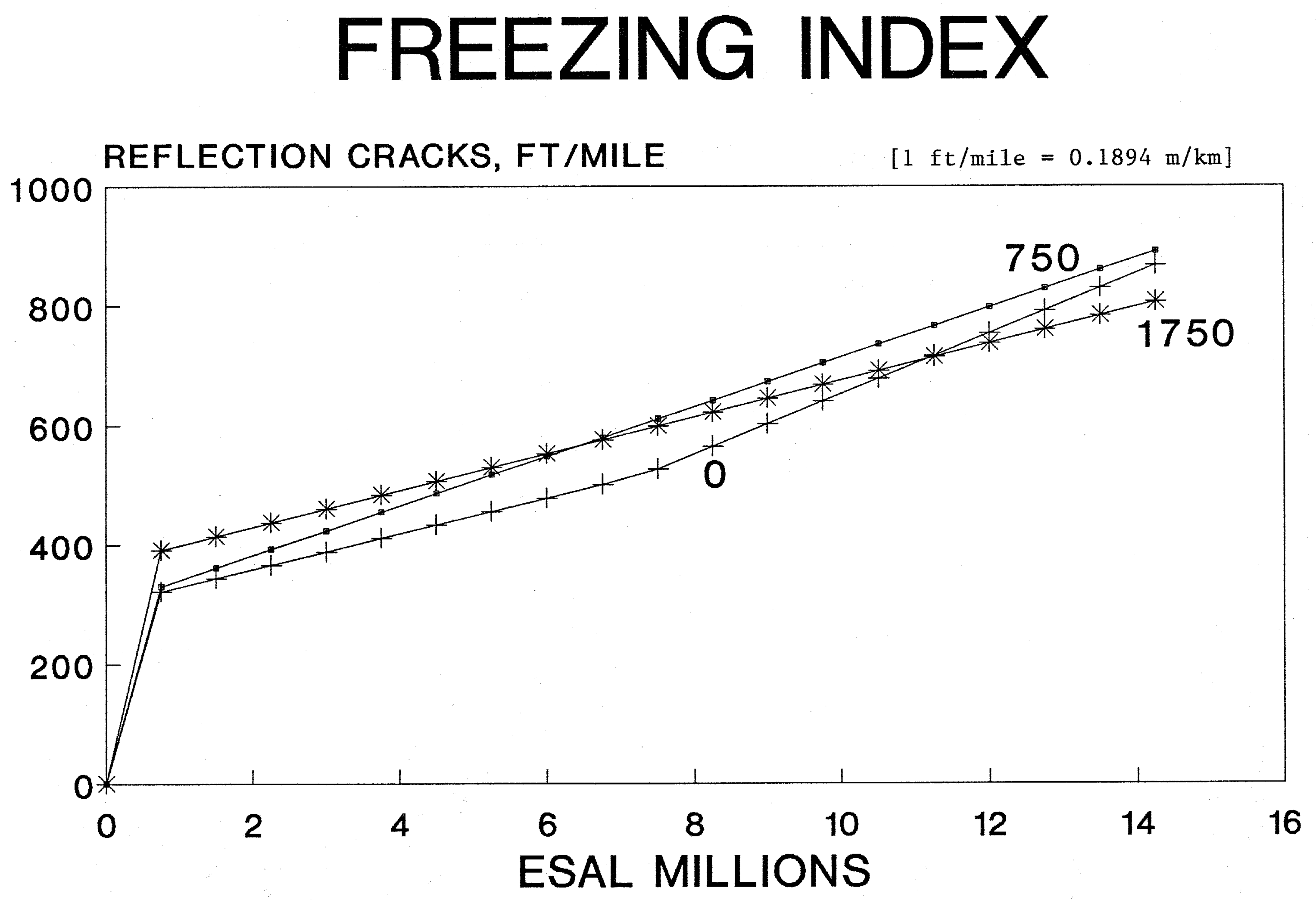


Figure 45. Influence of Freezing Index on reflection cracking.

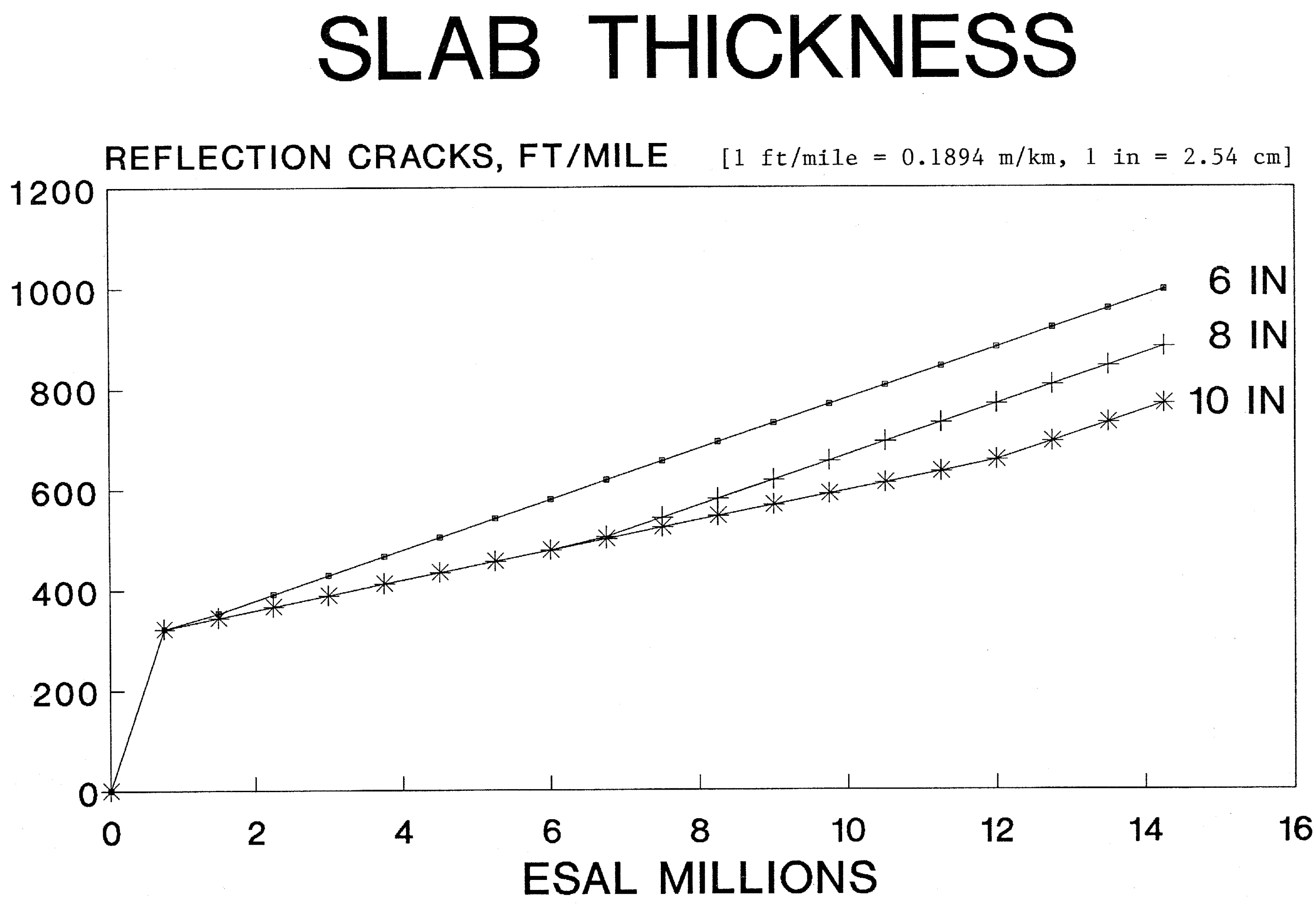


Figure 46. Influence of original concrete pavement thickness on reflection cracking.

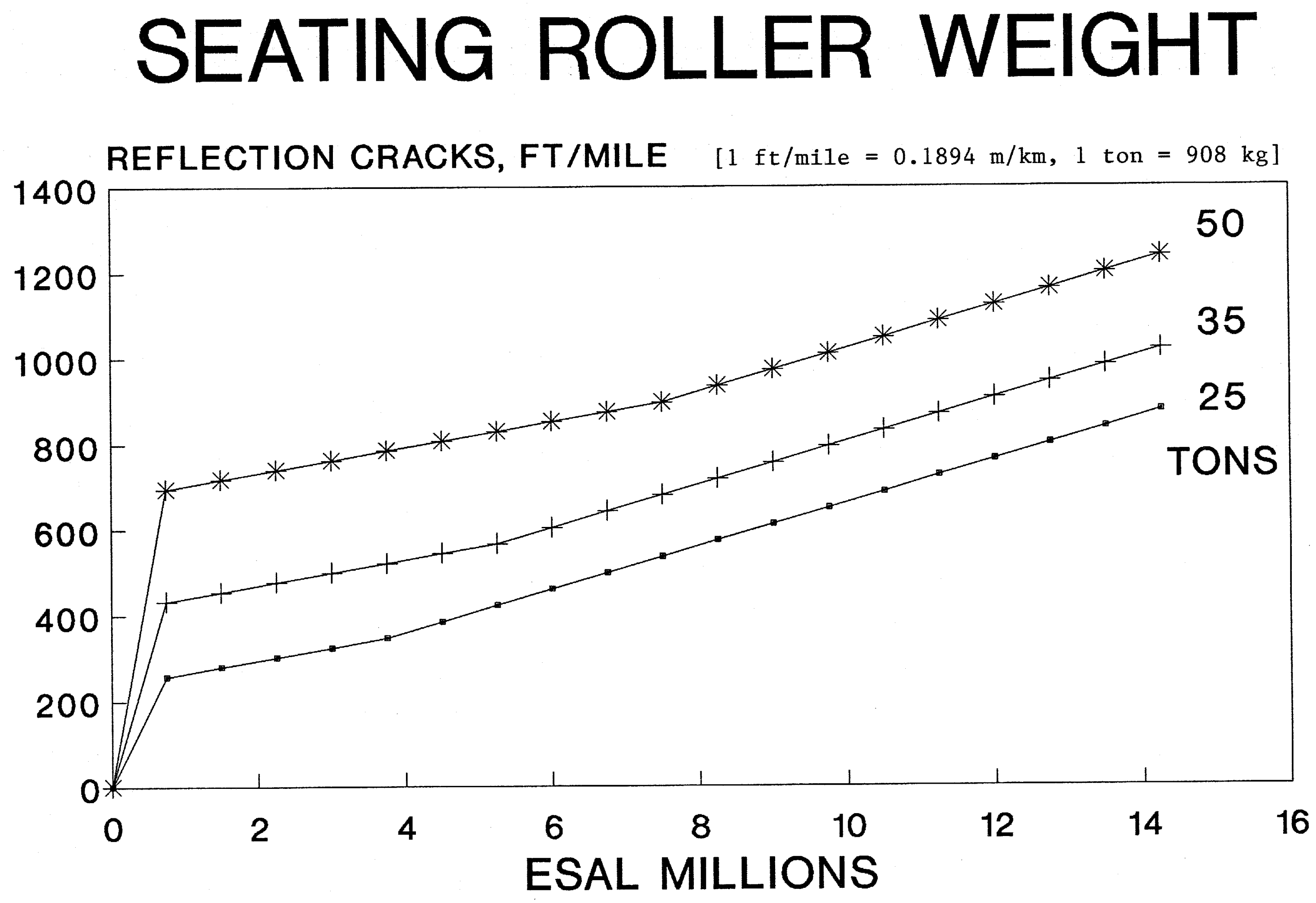


Figure 47. Influence of seating roller weight on reflection cracking.

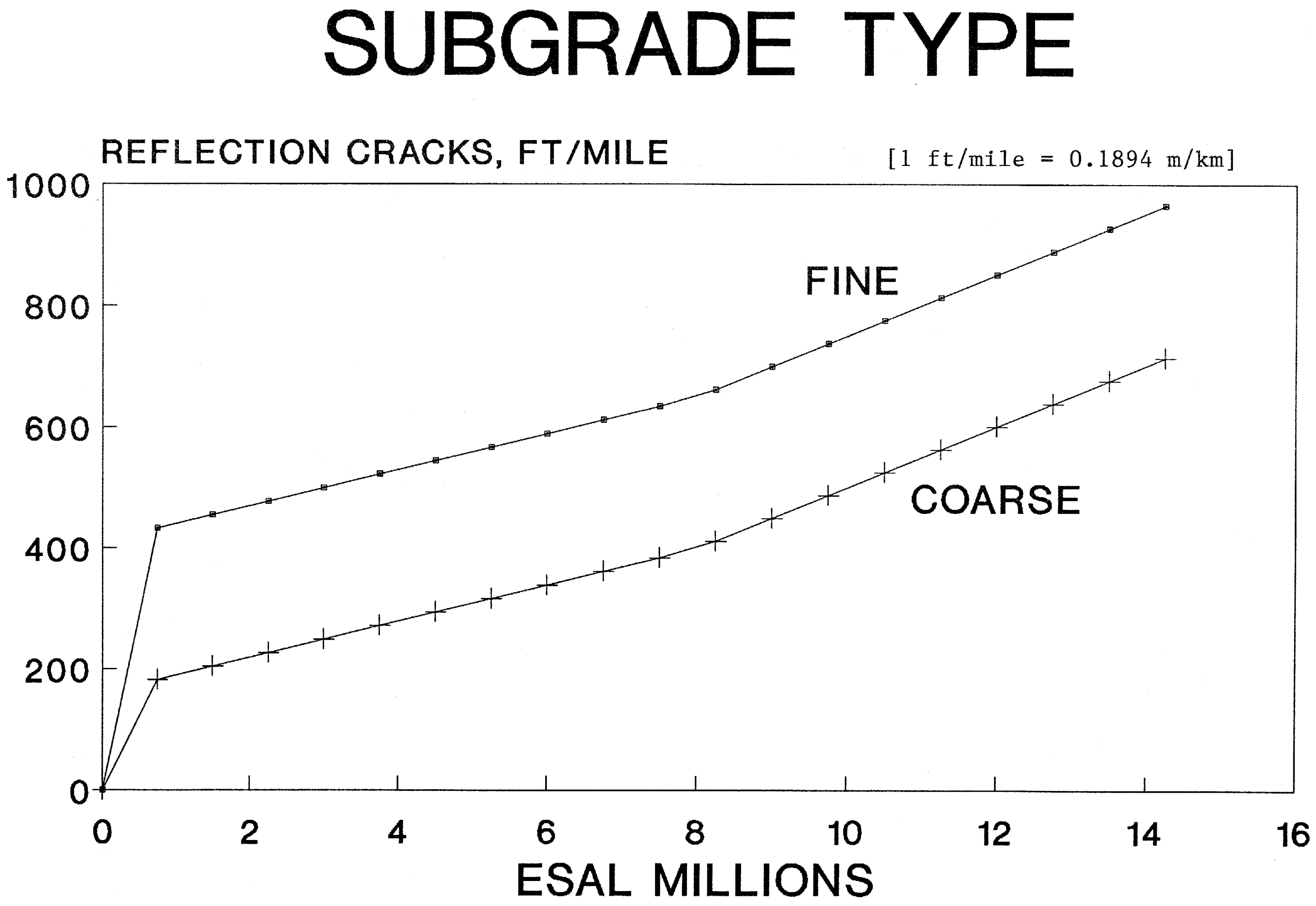


Figure 48. Influence of subgrade type on reflection cracking.

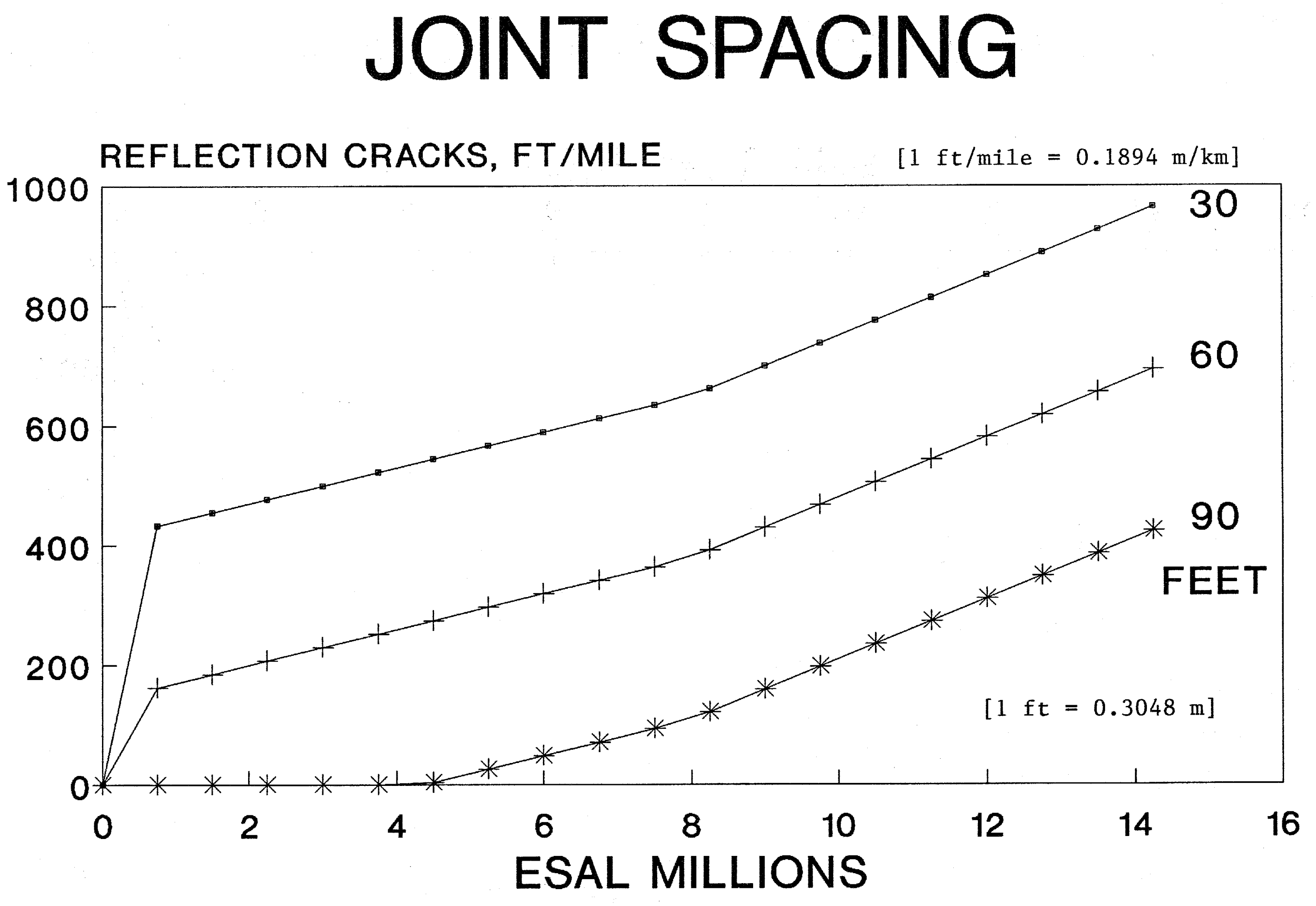


Figure 49. Influence of joint spacing on reflection cracking.

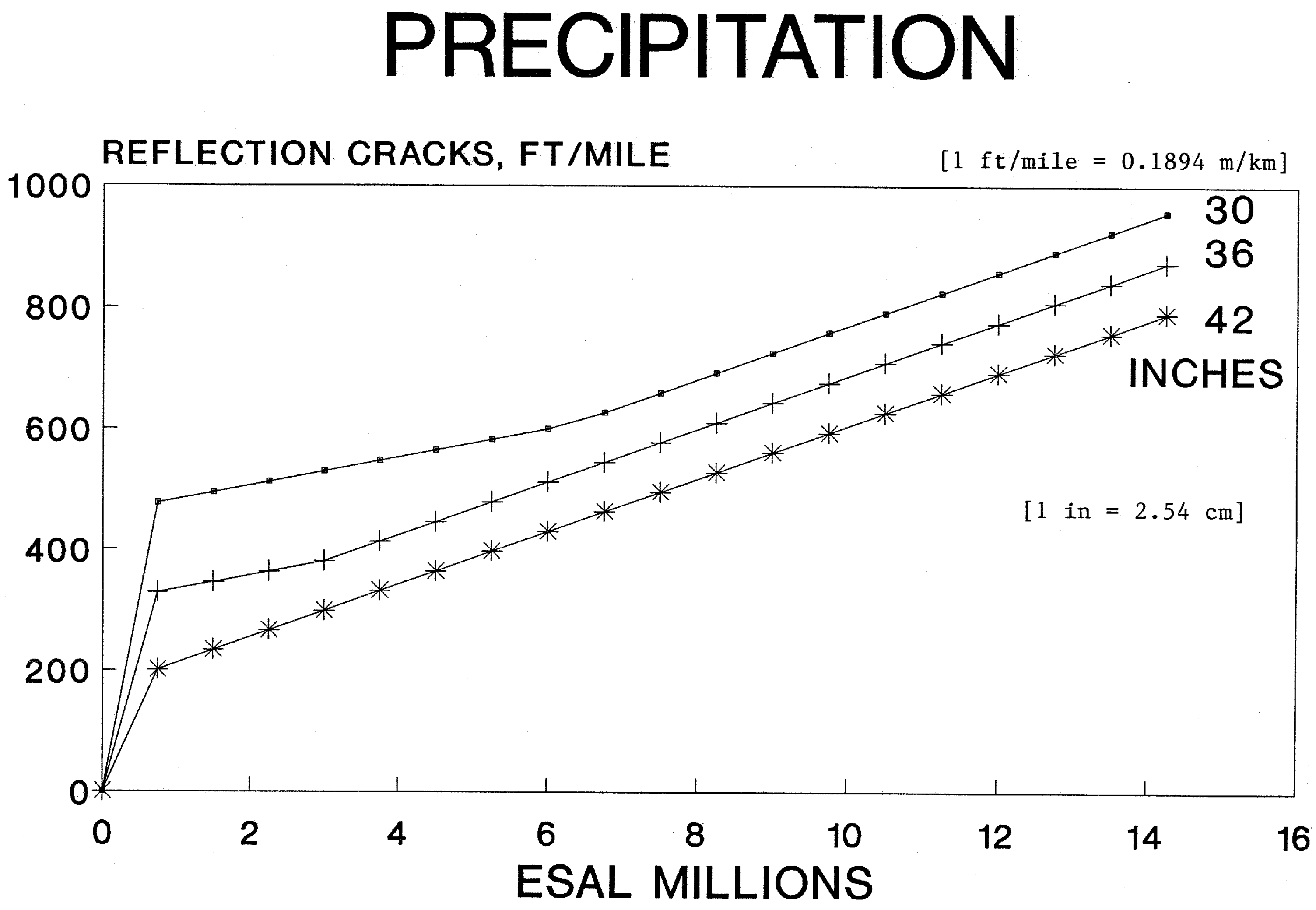


Figure 50. Influence of annual precipitation in inches on reflection cracking.

spacings. This is partly due to the fact that there are fewer joints in a long jointed pavement, and an examination of cracking as a percent of joints may be warranted as a better indicator of the performance of the procedure.

The interaction of age and ESAL loadings is unique. Low severity cracking increases with increasing axle loadings, with no relation to age of the overlay. The same amount of cracking can develop in different time periods, as long as the number of axle loadings are the same. The age of the overlay is a factor in the development of medium and high severity cracking, in addition to the effect of the axle loadings that accumulate during the year.

The climatic variables illustrate the impact of environment on reflection cracking performance. Areas with larger annual rainfall will have lower amounts of low severity cracking, while the development of medium and high severity cracking is greater in these same areas. Medium and high severity cracking develops over time, and higher annual rainfall will produce a lower support in the subgrade which accelerates breakdown of existing cracks. The higher amount of low severity cracking in areas of low rainfall may be due to greater temperature variations. The combined effect of the climatic factors cannot be totally separated and investigated independently. The annual average temperature and monthly average temperature range combine with the annual precipitation to describe the general climate in the area. Generally, the areas with warmer annual temperatures and a smaller temperature range perform better. For example, Florida and California crack and seat projects perform better than other areas.

4.3.3 Rutting

The same database was used to establish a predictive model for rutting. The rut depth was the average of the inner and outer wheel path in the outer lane in inches. The model developed is:

$$\begin{aligned} \mathrm{RUT} = {} & 0.084807 + .019208\,(\mathrm{ESAL}) + 0.012512\,(\mathrm{AGE}) \\ & + 0.001194\,(\mathrm{PCTRK}) - 0.0041766\,(\mathrm{ANNPREC}) \\ & + 0.0002798\,(\mathrm{FI}/\mathrm{OLTH}) + 0.0064465\,[\,0.14623\,(\mathrm{AVGTMP}) \\ & - 0.1307\,(\mathrm{ANNPREC}) + 0.01955\,(\mathrm{ANNRNG}) - 5.9531\,]\,(\mathrm{OLTH}) \end{aligned}$$

Statistics:
$R^2 = 0.71$
SEE = 0.06
N = 101

where:

PCTRK	Percent trucks in the traffic stream,
OLTH	Asphalt concrete overlay thickness, inches.

The other variables are as previously defined.

The rutting equation demonstrates that values normally expected to alter rut development in an overlay of a concrete pavement are indeed important in the development of rutting in a crack and seat and overlay rehabilitation project. The construction variables which were shown to be important to the development of reflection cracking are not significant for rutting. The traffic, overlay thickness, age, and environment are the important variables. Crack and seat parameters do not enter the equation. Thus, asphalt concrete should behave no differently in a crack and seat project than in another overlay project, other factors being equal.

Application Limits

The limits on the variables in the rutting equation are the same as for reflection cracking with the additions:

- OLTH — Overlay thickness of the asphalt concrete varied from 2.5 to 13.5 in [6.4 to 34.3 cm], with practical upper limit of 9 in.
- PCTRK — Percent trucks in the traffic stream varied from 15 to 75 percent with practical upper limit of 50 percent.

The sensitivity of this model is shown in figures 51 and 52. Increased traffic levels produce higher levels of rutting. Thicker overlays generally develop more rutting due to the presence of more material to be affected by the traffic. Higher average temperatures and larger temperature ranges produce more rutting. These influences of climate and traffic are considered typical for rutting.

4.4 DESIGN AND CONSTRUCTION GUIDELINES -- CRACK AND SEAT AND ASPHALT OVERLAY

4.4.1 Introduction

This section provides a summary of the design and construction of crack and seat and overlay projects. The information is a synthesis of that obtained from past research studies, published design procedures, field performance results from the database and staff experience. The guidelines are presented in a format intended to facilitate usage by practicing engineers.

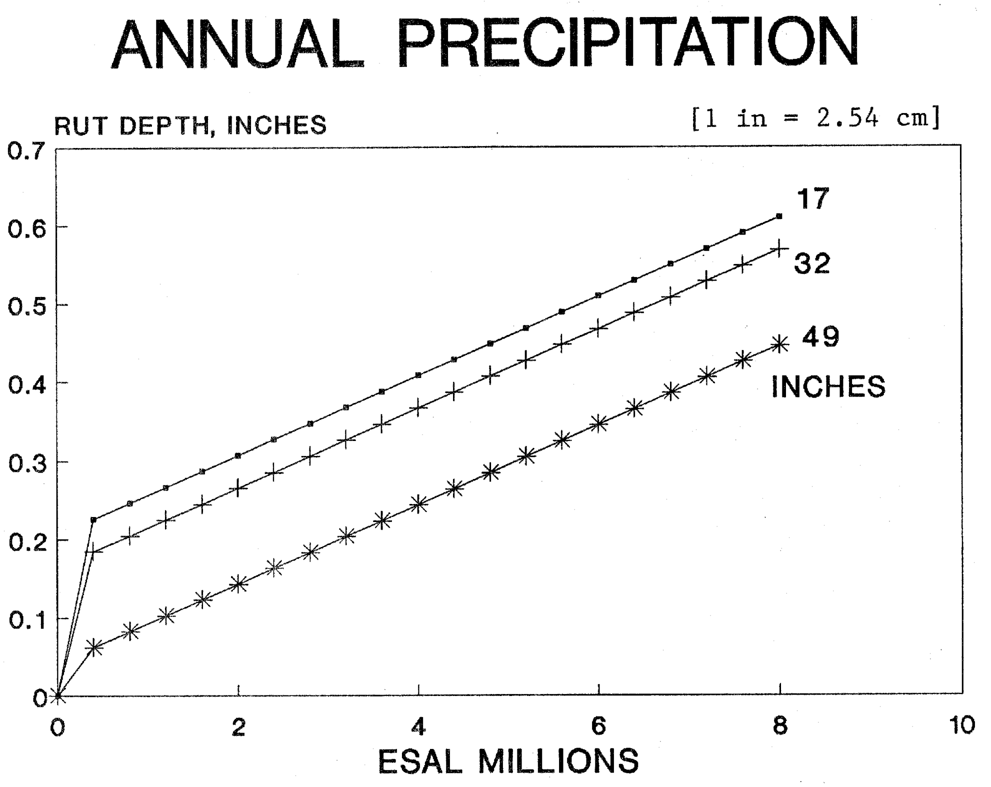
The following guidelines cover the overlay of existing jointed portland cement concrete (PCC) pavements following a crack and seat project.

Need for Crack and Seat and Overlay

The placement of an asphalt concrete overlay over a jointed portland cement concrete pavement is typically done to restore smoothness and/or structural adequacy to the overall pavement structure. There are design procedures to select the thickness of asphalt concrete to carry the predicted traffic.(87) These design procedures do not provide any means for preventing reflection cracking in the overlay, even though it is the major distress in an asphalt concrete overlay. Numerous treatments have been tried to eliminate reflection cracking, and all have met with varying levels of success.(93)

The crack and seat process is designed to eliminate the slab movement by decreasing the integrity of the concrete slab. When the slab is cracked, the temperature changes cannot produce contraction throughout the entire length of the slab, only over the distance between the cracks. The smaller this distance between cracks, the smaller the opening and curling movements, and the slower the progression of reflection cracking.

A major problem with jointed reinforced pavements is that cracking the slab and breaking the steel in the slab is difficult to do. If the steel is not ruptured, the integrity of the slab is not broken, and the slab will continue to move as an integral unit, propagating reflection cracks. The cracking process can be carried too far to ensure that the steel is ruptured. The breakdown of the concrete may be



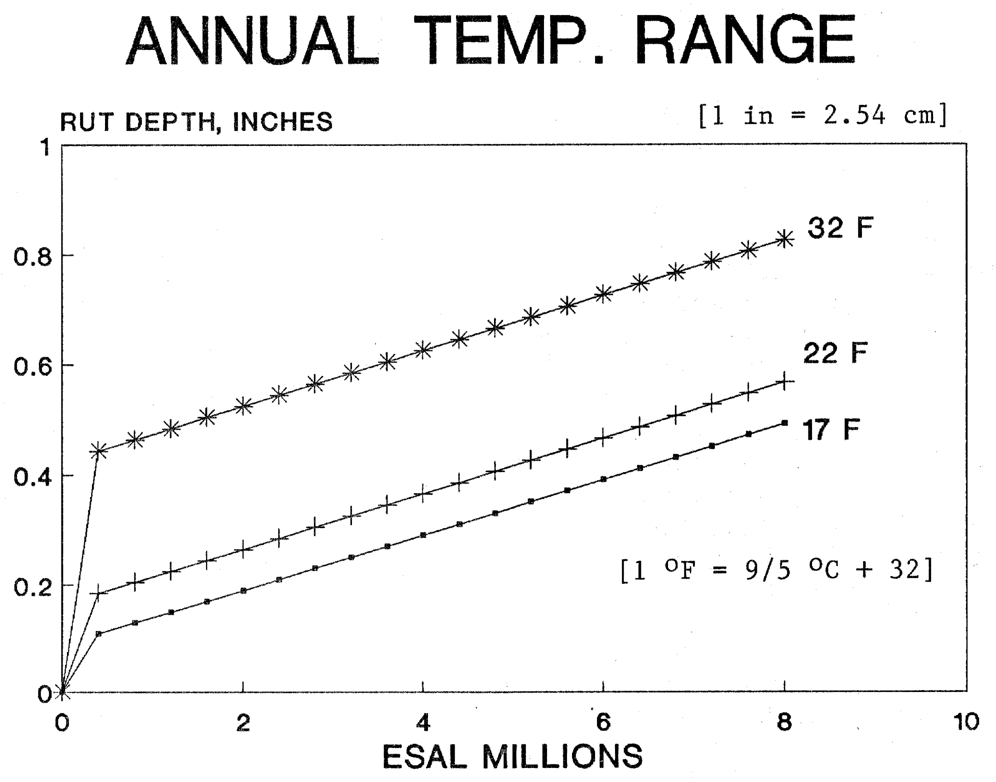
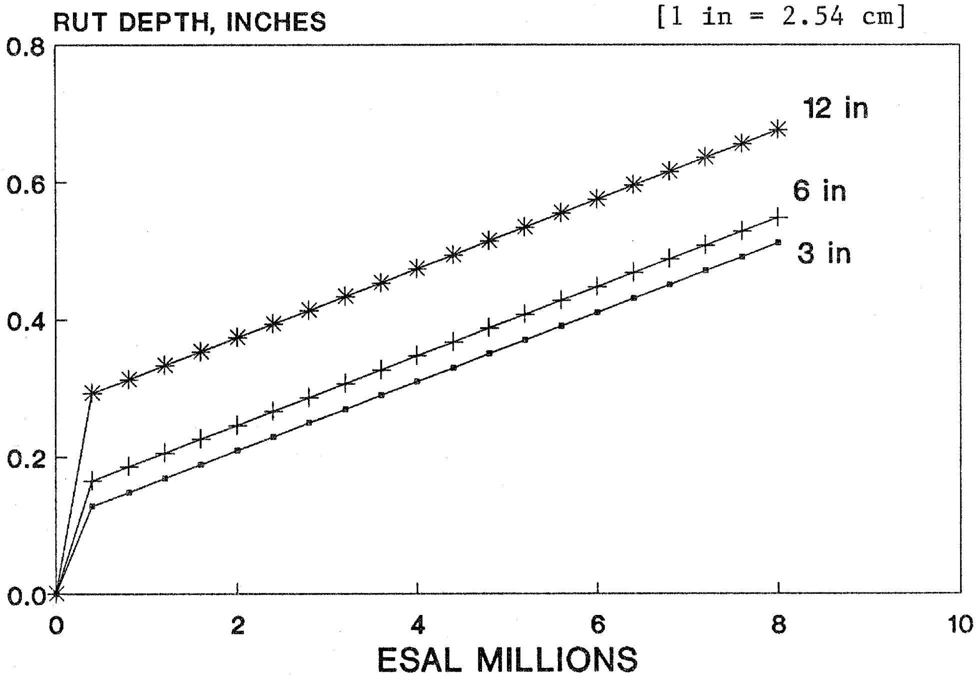


Figure 51. Influence of annual precipitation in inches and average monthly temperature range on rutting.

OVERLAY THICKNESS



PERCENT TRUCKS

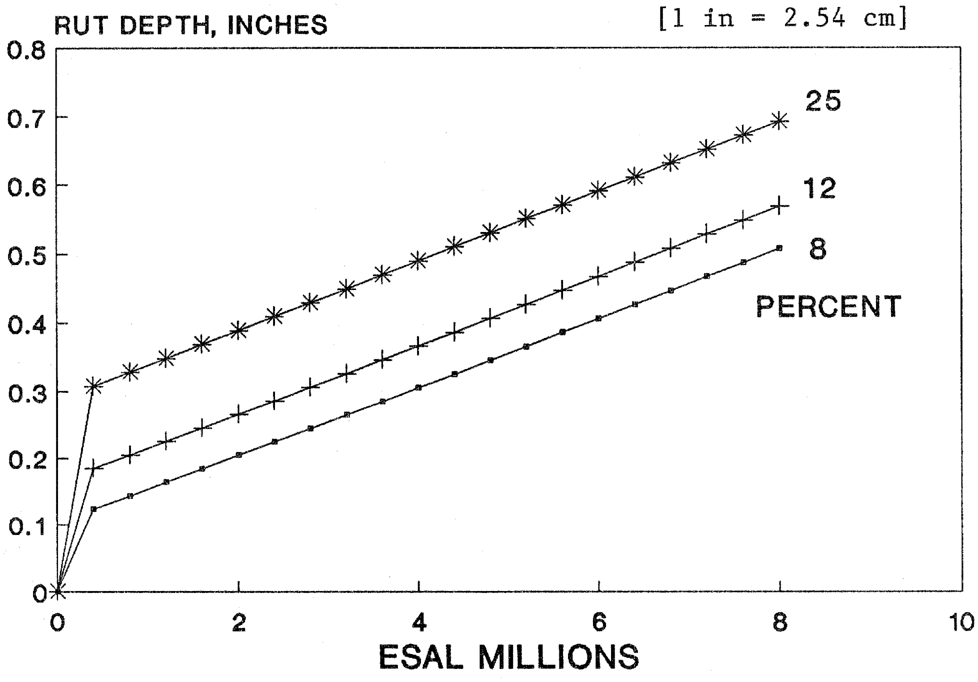


Figure 52. Influence of overlay thickness and percent trucks on rut depth.

so extreme that aggregate interlock is lost between the broken pieces producing pieces which are capable of moving independently under traffic. This can produce reflection cracking in the overlay.

The crack and seat process is designed specifically to reduce reflection cracking over the joints. To reduce the potential for cracks developing over the induced cracking pattern, the individual pieces are typically rolled with a heavy roller to firmly seat them into the foundation and eliminate the movement of the individual pieces. If the pieces are rolled either too many times or with too heavy a roller, damage to the foundation material may result, producing an unstable material leading to increased movements of the pieces. If the pieces are not seated properly, they will continue to move under traffic.

4.4.2 Concurrent Work

This rehabilitation scheme is cost-effective for pavements which do not require extensive slab replacement, and do not have an extensive amount of crack deterioration which requires repair before beginning any form of rehabilitation. The crack and seat process does not lend any extra structure to the pavement, and actually produces a layer with less structural adequacy than the original concrete slab.(90,91) Severely deteriorated joints and cracks may require repair to the same extent as would be required for a standard asphalt concrete overlay.

Slabs exhibiting excessive fatigue damage may indicate that the foundation does not provide sufficient support to the crack and seat section. Further, a fatigued concrete slab may produce a very different crack pattern than a sound slab, and damage to the fatigued slab may be easier, therefore requiring closer control of the cracking equipment and monitoring of the crack pattern to achieve the best performance.

When there is a drainage problem and moisture susceptible materials are in the pavement structure, drainage should be considered and installed prior to the crack and seat operation. This requires careful evaluation of the pavement to assure that drainage will improve the performance of the materials. There is no data at present to indicate the effectiveness of drainage when added in conjunction with crack and seat. <u>The database did not demonstrate a clear improvement in the performance of overlays when drainage was present.</u>

4.4.3 Design Considerations

<u>Structural</u>

The structural design considerations for crack and seat and overlay that are currently available do not address the question of design for reduction of reflection cracking. Any benefit provided in reducing reflection cracking, the main reason to perform crack and seat, at present is derived only as a result of the process. The only design recommendations currently available are contained in the AASHTO Pavement Design Guide.(87) The recommendations generally provide for a reduced structural layer coefficient for the concrete slab. The reduced value is a function of crack length:

Crack Spacing	Structural layer Coefficient
1 foot [0.3 m]	0.25
2 feet [0.6 m]	0.35
3 feet [0.9 m]	0.45

These recommended values have been shown to approximate the values derived from field studies conducted for NAPA where modulus values were back calculated from completed projects in Minnesota and Illinois.(82) These coefficients must not be applied indiscriminately, however, as they are highly dependent on the effectiveness of the cracking process. The mere presence of cracks with a specific pattern spacing does not guarantee that the layer coefficient will be anywhere close to the values listed here, and reliance on these coefficients for design is questionable at present.

The use of these layer coefficients in the AASHTO design procedure only provides a design to a level of load carrying ability with no guarantee of reflection cracking reduction. Because the cracking reduces the structural integrity of the concrete slab, the behavior of the pavement section under traffic approaches that of a high quality base. Because there are still individual pieces of slab, there is little likelihood of traditional fatigue in the asphalt concrete layer. The deformation that occurs over the cracks in the slabs will tend to propagate a crack that is not a reflection crack, but is not a fatigue crack either. At present there is no comprehensive design procedure that can incorporate the configuration of the crack and seat to predict life, although there are some being developed.(94)

Cracking Pattern

Current thought is that it is more difficult to obtain good cracking, and hence, seating in a reinforced pavement than in a plain pavement. Database analysis did not distinguish the performance of plain and reinforced pavements, although the design characteristics of the projects evaluated were quite different as pointed out earlier. Greater care must be taken to effectively crack a reinforced pavement. Heavier equipment must typically be used for the cracking procedure.

The cracking process must do more than produce a very fine crack for JRCP. All the cracks produced in the cracking process must extend through the slab to reduce the integrity of the slab. The cracking process must rupture the steel. At present there is no accepted procedure to evaluate the effectiveness of the cracking process in a manner that furnishes design values prior to placement of the asphalt concrete overlay. Much work must be done in this area before a rational design procedure using field data can be developed for asphalt concrete thickness design.

In general, the smaller the cracking pattern, the better the performance from the standpoint of reflection cracking. The smaller cracking pattern guarantees a lower level of structural integrity in the slab. When the cracking process is efficient, however, the small patterns of one foot on a side may produce an unacceptably high level of structure loss, and the overall performance of overlays over very small cracking patterns has not been as good as slightly larger pieces. General recommendations call for cracking that will produce pieces with an approximate area of 4 to 6 sq ft [0.37 to 0.56 sq m], typically 18 to 24 in [45.7 to 61.0 cm] on a side. Although the database indicates that the length to width ratio is important, it is felt at this time that the dimensions of the pieces should be kept approximately equal, with the longer dimension, if any, occurring along the longitudinal pavement direction.

Overlay Thickness

It is an established fact that thicker overlays reduce the rate of reflection cracking. Once a thickness of overlay has been designed to handle traffic considerations, questions remain whether the application of crack and seat to the pavement reduces the potential for reflection cracking, and what impact the crack and seat operation has on thickness requirements. The structural considerations indicate that a thicker overlay is required whenever a slab is cracked and seated. Whenever a thicker overlay is placed on a concrete pavement, a reduction in the rate of reflection cracking must be expected. This reduction will be present whether the pavement is cracked and seated or not. Thus, any overlay designed on a crack and seat project will exhibit better reflection crack performance than the thinner overlay required for the pavement without the crack and seat operation.

How much time, before reflection cracking develops, is due to the extra thickness required because of the cracking, and how much is due to the mechanical effect of the crack and seating operation? The results of previous field surveys provide a mixed indication. In general, reflection cracking is reduced initially, but approaches values seen in the control sections in several years.(83) The database analysis presented here, unfortunately provided no indication of overlay thickness influence in reducing reflection cracking. It is not felt that this is a true indication, and more data may be required before a conclusive statement can be made. The data strongly indicate that the severity of the cracking is significantly lower in the crack and seat sections which may be the benefit of crack and seat. Generally, failure of an asphalt concrete overlay is governed not by the amount of low severity cracking, but the amount of medium and high cracking. The database analysis indicates that while standard thicknesses selected for structural considerations may develop a significant amount of cracking, it is low severity for the most part.

Subgrade Quality

Subgrade support influences the performance of the crack and seat overlay. Better subgrade support will provide better support for the seated pieces, and provide better resistance to movements. Better subgrade support allows slightly bigger pieces to be produced in the cracking operation although there is no correlation available to relate size to support. Pavements with poor subgrades are not good candidates for crack and seat rehabilitation, and when poor support is expected, the seating operation should not use the heaviest roller as this definitely causes nonuniform or excessive movement of the pieces.

Types of Overlay

The predominant overlay has been asphalt concrete in thicknesses ranging from 2.5 to 13 in [6.4 to 33.0 cm]. PCC overlays have been placed in Iowa and Wisconsin.

4.4.4 Construction Considerations

Cracked Pattern

It is good practice to specify the cracking pattern desired. To ensure that specified cracking is obtained, it is recommended that test sections be designated prior to production. This allows the contractor to investigate various comibinations of equipment and striking patterns that will guarantee the desired result. Spalling along the cracks, and shattering of the pieces during the cracking operation should be avoided. The cracking pattern should be validated and recorded for comparison during the progress of the crack and seat operation.

Cracking Equipment

Devices which demonstrate the ability to produce the desired cracking pattern should be allowed on the job with the exception of free-fall devices such as headache balls. Pile drivers and guillotine hammers are the most common devices, generally used with modified striking plates shaped to produce the desired cracking pattern. These modified striking plates vary with pavement type and design. They vary in shape from a rectangular base shoe to chevrons to diamonds. The precise shape must be determined during the test section phase of the project. Sharp striking plates or small striking areas should be avoided, as these will tend to spall or penetrate the surface. Avoid cracking any closer than 10 in to a joint or crack in the original slab.

The whiphammer and the resonant breaker are two newer pieces of equipment that have been investigated for use on crack and seat operations. The whiphammer is a highly controllable device, but those tested to date have not had the force required for cracking some of the thicker pavements. The inability to control the resonant pavement breaker to produce precise cracking patterns has been the initial drawback for this device. It does an exceptional job of breaking the pavement, and may be too efficient. Further work with these devices and their operating characteristics is needed.(83)

Seating

The seating process seems to be a critical part of the crack and seat operation. Recent findings indicate that excessively heavy rollers may do more damage than good. A report from Indiana indicates that a 50 ton pneumatic roller increased deflections in the cracked pieces after each pass of the roller.(84) These increased deflections indicate less strength in the pavement section, producing a reduced load carrying capacity. Two projects in California with a 13 ton [11804 kg] roller showed that the cracking procedure reduced deflections at 92 percent of the joints, while subsequent rolling increased the deflection at the joint in 40 percent of the joints.(85) Both of these studies indicate that rolling may not be beneficial from a structural adequacy standpoint.

The primary purpose of the seating operation is not to increase the structural adequacy of the section, however. It is done to seat the pieces to reduce their potential to move under traffic and propagate another crack. The findings of these two reports provide no indication of the effect of increased deflections due to seating on the reflection cracking of the overlays. The database analysis indicates that heavy rolling may produce a higher level of reflection cracking, supporting the Indiana findings above. The results should be considered tentative at this time, as there may be an interaction of pavement type and roller type not fully explained in the available data. It is felt that seating is beneficial, but extremely heavy rolling may not be necessary.

It is recommended that a means of measuring deflections in the broken pieces be implemented to determine the most efficient weight of roller, and to determine the optimum number of passes of the roller before the pieces unseat. This can be a simple procedure using a Benkelman beam and a loaded dump truck that is run over the project periodically.

Maintenance of Traffic

There are several options to traffic control on crack and seat operations. Several States allow traffic to use the cracked and seated pavement prior to overlay. Some allow traffic to have unlimited access prior to overlay while others require that the overlay be placed within a specified time period following cracking. It is recommended that traffic should be allowed only limited access to a project where subgrade support may be low as the potential for unseating the pieces is higher for this pavement. Where the foundation support is good, and the base is strong, traffic can be allowed for a limited time. It is good practice to begin placing the overlay within 2 to 3 days following cracking and seating to prevent breakdown of the aggregate interlock and unseating of the pieces. If an excessive delay is encountered, it may be advisable to reseat the pieces.

Utilities, Culverts, Curbs and Gutters

Cracking operations directly over utilities, culverts, curbs and gutters should be avoided. This will require accurate marking of the locations of these appurtenances. The office of Direct Federal Programs of FHWA has a specification that does not permit cracking and seating operations within 5 ft [1.5 m] of subsurface utilities and structures. The contractor should be required to repair all damage to these installations. A survey might be required (or advisable) prior to crack and seat to determine the pre-operation condition.

Reflection Cracking Treatments

Several States routinely apply fabric with the overlay of the crack and seat operation. At present reflection crack treatments such as fabrics should not be routinely used in conjunction with crack and seat. This is due principally to cost, and the inability to predict the effectiveness of fabric installations in general. There is no data to indicate the performance of fabrics in a crack and seat job. If a State has had good experience with fabrics for reflection crack reduction, they may be used, and the projects should be studied to determine whether the fabric provides an advantage.

Cracking of a Composite-Asphalt Overlayed Pavement

It has been demonstrated, on the Illinois Tollway, that cracking could be done through an asphalt overlay. However, the extent of the cracking cannot be accurately verified without removing the asphalt concrete for visual inspection. It is recommended that the existing asphalt be removed by appropriate means, and considered for recycling for use in the new overlay.

Method of Measurement

There are several options available for measuring crack and seat. It can be measured in square yards of a specified cracking pattern, or it can be measured in lane miles, or in centerline miles. These procedures are generally limited to an area measurement, and prices are generally reported in dollars per square yard.

Costs for measuring crack and seat are typically about $0.75 per sq yd [$0.90 per sq m]. The range has extended from one-third of this figure to twice as much in different States. With increased volumes of work, the average cost is expected to stabilize in the range of $0.25 to $0.50 per sq yd [$0.30 to $0.60 per sq m], depending on equipment used, and required operating procedures to achieve desired cracking.

4.4.5 Preparation of Plans and Specifications

The Federal Highway Administration's Pavement Rehabilitation Manual best describes the required detail for plans and specifications.(76) It states:

> "The plans for a cracking and seating project do not have to be complex or numerous. Only the existing typical section and limits of work need to be shown along with the typical section of proposed overlay."

4.5 CONCLUSIONS AND RECOMMENDATIONS

Crack and seat rehabilitation with asphalt concrete overlays is the process whereby the existing concrete pavement is cracked to destroy the integrity of the slab. This cracking reduces the joint movement, thereby reducing reflection cracking in the asphalt concete. This type of overlay has been done since the mid 1940's, and has recently received increased attention with the increased need for rehabilitation of concrete pavements with the main distress being reflection cracking in the overlay. The crack and seat operation has as its primary goal the reduction of reflection cracking in the overlay.

A total of 70 projects were surveyed in 12 States for inclusion in the database. All data was recorded in units relating to sample unit length of 1000 ft [305 m]. Where the projects were long enough, two sample units were surveyed. This resulted in 108 sample units in the final database. These projects represent a cross section of projects constructed in the United States in recent years.

Surveys have indicated that crack and seat overlays can reduce reflection cracking, particularly in the early years of the overlay's life. There is some evidence that after a specific number of years, the effectiveness of the crack and seat operation may diminish. The projects surveyed in this study exhibited good performance in general with only one section exhibiting high severity reflection cracking and approximately one-third exhibiting medium severity reflection cracking of limited extent.

The design and construction of crack and seat overlays requires special considerations to reduce the effective slab length to minimize cracking, and to seat the cracked sections so they will not move under traffic. Overall conclusions and recommendations from this research study are as follows:

1. The presence of reinforcing steel has an influence on the effectiveness of the crack and seat operation. If the cracking operation does not rupture the steel the slab length will not be reduced. This means that the movement at the joints will not be reduced and reflection cracking will progress at the same rate as if the crack and seat operation had not been performed. If the steel is cracked, the performance of the overlay should be no different than that of an unreinforced pavement. The major difference is in the extra precautions which must be taken in the cracking operation on reinforced pavements. The database analysis did not show a difference in the performance of pavements with or without steel, due to other interactions.

2. Without deflection testing of the completed project, there is no way to evaluate the effectiveness of the cracking operation beyond a recognition of the size of the cracked pieces. At present there is no acceptable procedure for evalulating the cracking effectiveness on the concrete slab prior to overlay.

3. The crack and seat overlays will develop low severity reflection cracking relatvely easily, and the development appears to be influenced more by the variables in the crack and seat operation and not the original pavement design or environment. The progression of low severity cracking to medium and high severity does not occur as easily as the development of low severity cracking, and is more a function of environment, age, original pavement design, and traffic; and less a function of the crack and seat construction variables.

4. The seating roller weight has a dual action on reflection cracking. Heavier rollers will cause more low severity cracking to develop initially, while reducing the rate at which the low severity cracks progress to medium and high severity cracking. The impact of heavier rollers is related to foundation quality, and heavy rollers should not be used on weak foundations. The use of a heavy roller does not guarantee improved performance.

5. Cracking pattern is more complicated than merely investigating the area of the cracked pieces. The area should be minimized to the range of 4 to 6 sq ft [0.37 to 0.56 sq m], and the ratio of length to width should also be controlled. When the length of the cracked piece (length is measured along the longitudinal direction of the pavement, width is measured transversely across the pavement) is less than the width, more cracking will result than if the length and width are equal or the length is greater than the width. For construction it is recommended that the dimensions be kept equal with the operation having the potential to err on the side of producing a pattern with a slightly greater length than width.

6. Overlay thickness did not show an influence on reflection cracking which may be due to an interaction effect with the reinforcing steel. The reinforced pavements generally had a thicker overlay, had been in place longer, and had higher traffic levels than the plain concrete sections. The performance of the reinforced and plain sections were so similar that the effect of steel and thickness did not enter the predictive relationships. In general thicker overlays will perform better for a longer period than thinner overlays placed over the same crack and seat sections.

7. The quality of the asphalt concrete mixture has a significant impact on the performance of an overlay in resisting reflection cracking. The data in the database contained no indication of the mix quality on the individual projects. The rutting performance of these sections was typical of conventional overlays which indicates the mix quality was not exceptionally bad, and could be considered typical. Any comparisons of the performance of individual sections should be made realizing that variability in mix quality can alter reflection cracking.

8. The environment showed an effect on the progression of cracking to the medium and high severity levels. In general the milder climates showed the best performance. High monthly temperature extremes and low monthly average temperatures produce more medium and high severity cracking. This interaction is shown in the decreased cracking with lower freezing index, and the decreased cracking with higher precipitation. Higher precipitation generally occurs in areas with a more moderate climate without extreme swings in temperature.

9. Predictive models for low severity reflection cracking, medium and high severity reflection cracking, and rutting were developed using the database. These models can be used to estimate the development of distress, and serve as preliminary checks on designs of crack and seat overlay projects. The ability to predict medium and high severity reflection cracking is essential to establishing rehabilitation needs. Rehabilitation of asphalt concrete overlays is typically indicated by an amount of medium and high severity cracks, not low severity. This is important in crack and seat performance as the two levels of cracking are related to very different variables.

APPENDIX A -- DESCRIPTIONS OF SELECTED PROJECTS

A total of 31 bonded overlay uniform sections were surveyed at 11 bonded overlay project sites, and 14 uniform sections from seven unbonded overlay project sites were surveyed. A total of 70 uniform sections were surveyed in 12 States for the crack and seat rehabilitation technique. On the following pages, a description of the location, original pavement design, rehabilitation construction techniques, traffic, environmental conditions and performance are given for five representative bonded concrete overlay projects, five representative unbonded overlay projects, and seven crack and seat with asphalt overlay projects.

The following case studies are included to provide specific descriptions of some of the projects from which the database was developed. Detail is given for each uniform section included at each project site described. On several of the projects, there existed several uniform sections separated on the basis of design variables. There were also several projects that were two-lane two-way highways in which case both lanes are considered truck lanes. For these cases, each direction was considered a separate uniform section on the basis that traffic characteristics may be different and may therefore influence performance.

The projects described are listed below.

<u>BONDED CONCRETE OVERLAYS</u>

- New York, Interstate 81.
- Wyoming, Interstate 25.
- Louisiana, US Route 61.
- Iowa, Interstate 80 (MP 182).
- Iowa, County C17 (Clayton Co.).

<u>UNBONDED CONCRETE OVERLAYS</u>

- Illinois, East-West Tollway.
- Georgia, Interstate 85.
- Michigan, US Route 23.
- Colorado, Interstate 25.
- Pennsylvania, Interstate 376.

<u>CRACK AND SEAT AND ASPHALT OVERLAY</u>

- Illinois, Spring Creek Road (Rockford, IL).
- Illinois, Rockton Road (Rockton, IL).
- Illinois, Lincoln Trail Road (Fairview Heights, IL).
- Illinois, State Route 97.
- Illinois, State Route 101.
- Wisconsin, US Route 14 (Rock County).
- Wisconsin, US Route 14 (Dane and Rock Counties).

BONDED CONCRETE OVERLAYS

NEW YORK, I-81

Location:

The project begins at the North end of the I-481 interchange at North Syracuse, extends north 3 miles [4.8 km], to 1 mile [1.6 km] north of the Cicero interchange with New York State Route 31.

Original Pavement Design:

The original pavement built in 1957, was a six-lane jointed reinforced concrete pavement.(9) The slabs were 9 in [22.9 cm] thick placed directly on the subgrade. The transverse contraction joints were doweled with a joint spacing of 43 ft [13.1 m].(9) No provisions were made for subsurface drainage in the original design.

Bonded Overlay Rehabilitation Design:

The thin-lift, nonreinforced bonded concrete overlay was constructed in 1981. The typical design consisted of a 3-in [7.6 cm] overlay placed directly on the prepared pavement surface.(9) On some deteriorated joints, partial depth removal of the concrete was performed prior to the application of the overlay. At these joints, the overlay thickness may increase up to 6 in [15.2 cm]. The following design and construction procedures were employed for the typical section:

1. Initial surface preparation consisted of cold-milling followed by sandblasting and airblasting to remove remaining debris that may inhibit bonding. Once cleaned and prepared, the pavement was covered with polyethylene sheeting to protect the surface until placement operations began in the area.

2. Just ahead of the paving train, a mixture of water, sand and portland cement was spread as a bonding agent.

3. A 3-in [7.6 cm] lift of low slump portland cement concrete followed the preoverlay preparation.

4. Joints in the overlay were sawed directly above the existing pavement joints.

5. The overlay joints were sealed before the pavement was opened to traffic and as soon as possible during the curing period.

6. About 17 AC pressure relief joints, 7 to 17 ft [2.1 to 5.2 m] long were installed at previous compression failures at the time of the overlay.(9)

Traffic:

The current ADT and percent trucks is as follows:

ADT = 23000
% TRUCKS = 8

Accumulated 18-kip Equivalent Single Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 1.207 million

Environment:

The project, located in central New York State, is subject to a harsh Wet-Freeze environment and receives 39 in [99.1 cm] of annual precipitation.(35) The mean freezing index (accumulated degrees/days below freezing) is approximately 750.(35)

Observed Distress:

The pavement was surveyed in August 1985 and, after 4 years of service, the overlay was performing well. Surveys were performed in both the northbound and southbound lanes and the distress level appeared equivalent in both directions. However, there was a considerable amount of shrinkage cracking over entire slab areas in both lanes in both directions. For the most part this cracking was tight and showed no signs of deterioration.

Several transverse cracks were also observed; these cracks were generally low severity, but within two 1000-ft [305 m] survey sections, one full-lane width medium severity working crack in the southbound lanes and four in the northbound lanes had developed. These cracks are suspected to be reflective cracks from the underlying pavement. No longitudinal cracking was found and the overlay showed no signs of joint related distresses, such as corner breaks and spalling.

The mean faulting of the overlay joints in the northbound drive lane was 0.04 in [0.10 cm] while the southbound drive lane exhibited a mean faulting of 0.05 in [0.13 cm]. Several 6- to 8- ft [1.8 to 2.4 m] full-depth asphalt concrete patches were also found. The patching is not hindering the rideability significantly, although the approach joint faulting on the patches ranged from 0.10 to 0.24 in [0.25 to 0.61 cm].

The pressure relief joints are bulging and allowing contraction joints to open and fault. Therefore they are probably not desirable.

WYOMING, I-25

Location:

The project begins at the north end of the town of Douglas and extends north from milepost 139.63 to milepost 141.30.

Original Pavement Design:

The original pavement was built in 1968. The design consisted of 9-in [22.9 cm] thick jointed plain concrete slabs placed over a 6-in [15.2 cm] crushed stone granular subbase.(42) The joint spacing was random 12-13-19-18 ft [3.7-4.0-5.8-5.5 m] in the northbound lanes, and uniform at 20 ft [6.1 m] in the southbound lanes. The transverse contraction joints were skewed 2.0 ft [0.6 m] per lane, contain no mechanical load transfer devices, and therefore rely on aggregate interlock for load transfer.(42) No provisions were made in the original design for subsurface drainage.

Bonded Overlay Rehabilitation Design:

Wyoming constructed this fully-bonded concrete overlay in 1984. The typical design consisted of a 3-in [7.6 cm] overlay placed directly on the prepared pavement surface. In the southbound lanes a 500-ft [152 m] section of the overlay pavement was also constructed with a 10-ft [3 m] wide, 12-in [30.5 cm] thick retrofit concrete shoulder. On both sections, the overlay construction was identical and the following procedures were employed:

1. Initial surface preparation consisted of cold-milling, followed by airblasting to provide a clean pavement surface.
2. At a maximum distance of 8 ft [2.4 m] in front of the paving operation, a cement/water bonding agent was sprayed onto the cleaned original pavement surface. Specifications called for a bonding agent with a maximum water/cement ratio of 0.62. If the bonding agent showed a minor amount of surface drying prior to the overlay lift, the contractor was allowed to apply a light fogging of water. If excessive drying of the bonding agent was apparent, additional bonding agent was applied.
3. A 3-in [7.6 cm] lift of low-slump portland cement concrete followed the preoverlay preparation.
4. Joints in the overlay were sawed full depth (3 in [7.6 cm]) directly above the existing pavement joints.
5. The joints were sealed prior to opening to traffic.(42)

Traffic:

The current ADT and percent trucks is as follows:

ADT = 4390
% TRUCKS = 27

Accumulated 18-kip Equivalent Single Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 0.081 million

Environment:

The project is located in east central Wyoming, and is subjected to a Dry-Freeze climate and receives 13 in [33 cm] of annual precipitation.(34) The mean freezing index is approximately 620.(34)

Observed Distress:

This project was surveyed in June 1986. At the time the survey was conducted the overlay was in service nearly 2 years. Surveys were conducted in both directions, in order that early performance of the section with the retrofit tied concrete shoulder could be compared to that of the standard section.

Standard section: The standard section was in excellent condition. Very little reflective cracking had appeared in the overlay, just 96 ft of low severity transverse cracking per 1000 ft [96 m/km] of survey. These cracks were generally located at midslab, and are attributed to reflection of cracks from curling stresses that developed in the underlying pavement. Only a total of 16 ft [4.9 m] of longitudinal cracking was observed; two cracks, one on the outer lane and the other on the inner lane, extended about 8 ft [2.4 m] from the leave side of a joint. One corner break was observed on the leave side of an overlay joint, however the cracked overlay concrete did not appear to be debonded. The only evidence of debonding appeared on the leave side of a transverse joint where a 3-4-ft [0.9 to 1.2 m] by 1/2-ft [15.2 cm] wide section along the joint was completely missing. The mean faulting of the outer traffic lane transverse joints was 0.01 in [0.025 cm]. Although three slabs did contain localized shrinkage cracking, in general the concrete surface showed few signs of curing problems. Several localized areas of surface scaling were also observed.

Retrofit shoulder section: On this section, the overlay concrete contained extensive shrinkage cracking, nearly 90 percent of the 500-[152 m]-ft survey section. This is likely due to increased air temperatures during the curing period. The section also exhibited significantly more cracking than the standard section. In the 500-ft [152 m] section, 84 ft [26 m] of low severity transverse cracking was observed. This cracking was also located mainly at midslab. Low severity longitudinal cracking extended 240 ft [73 m] along the inner wheel path of the outer lane. The cracking showed no signs of deterioration and is suspected to be reflected from the underlying slab. No corner breaks were apparent on this section. Although several joints contained medium severity spalling, the problem is not considered to be influencing the bonding of the overlay. The mean faulting of the outer lane transverse joints was 0.01 in [0.025 cm].

LOUISIANA, US 61

Location:

This project begins north of Baton Rouge and extends north approximately 0.8 miles [1.3 km] in the southbound lanes.

Original Pavement Design:

The original pavement was built in 1959. The pavement was a two lane roadway and consisted of 20 ft [6.1 m] jointed plain concrete panels with doweled transverse contraction joints. The slabs were 9 in [22.9 cm] thick, placed over a 6-in [15.2 cm] sand subbase. The entire section was built on a heavy clay embankment.(7)

Bonded Overlay Rehabilitation Design:

The overlay project was constructed during April of 1981. Slab settlement problems and dowel bar misalignment in the contraction joints of the original pavement led to minor slab cracking and pavement damage.(7) Deflection testing showed the pavement to be structurally sound.(7) To design against the existing problems, Louisiana employed several other improvements concurrent with the overlay. The following procedures were employed:

1. A longitudinal subsurface drainage system was added to the pavement prior to the overlay. The system consisted of a 4-in [10.1 cm] slotted pipe placed in a filter-lined, gravel backfilled trench, located along the outer lane/shoulder joint.

2. At joints in which the concrete had spalled up from misaligned dowels, the concrete was removed partial depth and replaced with portland cement concrete prior to pavement surface preparation.

3. Louisiana elected to isolate the overlay section by placing three pressure relief joints, one at each end of the project and the other at the center of the project. The joints were sawed full depth, 4-in [10.1 cm] wide and were sealed with a Styrofoam type insert.

4. Cleaning of the existing transverse joints was performed with a saw blade and compressed air. The reservoirs were sealed with a preformed compression seal. This was done to seal the joints from incompressibles (shot) during surface preparation.

5. Initial surface preparation consisted of a shot blasting operation to remove approximately 1/8 in [0.3 cm] of concrete, followed by air blasting just prior to the application of the bonding agent.

6. The water/cement bonding agent was sprayed onto the pavement surface just ahead of the paving operation. When paving operations lagged behind the bonding agent application, wet burlap was used to cover the applied grout, to prevent the grout from completely hardening.

7. A thin lift of portland cement concrete followed immediately. A minimum thickness of 3 in [7.6 cm] was specified for the overlay, however an average thickness of approximately 4 in [10.2 cm] resulted because of design changes.

8. Overlay joints were sawed directly above the existing pavement joints. The transverse contraction joints were sealed with hot pour sealant, while the pressure relief joints were sawed and sealed with neoprene compression seals.(7)

Traffic:

Current ADT information for this project is given as:

ADT = 11860
% TRUCKS = 15

Accumulated 18-kip Equivalent Single Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 1.200 million

Environment:

The project, located in Louisiana, is subject to a Wet-No Freeze environment and receives 56 in [142 cm] of annual precipitation.(33) The area is not regularly subjected to frost penetration to depths below the subgrade surface.(33)

Observed Distress:

Distress data from two 1000-ft [305 m] survey sections were measured in June 1986. Reflective cracking was not a significant problem on this project. No longitudinal cracking in the paving lanes was observed, but a longitudinal crack had reflected through along the centerline of the entire project. This crack formed because a centerline joint was not sawed, however, the crack was not spalling and appeared to be performing well. Transverse cracks formed close to sawed transverse joints at approximately 12 percent of the joints contained in the survey sections. A disbondment survey indicated that these cracks were located in areas of delamination.(7) The outside edge of approximately 16 percent of the overlay joints experienced some delamination.(7) To alleviate the problem, Louisiana used an epoxy resin to rebond the overlay to the existing pavement just 4 months after construction of the overlay. After 4 years of service 12 percent of the corners had cracked.(7) The surveys in June 1986 after 5 years of service indicate no significant increase in the percentage of cracking in the disbonded areas. No other significant distress was observed, however, there were some small localized areas of surface scaling. The present serviceability of the overlay was rated as 3.7 and the mean faulting of outer lane transverse joints was 0.02 in [0.051 cm].

IOWA, I-80 (Milepost 182)

Location:

The project is located near the city of Grinnel. It begins at milepost 182.00 and extends easterly approximately 9.17 miles [14.7 km] to approximately milepost 191.17.

Original Pavement Design:

The original pavement built in 1964, was a four-lane jointed reinforced concrete pavement with a joint spacing of 76.5 ft [23.3 m].(44) The transverse contraction joints were doweled with 1.25-in [3.2 cm] dowels placed 12 in [30.5 cm] on centers. The reinforced slabs were 10 in [25.4 cm] thick placed over a 4-in [10.2 cm] gravel subbase.(44) Continuous longitudinal drainage pipes were placed along the lane/shoulder joint to facilitate subsurface drainage.(44)

Bonded Overlay Rehabilitation Design:

The thin-lift, nonreinforced bonded concrete overlay was constructed in 1984. The following design and construction procedures were employed for the typical section:

1. Initial surface preparation consisted of cold-milling the pavement surface followed by sandblasting.

2. Prior to the paving operation, a thin spray of cement/water bonding agent was applied to the cleaned surface of the existing pavement.

3. A 4-inch [10.2 cm] lift of portland cement concrete followed the initial preparation.

4. The joints were matched with the existing pavement contraction joints and were sealed prior to opening to traffic.(44)

Traffic:

The pavement is on a heavily traveled route which receives the following daily traffic:

ADT = 14100
% TRUCKS = 33

Accumulated 18-kip Equivalent Single Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 1.270 million

Environment:

The pavement is located in central Iowa and is subjected to a Wet-Freeze environment and receives 35 in [89 cm] of annual precipitation.(32) The mean freezing index is approximately 750.(32)

Observed Distress:

The project was surveyed in July 1985 and at that time the overlay had served traffic for approximately one year. The condition of the overlay was very good. Some reflective cracking had developed, but the majority were low severity "hairline" type cracks. An average of 500 ft [500 m/km] of low severity transverse cracking and 24 ft [24 m/km] of medium severity transverse cracking had developed per 1000 ft of pavement. No significant longitudinal cracking was evident. Several full-depth repairs were encountered in each survey section. These patches were likely placed to repair a reflective cracking problem from the severely "D" cracked underlying pavement. In several instances, where patches were applied in only one lane, a crack propagated through the overlay in the opposite lane at the location of the patch joints. At other locations, inner and outer lane joints were sawed mismatched by up to several feet. In almost every instance a crack developed in the opposite lane at the mismatched location. The survey sections contained no corner breaks, no shrinkage cracking and only one slightly spalled joint. The mean faulting of the drive lane transverse joints was 0.05 in [0.13 cm].

Even though this project has had only one year of service, it is performing similar to an identical project on Iowa I-80 constructed in 1979 (see Project C, table 4.3.1).

IOWA, County Route C17

Location:

This well documented project is located in the eastern portion of Clayton County Iowa. It begins at the town of Clayton and extends westerly a distance of 1.3 miles [2.1 km].

Original Pavement Design:

The original pavement was a standard design constructed in 1968. The nonreinforced slabs were 6 in [15.2 cm] thick placed directly on the subgrade. The transverse contraction joints were sawed at a 40 ft [12.2 m] spacing and were dowelled with 0.75-in [1.9 cm] dowels placed 12 in [30.5 cm] on centers. Expansion joints were placed at 120-ft [36.6 m] intervals.(5,44) No provision was made for subsurface drainage in the original design.

Bonded Overlay Rehabilitation Design:

The bonded concrete overlay sections placed on county route C17 in 1977 were part of a research project to evaluate the effectiveness, and constructability of this technique.(5) As part of the research, 2-, 3-, 4-, and 5-in [5.1, 7.6, 10.2, and 12.7 cm] overlay thicknesses were constructed with varying surface preparation methods and use of reinforcement. Patching of the original pavement was not performed in the reinforced sections, because the reinforcement was being tested as an alternative to preoverlay patching.(5) Preoverlay repair for each of the nonreinforced sections consisted of full-depth and partial-depth repairs of badly distressed areas.

For the analysis of the performance data, the Clayton county project has been divided on the basis of design variables. Therefore included in the database are seven sections of alternate design. For each section the construction procedures will be discussed.

SECTIONS 1 & 2.

1. Initial surface preparation consisted of sandblasting the pavement surface. Specifications on the equipment for this method required that enough capacity be generated to remove paint markings and adequately clean the pavement.(5,44)

2. Just ahead of the paving operation a mixture of sand cement and water was spread as a bonding agent. The mixture was spread with brooms and squeegees. This application technique presented some problems with uniformity of application.(5) The squeegee was reported to leave too thin a film of grout that would dry very rapidly. Brooming proved to be the better of the two application techniques, but still did not provide a uniform grout application.(5)

3. Following the application of bonding agent, a thin 3-in [7.6 cm] lift of portland cement concrete was laid on the prepared surface.

4. In section 2, a small amount of reinforcement was placed in the overlay. Number four bars, 12 ft [3.7 m] in length were placed in the transverse direction, staggered at 30-in [76.2 cm] centers.(5,44) The purpose of the reinforcement was to test the adequacy of steel as a substitute for full depth repair prior to overlay.

5. Transverse joints were sawed full depth over the existing pavement joints after sufficient curing had taken place. The longitudinal joint was not sawed in either section.(5)

SECTIONS 3 & 4.

1. Initial surface preparation consisted of cold milling the pavement. Specifications called for a 0.25-in [0.6 cm] depth of removal except at transverse joints that were faulted in excess of this amount. At joints of this nature, the high-side slab was planed to the depth of the step-off.(5)

2. Again just ahead of the paving operation a mixture of sand,cement and water was spread as a bonding agent.

3. Following the application of bonding agent, a 5-in [12.7 cm] lift of portland cement concrete was laid on the prepared surface.

4. In section 4 the same amount of reinforcement was placed as in section 2.

5. Transverse joints were sawed directly above the existing pavement joints, but the longitudinal joint was not sawed.

SECTION 5.

1. Initial surface preparation consisted of sandblasting followed by application of the sand-cement-water bonding agent to the surface. The same specifications and procedures were used on this section as were used in sections 1 and 2.(5)
2. Following the application of the bonding agent, a 4-in [10.2 cm] lift of portland cement concrete was laid on the prepared surface.
3. Transverse joints were sawed directly above the existing pavement joints, but the longitudinal joint was not sawed.

SECTION 6.

1. Initial surface preparation consisted of cold milling followed by application of the sand-cement-water bonding agent to the surface. The same cold milling procedures and specifications were used on this section.(5)
2. Following the application of the bonding agent, a 4-in [10.2 cm] lift of portland cement concrete was laid on the prepared surface.
3. This section contained the transverse reinforcement.
4. Transverse joints were sawed directly above the existing pavement joints, but the longitudinal joint was not sawed.

SECTION 7.

1. Initial surface preparation consisted of the same operation as in section 5 (sandblasting).(5)
2. Again, just ahead of the paving operation a mixture of sand cement and water was spread as a bonding agent.
3. Following the application of bonding agent, a very thin 2-in [5.1 cm] lift of portland cement concrete was laid on the prepared surface.
4. Transverse joints were sawed full depth over the existing pavement joints after sufficient curing had taken place.

Traffic:

Route C17 is a truck haul route which has an average daily traffic and percent trucks estimated as:

ADT = 651
% TRUCKS = 43

Accumulated 18-kip Equivalent Single Axle Loads on the overlay are estimated as:

ESAL = 0.100 million (eastbound lane)
ESAL = 0.004 million (westbound lane)

Environment:

The project is located in east central Iowa and is subjected to a Wet-Freeze environment which receives 33 in [84 cm] of annual precipitation.(32) The mean freezing index is approximately 750.(32)

Observed Distress:

Due to the long joint spacing and heavily loaded trucks using the pavement, there existed an extensive amount of slab cracking on the existing pavement prior to overlay. The overlay sections at Clayton county were surveyed in July 1985, approximately 7 years since construction. Each section shows a considerable amount of low and medium severity transverse cracking and several sections are exhibiting high severity cracks. A significant amount of longitudinal cracking has also developed in each section. A definite trend in the level of distress between the eastbound lanes and the westbound lanes is found. This effect is attributed to the truck traffic using the pavement. In the eastbound direction many trucks travel fully loaded, while in the westbound lane most trucks travel empty.

The following table gives a summary of cracking for each section at Clayton county. It is interesting to note that the thinnest overlay section (2-in [5.1 cm] nonreinforced) contains the lowest amount of total cracking. This result is of course contrary to what would be expected, however, it is likely attributed to the condition of the underlying pavement. After 7 years of service it is doubtful that any cracks in the underlying pavement have not reflected through the overlay. Surveys conducted by Darter and Barenberg in 1979 showed that, at that time, practically all cracks in the original slab had reflected through the overlay.(3) Thus, it is apparent that section 7 (2-in [5.1 cm] nonreinforced) was placed over a portion of the underlying pavement containing relatively fewer broken slabs than the other sections.

It is also interesting to compare the performance of the reinforced sections with the performance of the nonreinforced sections. Reinforced sections, which received no initial pavement patching, were "sandwiched" between the sections of similar thickness containing no reinforcement. Therefore it is likely that in these sections the underlying pavement was in the same condition. The reinforcement was not effective in reducing reflective cracking through the overlay, as the level of cracking (normalized to 1000 ft [305 m] of roadway in the drive lane) was greater for each reinforced section. Also, much of the cracking in the reinforced sections did deteriorate to medium and high severity.

3-in [7.6 cm] Reinforced	4-in [10.2 cm] Reinforced	5-in [12.7 cm] Reinforced
0 % LOW	26 % LOW	76 % LOW
100 % MED	63 % MED	24 % MED
0 % HIGH	11 % HIGH	0 % HIGH

None of the sections appeared to be delaminated, although some small areas of patching were found on sections 1, 4 and 5. These patches replaced small broken out pieces of the overlay. The joints on the overlay sections were performing well. Some secondary cracking adjacent to the saw cut was found on 25 percent of the sawed transverse joints. This type of distress was more prevalent in the thinner 2- and 3-in [5.1 and 7.6 cm] overlay sections. No shrinkage cracking problems were observed.

UNBONDED CONCRETE OVERLAYS

ILLINOIS, (I-88) East-West Tollway

Location:

The project begins on I-88 (East-West Tollway) near Naperville at approximately milepost 142 and extends 5 miles [8 km] to milepost 147.

Original Pavement Design:

The original pavement built in 1958, was a four-lane jointed reinforced concrete pavement.(23) The slabs were 10-in [25.4 cm] thick placed on 4 in [10.2 cm] of gravel-sand subbase and 10 in [25.4 cm] of select subgrade. The transverse contraction joints were spaced at 50 ft [15.2 m] and were dowelled with 1.0-in [2.5 cm] diameter dowels spaced 12 in [30.5 cm] on centers.(23) No provisions were made for subsurface drainage in the original design.

Unbonded Overlay Rehabilitation Design:

Considerable effort was spent on preoverlay repair and concurrent improvements. The pavement was overlayed in 1969 with a 3-in [7.6 cm] course of asphalt concrete.(23) Prior to the placement of the unbonded overlay in 1981, the asphalt overlay material was removed with a cold milling machine. Once exposed, the concrete pavement was patched full depth at various locations where prior failures, such as blow-ups and joint deterioration had been previously patched by maintenance crews, or at unpatched joints showing severe deterioration.(23) The design of the unbonded overlay section consisted of an 8-in [20.3 cm] plain jointed overlay constructed on approximately 0.5-in [1.3 cm] bond breaking layer which was placed directly on the existing concrete pavement.(23) In an effort to deter the build-up of excessive compressive stresses in the 8-in [20.3 cm] overlay from unequal expansion between the overlay and the underlying pavement, pressure relief joints were constructed at 1500-ft [457 m] intervals along the overlay section.(23) Portland cement concrete grade beam expansion joints were constructed in the existing pavement prior to placement of the bond breaking layer; the overlay was placed continuously over these joints, and were then sawed through the overlay after sufficient curing had taken place. In general, the following design and construction procedures were employed for the typical section:

1. After removal of the existing overlay and placement of full-depth patches, the exposed concrete pavement was surfaced with a bituminous prime coat and then a sand-asphalt bond breaking layer. This layer was intended to provide a slip plane for the overlay pavement.

2. A nominal 8-in [20.3 cm] lift of portland cement concrete followed the application of the bond breaking layer. Early observation during the construction of pressure relief joints showed evidence that the overlay concrete was bonding to the sand-asphalt layer. To counter act this bonding action, the bond-breaking layer was sprayed with water just ahead of the paving operation. When after a few days no signs of reflection cracking was found on the areas in which the bonding was initially discovered, the application of water was discontinued for subsequent paving.

3. Contraction joints were sawed into the overlay pavement at random intervals from 12 to 18 ft [3.7 to 5.5 m]. Placement of these joints as made to ensure that no overlay contraction joint would occur within 2 ft [0.6 m] of cracks and joints in the underlying pavement. This effectively created sleeper slabs beneath each overlay contraction joint. The designers relied on this for load transfer and did not use dowels in these joints.(23)

Traffic:

The current ADT and percent trucks is as follows:

ADT = 30500
% TRUCKS = 24

Accumulated 18-kip Equivalent Single Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 4.516 million

Environment:

The project is located west of Chicago and is subjected to a Wet-Freeze environment. The area receives 36 in [91 cm] of annual precipitation and the mean freezing index (accumulated degree/days below freezing) is approximately 700.(37)

Observed Distress:

The pavement was surveyed in July 1985 and, after 4 years of service, the overlay was performing very well. Surveys were performed in both the eastbound and westbound lanes and the pavement appeared to be in slightly worse condition in the westerly direction. There was no transverse fatigue cracking in the lanes of either direction, however some longitudinal cracking was found in the outer lane in the westerly direction. This cracking, located in the outer wheelpath, was tight and showed no signs of deterioration. No corner breaks were observed, indicating no loss of support beneath the overlay slabs. The joints showed no signs of significant distresses, such as corner or transverse spalling. The mean faulting of the overlay joints in the eastbound drive lane was 0.05 in [0.13 cm] while the westbound drive lane exhibited a mean faulting of 0.08 in [0.20 cm]. The differing conditions between the easterly and westerly lanes may be most likely attributed to the joint sealant conditions. There was a 75 percent failure in the sealant on the first 500-ft [152 m] sample unit and a 25 percent failure rate on the second 500-ft [152 m] sample unit. The failure mode of the sealant was adhesion failure with the joint reservoir walls. Although there was such a poor performance of the sealant, no evidence of pumping was found in either sample unit. This is a significant finding that exhibits the beneficial effects of mismatching joints in the overlay with those in the underlying slab. Through mismatching the joint locations, there is no direct access for the subbase and/or subgrade fines to escape through the overlay.

GEORGIA, I-85

Location:

The project is located on I-85 in Gwinnet County near the town of Braselton about 30 miles [48.3 km] north of Atlanta. The project extends from milepost 123 to approximately milepost 123.25.

Original Pavement Design:

The original pavement was built in 1960. The design consisted of 9-in [22.9 cm] thick jointed plain concrete slabs placed over a 3-in [7.6 cm] premixed bituminous stabilized crushed aggregate base course and a soil-aggregate subbase.(22) Transverse contraction joints were spaced at 30-ft [9.1 m] centers and relied on aggregate interlock for load transfer.(22) Slotted 6-in [15.2 cm] diameter drainage pipes were placed beneath the shoulder in all cut areas.(22)

Unbonded Overlay Rehabilitation Design:

The pavement was tested with a Dynaflect prior to the prepatory work for the overlay.(22) The data was used to determine where subsealing of the existing pavement slabs was necessary. Shattered slabs were removed and replaced with undowelled full-depth patches. The overlay consisted of a 6-in [15.2 cm] plain jointed pavement, in which a section with 30-ft [9.1 m] joint spacing, where joints were constructed directly over existing joints, and a section with 15-ft [4.6 m] joint spacing, where joints were matched with the existing joints and also constructed at the midpoint between existing joints, were constructed. The overlay joints that matched the existing joints were dowelled with 1 1/8-in [2.86 cm] dowels, but did not contain dowels when constructed at the mid-slab location.(22) Ten-ft [3 m] plain tied concrete shoulders on the outer lane and 4-ft [1.2 m] plain tied concrete shoulders on the inner lane were also included in the design. The following design and construction procedures were employed in the construction of this overlay in 1975:

1. After preoverlay repair was completed, the dowels were placed in baskets and the assemblies were positioned and tacked in place. Problems with contact and movement of the dowel assemblies during the initial paving operation prompted adjustments to the paver. However, most of the section had been placed before the problem had been diagnosed and properly solved.

2. Just before paving operations began, the exposed concrete pavement was coated with a coat of curing compound. The application of this compound was to be used as the bond breaking layer between the new overlay concrete and the existing surface.

3. A 6-in [15.2 m] lift of portland cement concrete followed the application of the bond breaking layer.

4. The paving of the shoulder followed that of the mainline pavement. The shoulder was not keyed, but was tied with tie bars spaced on 30-in [76.2 cm] centers.

5. Contraction joints were sawed into the mainline overlay pavement in the locations described above. Transverse joints in the shoulders were sawed at 30-ft [76.2 cm] intervals.

6. Transverse joints were sealed with an open-cell neoprene joint sealant and the longitudinal shoulder joint was sealed with hot-pour asphalt sealant.(22)

Traffic:

The current ADT and percent trucks is as follows:

ADT = 10922
% TRUCKS = 25

Accumulated 18-kip Equivalent Single Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 6.736 million

Environment:

The project, located in central Georgia, is subject to a Wet-No Freeze environment and receives 56 in [142 cm] of annual precipitation.(36) The mean freezing index (accumulated degrees/days below freezing) is approximately zero, thus the area does not regularly receive freezing below the subgrade surface.(36)

Observed Distress:

The pavement was surveyed in January 1986 in both of the southbound lanes on both the 30-ft [9.1 m] joint spacing and 15-ft [4.6 m] joint spacing sections. A 645-ft [196 m] sample unit was taken on the 15-ft [4.6 m] joint spacing section, and a 630-ft [192 m] sample unit on the 30-ft [9.1 m] section. After 10 years of service, both sections contained significant cracking, with the 30-ft [9.1 m] section containing 180 ft/ 1000 ft [180 m/km] and the 15-ft [4.6 m] section contained 285 ft/ 1000 ft [285 m/km] of low severity cracking. On the 30-ft [9.1 m] section, 53 percent of the slabs were cracked near the midslab region. Typically only one crack formed at this location, but two cracks in the midslab region were also noted. This cracking is attributed to differential curling of the overlay and the underlying pavement. None of the cracks, however, had deteriorated into working cracks. The cracking noted on the 15-ft [4.6 m] section was also only low-severity nondeteriorated cracks. The cracking was mostly located near the joints where problems were encountered during the paving of the overlay. Although very little longitudinal cracking was noted on the outer lane of the 30-ft [9.1 m] section, just 16 ft/ 1000 ft [16 m/km], the inner lane contained just over 100 ft/ 1000 ft [100 m/km] of pavement. Not nearly a marked difference was noted on the 15-ft [4.6 m] section where the inner lane exhibited 145 ft/ 1000 ft [145 m/km] and the outer lane only 96 ft/ 1000 ft [96 m/km] of pavement. The longitudinal cracking is also attributed to the curling phenomena. The average faulting was not significant as just 0.01 in [0.025 cm] on the 30-ft [9.1 m] section and 0.03 in [0.08 cm] on the 15-ft [4.6 m] section. No other structural related problems were evident. The surface on both sections showed some wear in isolated areas, but in general was showing good performance.

MICHIGAN, US 23

Location:

The project is located near the town of Dundee and extends from station 650+00 (approximately milepost 10.0) to station 1025+00 (approximately milepost 17.1). The overlay was constructed in both the northbound and the southbound lanes.

Original Pavement Design:

The original pavement was constructed and opened to traffic in 1959. The pavement was jointed reinforced concrete with dowelled joints spaced at 100 ft [30.5 m].(45) The dowels were 1.25-in [3.18 cm] diameter spaced 12 in [30.5 cm] on centers. The slabs were 9 in [22.9 cm] thick placed over a 4-in [10.2 cm] cement-stabilized subbase and 10 in [25.4 cm] of crushed granular material.(45) No provisions of subsurface drainage were made in the original design.

Unbonded Overlay Rehabilitation:

The reinforced unbonded concrete overlay was constructed in 1984. The design consisted of 7-in [17.8 cm] reinforced slabs with a 41-ft [12.5 m] joint spacing, placed on a sand-asphalt bond breaking layer.(45) Subsurface drainage was provided in the form of 4-in [10.2 cm] geotextile-wrapped pipe underdrain placed at the depth of the granular subbase.(45) Eight-ft [2.4 m] wide, 7-in [17.8 cm] thick reinforced tied concrete shoulders were also provided. The following design and construction procedures were employed:

1. The existing concrete pavement was surfaced with a sand-asphalt bond breaking layer. The application rates for this material varied from the center of the pavement out towards slab edges, in order to compensate for the removal of the parabolic crown built into the existing slabs. The estimated thickness is about 0.75 in [1.9 cm] at the center to about 1.5 in [3.8 cm] at the edges. This layer was therefore intended not only to provide a slip plane, but also to act as a "level-up" course.

2. Load transfer assemblies were placed and fastened to the existing concrete at the locations established for transverse contraction joints. These assemblies consisted of 1.25-in [3.2 cm] diameter dowels, 18 in [45.7 cm] long, placed at 12 in [30.5 cm] on centers.

3. A 7-in [17.8 cm] lift of portland cement concrete followed the application of the bond breaking layer. Reinforcement was placed at approximately mid-depth. The lanes were tied with 24-in [61 cm] #5 tie bars spaced at no more than 44 inches [111.8 cm] center to center.

4. The shoulders were tied to the existing pavement using the same tie bars as used to tie the lanes, however were spaced at 55 in [140 cm] on centers. The shoulders were constructed at the same cross-slope as the lanes.

5. Contraction joints were sawed into the overlay pavement at locations not to exceed 41 ft [12.5 m]. Placement of these joints was made to ensure that no overlay contraction joint would occur within 3 ft [0.9 m] of working cracks (crack open greater than 1/8 in [0.32 cm]) and joints in the underlying pavement.

6. After sawing the joint reservoirs, the joints were washed free of slurry from the sawing operation with a water spray. The transverse contraction joints were sealed with a neoprene joint sealant and the longitudinal lane and shoulder joints were sealed with hot-pour asphalt.(45)

Traffic:

The current ADT and percent trucks is as follows:

ADT = 19400
% TRUCKS = 17

Accumulated 18-kip Equivalent Single Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 0.380 million

Environment:

The project is located in south eastern Michigan and is subjected to a Wet-Freeze environment. The area receives 33 in [84 cm] of annual precipitation and the mean freezing index (accumulated degree/days below freezing) is approximately 500.(40)

Observed Distress:

The project was surveyed in late July 1985 in both the north and southbound directions. Two 1000-ft [305 m] sample units were taken in the northbound lanes and one 1000-ft [305 m] sample unit in the southbound lanes. At the time of the survey, the overlay performance was excellent. No cracking was observed on the shoulder, outer lane or inner lane in either direction. The concrete surface which had been tined, was in perfect condition with no surface defects. The mean outer lane transverse joint fault in the northbound direction was 0.02 in [0.051 cm], while the inner lane average faulting was 0.01 in [0.025 cm]. In the southbound lanes, the mean outer and inner lane transverse joint faulting was 0.01 in [0.025 cm]. The joints were sealed tightly with a neoprene joint sealant. The shoulders were in excellent condition; the joints were sealed tightly and exhibited a mean of 0.03 in [0.08 cm] of faulting in the northbound direction and a mean of 0.00 inches in the southbound lanes. The mean lane/shoulder drop-off was just 0.03 in [0.08 cm].

COLORADO, I-25

Location:

The project is located north of Denver near the town of Mead. The overlay extends from approximately milepost 246 (station 561+00) to milepost 253 (station 221+50).

Original Pavement Design:

The original pavement was built in 1964. The pavement was plain jointed with an average contraction joint spacing of 20 ft [6.1 m]. These joints were not dowelled and thus relied on aggregate interlock for load transfer.(50) Slabs were constructed 8 in [20.3 cm] thick and were placed over a 6-in [15.2 cm] crushed granular base course. This pavement system was placed on a course grained subgrade soil, with no provision of subsurface drainage.(50)

Unbonded Overlay Design:

Within the locations described above, three overlay sections were constructed with differing designs in the summer of 1985. Two overlay thicknesses were employed, 6.25 in [15.9 cm] and 7.75 in [19.7 cm].(50) The use of tied concrete shoulders was also employed. The sections will herein be referred to as sections A, B and C. Section A consisted of a 6.25-in [15.9 cm] overlay with tied shoulders, on section B a 7.75-in [19.7 cm] overlay was constructed without tieing the shoulders and section C consisted of a 7.75-in [19.7 cm] overlay with tied shoulders. Joints spacing on the overlay was a random 14-13-15-12 ft [4.3-4.0-4.6-3.7 m] and did not contain dowels.(50) The following procedures were employed in constructing the overlay:

1. The surface of the existing pavement was swept of debris prior to placement of an asphalt concrete bond breaking layer. This layer was constructed 0.5 in [1.3 cm] thick.

2. The overlay was paved to the thicknesses as described above. The lanes were tied with 30-in [76.2 cm] #4 tie bars spaced 30 in [76.2 cm] on centers.

3. Where tied shoulders were employed, the shoulders were also tied to the mainline pavement with 30-in [76.2 cm] #4 tie bars spaced 30 in [76.2 cm] on centers. Shoulders were constructed 10-ft [3.0 m] wide on the outer lane and 4-ft [1.2 m] wide on the inner lane. The shoulders were paved at a steeper cross-slope than the mainline pavement.

4. Joints were sawed in the overlay and shoulders at a skew of 2 ft [0.6 m] per lane (12 ft [3.7 m]). The overlay joints were constructed as weakened-plane joints and were sawed to match those on the lanes.(50)

Traffic:

The current ADT and percent trucks is as follows:

ADT = 25100
% TRUCKS = 16

Accumulated 18-kip Equivalent Single Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 0.920 million

Environment:

The project is located in a Dry-Freeze environment. The area receives only 12 in [30 cm] of annual precipitation and the mean freezing index (accumulated degree/days below freezing) is approximately 250.(39)

Observed Distress:

The surveys on this pavement were performed in late June of 1986. In each section, 1 500-ft [152 m] sample unit was taken. The overlay was only in service for 1 year at that time, therefore this limits the development of significant fatigue and environmental related distress.

SECTION	OVERLAY THICKNESS	SHOULDER
A	6.25 in [15.9 cm]	TIED
B	7.75 in [19.7 cm]	UNTIED
C	7.75 in [19.7 cm]	TIED

There was no evidence of cracking in either of the three sections. The faulting in the outer lane ranged from 0.00 in on section B to just 0.01 in [0.025 cm] on section A and C. On the inner lane, the faulting was 0.01 [0.025 cm] on both sections B and C, and 0.00 in on section A. The joints were not spalled, and the concrete showed no signs of surface or mix related defects. The shoulders on sections A and C were performing very well, although on section C there were 3 transverse cracks that had developed at the location of joints in the mainline pavement. It was apparent that these cracks had developed prior to the joint sawing operation and were left to perform as contraction joints, because no reservoir was sawed in these locations.

PENNSYLVANIA, I-376

Location:

The project is located in eastern Pittsburgh. The overlay extends from milepost 4.5 to milepost 12.0.

Original Project Design:

The original pavement constructed in 1946, was a four-lane jointed reinforced concrete pavement and lasted until 1983.(51) The slabs were 10 in [25.4 cm] thick placed on 8 in [20.3 cm] of crushed aggregate subbase. Load transfer was provided in the transverse contraction joints by 1.25-in [3.2 cm] diameter dowels spaced 12 in [30.5 cm] on centers.(51) The slabs were 90-ft [27.4 m] long and reinforced with welded wire fabric. Longitudinal drainage pipes were installed at the shoulders continuously along the project.(51)

Unbonded Overlay Design:

The overlay was constructed in 1983. Full-depth retrofit concrete shoulders were designed as part of the overlay. The overlay slabs were 8-in [20.3 cm] thick with a joint spacing of 30.75 ft [9.4 m].(51) The overlay joints contained 1.25-in [3.2 cm] diameter dowels on 12 in [30.5 cm] centers. The following procedures were employed in constructing the overlay:

1. Onto the surface of the existing pavement an asphalt concrete bond breaking layer was applied to a thickness of approximately 1.0 in [2.5 cm]. As a further means by which to break the bond between the existing pavement and the new overlay, polyethylene sheeting was placed on top of that layer.

2. The overlay was paved to a thickness of 8 in [20.3 cm]. The lanes were tied with 30-in [76.2 cm] #5 tie bars spaced 30 in [76.2 cm] on centers.

3. The shoulders were also tied to the mainline pavement with 30-in [76.2 cm] #4 tie bars spaced 30 in [76.2 cm] on centers. Shoulders were constructed 10-ft [3.0 m] wide on the outer lane and 4-ft [1.2 m] wide on the inner lane. The shoulders were paved at a steeper cross-slope than the mainline pavement.

4. Joints were sawed in the overlay and shoulders at a skew of 2 ft [0.6 m] per lane (12 ft [3.7 m]). Sealant was placed in the joints prior to opening to traffic.(51)

Traffic:

The current ADT and percent trucks is as follows:

ADT = 67500
% TRUCKS = 8

Accumulated 18-kip Equivalent Single-Axle Loads on the outer lane of the overlay are estimated as:

ESAL = 1.822 million

Environment:

The project is located in a Wet-Freeze environment. The area receives 36 in [0.9 m] of annual precipitation and the mean freezing index (accumulated degree/days below freezing) is approximately 150.(41)

Observed Distress:

The overlay on this route was surveyed in late August of 1985. Surveys were conducted in both directions. At that time, the overlay contained a significant amount of cracking. In the eastbound lanes, two 1000-ft [305 m] sample units were taken, both located in sections of cut of between 16 and 40 ft [4.9 and 12.2 m]. There was an average of 162 ft of low severity transverse cracking per 1000 ft [162 m/km] of pavement in the outer lane, and 60 ft per 1000 ft [60 m/km] in the inner lane. In the westerly direction, two sample units were taken, one in a similar cut section to those in the easterly direction, and one in a section at grade. The amount of transverse cracking in the cut section was 110 ft per 1000 ft [110 m/km] of low severity in the outer lane and 90 ft [90 m/km] in the inner. This is similar to that found in the east lanes. In the section built at the in-situ gradeline, there was slightly more low severity transverse cracking, 384 ft per 1000 ft [384 m/km] in the outer lane and 30 ft per 1000 ft [30 m/km] in the inner lane. The cracks were almost exclusively located at midslab and were not found on the outer lane only, which indicates that they had developed due to curling stresses. In either direction the transverse joint faulting of the outer lane joints was just 0.04 in [0.10 cm]. The shoulders experienced tremendous movement, both heaving and settling.

SAMPLE UNIT	DIRECTION	LANE/SHOULDER DROP-OFF
1	East	0.18 in [0.46 cm] Settlement
2	East	0.63 in [1.60 cm] Heave
1	West	0.52 in [1.32 cm] Settlement
2	West	0.07 in [0.18 cm] Heave

Although no direct correlation could be made to any of the measurements and observations of other distresses or conditions, the nonuniform movement of the shoulder slabs indicates a frost heave problem. The tie bars along the lane/shoulder joint are most likely failed due to the movement as well. Low severity longitudinal cracking on the average of 20 ft per 1000 ft [20 m/km] of pavement was found on the sample units in the easterly direction, while an average of 62 ft per 1000 ft [62 m/km] of pavement of low severity transverse cracking was found in the westerly direction.

CRACK AND SEAT AND ASPHALT OVERLAY

ILLINOIS, Spring Creek Road

Location:

The project, located in Rockford, IL, begins just east of Stone Ridge Drive and extends approximately 1.67 miles [2.7 km] to the east. The Illinois Department of Transportation regularly surveys the project between Driftwood Street and El Rancho Street near Eisenhower High School. The sample units for this study were selected near the IDOT location.

Original Pavement Design:

The original pavement was constructed in 1946 as a 6-in [15.2 cm] undowelled JPCP with a joint spacing of 50 ft [15.2 m]. The slabs were placed directly on the subgrade. The project has a granular shoulder. No provisions were made for subsurface drainage in the original design.

Crack and Seat and Asphalt Overlay Design:

Deteriorated portions of the pavement were repaired with asphalt concrete before the cracking operation was initiated. The original pavement was cracked with a pile drive hammer into 2-ft by 2-ft [0.6 m by 0.6 m] pieces. A 50-ton [45400 kg] pneumatic roller was then used to seat the concrete pieces. The overlay consisted of a 3-in [7.6 cm] asphalt concrete overlay. Also, an interlayer of asphalt-saturated geosynthetic fabric was placed between the binder and surface course. This rehabilitation was conducted in 1981.

Traffic:

The current ADT and percent trucks is as follows:

ADT = 20640
% TRUCKS = 2.5

Accumulated 18-kip [80 kN] ESALs on the outer lane are estimated as:

ESAL = 0.264 million

Environment:

The project, located in northern Illinois, is subject to a harsh Wet-Freeze environment and receives 37 in [94 cm] of annual precipitation. The mean freezing index (accumulated degree-days below freezing) is approximately 800.

Observed Distress:

The project was 4 years old at the time of survey and assigned a PSR of 3.8 by the survey crew. Two sample units were chosen; one in both the eastbound and westbound directions of travel. The pavement was evaluated for all flexible pavement distress types with reflective cracking and rutting being the most useful distress quantities collected.

The eastbound direction had a total of 95 ft/1000 ft [95 m/km] of reflective cracking, 47 ft/1000 ft [47 m/km] of low severity and the remainder being medium severity. Outer lane rut depths were measured in both the inner and outer wheelpaths. The outer wheelpath had an average rut depth of 0.11 in [0.3 cm], while the inner wheelpath had 0.03 in [0.08 cm]. The westbound direction had a total of 90 ft/1000 ft [90 m/km] of reflective cracking, 42 ft/1000 ft [42 m/km] of low severity and the remainder being medium severity. The outer wheelpath had an average rut depth of 0.08 in [0.2 cm], while the inner wheelpath had no rutting.

ILLINOIS, Rockton Road

Location:

The project, located in Rockton, IL, begins at the Rock River Bridge and extends approximately 3.4 miles [5.5 km] to the west.

Original Pavement Design:

The original pavement was constructed in 1932 as a 7.5-in [19.1 cm] undowelled JPCP with a joint spacing of 30 ft [9.1 m]. The slabs were placed directly on the subgrade. The project has a turf shoulder. No provisions were made for subsurface drainage in the original design.

Crack and Seat and Asphalt Overlay Design:

Deteriorated portions of the pavement were repaired with asphalt concrete before the cracking operation was initiated. The original pavement was cracked with a whip hammer into 2-ft by 2-ft [0.6 m by 0.6 m] pieces. A 50-ton [45400 kg] pneumatic roller was then used to seat the concrete pieces. It was unknown whether the slab reinforcement was broken. The overlay consisted of a 4-in [10.2 cm] asphalt concrete overlay. This rehabilitation was conducted in 1984.

Traffic:

The current ADT and percent trucks is as follows:

ADT = 2164
% TRUCKS = 2

Accumulated 18-kip [80 kN] ESALs on the outer lane are estimated as:

ESAL = 0.008 million

Environment:

The project, located in northern Illinois, is subject to a harsh Wet-Freeze environment and receives 37 in [94 cm] of annual precipitation. The mean freezing index (accumulated degree-days below freezing) is approximately 800.

Observed Distress:

The project was 1 year old at the time of survey and assigned a PSR of 4.0 by the survey crew. Two sample units were chosen; one in both the eastbound and westbound directions of travel. The pavement was evaluated for all flexible pavement distress types with reflective cracking and rutting being the most useful distress quantities collected.

The eastbound direction had a total of 110 ft/1000 ft [110 m/km] of reflective cracking, all low severity. Outer lane rut depths were measured in both the inner and outer wheelpaths. The outer wheelpath had an average rut depth of 0.08 in [0.2 cm], while the inner wheelpath had no rutting. The westbound direction had a total of 138 ft/1000 ft [138 m/km] of reflective cracking, also all low severity. The outer wheelpath had an average rut depth of 0.04 in [0.1 cm], while the inner wheelpath had no rutting.

ILLINOIS, Lincoln Trail Road

Location:

The project, located in Fairview Heights, IL, begins just left of the "T" intersection of Bunkum Road and Lincoln Trail Road from station 330+00 to 341+00.

Original Pavement Design:

The original pavement was constructed in 1926 as an 8.25-in [21.0 cm] undowelled JPCP with a joint spacing of 50 ft [15.2 m]. The slabs were placed directly on the subgrade. The project has a granular shoulder. No provisions were made for subsurface drainage in the original design. A 2-in [5.1 cm] asphalt concrete overlay was placed in 1956.

Crack and Seat and Asphalt Overlay Design:

Deteriorated portions of the pavement were not repaired before the cracking operation was initiated. The original pavement was cracked with a whip hammer into 2-ft by 2-ft [0.6 m by 0.6 m] pieces. A 50-ton [45400 kg] pneumatic roller was then used to seat the concrete pieces. It was unknown whether the slab reinforcement was broken. The overlay consisted of a 4.5-in [11.4 cm] asphalt concrete overlay. This rehabilitation was conducted in 1983.

Traffic:

The current ADT and percent trucks is as follows:

ADT = 5010
% TRUCKS = 2.8

Accumulated 18-kip [80 kN] ESALs in the outer lane are estimated as:

ESAL = 0.050 million

Environment:

The project, located in southwestern Illinois, is subject to a harsh Wet-Freeze-Thaw environment and receives 37 in [94 cm] of annual precipitation. The mean freezing index (accumulated degrees/days below freezing) is approximately 0.

Observed Distress:

The project was 2 years old at the time of survey and assigned a PSR of 4.0 by the survey crew. Two sample units were chosen; one in both the eastbound and westbound directions of travel. The pavement was evaluated for all flexible pavement distress types with reflective cracking and rutting being the most useful distress quantities collected.

The eastbound direction had a total of 65 ft/1000 ft [65 m/km] of reflective cracking, 12 ft/1000 ft [12 m/km] of low severity and the remaining being medium severity. Outer lane rut depths were measured in both the inner and outer wheelpaths. The outer wheelpath had an average rut depth of 0.03 in [0.08 cm], while the inner wheelpath had 0.05 in [0.13 cm]. The westbound direction had a total of 28 ft/1000 ft [28 m/km] of reflective cracking, all medium severity. The outer wheelpath had an average rut depth of 0.10 in [0.25 cm], while the inner wheelpath had 0.08 [0.20 cm].

ILLINOIS, State Route 97

Location:

The project, located in Oakford, IL, begins at station 895+00 and extends to station 915+00 on this rural road.

Original Pavement Design:

The original pavement was constructed in 1939 as an 8-in [20.3 cm] JRCP with a joint spacing of 50 ft [15.2 m]. The slabs were placed directly on the subgrade. The project has a granular shoulder. No provisions were made for subsurface drainage in the original design.

Crack and Seat and Asphalt Overlay Design:

Deteriorated portions of the pavement were not repaired before the cracking operation was initiated. The original pavement was cracked with a whip hammer into 2-ft by 2-ft [0.6 m by 0.6 m] pieces. A 50-ton [45400 kg] pneumatic roller was then used to seat the concrete pieces. It was known that the slab reinforcement was not broken. The overlay consisted of a 4-in [10.2 cm] asphalt concrete overlay. This rehabilitation was conducted in 1984.

Traffic:

The current ADT and percent trucks is as follows:

ADT = 2375
% TRUCKS = 24.2

Accumulated 18-kip [80 kN] ESALs on the outer lane are estimated as:

ESAL = 0.195 million

Environment:

The project, located in west-central Illinois, is subject to a harsh Wet-Freeze environment and receives 36 in [91 cm] of annual precipitation. The mean freezing index (accumulated degrees/days below freezing) is approximately 250.

Observed Distress:

The project was 1 year old at the time of survey and assigned a PSR of 4.0 by the survey crew. Four sample units were chosen; two in both the northbound and southbound directions of travel. The pavement was evaluated for all flexible pavement distress types with reflective cracking and rutting being the most useful distress quantities collected.

The northbound direction had a total of 167 ft/1000 ft [167 m/km] of reflective cracking, 136 ft/1000 ft [136 m/km] of low severity and the remaining being medium severity. Outer lane rut depths were measured in both the inner and outer wheelpaths. The outer wheelpath had an average rut depth of 0.04 in [0.10 cm], while the inner wheelpath had no rutting. The southbound direction had a total of 180 ft/1000 ft [180 m/km] of reflective cracking, 109 ft/1000 ft [109 m/km] of low severity and the remaining being medium severity. The outer wheelpath had an average rut depth of 0.02 in [0.05 cm], while the inner wheelpath also had no rutting.

ILLINOIS, State Route 101

Location:

The project, located in Brooklyn, IL, begins at station 625+00 and extends to station 645+00 on this rural road.

Original Pavement Design:

The original pavement was constructed in 1926 as an 8.25-in [21.0 cm] undowelled JRCP with a joint spacing of 50 ft [15.2 m]. The slabs were placed directly on the subgrade. The project has a granular shoulder. No provisions were made for subsurface drainage in the original design. A 4.5-in [11.4 cm] asphalt concrete overlay had also been placed in 1956.

Crack and Seat and Asphalt Overlay Design:

Deteriorated portions of the pavement were repaired with portland cement concrete before the cracking operation was initiated. The original pavement was cracked with a whip hammer into 2-ft by 2-ft [0.6 m by 0.6 m] pieces. A 50-ton [45400 kg] pneumatic roller was then used to seat the concrete pieces. It was unknown whether the slab reinforcement was broken. The overlay consisted of a 2-in [5.1 cm] asphalt concrete overlay. This rehabilitation was conducted in 1983.

Traffic:

The current ADT and percent trucks is as follows:

ADT = 437
% TRUCKS = 54

Accumulated 18-kip [80 kN] ESALs on the outer lane are estimated as:

ESAL = 0.106 million

Environment:

The project, located in west-central Illinois, is subject to a harsh Wet-Freeze environment and receives 38 in [97 cm] of annual precipitation. The mean freezing index (accumulated degree-days below freezing) is approximately 250.

Observed Distress:

The project was 2 years old at the time of survey. Four sample units were chosen; two in both the eastbound and westbound directions of travel. The pavement was evaluated for all flexible pavement distress types with reflective cracking and rutting being the most useful distress quantities collected.

The eastbound direction had no reflective cracking present. Outer lane rut depths were measured in both the inner and outer wheelpaths. The outer wheelpath had an average rut depth of 0.23 in [0.58 cm], while the inner wheelpath had 0.03 in [0.08 cm]. The westbound direction also had no reflective cracking present. The outer wheelpath had an average rut depth of 0.27 in [0.69 cm], while the inner wheelpath also had 0.08 in [0.20 cm].

WISCONSIN, US Route 14 (Rock County)

Location:

The project, located in Rock County, begins at Emerald Grove Bridge and extends to Interstate 90.

Original Pavement Design:

The original pavement was constructed as a 9-in [22.9 cm] undowelled JPCP with a joint spacing of 15.75 ft [4.8 m]. The project has a granular shoulder. No provisions were made for subsurface drainage in the original design.

Crack and Seat and Asphalt Overlay Design:

Deteriorated portions of the pavement were repaired with granular backfill materials before the cracking operation was initiated. The original pavement was cracked such that the longitudinal spacing between cracks was less than or equal to 4 ft [1.2 m]. No block width was specified. A 3-ton [2724 kg] vibratory roller was then used to seat the cracked concrete. It was unknown whether the slab reinforcement was broken. The overlay consisted of a 5.5-in [14.0 cm] asphalt concrete overlay with a 1-in [2.5 cm] interlayer. This rehabilitation was conducted in 1982.

Traffic:

The current ADT and percent trucks is as follows:

ADT = 7364
% TRUCKS = 73

Accumulated 18-kip [80 kN] ESALs in the outer lane are estimated as:

ESAL = 1.269 million

Environment:

The project, located in southeastern Wisconsin, is subject to a harsh Wet-Freeze environment and receives 31 in [79 cm] of annual precipitation. The mean freezing index (accumulated degrees/days below freezing) is approximately 1000.

Observed Distress:

The project was 3 years old at the time of survey and was assigned a PSR of 4.5 by the survey crew. Four sample units were chosen; two in both the eastbound and westbound directions of travel. The pavement was evaluated for all flexible pavement distress types with reflective cracking and rutting being the most useful distress quantities collected.

The eastbound direction had a total of 12 ft/1000 ft [12 m/km] of reflective cracking, all low severity. Outer lane rut depths were measured in both the inner and outer wheelpaths. The outer wheelpath had an average rut depth of 0.13 in [0.33 cm], while the inner wheelpath had 0.11 in [0.28 cm]. The westbound direction had a total of 9 ft/1000 ft [9 m/km] of reflective cracking, all low severity. The outer wheelpath had an average rut depth of 0.17 in [0.43 cm], while the inner wheelpath had 0.11 in [0.28 cm].

WISCONSIN, US Route 14 (Dane and Rock Counties)

Location:

The project, located in Dane and Rock Counties, begins at the town of Oregon and extends 6.1 miles [9.8 km] to the town of Evansville.

Original Pavement Design:

The original pavement was constructed as a 9-in [22.9 cm] undowelled JPCP with a joint spacing of 20 ft [6.1 m]. The project has a granular shoulder. No provisions were made for subsurface drainage in the original design.

Crack and Seat and Asphalt Overlay Design:

Deteriorated portions of the pavement were not repaired before the cracking operation was initiated. The original pavement was cracked with a hydraulic hammer into 3-ft by 3-ft [0.9 m by 0.9 m] pieces. A 50-ton [45400 kg] pneumatic roller was then used to seat the concrete pieces. The overlay consisted of a 4.5-in [11.4 cm] asphalt concrete overlay. This rehabilitation was conducted in 1980.

Traffic:

The current ADT and percent trucks is as follows:

ADT = 4192
% TRUCKS = 12

Accumulated 18-kip [80 kN] ESALs in the outer lane are estimated as:

ESAL = 0.896 million

Environment:

The project, located in southeastern Wisconsin, is subject to a harsh Wet-Freeze environment and receives 32 in [81 cm] of annual precipitation. The mean freezing index (accumulated degree-days below freezing) is approximately 950.

Observed Distress:

The project was 5 years old at the time of survey and was assigned a PSR of 4.5 by the survey crew. Four sample units were chosen; two in both the eastbound and westbound directions of travel. The pavement was evaluated for all flexible pavement distress types with reflective cracking and rutting being the most useful distress quantities collected.

The eastbound direction had a total of 126 ft/1000 ft [126 m/km] of reflective cracking, 66 ft/1000 ft [66 m/km] of low severity and the remaining being medium severity. Outer lane rut depths were measured in both the inner and outer wheelpaths. The outer wheelpath had an average rut depth of 0.20 in [0.51 cm], while the inner wheelpath had 0.21 in [0.53 cm]. The westbound direction also had a total of 126 ft/1000 ft [126 m/km] of reflective cracking, 60 ft/1000 ft [60 m/km] of low severity and the remaining being medium severity. The outer wheelpath had an average rut depth of 0.24 in [0.61 cm], while the inner wheelpath had 0.21 in [0.53 cm].

REFERENCES
VOLUME II -- OVERLAY REHABILITATION TECHNIQUES

1. Darter, M.I., Becker, J.M., Snyder, M.B. and Smith, R.E., "Concrete Pavement Evaluation System (COPES)," NCHRP Report No. 277, Transportation Research Board, 1985.

2. ERES Consultants, Inc., "Techniques For Pavement Rehabilitation", Participants Notebook, National Highway Institute/Federal Highway Administration, Third Revision, October, 1987.

3. Darter, M.I., Barenberg, E.J., "Bonding Concrete Overlays: Construction and Performance." Miscellaneous Paper GL-80-11. Corps of Engineers Waterways Experiment Station, 1980.

4. "Resurfacing With Portland Cement Concrete," National Cooperative Highway Research Program Synthesis of Highway Practice 99, Transportation Research Board, 1982.

5. Johnson, M.L., "Bonded, Thin-Lift, Non-reinforced Portland Cement Concrete Resurfacing," Final Report, Iowa Highway Research Board, 1980.

6. Schroeder, C.J., Britson, R.A., Bergren, J.V., "Bonded, Thin-Lift, Non-reinforced Portland Cement Concrete Resurfacing," Iowa Department of Transportation Division of Highways, 1977.

7. Temple, William H., Cumbaa, Steven L., "Thin Bonded PCC Resurfacing," Louisiana Department of Transportation and Development, FHWA/LA-85/181, 1985.

8. Smith, R.E., Darter, M.I., Herrin, S.M., "Highway Pavement Distress Identification Manual," DOT-FH-11-9175 / NCHRP 1-19, 1979.

9. Obuchowski, R.H., "Construction of Thin Bonded Concrete Overlay," Transportation Research Record No. 924, Transportation Research Board, 1983.

10. Felt, E.J., "Resurfacing and Patching Concrete Pavements with Bonded Concrete," Highway Research Board, Proc. Vol. 35, 1956.

11. "Construction Handbook on PCC Rehabilitation," FHWA Construction and Maintenance Division, 1984.

12. Bergren, J.V., "Bonded Portland Cement Concrete Resurfacing," Transportation Research Record No. 814, Transportation Research Board, 1981.

13. "Iowa's Bonded Concrete Overlays," Iowa Concrete Paving Association, Ames, IA, 1982.

14. "Bonded Concrete Resurfacing," Portland Cement Association, Skokie, IL, 1960.

15. Gould, V. A., "Summarized Committee Report 1948-1960: Salvaging Old Pavements By Resurfacing," Highway Research Bulletin No. 290, 1961.

16. Knutson, M.J., "An Evaluation of Bonded, Thin-Lift, Non-Reinforced Portland Cement Concrete Resurfacing and Patching," Iowa Concrete Paving Association, 1976.

17. Williams, R.I.T., "Thin Bonded Concrete Surfacings Applied to Existing Concrete Road Slabs," Roads and Road Construction, Vol. 37. No. 439, July 1959.

18. "PCC Inlay- Thin Bonded PCC Overlay- Unbonded PCC Overlay," Iowa Highway Project Open House, Iowa Department of Transportation, 1983.

19. Betterton, R.M., Knutson, M.J., Marks, V.J., "A Ten Year Performance Summary of Fibrous PC Concrete Overlay Research in Greene County, Iowa,"Iowa Department of Transportation, 1984.

20. "Concrete Resurfacing 1977 Condition Survey," American Concrete Paving Association and Portland Cement Association, Skokie, IL, 1977.

21. Calvert, G., and J. Lane, "Thin Bonded Concrete Overlay With Fast Track Concrete," Construction Report FR-71-7(32)--2G-11, FHWA NO. DTFH71-86-502-IA-22, Iowa Department of Transportation, 1986.

22. Tyner, H.L., Gulden, Wouter, Brown, Danny, "Resurfacing of Plain Jointed Concrete Pavements," Transportation Research Board Paper, 1981.

23. Biancalana, F., Ratterree, B., "Unbonded Non-Reinforced PCC Overlay Construction on Illinois State Toll Highway Authority East-West Tollway, Transportation Research Board Paper, 1983.

24. Darter, M.I., "Requirements for Reliable Predictive Pavement Models," Transportation Research Record No. 766, Transportation Research Board, 1980.

25. "Guide Specifications for Concrete Pavement Rehabilitation," American Association of State Highway and Transportation Officials, Association of General Contractors, ARTBA, Final Draft, 1984.

26. Darter, M.I., Barenberg, E.J., Yrjanson, W.A., "Joint Repair Methods for Portland Cement Concrete Pavements" NCHRP Report No. 281, Transportation Research Board, 1985.

27. Darter, M.I., Smith, R.E., Palmieri, R.P., Lytton, R.L., "Pavement Overlay Design Procedures and Assumptions, Analysis of Existing Procedures," Final Report, Volume 1, Report No. RD-85-008, Federal Highway Administration, Washington, D.C., 1984.

28. Dempsey, B.J., Thompson, M.R., "A Heat-Transfer Model for Evaluating Frost Action and Temperature Related Effects in Multilayered Pavement Systems," Illinois Cooperative Highway Research Program Project IHR-401, The Highway Research Program, University of Illinois Department of Civil Engineering, Engineering Experiment Station, 1969.

29. Dewitt, D.P., Incropera, F.P., "Fundamentals of Heat Transfer," John Wiley and Sons, New York, NY, 1981.

30. Domenichini, Lorenzo, "Factors Affecting Adhesion of Bonded Concrete Overlays (Abridgement)," Department of Hydraulics, Transportation and Road Construction, University of Rome, 1986.

31. "Concrete Overlays Reinforced with Welded Wire Fabric," Wire Reinforcement Institute, Washington, D.C., 1985.

32. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 Iowa", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

33. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 Louisiana", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

34. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 Wyoming", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

35. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 New York", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

36. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 Georgia", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

37. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 Illinois", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

38. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 South Dakota", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

39. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 Colorado", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

40. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 Michigan", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

41. "Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1951-80 Pennsylvania", National Oceanic and Atmospheric Administration/Environmental Data and Information Service, 1981.

42. Wyoming Department of Transportation, As-Built Plans and Rehabilitation Special Provisions, Wyoming DOT, Laramie, WY, 1985.

43. Louisiana Department of Transportation, Traffic Data, Louisiana, DOT, Baton Rouge, LA, 1985.

44. Iowa Department of Transportation, As-Built Plans and Rehabilitation Special Provisions, Iowa DOT, Ames, IA, 1985.

45. Michigan Department of Transportation, As-Built Plans and Rehabilitation Special Provisions, Michigan DOT, Lansing, MI, 1985.

46. Michigan Department of Transportation, Traffic Data, Michigan DOT, Lansing, MI, 1985.

47. Ohio Department of Transportation, As-Built Plans and Rehabilitation Special Provisions, Ohio DOT, Columbus, OH, 1985.

48. South Dakota Department of Transportation, As-Built Plans and Rehabilitation Special Provisions, South Dakota DOT, Pierre, SD, 1985.

49. Georgia Department of Transportation, Traffic Data, Georgia DOT, Atlanta, GA, 1985.

50. Conversations with Mr Werner Hutter and Mr. John Kiljin of Colorado Department of Transportation, 1986.

51. Correspondance with Mr. Wade Gramling, Pennsylvania Department of Transportation, 1985.

52. Tayabji, Shiiraz D., Okamoto, Paul A., "Thickness Design of Concrete Resurfacing," Portland Cement Association, Pr. Third International Conference on Concrete Pavement Design and Rehabilitation at Purdue University, 1985.

53. AASHTO Pavement Design Guide, 1986," American Association of State Highway and Transportation Officials, 1986.

54. Darter, M.I., Smith, R.E., "Evaluation of the FAA Overlay Design Procedures for Rigid Pavements," Technical Report Prepared for U.S. Army Corps of Engineers, Misc. Paper GL-80-11, WES, ERES Consultants, Inc., 1981.

55. White, Kenneth J., Horsman, Nancy G., "SHAZAM The Econometrics Computer Program," Version 5 Users Reference Manual, 1985.

56. Majidzadeh, K. and G. Ilves, "Evaluation of Rigid Pavement Overlay Design Procedure, Development of the OAR Procedure," FHWA/RD-83-090, Worthington, Ohio, 1983.

57. Treybig, H.C., McCullough, B.F., Smith, P., VonQuintus, H., and Jordahl, P., "Flexible and Rigid Pavement Overlay Design Procedure," FHWA-RD-77-133, Austin Research Engineers, Inc., Austin, Texas, 1977.

58. Personal Conversation with Paul Kuhn, Caltrans, 1986.

59. Chase, G. W. and J. Lane, "Thin-Bonded Portland Cement Concrete Overlay as a Solution to Interstate Highway Restoration," SP 93-4, American Concrete Institute, 1986, pp. 89-106.

60. "Experimental Repair Methods For CRCP - Final Report," FHWA/MN/RD-85/05, Minnesota Department of Transportation, 1985.

61. Gausman, R. H., "Status of Thin-Bonded Overlays," FHWA-EP-02-01, June, 1986, Demonstration Projects Division, Federal Highway Administration.

62. Johnson, D. P., "Construction of a This-Bonded Portland Cement Concrte Overlay in South Dakota," Paper presented at the January 1987 Annual Meeting of Transportation Research Board.

63. Van Dam, T., M. Y. Shahin and E. Blackman, "Effect of Concrete Overlay Debonding on Pavement Performance," U.S. Army CERL, Paper presented at the January 1987 Annual Meeting of the Transportation Research Board.

64. Krauss, P. D., "New Materials and Techniques for Rehabilitation of Portland Cement Concrete," FHWA/CA/TL-85/16, Final Report, California Department of Transportation, October 1985.

65. Lane, John, "Performance of Nongrouted Thin-Bonded PCC Overlays," Construction Report, Iowa Research Board, August 1986.

66. Tayabji, S. D. and C. G. Ball, "Field Evaluation of Bonded Concrete Overlays," Final Report Project HR-288, Iowa DOT, November 1986.

67. Kaler, M. K. and J. Lane, "Performance of Nongrouted Thin Bonded PCC Overlays," Construction Report, Iowa Highway Research Board, August, 1986.

68. Daring, Gordon, "Evaluation of Thin-Bonded Concrete Overlay in the State of Wyoming, Unpublished Report, Wyoming State Highway Department, 1984.

69. Horan, R. D., "Second Report on Evaluation of Thin-Bonded Concrete Overlay in the State of Wyoming," Unpublished Report, Wyoming State Highway Department, May 1985.

70. "Cross-Stitching -- A New Repair Procedure for PCC Pavements," American Concrete Pavement Association, Newsletter, Vol. 22, No. 2, March/April, 1986.

71. Personal Conversation with Mr. William Yrjanson, American Concrete Pavement Association, 1987.

72. Chou, Y., "Equations for Nonbonded Concrete Overlays", SP 93-5, American Concrete Institute, 1986, pp. 125-141.

73. Krauthammer, T. and H. Khanlarzadeh, "Numerical Assessment of Pavement Test Sections", Paper presented at the 1987 Annual Meeting of Transportation Research Board.

74. "Performance Evaluation of Concrete Pavement Overlays", Michigan Research Report R-1262 (Construction Report), May 1985.

75. Miller, K. and K. Majidzadeh, "Comparison of Concrete Pavement Rehabilitation Techniques in Ohio Demonstration Program", Paper presented at the 1987 Annual Meeting Of Transportation Research Board.

76. "State Highway Department Experience With 63 Pavement Rehabilitation Techniques", FHWA Pavement Rehabilitation Manual, Appendix A, Federal Highway Administration, Washington, D.C. 1985.

77. "Experiences With Polyethylene Bondbreaker for CRCP Overlay, Project IR 94-2(131), Jackson Co.", October 29, 1986, FHWA Memorandum from S. K. L. Fong to F. M. Meyer, Division Administrator.

78. Darter, M. I., "Design of Zero-Maintenance Plain Jointed Concrete Pavements", Vol. 1, Report No. FHWA-RD-77-11, Federal Highway Administration, Washington, D.C., June 1977.

79. Timms, A. G., "Evaluating Subgrade Friction-Reducing Mediums for Rigid Pavements", Highway Research Record 60, Highway Research Board, 1964.

80. Spellman, D. L., J. H. Woodstrom and B. F. Neal, "Investigation of Unbonded PCC Overlays", Research Report 635165, FHWA D-5-29, State of California Division of Highways, September 1971.

81. "Methods For Reducing Friction Between Concrete Slabs and Cement-Treated Subbases", Federal Highway Administration, Washington, D.C, September 1971.

82. Midwest Pavement Management, Inc., "Structural Evaluation of Crack and Seat Overlay Pavements", September, 1986.

83. "Crack and Seat Performance", Review report, Federal Highway Administration, Demonstration Projects Division and Pavement Division, April 1987.

84. Indiana Department of Highways, Division of Research and Training, Initial Construction and Interim Performance Report, September 1986.

85. California Department of Transportation, Memorandum, Report of construction, "Effects of Slab Breaking and Seating on Differential Vertical Movement at PCC Slab Joints and Cracks."

86. Minnesota Department of Transportation, Research and Development, Crack Reflectance on Bituminous Overlaid PCC Pavement, August 1981.

87. "Guide for Design of Pavement Structures", American Association of State Highway and Transportation Officials, 1986.

88. Allen, H. S., "Evaluation of Variable Thickness of Bituminous Overlay on Cracked PCC Pavement", Special Study No. 375, Minnesota Department of Transportation, 1981.

89. Eckrose, R. A., and W. E. Poston, "Asphalt Overlays on Cracked and Seated Concrete Pavements", National Asphalt Pavement Association, Information Series 83, January 1983.

90. Crawford, C., "Cracking and Seating of PCC Pavements Prior to Overlaying With Hot Mix Asphalt", National Asphalt Pavement Association, Information Series 91, March 1985.

91. "The Big Crackup", Workshop Proceedings, National Asphalt Pavement Association, 28th Annual Convention, Phoenix, Arizona, 1983.

92. Lyon, J. W., "Heavy Pneumatic Rolling Prior to Overlaying: A 10-Year Project Report", Highway Research Record No. 27, Highway Research Board, 1970, pp. 45-49.

93. National Cooperative Highway Research Program of Synthesis of Highway Practice No. 92, "Minimizing Reflection Cracking of Pavement Overlays", 1982.

94. Personal Communication, Marshall R. Thompson, University of Illinois.

95. Heinrichs, K. W., M. J. Liu, M. I. Darter, S. H. Carpenter, and A. M. Ioannides, "Rigid Pavement Analysis and Design," Technical Report, FHWA, October, 1987.

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