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16. Abstract


This document describes the development of updated rigid pavement distress prediction models for the Texas Department of Transportation's Pavement Management Information System (PMIS). It makes use of pavement condition data in databases maintained by the Texas Department of Transportation (TxDOT) and the Center for Transportation Research (CTR) at The University of Texas at Austin.

Models are presented to quantitatively predict the following distress types:
In jointed concrete pavement: patches, corner breaks, faulted joints and cracks, spalled joints and cracks, transverse crack spacing, and slabs with longitudinal cracks.

In continuously reinforced concrete pavement: punchouts, patches, serviceability loss as measured by ride score, transverse crack spacing, and crack spalling.

Modifying factors to the general model equation include the influence of structural effects, climate, and traffic loading on the various distress types. These models greatly improve the preliminary estimates, which were made in 1993 and are currently used in the PMIS.

These improvements to the models were made possible primarily by data collection efforts undertaken in the summer of 1994. This document discusses the analysis of the data collected, which includes a condition survey conducted by the Center for Transportation Research and a survey of Texas districts to determine coarse aggregate use in construction of rigid pavement in the state.


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# IMPROVED DISTRESS PREDICTION MODELS FOR RIGID PAVEMENTS IN TEXAS

by

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Research Report 1908-4

Texas Pavement Management Information System
Research Project 7-1908

Conducted for the

**Texas Department of Transportation**

by the

**CENTER FOR TRANSPORTATION RESEARCH**
**Bureau of Engineering Research**
**THE UNIVERSITY OF TEXAS AT AUSTIN**

August 1995

## IMPLEMENTATION STATEMENT

The rigid pavement distress prediction models provided in this report represent an improvement over those currently used in the Texas Pavement Management Information System. The equations presented herein are intended for direct implementation by TxDOT.

## ACKNOWLEDGMENTS

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## DISCLAIMERS



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## TABLE OF CONTENTS

## SUMMARY


This document describes the development of updated distress prediction models for the Texas Department of Transportation's Pavement Management Information System (PMIS), focusing on prediction models for rigid pavements in Texas. It makes use of pavement condition data in databases maintained by the Texas Department of Transportation (TxDOT) and by the Center for Transportation Research (CTR) at The University of Texas at Austin. Models are presented to quantitatively predict the following distress types:

- In jointed concrete pavement:
  - patches
  - corner breaks
  - faulted joints and cracks
  - spalled joints and cracks
  - transverse crack spacing
  - slabs with longitudinal cracks
- In continuously reinforced concrete pavement:
  - punchouts
  - patches
  - serviceability loss as measured by ride score
  - transverse crack spacing
  - crack spalling

The general model equation was modified to include the influence of structural effects, environmental loading, and traffic loading on the various distress types. These models greatly improve the preliminary estimates, which were made in 1993 and are currently used in the PMIS.

These improvements to the models were made possible primarily by data collection efforts undertaken during the summer of 1994. This document discusses the analysis of the data collected, which includes a condition survey conducted by the Center for Transportation Research and a survey of Texas districts to determine coarse aggregate use in construction of rigid pavement in the state.

# CHAPTER 1. INTRODUCTION AND BACKGROUND

## PAVEMENT MANAGEMENT SYSTEMS

Among other provisions of the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA), $17 billion was made available for an interstate maintenance program to ensure the rehabilitation, restoration, and resurfacing of the interstate system. As part of ISTEA, each state receiving federal aid was required to develop, establish, and implement six different management systems, including a pavement management system (Ref 1).

### *Definition of Pavement Management Systems*

A pavement management system (PMS) is a tool for selecting optimum strategies for keeping pavements in serviceable condition. It includes all the activities involved in planning, design, construction, rehabilitation, and maintenance of the pavement network in public works program. The use of this tool improves decision-making efficiency, provides feedback on consequences of decisions, facilitates the coordination of activities within an agency, and ensures consistency of decisions made at different management levels within an organization (Ref 2).

To better manage its 122,360 centerline kilometers of Texas highways, the Texas Department of Transportation (TxDOT) has developed the Texas Pavement Management System and the Texas Pavement Management Information System (PMIS). A pavement network of this size requires enormous resources to construct and maintain. For example, the U.S. spends approximately $30 billion annually on highway and bridge infrastructure, with the State of Texas alone spending approximately $1 billion annually on pavements and pavement-related expenses (Refs 3, 4). An organized and efficient method of allocating available resources is essential for proper allocation of these funds.

### *Operation of Pavement Management Systems*

A pavement management system is typically operated at two levels — at the project level and at the network level. A project-level pavement management system deals with individual lengths of pavement (i.e., sections), and functions to select the most cost-effective design or maintenance procedure for each section. At this level, detailed information about the pavement section, including soil type, environmental conditions, expected size and frequency of loading, and expected design life, is needed to ensure good design. A network-level pavement management system is concerned with the group of pavements that make up a network. The network-level pavement management system assists in optimizing the allocation of funds for maintenance, rehabilitation, and construction to maximize the resulting benefits over the set or group of projects. To aid in accomplishing this task, data are collected from a selected representative sampling of the pavements in the network. These data, less detailed than those taken at the project level, are used to identify trends in pavement performance or usability. These trends are then used to predict the condition of the network under various future funding and loading levels and/or maintenance and rehabilitation strategies.

Selecting an optimum maintenance and rehabilitation strategy for the existing infrastructure requires the ability to predict future pavement conditions, both with and without the use of the selected strategy. The life expectancy of the repair — along with the effects on pavement performance if no repair is made — must be considered. Selecting the optimum strategy, therefore, depends on determining the present condition of the pavement, as well as the ability to accurately predict its future performance. Thus, this study seeks to improve current predictive methods used in field work.

## DISTRESS MANIFESTATIONS IN RIGID PAVEMENTS

Distress is defined as damage to a pavement structure — that is, damage that may limit its usefulness to the traveling public. Degrees of pavement distress and roughness are measures commonly used to evaluate condition and performance, respectively. Manifestations of distress include loss in riding quality and a wide variety of surface cracking and damage. The combined and cumulative influences of traffic, pavement structure and materials, subgrade support, and climatic factors are known contributors to the deterioration and distress of pavements. The 1958-1961 AASHO Road Test in Ottawa, Illinois, established the importance of distress collection for the purpose of distress prediction (Ref 5).

### *Jointed and Jointed Reinforced Concrete Pavements*

Both the Texas Pavement Evaluation System Rater's Manual (Ref 6) and the Center for Transportation Research's Pavement Condition Survey forms (Ref 7) include the following distress manifestations for jointed concrete pavement (JCP) and jointed reinforced concrete pavement (JRCP):

- Failed joints and cracks
- Failures (corner breaks, punchouts, asphalt patches, D-cracking)
- Shattered slabs
- Slabs with longitudinal cracks
- Concrete patches
- Apparent joint spacing

Apparent joints include both constructed joints and transverse cracks. Large transverse joint spacing can lead to large stresses from traffic and environmental loading. These stresses can exceed the tensile strength of the concrete, causing transverse cracks that relieve the stresses and serve the function of a joint (Ref 8).

### *Continuously Reinforced Concrete Pavements*

The following distress manifestations are commonly surveyed for continuously reinforced concrete pavement (CRCP):

- Spalled cracks
- Punchouts
- Asphalt concrete patches
- Portland cement concrete patches
- Average transverse crack spacing

Average transverse crack spacing is used to determine the likelihood of punchouts occurring. A punchout is formed when longitudinal cracks and transverse cracks meet to create a block of pavement that is no longer bonded to the surrounding structure. When transverse cracks are closely spaced on average, there is a greater chance that punchouts will occur. Table 1.1 lists the types of distresses for the various types of rigid pavements used in distress prediction models.

## BACKGROUND FOR THE TEXAS PMIS DISTRESS PREDICTION MODEL

The Texas Pavement Management System (PMS) uses numerical models calibrated from observed data to predict pavement distress. The form of the equation, developed at the Texas Transportation Institute of Texas A&M University, is the same for all distress types in the Texas Pavement Evaluation System (PES) database (Ref 9).

$$D = \alpha e^{-\left(\frac{\chi \varepsilon \sigma \rho}{N}\right)^{\beta}}$$

where:

D is the predicted level of distress,

N is the age of the pavement,

$\alpha$ is an asymptote which controls the maximum level of distress,

$\beta$ is a coefficient which controls the shape of the curve (convex or concave),

$\rho$ controls the position of the first inflection point on the curve along the age axis,

$\chi$ is a factor to adjust for traffic,

$\varepsilon$ is a factor to adjust for climate,

$\sigma$ is a factor to adjust for pavement structure (subgrade support), and

e is the base of the natural logarithm.

*Table 1.1. List of distress manifestations for rigid pavements in Texas*

| DISTRESS MANIFESTATION | CRCP | JCP | JRCP |
|---|---|---|---|
| **Cracking:** | | | |
| Longitudinal Cracks | | • | • |
| Transverse and Diagonal Cracks | • | • | • |
| Corner Breaks | | • | • |
| **Joint Deficiencies:** | | | |
| Spalling at Joints | • | • | • |
| Faulting of Transverse Joints | | • | • |
| Faulting of Longitudinal Joints | | • | • |
| Failed Joints and Cracks | | • | • |
| **Other:** | | | |
| Patches/Patch Deterioration | • | • | • |
| Faulting at Cracks | | • | • |
| Punchouts | • | • | • |
| Spalling at Cracks | • | • | • |
| Shattered Slabs | | • | • |

The coefficients $\alpha$, $\beta$, $\rho$, $\chi$, $\varepsilon$, and $\sigma$ allow the general form of the model to be calibrated to Texas highway pavement data, so as to yield a different prediction equation for each distress type. The prediction equation is used to predict distresses in both asphalt and portland cement concrete pavements.

The form of the equation selected for the Texas PMIS was chosen because the sigmoidal curve shape gives the desired flexibility for modeling various types of distress. The coefficients that govern the shape of the curve make it possible to adjust the shape of the distress prediction curve to approximate three types of physical reality. Figures 1.1, 1.2, and 1.3 show examples of the various types of distresses to which the model can be fitted and used in predictions.

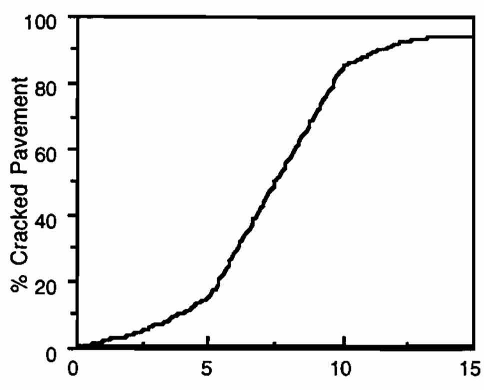


*Figure 1.1. General form of sigmoidal equation*

Figure 1.1 shows the full shape of the curve in a general model of percent of cracked pavement over time. This curve or shape describes the general physical tendency of pavements to have very little cracking when first constructed, followed by more extensive cracking as aging takes its toll. In reality, very few pavements reach the upper asymptotic arm of the curve as it approaches complete failure, because most are repaired or reconstructed before they reach this condition.

Figure 1.2 shows how the model can fit such distress types as punchouts, which occur infrequently in the younger years of pavement life, then increase exponentially as the structure begins to wear out. Careful examination shows that this distress type model is a special case of the sigmoidal model in Figure 1.1, which concentrates on the initial rising arm of the s-shape.


*Figure 1.2. Special case of the sigmoidal equation (late distress)*

Figure 1.3 shows a third physical case that the sigmoidal equation can model, which is represented by cracks per unit distance (a measure of crack spacing). This distress type is typified by no distress at construction, then a rapid increase as cracks initially form, followed by an almost constant value over the remainder of the life of the pavement.


*Figure 1.3. Special case of the sigmoidal equation (early distress)*

## DATA SOURCES

Historical data on the various types of distress were used to develop the distress models for prediction of future pavement condition. Data on CRCP and JCP are readily available from two databases maintained by the Center for Transportation Research (CTR) of The University of Texas at Austin. These databases, maintained on the IBM mainframe, are primarily analyzed using the Statistical Analysis System (SAS) software package (Refs 10, 11). Another primary source of data is the TxDOT's PES database.

### *The CTR JCP Database*

The CTR jointed concrete pavement database contains over 4,000 pavement test sections. Each section is approximately the same length — 0.322 kilometers. JCP sections are identified by a unique CFTR number (as are the CRCP sections). The database stores only distress survey data. Thus far, no provision has been made for collecting data on climate, traffic, materials, pavement design characteristics, or maintenance and rehabilitation histories. The following data are recorded in the JCP database:

- transverse cracks
- spalled joints and cracks
- faulted joints and cracks
- bad joint sealants
- corner breaks
- minor longitudinal cracks (number per slab)
- severe longitudinal cracks (number per slab)
- patches (ACC and PCC)
- condition of edge joints
- pumping

### *The CTR CRCP Database*

The CRCP network in Texas is represented in a database containing over 300 selected pavement sections. Sections range in length from 0.161 to 2.737 kilometers. Each section has consistent design characteristics throughout its length. Each is identified by a unique five-digit CFTR (Center for Transportation Research) number, with the first two digits identifying the TxDOT district in which the section is located and the last three indicating the pavement section in the district. The database contains periodically collected distress information and data on local climate, traffic loading, and construction materials for each pavement section.

Distress surveys for all or a portion of the CRCP sections that make up the database were performed in 1974, 1978, 1980, 1982, 1984, 1987, and 1994. Table 1.2 summarizes the specific distress types collected, as well as the frequency with which they were surveyed during these years.

A structural evaluation survey conducted in 1988 concentrated on structural evaluation data instead of on distress data (Ref 12). The data collected in this survey consisted of deflections measured with the falling weight deflectometer (FWD), crack width measured with a microscope, pavement temperature, and rut depth.

***The Texas PES Database***

While the Pavement Evaluation System (PES) database contains condition survey data for both flexible and rigid pavement sections, only the rigid pavement sections were considered for this study. PES includes three portland cement concrete pavement types: jointed plain concrete pavement (JPCP), jointed reinforced concrete pavement (JRCP), and continuously reinforced concrete pavement (CRCP). In all, the Texas PES stores data for over 1,400 rigid pavement sections.

PES pavement sections range in length from 0.161 to 4.83 kilometers, with the majority being 3.22 kilometers in length. Pavement sections are identified by reference markers at the beginning and end. The TxDOT Pavement Evaluation System Rater's Manual (Ref 6) details the standard procedure for establishing and interpreting reference markers. Each reference marker locates a particular pavement section with respect to a grid imposed on a map of Texas.

From the annual PES survey data collected for the period 1983–1990, we obtained the following information:

- routine condition survey data,
- traffic data,
- ride quality data,
- skid resistance data, and
- pavement structural capacity.

CTR Research Report 1908-1 (Ref 8) discussed the shortcomings in the PES database for distress models calibration. Data items that can be used to describe the inference space of the PES dataset include pavement age, temperature, rainfall, and pavement thickness. None of these data items were recorded in the PES database. Initial construction dates were obtained for a sample of PES pavement sections from the TxDOT district offices. Analysis of these sampled sections showed that a majority of the JRCP sections were 20 to 45 years old; similarly, the youngest JCP section in the sample was 20 years old. For these reasons, the CTR database was used for the distress models' calibration.

*Table 1.2. Summary of condition survey data in the CTR CRCP database*

| DISTRESS | | | SURVEY YEAR | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **TYPE** | **TYPE** | **INTENSITY** | **74** | **78** | **80** | **82** | **84** | **87** | **94** |
| Cracking | Transverse | Minor | • | • | | | | • | |
| | | Severe | • | • | | | | • | |
| | Longitudinal | | • | | | | | | |
| | Localized | Minor | • | | | | | | |
| | | Severe | • | | | | | | |
| Spalling | | Minor | • | • | • | • | | | |
| | | Severe | • | • | • | • | • | • | • |
| Pumping | | Minor | • | • | • | • | | | |
| | | Severe | • | • | • | • | | | |
| Punchouts | | Minor | • | • | • | • | | • | |
| | | Severe | • | • | • | • | • | • | • |
| Patch | AC | | • | • | • | • | • | • | • |
| | PCC | | • | • | • | • | • | • | • |
| Crack Spacing | Transverse | | | | | | | • | • |
| Reflected Cracks | | | | | | | | • | |
| Overlay Bond-Failure | | | | | | | | • | |

## INITIAL CALIBRATION OF DISTRESS PREDICTION MODELS

In 1993, Singh et al. calculated the basic $\alpha$, $\beta$, and $\rho$ coefficients for the various distress types observed in CRCP, JCP, and JRCP, using data from the CTR databases (Ref 8). These models were intended to be preliminary, with the coefficients that accounted for structural, traffic, and environmental factors not considered (or set equal to one). It was hoped that later analysis would elaborate on the preliminary models by including the missing coefficient values. Several of the preliminary models suffered because of a scarcity of applicable data, especially on JCP and JRCP. Although these models represented the best fit of the sigmoidal equation to the available data, it was hoped that further data collection would allow for the replacement of the JCP and JRCP models.

Some additional data were provided by Project 1342, "Updating and Maintaining the Rigid Pavement Condition Survey Data Base," undertaken by CTR in 1994. Project 1342 investigated the requirements for developing a long-term pavement performance (LTPP) program for Texas (Refs 13, 14). This study, sponsored by the Texas Department of Transportation, undertook to develop improved rigid pavement distress prediction models for the Texas Pavement Management Information System (PMIS). Test sections were identified that would provide missing data on climatic and geographic effects on pavement behavior in Texas. A distress survey was conducted to collect information on the selected sections.

## OBJECTIVES OF THIS STUDY

The primary objective of this study was to model distress development — and thus pavement performance — of rigid pavements for use at the network level. This includes quantitative assessment of the effects of environmental conditions, construction and subgrade conditions, and traffic loading on pavement performance. Developed using the new data gathered in 1994 under Research Project 1342 at CTR, these models are designed to replace those currently in use in the Texas PMIS.

## SCOPE OF THIS REPORT

This report describes efforts to use the data collected in 1994 to improve and modify the preliminary distress prediction models for rigid pavements in Texas. Chapter 1 discusses pavement management systems, the Texas PMIS, and distress prediction models. Chapter 2 presents the basic shape parameters for JCP and JRCP models. Chapter 3 presents the basic shape parameters for CRCP models, and also provides numerical values for appropriate structural, environmental, and traffic loading factors. Chapter 4 details the results of a survey of TxDOT district pavement engineers to determine coarse aggregate type used in rigid pavement construction across the state. Finally, Chapter 5 presents recommendations regarding limitations and use of the distress prediction models.

# CHAPTER 2. DISTRESS PREDICTION MODELS FOR JOINTED CONCRETE PAVEMENTS

## DATA SET USED IN CALIBRATION OF THE MODELS

Initial development of JCP distress models for the Texas PMIS used information from the CTR 1982 database as the primary source for model calibration (Ref 8). The 1982 data showed considerable scatter, and the equations developed using it were intended as preliminary ones. A 1994 distress data collection effort, conducted under Research Project 1342, selected sections for survey that established a factorial experiment design for the PMIS (Ref 13). A factorial experiment design is a systematic approach to experimentation and/or data collection that allows the researcher to evaluate the effects of many factors jointly (Ref 14). Since the pavement sections selected for survey in 1994 formed a well-balanced sample from the population of Texas pavements, we decided to use distress data collected from sections that were surveyed both in 1994 and in 1982 as the data set for the improvements described in this chapter. Sections that were surveyed in 1982 but not in 1994 were not used in this analysis.

### *Distress Classification in CTR and PES Database*

The CTR and PES databases are not completely identical in distress classification. The distress data collected for failed joints and cracks in the PES database and spalled joints and cracks in the CTR database have the same distress description. Both databases also stored data for the number of slabs with longitudinal cracks.

The distress data for corner breaks, punchouts, asphalt patches, failed concrete patches, and D-cracking are grouped in one distress classification called "failures" in the PES database. However, while the CTR database stored separate data for corner breaks, punchouts, and asphalt patches, condition data for failed PCC patches and D-cracking are not recorded. PES distress type "shattered slab" is a collection of five or more failures in one slab. Therefore, a measure of failures and shattered slabs cannot be directly calculated from the CTR database.

Both the databases recorded data for portland cement concrete patches. *PCC concrete patches* is a unique distress category in PES database; however, PCC patches and asphalt concrete patches are grouped in one distress category called "patches" in the CTR database.

PES recorded data for apparent joint spacing that were not classified as a distress type in the CTR database. CTR recorded data for faulted joints/cracks and transverse cracks; both are not classified as distress types in the PES database. Table 2.1 shows the data recorded in each database.

This report presents distress models for the distress classifications in the CTR database. However, by using the CTR database, it appears feasible to develop a combined model for failures per mile, a separate model for PCC patches, and a model for apparent joint spacing as needed by PMIS. The combined model for failures per mile can be developed by using CTR database without considering D-cracking and failed PCC patches. D-cracking is very uncommon on Texas pavements; furthermore, the failed PCC patches are not significant contributors to the total failures. A separate model for PCC patches can be developed by segregating the combined patches data in the CTR database into PCC patches and asphaltic concrete patches. There is also a possibility that a model for apparent joint spacing can be developed by using data for transverse crack spacing in the CTR database. These additions will be presented in the final report of the project.

*Table 2.1. JCP distress description in CTR and PES database*

| PES Distress Categories | CTR Distress Categories |
|---|---|
| Failed Joints and Cracks Per Mile | Spalled Joints and Cracks Per Mile |
| Failures | |
| Corner Breaks Per Mile | Corner Breaks Per Mile |
| Punchouts Per Mile | Punchouts Per Mile |
| Asphalt Conc. Patches Per Mile | Asphalt Conc. Patches Per Mile |
| Failed Conc. Patches Per Mile | - |
| D-Cracking Per Mile | - |
| Shattered Slab | - |
| 5 ≤ Failures in One Slab | - |
| No. of Slabs With Long. Cracking Per Mile | No. of Slabs With Long. Cracking Per Mile |
| Concrete Patches Per Mile | Concrete Patches Per Mile |
| Apparent Joint Spacing | - |
| - | Faulted Joints and Cracks Per Mile |
| - | Transverse Cracks Per Mile |

## INFERENCE SPACE FOR THE MODELS

Unlike the initial prediction models, which used observations ranging in age from 0 to 15 years, the models for JCP in this report use observations ranging from 0 to 16 years. This range was chosen after examination of the data for the various distress types. For most distress types, observations up to 16 years of age generally followed an increasing trend, though this trend dropped off sharply after 16 years. This decrease in observed distress at advanced ages may be attributable to two causes. First, pavement sections older than 16 years, which often are considerably worn, are often found to be overlaid and thereby do not have available data for this analysis. Second, those pavements that are not overlaid at advanced ages exhibit a "survivor effect," meaning that they may be stronger than average and therefore may not be representative of the whole population. The equations presented in this chapter should be used with caution on pavements nearing the age of 16 years. The sigmoidal equation presented here may not always be the best fit to the observed data, but at present it is the form requested by TxDOT for use in the Texas PMIS; accordingly, it is used throughout this report.

The distress prediction equations were calibrated with the understanding that they would be directly applicable in the Texas PMIS. Since the PMIS programming currently uses Imperial units (feet and miles), the models are presented in Imperial units for ease of implementation.

## VARIABILITY IN THE JCP MODELS

The models presented in this chapter make no differentiation between JRCP and JPCP sections. These two pavement types should theoretically have different performance characteristics by nature of their design, and ideally separate models should be developed for each pavement type. A division of the data used for analysis showed that JPCP sections, while fairly numerous, fell into less than five yearly age categories, which does not provide enough information for a cross-sectional analysis of JPCP sections. Some of the scatter observable in the combined distress data in this chapter may be attributed to the difference in these pavement types.

In addition, because of the scarcity of data, no modifying coefficient factors for structural, environmental, or traffic loading variables ($\sigma$, $\varepsilon$, and $\chi$ in the PMIS equation in Chapter 1) are considered for these models. These variables can significantly influence behavior (and thus performance), and may also account for some scatter in the observed data.

## CALIBRATION OF SHAPE PARAMETERS

Because of the non-linear nature of the models, the NLIN (non-linear regression) procedure in the Statistical Analysis System (SAS) software package was used for the calibration (Refs 10, 11). This procedure allows the general form of an equation to be specified, which can be a function of any number of dependent variables. The procedure asks for an estimate of the range in which the dependent variables are expected to fall, along with how precise the calculation should be. The NLIN routine then finds the best solution to the specified equation, given the available data set and variable inputs. Table 2.2 lists the calculated coefficients for JCP distress models. Table 2.2 also lists correlation coefficients ($R^2$) for the JCP curves. These values are presented primarily for the benefit of future researchers. It is assumed that the $\alpha$, $\beta$, and $\rho$ coefficients will be recalibrated after future distress surveys of Texas pavements. Additional data should help to more clearly define trends in distress manifestations, and should provide enough information to allow for the calibration of separate models for JCP and JRCP. Future modeling efforts can evaluate their improvements in predictive accuracy by comparison to the $R^2$ values in Table 2.2. Some of the $R^2$ values calculated for these models are lower than those usually desired for prediction purposes. This is probably due to the sources of scatter described above. It is hoped that future data collection and model revisions will be able to eliminate this variability.

Figures 2.1 through 2.6 show a plot of the PMIS equation for each distress type, respectively, along with observed data for average distress type versus age. The data points shown represent averages for each age group rather than individual observations, and were weighted for the regression according to frequency of observations in each age group. These weights are given in Tables 2.3 through 2.8.

*Table 2.2. Coefficients for JCP distress prediction models*

| | Model Coefficients | | | |
|---|---|---|---|---|
| **Distress Type** | α | β | ρ | $R^2$ |
| Patches | 478.60 | 0.37 | 504.57 | 0.42 |
| Corner breaks | 47.67 | 0.36 | 47.89 | 0.83 |
| Faulted Joints and Cracks | 20.46 | 1.15 | 10.84 | 0.33 |
| Spalled Joints and Cracks | 37.02 | 5.21 | 7.95 | 0.53 |
| Transverse Cracks | 157.08 | 5.49 | 10.24 | 0.48 |
| Longitudinal Cracks | 34.47 | 0.52 | 240.75 | 0.33 |

### *Patches*

Figure 2.1 shows the model for patches per mile. The 1994 distress survey recorded information on patch size and type of material used, as well as number of patches observed. Material used was classified as either portland cement concrete or asphalt concrete. Patch size was divided into three categories: less than 50 ft² (4.6 m²), 50 to 150 ft² (4.6 to 13.8 m²), and greater than 150 ft² (13.8 m²). The 1982 distress survey recorded only numbers of patches without regard to type or size, so the six categories of 1994 patch data are added together into one composite observation for this distress model. The 1994 distress survey also collected numbers of observed punchouts, but this information was not collected in the 1982 survey, so punchout data are not used in this model of patches per mile. For future updates of this model, however, numbers of punchouts and patches should be combined into a more comprehensive measure, such as failures per unit length.

This model describes an exponentially increasing trend with age. As shown in Table 2.3, there are more observations from ages 9 to 16 than from ages 0 to 9. The data points for average distress at young ages are not heavily weighted, but contribute visually to the scatter in this graph.


*Figure 2.1. Prediction model for average patches per mile*

*Table 2.3. Summary of data plotted in Fig. 2.1 for the patches model*

| Age | 3 | 4 | 5 | 6 | 7 | 9 | 11 | 12 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Distress | 10.3 | 1.8 | 5.3 | 0 | 9 | 0 | 10.8 | 5.3 | 0 | 29.5 | 23.2 |
| Frequency | 2 | 2 | 6 | 1 | 3 | 19 | 1 | 41 | 3 | 37 | 43 |

### *Corner Breaks*

The data for corner breaks show more scatter than the data for patches, though a gradually increasing trend with pavement age is visible. This distress type is likely to be heavily influenced by type of construction materials used for base and sub-base layers, soil conditions, and traffic loading. None of these factors are considered at this time, which may account for the observable variability.


*Figure 2.2. Prediction model for corner breaks per mile*

*Table 2.4. Summary of data plotted in Fig. 2.2 for the corner breaks model*

| Age | 3 | 4 | 5 | 6 | 7 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Distress | 0 | 0 | 10 | 0 | 10.6 | 19.9 | 18.3 | 7.5 | 0 | 9.7 | 11.4 |
| Frequency | 2 | 6 | 19 | 3 | 19 | 51 | 37 | 7 | 3 | 31 | 39 |

### *Faulted Joints and Cracks*

Figure 2.3 shows the model for faulted joints and cracks. The model describes a gradual increase, though the data show a rapid rise after roughly 8 years, from 0 to 12 faulted joints and cracks per mile. CTR section 20586 averaged close to 60 spalled joints and cracks per mile at 7 years of age; since this single section exhibited almost four times the maximum number of faulted joints and cracks observed elsewhere, its data were considered unrepresentative of the population and were consequently not used in the regression. Even with this section removed, there is still considerable scatter evident in the data.

The occurrence of faulting at joints is heavily dependent on the presence or absence of load transfer devices. Faulting at cracks occurs as a result of a loss of aggregate interlock on both sides of the crack. The presence of dowels or other load transfer devices, type of coarse aggregate used in construction, and presence of reinforcing steel affect the formation of this distress type. The effects of these factors are not considered at this time, and therefore may contribute to observable scatter.

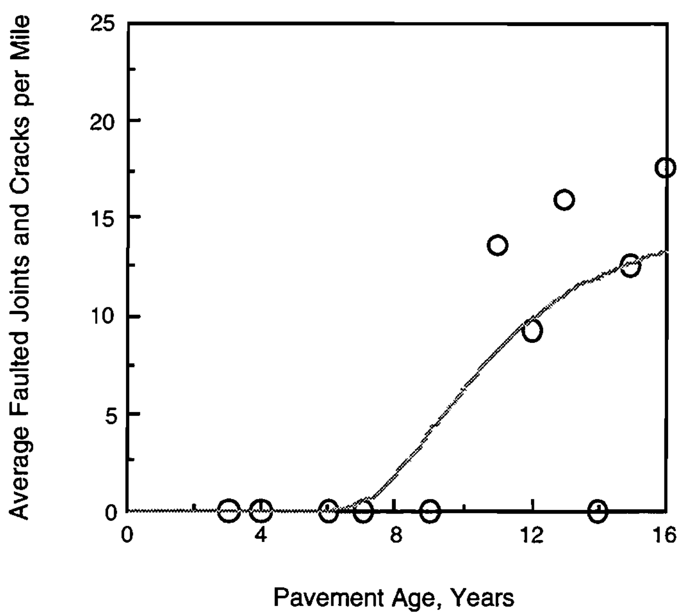


*Figure 2.3. Distress prediction model for faulted joints and cracks per mile*

*Table 2.5. Summary of data plotted in Fig. 2.3 for the faulted joints and cracks model*

| Age | 3 | 4 | 6 | 7 | 9 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Distress | 0 | 0 | 0 | 0 | 0 | 13.6 | 9.2 | 15.8 | 0 | 12.6 | 17.6 |
| Frequency | 2 | 6 | 3 | 26 | 1 | 39 | 18 | 1 | 1 | 17 | 3 |

### *Spalled Joints and Cracks*

Figure 2.4 shows the trend of the data for spalled joints and cracks with age. CTR section 20586 averaged over 160 spalled cracks per mile at 7 years of age, while other sections of approximately the same age showed almost no spalling at all. The data from section 20586 were considered unrepresentative of the whole population and were not considered in the regression.

These data also exhibit considerable scatter at ages greater than 9 years. This seems to indicate that spalling does not generally occur early in pavement life, but rather begins to occur after 8 to 10 years. Even after 10 years of age, the observable data in Figure 2.4 do not show the same increasing trend with age as do the other measures of pavement deterioration presented in this chapter.

The Texas Transportation Institute (TTI) at Texas A&M University is currently working on a mechanistic model to predict the development of crack spalling (Research Project 1244, conducted jointly with CTR). The preliminary findings of Project 1244 propose that the mechanism that leads to spalling occurs within or beneath a pavement structure soon after construction, then gradually develops until reaching the surface, not necessarily as a function of age (Refs 15, 16). This pattern conceptually fits the observable data in Figure 2.4. When completed, Project 1244 should provide useful details on the variables that most affect the development of spalled cracks, which will allow for refinement or replacement of this model.


*Figure 2.4. Distress prediction model for spalled joints and cracks per mile*

*Table 2.6. Summary of data plotted in Fig. 2.4 for the spalled joints and cracks model*

| Age | | 4 | 5 | 6 | 7 | 9 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average Distress | | 0 | 7 | 0 | 0 | 0 | 95 | 70 | 5 | 2 | 37 | 58 |
| Frequency | | 6 | 17 | 3 | 5 | 1 | 51 | 42 | 4 | 3 | 38 | 56 |

### *Transverse Cracks*

Figure 2.5 shows the trend of transverse crack development with age. The data show an increasing trend with age. Six observations (out of a total of over 700) taken in the 1994 survey from CTR sections 18602, 18606, and 18607 exhibited approximately 350 transverse cracks per mile at ages less than 7 years. Other sections less than 7 years old averaged less than 50 transverse cracks per mile. CTR sections 18602, 18606, and 18607 were considered unrepresentative of the population for this distress type and were not used for analysis.

Transverse crack formation in jointed pavements is affected by slab length, slab width, and pavement thickness. Because these factors are not considered as variables in this regression, they may contribute to observed scatter.

Everything else being equal, transverse cracking in continuous pavement is more affected by type of coarse aggregate used in construction than by pavement age (see Chapters 3 and 4). This may also be true for jointed pavement, though data from jointed pavements made with limestone aggregate were not sufficient for performing a legitimate cross-sectional analysis. While future data collection may show a separation in the population due to aggregate type, none is observable at this time.

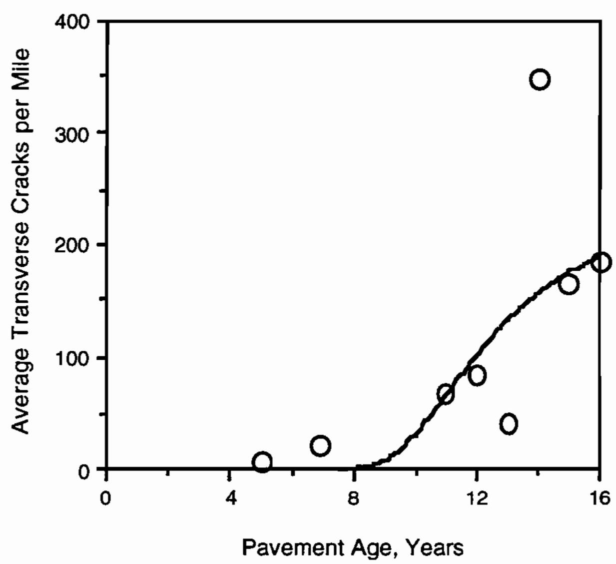


*Figure 2.5. Distress prediction model for transverse cracks per mile*

*Table 2.7. Summary of data plotted in Fig. 2.5 for the transverse cracks model*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Age | 5 | 7 | 11 | 12 | 13 | 14 | 15 | 16 |
| Average Distress | 6.0 | 19.4 | 67.4 | 83.4 | 40.6 | 346.7 | 165.0 | 182.8 |
| Frequency | 7 | 12 | 47 | 42 | 13 | 3 | 37 | 55 |

### *Longitudinal Cracks*

Longitudinal cracks are affected by a number of variables, including slab dimensions, traffic loading, structural support, and particularly the presence or absence of reinforcing steel. Figure 2.6 shows the trend of number of slabs with longitudinal cracks per mile. Two CTR sections (18164 and 20586) at age 7 contained 5 to 6 times more slabs with longitudinal cracks than observed anywhere else at any age. These two sections, considered unrepresentative of the population, were not used in analysis.


*Figure 2.6. Distress prediction model for slabs with longitudinal cracks per mile*

*Table 2.8. Summary of data plotted in Fig. 2.6 for the longitudinal cracks model*

| Age | 5 | 7 | 11 | 12 | 13 | 15 | 16 |
|---|---|---|---|---|---|---|---|
| Average Distress | 0 | 0 | 0.34 | 0 | 0.81 | 0 | 0 |
| Frequency | 36 | 3 | 62 | 40 | 13 | 33 | 56 |

## SUMMARY

The distress prediction models for jointed concrete pavement presented in this chapter all show considerable scatter, indicating that pavement age is not the only significant factor, and perhaps not the most important one, in predicting distress. All the models however describe reasonable trends of increasing distress as a function of age, and are a significant improvement over the preliminary models presented in Research Report 1908-1 (Ref 8). These models emphasize the need for regular data collection in order to better track pavement behavior over time. Their predictive accuracy should improve with future data collection and analysis performed as a part of the Texas PMIS.

# CHAPTER 3. DISTRESS PREDICTION MODELS FOR CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

## METHOD OF CALCULATING COEFFICIENT VALUES

The calibration of the sigmoidal distress prediction model to data from Texas pavements found in the CTR CRCP database was performed in two stages. In the first stage, only the shape parameters ($\alpha$, $\beta$, and $\rho$) for each distress type were considered. The second stage of the analysis involved calculation of additional modifying coefficients ($\sigma$, $\varepsilon$, and $\chi$) related to structural, environmental, and loading variables.

In some cases, there are many combinations of the three-shape variables that produce practically identical curves. Comparison of the shape variables presented here with those in Research Report 1908-1 (Ref 8) will show differences. The main reason for this is that, although the same database was used for the calculation, updates and refinements have been made since the earlier work was published. Table 3.1 summarizes the shape parameters for the CRCP distress prediction models calculated in this work.

*Table 3.1. Sigmoidal equation coefficient values*

| Distress Model | $\alpha$ | $\beta$ | $\rho$ |
|---|---|---|---|
| Severe Punchouts Per Mile | 101.517 | 0.438 | 538.126 |
| Portland Cement Patches Per Mile | 1293.840 | 0.536 | 399.932 |
| Asphalt Patches Per Mile | 96.476 | 0.375 | 824.139 |
| Loss of Ride Score | 0.720 | 0.060 | 59.780 |
| Cracks Per 100 Feet (SRG) | 35.370 | 0.861 | 0.059 |
| Percent Severely Spalled Cracks (SRG) | 1.690 | 22.090 | 10.270 |
| Cracks Per 100 Feet (LS) | 20.760 | 0.534 | 0.030 |
| Percent Severely Spalled Cracks (LS) | 0.120 | 1.279 | 8.538 |

1 foot=0.304 m; 1 mile=1.61 km

## DISTRESS PREDICTION MODELS

### *Severe Punchouts*

Figure 3.1 shows the basic model for severe punchouts per mile as a function of age. This curve shows the average frequency of punchout development with pavement age. In early years, pavements resist punchout development; but at advanced ages, the tendency to develop punchouts increases rapidly. The data points shown are the average values for all of the observations at each age. Some scatter is evident, which may be caused by varying district repair policies. Punchouts are usually repaired by patching or overlay, which removes them from this analysis. This means that roads that are well-maintained may have no evident punchouts at the time of a distress survey. The models for punchouts and patches can be added together to obtain a more comprehensive estimate of failures per mile.


*Figure 3.1. Distress prediction model for severe punchouts per mile (1 mile=1.61 km)*

### *Portland Cement Concrete Patches*

Figure 3.2 shows the model for portland cement concrete patches per mile. This curve is similar in shape to Figure 3.1, but begins to rise later than the model for punchouts. It shows an excellent predictive trend with age.

### *Asphalt Concrete Patches*

Figure 3.3 shows the basic model for asphalt concrete patches. Scatter in these data becomes more evident with increasing pavement age, or with increasing numbers of observed patches. This may be due to local repair policy — that is, the punchouts could have been repaired with portland cement concrete patches or by overlay.


*Figure 3.2. Distress prediction model for portland cement concrete patches per mile (1 mile=1.61 km)*


*Figure 3.3. Distress prediction model for asphalt concrete patches per mile (1 mile=1.61 km)*

It should be noted that the models shown in Figures 3.1, 3.2, and 3.3 are physically related. Severe punchouts that are observed in a condition survey are repaired by either patching or overlay by the time of the next survey. This means that these three distress types (portland cement concrete patches, asphalt concrete patches, and severe punchouts) are all indicators of a localized failure in the pavement structure, whether past or present. These three models should perhaps be considered in combination rather than separately. In Chapter 5, a recommended combined model for CRCP failures per mile is used by combining all three aforementioned distress types.

### *Loss of Ride Score*

Ride score is a measure of the smoothness of a pavement surface. It is usually collected by both subjective means (using human raters) and by objective means (using instruments). The instrument ratings, which are faster and cheaper to undertake over a large pavement network, are then calibrated to the subjective ratings using observable physical characteristics. Numerical scores are given to the overall smoothness of a section, usually on a scale of 0 (not passable) to 5 (perfectly smooth). This scaled score is called the Present Serviceability Index (Ref 2).

Loss of ride score is modeled as fractional Present Serviceability Index (PSI) loss vs. age, normalized to a hypothetical initial Serviceability Index (SI) of 4.5. The normalized SI loss (NSL) was calculated using the following equation:

$$NSL = (4.5 - PSI) / 4.5$$

NSL ranges from 0 ($PSI \geq 4.5$) to 1 ($PSI = 0$). As an example, if the present serviceability index (PSI) of a section is 2.5, then the section is assumed to have lost 2 SI units of ride quality, giving an NSL of 0.44. This means the section has lost 44 percent of its initial smoothness. Figure 3.4 shows the best fit to the data used in this study.


*Figure 3.4. Distress prediction model for loss of ride score*

### *Transverse Cracks*

Transverse cracks, as stated previously, are not specifically a distress, but may be an indicator of pavement condition that leads to distress. Frequent closely spaced transverse cracks can combine with longitudinal cracks to form punchouts. The model chosen for crack spacing is numerically calibrated to calculate transverse cracks per 161 m (100 feet) of pavement length, since continuously reinforced concrete pavement has no discrete slab length.

*Need for separate models by coarse aggregate type:* An analysis of the variance of crack manifestation data with other variables in the database has shown that crack spacing and crack spalling are more affected by the type of coarse aggregate used in construction than by age (Refs 8, 17). Figure 3.5 displays the best fit of the sigmoidal equation to all data without consideration of coarse aggregate type.

Figure 3.5 shows no clear trend with age, and the predictive accuracy of this model is limited. However, if the data are split into populations of pavements constructed with river gravel and those with limestone, two separate populations clearly emerge. A single model for crack spacing, which includes both pavements constructed with siliceous river gravel and those with limestone, does justice to neither. For this reason, two curves were proposed in the original calibration of the sigmoidal equation (Ref 8). Figure 3.6 shows the two suggested models.


*Figure 3.5. Distress prediction model for average transverse crack spacing (1 foot=0.304 m)*

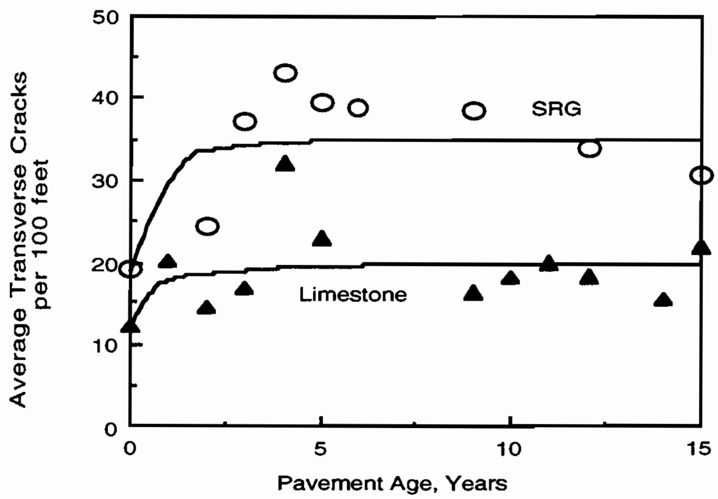


*Figure 3.6. Separate distress prediction models for crack spacing by coarse aggregate type (1 foot=0.304 m)*

*A composite model for both aggregates:* At the present time, the PMIS program at TxDOT uses only one model for crack spacing and for crack spalling (the one calibrated for limestone pavements), despite the recommendations of earlier research. This decision was made for two reasons. First, the structure of the PMIS algorithm at TxDOT was not designed to accommodate two models for the same distress type. A further drawback to the use of two models is that the coarse aggregate type used in construction was not always known. Two solutions to this problem are currently available.

First, Chapter 4 provides details of the results of a survey of the district engineering offices across the state. This survey asked a knowledgeable source from each district office about the local practices regarding coarse aggregate type used for portland cement concrete pavements. The results of this survey provide an estimate of coarse aggregate type used by county when this information is unavailable on an individual project basis. Since this information will make use of two separate models practically possible, coefficients have been calculated for both.

The second solution is to change from the model for limestone aggregate (currently in use by the PMIS) to the model for siliceous river gravel aggregate. The siliceous river gravel model generally predicts higher values, which would compensate for the inability of a structural coefficient ($\sigma$) to sufficiently change the shape of the average curve as intended.

The modifying coefficients for structural, environmental, and traffic loading in the general equation were intended to provide an adjusting constant that would modify the shape of the general distress prediction curve to improve accuracy with more information about the pavement section. However, attempts at changing the shape of the prediction curve have proven to be less effective than originally hoped. In particular, any single model for CRCP crack spacing does not have the flexibility to adjust adequately to dividing the population, particularly by coarse aggregate type. To illustrate, Figure 3.7 shows the effect of varying any of the coefficients $\sigma$, $\varepsilon$, or $\chi$. This figure illustrates that for a distress type such as crack spacing (zero initial distress, then rapid rise in predicted numbers of cracks as they form in the first few years, then relatively constant crack spacing for the rest of the life of the model), variation of the modifying coefficient cannot successfully model two populations, such as those shown in Figure 3.6. The mathematical form of the chosen equation makes an increase over the maximum predicted level of the original equation ($\alpha$) impossible. However, the curve can be modified to fit amounts smaller than the maximum with moderate accuracy. This observation makes it clear that if only one model is used, it should be the one for pavements constructed with river gravel.

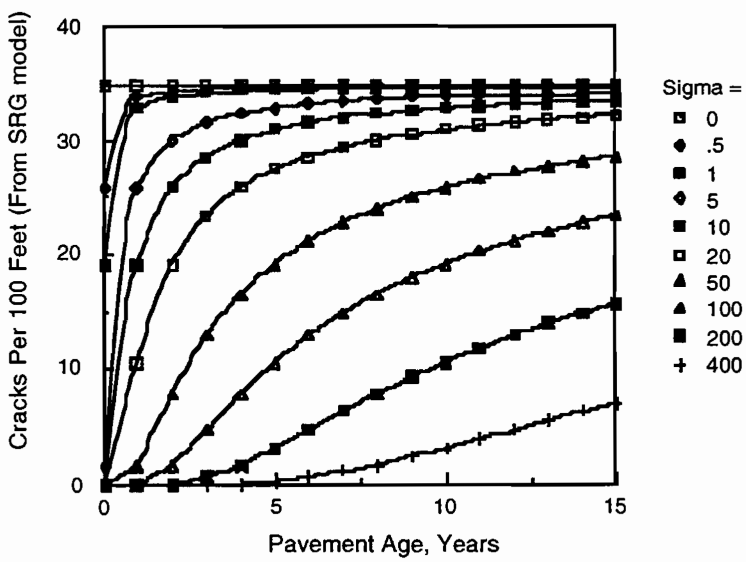


*Figure 3.7. Modification of crack spacing distress prediction model by structural factor (1 foot=0.304 m)*

***Severely Spalled Cracks***

Crack spalling, like crack spacing, is more affected by coarse aggregate type than by age. However, crack spalling data tend to remain at small values for long periods of time, then increase as the pavement begins to wear out. The problem with using the same model to predict spalling in both limestone and siliceous river gravel populations is that the distress levels predicted for pavements with siliceous gravel are a different order of magnitude from those with limestone. Figure 3.8 shows the separate models for the two populations, along with the average population data points.

The modifying effect of using one coefficient on the form of the crack spalling models is also not as effective as originally expected in describing the behavior of two different populations. Figure 3.9 shows the effect on the siliceous river gravel curve of varying the structural coefficient ($\sigma$). As discussed above, two models based on the different coarse aggregate types are again suggested, assuming that the results of the survey in Chapter 4 will provide enough information to make this possible. Alternatively, since the siliceous river gravel curve can be modified to fit the range of the limestone data, and since the limestone curve *cannot* be modified to fit the river gravel data, the SRG curve should be used as the general curve if only one is used.


*Figure 3.8. Distress prediction models for crack spalling: SRG, LS, and average populations (1 foot=0.304 m)*

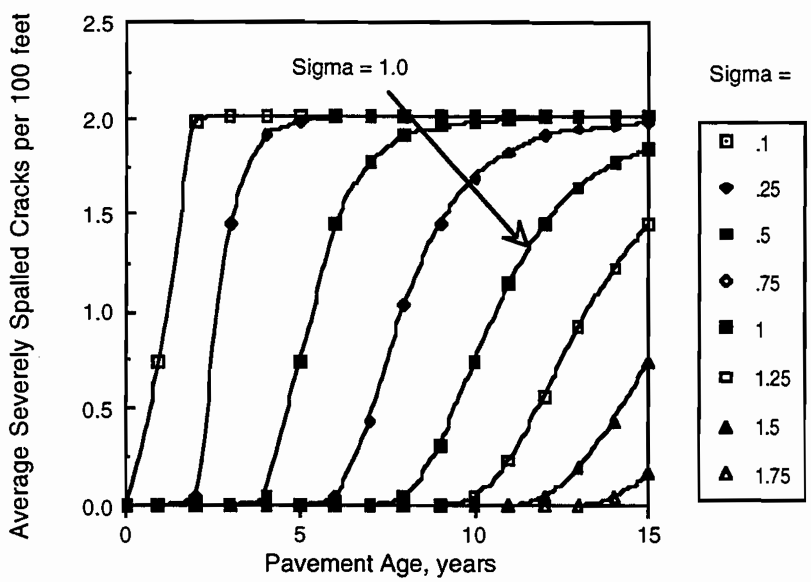


*Figure 3.9. Modification of SRG crack spalling model by a constant coefficient ($\sigma$)*
*(1 foot=0.304 m)*

# CHAPTER 4. MODIFICATION OF THE GENERAL DISTRESS PREDICTION MODELS BY ADDITION OF STRUCTURAL, CLIMATIC, AND TRAFFIC COEFFICIENTS FOR CRCP

## MODIFYING COEFFICIENTS

The desired effect of the structural, climatic, and traffic loading coefficients specified in the Texas PMIS distress prediction model is to modify the average equation to be as accurate as possible, given the data available on a specific project. The algorithm that uses the distress prediction equations incorporates as much information as is available about a particular section. The general equation makes use of only the variables $\alpha$, $\beta$, and $\rho$, which have numerical values calibrated to all observed data for a particular distress type. The variables for traffic loading ($\chi$), climatic loading ($\varepsilon$), and structural factors ($\sigma$) allow modification of the distress prediction model to fit the circumstances of an individual project. These variables are originally set equal to 1 in the general equation, but if data are available from construction records, traffic counts, weather stations, or other sources of information that affect these variables, an appropriate constant is substituted. This method is already in use and has been proven successful in distress prediction for flexible pavements.

The method for calculating the various additional modifying factors was chosen based on the theory that the average population for a distress type could be split into two or more distinct groupings of distress as a function of observed variables. For example, PCC pavements made with siliceous river gravel coarse aggregate generally contain greater damage, on average, than pavements made with dolomitic limestone, as shown in Figures 3.6 and 3.8. The same sort of groupings can be shown for variables such as soil type and sub-base type.

### *Analysis of Variance (ANOVA) To Determine Specific Variables*

An analysis of variance (ANOVA) was performed (using the procedure in SAS) to determine which of these variables or combinations thereof were significant in the prediction of each distress type. Each variable in the CTR and PES database that was identified as significant by the analysis of variance was placed into one of the three modifying categories shown in Table 4.1; the results of the analysis of variance are shown in Table 4.2. It is important to note that the analysis of variance does not suggest that these are the only variables that are significant for distress prediction, but, instead, suggests that these data in the CTR database make the most significant difference in the models calibrated from the same data.

*Table 4.1. Identification of factors for modifying coefficients*

| | |
|---|---|
| Structural Factors: | Coarse aggregate type, Soil type, Sub-base type |
| Climatic Factors: | Average annual rainfall, Average annual minimum temperature |
| Traffic Factors: | 18-kip Equivalent Single Axle Loads per year |

1 kip=4.448 kN

*Table 4.2. Significant variables for CRCP distress models from analysis of variance using CTR database*

| Distress Type | Significant Variables |
|---|---|
| Severe Punchouts | Coarse Aggregate Type, Average Annual Minimum Temperature, Soil Type, Average Annual Rainfall |
| Portland Cement Concrete Patches | Coarse Aggregate Type, Sub-base Type, Average Annual Rainfall |
| Asphalt Concrete Patches | Average Annual Minimum Temperature, Average Annual Rainfall |
| Transverse Crack Spacing | (Average Annual Minimum Temperature•Coarse Aggregate Type), (18-kip ESALs per year•Average Annual Rainfall) , Average Annual Rainfall |
| Crack Spalling | Coarse Aggregate Type, Average Annual Rainfall , Sub-base Type |
| Loss of Ride Score | Soil Type, Sub-base Type, Average Annual Rainfall |

1 kip=4.448 kN

### *Method of Division of Variable Populations*

Each distress variable in the CTR database is divided into discrete sections. The two most commonly used coarse aggregate types (CATs) in Texas are siliceous river gravel (SRG) and dolomitic limestone (LS). Soils in the state include various sands, silts, and clays. Soil type in the database is grouped into high-swelling (H) and low-swelling (L) categories. Sub-base types are divided into four categories: asphalt treated (1), cement treated (2), lime treated (3), and crushed stone (4).

For significant factors with continuous distributions, the population of observed data was divided into halves for calculation of the appropriate constant. Average annual rainfall per year was divided into upper and lower halves at the level of 76.2 cm per year (H and L). An average minimum temperature level of -1.1 C was selected as the dividing line between "high temperature" and "low temperature" regions (H and L). We used 80-kN equivalent single axle loads (ESALs), 1.4 million ESALs per year, as the dividing line between high and low traffic (H and L) (Refs 8, 16, 17, 18).

### *Numerical Values for Coefficients*

Each modifying coefficient was calculated using the NLIN (non-linear regression) technique in SAS in a manner very similar to that used for calculation of the general shape factors. For this analysis, the $\alpha$, $\beta$, and $\rho$ calculated for the average distress prediction equation were set as constants, and the only variable was the $\sigma$, $\varepsilon$, or $\chi$ coefficient being examined. The NLIN procedure was used to calculate the best value of the coefficient (or fit of the equation modified by a single coefficient) that fits the relevant data to the coefficient being calculated. Each set of data and its corresponding best fit were displayed and visually evaluated for reasonable validity.

In some cases, the data are insufficient to provide for a reasonable cross-sectional analysis of pavement performance over the 15-year range of the model. It has been recommended in these cases that the modifying constants be set equal to 1 until further data collection makes a reasonable value possible. Tables 4.3 through 4.11 list the recommended modifying coefficients for each distress type.

*Table 4.3. Modifying coefficients for severe punchouts per mile distress prediction model*

| | | |
|---|---|---|
| if | CAT = SRG | $\sigma = 0.791$ |
| | CAT = LS | $\sigma = 1.248$ |
| if | soil type = H | $\sigma = 1.046$ |
| | soil type = L | $\sigma = 0.977$ |
| if | CAT = SRG and soil type = H | $\sigma = 0.785$ |
| | CAT = LS and soil type = H | $\sigma = 1.0$ |
| | CAT = SRG and soil type = L | $\sigma = 0.819$ |
| | CAT = LS and soil type = L | $\sigma = 1.123$ |
| if | temp = H | $\varepsilon = 0.913$ |
| | temp = L | $\varepsilon = 1.484$ |
| if | rain = H | $\varepsilon = 0.919$ |
| | rain = L | $\varepsilon = 1.318$ |
| if | temp = H and rain = H | $\varepsilon = 0.883$ |
| | temp = H and rain = L | $\varepsilon = 1.187$ |
| | temp = L and rain = H | $\varepsilon = 1.0$ |
| | temp = L and rain = L | $\varepsilon = 1.143$ |

*Table 4.4. Modifying coefficients for portland cement patches per mile distress prediction model*

| | | |
|---|---|---|
| if | CAT = SRG | $\sigma = 0.829$ |
| | CAT = LS | $\sigma = 1.205$ |
| if | sub-base type = 1 | $\sigma = 1.232$ |
| | sub-base type = 2 | $\sigma = 0.999$ |
| | sub-base type = 3 | $\sigma = 0.968$ |
| | sub-base type = 4 | $\sigma = 0.787$ |
| if | sub-base type = 1 and CAT = SRG | $\sigma = 1.070$ |
| | sub-base type = 2 and CAT = SRG | $\sigma = 0.824$ |
| | sub-base type = 3 and CAT = SRG | $\sigma = 1.079$ |
| | sub-base type = 4 and CAT = SRG | $\sigma = 0.485$ |
| | sub-base type = 1 and CAT = LS | $\sigma = 1.500$ |
| | sub-base type = 2 and CAT = LS | $\sigma = 1.195$ |
| | sub-base type = 3 and CAT = LS | $\sigma = 1.0$ |
| | sub-base type = 4 and CAT = LS | $\sigma = 1.0$ |
| if | rain = H | $\varepsilon = 0.924$ |
| | rain = L | $\varepsilon = 1.276$ |

*Table 4.5. Modifying coefficients for asphalt patches per mile distress prediction model*

| | | |
|---|---|---|
| if | CAT = SRG | $\sigma = 0.948$ |
| | CAT = LS | $\sigma = 1.001$ |
| if | temp = H | $\varepsilon = 0.890$ |
| | temp = L | $\varepsilon = 1.471$ |
| if | rain = H | $\varepsilon = 1.034$ |
| | rain = L | $\varepsilon = 0.967$ |
| if | temp = H and rain = H | $\varepsilon = 1.015$ |
| | temp = H and rain = L | $\varepsilon = 0.502$ |
| | temp = L and rain = H | $\varepsilon = 1.244$ |
| | temp = L and rain = L | $\varepsilon = 1.0$ |

*Table 4.6. Modifying coefficients for loss of ride score distress prediction model*

| | | |
|---|---|---|
| if | soil type = H | $\sigma = 1.647$ |
| | soil type = L | $\sigma = 0.812$ |
| if | sub-base type = 1 | $\sigma = 0.409$ |
| | sub-base type = 2 | $\sigma = 4.870$ |
| | sub-base type = 3 | $\sigma = 1.072$ |
| | sub-base type = 4 | $\sigma = 0.132$ |
| if | rain = H | $\varepsilon = 0.448$ |
| | rain = L | $\varepsilon = 0.931$ |

*Table 4.7. Modifying coefficients for cracks per 161 m distress prediction model (if CAT = SRG)*

| | | |
|---|---|---|
| if | rain = H | $\varepsilon = 1.026$ |
| | rain = L | $\varepsilon = 0.0$* |
| if | temp = H | $\varepsilon = 1.206$ |
| | temp = L | $\varepsilon = 0.0$* |
| if | traffic = H | $\chi = 1.301$ |
| | traffic = L | $\chi = 0.942$ |

*Zero $\varepsilon$ reduces $D = \alpha$ , a constant line which is reasonable for crack spacing.

*Table 4.8. Modifying coefficients for cracks per 161 m distress prediction model (if CAT = LS)*

| | | |
|---|---|---|
| if | rain = H | $\varepsilon = 1.299$ |
| | rain = L | $\varepsilon = 1.0$ |
| if | temp = H | $\varepsilon = 1.239$ |
| | temp = L | $\varepsilon = 1.0$ |
| if | traffic = H | $\chi = 1.124$ |
| | traffic = L | $\chi = 0.967$ |

*Table 4.9. Modifying coefficients for percent severely spalled cracks distress prediction model (if CAT = SRG)*

| | | |
|---|---|---|
| if | rain = H | $\varepsilon = 1.091$ |
| | rain = L | $\varepsilon = 0.925$ |
| if | sub-base type = 1 | $\sigma = 1.285$ |
| | sub-base type = 2 | $\sigma = 0.880$ |
| | sub-base type = 3 | $\sigma = 1.100$ |
| | sub-base type = 4 | $\sigma = 1.375$ |

*Table 4.10 Modifying coefficients for percent severely spalled cracks distress prediction model (if CAT = LS)*

| | | |
|---|---|---|
| if | rain = H | $\varepsilon = 0.893$ |
| | rain = L | $\varepsilon = 1.607$ |
| if | sub-base type = 1 | $\sigma = 0.968$ |
| | sub-base type = 2 | $\sigma = 1.201$ |
| | sub-base type = 3 | $\sigma = 0.953$ |
| | sub-base type = 4 | $\sigma = 0.556$ |

## A TEST OF SIGNIFICANCE OF THE MODIFYING COEFFICIENTS

The modifying coefficients were intended to make the distress prediction models more accurate as additional data on the pavement structure, environment, or history became available. After calculation of the best values of the $\sigma$, $\varepsilon$, and $\chi$ coefficients for the data available, their accuracy was tested against the general equation. The purpose of this test was to determine whether prediction accuracy of the distress models was significantly improved by using the modifying coefficients.

### *Method of Conducting the Test*

For each observation (a condition survey of a specific pavement section at a specified time) in the database, two estimates were made of the distress types — one each with and without coefficients.

$$\text{Distress predicted (with)} = \alpha\, e^{-\left(\frac{\chi\,\varepsilon\,\sigma\,\rho}{\text{Age}}\right)^{\beta}}$$

$$\text{Distress predicted (without)} = \alpha\, e^{-\left(\frac{\rho}{\text{Age}}\right)^{\beta}}$$

An absolute error term was then calculated for each prediction as follows:

error (with) = observed - predicted (with coefficients)

error (without) = observed - predicted (without coefficients)

For a large number of error observations as defined above (greater than 260 in this case), these observations can be assumed to be normally distributed with mean m=0 and variance $s^2$. If the coefficients are helpful in prediction, then the error distribution with the coefficients should have a smaller variance than the error distribution without the coefficients. In statistical terminology, this can be stated as:

$$H_o\!: \ \sigma^2_{wo} = \sigma^2_{w}$$

vs.

$$H_a\!: \ \sigma^2_{wo} > \sigma^2_{w}$$

The test statistic for this hypothesis was calculated by the following formula:

$$F = \frac{S^2_{wo}}{S^2_{w}}$$

For 120 degrees of freedom in both the numerator and denominator (the limit for most statistical tables), the hypothesis is rejected for values of $F \geq 1.26$, with a 10 percent probability of type I error. For an infinite number of degrees of freedom in both numerator and denominator, the hypothesis is rejected for values of $F \geq 1$. The degrees of freedom for this situation are approximately 270. The test statistics (F) calculated for the various distress types are given in the Table 4.11:

*Table 4.11. Test statistics for significance of predictive accuracy improvement*

| Distress Type | Test Statistic 'F' | Conclusion |
|---|---|---|
| Severe Punchouts Per Mile | 0.994 | No Improvement |
| Portland Cement Patches Per Mile | 1.268 | Improvement |
| Asphalt Patches Per Mile | 1 | No Improvement |
| Loss of Ride Score | 1.08 | No Improvement |
| Cracks Per 100 Feet | 0.56 | No Improvement |
| Percent Spalled Cracks | 1.333 | Improvement |

The significance test for the distress types, cracks per 161 m and percent spalled cracks were conducted by using shape parameters for SRG coarse aggregate type. SRG models are recommended, if a single model is used in PMIS.

***Results of the Test***

Table 4.11 shows that for most cases, such as severe punchouts, asphalt patches, loss of ride score, and cracks per 161 m, the data do not present enough evidence to reject the hypothesis that no significant improvement is made. However, significant result is obtained for PCC patches and percent spalled cracks to accept the hypothesis that significant improvement is made. The most likely explanation is that the interaction of the modifying coefficient variables causes an increase in predictive error rather than a decrease, as was anticipated. The $\sigma$, $\varepsilon$, and $\chi$ variables as defined now may not be sufficient to explain the variability in the model, even though the data that these coefficients represent have been shown to be significant.

***Comparison of Models with and without Modifying Coefficients***

It was proved statistically that no significant increase in predictive accuracy of the distress models for punchouts, asphalt patches, ride score and transverse cracks was achieved by using the structural, climatic and traffic modifying coefficients $\sigma$, $\varepsilon$, and $\chi$. However, the distress models for PCC patches and crack spalling did show some statistical significance for the use of modifying coefficients. To elaborate the distress prediction trends, plots were developed for each model with and without using modifying coefficients. Extreme numerical values were selected among the modifying coefficients to show the range of modified distress values for each model. The following cases were selected to show the distress prediction trends by using $\sigma$, $\varepsilon$, and $\chi$.

*Distress Model for Portland Cement Concrete Patches:* The distress model for PCC patches showed some potential for improvement in distress prediction by using the modifying coefficients, though this result had weak statistical significance. A test statistic $F > 1.26$ was the test criterion, and a test statistic value of 1.268 was observed, which was just fractionally greater than the criterion value. A plot of distress values with and without using modifying coefficients showed some relatively large shift of the curve. The distress curves for $\sigma = 1.0$ and $\sigma = 0.787$ showed the distress values of 1.0 and 2.2 for year 10, and 3.9 and 7.9 for year 15. Although these distress values showed some relatively large change in the predicted distress values, the statistical power of the test is still not convincing enough to recommend the use of modifying coefficients. Furthermore, it is recommended later in the report that punchouts, PCC patches, and asphalt patches be combined into in a single failures per mile distress model. Therefore, we recommend not using modifying coefficients for PCC patches distress model at this stage of the PMIS implementation. Figure 4.1 shows the distress curves with and without using modifying coefficients.


*Figure 4.1. Distress curves for PCC patches with and without modifying coefficients (1 mile=1.61 km)*

*Distress Model for Average Transverse Crack per 161 m:* The distress model for transverse crack spacing showed least improvement in the predictive accuracy by using the modifying coefficients. A test statistic F = 0.56 was obtained indicating an increase in variance of the absolute error term, rather than an anticipated decrease with the use of modifying coefficients. The plots of distress curves showed a minor shift by using modifying coefficients. Figure 4.2 shows the plotted distress curves.

*Distress Model for Average Severely Spalled Cracks per 161 km:* The distress model for crack spalling was another model that showed the potential for improvement in distress prediction values by using the modifying coefficients. A test statistic value of 1.333 was observed for the crack spalling distress model. A plot of distress values with and without using modifying coefficients showed a relatively large shift of the curves for SRG coarse aggregate type. The distress curves for $\sigma = 1.0$ and $\sigma = 1.375$ showed the distress values of 0.5 and 0 for year 10, and 1.9 and 1.0 for year 15. Crack spalling, a complex mechanism, is not simply a function of age.

Some further research is needed before recommending the use of the coefficients for crack spalling. The limited scope of this study precluded an investigation into all the different factors affecting crack spalling. An ongoing unpublished report by CTR/TTI under TxDOT Project 1244 has identified many complex scenarios for crack spalling (Refs 15, 16). Some further conclusions can be drawn after all the results of Research Study 1244 are published. Therefore, it is recommended that the use of modifying coefficients for crack spalling be deferred at this stage of PMIS implementation.

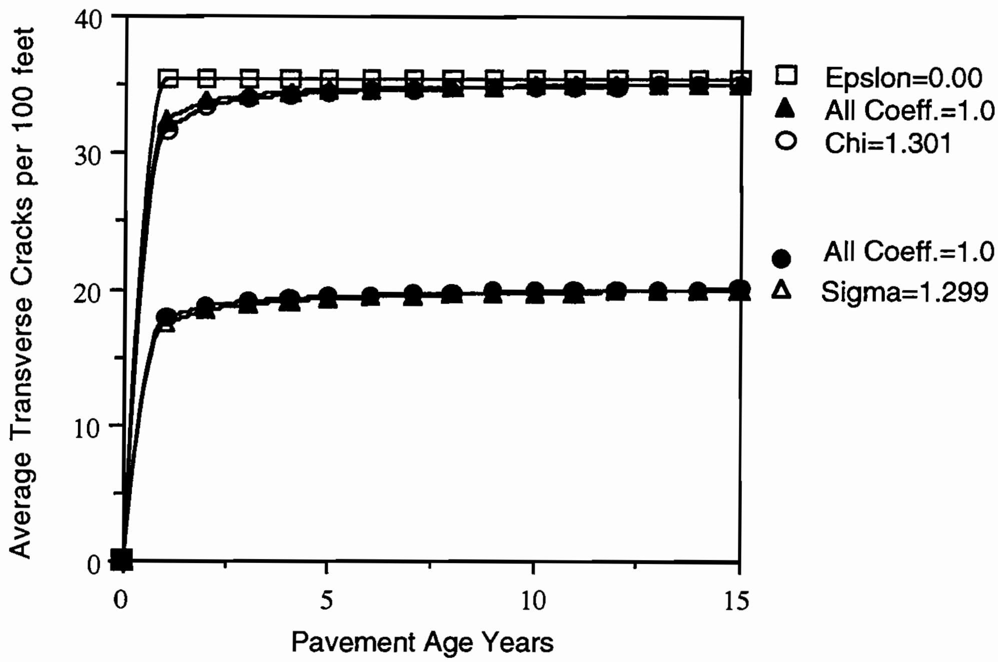


*Figure 4.2. Distress curves for transverse crack spacing with and without modifying coefficients (1 foot=0.304 m)*

The numerical values associated with the distress curves for limestone coarse aggregate type were very small and had little practical significance. Furthermore, the siliceous river gravel coarse aggregate type model is recommended for use as a single distress model. It was therefore concluded that the modifying coefficients for the spalled cracks distress model should not be used at this stage. Figures 4.3 and 4.4 shows the distress curves with and without using coefficients.

Considering aforementioned factors, it can be concluded that the structural, environmental, and traffic modifying coefficients $\sigma$, $\varepsilon$, and $\chi$ should remain equal to 1.0 in distress prediction equation at this stage of PMIS implementation.

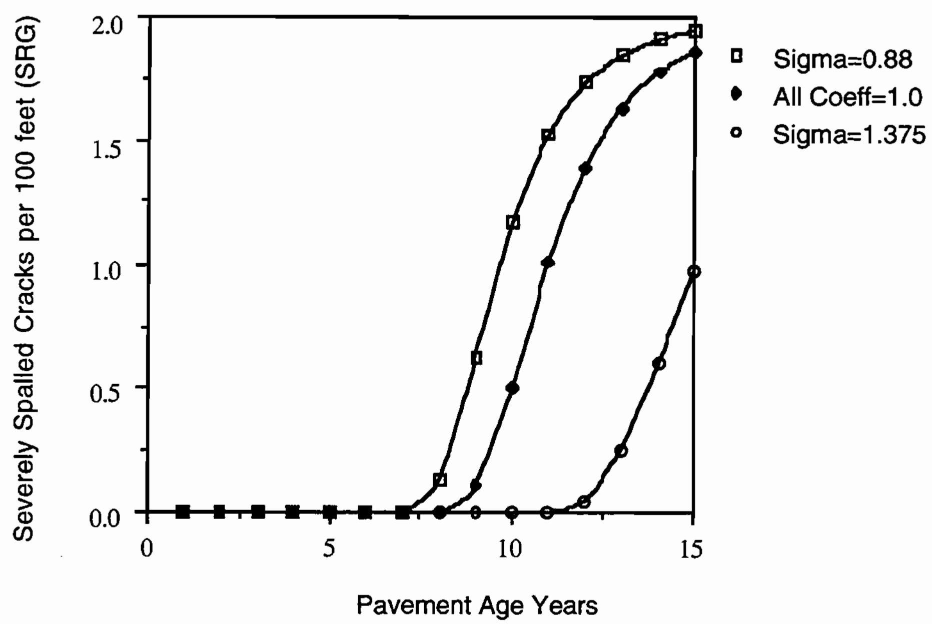


*Figure 4.3. Distress curves for severely spalled cracks for CAT = SRG with and without modifying coefficients (1 foot=0.304 m)*


*Figure 4.4. Distress curves for severely spalled cracks for CAT = LS with and without modifying coefficients (1 foot=0.304 m)*

## A TEST OF THE MODELS USING 1994 DISTRESS SURVEY DATA

The 1994 distress survey conducted by Project 1342 provided a means to test the models on data that were not used in their calibration. Twenty-three sections surveyed fall into the 15-year predictive range of the PMIS models presented above. In particular, the 1994 data contained very detailed crack spacing information. These data are plotted in Figure 4.5. Also shown in this figure are the predictive equations for crack spacing in pavements made with river gravel and with limestone (see Figure 3.6). Sections made with river gravel are shown with circles, and sections made with limestone are shown with triangles. The 'x' plotted in Figure 4.5 on the LS predictive curve represents severe points from a experimental project using SRG; it is probably not representative of normal construction practice. Generally, this figure reinforces the strong relationship between crack spacing and coarse aggregate type, and shows a reasonable accuracy in prediction.

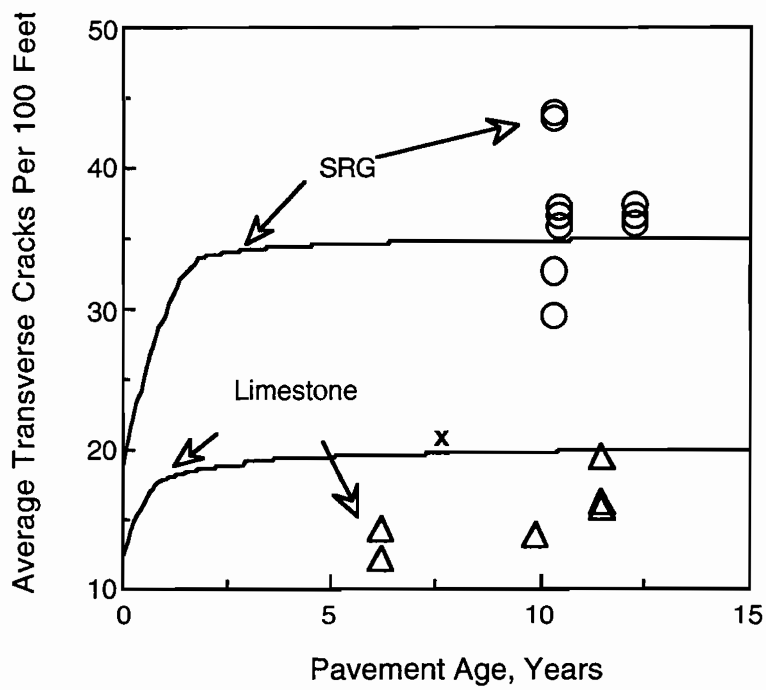


*Figure 4.5. 1994 distress survey crack spacing data (1 foot=0.304 m)*

Predictive accuracy of the other distress prediction models (portland cement concrete patches, asphalt concrete patches, severe punchouts) applied to the 1994 data was not as good. Figures 4.6, 4.7, and 4.8 show these data plotted against their respective prediction equations.

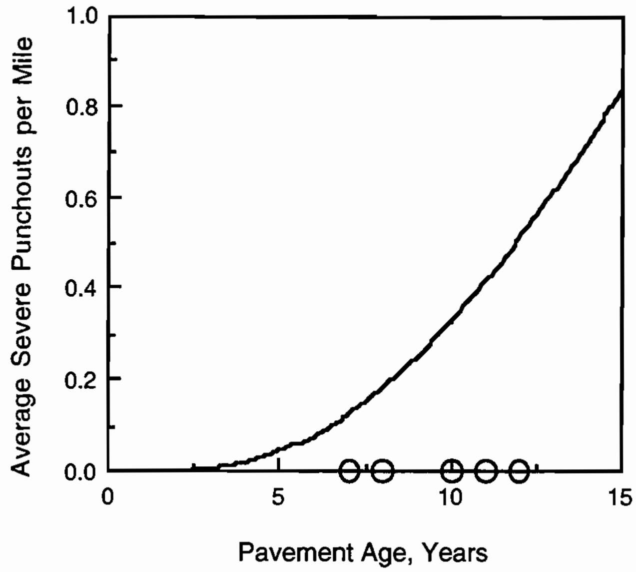


*Figure 4.6. Severe punchouts per mile prediction vs. 1994 condition survey data (1 mile=1.61 km)*

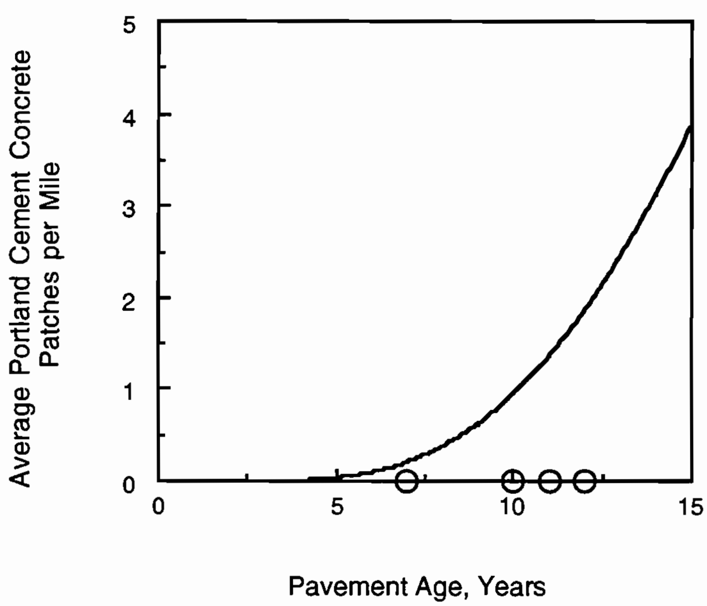


*Figure 4.7. Portland cement concrete patches per mile prediction vs. 1994 condition survey data (1 mile=1.61 km)*

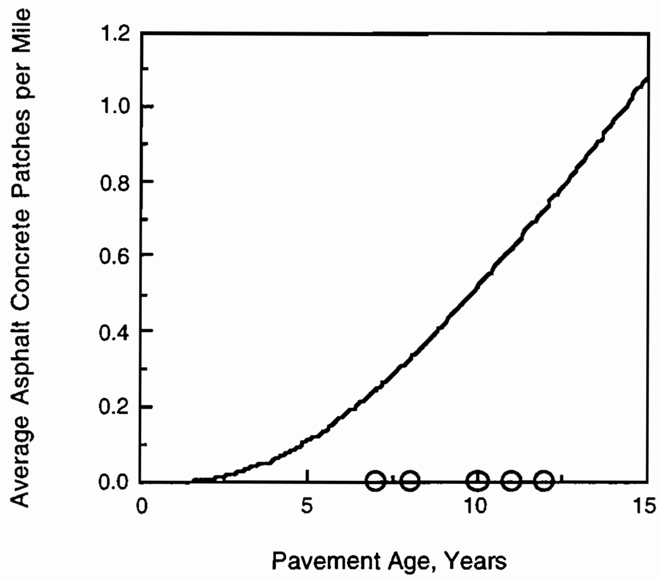


*Figure 4.8. Asphalt concrete patches per mile prediction vs. 1994 condition survey data (1 mile=1.61 km)*

The general trend shown in these figures is that the sections surveyed in 1994 show very little to no distress as measured by punchouts or patches. Three explanations of this phenomenon are possible. First, only 23 data points fall into the predictive range of the models. This small sample size may not truly represent pavement conditions across the state. Second, the lack of distress seen at ages 7 to 12 years may be the effect of improved construction practices. The data points shown in Figures 4.6, 4.7, and 4.8 represent pavements that were constructed in the early to mid-1980s, while those points that were used to calibrate the prediction equations included some pavements that were constructed soon after the development of continuously reinforced concrete pavement. A third explanation is that the lack of distress shows an increased commitment by TxDOT to pavement maintenance, particularly crack sealing. Furthermore, an increased use of tied shoulders and better subbases has reduced distress. Regular maintenance can help to prevent the start and spread of punchouts (and thus patches). An increased commitment to maintenance may be due to the influence of early pavement management work in Texas. This shows evidence of the advantages of a properly used pavement management system.

# CHAPTER 5. A SURVEY OF COARSE AGGREGATE USAGE IN RIGID PAVEMENT IN TEXAS

## OBJECTIVE

Chapter 3 listed coefficients for improving existing distress prediction models for portland cement concrete pavements in Texas. For some distress types, it was shown that the type of coarse aggregate used in construction was one of the factors that most affected the equations, sometimes having a more significant impact on distress prediction than pavement age. The original models proposed to TxDOT for crack spacing and crack spalling, in particular, suggested separate models for pavements made with siliceous river gravel and with limestone (Ref 8).

One of the biggest obstacles to using two models is that information on which type of aggregate had been used in construction was not always available for many of the projects in the state. The current programming of the TxDOT PMIS for future network condition optimization uses the basic equation — unless more detailed information is available for each project. The lack of information on aggregate type used in construction, therefore, threatened and severely limited the usefulness of the model modifications for structural effects. The accuracy of the models for crack spacing and crack spalling, in particular, would be affected.

## SOURCES OF INFORMATION

### *The CTR Databases*

The most readily available source of information on coarse aggregate use was found in the research databases at CTR. The CRCP and JCP databases from which the models in Chapters 2 and 3 were calculated contain survey information on pavement sections scattered across the state. In most cases, at least one of the database entries for a particular section includes the coarse aggregate type used in construction. It was hypothesized that sections of unknown aggregate that were located in the same geographic region as those with known aggregate would probably contain the same type. This information was examined and plotted on a state map to identify completeness and/or geographic trends. The information available from the CTR databases is shown in Figure 5.1. There is no obvious geographic trend, and the information is not as complete as was hoped. Other sources were therefore consulted.

### *Location of SRG Mining Quarries*

The second source of information, also easily available, was the location of river gravel sources. It was assumed that pavement sections located close to a source of river gravel would have a tendency to use such close-at-hand material. An investigation of the locations of river gravel sources in Texas, and estimates of coarse aggregate use based on proximity of location, was undertaken by Saeed in 1993. Figure 5.2 shows the estimate of coarse aggregate use by proximity to a gravel source.

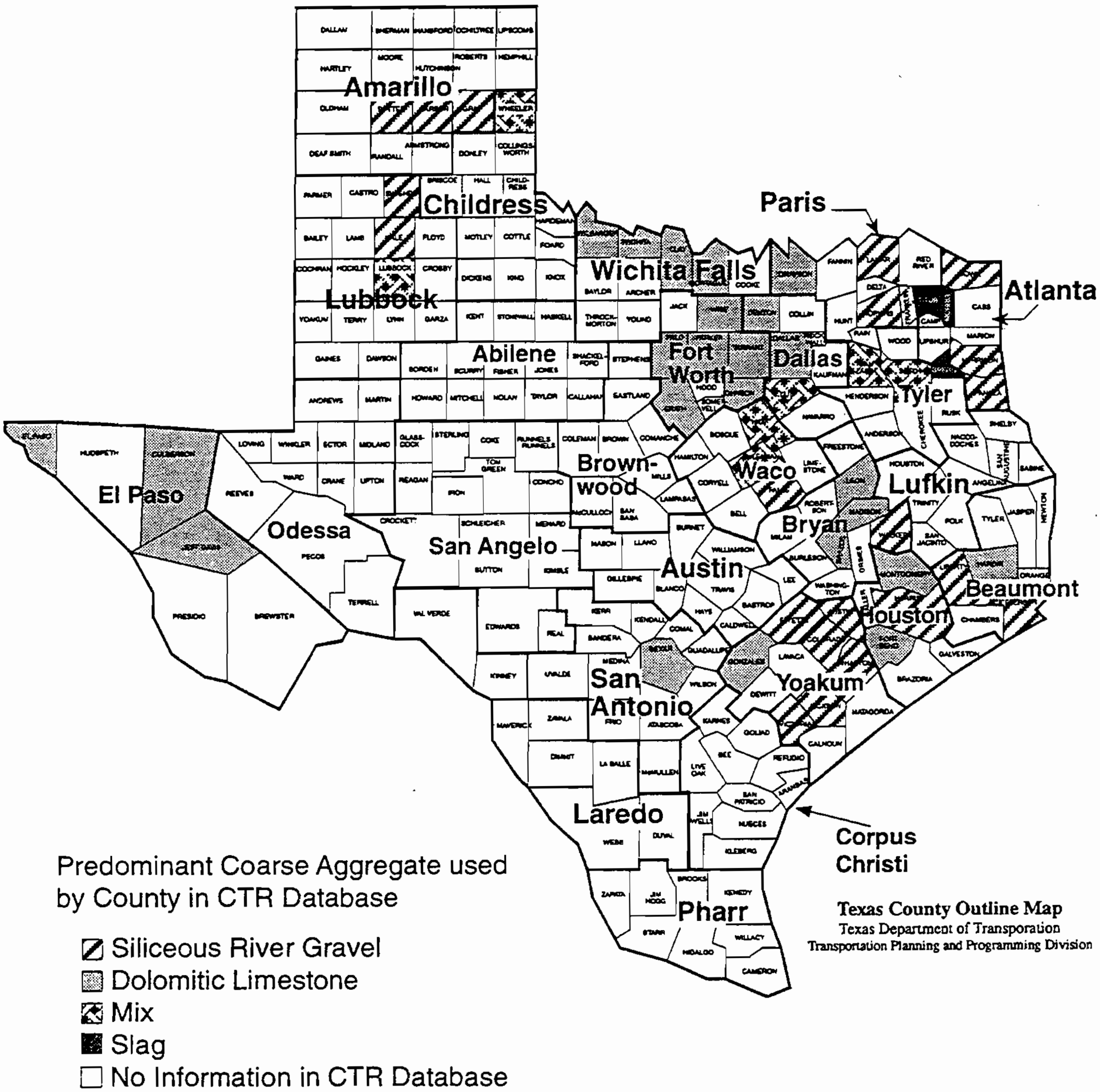


*Figure 5.1 Information from CTR databases*

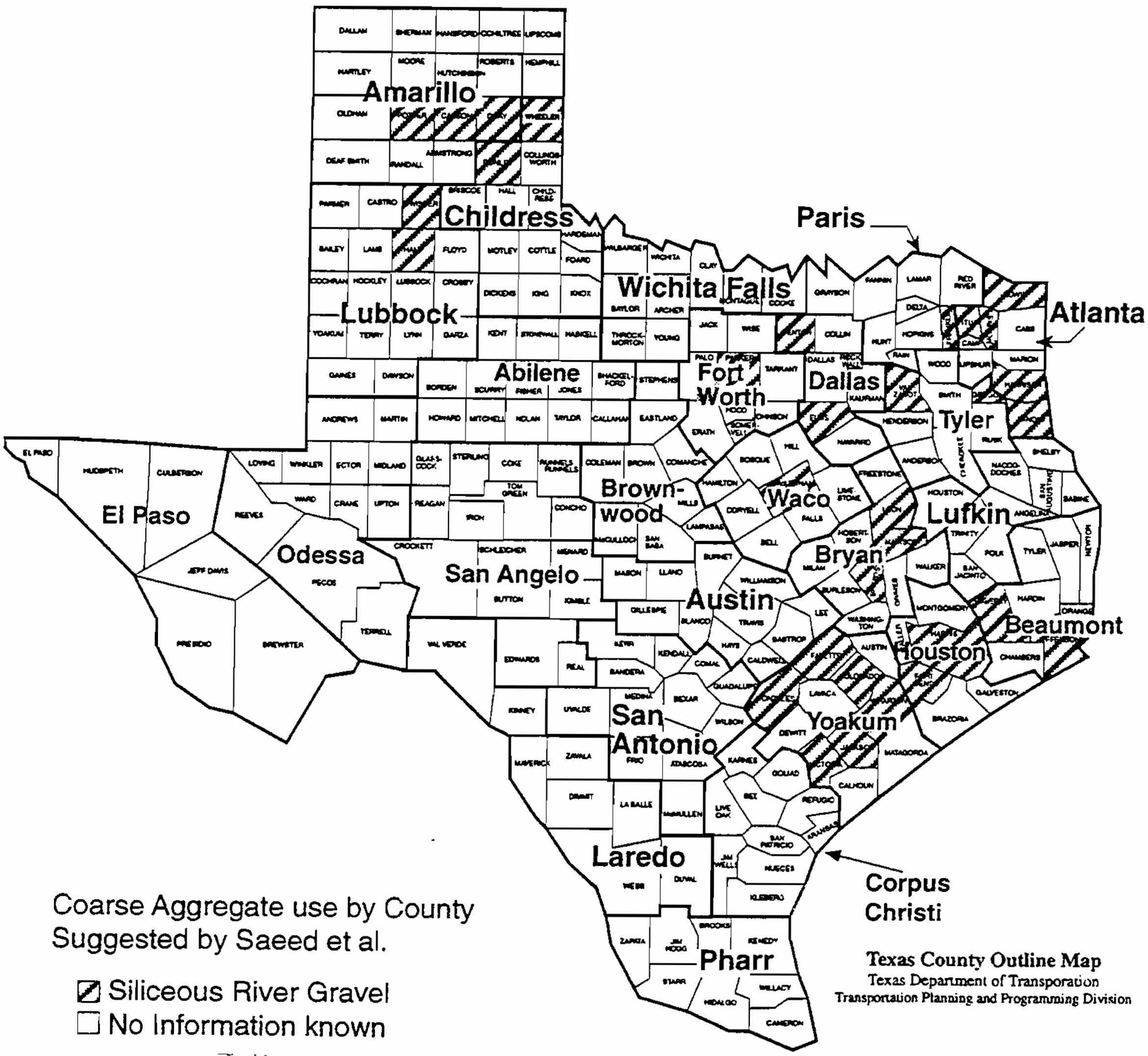


*Figure 5.2 Information from Research Report 1908-2*

### *Survey of the District Engineers*

Since the two easily available sources of information produced an incomplete picture, a more direct and authoritative information-gathering approach was undertaken. TxDOT is divided into 24 districts made up of several counties, each under the direction of a district engineer. In some cases, the district engineer's office has a designated pavement engineer or pavement specialist. These engineers were judged to be the most reliable, up-to-date, and complete source of information across the state. Letters were sent to the offices of the various district engineers, directly to the district pavement engineers if possible, asking what coarse aggregate type was predominantly used in the district in past and present construction of all types of portland cement concrete pavement (PCCP). Whenever possible, more detailed information regarding the various counties or specific projects within each district was requested. The letters were followed by phone calls to the district offices.

## INFORMATION OBTAINED FROM THE SURVEY

### *General Information*

Most of the districts responded that pavements using portland cement were scarce to nonexistent, due primarily to the higher cost of portland cement concrete pavement (PCCP) versus asphalt concrete pavement (ACP). The vast majority of existing PCC pavements ranged in age from 15 to 25 years. Many of the original surfaces had been overlaid. Since the current distress prediction models are only applicable to non-overlaid pavements less than 15 years old, many of the existing PCC pavements lie outside the range predictable by the distress models.

Owing to the advanced age of most PCC pavements, most of the engineers contacted by the survey did not have first-hand knowledge of the original design and construction. Most districts claimed to have such information as test records or as-built plans, but such information was usually archived and not easily available. Furthermore, information of this type would be on specific projects, rather than on a district or area. Although many offers of further assistance were made by the district engineers or their representatives, it was felt that the additional knowledge gained by requesting an extensive record search in each district would not justify the man-hours necessary to accomplish the search.

In almost every case across the state, from 25-year-old projects to the new construction of the North Loop in El Paso, the choice of coarse aggregate used in construction has been the decision of the contractor or his sub-contractors. Although some district offices make construction recommendations to the contractors, the cheapest available aggregate is predominantly used.

In some cases, the opinion obtained from the district contacts conflicted with information in the CTR database that was used to formulate the preliminary distress prediction models. When such situations occurred, the information in the CTR database was discussed with the engineer or designer. In a few cases, the district representative held to the opinion that the district or county in question used a certain aggregate type as a general rule, regardless of the information about a specific project or projects in the CTR database.

Tables 5.1, 5.2, 5.3, and 5.4 summarize the information obtained on coarse aggregate use in the state, along with a list the contact personnel in each district. Figure 5.3, which shows the information obtained from the various districts, indicates no obvious geographical trends across the state. Most district representatives held the opinion that coarse aggregate use was consistent throughout the district.

Table 5.5 lists the various personnel contacted during the survey that provided helpful information. The names include District Engineers, Pavement Engineers, Transportation Planners, lab managers, and other technical personnel who assisted in information gathering from each district.

### *Applicability of Information*

There seems to be no authoritative source on the location of all of the portland cement concrete pavements in the state. In some cases, the district engineers or designers were not sure of the use and extent of PCC pavements within their own jurisdiction (e.g., many of the roads *and* engineers are new). Figure 5.3 and the list of counties that use the various aggregate types as recommended by the districts probably contain recommendations on counties that do not use PCC pavements at all.

The information obtained from this survey is primarily intended to serve as a surrogate data source for the structural modifying coefficient in the distress prediction equation. It is recommended that the opinions of the district engineers be used (rather than geographic proximity to a CTR database section or SRG source) in determining coarse aggregate type for the purposes of distress prediction modeling.

### *Additional Information About Specific Districts*

In addition to the most basic information sought about predominant aggregate use, the contacts provided the following further information about their districts.

- The Abilene District reported no use of CRCP at all, with most JCP used at intersections.
- The Amarillo District reported that all PCC pavements that are known to exist use SRG aggregate. PCC pavements exist only on Interstates 27 and 40, and most of Interstate 40 has been overlaid.
- The Atlanta District reported primarily use of ACP, with the exception of two sections of interstate. Only one short section of Interstate 30 remains non-overlaid.
- The rest of the PCCP sections in the district were constructed in the 1960s, and have been overlaid by the present date.
- The Bryan District reported that the most recently constructed piece of PCCP was approximately 10 years old, and the newest sections were constructed with crushed limestone coarse aggregate. Most of Interstate 45 in the district has been overlaid with 20.32 cm of hot mix asphalt.

- The Childress District reported that all pavements use SRG, with the exception of a single project undertaken approximately 8 years ago, which laid 33.02 cm of JCP through the city of Childress using limestone. Most SRG used in the district is grade 4 rock from Quanna. Most crushed limestone is from Delicey.
- The Dallas District reported that limestone aggregate, which is used across the district, is obtained from Bridgeport.
- The El Paso District was able to report on a project currently underway, on the North Loop in El Paso, phases 1 and 2. This pavement section will be constructed of 33.02 and 20.32 cm CRCP, using limestone aggregate. Stanley Job is the concrete subcontractor for the project. The district also reported a predominant use of limestone in all PCCP.
- The Fort Worth District reported that their source of limestone coarse aggregate was in Bridgeport. Their fine aggregates usually came from Tintop or Brazospoint. Not much manufactured sand is used in the district.
- The Lufkin District reported almost no use of PCCP, and the very old projects that did use it have all been overlaid.
- The Paris District reported that only Grayson County used limestone aggregate obtained from Oklahoma. The rest of the counties in the district use sandstone coarse aggregate.
- The San Antonio District reported that the vast majority of their pavements were asphaltic, and that limestone aggregate was used in ACP construction, owing to its good performance.
- The Tyler District reported that the counties on the west side of the district tended to use limestone owing to their proximity to a source, and those on the east side of the district tended to use river gravel. A small section in Gregg County (location unknown) used slag.
- The Waco District reported that most of its PCCP was in McLennan County. All pavements across the district used river gravel, with the possible exception of a small section of State Highway 6 in Marlin.
- The Yoakum District has only one section of CRCP that uses limestone (a section in Gonzalez County on Interstate 10). The limestone came from New Braunfels. CRCP with SRG aggregate is used only on Interstate 10 and on SH-59. JCP sections are scattered in all the counties, all use river gravel, and all are fairly old.

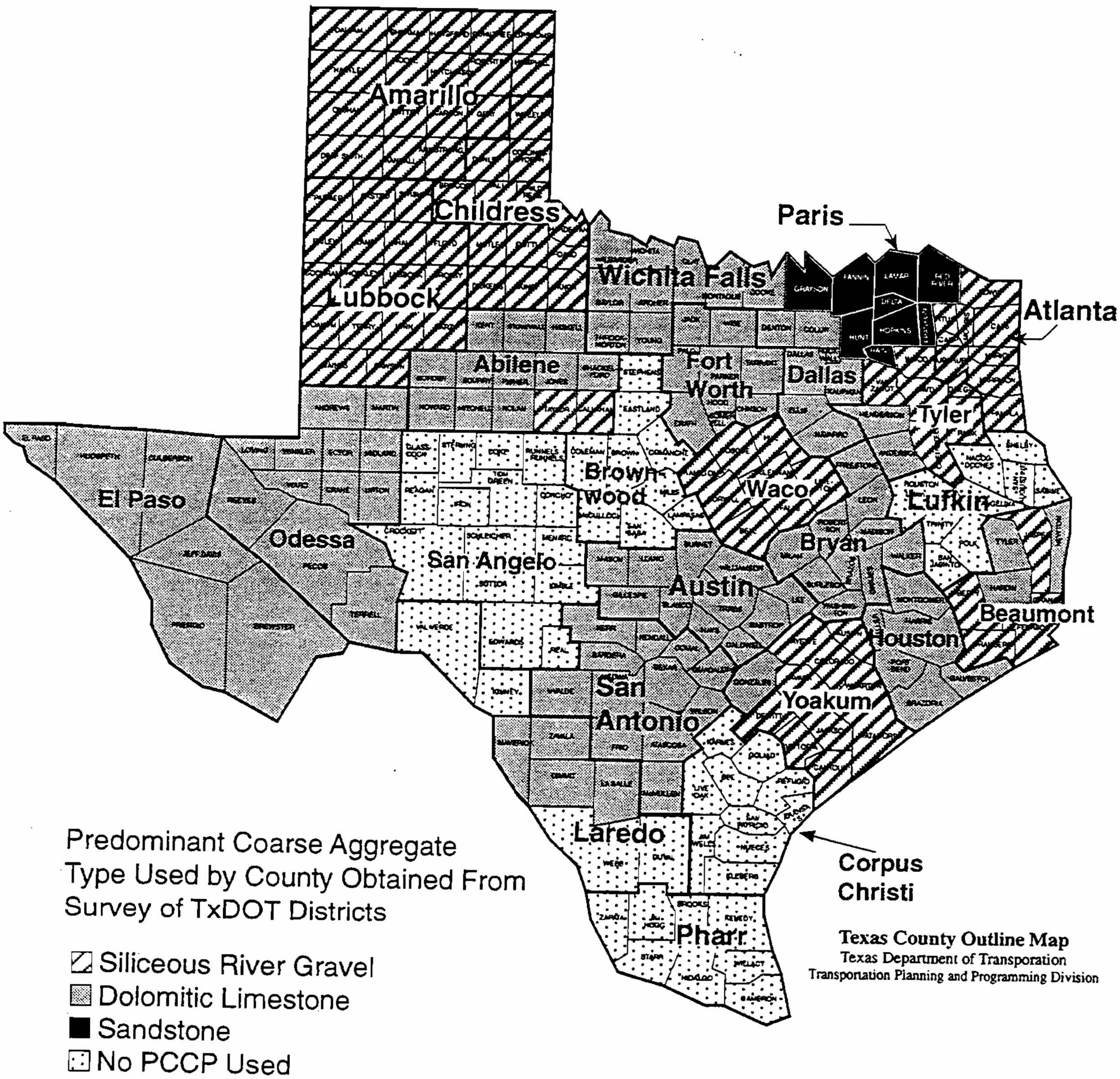


*Figure 5.3 Information obtained from TxDOT districts*

*Table 5.1. Counties using primarily siliceous river gravel*

| District Name | County Names |
|---|---|
| Abilene | Callahan, Taylor |
| Amarillo | Armstrong, Carson, Dallam, Deaf Smith, Gray, Hansford, Hartley, Hemphill, Hutchinson, Lipscomb, Moore, Ochiltree, Oldham, Potter, Randall, Roberts, Sherman |
| Atlanta | Bowie, Camp, Cass, Harrison, Marion, Morris, Panola, Titus, Upshur |
| Beaumont | Chambers, Jasper, Jefferson, Liberty, Orange |
| Childress | Briscoe, Collingsworth, Cottle, Dickens, Donley, Foard, Hall, Hardeman, King, Knox, Motley, Wheeler |
| Lubbock | Bailey, Castro, Cochran, Crosby, Dawson, Floyd, Gaines, Garza, Hale, Hockley, Lamb, Lubbock, Lynn, Parmer, Swisher, Terry, Yoakum |
| Tyler | Cherokee, Gregg, Rusk, Smith, Van Zandt, Wood |
| Waco | Bell, Bosque, Coryell, Falls, Hamilton, Hill, Limestone, McLennan |
| Yoakum | Austin, Calhoun, Colorado, Dewitt, Fayette, Jackson, Lavaca, Matagorda, Victoria, Wharton |

*Table 5.2. Counties using primarily dolomitic limestone*

| District Name | County Names |
|---|---|
| Abilene | Borden, Fisher, Haskell, Howard, Jones, Kent, Mitchell, Nolan, Scurry, Shackelford, Stonewall |
| Austin | Bastrop, Blanco, Burnet, Caldwell, Gillespie, Hays, Lee, Llano, Mason, Travis, Williamson |
| Beaumont | Hardin, Newton, Tyler |
| Bryan | Brazos, Burleson, Freestone, Grimes, Leon, Madison, Milam, Robertson, Walker, Washington |
| Childress | Childress |
| Dallas | Collin, Dallas, Denton, Ellis, Kaufman, Navarro, Rockwall |
| El Paso | Brewster, Culberson, El Paso, Hudspeth, Jeff Davis, Presidio |
| Fort Worth | Erath, Hood, Jack, Johnson, Palo Pinto, Parker, Somervell, Tarrant, Wise |
| Houston | Brazoria, Fort Bend, Galveston, Harris, Montgomery, Waller |
| Laredo | Dimmit, Lasalle, Maverick, Zavala |
| Odessa | Andrews, Crane, Ector, Loving, Martin, Midland, Pecos, Reeves, Terrell, Upton, Ward, Winkler |
| Paris | Grayson |
| San Antonio | Atascosa, Bandera, Bexar, Comal, Frio, Guadalupe, Kendall, Kerr, McMullen, Medina, Uvalde, Wilson |
| Tyler | Anderson, Henderson |
| Wichita Falls | Archer, Baylor, Clay, Cooke, Montague, Throckmorton, Wichita, Wilbarger, Young |
| Yoakum | Gonzales |

*Table 5.3. Counties using primarily sandstone*

| District Name | County Names |
|---|---|
| Paris | Delta, Fannin, Franklin, Hopkins, Hunt, Lamar, Rains, Red River |

*Table 5.4. Counties reporting no portland cement concrete pavement used*

| District Name | County Names |
|---|---|
| Brownwood | Brown, Coleman, Comanche, Eastland, Lampasas, McCulloch, Mills, San Saba, Stephens |
| Corpus Christi | Aransas, Bee, Goliad, Jim Wells, Karnes, Kleberg, Live Oak, Nueces, Refugio, San Patricio |
| Laredo | Duval, Kinney, Val Verde, Webb |
| Lufkin | Angelina, Houston, Nacodoches, Polk, Sabine, San Augustine, San Jacinto, Shelby, Trinity |
| Pharr | Brooks, Cameron, Hidalgo, Jim Hogg, Kennedy, Starr, Willacy, Zapata |
| San Angelo | Coke, Concho, Crockett, Edwards, Glasscock, Irion, Kimble, Menard, Reagan, Real, Runnels, Schleicher, Sterling, Sutton, Tom Green |

*Table 5.5. List of information sources in each district*

| District | Contact Person(s) |
|---|---|
| Abilene | Doug Eichorst |
| Amarillo | Greg Malatek, Tracy Bonning |
| Atlanta | Tommy Ellison |
| Austin | Bryan Stampley |
| Beaumont | Susan Chu |
| Brownwood | Robert Spaugh |
| Bryan | Jim Hanks |
| Childress | Terry Keener, Jim Freeman |
| Corpus Christi | Mario R. Garza |
| Dallas | Joe Thompson |
| El Paso | Tim Tumy, Ray Guerra |
| Fort Worth | Marcy Newman |
| Houston | Pat Henry |
| Lubbock | Steven P. Warren |
| Lufkin | Robert Neal |
| Odessa | Charles Webb |
| Paris | Cliff Clottey |
| Pharr | Amadeo Saenz, Jr. |
| San Angelo | Mark Tomlinson |
| San Antonio | Patrick Downey |
| Tyler | John Goodwin |
| Waco | Billy Pigg |
| Wichita Falls | Richard Steger |
| Yoakum | Gerald Freytag |

# CHAPTER 6. DISCUSSION

## LIMITATIONS OF THE MODELS

The models in this report describe the performance of non-overlaid portland cement concrete pavements in Texas, as observed using data collected by the Center for Transportation Research. These prediction models were calibrated by regression with observed data, and are descriptive rather than mechanistic. It should be remembered that empirical models are intended for interpolation, not for extrapolation, and are not valid outside the boundaries of the models described in Chapters 2 and 3. In the strictest sense, these models are applicable only to one pavement type: non-overlaid portland cement concrete pavements.

The models presented in this report provide a marked increase in accuracy over the initial PMIS models proposed in Research Report 1908-1 (Ref 8). They represent the most accurate regression possible, given the data available. The accuracy of the models, however, is impaired in some cases by (1) the form of the distress prediction equation used, (2) the grouping of different pavement types for analysis purposes, and (3) the scarcity of data in the database. These factors are discussed in more detail below.

## FORM OF THE PMIS DISTRESS PREDICTION EQUATION

One of the main possible sources of inaccuracy in the models derives from the form of the PMIS distress prediction equation. The Texas Pavement Management Information System uses the sigmoidal distress prediction equation discussed in Chapter 1 for predicting all types of distress in both rigid and flexible pavements. The main advantages of the sigmoidal equation are logical boundary conditions — for example, zero distress at construction, and ease of modification. The flexibility of the general sigmoidal form allows for a great variety of shapes of general prediction curves to be created by installation of the primary modifying coefficients $\alpha$, $\beta$, and $\rho$. These coefficients can be stored in a table and updated easily within the PMIS program. However, the sigmoidal equation has several drawbacks, including inflexibility with respect to the effect of second level modifying coefficients ($\sigma$, $\varepsilon$ and $\chi$ structural, environmental, and traffic coefficients discussed in Chapter 3). In addition, the boundary condition that distress must be zero at early ages does not allow the sigmoidal equation to effectively model any distress type that manifests early in pavement life, then grows at a slower rate afterward, or indeed any distress type that exhibits other than a gradual exponential increase over time.

These inflexibilities mean that in some cases the sigmoidal equation is less accurate in a least-squares regression than other equation forms. In cases where the sigmoidal equation is not able to accurately reflect observed behavior, the use of the sigmoidal equation sacrifices predictive accuracy for uniformity and for the ease of modification by changing basic shape coefficients. Since these distress prediction models are not intended to be mechanistic, other equation forms might be considered when selecting a regression model, even if the most accurate fit to observed data does not meet logical boundary conditions, such as zero distress at zero age or 100 percent distress at overlay. For example, there is a possibility that an approximation procedure using the concept that any function may be approximated by a Taylor series expansion may fit the data better. The resulting least-squares regression procedure for linear, logarithmic, exponential, or quadratic equation forms is, from a programming standpoint, straightforward and algorithmic. Future modeling efforts could choose among the best predictive fit of all of these equations, or any other equation with a single dependent variable. An indicator variable could be added to the PMIS TACS table that could select the most accurate equation form into which the rest of the stored coefficients could be substituted. The addition of such a package to the Texas PMIS would allow future modifications to be performed quickly and easily after each data collection effort.

## USE OF $\sigma$, $\varepsilon$, AND $\chi$ MODIFYING COEFFICIENTS

Although the addition of $\sigma$, $\varepsilon$, and $\chi$ modifying factors that account for the effects of structural, climatic, and traffic loading to the general distress prediction equation have proven effective in accurately predicting distress in flexible pavements, the same is not currently true for rigid pavements. In some cases, this is due to the inability of a single one of these coefficients to significantly change the form of the sigmoidal model after it has already been set by the coefficients $\alpha$, $\beta$, and $\rho$, as described in Chapter 3. In other cases, the inability of the additional modifying coefficients to improve predictive accuracy may be caused by a lack of sufficient historical data in the rigid pavement database. Texas has many times the number of centerline miles of asphalt pavement as it does of rigid pavement; hence, there are many more datapoints for flexible pavements than there are for rigid pavements. It is conceivable that future data collections may allow clearer descriptions of pavement behavior and, thus, more advantageous definitions for modifying coefficient values. At present, however, the use of the $\sigma$, $\varepsilon$, and $\chi$ coefficients produces no significant improvement in predictive accuracy in CRCP models.

Another possible source of lack of improvement in predictive accuracy by use of $\sigma$, $\varepsilon$, and $\chi$ modifying coefficients may be due to the incorrect assignment of the available physical data into these three categories. The current assignment of collected data into structural, climatic, and traffic variables should be re-evaluated for future efforts to calibrate these coefficients. For example, local soil type (swelling or non-swelling) might be considered an climatic rather than a structural variable, or perhaps only rainfall amount might be considered for the climatic variable rather than the combination of rainfall and temperature. Certainly, if the present definitions for these coefficients from the data types fail to improve predictive accuracy when the coefficients are used, other avenues might be explored.

## NEED FOR FURTHER DATA COLLECTION

The distress prediction models described in this report would be improved with more available data on rigid pavement conditions. The relatively small amount of rigid pavement, as opposed to flexible pavement, in Texas has possibly contributed to inconsistent data collection over the past 30 years. Distress prediction models as a function of age should ideally be based upon consistently collected data over the period of study. However, that was not possible for this research. Owing to the 12-year time lapse between the available 1982 and 1994 distress surveys, it was not possible to conduct a time-series analysis of specific pavement sections. Instead, a cross-sectional analysis method was used, in which distress types were regressed against pavement age. Data from these two surveys were used together for the purpose of this model calibration, even though the data were collected under different rating schemes, by different projects, and in different decades (a description of the data collected by the various projects is included in Chapter 1). Grouping data from the 1982 and 1994 surveys may present some problems in this analysis. Most notably, construction knowledge and funding for maintenance and rehabilitation (M&R) practices have improved between 1982 and 1994. Logically, it can be assumed that, as a result of this increased knowledge, pavements constructed in more recent years will perform better than those constructed in earlier years. Grouping the data from these two surveys may in some sense represent the merging of two disparate statistical populations, and thereby contribute to data variability and model inaccuracy.

More frequent distress and condition surveys would facilitate evaluation of the effects of improved construction and maintenance processes, as well allow for the time-series analysis of specific sections. Although JRCP and JPCP behave differently, the present amount of data available does not allow the development of separate models for each type. Scatter evident in the jointed models in this report should be greatly diminished by establishing separate model categories for each type. A time-series analysis of several pavement sections would be an extremely clear window for observation of pavement behavior and performance. A long-term commitment to rigid pavement data collection would also allow for consistency with respect to data type collected and project oversight. Future surveys could be followed by testing and by recalibration of the PMIS distress prediction models; thus consistent data collection will allow these models to be as up-to-date as possible.

## MODEL ACCURACY

It is assumed that the distress prediction models for the Texas PMIS will be improved and updated with each future data collection. While the models (or calibrations) presented in this report provide the most recent and most accurate version of the PMIS models, it should be stressed that regression models of this type are, by their very nature, never the final answer. With recent federal mandates for each state to implement a pavement management system, public engineering knowledge and available data should grow rapidly in the next decade. The Texas PMIS should make every effort to stay abreast of work in other areas, so that the most accurate models possible can be used to obtain the maximum benefit to the taxpayers.

## A COMBINED MODEL FOR FAILURES IN CRCP

Although the study specifically requests separate performance models for punchouts, asphalt patches, and portland cement concrete (PCC) patches, it must be remembered that it is only through a maintenance decision that a punchout becomes an asphalt or PCC patch, or for that matter, a patch at all. From a standpoint of predicting pavement deterioration, a more useful concept is that of failures per mile, which for this purpose is defined as the sum of unrepaired punchouts, asphalt patches, and PCC patches. Although it is possible to estimate failures by summing together the separate models given in the previous chapters, a more direct approach is to estimate $\alpha$, $\beta$, and $\rho$ by regression directly on the composite failure variable. Figure 6.1 shows the results of this approach.

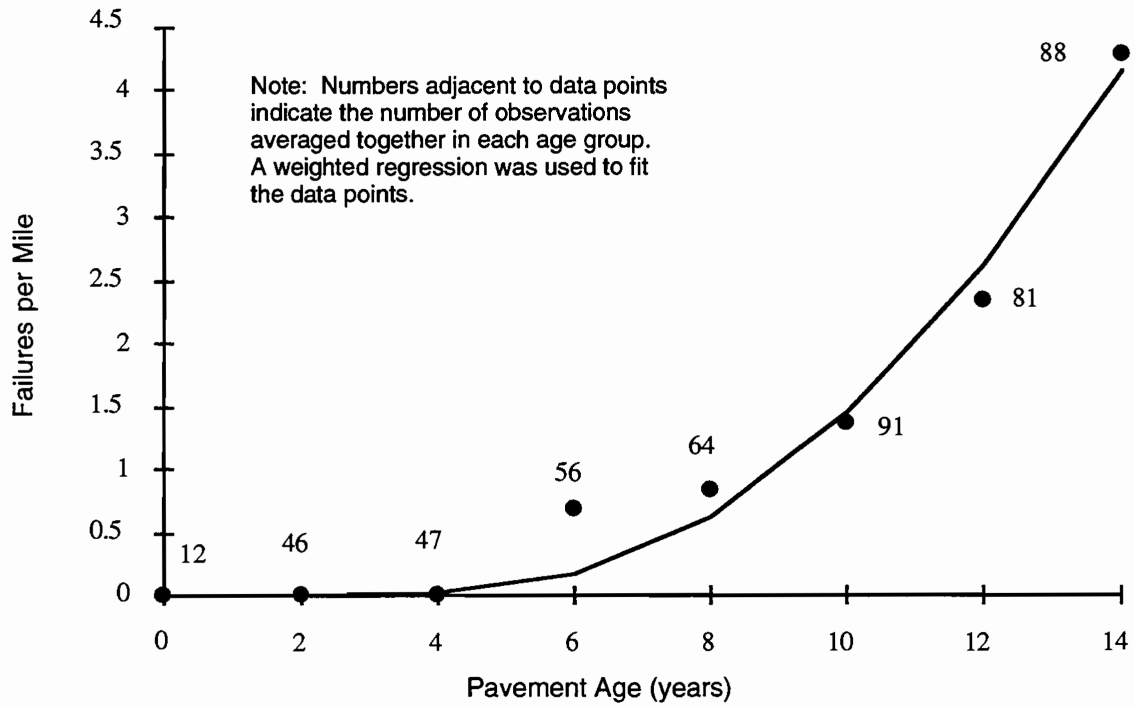


*Figure 6.1. A direct sigmoidal model for CRCP failures (1 mile=1.61 km)*

The coefficients producing the curve shown above were obtained by a non-linear least squares fit procedure using the same sigmoidal form as for previous distresses. Their values are: $\alpha = 434$, $\beta = 0.611$, $\rho = 173$. Although these coefficients produce the curve shown above, they are by no means unique; many other coefficient combinations would also result in an identical curve. The sigmoidal form, in this case, is an overly complex way of describing the shape of this simple exponential curve. However, to maintain compatibility with the TACS table and the other models, it has been presented in terms of $\alpha$, $\beta$, and $\rho$.

The number adjacent to each point on the graph indicates the number of observations (pavement section) that were averaged into each data point shown. The analysis procedure was weighted to take into account the number of observations in each age group. Although observations on non-overlaid CRCP sections up to 24 years old were present in the database, the declining number of older sections prompted the decision to cut off the analysis after 14 years.

Unlike the previous models for distress on non-overlaid CRCP, where a decrease in distress (or survivor effect) was noted after about 15 years, the raw data used in this analysis show a rapid increase in distress after 15 years, reaching a peak of around 70 failures per mile at 24 years but with only 6 observations to average. Most of this distress took the form of patches in increasing number and size.

As a check on the accuracy of this procedure, a comparison can be made to similar research recently completed under TxDOT Project 1244, “Evaluation of Performance of Texas Pavements Made with Different Coarse Aggregates” (Refs 15,16). In Figure 6.2, failure curves are presented for three different reliabilities based on cumulative traffic exposure. The curve given for 50 percent reliability should closely resemble the failure curve presented above, since under 50 percent reliability, half of the field sections would perform better and half worse than the prediction, which amounts to fitting a curve through the center of the points.

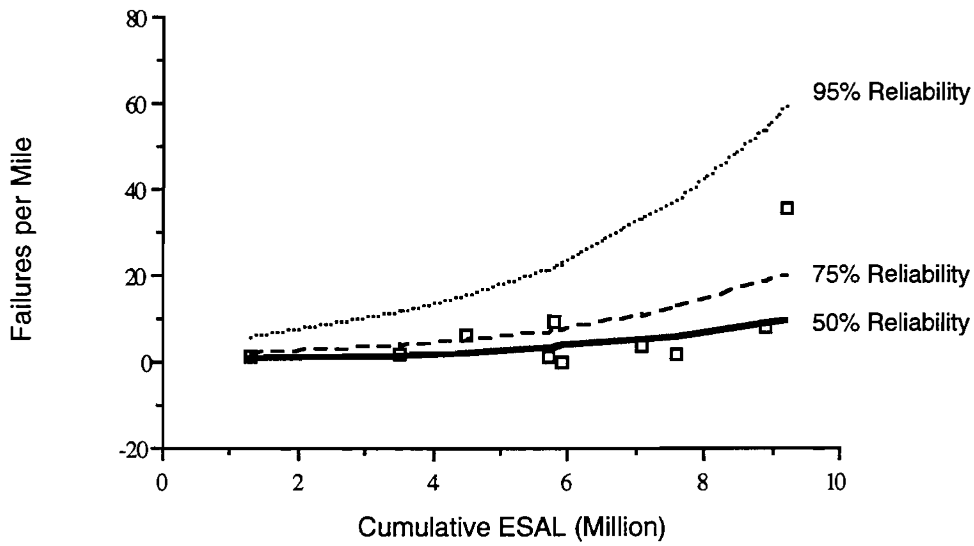


*Figure 6.2. Failures per mile curves from Project 1244 (LS, high swelling) (Ref 16)*
*(1 mile=1.61 km)*

In Figure 6.2, an average yearly two-way ESAL for CRCP is given as 1.4 million ESALs/year. If we assume even traffic distribution and a heavy right-lane distribution, in 10 years a cumulative ESAL of somewhere around 7 million would be reached. At 10 years, the failure model developed for this project predicts about 1.2 failures per mile, and the Project 1244 model predicts fewer than 2 failures per mile, as well as can be determined from the graph. Thus, the two models developed independently tend to support each other and give some confidence that the failure model presented here is reasonable.

# CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

## CONCLUSIONS

The following conclusions can be drawn from the studies described and discussed herein.

### *Improved Distress Prediction Models*

The models developed in this report constitute a marked improvement over the initial PMIS models presented in CTR Research Report 1908-1 (Ref 8). They represent the most accurate regression possible using the sigmoidal equation with the available data. Tables 7.1 and 7.2 outlined the shape coefficients $\alpha$, $\beta$, and $\rho$ for both the JCP and CRCP, and modifying coefficients $\sigma$, $\varepsilon$ and $\chi$ for CRCP distress prediction model.

*Table 7.1. Coefficients for JCP distress prediction models*

| | **Shape Coefficient** | | | **Modifying Coeff.** | | |
|---|---|---|---|---|---|---|
| **Distress Type** | $\alpha$ | $\beta$ | $\rho$ | $\sigma$ | $\varepsilon$ | $\chi$ |
| Patches Per Mile | 478.600 | 0.370 | 504.570 | 1.000 | 1.000 | 1.000 |
| Corner Breaks Per Mile | 47.670 | 0.360 | 47.890 | 1.000 | 1.000 | 1.000 |
| Faulted Joints and Cracks Per Mile | 20.460 | 1.150 | 10.840 | 1.000 | 1.000 | 1.000 |
| Spalled Joints and Cracks Per Mile | 37.020 | 5.210 | 7.950 | 1.000 | 1.000 | 1.000 |
| Transverse Cracks Per Mile | 157.080 | 5.490 | 10.240 | 1.000 | 1.000 | 1.000 |
| Slabs with Longitudinal Cracks Per Mile | 34.470 | 0.520 | 240.750 | 1.000 | 1.000 | 1.000 |

(1 mile=1.61 km)

*Table 7.2. Coefficients for CRCP distress prediction models*

| | **Shape Coefficients** | | | **Modifying Coeff.** | | |
|---|---|---|---|---|---|---|
| **Distress Type** | $\alpha$ | $\beta$ | $\rho$ | $\sigma$ | $\varepsilon$ | $\chi$ |
| Punchouts Per Mile | 101.517 | 0.438 | 538.126 | 1.000 | 1.000 | 1.000 |
| Portland Cement Concrete Patches Per Mile | 1293.840 | 0.536 | 399.932 | 1.000 | 1.000 | 1.000 |
| Asphalt Concrete Patches Per Mile | 96.476 | 0.375 | 824.139 | 1.000 | 1.000 | 1.000 |
| Loss of Ride Score | 0.720 | 0.060 | 59.781 | 1.000 | 1.000 | 1.000 |
| Transverse Cracks Per 100 Ft (SRG) | 35.370 | 0.861 | 0.059 | 1.000 | 1.000 | 1.000 |
| Severely Spalled Cracks Per 100 Ft (SRG) | 1.690 | 22.090 | 10.270 | 1.000 | 1.000 | 1.000 |
| Transverse Cracks Per 100 Ft (LS) | 20.760 | 0.534 | 0.030 | 1.000 | 1.000 | 1.000 |
| Severely Spalled Cracks Per 100 Ft (LS) | 0.120 | 1.279 | 8.538 | 1.000 | 1.000 | 1.000 |

(1 mile=1.61 km) (1 foot=0.304 m)

### *Scarcity of Pavement Distress Data*

Time-series analysis of specific pavement sections for model calibration could not be performed owing to a lack of data. Many improvements in pavement maintenance strategies may have been instituted between 1982 to 1994, and an incremental effect of these changes could not be observed because of the 12-year time lapse in the data collection.

Although, the JRCP and JPCP are designed to behave differently, the distress data for these two pavements types are grouped in one category in the rigid pavements database. The database is therefore insufficient for performing a reasonable cross-sectional analysis for each pavement type separately.

### *Use of Modifying Coefficients is Insignificant*

The statistical analysis showed that the modifying coefficients do not currently significantly improve the predictive accuracy in most of the CRCP distress prediction models. This result was also verified by plotting distress prediction curves with and without using the modifying coefficients.

### *Shortcomings in the Use of Sigmoidal Form of Equation*

The sigmoidal form of the PMIS distress equation is flexible in its general form; primary coefficients $\alpha$, $\beta$, and $\rho$ for predictive models for various distress types can be stored in a database and easily updated. This equation, however, may not always be the most accurate fit to the observed data. In cases where the sigmoidal equation is not able to adequately reflect observed behavior, its use may compromise predictive accuracy for uniformity and general flexibility.

### *Combined Model for Failures in CRCP*

A combined distress model developed for CRCP failures (including punchouts, asphalt concrete patches, and portland PCC patches) gives a good fit for the combined distress data for these currently uniquely defined distress categories in PMIS.

## RECOMMENDATIONS

Based on the research and analysis documented in this report, the following actions are recommended.

### *Additional Data Collection on Jointed Concrete Pavements*

At present, JCP data in the database are only sufficient for a first-level calibration of the PMIS distress prediction models. Further data collection will be necessary to specify additional modifying coefficients and to improve model accuracy. This data collection should be a part of a regular, comprehensive data collection procedure, one that covers as many different conditions in the state as possible. Such a program should be made a part of the Texas Pavement Management Information System feedback database.

### *Separation of JCP and JRCP Models*

Jointed and jointed reinforced concrete pavements behave differently, but the present amount of data available forces the PMIS models to consider them as a single pavement type. Future data collection and model improvement efforts should place JCP and JRCP data into separate populations if possible. The scatter evident in the jointed models presented in this report should be greatly diminished by the establishment of two model categories.

### *Provision for Other Model Forms*

In some of the cases described in this report, the sigmoidal PMIS model does not provide a very accurate fit to observed data. Other equations may provide a better fit, and should be considered in future updates of the PMIS models.

### *No Present Use of $\sigma$, $\varepsilon$ and $\chi$ Factors*

This report has shown that the use of $\sigma$, $\varepsilon$, and $\chi$ modifying coefficients to account for the effects of structural, environmental, and traffic variables on the current CRCP models does not significantly improve predictive accuracy over models not having these modifying coefficients. Analysis of future data, or reassignment of variables in these categories, may allow the modifying coefficients to be used. At present, it is recommended that the CRCP distress prediction models developed in this report be used without the additional modifying coefficients in the Texas PMIS.

### *Use of Combined Distress Model for CRCP Failures*

This report has shown that a combined model developed for punchouts, asphalt patches, and PCC patches in CRCP gives a good fit to the combined distress data. We recommend that the above distresses be grouped in one data category, and that a combined distress prediction model be used.

### *Need to Define Performance Models by Treatment*

PMIS analysis programs define four broad treatment type groups:

1. PM — Preventative Maintenance
2. LRHB — Light Rehabilitation
3. MRHB — Medium Rehabilitation
4. HRHB — Heavy Rehabilitation

Performance models should eventually be defined for each of these treatment types. This would allow comparisons of the cost effectiveness of alternative treatments.

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