

**Development of a Validation Process for  
Parameters Utilized in Optimizing  
Construction Quality Management of  
Pavements**

**Research Report 0-4046-2**

**Project Number 0-4046**

**Conducted for**

**Texas Department of Transportation**

**P.O. Box 5080**

**Austin, Texas 78763**

**January 2006**

**Center for Transportation Infrastructure Systems**

**The University of Texas at El Paso**

**El Paso, TX 79968**

**(915) 747-6925**

**<http://ctis.utep.edu>**

This page replaces an intentionally blank page in the original.

-- CTR Library Digitization Team

TECHNICAL REPORT STANDARD TITLE PAGE

|   |  |  |   |   |           |
|---|--|--|---|---|-----------|
| 1. Report No.<br>FHWA/TX-05/0-4046-2  |  | 2. Government Accession No.                          |   | 3. Recipient's Catalog No.  |           |
| 4. Title and Subtitle<br>Development of a Validation Process for Parameters Utilized in Optimizing Construction Quality Management of Pavements<br><br>Impacts of construction Quality on the Life-Cycle Performance of Pavements Using Mechanistic Analysis  |  |  |   | 5. Report Date<br>January 2006  |           |
|   |  |  |   | 6. Performing Organization Code   |           |
| 7. Author(s)<br>I. Abdallah, B. Haggerty and S. Nazarian  |  |  |   | 8. Performing Organization Report No.<br>0-4046-2   |           |
| 9. Performing Organization Name and Address<br>Center for Transportation Infrastructure Systems<br>The University of Texas at El Paso<br>El Paso, Texas 79968-0516  |  |  |   | 10. Work Unit No.   |           |
|   |  |  |   | 11. Contract or Grant No.<br>Study No. 0-4046   |           |
| 12. Sponsoring Agency Name and Address<br>Texas Department of Transportation,<br>Research and Technology Implementation Office,<br>P.O. Box 5080,<br>Austin, Texas 78763-5080   |  |  |   | 13. Type of Report and Period Covered<br>Technical Report<br>Sept. 1, 2002 –August 31, 2003 |           |
|   |  |  |   | 14. Sponsoring Agency Code  |           |
| 15. Supplementary Notes<br>Research Performed in Cooperation with TXDOT and FHWA under project entitled "Impacts of construction Quality on the Life-Cycle Performance of Pavements Using Mechanistic Analysis"   |  |  |   |   |           |
| 16. Abstract<br>The implementation of an effective performance-based construction quality management requires a tool for determining impacts of construction quality on the life-cycle performance of pavements. This report presents an update on the efforts in the development of a statistical-based algorithm that reconciles the results from several pavement performance models used in the state of practice with systematic process control techniques. The development and limited implementation of the ongoing validation process is presented in this report. |  |  |   |   |           |
| 17. Key Words<br>Pavement life-cycle, construction quality, performance-based, impact analysis, probabilistic methods   |  |  | 18. Distribution Statement<br>No restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161, <a href="http://www.ntis.gov">www.ntis.gov</a> |   |           |
| 19. Security Classif. (of this report)<br>Unclassified  |  | 20. Security Classif. (of this page)<br>Unclassified |   | 21. No. of Pages<br>91  | 22. Price |

This page replaces an intentionally blank page in the original.

-- CTR Library Digitization Team

# **Development of a Validation Process for Parameters Utilized in Optimizing Construction Quality Management of Pavements**

by

**Imad Abdallah, MSCE  
Brett Haggerty, BSIE  
and  
Soheil Nazarian, Ph.D., P.E.**

Research Project Number 0-4046  
Report Number 0-4046-2

**Project Title: Impacts of construction Quality  
on the Life-Cycle Performance of Pavements  
Using Mechanistic Analysis**

Performed in cooperation with the  
**Texas Department of Transportation  
and the Federal Highway Administration**

The Center for Transportation Infrastructure Systems  
The University of Texas at El Paso  
El Paso, TX 79968-0516  
January 2006

## **DISCLAIMER**

The contents of this report reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

**NOT INTENDED FOR CONSTRUCTION, BIDDING, OR  
PERMIT PURPOSES**

Imad Abdallah, MSCE  
Brett Haggerty, BSIE  
Soheil Nazarian, Ph.D., P.E. (69263)

## **Acknowledgements**

The successful progress of this project could not have happened without the help and input of many personnel of TXDOT. The authors acknowledge Mr. Steve Smith, the project PD and David Head, the project PC for facilitating the collaboration and with TXDOT Districts. They have also provided valuable guidance and input.

Special thanks to the PAs, Ms. Lisa Lukefahr, and Mr. Tomas Saenz whom were involved in development of the protocol for data collection and have helped in the success of the product being developed under this project.



## **Abstract**

The implementation of an effective performance-based construction quality management requires a tool for determining impacts of construction quality on the life-cycle performance of pavements. This report presents an update on the efforts in the development of a statistical-based algorithm that reconciles the results from several pavement performance models used in the state of practice with systematic process control techniques. The development and limited implementation of the ongoing validation process is presented in this report.



## **Executive Summary**

The ability of a flexible or rigid pavement to perform adequately throughout its design life is one of the biggest challenges that transportation agencies face. One factor that has a large impact on the performance of a pavement is the quality of construction. The implementation of an effective performance-based construction quality management program is one way of ensuring that pavements are meeting their expected service lives. As a part of that program a tool for determining the impact of construction quality on life-cycle performance of pavements is required.

TXDOT, amongst other highway agencies, has adopted statistic-based quality assurance/quality control (QA/QC) techniques to improve the quality of roadways. In this report a method of optimizing construction quality management of pavements using mechanistic performance analysis method based on statistical techniques is presented. This method was developed for both flexible and rigid pavements.

Ideally, if a pavement section is designed with the same cross section and constructed with the same materials, its performance should be uniform throughout the section. This is not the case in the real world. Almost every constructed road develops distresses randomly in different subsections of the pavement. One reason for the random development of distress is the variability in construction quality. The goal of this project is to devise a tool that can be used to identify and minimize variability in material properties that impact the performance of the pavement to ensure a performance period compatible with the expected life of the pavement. With that framework, structural models that predict performance of pavements and material models that relate construction parameters to primary design parameters were identified. Finally, a statistical approach that relates the impact of each construction parameter to the performance of a pavement is incorporated into the algorithm.

To arrive at realistic conclusions, the material models have to be calibrated to the local conditions. This report contains the information and process necessary for calibrating such models.



## **Implementation Statement**

At this stage of the project the developed tools are being modified and can be used for limited implementation. The software is undergoing major changes to increase its flexibility and expand its ability to identify and minimize variability in material properties that impact the performance of the pavement to ensure a performance period compatible with the expected life of the pavement. The software package, which is called Rational Estimation of Construction Impact on Pavement Performance (RECIPPE), can be used to reconcile the results from pavement-performance models used in the state of practice, or those widely accepted by state agencies, with statistical process control techniques and uncertainty analysis methods, to determine project-specific parameters that should be used in construction quality management.



# Table of Contents

|   |           |
|---|-----------|
| <b>Chapter 1 - Introduction .....</b>                                     | <b>1</b>  |
| <b>Objective.....</b>   | <b>2</b>  |
| <b>Organization of Report .....</b>                                       | <b>2</b>  |
| <br>  |           |
| <b>Chapter 2 - Background.....</b>  | <b>3</b>  |
| <b>Progress of Research .....</b>   | <b>3</b>  |
| <br>  |           |
| <b>Chapter 3 - A Document for Validation of Different Parameters.....</b> | <b>7</b>  |
| <b>Overview of RECIPPE .....</b>  | <b>8</b>  |
| <b>Validation of Probabilistic Process .....</b>                          | <b>10</b> |
| <b>Appropriateness of Material Models .....</b>                           | <b>13</b> |
| <b>Calibration of Material Models.....</b>                                | <b>17</b> |
| <b>Single Variable Calibration.....</b>                                   | <b>17</b> |
| <b>Modifying Coefficients of Witczak Equation.....</b>                    | <b>20</b> |
| <b>AC Material Model Based on LTPP Data .....</b>                         | <b>21</b> |
| <b>Base and Subgrade Material Models.....</b>                             | <b>22</b> |
| <br>  |           |
| <b>Chapter 4 - Limited Implementation of Validation Process.....</b>      | <b>25</b> |
| <b>Case Study .....</b>   | <b>25</b> |
| <br>  |           |
| <b>Chapter 5 - Summary and Conclusions .....</b>                          | <b>33</b> |
| <b>Recommendations.....</b>   | <b>33</b> |
| <br>  |           |
| <b>References.....</b>  | <b>35</b> |
| <br>  |           |
| <b>Appendix A - Standards to Measure Construction Parameters.....</b>     | <b>37</b> |

**Appendix B - Protocol for Collecting Construction Parameters  
Information for Sites in Texas ..... 53**

**Appendix C - Results of the Validation Study for Asphalt Content of AC Layer ..... 61**

**Appendix D - Results of the Validation Study for Air Voids of AC Layer ..... 69**

## List of Figures

|   |           |
|---|-----------|
| <b>Figure 2.1 - Flow chart of Mechanistic Algorithm.....</b>  | <b>4</b>  |
| <b>Figure 3.1 - Conceptual Framework of RECIPPE .....</b>   | <b>8</b>  |
| <b>Figure 3.2 - Flowchart of Process Developed in RECIPPE .....</b>   | <b>9</b>  |
| <b>Figure 3.3 - Flowchart of the Algorithm Used in RECIPPE<br/>for Determining the Impact Value of Construction on Performance .....</b>    | <b>11</b> |
| <b>Figure 3.4 - Comparison of Impact Values from Monte Carlo and TPM Methods. ....</b>  | <b>13</b> |
| <b>Figure 3.5 - Comparison of Moduli based on Witczak Model<br/>and Backcalculated Results.....</b>   | <b>19</b> |
| <b>Figure 3.6 - Results of Calibration of Witczak Model<br/>Using Single-Variable Regression .....</b>                                      | <b>20</b> |
| <b>Figure 3.7 - Results of Modifying Coefficients of Witczak Model.....</b>   | <b>21</b> |
| <b>Figure 3.8 - Results of New Model Using LTPP Database.....</b>   | <b>22</b> |
| <b>Figure 4.1 - Results of Impact of Variability of Asphalt Content<br/>on Remaining Life Varying AC Modulus.....</b>                       | <b>28</b> |
| <b>Figure 4.2 - Results of Impact of Variability of Asphalt Content<br/>on Remaining Life for Four Typical Pavement Sections .....</b>      | <b>29</b> |
| <b>Figure 4.3 - Results of Impact of Variability of Air Voids<br/>on Remaining Life Varying AC Modulus.....</b>                             | <b>30</b> |
| <b>Figure 4.4 - Results of Impact of Variability of Air Voids<br/>on Remaining Life for Four Typical Pavement Sections .....</b>            | <b>31</b> |
| <b>Figure C1 - Results of Impact of Variability of Asphalt Content<br/>on Remaining Life Varying AC Modulus for Thin-Thin Section.....</b>  | <b>63</b> |
| <b>Figure C2 - Results of Impact of Variability of Asphalt Content<br/>on Remaining Life Varying AC Modulus for Thin-Thick Section.....</b> | <b>64</b> |
| <b>Figure C3 - Results of Impact of Variability of Asphalt Content<br/>on Remaining Life Varying AC Modulus for Thick-Thin Section.....</b> | <b>65</b> |
| <b>Figure C4 - Results of Impact of Variability of Asphalt Content</b>  |           |

|  |   |    |
|--|---|----|
|  | on Remaining Life Varying AC Modulus for Thick-Thick Section..... | 66 |
| <b>Figure D1 - Results of Impact of Variability of Air Voids</b> |   |    |
|  | on Remaining Life Varying AC Modulus for Thin-Thin Section.....   | 71 |
| <b>Figure D2 - Results of Impact of Variability of Air Voids</b> |   |    |
|  | on Remaining Life Varying AC Modulus for Thin-Thick Section.....  | 72 |
| <b>Figure D3 - Results of Impact of Variability of Air Voids</b> |   |    |
|  | on Remaining Life Varying AC Modulus for Thick-Thin Section.....  | 73 |
| <b>Figure D4 - Results of Impact of Variability of Air Voids</b> |   |    |
|  | on Remaining Life Varying AC Modulus for Thick-Thick Section..... | 74 |

## List of Tables

|  |           |
|--|-----------|
| <b>Table 3.1 - Advantages and Disadvantages of Probabilistic Techniques.....</b>   | <b>10</b> |
| <b>Table 3.2 - Synthetic Data for a Typical Pavement Section<br/>Used in Comparing Two Probabilistic Algorithms.....</b>       | <b>13</b> |
| <b>Table 3.3 - List of Construction Parameters of each Pavement Layer .....</b>  | <b>15</b> |
| <b>Table 3.4 - LTPP data used in AC material model development .....</b>   | <b>18</b> |
| <br>   |           |
| <b>Table 4.1 - Values of AC Material model Parameters Used in Case Study.....</b>  | <b>26</b> |
| <b>Table 4.2 - Matrix of Pavement Sections Used for Validation of RECIPPE.....</b>   | <b>26</b> |
| <br>   |           |
| <b>Table B1 - Frequency of Measurements for Asphalt/Concrete Layer.....</b>  | <b>57</b> |
| <b>Table B2 - Frequency of Measurements for Base Layer.....</b>  | <b>58</b> |
| <b>Table B3 - Frequency of Measurements for Subgrade Layer .....</b>   | <b>59</b> |
| <br>   |           |
| <b>Table C1 - Summary of Results of Impact of Variability of Asphalt Content<br/>on Remaining Life Varying AC Modulus.....</b> | <b>67</b> |
| <br>   |           |
| <b>Table D1 - Summary of Results of Impact of Variability of Air Voids<br/>on Remaining Life Varying AC Modulus.....</b>       | <b>75</b> |



# Chapter 1

## Introduction

Constructing pavements that will perform well throughout its expected design life is the objective of any highway agency. The as-designed requirements are usually not met due to the uncertainty related to the quality of construction. Many variables are involved in the construction practices that allow for deviation from acceptable target design values. For that reason, many transportation agencies agree that a cost-based incentive/disincentive mechanism should be a part of the process to implement an effective performance-based construction quality management program. This project attempts to develop a mechanism that assesses the quality of construction by ensuring that the structural-related target variables are within reasonable tolerances.

In that context, the objective is to devise a process that accounts for the variation in pavement performance based on construction practices. This process can be used to optimize the efforts related to the effectiveness of inspection and testing resources during construction to maintain the targeted pavement performance.

The process developed under this project is a method that ties in parameters related to construction practices for quality assurance/quality control (QA/QC) to pavement performance models based on mechanistic analysis. The process uses statistical algorithms to optimize the construction quality management of pavements.

The algorithm considers the fact that relevant construction parameters change with the structure of the pavement. Many parameters that are important for a thick pavement designed for an interstate highway may be of secondary significance to a secondary road. The level of acceptable deviations from the target design value for each parameter is established based on quantification of the variability of the construction parameters introduced by: (a) the construction processes, (b) the material properties, (c) the models used to predict pavement performance and those used for data analysis, and (d) the resolution of the procedures used in the field for quality control.

The software developed for this purpose is called Rational Estimation of Construction Impact on Pavement Performance (RECIPPE). This software can be used to reconcile the results from pavement-performance models used in the state of practice, or those widely accepted by state

agencies. RECIPPE determines project-specific parameters that should be used in construction quality management based on statistical process control techniques and uncertainty analysis methods.

## **Objective**

This research study is based on three main objectives. The first objective is the development of rational algorithms. The algorithms have been developed and packaged into a program called RECIPPE. In Research Report 4046-1 (Abdallah et al., 2004), details of the algorithms and a case study using the prototype version of the program (Excel version) were discussed. The final version of the program will be delivered by the end of this project.

The second objective is to propose field tests that can be used to measure parameters identified in a cost-effective manner. A document that identifies methods for measuring several parameters based on testing standards was developed and linked into RECIPPE for ease of access. A copy of that document is included in this report.

The third objective is to establish protocols to validate the algorithms and processes developed during this project. The efforts toward establishing this process are also described in this report.

## **Organization of Report**

Chapter 2 of this report provides a review of research efforts as documented in Research Report 4046-1. Also summarized in Chapter 2 are the algorithms and methodology based on existing models. In Chapter 3, the efforts toward developing the validation procedures of different parameters are presented. Chapter 3 also includes the calibration of the AC material model using data extracted from the Long Term Pavement Performance (LTTP) database. Chapter 4 includes a limited implementation of the algorithms developed under this project. A case study demonstrating the impact of variability of construction parameters is presented in Chapter 4. The last chapter, Chapter 5, includes the summary of the work accomplished and work remaining in this project. Appendix A contains a compilation of ways to measure parameters based on existing standards as proposed under Task 3 of the project. Appendix B contains the protocol developed that will be used to locate, identify and test sites for calibrating and validating material models. Finally, Appendices C and D provide the detailed results of the case study discussed in Chapter 4.

## **Chapter 2**

### **Background**

Analytical tools to estimate the impact of construction on pavement performance were presented in the first report. These tools can assist the construction engineer in identifying the parameters that most impact the performance of a project under consideration and can guide her/him in reducing the variability associated with them. The algorithms developed were based on systematic statistical process control techniques and uncertainty analysis methods to reconcile the results from existing pavement-performance models used in the state of practice. The algorithms were developed for flexible pavement systems. The outcome is a software package that estimates the impact of construction parameters on performance indicators. A combination of two probabilistic techniques, the Monte Carlo simulation and the Two Point Mass (TPM) methods were used to assess the impact of construction and design parameters on pavement performance. The algorithms can also be applied to rigid pavements. The rigid pavement design methodology as currently practiced by TXDOT does not warrant the use of the statistical based algorithms because of its lack of sensitivity to the properties of constructed layers below the slab. As such, the focus of this project is on finalizing the tools for flexible pavements.

### **Progress of Research**

The research efforts for the first two years of this project, which are documented in Abdallah et al. (2004), were focused on the following tasks:

- a) Information search on existing mechanistic models and ways that they can be used in developing an algorithm to relate the impact of construction parameters to performance. After a national search, several material models were identified and feasible models were selected. Several popular and well-established performance-based models were also selected. The next step in the research process was the development of the probabilistic algorithms.
- b) A probabilistic analysis based on Monte Carlo simulation and TPM: The probabilistic approach differs from a deterministic approach by explicitly accounting for the variability of

a parameter. A random parameter can take a range of values and can be represented by different types of probability distributions. In this research project, all input parameters are assumed to be normally distributed. The Monte Carlo simulation method is a common probabilistic method for simulating and accounting for the variability of a parameter. Since many parameters are used in the analysis, the two-point mass method (TPM, Rosenblueth, 1975) was combined with the Monte Carlo method to accelerate the process. The TPM method can be used to approximate mean and standard deviation of random variables. The detail of both methods is provided in Chapter 2 of Report 4046-1 (Abdallah et al., 2004).

- c) Develop algorithms to quantify impact of variability on performance: Once the models were selected and the flow of probabilistic algorithm was defined, a prototype algorithm was developed. Figure 2.1 shows the general flow of information used in mechanistic algorithm with the probabilistic methods. The detail and a case study of how to use the program are also provided in the first report.

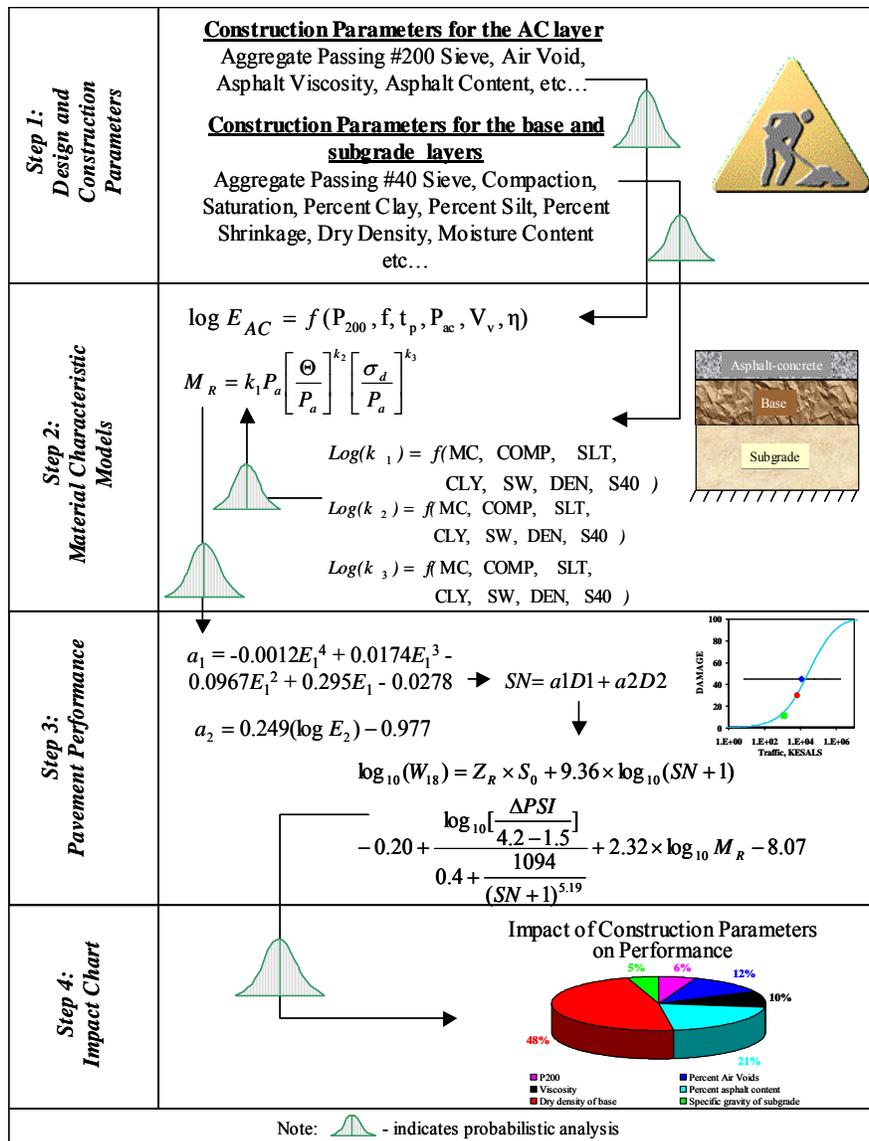


Figure 2.1 - Flow chart of Mechanistic Algorithm

- d) Sensitivity analysis to determine and identify important parameters: The mechanistic models selected provide a number of parameters that are used as a measure of construction practices. To optimize the process, a sensitivity analysis was conducted to primarily identify the relative importance of construction parameters on performance indicators. The results of this study, as presented in Abdallah et al. (2004), provided an indication of important parameters for pavements with different traffic levels.
- e) Methods to measure significant parameters: Based on results of the sensitivity study, a search to document methods on measuring important parameters was carried out. The document was embedded into RECIPPE. In that manner, the users can easily access the different ways to measure any given parameter. Another advantage of including the document into the program is that when new parameters are added, the document can be easily amended or updated. The document is included in Appendix A of this report.

The focus of the third year of the project was on developing a document for validation using few of construction parameters and to demonstrate the validation process using the selected parameters. The details of these tasks are included in this report.



## **Chapter 3**

### **A Document for Validation of Different Parameters**

The validation of the algorithm to quantify the impact of construction parameters on performance is the initial step before being able to utilize RECIPPE with confidence. As in any validation process, the ultimate goal is to compare the results from the proposed methodology to known and measurable parameters. On that account, the models in RECIPPE would need to be calibrated. Three types of models make up the mechanistic algorithm developed: a) the material models, b) the structural models and c) the performance models. The material models will be calibrated with information from existing databases and from field data collected at several sites in Texas. The plan for validating and identifying the sites are presented in this report. The efforts of this calibration and validation process will continue throughout the length of this project.

The structural and performance models incorporated into the algorithm are well-established. The structural model is based on a nonlinear model using equivalent linear algorithm. The equivalent linear model was developed under TXDOT Project 0-1780 (Ke et al. 2000, and Abdallah et al., 2003). The calibration and validation of these models are outside the scope of this project.

The probabilistic process and the models in the algorithm need to be validated for optimal functionality of the program. In this report, the validity of the mechanistic analysis using a probabilistic process in RECIPPE to determine the impact of the variability of construction parameters on performance is presented. This is accomplished with the following steps:

- a) Determining the validity of the probabilistic process to identify impact of variability of input parameters on output parameters.
- b) Determining the appropriateness of using the existing material models used in obtaining the modulus of each pavement layer.
- c) Determining the accuracy of the life cycle analysis or remaining life models to accurately predict the pavement performance.

The progress and results on the first two items are discussed in this report. The algorithms are currently being optimized and finalized as field data become available.

## Overview of RECIPPE

An overview of the algorithm used in RECIPPE is appropriate before discussing the validation process. The details of the preliminary algorithm developed are presented in Abdallah et al. (2004). A summary of the process with the latest modifications are presented here.

As presented in Figure 3.1, the methodology is divided into three phases. The first phase is the determination of the construction parameters (represented by the inner circle). The second phase is the selection of the material characteristics models (represented by the middle circle), which is the link between the construction parameters and the pavement performance (represented by the outer circle). These three phases form the mechanistic process, and are used in RECIPPE to estimate the impact of construction variability on performance. Once the parameters and models from the three phases are established, the probabilistic algorithms allow pavement engineers to maximize the effectiveness of inspection and to optimize the testing resources during the construction process.

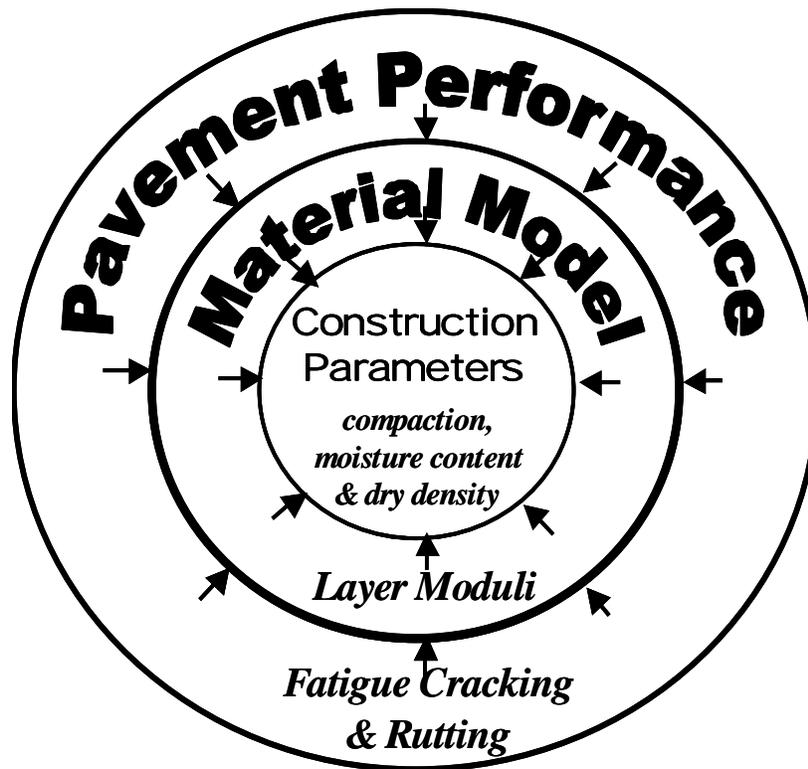
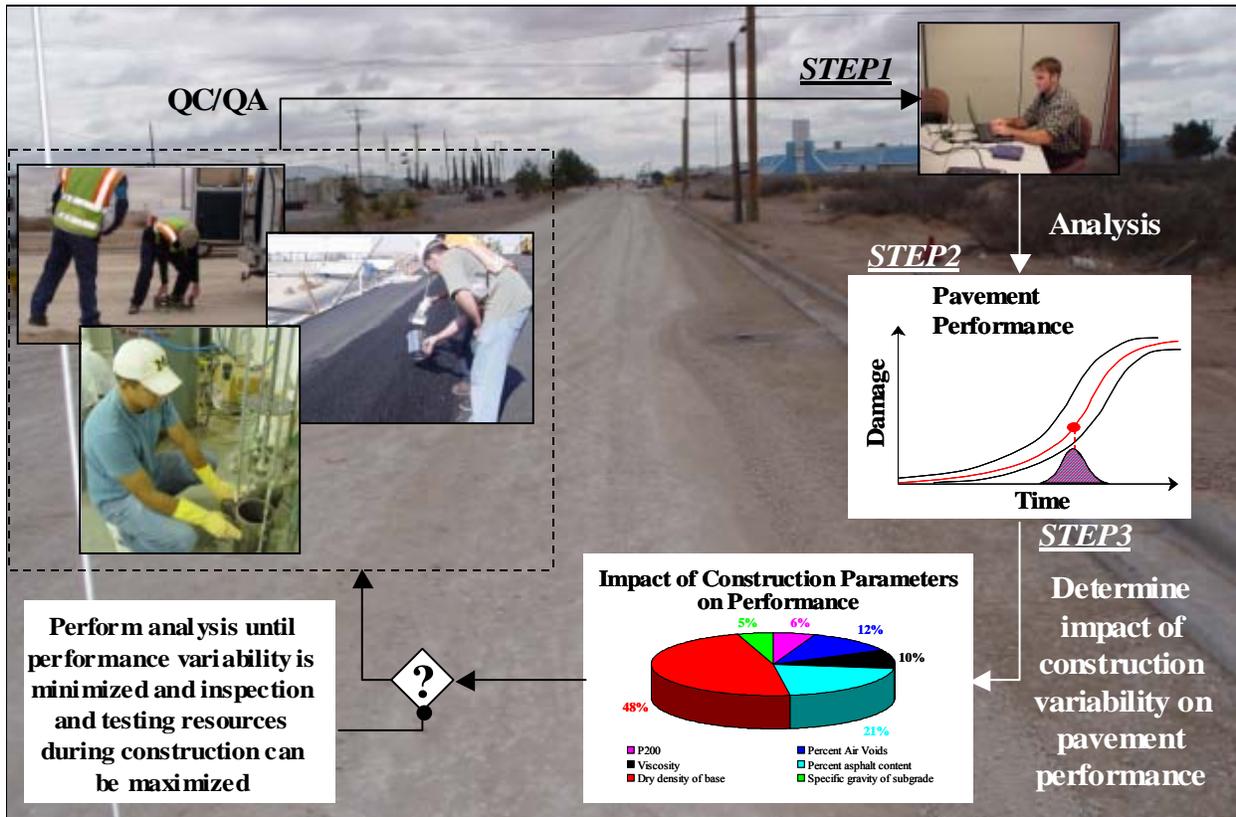


Figure 3.1 - Conceptual Framework of RECIPPE

To demonstrate the conceptual use of the algorithm, let us assume that the construction parameters are defined and are used as input to the material models. Also, let us assume that the performance models are selected and the results of material models are used in mechanistic analysis to calculate pavement performance. With these assumptions, Figure 3.2 illustrates the role of RECIPPE in construction quality management.



**Figure 3.2 - Flowchart of Process Developed in RECIPPE**

As a new pavement is being constructed, samples of construction materials for each layer are collected. Appropriate in situ and laboratory tests are performed to obtain statistical values that can be used as input into the program (indicated in Step 1 of Figure 3.1). Most of these measurements are typically made for QA/QC based on tests from the TXDOT guide schedule. The initial sampling rate can also be adopted from the guide schedule. Once the measurements are made, the values are transferred to RECIPPE for analysis. The algorithm uses the probabilistic process to obtain the variability of performance values based on mechanistic analysis as depicted in Step 2. In Step 3, RECIPPE produces an impact chart that identifies the construction parameters that impact the pavement performance variability. This impact chart varies based on performance models selected. If the pavement performance variability is less than expected, the construction parameter that impacts the performance variability the most is identified from the impact chart. The variability of that critical parameter is then reduced. The analysis is repeated until the expected performance is achieved. With each new iteration, a different parameter can be identified as critical in impacting performance. Once the performance criteria are satisfied, inspectors and testing resources can be focused on the critical construction parameters to optimize the resources and to ensure quality and performance of pavement. The role of RECIPPE, as illustrated in the figure, can be very useful in monitoring impact of construction variability on performance.

## Validation of Probabilistic Process

The effectiveness of the probabilistic process incorporated in RECIPPE is first discussed. The probabilistic approach differs from a deterministic approach by explicitly accounting for the variability of a parameter. The differences between the two approaches are documented in Report 4046-1. The algorithm in RECIPPE assumes that the variability and/or uncertainty in a parameter are defined by assuming a normal distribution represented with a mean and a coefficient of variation (COV).

The COVs of the inputs and outputs are used to develop the impact values. As indicated before, two techniques are used in simulating the variability of each input parameter. Table 3.1 summarizes the advantages and disadvantages of each technique. If processing time is of no concern, the Monte Carlo simulation is advisable. The Monte Carlo simulation requires a large number of simulated values to account for the variability of each parameter. However, with that method, higher order statistics (beside the mean and COV) can be estimated. On the other hand, in instances where processing time is a factor, the Monte Carlo simulation is not advantageous, since as the number of parameters increases, the processing time increases.

**Table 3.1 - Advantages and Disadvantages of Probabilistic Techniques**

| <b>Technique</b>              | <b>Advantages</b>  | <b>Disadvantages</b>  |
|-------------------------------|--|---|
| <b>Monte Carlo Simulation</b> | Simulating several parameters simultaneously is independent of number of simulated variables. Also, higher order statistics can be determined. | Processing time increases as the number of simulated parameters increases.  |
| <b>Two Point Mass</b>         | Simulating one parameter requires only two simulated values to represent the distribution of that parameter.                                   | Simulating several parameters at one time requires the number of simulation to be 2 to the power of the number of simulated parameters. |

In the Monte Carlo simulation, if the number of simulations to represent each parameter as a normal distribution is 500 and there are 20 parameters involved, the total number of simulations is ten thousand. If, however, the interest is in determining the impact of all 20 parameters simultaneously, the total number of simulations is 500 as indicated in Table 3.1. As for the Two Point Mass (TMP) technique, the opposite is true. Only two simulated values are required to describe the variability of each input parameter. For 20 parameters, only 40 runs are required. However, to investigate the effect of all twenty parameters simultaneously, the number of runs is over one million. To take advantage of the strengths of both techniques, RECIPPE utilizes each technique at different stages in the analysis. To determine the impact of each parameter independently, the TMP method is used, while assessing the impact of all parameters simultaneously, the Monte Carlo simulation is used.

Figure 3.3 provides a flow chart of the use of either technique in RECIPPE. The construction parameters that are identified as part of the analysis require the results of the sampling statistics (Mean and COV) to develop the impact chart. The simulated cases are used to determine the modulus of each pavement layer. The probabilistic moduli are then used to estimate the remaining life.

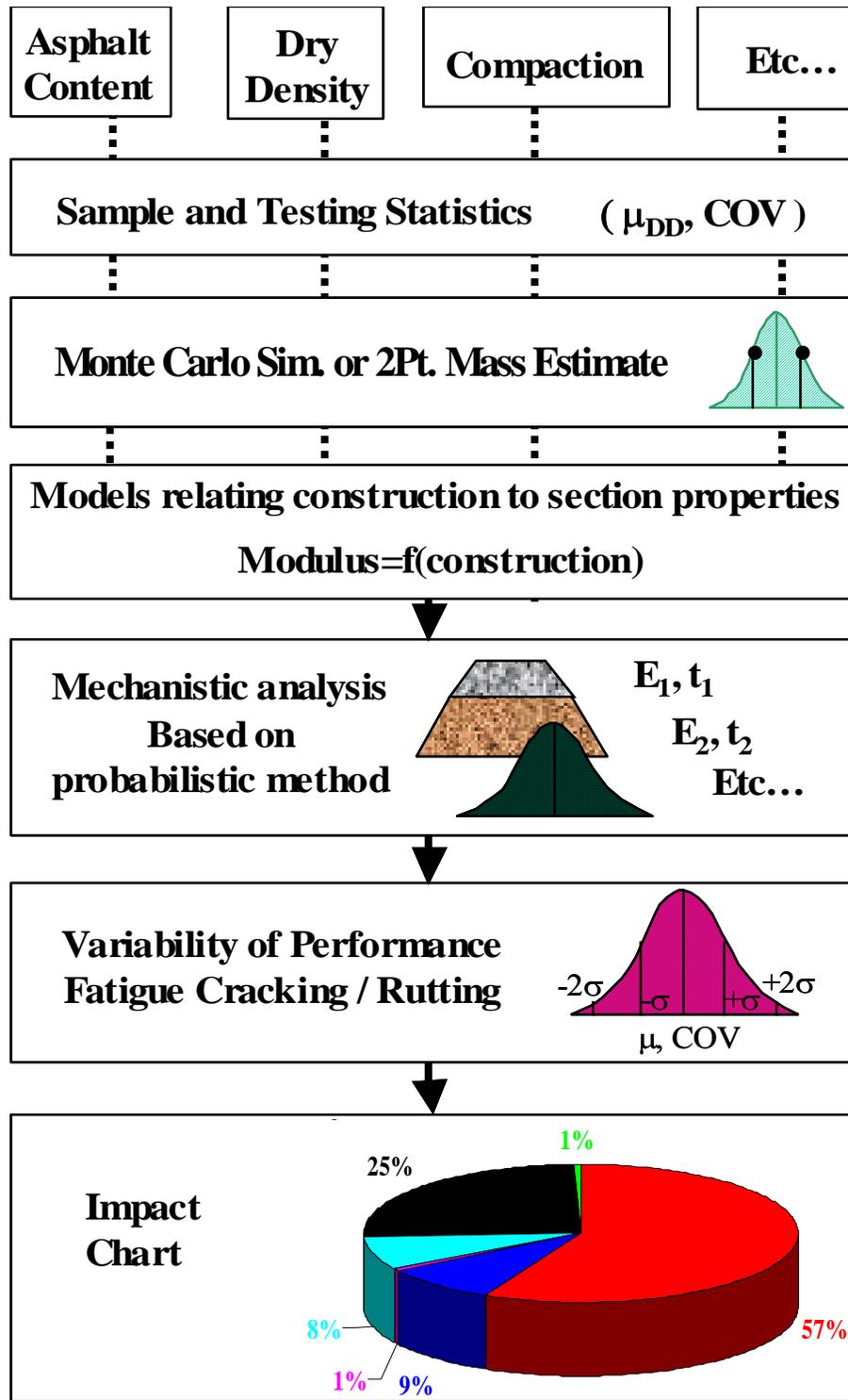


Figure 3.3 - Flowchart of the Algorithm Used in RECIPPE for Determining the Impact Value of Construction on Performance

The impact value,  $I$ , is defined as:

$$I = \frac{COV_{output}}{COV_{input}} \quad (3.1)$$

where  $COV_{output}$  is variability of performance and  $COV_{input}$  is the variability of construction parameter. The impact of each parameter is then normalized with:

$$NIV_i = \frac{I_i}{\sum_{i=1}^n (I_i)} \quad i = 1, 2, \dots, n \quad (3.2)$$

where  $NIV_i$  is the normalized value of parameter  $i$ . The normalized impact values are further compiled to develop an impact chart that assists in identifying the level of impact of each parameter on performance as illustrated in the bottom of Figure 3.3.

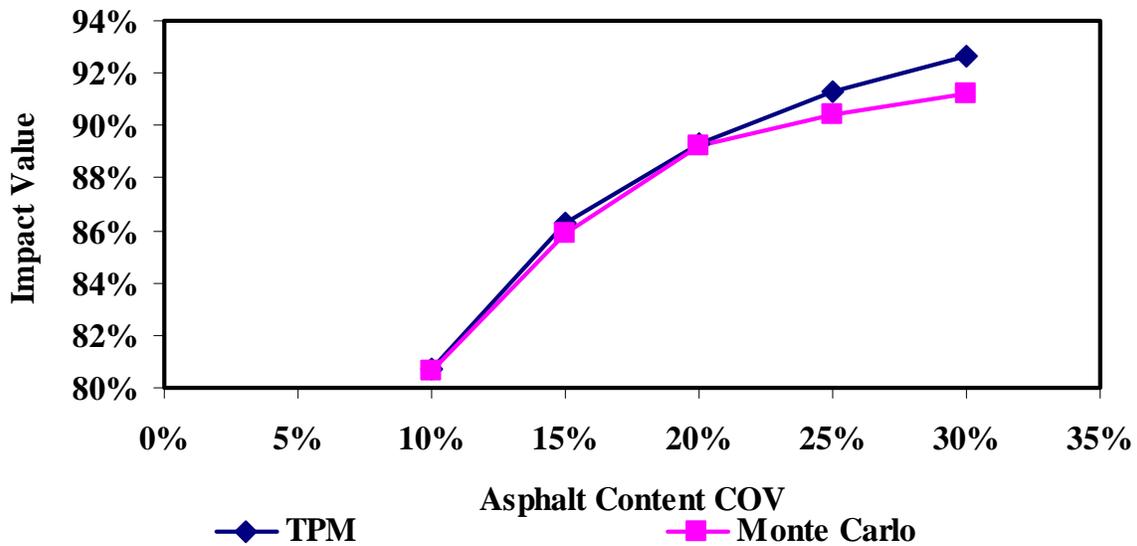
To determine the validity of the process, several simulations were performed to identify the accuracy of the process. The first step in the process was to determine the appropriate number of simulations required for a satisfactory representation of a parameter. As reported in Abdallah et al. (2004), the selected number of simulations is 500.

The appropriateness of using the TPM method in the analysis was also investigated. As an example, the results from the TPM and Monte Carlo simulations are compared Figure 3.4. A typical pavement in Texas with the parameters shown in Table 3.2 was used. In this example, only the material model for the AC layer was activated and the base and subgrade material models were not used. The moduli of the base and subgrade layers were assumed constant and set to their corresponding design values. The mean and COV values for all parameters were set according to the table, and only the COV of the asphalt content was varied. The program was executed five times by varying the COV from 10% to 50%, in 10% increments. As reflected in Figure 3.4, the results from the two analyses are fairly similar when the COVs are less than 20%. For higher COVs, the impact values from the two methods are comparable. This example shows the interchangeability of the two simulation methods in the practical ranges of construction variabilities.

These results are independent of construction parameters and pavement performance models used. Another factor to examine in the figure is change in variability of the output based on the variability of the input. The impact due to variability might change for every parameter and the shape of the curve in the figure will not be the same for all parameters. That is, the effectiveness of this algorithm to account for the impact of variability is independent of the analysis process used. What is also shown in the figure is the direction of change in the analysis. The change is monotonic, meaning the impact value increases as the variability of impact value increases. As the COV value of the input changes the impact value on the performance parameter changes as well. This demonstrates the usefulness of the probabilistic algorithm to identify the impact of variability of the construction parameters on the variability of performance. The final version of RECIPPE will be optimized by balancing both accuracy and processing time.

**Table 3.2 - Synthetic Data for a Typical Pavement Section Used in Comparing Two Probabilistic Algorithms.**

| Data Type      | Input Values             |              |      |
|----------------|--------------------------|--------------|------|
|                | Parameter                | Mean         | COV  |
| Design         | AC Thickness             | 5 in.        | 1%   |
|                | Base Thickness           | 12 in.       | 0%   |
|                | AC Modulus               | 500 ksi      | N/A  |
|                | Base Modulus             | 50 ksi       | N/A  |
|                | Subgrade Modulus         | 10 ksi       | N/A  |
| Material Model | Aggregate Passing No.200 | 10%          | 5%   |
|                | AC Mix Air Void          | 1.50%        | 10%  |
|                | Asphalt Viscosity        | 100000 poise | 3%   |
|                | Asphalt Content          | 5%           | Vary |
|                | Loading Frequency        | 18 Hz        | N/A  |
|                | Temperature              | 78.5 °F      | N/A  |



**Figure 3.4 - Comparison of Impact Values from Monte Carlo and TPM Methods.**

### Appropriateness of Material Models

The next stage in the validation is to investigate the adequacy of the material models selected based on the literature search. The models were developed based on studies conducted on different pavement layers. The material models selected for the AC, base and subgrade layers relate the corresponding construction parameters to their moduli. One model was selected for each layer of a flexible pavement.

The material model for the AC layer is an equation that relates the dynamic modulus of the AC to parameters such as temperature, asphalt content and air voids content. A popular model known as the “Witczak” model serves this purpose (Ayres et al., 1998). That model is in the form of:

$$\begin{aligned} \log E_{AC} = & 5.553833 + 0.028829 \frac{P_{200}}{f^{0.17033}} - 0.03476V_v \\ & + 0.070377\eta + 0.000005t_p^{(1.3+0.49825\log f)} P_{ac}^{0.5} - \\ & 0.00189t_p^{(1.3+0.49825\log f)} \frac{P_{ac}^{0.5}}{f^{1.1}} + 0.931757 f^{-0.02774} + \epsilon \end{aligned} \quad (3.3)$$

where  $E_{AC}$  is the dynamic modulus of the AC mix (in  $10^5$  psi),  $\eta$  is the bitumen viscosity (in  $10^6$  poise),  $f$  is the load frequency (in Hz),  $V_v$  is percent air voids in the mix by volume,  $P_{ac}$  is percent effective bitumen content by volume, and  $P_{200}$  is percent passing No. 200 sieve by total aggregate weight. The advantage of using the Witczak model was that a version of it is a part of the newly-developed mechanistic design guide.

The base and subgrade models were based on a common constitutive model. The general form of the universal equation is:

$$M_R = k_1 \theta^{k_2} \sigma_d^{k_3} \quad (3.4)$$

where  $\theta = \sigma_1 + \sigma_2 + \sigma_3 =$  bulk stress ;  $\sigma_d = \sigma_1 - \sigma_3 =$  deviator stress ( $\sigma_1, \sigma_2$  and  $\sigma_3$  are the three principal stresses). Parameters  $k_1, k_2$  and  $k_3$  are material regression constants statistically obtained from laboratory tests. This material model is applicable to both granular and cohesive materials.

Santha (1994) developed regression equations for cohesive and granular materials that estimate parameters  $k$  from various construction parameters such as the moisture content, compaction, and percent saturation. Those equations were adopted here.

The list of parameters used in the material models is provided Table 3.3. The range of feasible parameters based on the current TXDOT specification found in the literature search is also listed in Table 3.3. The range of values for each parameter and the typical acceptance values used in construction practices are reflected in the table. These values will be provided in the users guide to assist users of RECIPPE with default means and coefficients of variation.

To test the algorithm and the validity of the models using field data, a database search was conducted. The field data was to be used to check the appropriateness of the models and to calibrate the models for Texas road conditions and construction practices. The database search effort was conducted both locally in Texas and nationally with limited success. Most databases contained partial information. Unable to locate a comprehensive database, the search pattern focused on identifying data for parameters of each material model separately. On that consideration, the Long-Term Pavement Performance (LTPP) database was found to contain data that can be used for the asphalt-concrete layer.

**Table 3.3 - List of Construction Parameters of each Pavement Layer**

| Layer                   | Parameter                  | Range  | Acceptance |
|-------------------------|----------------------------|--|------------|
| <b>Asphalt-concrete</b> | Thickness, in.             | -  | ± 0.75     |
|                         | Modulus                    | -  | -          |
|                         | Poisson Ratio              | 0.33   | -          |
|                         | Asphalt Content            | 3%-7%  | ± 1%       |
|                         | AC Mix Air Void            | 5% - 9%  | ± 2%       |
|                         | Asphalt Viscosity, Poisses | 100 – 9000   | ± 20%      |
|                         | Agg. Passing Sieve No.200  | 2% - 7%  | ± 5%       |
|                         | Loading Frequency, Hz      | 18   | -          |
|                         | Temperature, °F            | 77   | -          |
| <b>Base</b>             | Thickness, in.             | -  | ± 1        |
|                         | Modulus                    | -  | -          |
|                         | Poisson Ratio              | 0.33 – 0.4   | -          |
|                         | Maximum Dry Density, pcf   | -  | ± 3        |
|                         | Degree of Compaction       | ≥ 100%   |            |
|                         | Aggregate Passing No. 40   | 50% - 85%  | ± 5%       |
|                         | Percent of Clay            | -  | -          |
|                         | Percent of Silt            | -  | -          |
|                         | Optimum Moisture Content   | -  | -          |
|                         | Moisture Content           | -  | -          |
| <b>Subgrade</b>         | Thickness                  | -  | -          |
|                         | Modulus                    | -  | -          |
|                         | Poisson Ratio              | 0.35 – 0.45  | -          |
|                         | Maximum Dry Density, pcf   | -  | ± 3        |
|                         | Optimum Moisture Content   | -  | -          |
|                         | Moisture Content           | Opt. Moist. for PI > 35  | -          |
|                         | Degree of Compaction       | ≥ 98% for PI ≤20<br>≤ 105% for 20<PI ≤35<br>95% - 100% for PI < 35 | -          |
|                         | Aggregate Passing No. 40   | -  | ± 5%       |
|                         | Percent of Clay            | -  | -          |
|                         | Percent of Silt            | -  | -          |
|                         | Liquid Limit               | -  | -          |
|                         | Plastic Index              | -  | ± 2%       |

The Long-Term Pavement Performance (LTPP) database has been populated since 1987 with more than 2,400 test sections on in-service highways at over 900 locations throughout North America. The extensive data collection effort includes inventory, material testing, pavement performance monitoring, climatic, traffic, maintenance, rehabilitation, and seasonal testing modules. The data are housed in an information management system that is the world's largest pavement performance database.

The online LTPP database offers a user-friendly format for exploring, extracting, and organizing the extensive LTPP data from all over the nation. In addition, the website provides the capability to identify the LTPP database tables and fields for data extraction.

A filtration process is used to extract specific data that is necessary by users to minimize unnecessary information that are contained in the multiple tables in the database. The research effort was first focused on SPS sites and later expanded to other Texas sections. The required information to be extracted from the LTPP database was:

- Asphalt content
- Viscosity
- Percent of aggregate passing sieve #200
- Percent air voids
- Elastic Modulus of the AC

To illustrate the filtration process, the example of extracting data for the asphalt content is discussed. The asphalt content can be found in the Inventory IMS module which contains tables with listings of plant mixed asphalt data. One of the tables, “Plant-mixed asphalt bound layers original mixture properties”, contains information such as the following.

|                              |                              |
|------------------------------|------------------------------|
| STATE_CODE,                  | NO_SAMP_ASPHALT_CONTENT,     |
| LAYER_NO,                    | ASPHALT_PLANT_TYPE,          |
| SHRP_ID,                     | CONSTRUCTION_NO,             |
| SAMPLE_TYPEHVEEM_COHESIOMETE | ASPHALT_CONTENT_MAX,         |
| R,BULK_SPEC_GRAVITY_MEAN,    | ASPHALT_CONTENT_MIN,         |
| MAX_SPEC_GRAVITY,            | ASPHALT_CONTENT_MEAN,        |
| NUMBER_BLOW,                 | BULK_SPEC_GRAVITY_STD_DEV,   |
| PCT_AIR_VOID_S_MAX,          | BULK_SPEC_GRAVITY_MIN,       |
| PCT_AIR_VOID_S_MIN,          | MARSHALL_STABILITY,          |
| PCT_AIR_VOID_S_MEAN,         | BULK_SPEC_GRAVITY_MAX,       |
| ASPHALT_CONTENT_STD_DEV,     | VOIDS_MINERAL_AGGR,          |
| RECORD_STATUS,               | NO_SAMP_PCT_AIR_VOID_S,      |
| ANTISTRIP_AGENT_TYPE,        | PCT_AIR_VOID_S_STD_DEV,      |
| ASPHALT_PLANT_TYPE_OTHER,    | MOISTURE_SUSCEPT_TEST,       |
| HVEEM_STABILITY,             | ANTISTRIP_AGENT_AMOUNT,      |
| MARSHALL_FLOW,               | ANTISTRIP_AGENT_CODE,        |
| RETAINED_STRENGTH_INDEX,     | ANTISTRIP_AGENT_TYPE_OTHER,  |
| PERCENT_STRIPPED,            | MOISTURE_SUSCEPT_TEST_OTHER, |
| HVEEM_STABILITY_NO,          | NO_TESTS_BULK_SPEC_GRAVITY   |
| TENSILE_STRENGTH_RATIO,      |                              |
| EFFECTIVE_ASPHALT_CONTENT,   |                              |

This list shows a considerably large amount of information to filter through in order to obtain the asphalt content. Identification keys are used to link the variety of tables together from a given site. Crucial identification keys such as SHRP ID, the road identification key, are used to extract, link, and match the appropriate data that is required. Few of the other identification keys

that were used are: SHRP\_ID, STATE\_CODE, LAYER\_NO, RECORD\_STATUS, ASPHALT\_GRADE, CONSTRUCTION\_NO, and ASPHALT\_SPECIFIC\_GRAVITY.

The next set of extraction was the backcalculated FWD moduli. Also extracted were the pavement properties and the raw FWD data. The extracted data from the database were then subjected to a data mining process to ensure the best set of data possible was used in the calibration of the AC material model. Parameters such as consistency in drop heights for FWD data, number of backcalculated layers, and RMS error after the completion of the backcalculation process were consideration in ensuring data reliability.

## Calibration of Material Models

The current form of the Witczak equation can be used to estimate the modulus of the AC layer in the RECIPPE program. However, in an effort to further enhance the prediction of the AC modulus for Texas pavements, a calibration of the model was carried out. The calibration of the AC material model using data collected from Texas sites is performed in three different ways. The first method is based on least squares single variable calibration. The second equation is based on modifying the existing coefficients of the current Witczak equation. The final approach is to develop a new model using similar parameters used by the Witczak equation. Summary of the results are presented in Table 3.4. The table contains the construction parameters and the backcalculated moduli from data measured in the field. Also included in the table is the calculated modulus values based on Equation 3.3. As shown in the table, the backcalculated values and those calculated using Equation 3.3 vary. The assumption in this case is that the backcalculated values are true representation of the actual condition for the pavement. Also incorporated in Table 3.4 is a cluster value. This value represents the offset or inaccuracy between the two sets of moduli. The equation used is as follows:

$$ClusterValue\% = \frac{abs(M_{backcalculated} - M_{Witczak})}{M_{backcalculated}} \quad (3.5)$$

Figure 3.5 compares the measured and estimated moduli. The two results are clearly different. In order to perform the calibration, the backcalculated moduli are assumed to represent the condition of the pavement at the time of testing. As such the modulus results estimated from the construction parameters based on the Witczak equation were calibrated to the backcalculated moduli. Users of RECIPPE have the flexibility to incorporate any model of their choosing in the analysis. The three methods to fit the data and generate new models are discussed next.

### *Single Variable Calibration*

The form of the equation used in the calibration of the Witczak equation is expressed as follows:

$$y = mx + b \quad (3.6)$$

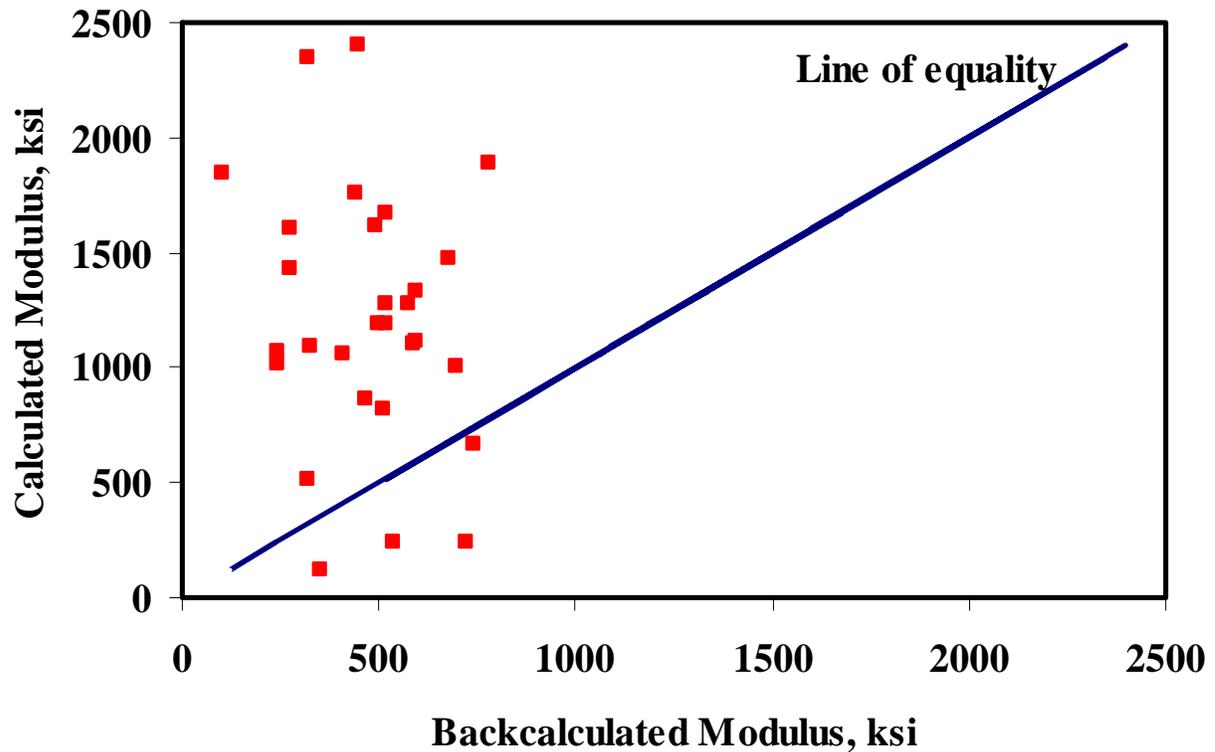
where x is the independent variable, m is the slope of the line, b is the intercept for the dependent variable and y represents the dependent variable. Variable x is expressed as follows:

**Table 3.4 - LTPP data used in AC material model development**

| No. | Site ID | AC Material Model Parameters |                        |                         |              |           |           | M <sub>B</sub> *<br>(psi) | M <sub>W</sub> **<br>(psi) | Cluster value |
|-----|---------|------------------------------|------------------------|-------------------------|--------------|-----------|-----------|---------------------------|----------------------------|---------------|
|     |         | V <sub>V</sub><br>(%)        | P <sub>AC</sub><br>(%) | P <sub>200</sub><br>(%) | η<br>(poise) | F<br>(Hz) | T<br>(°F) |                           |                            |               |
| 1   | 1068    | 7.9                          | 5.4                    | 6.0                     | 0.00198      | 18        | 54.3      | 662867                    | 741162                     | 12%           |
| 2   | 1047    | 7.0                          | 5.0                    | 5.0                     | 0.00118      | 18        | 58.6      | 1004921                   | 694742                     | 31%           |
| 3   | 1122    | 2.8                          | 4.0                    | 6.0                     | 0.00099      | 18        | 82.0      | 817177                    | 511980                     | 37%           |
| 4   | 1181    | 2.4                          | 4.3                    | 3.0                     | 0.00093      | 18        | 89.5      | 517531                    | 322365                     | 38%           |
| 5   | 1065    | 2.1                          | 5.4                    | 3.0                     | 0.0012       | 18        | 76.4      | 866992                    | 468589                     | 46%           |
| 6   | 1130    | 4.4                          | 4.5                    | 4                       | 0.001008     | 18        | 70        | 1114637                   | 593957                     | 47%           |
| 7   | 1169    | 3.7                          | 5                      | 4                       | 0.00187      | 18        | 70        | 1100145                   | 586114                     | 47%           |
| 8   | 1049    | 3.9                          | 7.4                    | 6.0                     | 0.00206      | 18        | 61.3      | 1470466                   | 676469                     | 54%           |
| 9   | 1096    | 4.7                          | 4.5                    | 8.0                     | 0.00113      | 18        | 74.7      | 1281383                   | 574762                     | 55%           |
| 10  | 3629    | 2.4                          | 5.7                    | 4                       | 0.001854     | 18        | 70        | 1337024                   | 593430                     | 56%           |
| 11  | 3689    | 3.7                          | 7.5                    | 5.0                     | 0.00197      | 18        | 66.9      | 1185704                   | 517165                     | 56%           |
| 12  | 1048    | 4.5                          | 5.6                    | 3.0                     | 0.00056      | 18        | 69.4      | 1188200                   | 499365                     | 58%           |
| 13  | 3669    | 4.1                          | 8.5                    | 6.0                     | 0.00211      | 18        | 55.3      | 1887475                   | 776873                     | 59%           |
| 14  | 3835    | 3.4                          | 5.7                    | 3.0                     | 0.00176      | 18        | 70.5      | 1273637                   | 515611                     | 60%           |
| 15  | 3579    | 5.3                          | 5.8                    | 1                       | 0.002119     | 18        | 70        | 1059546                   | 411378                     | 61%           |
| 16  | 1050    | 3.9                          | 5.8                    | 4                       | 0.00198      | 18        | 70        | 1673964                   | 519705                     | 69%           |
| 17  | 1109    | 5.0                          | 5.2                    | 3.0                     | 0.0018       | 18        | 70.0      | 1618405                   | 493774                     | 69%           |
| 18  | 1       | 9.9                          | 5                      | 2                       | 0.002139     | 18        | 70        | 1089450                   | 329040                     | 70%           |
| 19  | 2133    | 6.3                          | 5.3                    | 3                       | 0.002133     | 18        | 70        | 1760070                   | 439164                     | 75%           |
| 20  | 1077    | 3.6                          | 4.2                    | 1.0                     | 0.00102      | 18        | 92.2      | 1015125                   | 245871                     | 76%           |
| 21  | 1183    | 10.8                         | 6.9                    | 3.0                     | 0.00092      | 18        | 70.8      | 1074224                   | 242947                     | 77%           |
| 22  | 1092    | 3.0                          | 5.2                    | 2.0                     | 0.00202      | 18        | 86.5      | 1425218                   | 277885                     | 81%           |
| 23  | 9005    | 7.2                          | 4.7                    | 4.0                     | 0.00111      | 18        | 70.7      | 2399228                   | 449937                     | 81%           |
| 24  | 1060    | 4.7                          | 5.4                    | 1.0                     | 0.00205      | 18        | 81.8      | 1600674                   | 277737                     | 83%           |
| 25  | 3559    | 5.9                          | 6.5                    | 7.0                     | 0.0025       | 18        | 78.3      | 2347916                   | 316691                     | 87%           |
| 26  | 1178    | 3.2                          | 5.9                    | 7                       | 0.002037     | 18        | 70        | 7490028                   | 613084                     | 92%           |
| 27  | 1094    | 3.2                          | 26                     | 2                       | 0.001094     | 18        | 70        | 1845473                   | 99415                      | 95%           |
| 28  | 1076    | 2.1                          | 6.4                    | 3                       | 0.000895     | 18        | 70        | 238458                    | 535411                     | 125%          |
| 29  | 1061    | 7                            | 6.6                    | 3                       | 0.000858     | 18        | 70        | 123367                    | 353223                     | 186%          |
| 30  | 3679    | 3.3                          | 6.6                    | 5.0                     | 0.0021       | 18        | 61.7      | 236279                    | 720591                     | 205%          |

\* M<sub>B</sub> = Backcalculated modulus from FWD deflections

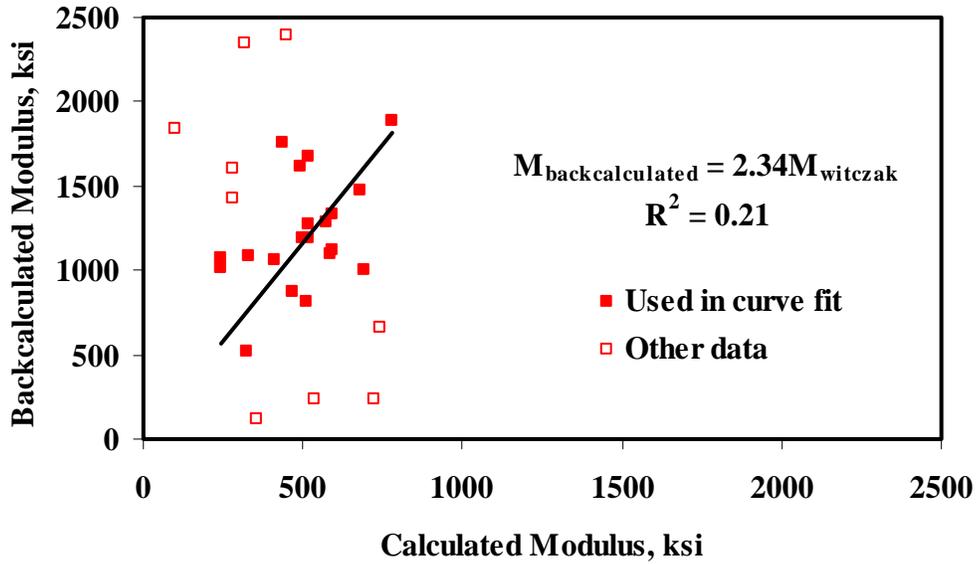
\*\* M<sub>W</sub> = Modulus value calculated from Witczak model



**Figure 3.5 - Comparison of Moduli based on Witczak Model and Backcalculated Results**

$$\begin{aligned}
 \log(x) = & 5.553833 + 0.028829 \frac{P_{200}}{f^{0.17033}} - 0.03476V_v \\
 & + 0.070377\eta + 0.000005t_p^{(1.3+0.49825\log f)} P_{ac}^{0.5} \\
 & - 0.00189t_p^{(1.3+0.49825\log f)} \frac{P_{ac}^{0.5}}{f^{1.1}} + 0.931757f^{-0.02774}
 \end{aligned} \tag{3.7}$$

A mining process was performed before curve fitting the data. Some of the values were not included in the calibration to maximize the fit and to minimize the error between the two sets of data. A simple clustering process was used to determine which data would be eliminated from the curve fitting. A multiplication factor was used to adjust the values based on Equation 3.6 with the intercept set to zero. The cluster value can be used to cluster sets of data that show similar trends to the backcalculated values. In this case, three clusters were formed as highlighted in Table 3.4. The first cluster was for cluster values less than 20%, the second cluster for values between 20% and 80%, and the last cluster for values greater than 80%. The largest cluster set is for cluster values between 20% and 80%. Therefore, this set was used in the regression process. After curve fitting, a slope of 2.34 was obtained. Figure 3.6 shows the results of the calibration based on Equation 3.6 using all data in Table 3.4. The data used in curve fitting is presented as the solid points and the data in the other clusters are presented with the hollow points.



**Figure 3.6 - Results of Calibration of Witczak Model Using Single-Variable Regression**

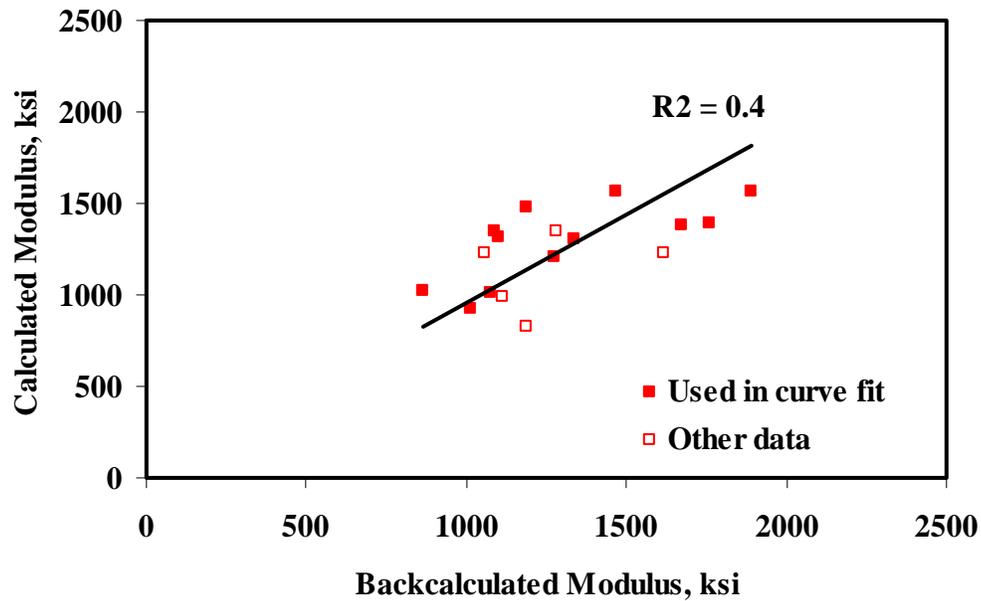
### *Modifying Coefficients of Witczak Equation*

The second calibration process consisted of adjusting the coefficients of the Witczak equation based on the data in Table 3.4. Data from the middle cluster was used for that analysis as well. Out of the twenty points available; seventeen were used for developing the equation and three randomly selected points was saved for validation. Equation 3.6 is rewritten as follows:

$$\begin{aligned} \log(E_{ac}) = & C^1 + (C^2) \left( \frac{P_{200}}{F^{0.17033}} \right) + (C^3)V_v + (C^4)\eta \\ & + (C^5)t_p^{(1.3+0.49825\log(F))} P_{ac}^{0.5} + \frac{(C^6)}{F^{1.1}} t_p^{(1.3+0.49825\log F)} P_{ac}^{0.5} \end{aligned} \quad (3.8)$$

where  $C^1$  to  $C^6$  are the coefficients to be determined. The remaining terms were left unadjusted. Also, the last term in Equation 3.6 was combined into  $C^1$  since this term is related to frequency. The frequency for all points in the database was set to a constant value of 18 Hz. To estimate the coefficients, a nonlinear estimation algorithm using the Gauss-Newton estimation method was used (Dennis and Schnabel 1983). The least squares method was used as a minimization function. This process is more complicated than the single variable regression. However, since the form of the equation is fixed, the determination of the coefficients was straight forward. Equation 3.9 presents the results of the estimation process. Figure 3.7 presents the results of the model.

$$\begin{aligned} \log(E_{ac}) = & 5.560 + 0.43 \left( \frac{P_{200}}{F^{0.17033}} \right) + .004V_v \\ & + 140.953\eta + 21.280t_p^{(1.3+0.49825\log(F))} P_{ac}^{0.5} \\ & - \frac{511.418}{F^{1.1}} t_p^{(1.3+0.49825\log F)} P_{ac}^{0.5} \end{aligned} \quad (3.9)$$



**Figure 3.7 - Results of Modifying Coefficients of Witczak Model**

***AC Material Model Based on LTPP Data***

The development of a new model based on n independent variables requires a multivariable nonlinear estimation algorithm. In general the form of the equation is:

$$Y = C^1 + C^2(x_1) + C^3(x_2) + \dots + C^n(x_n) \quad (3.10)$$

where  $C^1$  to  $C^n$  are model coefficients,  $X_1$  to  $X_n$  are independent model variables (n is an integer from 1 to number of variables available) and Y is the dependent variable. The complexity of this equation is in the model variables. Each variable in Equation 3.10 can be a function of several parameters. This complicates the process since an endless number of possible combinations exist. In order to solve this problem and determine a feasible solution, the possible number of combinations was reduced. First, all trigonometric functions were eliminated based on the nature and current status of the AC material models. Common functions such as addition, subtraction, multiplication, division, logarithms, and natural logarithms were used in the regression analysis. Through an iterative process, resulting coefficients for each of the possible independent variable equations were determined. The combination with the lowest least squares error was selected.

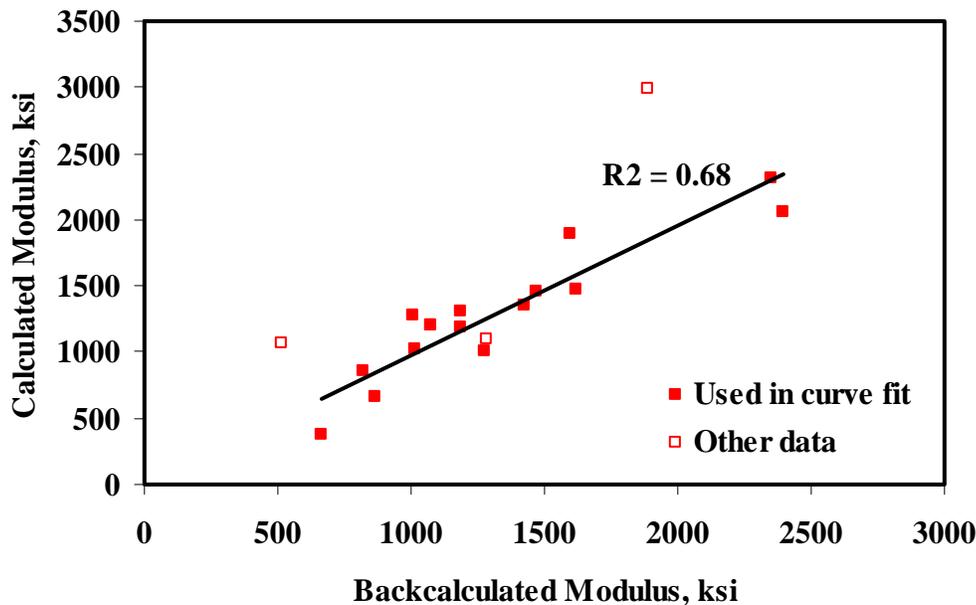
Based on the assumptions discussed, a regression analysis process with four independent variables was carried out. The analysis differed slightly from linear regression in the fact that each of these four variables can also be multiplied, divided, taken the logarithm of, etc. The result is a nonlinear, multivariable regression equation based on the measured parameters from the LTPP database. In this case, as in the previous methods, data from the middle clusters was used (seventeen used for generating the model and three for testing and validating the model). Equation 3.11 presents the

results of the best model.

$$\begin{aligned}
 E_{AC} = & -64342 + 169 \ln(V_v)(t_p^2) + 1.25(e^{Pac})(e^{P_{200}}) \\
 & - 2.44(P_{200}^3)(e^{V_v}) - 7.38 \times 10^{-26}(\eta^3)(e^{t_p}) \\
 & + 109.7(f)(V_v^3) - 157.3\sqrt{t_p}(P_{200}^3)
 \end{aligned}
 \tag{3.11}$$

As depicted in Figure 3.8, the predicted moduli were fairly reasonable. The untested data, plotted as hollow points, exhibited a slightly higher error than the rest of the data.

Overall, the models generated are reasonable keeping in mind the limited data that was available and used. A total of four material models for the AC layer are now available and can be used in the RECIPPE. Also, the calibration and model development algorithms developed here are being incorporated into RECIPPE in the case that more data becomes available.



**Figure 3.8 - Results of New Model Using LTPP Database**

***Base and Subgrade Material Models***

The compilation of field data for base and subgrade material models was not as successful. As presented in Table 3.3, nine parameters for base and eleven parameters for subgrade are required. A comprehensive database that contained all the parameters that was specific to TXDOT conditions could not be found. Therefore, a test plan was developed to help locate several on-going projects in Texas where data would be collected. The initial attempt to locate sites was based on trying to identify new construction projects where parameters for subgrade, base, and AC could be simultaneously collected and therefore creating a small database that could be used for validation and calibration. The Project Management Committee in a day-long meeting outlined a strategy to

search for sites. A protocol that would measure each parameter and the number of samples and tests that would be required, was developed. As shown in Appendix B, the protocol provided a simple explanation of the purpose of the data collection followed by a listing of all parameters required for each pavement layer. For each parameter a designated testing process was identified, and the frequency of testing was provided. The parameters that were not feasible to be tested by TXDOT personnel were also identified. These tests were carried out by UTEP personnel. Also, due to the time limitations, all projects independent of the stage of construction were targeted. This allowed for the pool of available project to be expanded. The protocol was sent out to several districts to help locate potential sites. More than a half-dozen sites from different locations in Texas were located. The data collection process and the calibration and validation results will be included in the next report.



## **Chapter 4**

### **Limited Implementation of Validation Process**

The AC material model is calibrated based on the LTPP database. As for the base and subgrade material models, the field and laboratory testing efforts are on the way. Once actual data becomes available, the validation process will be undertaken. In this chapter, a limited implementation of the validation process is presented to illustrate the consequence of variability in construction. This process will provide a guideline for the validation of the calibrated models.

#### **Case Study**

The case study presented in this project will demonstrate the use of RECIPPE to identify the impact of construction variability on the pavement performance. In this case study, the impact of variability of parameters of AC layer on the performance of the pavement is illustrated. The moduli for the base and subgrade layer are assumed constant and uniform with values of 50 ksi and 10 ksi, respectively.

The parameters of the AC layer are based on material model presented in Chapter 3 (Equation 3.3). The model is based on the following parameters: viscosity of binder, load frequency, percent air voids, percent asphalt content, and percent passing No. 200 sieve. Table 4.1 contains three sets of values for the parameters used in analyzing the AC layer. Two of the parameters, temperature and loading frequency are not controlled by the contractor during construction and as such these parameters are fixed as illustrated in Table 4.1. The remaining four parameters are controlled by the contractor and the variability of these parameters could change due to construction practices. In this study two parameters (the asphalt content and air voids) were selected to illustrate their impacts on the performance of the pavement are. The variability of remaining parameters was held constant. The performance models selected were fatigue cracking, subgrade rutting and AC rutting.

The four typical pavement sections used in this study have AC thickness varying from 2 in. to 6 in. and for the base layer varying from 6 in. to 12 in. The matrix presented in Table 4.2 show all the combination of cases that were analyzed.

**Table 4.1 - Values of AC Material model Parameters Used in Case Study**

| Case | Agg. Passing Sieve No.200 | Air Voids | Asphalt Content | Asphalt Viscosity | Temp.* | Loading Frequency* |
|------|---------------------------|-----------|-----------------|-------------------|--------|--------------------|
| 1    | 5                         | 12        | 5               | 0.0022            | 77     | 18                 |
| 2    | 10                        | 8         | 5               | 0.0022            |        |                    |
| 3    | 15                        | 4         | 5               | 0.0022            |        |                    |

\* - contractor does not have control over these parameters.

**Table 4.2 - Matrix of Pavement Sections Used for Validation of RECIPE**

| Modulus (ksi)  |     | Pavement Sections        |                            |                           |                             |
|----------------|-----|--------------------------|----------------------------|---------------------------|-----------------------------|
| Base /Subgrade | AC* | Thin-Thin<br>2in. - 6in. | Thin-Thick<br>2in. - 12in. | Thick-Thin<br>6in. - 6in. | Thick-Thick<br>6in. - 12in. |
| 50 / 10        | 240 | Case 1                   | Case 1                     | Case 1                    | Case 1                      |
|                | 400 | Case 2                   | Case 2                     | Case 2                    | Case 2                      |
|                | 680 | Case 3                   | Case 3                     | Case 3                    | Case 3                      |

\* - AC moduli are determined from AC material model.

The detailed results from this case study are included in Appendices C and D. As an example, the variations in the COV of the remaining life as a function of the COV of the AC content for the thin AC and thick base pavements for the three cases in Table 4.1 are presented in Figure 4.1. The mean value of the asphalt content, across a pavement section, is fixed at 5%. The three performance indicators used are: a) fatigue cracking, b) subgrade rutting, and c) AC rutting. In all three cases, the performance indicator that is impacted the most is fatigue cracking. In Case 1, where the mean air voids is 12%, the COV due to fatigue cracking is 81% for a 50% COV for AC content. As the mean air voids decrease to 8% and 4%, the COVs of the remaining life due to fatigue cracking decrease to 39% and 19%, respectively.

The variability of the asphalt content on the variability of the performance in terms of subgrade rutting and AC rutting are small in all three cases. For a COV of 50% for AC content, the variability in remaining life due to subgrade rutting increased from 14% to 15% to 19% for Cases 1, 2 and 3, respectively. For remaining life due to AC rutting, the variability was less than 13%.

The variations in performance indicators as a function of the COV of AC content, at a mean air voids of 8% for the four typical pavement sections are shown in Figure 4.2. Depending on the thickness of the layers, the most sensitive performance indicator changes. For the thin AC pavements (Figures 4.2a and 4.2b) the fatigue cracking is the most sensitive parameter; while for the thick AC pavements, (Figures 4.2c and 4.2d), the subgrade rutting is the most sensitive. In the case of thin AC pavements, the subgrade rutting and AC rutting performance indicators show little sensitivity to the COV of the asphalt content. As the thickness of the AC layer increases, the sensitivity of the subgrade rutting and AC rutting performance indicators also increases. This trend shows that as the AC layer thickness increases and the base layer thickness decreases the impact of variability of asphalt content on pavement performance becomes more pronounced. The results of all twelve cases depicted in Table 4.2 are graphically presented and summarized in a tabular form in Appendix C.

In part 2 of the case study, the variations in the COV of the remaining lives as a function of the COV of the air voids are analyzed. The air voids of the AC layer were changed from 12% to 8% to 4%. As an example, the results from the thin AC-thin base section are shown in Figure 4.3. As in the previous case, the variability of each performance indicator increases with increasing the variability in construction parameter. Comparing the three graphs, the impact of construction variability on performance is less significant as the air voids gets smaller. The largest impact is for the air voids of 12%. Another observation is that the fatigue cracking as a performance indicator is much more sensitive to the variability in air voids than the other two performance indicators.

The variations in the variability of the performance indicators as a function of the variability in air voids for the four typical pavement sections are shown in Figure 4.4. The same trends observed in Figure 4.2 are present here. The fatigue cracking as a performance indicator is more sensitive to the variability of air voids for the thin AC pavements as compared to the thick AC pavements. Also, as in Figure 4.2, the subgrade rutting criterion is more impacted by the variability in air voids for the thick AC pavements than for the thin AC pavements. The results of all twelve cases depicted in Table 4.2 for investigating the impact of varying percent air voids are graphically presented in Appendix D.

The overall results of these experiments illustrate the versatility of the algorithm in RECIPPE to analyze different flexible pavement sections. This case study showed two situations where the effect of one parameter is varied. However, for actual field data, the number of varying construction parameters is more, and the combining effect of their variability increases the complexity of the analysis. The algorithm incorporated in RECIPPE is able to handle such complexities.

The next step, after the preliminary validation process presented in this chapter, is to test the flexibility of each of the material models with field data. Also, as the algorithm is optimized, the validation process will continue and will be documented in future reports. As more data becomes available more case studies will be presented to illustrate the use and advantages of utilizing RECIPPE.

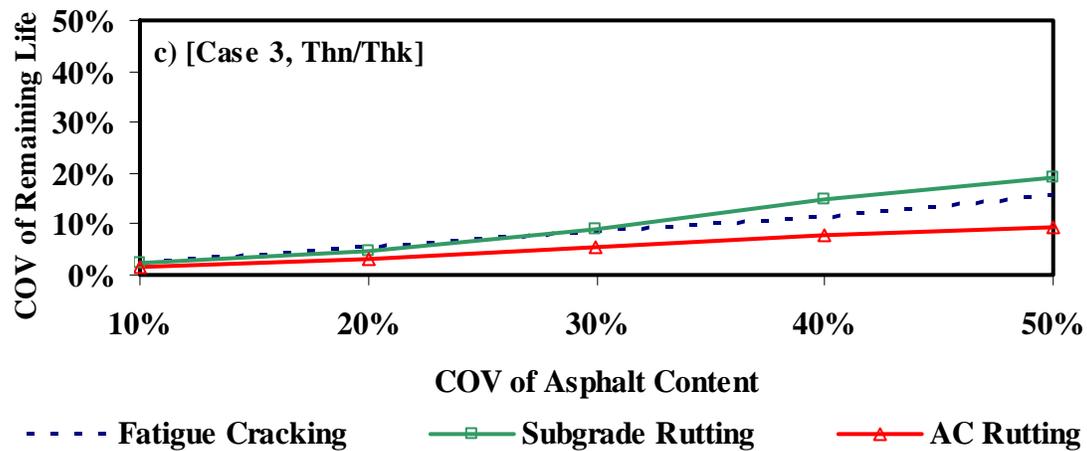
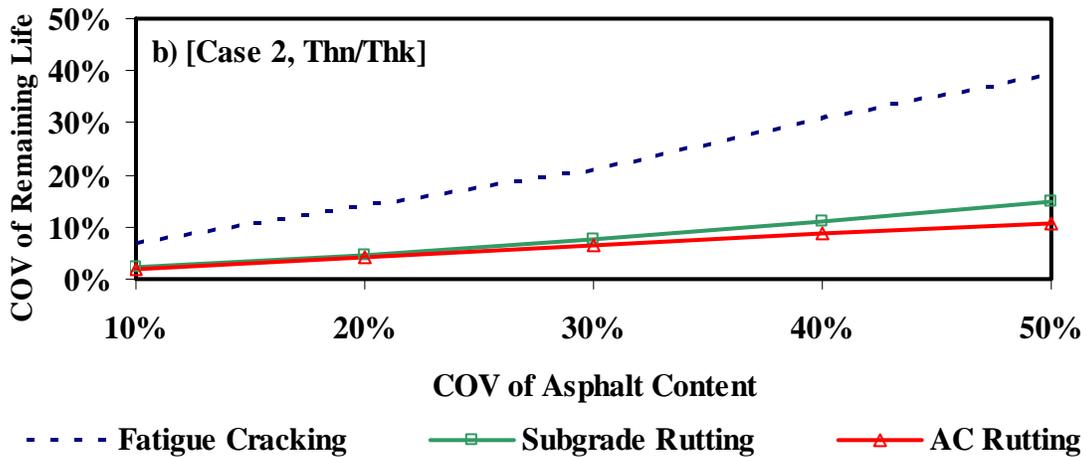
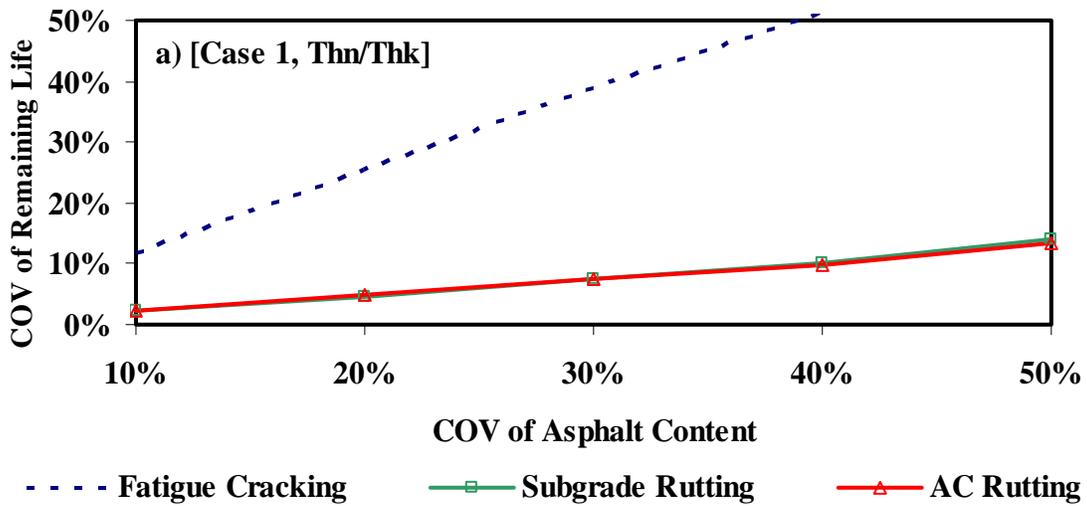


Figure 4.1 - Results of Impact of Variability of Asphalt Content on Remaining Life Varying AC Modulus

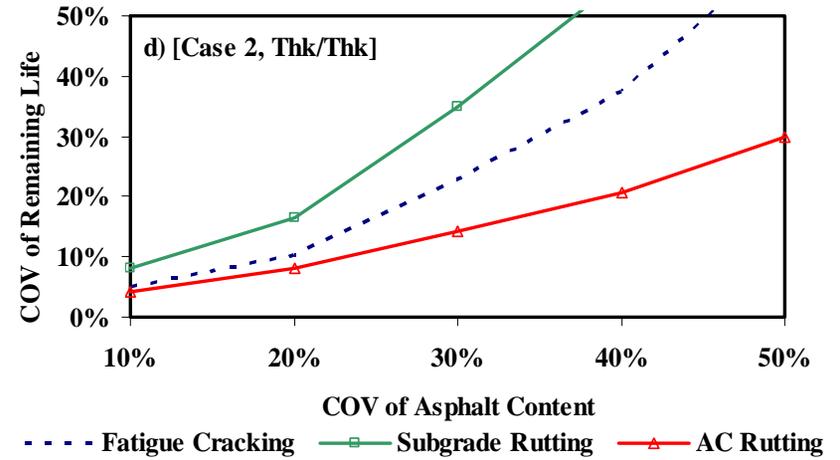
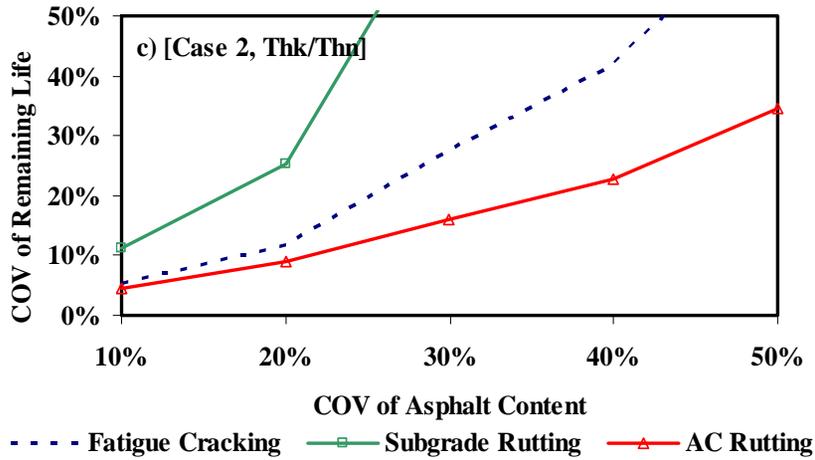
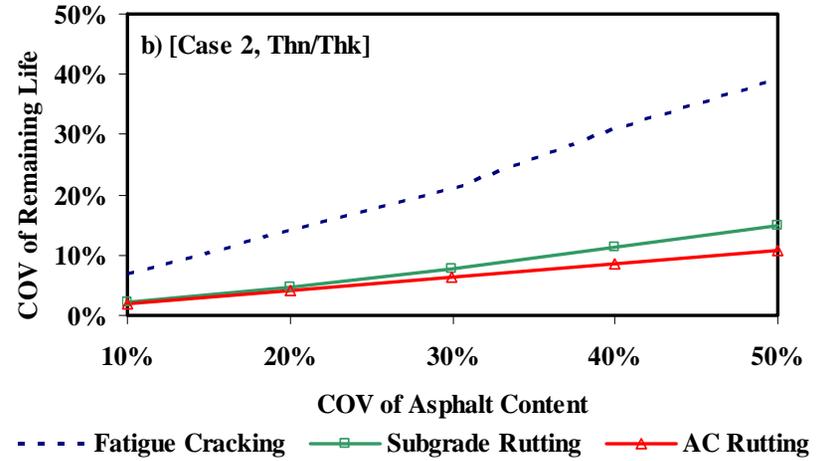
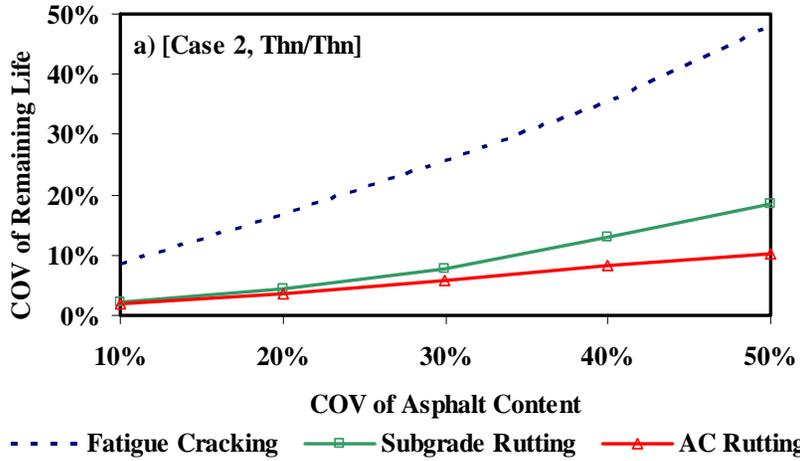
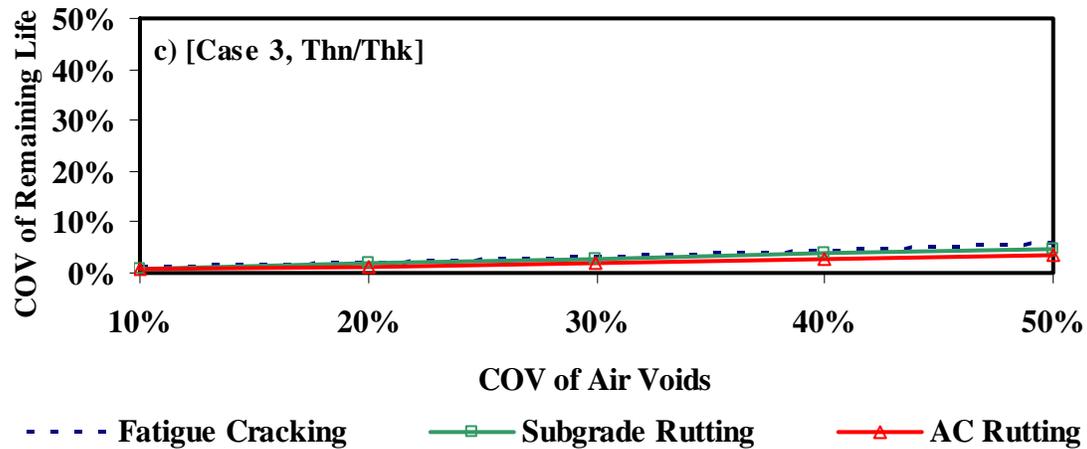
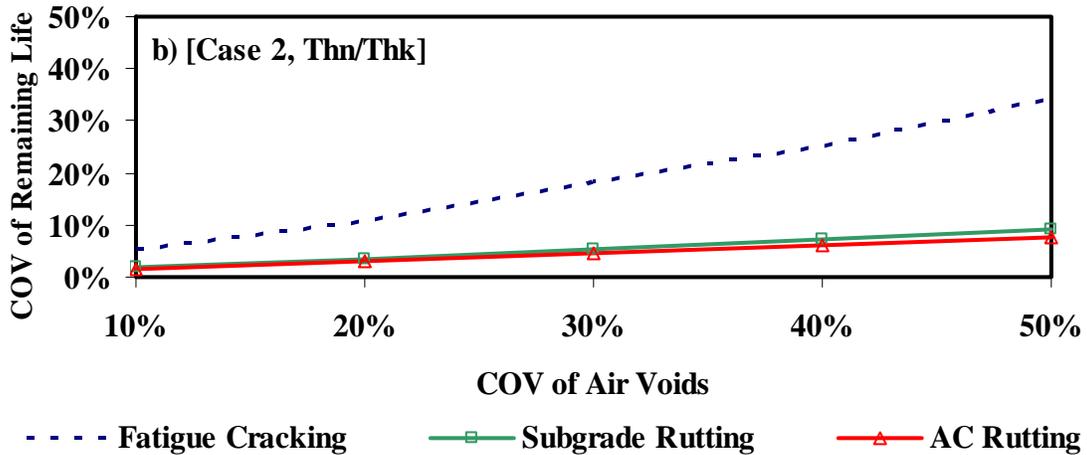
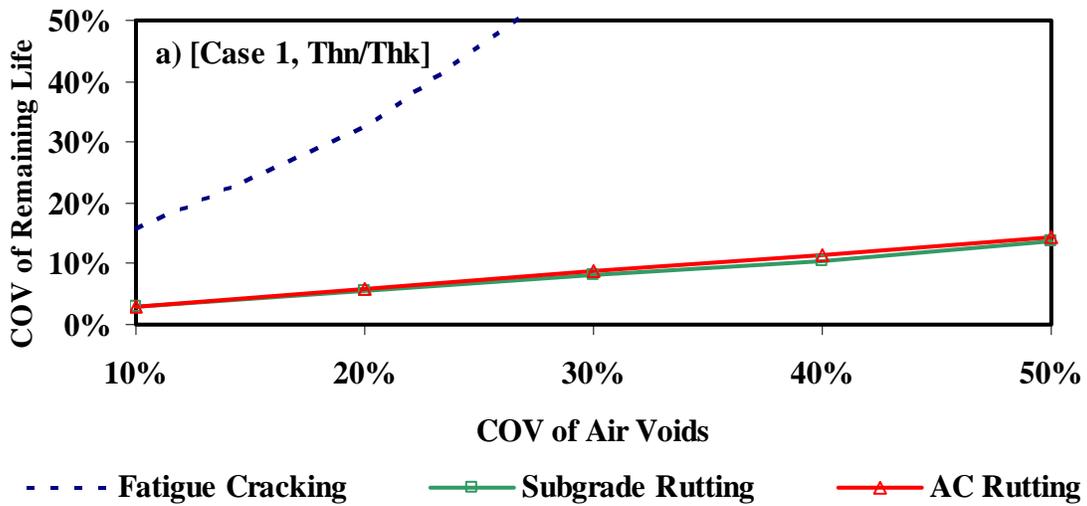


Figure 4.2 - Results of Impact of Variability of Asphalt Content on Remaining Life for Four Typical Pavement Sections



**Figure 4.3 - Results of Impact of Variability of Air Voids on Remaining Life Varying AC Modulus**

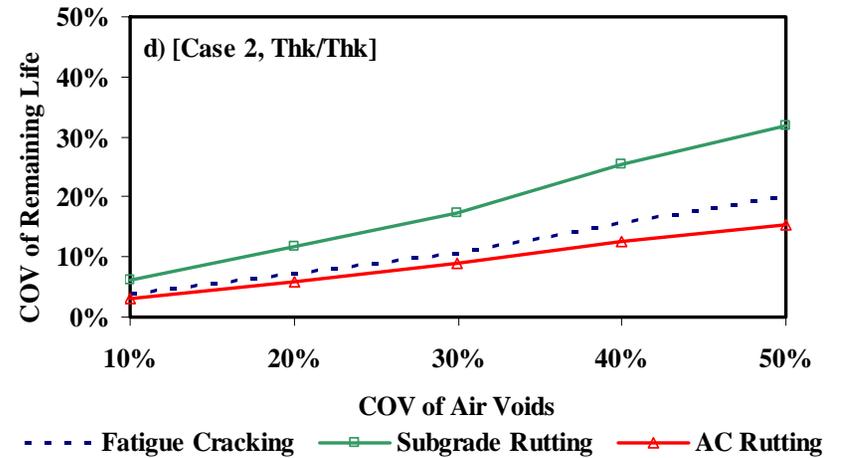
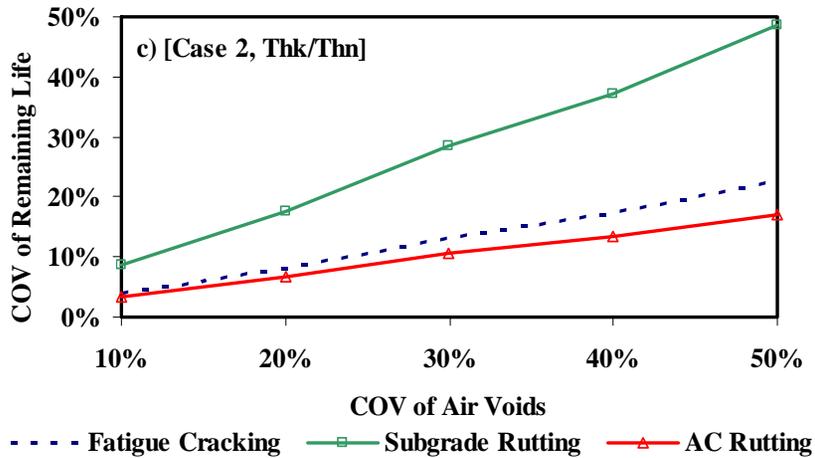
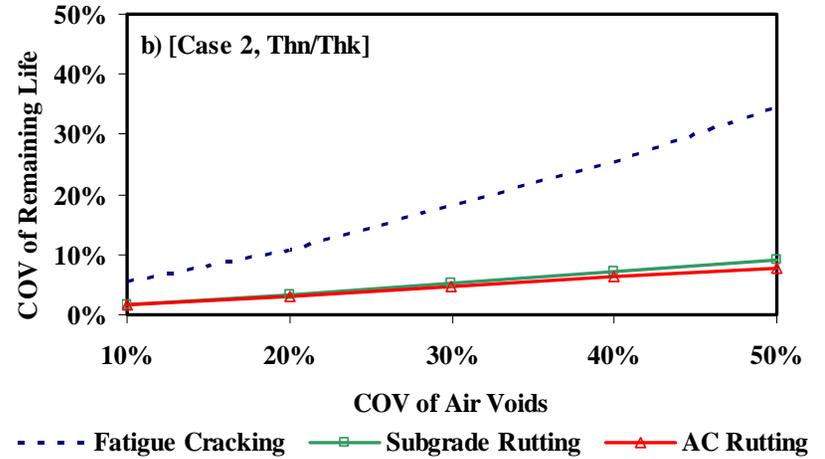
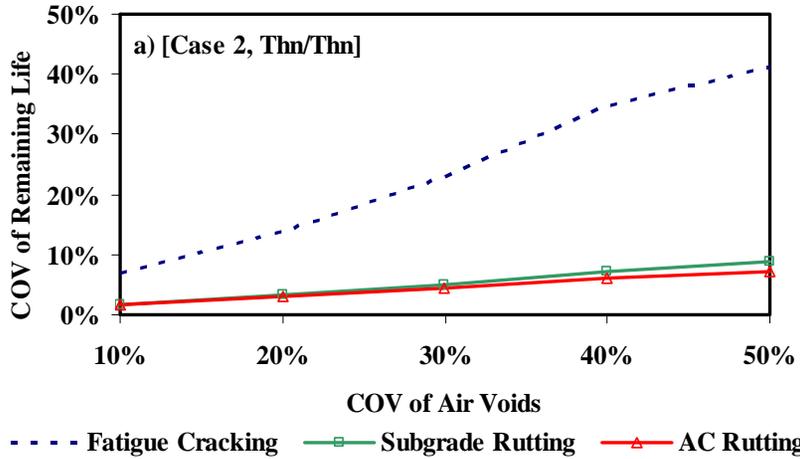


Figure 4.4 - Results of Impact of Variability of Air Voids on Remaining Life for Four Typical Pavement Sections



## **Chapter 5**

### **Summary and Conclusions**

This report provides the validation strategy to calibrate and validate the material models that are being incorporated into RECIPPE. The efforts in extracting data from the LTPP database for the AC layer material model are discussed. The protocol for targeting sites and collect data for base and subgrade material models is presented. The calibration of AC material model using data extracted from LTPP database for Texas sites is also presented in this report.

In addition, a case study showing a limited implementation of the validation process is presented. The validation process is presented by demonstrating the impact variability of one construction variable on the variability of performance. The validation effect will continue as the project progresses.

### **Recommendations**

The recommendations for improvements of the algorithm and the future work involved are as follows:

- a) Incorporating AASHTO 2002 Mechanistic Models: RECIPPE combines mechanistic and AASHTO performance models. The next step is to incorporate the AASHTO 2002 mechanistic models into this software. The probabilistic analyses routine will be updated to incorporate the AASHTO 2002 models. This process will require expanding the current probabilistic algorithm for adapting the ASSHTO 2002 models.
- c) Field Calibration of Base and Subgrade Material Models: Unfortunately, the LTPP database cannot be used to validate the constitutive models of the base and subgrade layers. The comprehensive LTPP database, although contains a wealth of information about the pavements in Texas, it does not contain all construction parameters required for models being used in the algorithm. A protocol for a comprehensive data collection scheme from several Texas sites for calibration of the constitutive models for base and subgrade layers has been devised. In order to cover all Texas regions, sites in East Texas, West Texas, South Texas and North Texas has been tested. This will provide data that is representative

of Texas' varying environment and geology. At each site material from the base and subgrade layers will be retrieved and tested to obtain information that is required to calibrate the constitutive models.

- d) **Development of Regression Models Based on Field Data:** Regression equations for determining the parameters of the constitutive model from construction parameters will be developed. These models will be calibrated with the field data collected. These models will be compared to the existing models to determine their applicability. If the new models prove to behave better than existing models, the new models could either replace the existing models or be added in as an alternative option.
- e) **Incorporate a Sampling Rate Algorithm:** An algorithm will be incorporated that will provide users of this software with the capability to determine the number of test samples required to meet a certain reliability level for each construction parameter. This will prove beneficial to both inspectors and contractors.
- f) **Incorporate a Cost Allocation Algorithm:** In addition to the sampling rate, an option to incorporate a cost-benefit analyses for the sampling of each parameter will be investigated and could be incorporated. The results of such a cost-benefit analysis will provide the user with a tool that can be used to optimize material selection and improve quality management program in a cost-effectively and systematic manner. The inspector and contractor can also benefit from such an algorithm because they will conveniently know which activities of cost allocation can be attributed to sample testing.

## References

- Abdallah, I., Yin, H., Nazarian, S., Ferregut, C., (2004), “Optimizing Construction Quality Management of Pavements Using Mechanistic Performance Analysis,” Research Report 4046-1, The Center for Transportation Infrastructure Systems, The University of Texas at El Paso.
- Abdallah, I., Yuan, D., and Nazarian, S., (2002), “Validation of Software Developed for Determining Design Modulus from Seismic Testing,” Research Report 1780-5, The Center for Highway Materials Research, The University of Texas at El Paso.
- Ayres, M. Jr. and Witczak, M.W., (1998), “AYMA - A Mechanistic Probabilistic System to Evaluate Flexible Pavement Performance,” Transportation Research Record 1629, Washington, DC., pp. 137-148.
- Dennis, J.E., Jr. and Schnabel, R.B., 1983, Numerical methods for unconstrained optimization and nonlinear equations: Englewood Cliffs, N.J., Prentice-Hall, 378 p.
- Ke, L., Nazarian, S., Abdallah, I., and Yuan, D., (2000), “A Sensitivity Study of Parameters Involved in Design with Seismic Moduli,” Research Report 1780-2, The Center for Highway Materials Research, The University of Texas at El Paso.
- Rosenblueth, E., (1975), “Point Estimates for Probability Moments,” *Proceedings of the National Academy Of Science*, 72(10), 3812-3814.
- Santha, B.L., (1994), “Resilient Modulus of Subgrade Soils: Comparison of Two Constitutive Equations,” Transportation Research Record 1462, Washington D.C., pp. 79-90.



## **Appendix A**

### **Standards to Measure Construction Parameters**



## **Aggregate Passing No. 200**

### **TXDOT Designation**

(Tex-110-E) Particle Size Analysis of Soils

### **AASHTO Designation**

(T 11-91) Materials Finer Than 75 mm (No. 200) Sieve in Mineral Aggregates by Washing

### **ASTM Designation**

(C 117-95) Standard Test Method for Materials Finer Than 75 mm (No. 200) Sieve in Mineral Aggregates by Washing

### **Basic Principle**

This test method covers determination of the amount of material finer than a 75 mm (No. 200) sieve in aggregate by washing. Clay particles and other aggregate particles that are dispersed by the wash water, as well as water-soluble materials, will be removed from the aggregate during the test.

### **Method**

Dry the test sample to constant mass at a temperature of  $110 \pm 5^\circ \text{C}$  ( $230 \pm 9^\circ \text{F}$ ). Determine the mass to the nearest 0.1 percent of the mass of the test sample. If the applicable specifications require that the amount passing the 75 mm (No. 200) sieve shall be determined on a portion of the sample passing a sieve smaller than the nominal maximum sieve of the aggregate. Separate the sample on the designated sieve and determine the mass of the material passing sieve to 0.1 percent of the mass of this portion of the test sample.

After drying and determining the mass, place the test sample in the container and add sufficient water to cover it. Agitate the sample with sufficient force as to achieve complete separation of particles finer than 75 mm (No. 200) sieve from the coarser particles, and to bring the fine material into suspension. Add a second charge of water to the sample in the container, agitate, and decant as before. Repeat procedure until wash water is clear. Return all material retained on the nested sieves by flushing to the washed sample. Dry the washed aggregate to constant mass temperature of  $110 \pm 5^\circ \text{C}$  ( $230 \pm 9^\circ \text{F}$ ) and determine the mass to the nearest 0.1 percent of the original mass of the sample.

## **Aggregate Passing No. 200 (Continued)**

### **TXDOT Designation**

(Tex-110-E) Particle Size Analysis of Soils

### **AASHTO Designation**

(T 11-91) Materials Finer Than 75 mm (No. 200) Sieve in Mineral Aggregates by Washing

### **ASTM Designation**

(C 117-95) Standard Test Method for Materials Finer Than 75 mm (No. 200) Sieve in Mineral Aggregates by Washing

### **Advantage(s)**

The major advantage is that this procedure is one of the most common test methods for determining aggregates passing No. 200 sieve.

### **Disadvantage/s**

There is not a major disadvantage associated with this method except that it is time consuming.

## **Maximum Dry Density**

### **TXDOT Designation**

(Tex-115-E) Field Method for Determining In-Place Density of Soils and Base Materials

### **AASHTO Designation**

(T191-93) Density of soil in-place by the Sand-Cone Method

### **ASTM Designation**

( D1556-00) Standard Test Method for density and Unit Weight of Soil in Place by the Sand-Cone Method

### **Basic Principle**

The objective of this method is being able to determine the in-place density of soils.

### **Method**

Weigh the assembled apparatus\* and record. Open the valve when the apparatus is placed on its upright position and fill with water until it appears over the valve. Immediately, close valve and remove excess water. Weigh the apparatus and water and obtain temperature of the water. Next, determine the bulk density of the sand in the test. In order to accomplish this task, place the empty apparatus upright on a firm level surface, close the valve and fill funnel with sand. Fill the apparatus, ensuring that the valve is open and keeping funnel at least half full of sand. Close the valve sharply and empty excess sand. After weighing the apparatus, determine the net mass of sand by subtracting the mass of the apparatus.

Next, pour the sand in the apparatus and secure mass of apparatus and sand. With the apparatus in a level surface, open the valve of and keep it open until the sand stops running. Close the valve and weigh the apparatus with remaining sand and determine the amount of sand that was lost. Replace the sand removed in the funnel determination and close the valve. To determine the density of the soil, seat the inverted apparatus on the prepared plane surface and mark the outline of the funnel. Open the valve and after the sand has stopped flowing, close the valve. Weigh the sand remaining in the apparatus and obtain mass of sand used in the test. Weigh the material that was removed from test hole. Mix the material and weigh a representative sample for moisture determination (according with T 265 test method). Finally, after obtaining the value from Table 1 on page 590 of the ASTM Manual and with a series of calculations, as stated on that same page, the in-place dry density is obtained.

## **Maximum Dry Density (Continued)**

### **Advantage(s)**

This is one of the most efficient ways for the determination of the maximum dry density.

### **Disadvantage(s)**

The major disadvantage is the use of hard-to-carry apparatus.

\*Refer to pg. 588 of ASTM Manual

## **Maximum Dry Density**

### **TXDOT Designation**

(Tex-115-E) Field Method for Determining In-Place Density of Soils and Base Materials

### **AASHTO Designation**

(T205-86) Density of soil in-place by Rubber Balloon Method

### **ASTM Designation**

(D2167-94 (2001) Standard Test Method for density and Unit Weight of Soil in Place by the Rubber Balloon Method

### **Basic Principle**

This method serves to establish the in place density of compacted soils or firmly bonded soil using a rubber-balloon apparatus.

### **Method**

Set the apparatus on the test hole site, making sure is reasonably plane, and take the initial reading on the volume indicator using the same pressure used on the calibration procedure on page 647 of the ASTM Manual. Then, scribe the outline of the apparatus on the test hole site. Record the pressure on the amount of surcharge, pressure used and initial volume reading. The apparatus has to be removed from the test hole site and a hole is to be dug centered within the outline scribed by the apparatus. Try to disturbed the soil as less as possible wile digging the hole. The soil removed shall be stored in an airtight container and tested for mass and moisture content. The minimum volume for the test hole has to be in accordance to Table 2 on page 647.

The apparatus is to be set over the test hole in the same position used for the initial reading and the flexible membrane is to be placed in the hole and inflated. Again, use same surcharge and pressure as utilized in the calibration process. Record the reading on the volume indicator and determine the test hole by subtracting it from the initial reading. The moisture content obtained from the sample will be used in accordance with the calculation section of this procedure (page 648).

## **Maximum Dry Density**

### **TXDOT Designation**

(Tex-113-E) Laboratory Compaction Characteristics and Moisture-Density Relationship of Base Materials

(Tex-113-E) Laboratory Compaction Characteristics and Moisture-Density Relationship of Subgrade and Embankment Soils

### **AASHTO Designation**

(T204-90) Density of soil in-place by the drive Cylinder Method

### **ASTM Designation**

NONE

### **Basic Principle**

This test method utilized for determining in-place density of soil is used only of soils with the following characteristics: moist, cohesive, and fine-grained material.

### **Method**

The drive cylinder is lubricated with a light coating of motor oil and is placed on the soil surface. The surface has to be prepared by smoothing it and cleaning it of loose particles. The drive head is then seated on the cylinder. The cylinder penetration is accomplished by raising the drop hammer and releasing it; letting it strike the drive head. The drive hammer must be kept at a vertical position at all times. Driving should be continued until the top of the cylinder is approximately 12 mm (0.5 in.) below the surface. After this procedure, the drive head should be removed and the cylinder must be taken out of the ground. In order to accomplish a successful removal, the soil must be cut several centimeters away from the cylinder and undercutting the cylinder several centimeters. Exercise care at all times to protect the soil from being disturbed if otherwise discard of sample.

In order to prevent loss of moisture from the sample, the mass of the cylinder and sample should be obtained as quickly as possible. The soil sample is the taken out of the cylinder and appropriate moisture content and dry unit mass are to be determined. Calculations should be run as stipulated on page 644 of the ASTM Manual.

## **Maximum Dry Density**

### **TXDOT Designation**

NONE

### **AASHTO Designation**

(T233-86) Density of soil in-place by Block, Chunk, or Core Sampling

### **ASTM Designation**

NONE

### **Basic Principle**

This test method is intended to determine the density of cohesive soil in the natural state, compacted cohesive soil, and stabilized soil by measuring the weight and volume of undisturbed samples.

### **Method**

After removal of the undisturbed sample, take a representative moisture sample from the wall of the hole, or from the trimmings obtained in cutting the undisturbed sample, place in a container, determine the mass to the nearest 0.1g, dry to constant mass, and determine the moisture content. The minimum size of the moisture content sample, based on the maximum particle size, is given in Table 1. Trim any loose material from the undisturbed sample and determine the mass of the sample to the nearest 1.0g. The minimum sample volume, after trimming, is given in Table 1, on page 770 of the ASTM Manual. Immerse the undisturbed sample in melted paraffin, being careful that the sample is completely coated. Allow the paraffin coating to cool, and then determine the mass of the coated sample to the nearest 1.0g. The gain in mass represents the mass of paraffin and the volume of the coating is calculated using the density of paraffin.

The volume of the paraffin-coated sample in water shall be determined by one of the following methods. Determine the mass of the paraffin-coated sample submerged in the water bath described in Section 2.3 and record the mass to the nearest 1.0g. Determine the volume of the sample in accordance with Section 5.2. Fill the volume-measuring device with water above the overflow. Permit the excess water to drain. Immerse the coated sample and determine the mass of the displaced water to the nearest 1.0g. Determine the volume of the sample in accordance with Section 5.2.

### **Advantage(s)**

N/A

### **Disadvantage(s)**

A disadvantage is the need of special apparatus to carry on procedure.

## **Maximum Dry Density**

### **TXDOT Designation**

(Tex-115-E) Field Method for Determining In-Place Density of Soils and Base Materials

### **AASHTO Designation**

(T238-97) Density of Soil and Soil-Aggregate in-place by Nuclear Methods (Shallow Depth); Method A - Backscatter

### **ASTM Designation**

NONE

### **Basic Principle**

This method covers the determination of the total or wet density of soil and soil aggregate in place by the attenuation of gamma rays where the gamma source of the gamma detector, or both, remain at or near the surface.

### **Method**

Select a test location where the gage in test position will be at least 150 mm (6 in.) away from any vertical projection. Prepare the test site in the following manner. Remove all loose and disturbed material and additional material as necessary to expose the top of the material to be tested. Prepare a horizontal area sufficient in size to accommodate the gage, by planning the area to a smooth condition so as to obtain maximum contact between the gage and material being tested. The maximum void beneath the gage shall not exceed 3 mm (1/8 in.). Use native fines of fine sand to fill these voids and smooth the surface with a rigid plate or other suitable tool. Proceed with the test in the following manner. Seat the gage firmly. Keep all other radioactive sources away from the gage to avoid affecting the measurement. Warm up the equipment in accordance with the manufacturer's recommendation. Secure and record one or more 1-minute readings. Determine the in-place wet density by use of the calibration curve previously established.

### **Advantage(s)**

The major advantage to this test procedure is the accurate results obtained from this experiment.

### **Disadvantage(s)**

The major disadvantage is the use of possibly radioactive material.

## **Moisture Content**

### **TXDOT Designation**

(Tex-103-E) Determining Moisture Content in Soil Materials

### **AASHTO Designation**

(T265-93) Laboratory Determination of Moisture Content of Soils (Conventional Oven Method)

### **ASTM Designation**

(D4643-00) Standard Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Oven Method

### **Basic Principle**

This test method serves as a basis for establishing the moisture (water) content of soil, rock and soil-aggregate mixtures. This parameter is expressed as a percentage using the conventional oven method or by using a microwave oven.

### **Method**

A dry and clean container (preferably with a lid) is to be weighed. The moisture content sample is placed in this container and then heated inside either a conventional or microwave oven. The sample should be left overnight (15 or 16 hours is sufficient) at a temperature of  $110 \pm 5^\circ \text{C}$  ( $230 \pm 9^\circ \text{F}$ ), when using a conventional oven. When a microwave oven is used, the sample should be heated for 3 minutes per 100 grams sample. Remove the container from the oven and allow it to cool to room temperature. Weigh the container and dried sample. Finally, subtract the weight of container after drying to the weight before removing moisture from the sample; this value represents the weight of the water in the sample.

### **Advantage(s)**

This method is efficient and cost effective.

### **Disadvantage(s)**

This type of test usually requires a bulky oven thus making it hard to perform in the field.

## **Moisture Content**

### **TXDOT Designation**

NONE

### **AASHTO Designation**

(T217-96) Determination of Moisture in Soils by means of Calcium Carbide Gas Pressure Moisture Tester

### **ASTM Designation**

NONE

### **Basic Principle**

The purpose for using the Calcium Carbide Gas Pressure Moisture Tester is to determine the moisture content of a given sample of soil.

### **Method**

Place three scoops (approximately 24 g) of calcium carbide in the body of the moisture of a 20 g or 26 g tester and when a super 200 D tester is used, place six scoops (approximately 48 g) of calcium carbide. Weigh a sample of the exact mass specified by the manufacturer of the instrument and place it on cap of the tester. Place two 31.75-mm (1.25-in) steel balls in the body of the tester when a 20 g or 26 g tester is utilized. With the pressure vessel in an approximately horizontal position, insert the cap in the pressure vessel and seal the unit by tightening the clamp, taking care that no carbide comes in contact with the soil until a complete seal is achieved. With the moisture tester in a vertical position the soil in the cap should fall into the pressure vessel. In order to allow the calcium carbide to react with all the free moisture make sure to break up the lumps by shaking the instrument in a rotating motion.

After the needle stops moving, read the dial while holding the instrument in a horizontal position at eye level. Record both the sample mass and dial reading. Slowly release the gas pressure making sure the cap of the instrument is always pointing away from operator. The test was not performed efficiently if after emptying the pressure vessel the sample contains lumps and another test have to be performed. However, if the material is uniformly mixed, the dial reading will then represent percent of moisture by wet mass and should be converted to dry mass.

### **Disadvantage(s)**

A major disadvantage is the need of special equipment to perform test procedure.

## **Moisture Content**

### **TXDOT Designation**

NONE

### **AASHTO Designation**

(T239-97) Moisture Content of Soil and Soil Aggregate in-place by Nuclear Methods (Shallow Depth)

### **ASTM Designation**

NONE

### **Basic Principle**

This method covers determination of the moisture content of soil and soil-aggregate in-place by moderation or slowing of fast neutrons where the neutron source and the thermal neutron detector both remain at the surface.

### **Method**

Standardize the equipment in accordance to the manufacturer's specifications. Test site preparation requires the opt for a location where the gage in the test position will be at least approximately 150 mm (6 in) away from any vertical projection. Remove all loose and disturbed material from the test site and prepare a flat area sufficient in size to accommodate the gage. The maximum depressions beneath the gage shall not exceed 3 mm (1/8 in). Use native fines or fine sand to fill voids and level the excess with a rigid plate or other suitable tool.

Seat the gage firmly onto the ground. In order for the reading not to be affected, keep all radioactive sources away from the gage. Warm up the instruments with enough time, as specified in the manufacturer's instructions. Place the source in the use position and take one or more 1-minute readings. Calculate the moisture content in accordance with calculation method on page 793 of the ASTM Manual.

### **Advantage(s)**

N/A

### **Disadvantage(s)**

A major disadvantage is the use of special equipment to perform test procedure.

## **Moisture Content**

### **TXDOT Designation**

(Tex-113-E) Laboratory Compaction Characteristics and Moisture-Density Relationship of Base Materials

### **AASHTO Designation**

(T 99-97) The Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in) Drop---Method A

### **ASTM Designation**

NONE

### **Basic Principle**

This test method is intended for determining the relation between the moisture content and density of soils compacted in a mold of a given size with a 2.5-kg (5.5-lb) rammer dropped from a height of 305 mm (12 in).

### **Method**

Thoroughly mix the selected representative sample with enough water to dampen it to approximately four percentage points below the optimum moisture content. Form a specimen by compacting the prepared soil in the 101.6-mm (4 in) mold (with collar attached) in three equal layers to give a compacted depth of 125mm (5 in). To compact soil successfully, follow the instructions specified on page 302 of the ASTM Manual. After compaction, determine the mass of the mold and moist soil in kg to the nearest 5 g. Remove the material from the mold and slice vertically through the center. Take a representative sample of the material from one of the cut faces, weigh and dry with accordance to T 265, to determine the moisture content.

### **Advantage(s)**

This is a simple procedure as long as the proper equipment is at hand and its efficiency goes accordingly to the care of the experiment performance.

### **Disadvantage(s)**

Special equipment is required.

## **Moisture Content**

### **TXDOT Designation**

NONE

### **AASHTO Designation**

(T 93-86) Determining the Field Moisture of Soils

### **ASTM Designation**

NONE

### **Basic Principle**

The minimum water content at which a drop of water placed on a smoothed surface of the soil will not be completely absorbed in 30 seconds but will spread out over the surface leaving a thin film of moisture is known as the field moisture equivalent.

### **Method**

The sample to be tested should be placed in a mixing dish and stirred and chopped with the spatula, adding water from a pipette. This procedure is to be continued until the wetted soil forms into small balls. With five light strokes of the spatula form a smoothed surface in a manner that a slight depression should be imprinted on the soil sample. Place a drop of water in this depression and if it disappears in 30 seconds or less, two or three drops of water shall be added to the soil and the mixing. Smoothing of the surface as well as previous procedure shall be repeated until the drop of water does not disappear but spreads over the smoothed area leaving a shiny spot without the presence of free water.

If the end point is exceeded, a new sample shall be taken and the test procedure repeated adding smaller increments of water. A portion of the soil including the smoothed area should be placed in a container and weighed to the nearest 0.01 g. The soil and container should be oven dried to constant mass at  $110 \pm 5^{\circ}\text{C}$  ( $230 \pm 9^{\circ}\text{F}$ ) and weighed to the nearest 0.01 g. Finally, the field moisture equivalent shall be calculated as stipulated on page 283 of the ASTM Manual.

## **Plastic Limit and Plasticity Index**

### **TXDOT Designation**

(Section 7. Tex.-105-E) Determining Plastic Limit of Soils and (Section 8. Tex-106-E) Calculating the Plasticity Index of Soils

### **AASHTO Designation**

(T 90-96) Determining the Plastic Limit and Plasticity Index of Soils

### **ASTM Designation**

NONE

### **Basic Principle**

The plastic limit of a soil is the lowest water content determined in accordance with the following procedure at which the soil remains plastic. The plasticity index of a soil is the range in water content, expressed as a percentage of the mass of the oven-dried soil, within which the material is in a plastic state.

### **Method**

Form a test sample, as stipulated on page 278 of ASTM Manual, into an ellipsoidal-shape mass. Roll this mass between the fingers or palm and the ground-glass plate or a smooth surface. Roll the sample into a thread of uniform diameter throughout its length. When the diameter of the thread becomes 3 mm, break the thread into six or eight pieces. Squeeze the pieces together into a uniform mass roughly ellipsoidal shape and re-roll. Continue this alternate rolling to a thread 3 mm in diameter, gathering together and re-rolling, until the thread crumbles under the pressure required for rolling and the soil can no longer be rolled into a thread. Gather the portions of the crumbled soil together and place it into a container. The soil shall be dried in accordance with T 265 to determine moisture content. Perform calculations, using the formulas on page 279 of the ASTM Manual, to determine plastic limit and plasticity index.

### **Advantage(s)**

This is one of the easiest procedures for determining any of the parameters related in this summary.

### **Disadvantage(s)**

No disadvantage found.

## **Appendix B**

### **Protocol for Collecting Construction Parameters Information for Sites in Texas**



## 1. Purpose

The purpose of establishing this protocol is to be able to perform the following two tasks:

- a) Calibrate existing models that are incorporated in RECIPE, a program developed under Project 0-4046 and
- b) Develop regression models that can be used in the program based on Texas construction practices.

## 2. Overall Procedure

This goal can be accomplished by identifying sites across Texas for obtaining measurements of construction parameters for typical asphalt-concrete, base, and subgrade layers.

The construction parameters are strictly based on existing material models that are used by the program. These parameters are the least amount required in order to accomplish the tasks vital to completion of this project. The tables below provide a summary of the information on the testing of parameters required. The tables are divided per layer. Table 1 summarizes the parameters for the AC layer. It identifies the protocol currently used by TXDOT and lists a proposed frequency of testing or collecting samples. The same layout is presented in Tables 2 and 3 for the base and subgrade layers, respectively.

Any parameter that is not tested by TXDOT only needs to be sampled. The research team at UTEP will perform the laboratory testing.

## 3. *Establish a matrix of candidate sites*

Although it would be ideal to collect data for all three layers at the same site, this will not be feasible due to the time constraint. Therefore, the only requirement is to collect the data of all variables of the same layer at each site. This will expand the search pool for sites with ongoing projects. Based on modification of Project 0-4046, six Texas sites are to be identified: two in West Texas, one in North Texas, one in South Texas, and Two in East Texas. The reason for this number of sites was to cover the majority of pavements in the area with the assumption that parameters for all pavement layers would be collected from the same site. Since that assumption does not hold due to time constraint, six sites are needed to be selected per pavement layer.

Candidate sites can be categorized into two groups: a) recently completed projects where the parameters identified were measured and b) candidate projects that are currently being constructed or are scheduled to be constructed shortly.

In the case where data is available on recently completed projects, a schedule needs to be developed on acquiring the available data. For those parameters, that data might not be available, such as the layer modulus, arrangements needs to be made to measure that parameter. In this case, either of FWD, SPA or PSPA (which ever is more appropriate) should collect data to determine the layer modulus. UTEP will either conduct or coordinate this activity.

In the later case, where a new site is identified for data collection, a plan is to be established with the project engineer to set a testing schedule and the number of samples that can

collected for each parameter. The recommendation of the frequency of samples is provided in Tables 1, 2 and 3.

**Table B1 - Frequency of Measurements for Asphalt/Concrete Layer**

| <b>PARAMETER</b>                              | <b>ARE MEASUREMENTS IN TXDOT GUIDELINE SCHEDULE?</b> | <b>HOW OFTEN DOES TXDOT MEASURE?</b>  | <b>IS IT ENOUGH FOR THIS PROJECT?</b>                | <b>SAMPLING REQUIRED</b>   |
|---|--|---|--|--|
| <b>Thickness</b>                              | Yes (declared as dimensions)                         | One total depth per travel-way per 2 miles or fraction thereof or as necessary for control after completion | No   | GPR and one core test sample per 0.1 miles per roadway             |
| <b>Modulus</b>                                | No   | -   | -  | UTEP to measure at least 30 samples or every 0.1 miles per roadway |
| <b>% Aggregate Passing #200</b>               | Yes (in the gradation of fine aggregates)            | Contractor samples once per subplot (4x daily) / TXDOT samples one subplot every third day                  | Yes provided we can get the results from contractors | Current sampling is sufficient                                     |
| <b>Cumulative % Retained on 3/4in. Sieve</b>  | Yes (in the gradation of fine aggregates)            | Contractor samples once per subplot (4x daily) / TXDOT samples one subplot every third day                  |  |  |
| <b>Cumulative % Retained on 3/8 in. Sieve</b> | Yes (in the gradation of fine aggregates)            | Contractor samples once per subplot (4x daily) / TXDOT samples one subplot every third day                  |  |  |
| <b>Cumulative % Retained on #4 Sieve</b>      | Yes (in the gradation of fine aggregates)            | Contractor samples once per subplot (4x daily) / TXDOT samples one subplot every third day                  |  |  |
| <b>AC Mix Air Voids</b>                       | Yes (as part of TEX-207-F, test for density)         | Sampled one per subplot (4x per lot) per day of production  | Yes  | Current sampling is sufficient                                     |
| <b>Viscosity</b>                              | No, see Tex-535-C, ASTM D5 or AASHTO T49             | -   | -  | Sample once per day  |
| <b>% Asphalt Content</b>                      | Yes  | Once per day production   | Yes  | Current sampling is sufficient                                     |

**Table B2 - Frequency of Measurements for Base Layer**

| <b>PARAMETER</b>                     | <b>ARE MEASUREMENTS IN TXDOT GUIDELINE SCHEDULE?</b> | <b>HOW OFTEN DOES TXDOT MEASURE?</b>            | <b>IS IT ENOUGH FOR THIS PROJECT?</b> | <b>SAMPLING REQUIRED</b>   |
|--------------------------------------|--|---|---------------------------------------|--|
| <b>Thickness</b>                     | Yes  | One depth per 3,000 linear ft. per travel-way   | No                                    | Minimum of 30 samples or once every 0.1 miles                            |
| <b>Modulus</b>                       | No   | -   | -                                     | UTEP to measure at least 30 samples or every 0.1 miles                   |
| <b>Max Dry Density</b>               | Yes (as part of TEX-117-E, Triaxial)                 | Each 20,000 C.Y. or 25,000 tons                 | No                                    | Collect samples to be tested by UTEP once every 2000 C.Y. or 2500 tons   |
| <b>Optimum Moisture Content</b>      | Yes (as part of TEX-117-E, Triaxial)                 | Each 20,000 C.Y. or 25,000 tons                 | No                                    |  |
| <b>Moisture Content</b>              | Yes (as part of TEX-117-E, Triaxial)                 | Each 3,000 linear ft. per course per travel-way | No                                    | Minimum of 30 samples or once every 0.1 miles                            |
| <b>Degree of Compaction</b>          | Yes (as part of TEX-117-E, Triaxial)                 | Each 3,000 linear ft. per course per travel-way | No                                    | Minimum of 30 samples or once every 0.1 miles                            |
| <b>% Aggregate Passing #40 Sieve</b> | Yes  | Each 4,000 C.Y. or 6,000 tons                   | No                                    | Collect samples to be tested by UTEP once every 2,000 C.Y. or 2,500 tons |
| <b>% Swell</b>                       | Yes  | Each 20,000 C.Y. or 25,000 tons                 | No                                    | Collect samples to be tested by UTEP once every 8,000 C.Y. or 10000 tons |
| <b>% Clay</b>                        | Yes (as part of TEX-105-E)                           | Each 4,000 C.Y. or 6,000 tons                   | Yes                                   | Current sampling is sufficient   |
| <b>% Silt</b>                        | No   | -   | -                                     | Collect samples to be tested by UTEP once every 4,000 C.Y. or 6,000 tons |

**Table B3 - Frequency of Measurements for Subgrade Layer**

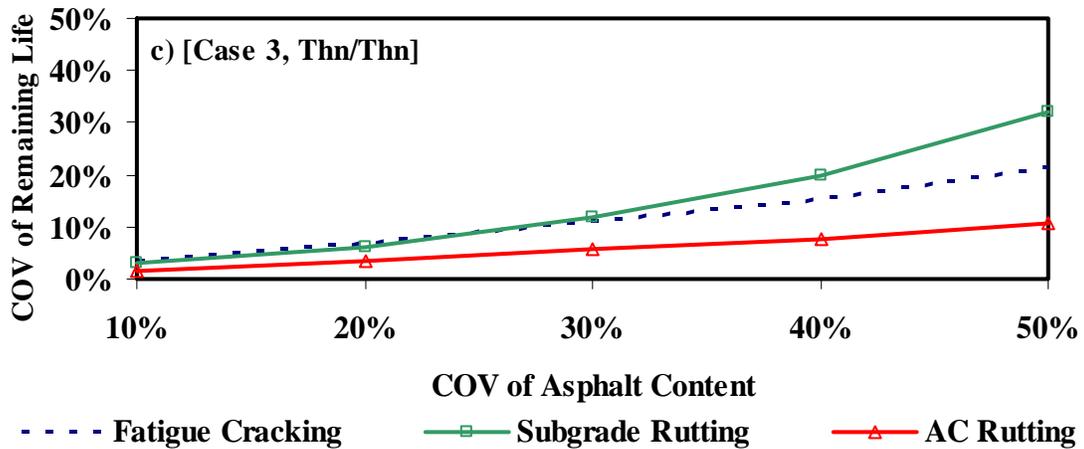
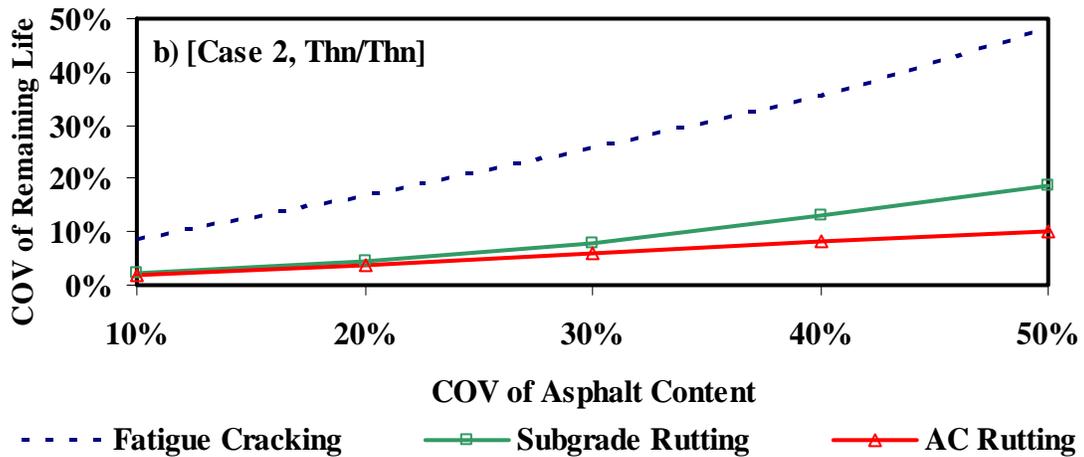
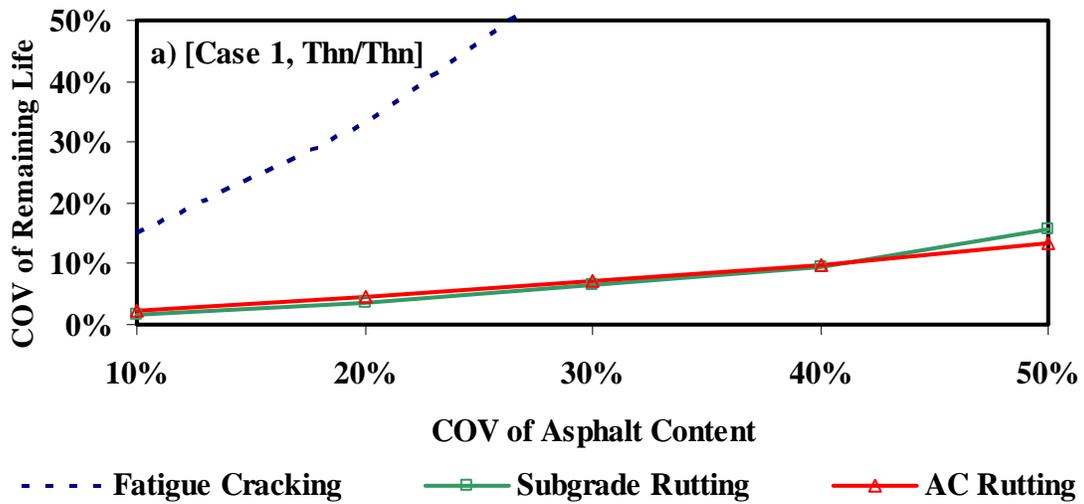
| <b>PARAMETER</b>                     | <b>DOES TXDOT MEASURE PER GUIDELINE SCHEDULE?</b> | <b>HOW OFTEN DOES TXDOT MEASURE?</b> | <b>IS IT ENOUGH FOR THIS PROJECT?</b> | <b>SAMPLING REQUIRED</b>   |
|--------------------------------------|---|--------------------------------------|---------------------------------------|--|
| <b>Modulus</b>                       | No  | -                                    | -                                     | UTEP to measure at least 30 samples or every 0.1 miles   |
| <b>Max Dry Density</b>               | Yes (as part of TEX-1175-E)                       | Each 5,000 C.Y.                      | No                                    | Collect samples to be tested by UTEP once every 2000 C.Y. or 2500 tons or change in Materials. |
| <b>Optimum Moisture Content</b>      | Yes as part of TEX-1175-E)                        | Each 5,000 C.Y.                      | No                                    |  |
| <b>Moisture Content</b>              | Yes (as part of TEX-1175-E)                       | Each 5,000 C.Y.                      | No                                    | Minimum of 30 samples or once every 0.1 miles  |
| <b>Degree of Compaction</b>          | Yes (as part of TEX-1175-E)                       | Each 5,000 C.Y.                      | No                                    |  |
| <b>% Aggregate Passing #40 Sieve</b> | No  | -                                    | -                                     | Collect samples to be tested by UTEP once every 2000 C.Y. or 2500 tons                         |
| <b>% Swell</b>                       | No  | -                                    | -                                     | Collect samples to be tested by UTEP once every 8000 C.Y. or 10000 tons                        |
| <b>% Clay</b>                        | Yes (as part of TEX-247)                          | Varies                               | -                                     | Collect samples to be tested by UTEP once every 2000 C.Y. or 2500 tons                         |
| <b>% Silt</b>                        | Yes (as part of TEX-247)                          | Varies                               | -                                     |  |
| <b>Liquid Limit</b>                  | Yes (as part of TEX-247)                          | Varies                               | -                                     |  |
| <b>Plastic Index</b>                 | Yes (as part of TEX-247)                          | Varies                               | -                                     |  |



## **Appendix C**

### **Results of the Validation Study for Asphalt Content of AC Layer**





**Figure C1 - Results of Impact of Variability of Asphalt Content on Remaining Life Varying AC Modulus for Thin-Thin Section**

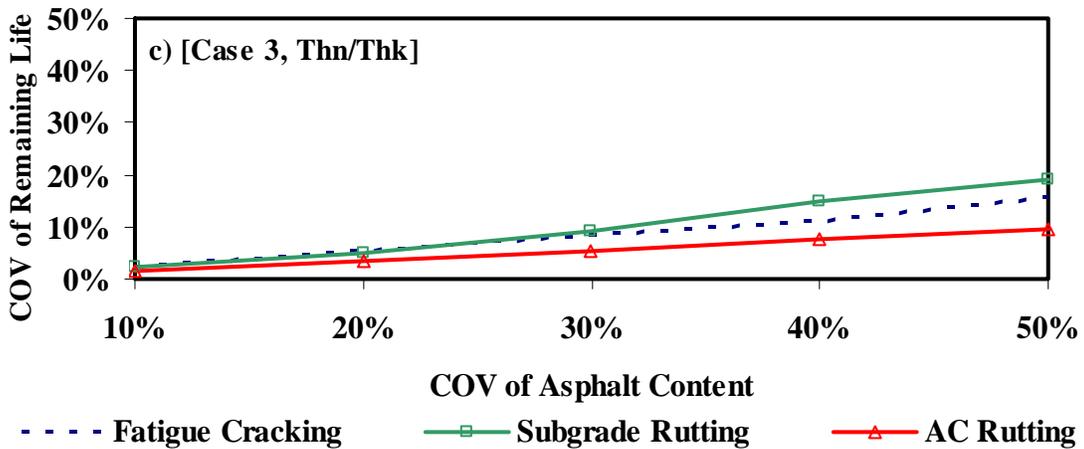
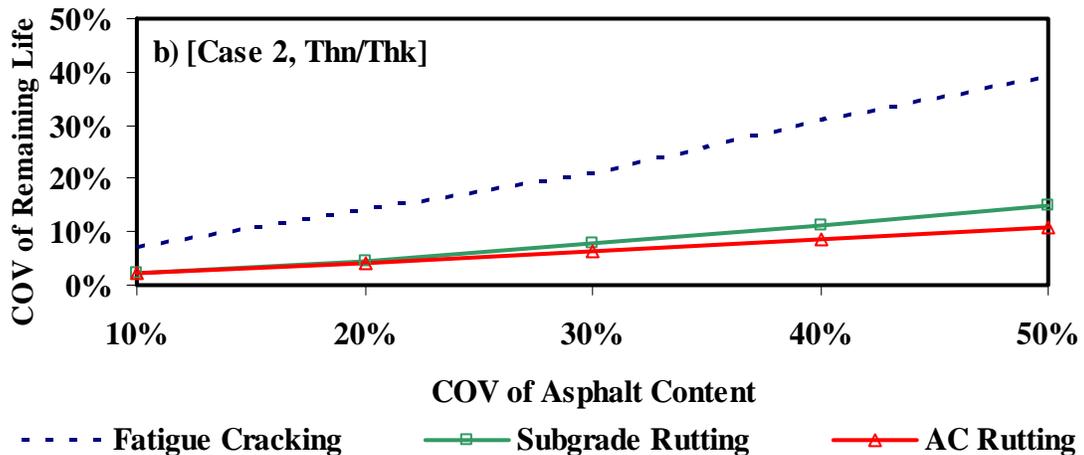
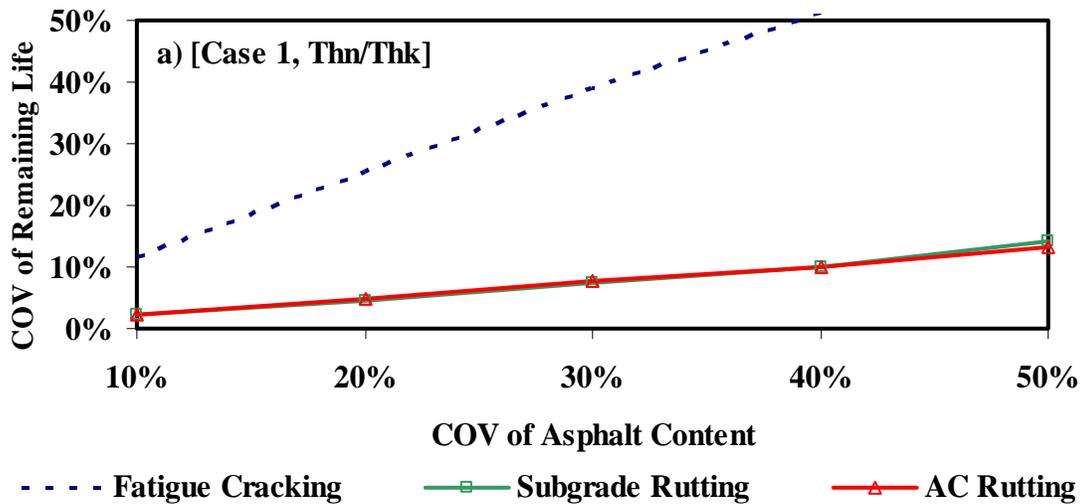


Figure C2 - Results of Impact of Variability of Asphalt Content on Remaining Life Varying AC Modulus for Thin-Thick Section

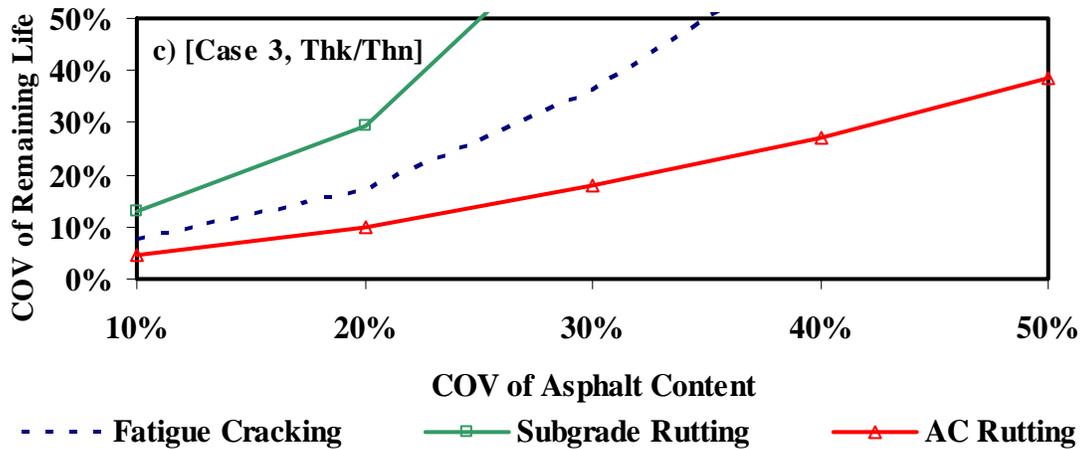
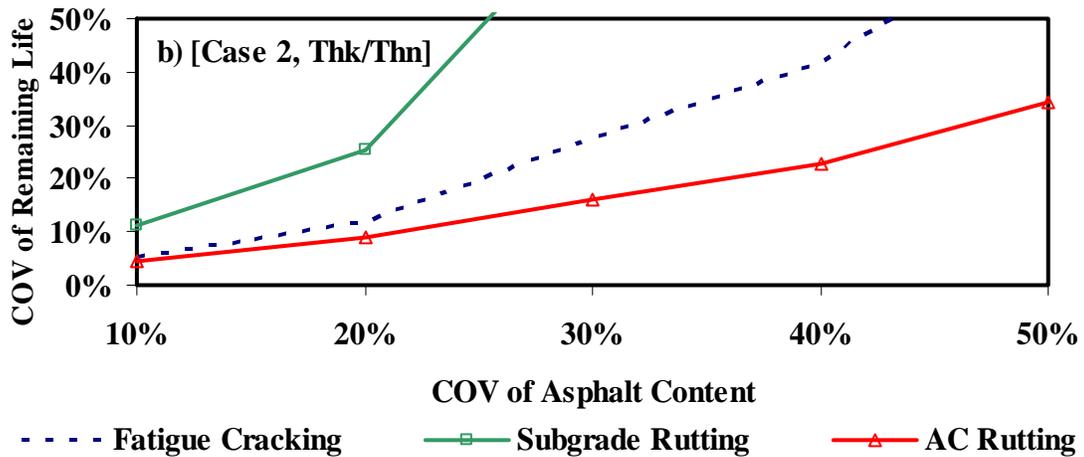
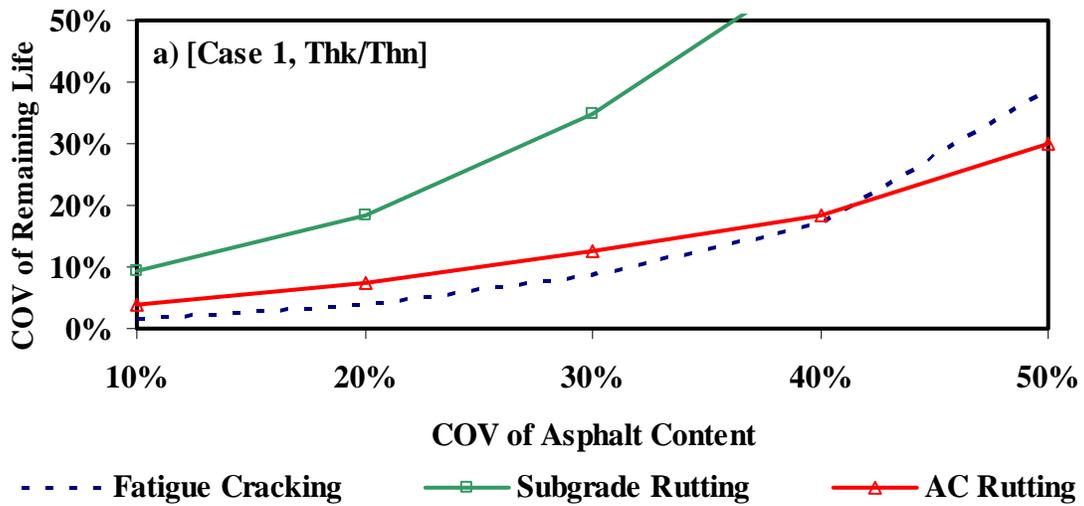


Figure C3 - Results of Impact of Variability of Asphalt Content on Remaining Life Varying AC Modulus for Thick-Thin Section

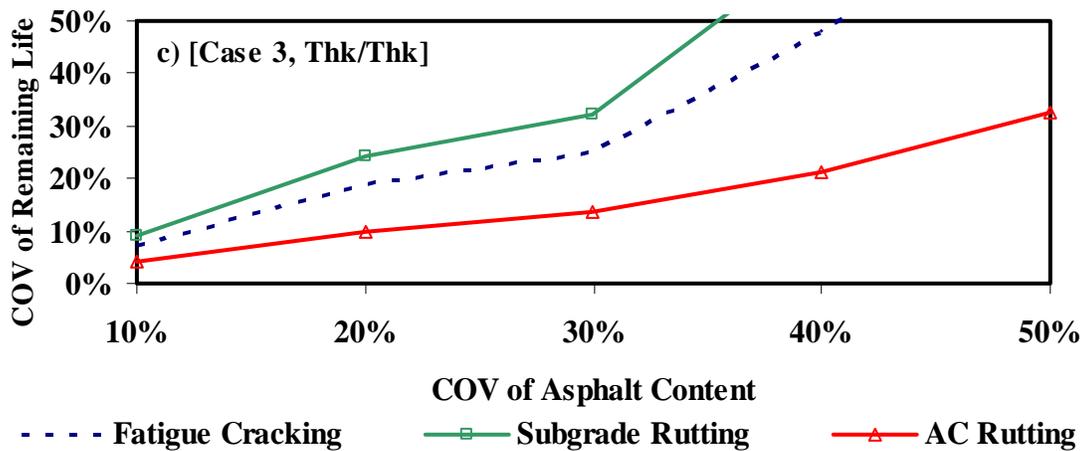
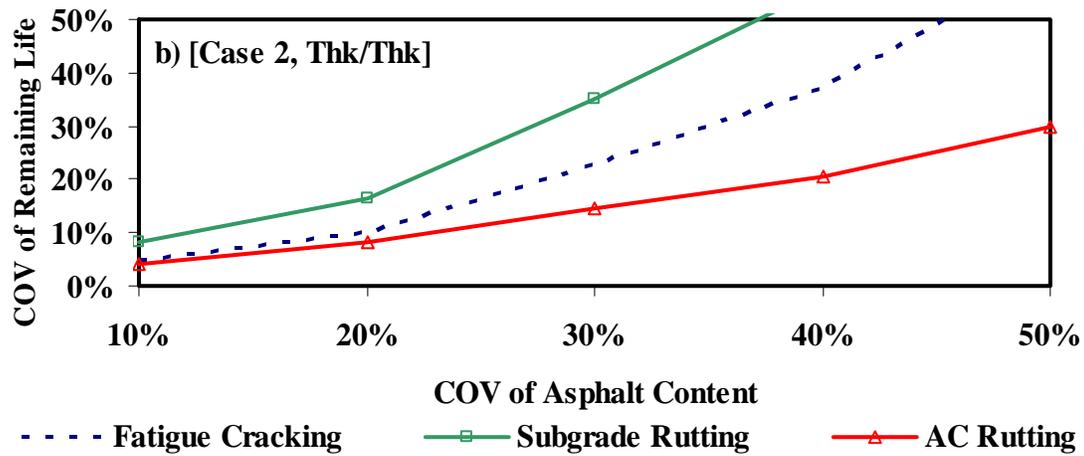
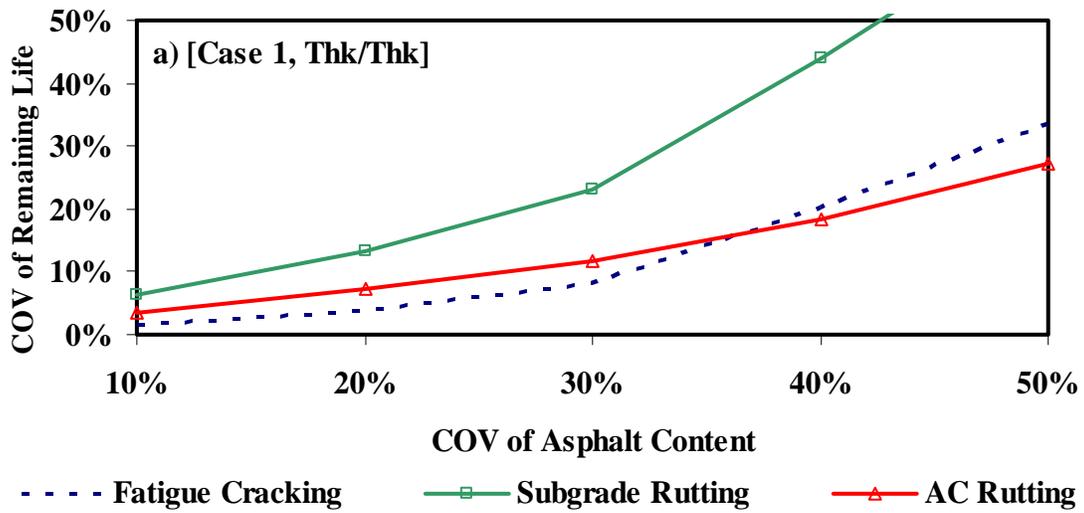


Figure C4 - Results of Impact of Variability of Asphalt Content on Remaining Life Varying AC Modulus for Thick-Thick Section

**Table C1 - Summary of Results of Impact of Variability of Asphalt Content on Remaining Life Varying AC Modulus**

| Case     | COV | Fatigue Cracking |       |       |       | Subgrade Rutting |       |       |       | AC Rutting |       |       |       |
|----------|-----|------------------|-------|-------|-------|------------------|-------|-------|-------|------------|-------|-------|-------|
|          |     | Tn/Tn            | Tn/Tk | Tk/Tn | Tk/Tk | Tn/Tn            | Tn/Tk | Tk/Tn | Tk/Tk | Tn/Tn      | Tn/Tk | Tk/Tn | Tk/Tk |
| <b>1</b> | 10% | 15%              | 12%   | 2%    | 2%    | 2%               | 2%    | 9%    | 6%    | 2%         | 2%    | 4%    | 3%    |
|          | 20% | 33%              | 25%   | 4%    | 4%    | 4%               | 5%    | 18%   | 13%   | 5%         | 5%    | 8%    | 7%    |
|          | 30% | 60%              | 39%   | 9%    | 8%    | 6%               | 7%    | 35%   | 23%   | 7%         | 8%    | 13%   | 12%   |
|          | 40% | 87%              | 51%   | 17%   | 20%   | 10%              | 10%   | 59%   | 44%   | 10%        | 10%   | 18%   | 18%   |
|          | 50% | 108%             | 81%   | 39%   | 33%   | 16%              | 14%   | 116%  | 67%   | 13%        | 13%   | 30%   | 27%   |
| <b>2</b> | 10% | 9%               | 7%    | 5%    | 5%    | 2%               | 2%    | 11%   | 8%    | 2%         | 2%    | 4%    | 4%    |
|          | 20% | 17%              | 14%   | 12%   | 10%   | 4%               | 5%    | 25%   | 17%   | 4%         | 4%    | 9%    | 8%    |
|          | 30% | 26%              | 21%   | 27%   | 23%   | 8%               | 8%    | 71%   | 35%   | 6%         | 6%    | 16%   | 14%   |
|          | 40% | 35%              | 31%   | 42%   | 37%   | 13%              | 11%   | 105%  | 56%   | 8%         | 9%    | 23%   | 21%   |
|          | 50% | 48%              | 39%   | 68%   | 61%   | 18%              | 15%   | 151%  | 90%   | 10%        | 11%   | 34%   | 30%   |
| <b>3</b> | 10% | 4%               | 2%    | 8%    | 7%    | 3%               | 2%    | 13%   | 9%    | 2%         | 2%    | 5%    | 4%    |
|          | 20% | 7%               | 5%    | 17%   | 19%   | 6%               | 5%    | 29%   | 24%   | 3%         | 3%    | 10%   | 10%   |
|          | 30% | 11%              | 9%    | 36%   | 25%   | 12%              | 9%    | 70%   | 32%   | 6%         | 5%    | 18%   | 14%   |
|          | 40% | 15%              | 11%   | 64%   | 48%   | 20%              | 15%   | 146%  | 65%   | 8%         | 8%    | 27%   | 21%   |
|          | 50% | 22%              | 16%   | 90%   | 78%   | 32%              | 19%   | 177%  | 106%  | 11%        | 10%   | 38%   | 33%   |



## **Appendix D**

### **Results of the Validation Study for Air Voids of AC Layer**



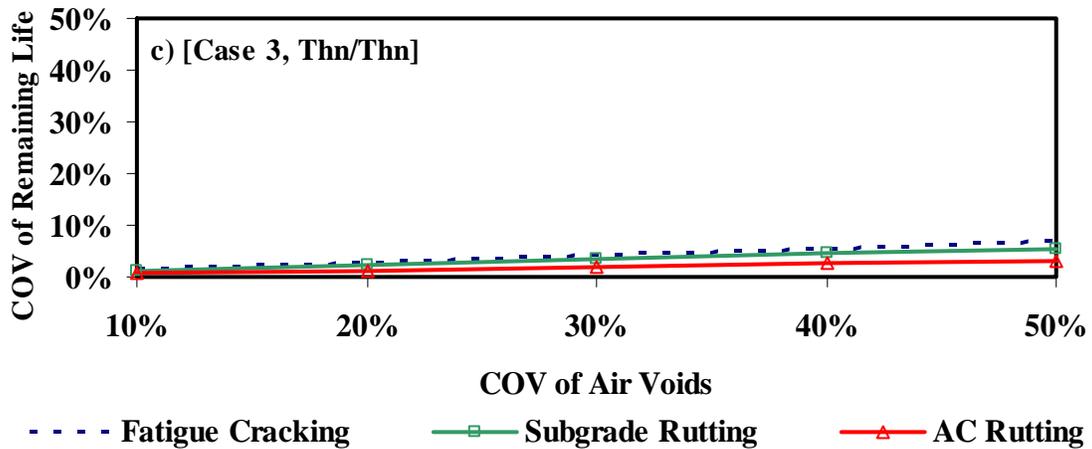
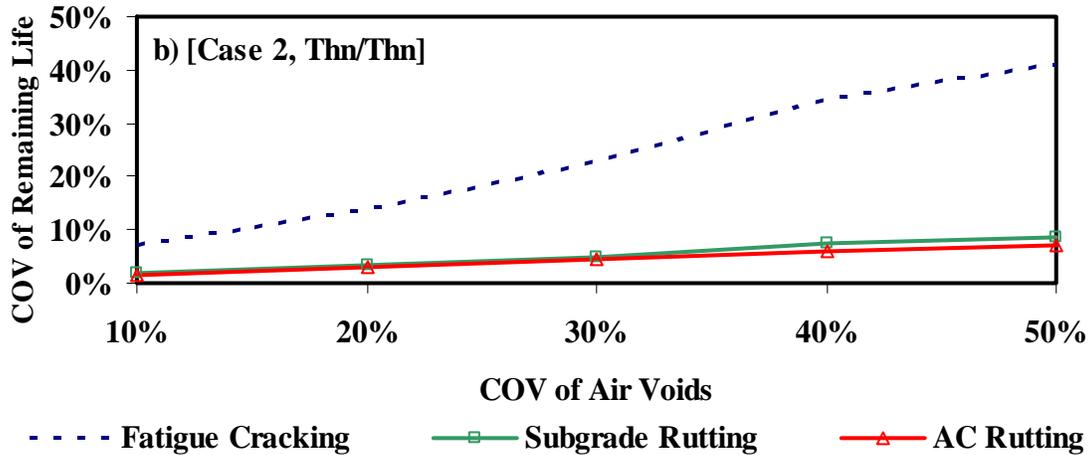
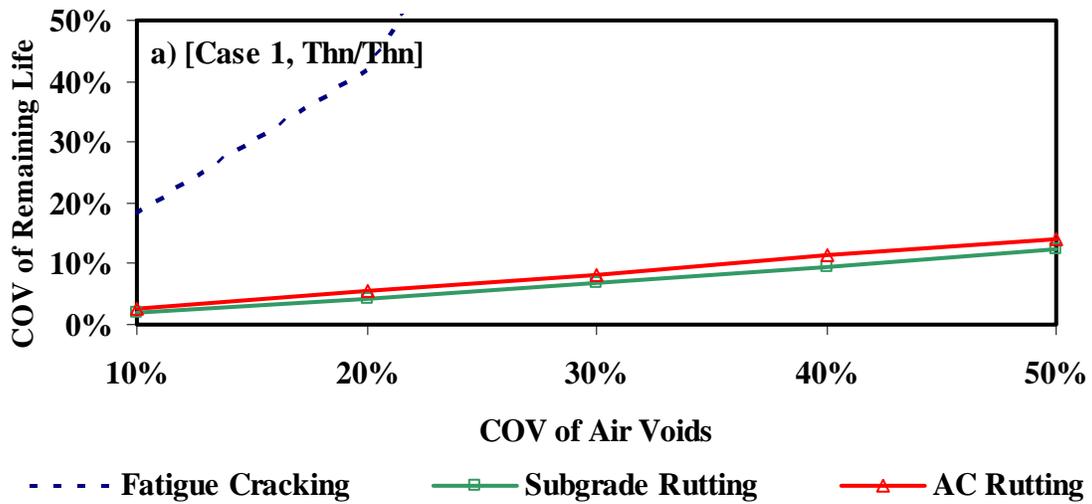


Figure D1 - Results of Impact of Variability of Air Voids on Remaining Life Varying AC Modulus for Thin-Thin Section

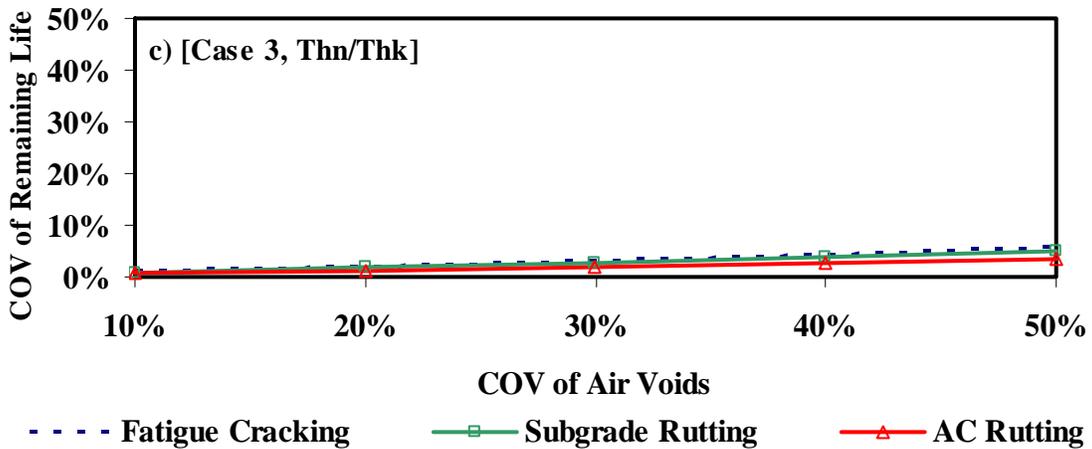
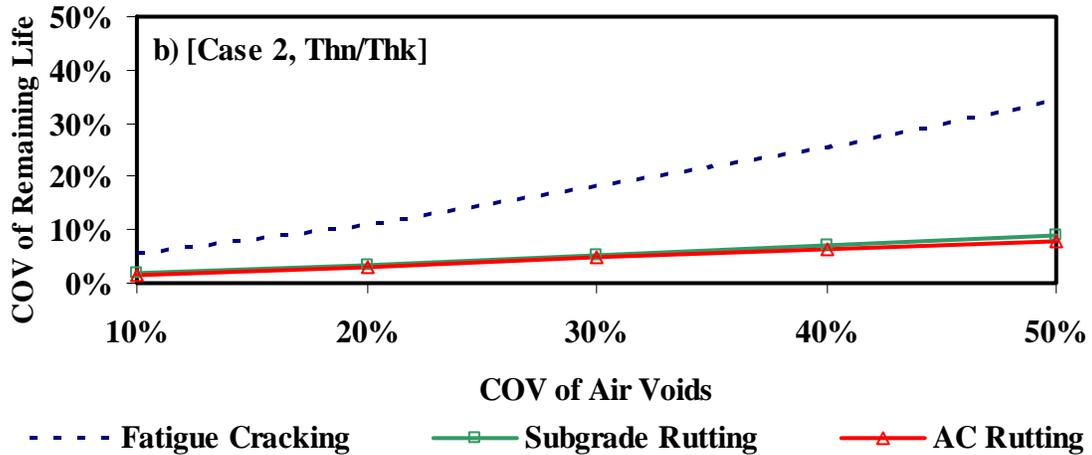
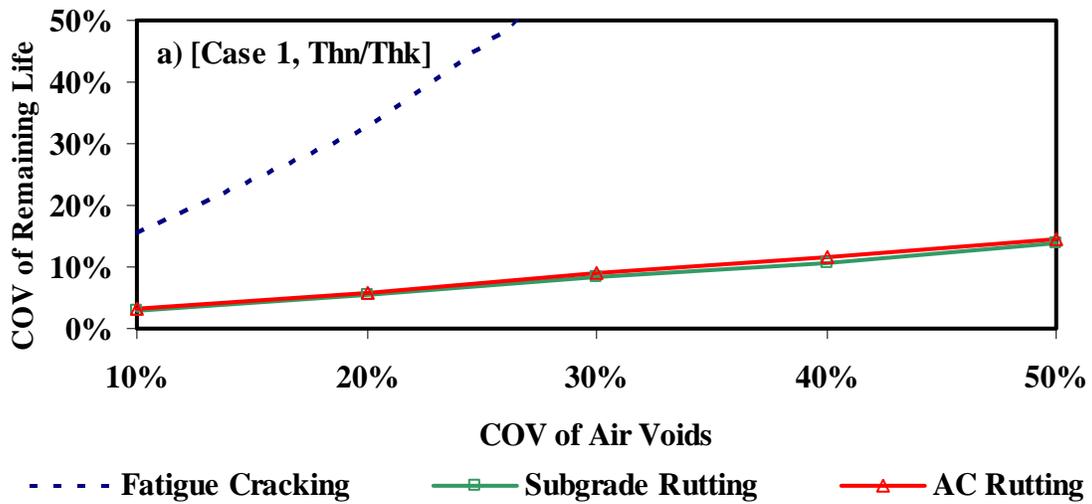


Figure D2 - Results of Impact of Variability of Air Voids on Remaining Life Varying AC Modulus for Thin-Thick Section

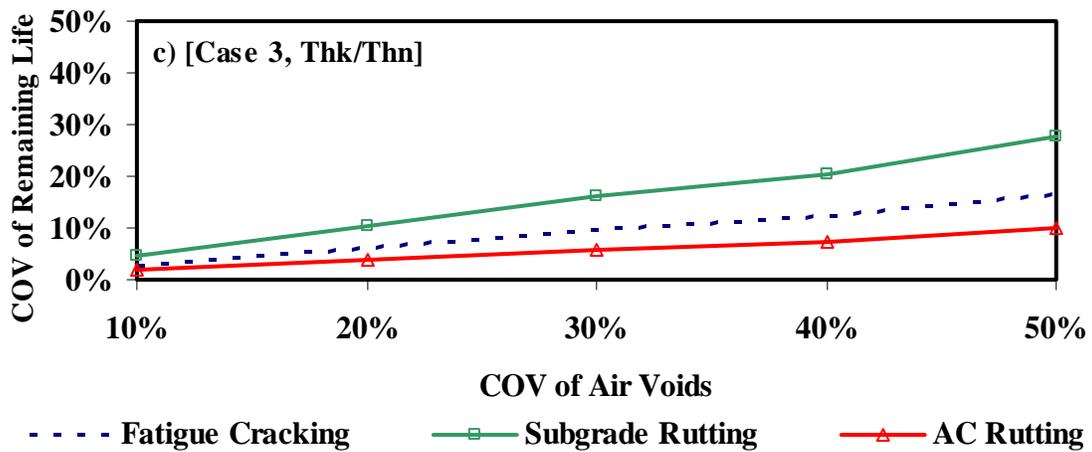
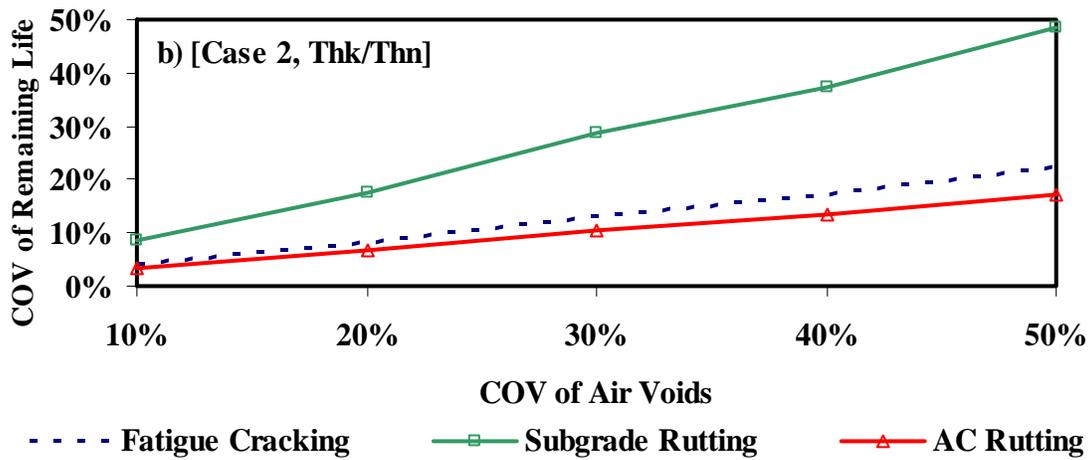
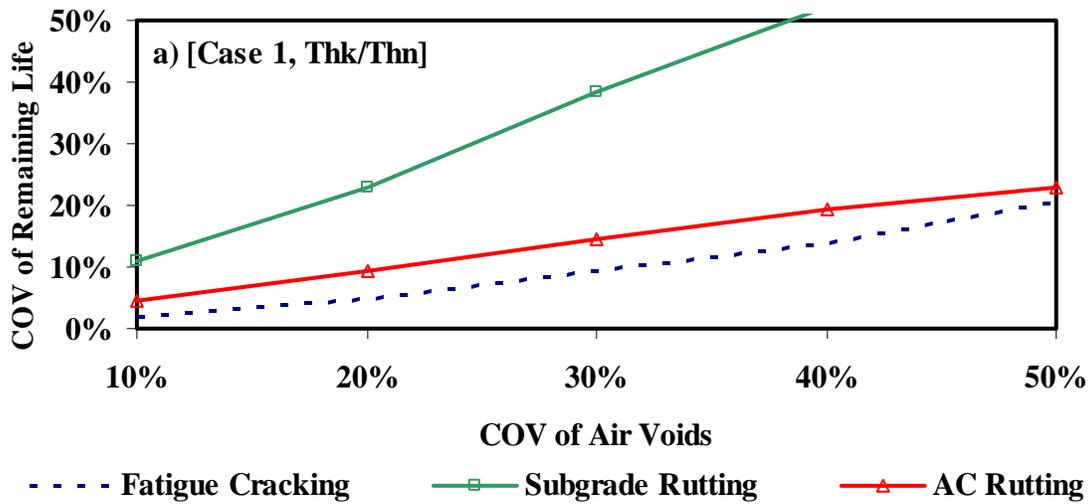


Figure D3 - Results of Impact of Variability of Air Voids on Remaining Life Varying AC Modulus for Thick-Thin Section

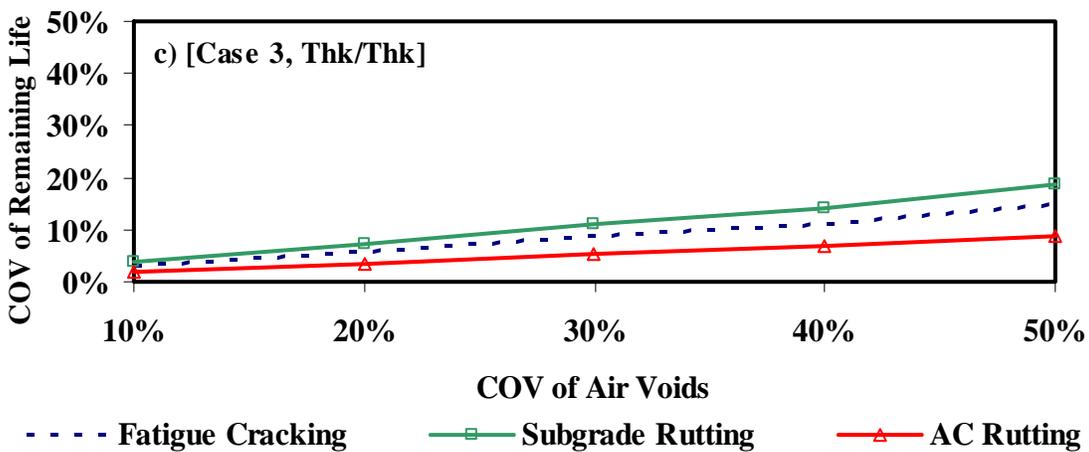
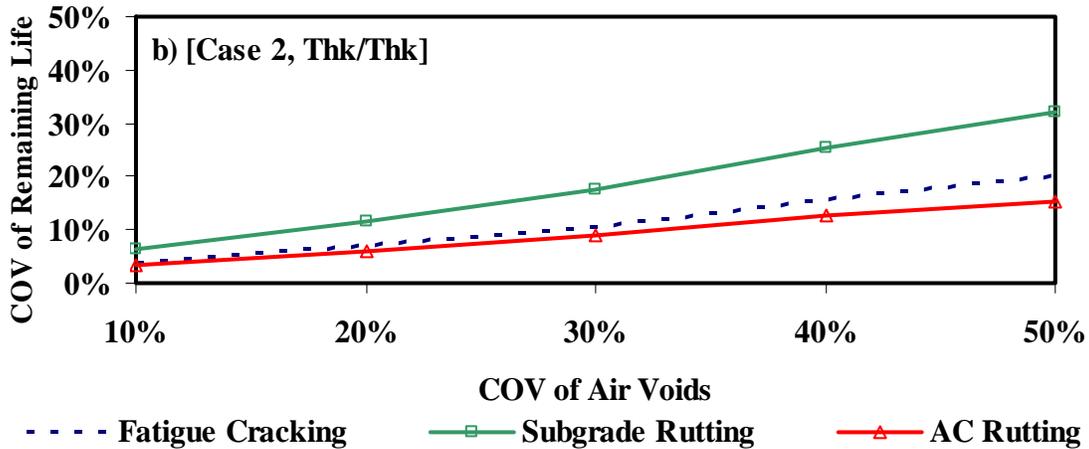
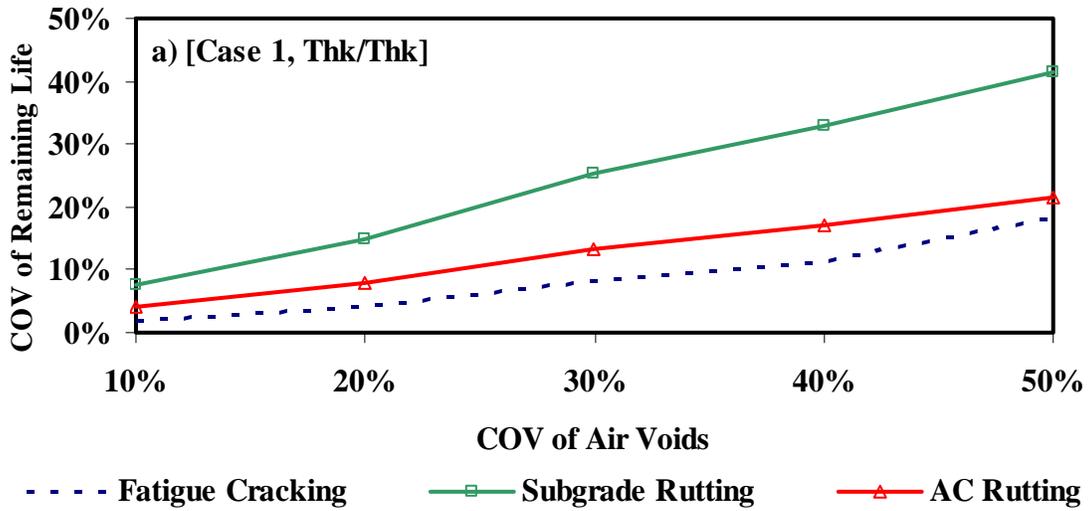


Figure D4 - Results of Impact of Variability of Air Voids on Remaining Life Varying AC Modulus for Thick-Thick Section

**Table D1 - Summary of Results of Impact of Variability of Air Voids on Remaining Life Varying AC Modulus**

| Case     | COV | Fatigue Cracking |       |       |       | Subgrade Rutting |       |       |       | AC Rutting |       |       |       |
|----------|-----|------------------|-------|-------|-------|------------------|-------|-------|-------|------------|-------|-------|-------|
|          |     | Tn/Tn            | Tn/Tk | Tk/Tn | Tk/Tk | Tn/Tn            | Tn/Tk | Tk/Tn | Tk/Tk | Tn/Tn      | Tn/Tk | Tk/Tn | Tk/Tk |
| <b>1</b> | 10% | 18%              | 16%   | 2%    | 2%    | 2%               | 3%    | 11%   | 8%    | 3%         | 3%    | 5%    | 4%    |
|          | 20% | 42%              | 32%   | 5%    | 4%    | 4%               | 5%    | 23%   | 15%   | 5%         | 6%    | 9%    | 8%    |
|          | 30% | 100%             | 59%   | 9%    | 8%    | 7%               | 8%    | 39%   | 25%   | 8%         | 9%    | 14%   | 13%   |
|          | 40% | 238%             | 120%  | 14%   | 11%   | 9%               | 11%   | 52%   | 33%   | 11%        | 11%   | 19%   | 17%   |
|          | 50% | 1728%            | 281%  | 21%   | 18%   | 12%              | 14%   | 62%   | 41%   | 14%        | 14%   | 23%   | 21%   |
| <b>2</b> | 10% | 7%               | 5%    | 4%    | 4%    | 2%               | 2%    | 9%    | 6%    | 2%         | 2%    | 3%    | 3%    |
|          | 20% | 14%              | 11%   | 8%    | 7%    | 3%               | 3%    | 18%   | 12%   | 3%         | 3%    | 7%    | 6%    |
|          | 30% | 23%              | 18%   | 13%   | 11%   | 5%               | 5%    | 29%   | 17%   | 4%         | 5%    | 10%   | 9%    |
|          | 40% | 35%              | 25%   | 17%   | 16%   | 7%               | 7%    | 37%   | 25%   | 6%         | 6%    | 14%   | 13%   |
|          | 50% | 41%              | 34%   | 23%   | 20%   | 9%               | 9%    | 49%   | 32%   | 7%         | 8%    | 17%   | 15%   |
| <b>3</b> | 10% | 1%               | 1%    | 3%    | 3%    | 1%               | 1%    | 5%    | 4%    | 1%         | 1%    | 2%    | 2%    |
|          | 20% | 3%               | 2%    | 6%    | 6%    | 2%               | 2%    | 10%   | 7%    | 1%         | 1%    | 4%    | 3%    |
|          | 30% | 4%               | 3%    | 10%   | 9%    | 4%               | 3%    | 16%   | 11%   | 2%         | 2%    | 6%    | 5%    |
|          | 40% | 5%               | 4%    | 12%   | 11%   | 5%               | 4%    | 20%   | 14%   | 3%         | 3%    | 7%    | 7%    |
|          | 50% | 7%               | 6%    | 17%   | 15%   | 5%               | 5%    | 28%   | 19%   | 3%         | 3%    | 10%   | 9%    |