Preparation for Implementation of the Mechanistic-Empirical Pavement Design Guide in Michigan Part 2: Evaluation of Rehabilitation Fixes

Final Report

Michigan Department of Transportation
Office of Research Administration
8885 Ricks Road
Lansing MI 48909

By

Neeraj Buch, Karim Chatti, Syed W. Haider,
Gilbert Baladi, Wouter Brink, and Iman Harsini

Report # RC-1594

Michigan State University
Department of Civil and Environmental Engineering
3546 Engineering Building
East Lansing, MI 48824

August 2013

Technical Report Documentation Page

1. Report No. Research Report RC-1594	**2. Government Accession No.**	**3. MDOT Project Manager** Mike Eacker
4. Title and Subtitle Preparation for Implementation of the Mechanistic-Empirical Pavement Design Guide in Michigan Part 2: Evaluation of Rehabilitation Fixes		**5. Report Date** **6. Performing Organization Code**
7. Author(s) Neeraj Buch, Karim Chatti, Syed W. Haider, Gilbert Baladi, Wouter Brink, and Iman Harsini		**8. Performing Org. Report No.**
9. Performing Organization Name and Address Michigan State University Department of Civil and Environmental Engineering 428 S. Shaw Lane, 3546 Engineering Building East Lansing, MI 48824 Tel: (517) 355-5107, Fax: (517) 432-1827		**10. Work Unit No. (TRAIS)** **11. Contract No.** **11(a). Authorization No.**
12. Sponsoring Agency Name and Address Michigan Department of Transportation Office of Research Administration 8885 Ricks Road Lansing MI 48909		**13. Type of Report & Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

The main objectives of Task 2 of the project were to determine the impact of various input variables on the predicted pavement performance for the selected rehabilitation design alternatives in the MEPDG/DARWin-ME, and to verify the pavement performance models for MDOT rehabilitation design practice. In general, for HMA over HMA, the overlay thickness and HMA volumetrics are the most significant inputs for the overlay layer while the existing thickness and pavement condition rating have a significant effect on pavement performance among the inputs related to the existing pavement. For composite pavements, overlay thickness and HMA air voids are significant inputs for the overlay layer. In addition, among the inputs related to the existing intact PCC pavement, the existing thickness and PCC layer modulus have a significant effect on pavement performance. For rubblized pavements, the HMA air voids and effective binder content are the most significant inputs for the overlay layer. Furthermore, for longitudinal cracking and IRI, existing PCC thickness is more important as compared to the existing PCC layer modulus. However, existing PCC layer modulus is more significant for alligator cracking and rutting. For unbonded overlays, all overlay related inputs significantly impact the cracking performance while the PCC elastic modulus is the most important among inputs related to existing layers. The interaction between overlay air voids and existing pavement thickness significantly impacts all performance measures among HMA rehabilitation options. The interaction between overlay thickness and existing PCC layer modulus is the most significant effect on unbonded overlay performance. It should be noted that all analyses were conducted using the inputs ranges reflecting Michigan practices. The verification of the performance prediction models based on the selected projects for different rehabilitation options show the need for local calibration.

17. Key Words MEPDG, DARWin-ME, Rehabilitation fixes, Sensitivity analysis, Verification, and Calibration		**18. Distribution Statement** No restrictions. This document is available to the public through the Michigan Department of Transportation.	
19. Security Classification - report Unclassified	**20. Security Classification - page** Unclassified	**21. No. of Pages**	**22. Price**

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The main objectives of Task 2 of the project were to determine the impact of various input variables on the predicted pavement performance for the selected rehabilitation design alternatives in the MEPDG/DARWin-ME, and to validate the pavement performance models for MDOT rehabilitation design practice. Therefore, the significant inputs related to material characterization, existing pavement condition, and structural design for the selected rehabilitation options were identified. Subsequently, the accuracy of the rehabilitation performance models was evaluated by comparing measured and predicted performance.

In general, for HMA overlays, the overlay thickness and HMA volumetrics are the most significant inputs for the overlay layer while the existing thickness and pavement condition rating have a significant effect on pavement performance among the inputs related to the existing pavement. For composite pavements, overlay thickness and HMA air voids are significant inputs for the overlay layer. In addition, among the inputs related to the existing intact PCC pavement, the existing thickness and PCC layer modulus have a significant effect on pavement performance. For rubblized pavements, the HMA air voids and effective binder content are the most significant inputs for the overlay layer. Furthermore, for longitudinal cracking and IRI, existing PCC thickness is more important as compared to the existing PCC layer modulus. However, existing PCC layer modulus is more significant for alligator cracking and rutting. For unbonded overlays, all overlay related inputs significantly impact the cracking performance while the PCC elastic modulus is the most important among inputs related to existing layers. The interaction between overlay air voids and existing pavement thickness significantly impacts all performance measures among HMA rehabilitation options. The interaction between overlay thickness and existing PCC layer modulus is the most significant effect on unbonded overlay performance. It should be noted that all analyses were conducted using the inputs ranges reflecting Michigan practices.

The verification of the performance prediction models based on the selected projects for different rehabilitation options show the need for local calibration. All of the identified projects used for verification will be utilized in Task 3 for local calibration. Based on the results of the analyses, various conclusions and recommendations were made and are presented in the next sections.

CHAPTER 1 - INTRODUCTION

1.1 PROBLEM STATEMENT

There are apprehensions on the part of State Highway Agencies (SHAs) towards the adoption of the MEPDG/DARWin-ME because of (i) the complex nature of the design software (numerous inputs and their hierarchical nature); (ii) perceived needs to collect more laboratory and/or field data; (iii) necessity to retool the PMS for making it compatible with the outputs of the design guide and the required inputs for the guide; (iv) the need for the calibration of the performance equations to local conditions; (v) the need to employ or train pavement professionals at the regional level; and (vi) shrinking manpower and funds. The successful completion of this project will go a long way in reducing some of the uncertainties associated with the implementation of the MEPDG/DARWin-ME. Guidance with respect to practical ranges of significant inputs for flexible and rigid pavement designs, calibration coefficients for the transfer functions reflecting local conditions and hot mix asphalt (HMA) mixture characteristics |E*| will demonstrate to Michigan Department of Transportation (MDOT) pavement engineers the viability of implementing the MEPDG/DARWin-ME in the near future. An extensive test (for rehabilitation designs) of the software will add evidence on the viability and accuracy of the software. Identifying the list of input variables for rehabilitation designs that significantly impact pavement performance would assist MDOT in determining the types of new data elements needed. The technology transfer packages to be developed in this timely and significant project will serve as invaluable training tools that would enhance the capability of MDOT.

The research study has three distinct tasks: (1) characterization of asphalt mixtures for the MEPDG/DARWin-ME in Michigan, (2) evaluation of the MEPDG/DARWin-ME for pavement rehabilitation design in Michigan, and (3) calibration and validation of the MEPDG/DARWin-ME performance models for Michigan conditions. Therefore, the study was divided into three separate tasks. The HMA mixtures in Michigan were characterized in Task 1 and the final report was submitted to MDOT in December 2012. This report contains the details for Task 2 of the study. In Task 3, the calibration and validation of performance models will be executed and a separate report will be submitted at the end of the project.

1.2 BACKGROUND AND SIGNIFICANCE OF WORK

The MEPDG/DARWin-ME is becoming the state-of-the-practice for flexible and rigid pavement designs in some states. While several design inputs are identical for both new and rehabilitation design processes, there are variations in how some inputs are selected for use in rehabilitation design. The material properties to characterize existing pavement play a vital role in the MEPDG/DARWin-ME rehabilitation analysis and design process. In this study, material characterization needs for pavement rehabilitation are addressed and the results are used in evaluating the rehabilitation analysis and design process of the MEPDG/DARWin-ME. By adopting the MEPDG/DARWin-ME, MDOT can achieve the most cost-effective and sound rehabilitation strategies for repairing flexible and rigid pavements.
MDOT has already laid the foundation for the adoption of the MEPDG/DARWin-ME by supporting several studies in the last five years. The key deliverables of these studies

included: (a) critical/sensitive inputs for the design of new flexible and jointed plain concrete pavements, (b) Levels 2 and 3 traffic inputs for the design of new and rehabilitated flexible and rigid pavements, (c) Catalog of level 2 inputs for coefficient of thermal expansion (CTE) of typical paving concrete mixtures, and (d) Ranges for levels 2 and 3 resilient moduli for subgrade and unbound materials. It should be noted that results from all these previous studies were utilized in Task 2 of this study wherever applicable.

1.3 RESEARCH OBJECTIVES

The objectives of the research in Task 2 were to: (a) determine the sensitivity of various input variables to the predicted performance for each of the rehabilitation design alternatives in the MEPDG/DARWin-ME, and (b) validate the current globally calibrated performance models for different rehabilitation types in Michigan

1.4 BENEFITS TO MDOT

The outcomes of research conducted in Task 2 of the study will have several short-term and long-term benefits in implementing the MEPDG/DARWin-ME in Michigan. The short-term benefits include:

- Recommendations on the application of the MEPDG/DARWin-ME for Michigan specific rehabilitation fixes.
- A list of the most important inputs and typical values needed for using the MEPDG/DARWin-ME rehabilitation design of both flexible and rigid pavements.
- Ranking of the important inputs based on their level of impact on the predicted performance.
- Recommendations for falling weight deflectometer (FWD) procedures and practices in support of the MEPDG/DARWin-ME implementation.

The long-term benefits will emerge by knowing the following:

- A set of recommendations for the type of data needed in MDOT Pavement Management System (PMS) to support use of the MEPDG/DARWin-ME in the future. The recommendations will be made at the conclusion of Task 3 of the study.
- A set of recommendations regarding a comprehensive and systematic database that houses project construction data (materials, layer properties and thicknesses, costs), design information and PMS pavement condition data. The recommendations will be made at the conclusion of the Task 3 of the study.

1.5 RESEARCH PLAN

Task 2 of the study was accomplished through six subtasks described below:

1.5.1 Task 2-1: Literature Search

Over the last five years, the pavement group at MSU has been working with MDOT to explore the various attributes of the MEPDG/DARWin-ME and to assist with its

implementation process. As a result of this effort the following final reports have been published:

- Quantifying Coefficient of Thermal Expansion Values of Typical Hydraulic Cement Concrete Paving Mixtures (*1*). The principal investigator (PI) for this project was Dr. Neeraj Buch
- Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavements (*2*). The PIs for this project were Drs. Buch, Chatti and Haider
- Characterization of Traffic for the New M-E Pavement Design Guide in Michigan (*3*). The PIs for this project were Drs. Buch, Chatti and Haider
- Pavement Subgrade MR Design Values for Michigan's Seasonal Changes (4): the PI for this project was Dr. Baladi
- Backcalculation of Layer Moduli of Unbound Granular Layers for both Rigid and Flexible Pavements (5). The PI for this project was Dr. Baladi.

In addition to this work, the team has conducted a 1-1/2 day technology transfer workshop designed for MDOT pavement professionals highlighting the salient features of the MEPDG software. The results from these projects have also been highlighted in MDOT's Research Administration newsletters. As a result of these efforts the research team is very familiar with the MEPDG.

The project team also reviewed national literature to benchmark the efforts made by other state DOTs in this area. The sources for collecting such information include (i) National Cooperative Highway Research Program (NCHRP) and Federal Highway Administration (FHWA) reports and research circulars; (ii) papers published in the journal of the Transportation Research Record; and (iii) project reports published by the various state DOTs on the subject.

1.5.2 Task 2-2: Review MDOT's Rehabilitation Fixes and Design Methods

The commonly used rehabilitation fixes in Michigan that can be designed using the MEPDG/DARWin-ME software include (i) HMA overlay placed on top of rubblized portland cement concrete (PCC) pavements; (ii) HMA overlays constructed over HMA and PCC pavements; (iii) Crush and shape (pulverize the existing HMA followed by new HMA surfacing) (iv) Unbonded concrete overlays and (v) PCC overlay constructed over HMA pavements. It should be noted that only a few PCC overlays over HMA experimental projects have been constructed in Michigan. *Currently MDOT does not use bonded concrete overlays, continuously reinforced concrete pavement (CRCP), and crack and seat techniques to rehabilitate the pavement network; therefore these fixes were not considered in the analyses for Tasks 2 and 3.*

At the initiation of this part, the project team met with the MDOT research advisory panel (RAP) to better understand the pavement rehabilitation design practices. The applicability and usefulness of the MEPDG/DARWin-ME process for rehabilitation designs hinges on what type of design and construction information are (or can be) collected by MDOT and on the availability and compatibility of performance (distress and roughness)

data in the MDOT PMS database and other sources such as the long-term pavement performance (LTPP) database.

An important part of the evaluation process is the use of non-destructive testing (NDT) to characterize existing pavements to establish Level 1 inputs. Two important tests should be included in this process: The ground penetrating radar (GPR) test to determine layer thicknesses and the FWD test to characterize in-situ layer moduli. The GPR testing has been effectively used in conjunction with FWD testing in rehabilitation projects by several DOT's (for example Texas). FWD usage is imperative for cost effective mechanistic rehabilitation design. MDOT has been using the FWD test on a selective basis depending on the region. A more systematic use of FWD testing is envisioned if/when the MEPDG/DARWin-ME is adopted by MDOT for rehabilitation design. The MEPDG/DARWin-ME requires FWD testing only for level 1 analysis. The MEPDG recommends ratios of lab to field moduli based on LTPP data. However, these were obtained from fairly weak statistical correlations, and depend on the existing pavement cross-section. Dr. Baladi has looked at this issue as part of two MDOT projects on estimating resilient moduli for subgrade and base/subbase unbound materials. In these studies both back-calculated in-situ and laboratory MRs are reported. Drs. Chatti and Kutay have also been working on relating FWD derived to laboratory measured HMA moduli as part of a FHWA funded project FHWA DTFH61-08-R-00032 "Relationships Between Laboratory-Measured and Field-Derived Properties of Pavement Layers". The issue there is that MEPDG requires the E^* curve for each HMA layer as an input, while standard back-calculation only gives one "effective" modulus. To circumvent this problem, the MEPDG/DARWin-ME rehabilitation design procedure calls for using the back-calculated modulus to calculate a damage index, which is then used to shift the undamaged E^* curve (using volumetric information obtained from cores) to get a damaged E^* curve. Also related to this, Dr Chatti was involved in the FHWA project DTFH61-06-C-00046 "Using FWD data with M-E Design and Analysis", which reviewed various pavement deflection testing procedures and commonly used deflection analysis approaches and back-calculation programs for flexible, rigid, and composite pavement structures. The relevance of the different procedures and approaches to the current MEPDG/DARWin-ME were explored in this study.

1.5.3 Task 2-3: Sensitivity Analysis of Rehabilitation Options

For rigid pavements the MEPDG/DARWin-ME considers the design of the following rehabilitation fixes: (1) concrete pavement restoration (CPR) for jointed concrete pavements, (2) unbonded jointed plain concrete pavement (JPCP) or CRCP overlays over existing rigid or composite pavements, (3) bonded JPCP or CRCP overlays over existing JPCP or CRCP pavements, and (4) conventional JPCP or CRCP on existing flexible. For flexible pavements, the rehabilitation fixes include: (1) HMA overlay of existing HMA surfaced pavements, both flexible and semi-rigid, (2) HMA overlay of existing PCC pavement that has received fractured slab treatments; crack and seat, break and seat, and rubblization, and (3) HMA overlay of existing intact PCC pavement (JPCP and CRCP), including composite pavements or second overlays of original PCC pavements. Given that Michigan does not support CRCP, only preliminary sensitivity analysis was performed for CRCP in this study. Also, fractured slab treatments was limited to rubblization of JPCP and jointed reinforced concrete pavement (JRCP), since MDOT practice does not allow for crack and seat and break and seat techniques. The input parameters considered for the design of the various rehabilitation

strategies are summarized below**.** A significant number of these inputs are independent of the type of design, i.e. new versus rehabilitation. The input parameters that are unique to the rehabilitation design process are *italicized* for easy identification.

A. General and Project Information: Project identities, construction dates of the existing pavement and the new overlay, restoration date, traffic opening date, and type of rehabilitation strategy
B. Analysis Parameters: Initial smoothness, IRI (post rehabilitation), and performance criteria (IRI, cracking and faulting)
C. Climate Data: Weather station close to the selected project or interpolation of multiple weather stations if a weather station is not available at the project site
D. Traffic: ADTT, percent trucks, vehicle speed, traffic volume and axle adjustment factors, wheel location, traffic wander and others
E. Drainage and Surface Properties: Pavement cross-slope and length of drainage path, and surface absorptivity
F. Layer Definition and Material Properties: Number of layers, description and material type, pavement cross-section details, PCC mechanical and thermal properties, HMA material properties, traffic opening date, and type of rehabilitation strategy
G. Design Features: Transverse and longitudinal joint design parameters, reinforcing details (CRC pavements only), load transfer efficiency (LTE) details and edge support type, and traffic opening date
H. Rehabilitation: Existing distress (CPR), percent of slabs with repairs after restoration (CPR), and foundation support

Differences between the analyses of new pavements and pavement rehabilitation strategies are due to two possible sources: (1) performance prediction models, and (2) inputs to characterize the existing pavement structure and materials. For flexible overlays, all the performance prediction models are the same as those for new flexible pavement analysis and design. Only the roughness model changes when an HMA overlay is placed over existing PCC pavement. Also, an additional reflective cracking model is added for rehabilitation design. For rigid pavement restoration and unbonded overlays, only the faulting model coefficients are different than that used for new rigid pavements. Additional inputs that need to be considered in the sensitivity analysis are as follows:

- For flexible overlays, rehabilitation levels need to be considered. For level 1, back-calculation of layer moduli from FWD testing is required; measured rutting in the existing pavement layers are needed along with the thickness of existing HMA layer to be milled. For level 2, only estimates of layer moduli are needed (based on correlations); estimated rutting in the existing layers and cracking in the existing HMA layers along with HMA milling thickness are required. For level 3, pavement rating (excellent to very poor) to represent pavement condition and total surface rutting are needed. All other material-related inputs are similar to those of a new flexible pavement.
- For HMA overlays of existing JPCP, the information of percent slabs with transverse cracking before and after restoration of existing JPCP and dynamic modulus of subgrade reaction (back-calculated using FWD data, or internally calculated based on MR) are required.

- For HMA overlays of fractured concrete, the resilient modulus of the fractured concrete and type of fracture (crack/seat or rubblization) are needed.
- For JPCP restoration, the information of percent slabs with transverse cracking before and after restoration and dynamic modulus of subgrade reaction are required.
- For PCC overlays of JPCP/CRCP, the resilient modulus, the existing thickness, the thermal properties of the existing concrete layer, type of fracture (crack/seat or rubblization) and dynamic modulus of subgrade reaction are required. In addition, the properties of the bond-breaker asphalt layer are required which are similar to the HMA properties mentioned above in the flexible pavement section.

The multi-step process presented below will be utilized to identify the most critical/sensitive input parameters for use in the MEPDG/DARWin-ME for pavement rehabilitation designs.

FIRST STEP - Determination of the mathematical viability and "reasonableness" of the performance models for rehabilitated HMA and JPC pavements. To conduct the "reasonableness" analyses of the performance models, it is essential to determine practical ranges of the input variables listed above. The primary sources for the magnitudes of input parameters (material characteristics and pavement structure) are, but not limited to, (i) typical design inputs used by MDOT for flexible and rigid rehabilitation designs; (ii) General Pavement Studies (GPS) and Specific Pavement Studies (SPS) in the LTPP database, these pavement sections are located in various climatic regions in the US and (iii) default input variable ranges recommended in the MEPDG/DARWin-ME software for inputs where data are not available from the LTPP or MDOT. To evaluate the significance of input variables from both a practical and statistical point of view, there is a need to assess their effect rationally based on some performance criteria which are more acceptable by the pavement community. Therefore, to determine the consequence of various levels of each input variable, rather than using subjective criteria based on the visual inspection of the performance curves, a more coherent criterion was adopted in this study. It is proposed that two different approaches be investigated to determine the significant effects:

- Performance threshold, and
- Age threshold

For performance threshold, acceptable failure criteria at national/local (MDOT) levels can be considered for various performance measures. Performance(s) threshold may be used to determine ages, at which the performance threshold is exceeded, for each input level for the same variable. From these ages significance (statistical and practical) will be determined. For example, if the difference in ages is more than 5 years, one can consider this variable has a practically significant effect. On the other hand if the difference is less than 5 years, one can assume practically insignificant effect. For the age threshold, the performance for each input level of a variable can be determined based on distress magnitude at a pre-specified age. The difference in performances at a particular age (10, 15 or 20 years) can be compared to the national common characteristics of good and poorly performing pavements. The acceptable thresholds were determined after discussion with the RAP.

SECOND STEP - Cataloging the various performance parameters associated with the flexible and rigid rehabilitation designs based on the MEPDG/DARWin-ME "runs." A

preliminary assessment of the input sensitivity will be made based on visual trend, engineering judgment, and performance thresholds identified in step 1.

THIRD STEP - Designing the full-cell factorial matrix consisting of the sensitive input variables identified in the second step. The performance magnitudes based on performance thresholds or age thresholds will be cataloged and subjected to an analysis of variance (ANOVA). This analysis will assist in highlighting the significant main effects and possible two-way interactions. At the end of this three step process, the research team will be able to identify input variables that have a significant impact on the performance of flexible and rigid pavement rehabilitation designs and recommend appropriate ranges of these input variables. The results of this process will assist MDOT in customizing the use of the software by focusing on the most important input variables and their levels.

1.5.4 Task 2-4: Project Selection

Information was collected to select pavement sections (rehabilitation design) to compare measured and predicted performance histories. The measured performance data was obtained from MDOT PMS. The collected data included the following:

A. Rehabilitation type: unbonded concrete overlay, HMA over existing HMA, existing PCC or rubblized PCC. Maintenance type and history over the performance life of the overlay
B. Site factors: The site factors will address the various regions in the state, climatic zones and subgrade soil types.
C. Traffic: The various levels of traffic will assist in distinguishing between Michigan routes, US routes and Interstate routes.
D. Overlay thicknesses: The range of constructed overlay thicknesses.
E. Open to traffic date: This information determines the performance period.
F. As built cross-section details (existing and overlay structure)
G. Pre-overlay repairs performed on the existing pavement (such as partial and/or full depth repairs, dowel bar retrofit)
H. Material properties of both the existing and new structure

Based on this list, the project team populated (in consultation with the RAP) a test matrix which was used in Task 2-5. The research team selected projects that have been subjected to FWD tests in prior years and for which inventory and laboratory test data were available. The pool of projects in the test matrix corresponded to the two recent MDOT projects “Pavement Subgrade MR Design Values for Michigan’s Seasonal Changes” and “Back-calculation of Resilient Modulus Values for Unbound Pavement Materials”. This database included over 4000 and 2500 FWD tests for rigid and flexible pavement projects, respectively. The data fields included regions, county, control section and beginning mile post, location, pavement type and cross-section. However, no fix type information is available. Additional projects were identified in order to include rehabilitation strategies that may not be covered in the above mentioned projects.

1.5.5 Task 2-5: Verification of Rehabilitation Performance Models

Based on the inputs identified as a result of Task 2.3 and projects selected in Task 2.4, MEPDG/DARWin-ME runs will be executed. The predicted results will be compared with the field performance of the projects. It is recommended that 5 projects per rehabilitation strategy be used for the comparative analysis. For the selected projects the data needs will include (i) inventory (as constructed wherever possible or at the bid stage); (ii) falling weight deflectometer data for establishing layer moduli; (iii) traffic; and (iv) pavement condition. Each project will constitute a case study where MEPDG will be run at the different input levels (1, 2 and 3).

The comparison will be done with the understanding that differences can be attributed to the performance models in the MEPDG/DARWin-ME (these will be the subject of verification/calibration in Part 3 of the study) or the input values for the various variables used in the MEPDG/DARWin-ME analysis (these will be investigated as part of tasks 2-2 and 2-3). Recommendations will be made on rehabilitation design inputs, including back-calculation results, and their effects on predicted MEPDG performance curves.

1.5.6 Task 2-6: Deliverables

Several types of reports will be submitted, quarterly, draft final and final report, according to the format specified in the Research & Implementation Manual. A PowerPoint presentation showing the basis and results of the study will also be submitted. The draft final report documenting the findings of Part 2 will be submitted to the MDOT RAP no later than March 31, 2013 and the revised (based on the comments of the project panel) will be submitted to MDOT no later than June 20, 2013.

1.6 OUTLINE OF REPORT

The report consists of the following five chapters:

1. Introduction
2. Literature Review
3. Sensitivity Analysis
4. Validation of Performance Models
5. Conclusions and Recommendations

Chapter 1 outlines the problem statement, research objectives and the outline of the final report. Chapter 2 documents the review of literatures from the previous studies related to sensitivity analysis and aspects of the MEPDG/DARWin-ME related to pavement rehabilitation types for rigid and flexible pavements. The review of MDOT pavement rehabilitation practice is also presented in this chapter (Tasks 2-1 and 2-2). Chapter 3 entails sensitivity analysis and results for different rehabilitation options (Task 2-3). Chapter 4 summarizes the project selection process for validation of the rehabilitation models and discusses the validation results by comparing the observed pavement performance to the predicted performance for all the selected projects (Tasks 2-4 and 2-5). Chapter 6 includes the conclusions and detailed recommendations for each rehabilitation option.

CHAPTER 2 - LITERATURE REVIEW

2.1 INTRODUCTION

The MEPDG/DARWin-ME software was made public in mid-2004. Since the release of the software, many State Highway Agencies (SHA's) have worked on exploring several aspects of the design and analysis procedures. Most of the efforts focused on (a) determining significant input variables through sensitivity studies, (b) evaluating local calibration needs, and, (c) implementation issues. To support the MEPDG/DARWin-ME implementation process in the state of Michigan, the pavement researchers at Michigan State University (MSU) have been working with MDOT to explore the various attributes of the design and analysis software. As a result of these efforts over the last five years, the following reports have been published:

- Quantifying Coefficient of Thermal Expansion Values of Typical Hydraulic Cement Concrete Paving Mixtures (Report No. RC-1503)
- Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavements (Report No. RC-1516)
- Characterization of Traffic for the New M-E Pavement Design Guide in Michigan (Report No. RC-1537)
- Pavement Subgrade MR Design Values for Michigan's Seasonal Changes (Report No. RC-1531)
- Backcalculation of Unbound Granular Layer Moduli (Report No. RC-1548)

Furthermore, the NCHRP 1-47 (Sensitivity Evaluation of MEPDG Performance Prediction) project performed a similar study to determine the sensitive input variables for newly designed rigid and flexible pavements. Since very limited literature is available for sensitivity analysis of rehabilitation options in the MEPDG/DARWin-ME, the literature review will consist of the following topics:

a. Summary of findings from the previous MDOT studies (*1-8*), and the NCHRP 1-47 (*9*) study, and
b. Overview of the differences between new and the rehabilitation models in the MEPDG/DARWin-ME.

It is anticipated the former information on the sensitive inputs related to material characterization, pavement design, and site conditions will also assist the pavement designer in understanding their role in the rehabilitation analysis and design using the MEPDG/DARWin-ME. It should be noted that previous findings will be valid for an overlay layer. On the other hand, the latter knowledge of unique differences in the pavement analysis and design between new and rehabilitation modules of the MEPDG/DARWin-ME will enhance and assist in basic understanding about the rehabilitation design process.

2.2 SUMMARY OF PREVIOUS SENSITIVITY STUDIES

2.2.1 MDOT Sensitivity Study

The MSU research team conducted a study entitled "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA pavements"(*3*). The main objectives of the study were to:

a. Evaluate the MEPDG pavement design procedures for Michigan conditions
b. Verify the relationship between predicted and observed pavement performance for selected pavement sections in Michigan and
c. Determine if local calibration is necessary

The report outlined the performance models for JPCP and HMA pavements. Two types of sensitivity analyses were performed namely, a preliminary one-variable-at-a-time (OAT), and a detailed analysis consisting of a full factorial design. Both analyses were conducted to reflect MDOT pavement construction, materials, and design practices. For both new rigid and flexible pavement designs, the methodology contained the following steps:

1. Determine the input variables available in the MEPDG/DARWin-ME and the range of values which MDOT uses in pavement design,
2. Determine the practical range for each input variable based on MDOT practice and Long Term Pavement Performance (LTPP) data,
3. Select a base case and perform the OAT
4. Use OAT results to design the detailed sensitivity analysis
5. Determine statistically significant input variables and two-way interactions
6. Determine practical significance of statistically significant variables
7. Draw conclusions from the results

Tables 2-1 and 2-2 show the impact of input variables on different pavement performance measures for rigid and flexible pavements, respectively.

Table 2-1 Impact of input variables on rigid pavement performance

Design/Material Variable	Impact on distress/smoothness		
	Transverse joint faulting	Transverse cracking	IRI
PCC thickness	High	High	High
PCC modulus of Rupture	None	High	Low
PCC coefficient of thermal expansion	High	High	High
Joint spacing	Moderate	High	Moderate
Joint load transfer efficiency	High	None	High
PCC slab width	Low	Moderate	Low
Shoulder type	Low	Moderate	Low
Permanent curl/warp	High	High	High
Base type	Moderate	Moderate	Low
Climate	Moderate	Moderate	Moderate
Subgrade type/modulus	Low	Low	Low
Truck composition	Moderate	Moderate	Moderate
Truck volume	High	High	High
Initial IRI	NA	NA	High

Table 2-2 Impact of input variables on flexible pavement performance

Fatigue cracking	Longitudinal cracking	Transverse cracking	Rutting	IRI
HMA thickness HMA effective binder content HMA air voids Base material type Subbase material type	HMA thickness HMA air voids HMA effective binder content Base material Subbase material Subgrade material	HMA binder grade HMA thickness HMA effective binder content HMA air voids HMA aggregate gradation	HMA thickness Subgrade material Subgrade modulus HMA effective binder content HMA air voids Base material Subbase material Base thickness Subbase thickness	HMA thickness HMA aggregate gradation HMA effective binder content HMA air voids Base material type Subbase thickness Subbase material type Subgrade material type

Note: The input variables are listed in order of importance.

2.2.2 NCHRP 1-47 Study

The NCHRP 1-47 study investigated the impacts of different input variables on pavement performance. The study quantified the importance of inputs by using a sensitivity index by using a range for a particular input. The sensitivity metric adopted in the study is referred to as normalized sensitivity index (NSI) which is defined as the percentage change of predicted distress relative to its design limit caused by a given percentage change in the design inputs. The NSI is calculated based on Equation (1):

$$NSI = S_{ijk}^{DL} = \frac{\Delta Y_{ji}}{\Delta X_{ki}} \frac{X_{ki}}{DL_j} \tag{1}$$

where:

S_{ijk}^{DL} = sensitivity index for input *k*, distress *j*, at point *i* with respect to a given design limit (DL)

ΔY_{ji} = change in distress j around point i $\left(Y_{j,i+1} - Y_{j,i-1}\right)$

X_{ki} = value of input X_k at point i

ΔX_{ki} = change in input X_k around point i $\left(X_{k,i+1} - X_{k,i-1}\right)$

DL_j = design limit for distress j

The largest *NSI* was determined based on mean and standard deviation $\left(NSI_{\mu\pm2\sigma}\right)$ as the measure for ranking and comparing the sensitivity for different design inputs. The following categories for NSI were used to gauge the sensitivity of each design input:

- Hypersensitive: $NSI_{\mu\pm2\sigma} > 5$
- Very sensitive: $1 < NSI_{\mu\pm2\sigma} < 5$
- Sensitive: $0.1 < NSI_{\mu\pm2\sigma} < 1$
- Non-sensitive: $NSI_{\mu\pm2\sigma} < 0.1$

The sensitivity analyses were performed for five pavement types: new HMA, HMA over stiff foundation, new JPCP, JPCP over stiff foundation, and CRCP. The new HMA and JPCP over stiff foundation represented either stabilized base/subgrade condition or flexible/rigid overlay on the existing pavement. The summary of Global Sensitivity Analysis (GSA, further details in Chapter 4) results for different pavement types are shown in Tables 2-3 to 2-7.

Table 2-3 Ranking of new HMA design inputs by maximum NSI values (9)

Design Input	Maximum $NSI_{\mu\pm2\sigma}$ Values (ANN RSMs)[1]							
	Long. Crack	Alligator Crack	Thermal Crack	AC Rut Depth	Total Rut Depth	IRI	Max	OAT[2]
HMA E* Alpha Parameter[3]	-29.52	-15.94	-0.58	-24.40	-8.98	-3.58	-29.52	HS
HMA E* Delta Parameter[3]	-23.87	-13.18	2.41	-24.43	-8.99	-2.80	-24.43	HS
HMA Thickness	-10.31	-7.46	-0.86	-4.21	-1.58	-1.11	-10.31	HS
HMA Creep Compliance m Exponent	*N.A.*	*N.A.*	*-4.85*	*N.A.*	*N.A.*	*N.A.*	*-4.85*	*VS*
Base Resilient Modulus	*-4.72*	*-2.73*	*-0.17*	*0.14*	*-0.15*	*-0.36*	*-4.72*	*VS*
Surface Shortwave Absorptivity	*4.32*	*1.28*	*-0.20*	*4.65*	*1.67*	*0.67*	*4.65*	*VS*
HMA Air Voids	*4.47*	*3.39*	*1.33*	*-0.05*	*0.03*	*0.29*	*4.47*	*VS*
HMA Poisson's Ratio	*-2.38*	*-1.01*	*0.23*	*-4.33*	*-1.46*	*-0.43*	*-4.33*	*VS*
Traffic Volume (AADTT)	*3.72*	*3.94*	*0.02*	*1.87*	*0.66*	*0.51*	*3.94*	*VS*
HMA Effective Binder Volume	*-3.88*	*-2.93*	*-0.17*	*0.05*	*0.06*	*-0.24*	*-3.88*	*VS*
Subgrade Resilient Modulus	*-2.07*	*-3.41*	*0.15*	*0.08*	*-0.28*	*-0.44*	*-3.41*	*VS*
Base Thickness	*-2.40*	*-1.02*	*-0.03*	*0.22*	*0.04*	*-0.09*	*-2.40*	*VS*
Subgrade Percent Passing No. 200	*-1.71*	*-0.68*	*0.08*	*-0.10*	*-0.10*	*-0.12*	*-1.71*	*S*
HMA Tensile Strength at 14°F	*N.A.*	*N.A.*	*-1.59*	*N.A.*	*N.A.*	*N.A.*	*-1.59*	*S*
Operational Speed	*-1.26*	*-0.83*	*-0.04*	*-1.06*	*-0.39*	*-0.15*	*-1.26*	*S*
HMA Creep Compliance D Parameter	*N.A.*	*N.A.*	*-1.03*	*N.A.*	*N.A.*	*N.A.*	*-1.03*	*S*
HMA Unit Weight	*-0.88*	*0.97*	*-0.76*	*-0.88*	*-0.30*	*-0.08*	*0.97*	*S*
Base Poisson's Ratio	*0.91*	*0.90*	*0.18*	*-0.19*	*-0.05*	*0.09*	*0.91*	*S*
HMA Heat Capacity	*-0.76*	*-0.55*	*-0.77*	*-0.81*	*-0.28*	*-0.14*	*-0.81*	*S*
Subgrade Liquid Limit	*-0.67*	*-0.79*	*-0.10*	*-0.10*	*0.07*	*0.03*	*-0.79*	*S*
Binder Low Temperature PG	*0.56*	*0.09*	*-0.74*	*0.25*	*0.09*	*0.02*	*-0.74*	*S*
HMA Thermal Conductivity	*-0.53*	*-0.40*	*-0.67*	*0.20*	*0.04*	*0.02*	*-0.67*	*S*
Binder High Temperature PG	*-0.60*	*-0.48*	*0.00*	*-0.66*	*-0.25*	*-0.09*	*-0.66*	*S*
Subgrade Poisson's Ratio	*0.44*	*-0.59*	*0.16*	*0.08*	*0.07*	*0.04*	*-0.59*	*S*
Groundwater Depth	*0.20*	*-0.16*	*0.08*	*0.01*	*-0.02*	*-0.02*	*0.20*	*S*
Subgrade Plasticity Index	*-0.15*	*0.11*	*0.03*	*0.01*	*0.02*	*0.00*	*-0.15*	*S*
Aggregate Coef. Of Thermal Contraction	N.A.	N.A.	-0.07	N.A.	N.A.	N.A.	-0.07	NS

[1]Maximum sensitivity over all baseline cases and distresses. Note: The ranking is based on absolute NSI value.
[2]HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.
[3]See Equation (4)

Table 2-4 Ranking of HMA/stiff foundation design inputs by maximum NSI values (9)

Design Input	Maximum $NSI_{\mu \pm 2\sigma}$ Values (ANN RSMs)[1]							
	Long. Crack	Alligator Crack	Thermal Crack	AC Rut Depth	Total Rut Depth	IRI	Max	OAT[2]
HMA E* Delta Parameter[3]	-19.60	9.00	3.52	-43.25	-12.76	-3.49	-43.25	HS
HMA E* Alpha Paramater[3]	-22.02	-3.91	-2.82	-39.33	-13.12	-3.67	-39.33	HS
HMA Unit Weight	10.77	3.69	-1.02	-1.70	-0.65	-0.38	10.77	VS
HMA Air Voids	*-8.12*	*-2.53*	*1.84*	*0.62*	*-0.26*	*-0.08*	*-8.12*	*VS*
Surface Shortwave Absorptivity	*-4.90*	*-1.86*	*-0.38*	*7.43*	*2.50*	*0.86*	*7.43*	*HS*
HMA Poisson's Ratio	*-6.93*	*-2.11*	*-0.30*	*-5.57*	*-1.96*	*-0.61*	*-6.93*	*HS*
Subgrade Liquid Limit	*6.76*	*2.47*	*0.18*	*0.97*	*0.19*	*-0.16*	*6.76*	*S*
HMA Creep Compliance m Exponent	*N.A.*	*N.A.*	*-6.65*	*N.A.*	*N.A.*	*N.A.*	*-6.65*	*VS*
Sub Resilient Modulus	*5.82*	*0.94*	*0.37*	*1.85*	*-1.72*	*-0.29*	*5.82*	*S*
HMA Effective Binder Volume	*-5.61*	*0.90*	*-0.70*	*-1.98*	*-0.40*	*-0.16*	*-5.61*	*VS*
Base Poisson's Ratio	*5.55*	*2.26*	*-0.46*	*-2.78*	*-0.56*	*-0.16*	*5.55*	*S*
HMA Heat Capacity	*-5.24*	*-1.88*	*-0.68*	*-1.36*	*-0.38*	*-0.24*	*-5.24*	*S*
Base Thermal Conductivity	*-5.05*	*-1.42*	*-0.84*	*-1.13*	*-0.42*	*-0.18*	*-5.05*	*HS*
Base Thickness	*3.25*	*1.67*	*0.22*	*2.00*	*0.32*	*0.10*	*3.25*	*VS*
HMA Thickness	*2.73*	*1.82*	*-0.70*	*3.11*	*0.87*	*0.30*	*3.11*	*VS*
Operational Speed	*3.09*	*0.56*	*-0.14*	*-1.62*	*-0.58*	*-0.16*	*3.09*	*VS*
Traffic Volume (AADTT)	*0.74*	*0.56*	*-0.06*	*2.94*	*0.91*	*0.26*	*2.94*	*VS*
Subgrade Percent Passing No. 200	*2.78*	*0.53*	*-0.35*	*0.57*	*-0.23*	*0.10*	*2.78*	*S*
Base Resilient Modulus	*-1.84*	*0.58*	*-0.47*	*-2.23*	*-0.33*	*0.22*	*-2.23*	*S*
Base Heat Capacity	*-2.18*	*-0.50*	*-0.40*	*-0.86*	*-0.45*	*-0.23*	*-2.18*	*S*
Subgrade Plasticity Index	*1.66*	*0.49*	*-0.07*	*0.70*	*0.09*	*0.02*	*1.66*	*S*
HMA Tensile Strength at 14°F	*N.A.*	*N.A.*	*-1.65*	*N.A.*	*N.A.*	*N.A.*	*-1.65*	*VS*
Base Resilient Modulus	*-1.63*	*-0.25*	*-0.09*	*0.94*	*0.30*	*-0.13*	*-1.63*	*S*
Groundwater Depth	*-1.30*	*-0.24*	*0.09*	*0.34*	*-0.06*	*-0.02*	*-1.30*	*S*
Binder High Temperature PG	*-0.68*	*-0.23*	*0.00*	*-1.15*	*-0.38*	*-0.11*	*-1.15*	*VS*
HMA Creep Compliance D Parameter	*N.A.*	*N.A.*	*-1.10*	*N.A.*	*N.A.*	*N.A.*	*-1.10*	*VS*
Binder Low Temperature PG	*-0.51*	*-0.09*	*-0.92*	*0.38*	*0.15*	*0.07*	*-0.92*	*S*
HMA Thermal Conductivity	*0.83*	*-0.60*	*-0.56*	*0.62*	*0.24*	*0.15*	*0.83*	*S*
Aggregate Coef. Of Thermal Contraction	N.A.	N.A.	-0.16	N.A.	N.A.	N.A.	-0.16	NS

[1]Maximum sensitivity over all baseline cases and distresses. Note: The ranking is based on absolute NSI value.
[2]HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.[3]See Equation (4), [4]20-year strength ratio values not considered explicitly in OAT analyses

Table 2-5 Ranking of new JPCP design inputs by maximum NSI values (9)

Design Input	Maximum $NSI_{\mu \pm 2\sigma}$ Values (ANN RSMs)[1]				
	Faulting	Transverse Cracking	IRI	Maximum	OAT[2]
Slab Width	-17.97	-5.04	-8.81	-17.97	HS
PCC 28-Day Modulus of Rupture	*0.92*	*-4.21*	*-0.63*	*-4.21*	*HS*
PCC Thickness	*0.51*	*-3.88*	*-0.50*	*-3.88*	*HS*
Design Lane Width	*1.58*	*-3.78*	*0.65*	*-3.78*	*HS/NS[3]*
PCC Unit Weight	*-2.33*	*3.13*	*-1.19*	*3.13*	*VS*
PCC Coef. of Thermal Expansion	*2.16*	*2.81*	*1.25*	*2.81*	*VS*
PCC Ratio of 20-year to 28-day Modulus of Rupture	*0.50*	*-2.69*	*-0.26*	*-2.69*	*-[4]*
PCC 28-Day Elastic Modulus	*0.21*	*2.57*	*0.37*	*2.57*	*HS*
Surface Shortwave Absorptivity	*0.68*	*2.27*	*0.55*	*2.27*	*HS*
Joint Spacing	*0.66*	*1.79*	*0.36*	*1.79*	*HS*
PCC Water-to-Cement Ratio	*0.62*	*1.62*	*0.82*	*1.62*	*S*
PCC Thermal Conductivity	*-0.21*	*-1.12*	*-0.21*	*-1.12*	*HS*
Subgrade Resilient Modulus	*-0.20*	*-0.34*	*-0.99*	*-0.99*	*S*
Dowel Diameter	*-0.69*	*0.98*	*-0.37*	*0.98*	*VS*
PCC Poisson's Ratio	*0.26*	*-0.75*	*0.19*	*-0.75*	*VS*
Traffic Volume (AADTT)	*0.63*	*0.56*	*0.37*	*0.63*	*VS*
PCC Cement Content	*0.30*	*0.55*	*0.18*	*0.55*	*S*
Base Resilient Modulus	*0.33*	*0.40*	*0.22*	*0.40*	*VS*
Groundwater Depth	*0.08*	*-0.37*	*-0.06*	*-0.37*	*S*
Base Thickness	*-0.12*	*0.35*	*-0.08*	*0.35*	*S*
Edge Support – Load Transfer Efficiency	*-0.13*	*-0.26*	*-0.07*	*-0.26*	*NS*
Erodibility Index	*0.25*	*-0.19*	*0.16*	*0.25*	*S*
Construction Month	*0.11*	*0.22*	*0.07*	*0.22*	*S*

[1]Maximum sensitivity over all baseline cases and distresses. Note: The ranking is based on absolute NSI value.
[2]HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive, [3]See Equation (4).

Table 2-6 Ranking of JPCP/stiff foundation design inputs by maximum NSI values (9)

Design Input	Maximum $NSI_{\mu \pm 2\sigma}$ Values (ANN RSMs)[1]				
	Faulting	Transverse Cracking	IRI	Maximum	OAT[2]
Slab Width	-16.34	-4.74	-9.63	-16.34	HS
PCC 28-Day Modulus of Rupture	0.49	-5.52	-0.62	-5.52	HS
PCC Thickness	0.40	-5.05	-0.51	-5.05	HS
PCC Unit Weight	*-4.16*	*2.68*	*-2.63*	*-4.16*	*HS*
Design Lane Width	*1.67*	*-3.23*	*-0.74*	*-3.23*	*HS/NS*[3]
PCC Coef. of Thermal Expansion	*2.54*	*3.10*	*1.42*	*3.10*	*VS*
PCC Ratio of 20-year to 28-day Modulus of Rupture	*0.31*	*-3.02*	*-0.29*	*-3.02*	*-*[4]
PCC 28-Day Elastic Modulus	*0.47*	*2.40*	*0.45*	*2.40*	*HS*
PCC Water-to-Cement Ratio	*0.28*	*2.23*	*0.78*	*2.23*	*S*
Joint Spacing	*0.70*	*1.98*	*0.33*	*1.98*	*HS*
Surface Shortwave Absorptivity	*0.67*	*1.97*	*0.58*	*1.97*	*HS*
PCC Thermal Conductivity	*-0.54*	*-1.29*	*-0.33*	*-1.29*	*HS*
Dowel Diameter	*-0.44*	*1.13*	*-0.36*	*1.13*	*VS*
Subgrade Resilient Modulus	*-0.38*	*0.24*	*-1.06*	*-1.06*	*VS*
PCC Poisson's Ratio	*0.26*	*0.72*	*0.24*	*0.72*	*VS*
Traffic Volume (AADTT)	*0.47*	*0.72*	*0.35*	*0.72*	*VS*
Base Thickness	*-0.32*	*-0.51*	*-0.17*	*-0.51*	*VS*
Edge Support – Load Transfer Efficiency	*-0.12*	*-0.47*	*-0.10*	*-0.47*	*S*
Erodibility Index	*0.27*	*-0.12*	*0.15*	*0.27*	*S*
Loss of Friction	*0.03*	*-0.26*	*-0.02*	*-0.26*	*S*
PCC Cement Content	*0.21*	*0.22*	*0.12*	*0.22*	*S*
Groundwater Depth	*-0.07*	*-0.21*	*-0.05*	*-0.21*	*S*
Stabilized Base Resilient Modulus	*0.06*	*-0.19*	*-0.06*	*-0.19*	*NS*
Construction Month	*0.10*	*0.14*	*0.06*	*0.14*	*VS*

[1]Maximum sensitivity over all baseline cases and distresses. Note: The ranking is based on absolute NSI value.
[2]HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.
[3]20-year strength ratio values not considered explicitly in OAT analyses

Table 2-7 Ranking of New CRCP design inputs by maximum NSI values (9)

Design Input	Maximum $NSI_{\mu \pm 2\sigma}$ Values (ANN RSMs)[1]					
	Punchout	Crack Width	Crack LTE	IRI	Max	OAT[2]
PCC 28-Day Indirect Tensile Strength	11.13	61.48	-1.33	2.37	61.48	-[3]
PCC 28-Day Modulus of Rupture	-40.29	-47.80	2.35	-7.37	-47.80	HS
PCC Thickness	-44.43	-10.47	1.57	-8.94	-44.43	HS
PCC Water-to-Cement Ratio	8.42	36.09	-0.82	1.88	36.09	HS
PCC Unit Weight	-17.22	-35.27	0.53	-3.22	-35.27	HS
Bar Diameter	11.41	23.29	-1.49	1.93	23.29	HS
Base Slab Friction	-4.17	-21.62	0.35	-0.78	-21.62	HS
PCC Cement Content	7.56	21.55	-0.65	1.38	21.55	HS
PCC Ratio 20-year to 28-day Modulus of Rupture	-18.81	7.88	-0.50	-3.48	-18.81	-[3]
Percent Steel	-15.41	-18.00	1.04	-2.99	-18.00	HS
PCC 28-Day Elastic Modulus	10.90	15.97	-0.61	2.13	15.97	HS
Steel Depth	6.43	13.39	-0.61	1.51	13.39	HS
Traffic Volume (AADTT)	8.47	1.03	-0.42	1.61	8.47	HS
Base Resilient Modulus	-6.39	-4.71	0.10	-1.16	-6.39	VS
PCC Coef. of Thermal Expansion	6.19	5.54	-0.06	1.19	6.19	VS
PCC Ratio 20-year to 28-day Indirect Tensile Strength	1.62	-5.81	0.14	-0.29	-5.81	-[3]
Surface Shortwave Absorptivity	3.32	-5.44	0.20	0.74	-5.44	HS
Base Thickness	*-1.79*	*4.71*	*-0.10*	*-0.42*	*4.71*	*S*
Subgrade Resilient Modulus	*-3.23*	*-4.64*	*0.06*	*-1.17*	*-4.64*	*VS*
Edge Support – Load Transfer Efficiency	*-3.26*	*2.16*	*0.30*	*-0.59*	*-3.26*	*S*
PCC Poisson's Ratio	*1.79*	*-2.44*	*0.04*	*0.34*	*-2.44*	*S*
Construction Month	*1.62*	*2.33*	*-0.08*	*0.25*	*2.33*	*S*
Groundwater Depth	*0.43*	*-1.19*	*0.03*	*-0.09*	*-1.19*	*S*

[1]Maximum sensitivity over all baseline cases and distresses. Note: The ranking is based on absolute NSI value.
[2]HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.
[3]20-year strength ratio values not considered explicitly in OAT analyses

The results in above tables show the ranking of significant input variables. The variables located in the top portion are hypersensitive while the portions below show input variables that are very sensitive and sensitive, respectively. The shaded cells represent the top three sensitive variables (based on absolute NSI values) for each performance measure. The results in Tables 2-3 and 2-4 show that HMA master curve parameters have the most significant impact on flexible pavement distresses. On the other hand, among the design inputs, slab width and thickness have significant impact of rigid pavement performance. In addition, among the material properties, PCC modulus of rupture (MOR) has very important impact on predicted performance in rigid pavements (see Tables 2-5 to 2-7).

Another study related to the implementation of the MEPDG was performed in Tennessee (*10*). The State of Tennessee validated the MEPDG models using their typical pavement designs. The study analyzed 19 highway pavement sections for validation. The predicted performance was compared to the measured performance for each project. The analysis considered asphalt concrete overlays on PCC and HMA pavements. The pavements were analyzed using the new/reconstruct pavement design procedures in the MEPDG instead of rehabilitation design options. The roughness (IRI) and rutting predicted performance was determined and compared to the measured values. It was found that the initial IRI value needs to be determined before calculation. The MEPDG predicted rutting values gave satisfactory results for level 1, and over-predicted AC rutting for level 3 analyses. Over predictions also occurred for base and subgrade rutting. Traffic was found to be an important variable. Finally, local calibration of the MEPDG performance models was recommended.

2.2.3 Traffic Inputs in Michigan

The research team has extensively worked on the traffic characterization for the MEPDG/DARWin-ME in Michigan (*5, 6*). The following traffic characteristics were investigated:

1. Monthly distribution factors
2. Hourly distribution factors
3. Truck traffic classifications
4. Axle groups per vehicle
5. Axle load distributions for different axle configurations

The data was collected from 44 Weigh-in-motion (WIM) sites distributed in the entire state of Michigan. The data were used to develop Level 1 (site specific) traffic inputs for the WIM locations. Cluster analysis was conducted to group similar sites with similar characteristics for development of Level 2 (regional) inputs. Statewide (Level 3) averages were also determined. The inputs and their recommended input levels are summarized in Table 2-8.

Table 2-8 Conclusions and recommendations for traffic input levels

Traffic Characteristic	Impact on pavement Performance		Suggested Input Levels	
	Rigid Pavement	Flexible Pavement	Rigid Pavement	Flexible Pavement
TTC	Significant	Moderate	Level II	
HDF	Significant	Negligible	Level II	Level III
MDF	Negligible		Level III	
AGPV	Negligible		Level III	
Single ALS	Negligible		Level III	
Tandem ALS	Significant	Moderate	Level II	
Tridem ALS	Negligible	Negligible	Level III	
Quad ALS	Negligible	Moderate	Level III	

2.2.4 Unbound Material Inputs in Michigan

Two studies to characterize unbound material in Michigan were carried out in the last few years(*7, 8*). The first study outlined the importance of the resilient modulus (MR) of the roadbed soil and how it affects pavement systems. The study focused on developing reliable methods to determine the MR of the roadbed soil for inputs in the MEPDG/DARWin-ME. The study divided the state of Michigan into fifteen clusters based on the similar soil characteristics. Lab tests were performed to determine moisture content, grain size distribution, and Atterberg limits. Furthermore, another aspect of the study was to determine the differences between laboratory tested MR values and back-calculated MR. Based on the analysis it was concluded that the values between laboratory tested MR and back-calculated MR are almost equal if the stress boundaries used in the laboratory matched those of the FWD tests. Table 2-9 summarizes the recommended MR values for design based on different roadbed types in Michigan. The study suggests that the design recommended value should be used for design.

Table 2-9 Average roadbed soil MR values (*7*)

Roadbed Type		Average MR			
USCS	AASHTO	Laboratory determined (psi)	Back-calculated (psi)	Design value (psi)	Recommended design MR value (psi)
SM	A-2-4, A-4	17,028	24,764	5,290	5,200
SP1	A-1-a, A-3	28,942	27,739	7,100	7,000
SP2	A-1-b, A-2-4, A-3	25,685	25,113	6,500	6,500
SP-SM	A-2-4, A-4	21,147	20,400	7,000	7,000
SC-SM	A-2-6, A-6, A-7-6	23,258	20,314	5,100	5,000
SC	A-4, A-6, A-7-6	18,756	21,647	4,430	4,400
CL	A-4, A-6, A-7-6	37,225	15,176	4,430	4,400
ML	A-4	24,578	15,976	4,430	4,400
SC/CL/ML	A-2-6, A-4, A-6, A-7-6	26,853	17,600	4,430	4,400

The second study focused on the backcalculation of MR for unbound base and subbase materials and made the following recommendations (*8*):

1. In the design of flexible pavement sections using design levels 2 or 3 of the MEPDG, the materials beneath the HMA surface layer should consist of the following two layers:
   a. Layer 1 - An aggregate base whose modulus value is 33,000 psi
   b. Layer 2 - A sand subbase whose modulus is 20,000 psi
2. In the design of rigid pavement sections using design levels 2 or 3 of the MEPDG, the materials beneath the PCC slab could be either:
   a. An aggregate base layer whose modulus value is 33,000 psi supported by sand subbase whose modulus value is 20,000 psi
   b. A granular layer made up of aggregate and sand mix whose composite modulus value is 25,000 psi
   c. A sand subbase whose modulus value is 20,000 psi
3. For the design of flexible or rigid pavement sections using design level 1 of the MEPDG, it is recommended that:
   - For an existing pavement structure where the PCC slabs or the HMA surface will be replaced, FWD tests be conducted every 500 feet along the project and the deflection data be used to backcalculate the moduli of the aggregate base and sand subbase or the granular layer. The modulus values to be used in the design should correspond to the 33rd percentile of all values. The 33rd percentile value is the same as the average value minus half the value of the standard deviation.
   - For a total reconstruction or for a new pavement section, the modulus values of the aggregate base and the sand subbase or the granular layer could be estimated as twice the average laboratory determined modulus value.
4. Additional FWD tests and backcalculation analyses should be conducted when information regarding the types of the aggregate bases under rigid and flexible pavements becomes known and no previous FWD tests were conducted.
5. MDOT should keep all information regarding the various pavement layers. The information should include the mix design parameters of the HMA and the PCC, the type, source, gradation and angularity of the aggregate and the subbase material type, source, gradation and angularity. The above information should be kept in easily searchable electronic files.

2.3 OVERVIEW OF DIFFERENCES BETWEEN NEW AND REHABILITATION DESIGN

2.3.1 Rehabilitation Options in MEPDG/DARWin-ME

It is important to determine the effect of input variables on the pavement performance specific to the rehabilitation models in the MEPDG/DARWin-ME.
The different rehabilitation options in the MEPDG/DARWin-ME are divided into two categories—rigid and flexible rehabilitation. Within each category, several different rehabilitation design options are available as shown below:

Rigid pavement rehabilitation options

- JPCP over JPCP/CRCP (unbonded)
- CRCP over JPCP/CRCP (unbonded)
- PCC over JPCP/CRCP (bonded)
- JPCP over HMA

Flexible pavement rehabilitation options

- HMA over HMA
- HMA over JPCP
- HMA over CRCP
- HMA over fractured JPCP/CRCP (Rubblized, crack and seat)

None of the previous studies investigated the rehabilitation options of the MEPDG/DARWin-ME. However, to investigate the impact of input variables, it is important to highlight some important differences between new and rehabilitation pavement analysis and performance prediction models in the MEPDG/DARWin-ME.

While distress prediction models (transfer functions) in new and rehabilitation designs are similar, there are some basic differences in the way the damage is calculated in the pavement layers. These differences between new and rehabilitation designs using MEPDG/DARWin-ME include the:

1. Location with the pavement layers where damage is calculated for flexible rehabilitation options,
2. Hardening of the existing HMA layers due to aging, and
3. Characterization of the existing pavement damage.

Since the location of fatigue calculation is different in rehabilitation and new flexible pavement design, the percent alligator cracking is different. Also, the reflective cracking is only considered in rehabilitation analyses but not in the new pavement design. On the other hand, due the reduction in existing modulus because of the age hardening of the asphalt layer over time, rutting and longitudinal cracking and hence IRI are different for the rehabilitation options.

2.3.1.1. Rigid Pavement Rehabilitation

The approach for rigid pavement rehabilitation design follows a similar procedure to the new designs. In addition, the performance models (transfer functions) used to predict pavement performance for each rigid rehabilitation option do not change. The main difference between new and rehabilitated pavement design corresponds to characterizing the existing pavement structure damage. The typical pavement structure layout for all the available rigid rehabilitation designs are shown in Figure 2-1.

The overlay input variables are identical to new rigid pavement designs in the MEPDG/DARWin-ME, and therefore will not be discussed in detail. For a full description on new rigid pavement design using the MEPDG/DARWin-ME refer to the previous MDOT study (*3*). For unbonded overlays, the asphalt interlayer is unique to rigid pavement rehabilitation and is used to ensure that that no bond exists between the existing pavement structure and the overlay. The interlayer separates the existing PCC slab from the overlay to prevent distresses from propagating to the overlay slab. The interlayer material input values are also identical to new HMA layer properties. The existing PCC pavement properties differ compared to new rigid designs. The following input variables are used to characterize the existing PCC layer:

- PCC thickness
- PCC unit weight
- PCC Poisson's ratio
- Is the slab fractured? (if yes: specify fracture technique)
- PCC elastic modulus (in-tact or fractured)
- Thermal conductivity
- Heat capacity

Another input parameter unique to rehabilitation design is the option to input the dynamic modulus of subgrade reaction (*k*) directly, which overrides the internal calculation of *k* established considering base, subbase and subgrade soil information. For rigid pavement rehabilitation, the existing PCC elastic modulus is the only way to classify the condition of the existing PCC pavement.

The existing PCC pavement elastic modulus should be determined either by testing cores taken from the field or by using back-calculation techniques. Once the elastic modulus value is obtained from testing, Equation (2) should be used to calculate the value to be used in the MEPDG/DARWin-ME.

$$E_{base/design} = C_{BD} \times E_{Test} \tag{2}$$

where:

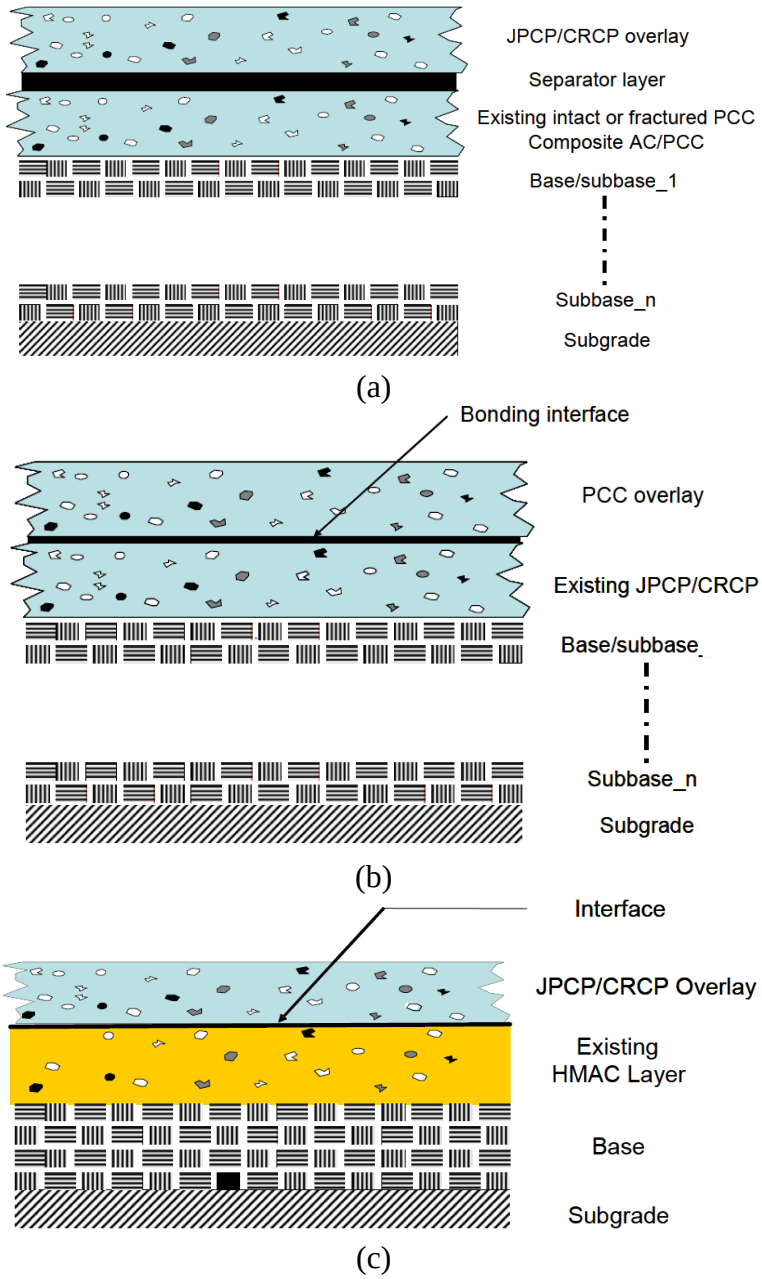
$E_{base/design}$ = Elastic modulus of the existing layer used in the software

E_{Test} = Static elastic modulus obtained from coring and laboratory testing or back-calculation of an intact slab

C_{BD} = Factor based on the overall condition of the existing PCC pavement, recommended range based on the existing pavement condition are given below (*11*).

- 0.42 – 0.75 for pavements in "good" structural conditions
- 0.22 – 0.42 for pavements in "moderate" structural conditions
- 0.042 – 0.22 for pavements in "severe" structural conditions

Table 2-10 summarizes characterization of the existing pavement (all hierarchical Levels) based on measured cracking performance. Once, a pavement condition is determined based on the distress data (percent slab cracked), the value of C_{BD} is estimated. Subsequently, the C_{BD} and the elastic modulus (E_{Test}) are used in Equation (2) to determine $E_{base/design}$. However, for $E_{base/design}$, the software recommends a maximum value of 3,000,000 psi to account for existing joints even if few cracks exist. To characterize the existing pavement structural capacity, the software specifies three different input levels with varying data needs (see Table 2-11).



Layer Numbers:

1. JPCP or CRCP overlay
2. Separator Layer (HMA) – considered the base in structural and non-structural analysis
3. Existing JPCP/CRCP – considered the base in structural analysis
4. Stabilized or unstabilized subbase
5. Subbase (if applicable)
6. Subgrade

Layer Numbers:

1. JPCP or CRCP overlay (bonded to the existing layer)
2. Existing JPCP/CRCP
3. Stabilized or unstabilized subbase – considered the base in structural analysis
4. Stabilized or unstabilized subbase (if applicable)
5. Subgrade

Layer Numbers:

1. JPCP or CRCP overlay (bonded to the existing layer)
2. Existing HMA layer – considered the base in structural and non-structural analysis
3. Stabilized or unstabilized subbase
4. Stabilized or unstabilized subbase (if applicable)
5. Subgrade

Figure 2-1 Typical cross-sections of PCC rehabilitation strategies. (a) Unbonded PCC overlays, (b) Bonded PCC overlays, (c) PCC overlays of HMA pavements (1)

Table 2-10 Structural condition of rigid pavements (*11*)

Existing pavement type	Structural condition		
	Good	Moderate	Severe
JPCP (percent slabs cracked)	<10	10 to 50	>50
JRCP (percent area deteriorated)	< 5	5 to 25	> 25
CRCP (percent area deteriorated)	< 3	3 to 10	>10

Table 2-11 Rigid pavement rehabilitation hierarchical levels for the elastic modulus of the existing pavement

Input data	Hierarchical level		
	1	2	3
Existing PCC slab design elastic modulus	Determine the elastic modulus of the existing pavement (E_{test}) from coring, or through FWD back-calculation techniques. Determine the $E_{base/design}$ by using Equation 2	Determine the compressive strength of the existing pavement from PCC cores and convert to elastic modulus. Determine $E_{base/design}$ as described for level 1	Estimate $E_{base/design}$ from historical agency data and local experience for the existing project under design

2.3.1.2. The MEPDG/DARWin-ME Analysis for Rigid Pavement Rehabilitation

The performance prediction for rehabilitation analysis and design based on the structural response models is the same as new JPCP designs. Figure 2-2 illustrates the analysis and design selection process for rigid rehabilitation design. More details about the response models and performance prediction can be found in the NCHRP 1-37A Report (*11*). As an overview, the internal steps necessary to determine various distresses for rigid pavement rehabilitation in the software are presented below:

- Transverse joint faulting is estimated by determining the differential elevation across a joint. Faulting can vary significantly from joint to joint; therefore, the mean faulting across all transverse joints in a pavement section is predicted. The faulting model uses an incremental approach and accumulates over the entire analysis period. The procedure for predicting JPCP transverse joint faulting consists of the following steps:

    1. Tabulate input data needed for predicting JPCP faulting,
    2. Process the traffic input to determine the equivalent number of single, tandem and tridem axles produced by each passing of tandem, tridem, and quad axles,
    3. Process the pavement temperature profile data by converting the temperature profiles generated using the EICM to an effective nighttime difference by calendar month,
    4. Process the monthly relative humidity data to account for the monthly deviations in slab warping,
    5. Calculate the initial maximum faulting,
    6. Evaluate the joint load transfer efficiency,
    7. Determine the critical pavement responses for each increment,
    8. Evaluate the loss of shear capacity and dowel damage,
    9. Calculate the faulting increment,
    10. Calculate the cumulative faulting over the analysis period.

- Transverse cracking is estimated by calculating the fatigue damage at the top and bottom of the concrete slab for each month over the entire analysis period. The

software internally uses the following steps to estimate fatigue damage and subsequently, transverse cracking:

1. Tabulate input data needed for predicting JPCP cracking,
2. Process the traffic input to determine the equivalent number of single, tandem and tridem axles produced by each passing of tandem, tridem, and quad axles,
3. Process the pavement temperature profile data by converting the temperature profiles generated using the EICM to a distribution of equivalent linear temperature differences (temperature gradient) in each month,
4. Process the monthly relative humidity data to account for the monthly deviations in slab warping,
5. Calculate the stress corresponding to each load configuration, load level, load position, and temperature difference for each month,
6. Calculate fatigue damage for both bottom-up and top-down damage over the design life,
7. Calculate bottom-up and top-down cracking based on the fatigue damage,
8. Calculate total cracking by combining both bottom-up and top-down cracking.

- The calculation of smoothness (IRI) is related to the development of joint faulting and transverse cracking and other distresses.

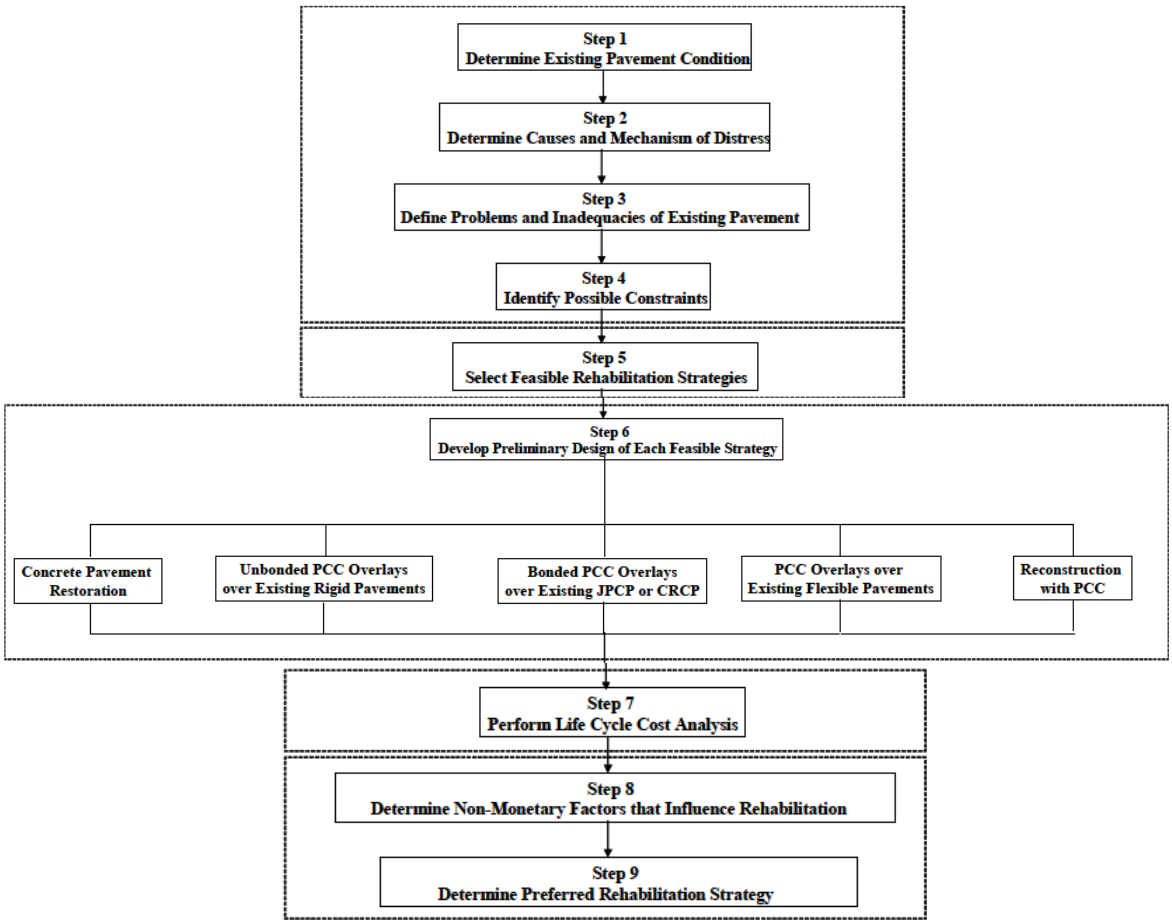


Figure 2-2 Rigid rehabilitation design process (*11*)

2.3.1.3. Flexible Pavement Rehabilitation

Figure 2-3 illustrates the flowchart for HMA rehabilitation analysis and design selection procedure. The focus of this study is the structural rehabilitation design, which starts from step 6 of the flowchart. The procedure for distress prediction in the overlay analyses is the same as for new flexible pavements. The following distresses are considered:

- Load associated fatigue damage
    - HMA layers
        - Top-down cracking
        - Bottom-up cracking
        - Reflective cracking
    - Any chemically stabilized layer
- Permanent deformation
    - HMA layers
    - Unbound layers
- Thermal fracture in HMA surface layers
- IRI

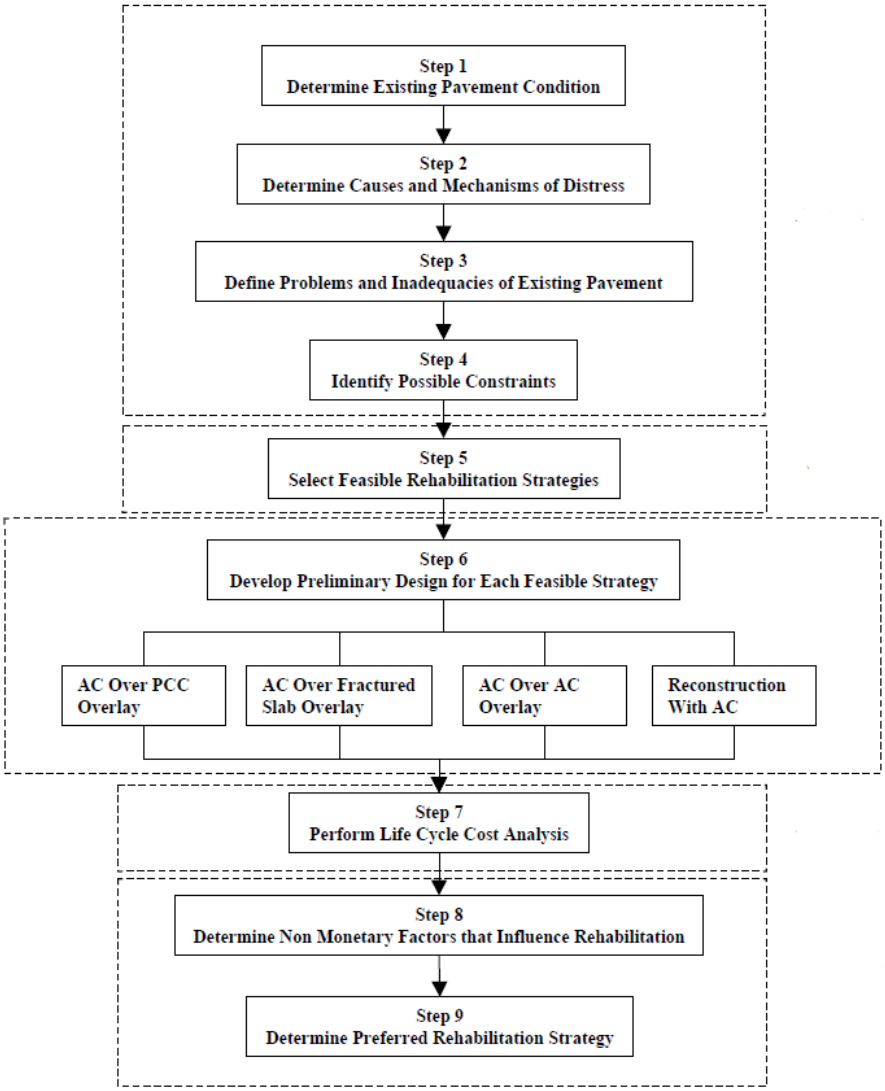


Figure 2-3 Flexible rehabilitation design process (*11*)

For the rehabilitation option, distresses can be analyzed for four general overlay structures shown in Figure 2-4. However, in the case of multiple layers, those may need to be combined to keep the number of layers and evaluation locations within the limits of the MEPDG/DARWin-ME.

Case 1	Case 2	Case 3	Case 4
AC 1	AC 1	AC 1	AC 1
AC 2	AC 2	AC 2	AC 2
AC 3/ATB	AC 3/ATB	GB	AC 3/ATB
Existing Pavement	GB	AC 3/ATB	CTB
	Existing Pavement	Existing Pavement	Existing Pavement

ATB: Asphalt treated base, GB: Granular base, CTB: Cement treated base

Figure 2-4 Overlay design strategies available for flexible pavement rehabilitation

Case 1 is a representation of a conventional HMA overlay. This case can also be used to represent the in-place recycling of existing HMA layers. Cases 2 and 3 represent an overlay where an unbound granular layer is used to control reflection cracking of an underneath PCC layer. These cases may also be used to convert an existing flexible pavement into a sandwich type pavement. Case 4 represents an example of in-place recycling (i.e., full-depth reclamation, FDR) of HMA surface and granular base using cement stabilization. Tables 2-12 through 2-15 summarize the distress prediction locations in the overlay and the existing pavement for the cases shown in Figure 2-4.

Table 2-12 Summary of distress computation locations for flexible overlay designs (*11*)

Distress	Case 1	Case 2	Case 3	Case 4
Longitudinal cracking	Top layer	Top layer	Top layer	Top layer
Alligator cracking	Bottom HMA layer	Bottom HMA layer	1st HMA layer above granular layer; bottom HMA layer	Bottom HMA layer
Thermal cracking	Top layer	Top layer	Top layer	Top layer
Rutting in HMA layers	All HMA layers	All HMA layers	All HMA layers	All HMA layers
Rutting in unbound layers	NA	Granular layer	Granular layer	NA
CSM* modulus reduction	NA	NA	NA	CTB layer
CSM* fatigue cracking	NA	NA	NA	CTB layer
Reflection cracking	Top layer	Top layer	Top layer	Top layer

*CSM: Chemically stabilized material

Table 2-13 Summary of distress computation locations for existing pavement in HMA overlay of flexible and stabilized pavements

Distress	Flexible	Stabilized pavements
Alligator cracking	Existing HMA layer	Existing HMA layer
Rutting in HMA layers	Existing HMA layer	Existing HMA layer
Rutting in unbound layers	All unbound layers	All unbound layers
CSM modulus reduction	NA	CSM layer

Table 2-14 Summary of distress computation location for existing pavement in HMA overlay of fractured slabs

Distress	Fractured slab
Rutting in HMA layers	HMA base if present
Rutting in unbound layers	All unbound layers

Table 2-15 Summary of distress computation locations for existing pavement in HMA overlay of intact PCC pavements

Distress	PCC	Composite
Alligator cracking	NA	Top of existing JPCP layer
Rutting in HMA layers	NA	Existing HMA layer
CTB modulus reduction	CTB layer if present	CTB if present
PCC damage	JPCP and CRCP	JPCP and CRCP

2.3.1.4. The MEPDG/DARWin-ME Analysis for Flexible Pavement Rehabilitation

One of the critical factors in the design of an HMA overlay is the characterization of the existing pavement structure. Based on the available data, the designer has options to consider a three-level hierarchy for inputs for rehabilitation in the MEPDG/DARWin-ME. Three levels are available for the characterization of the existing pavement (*11, 12*). Each level depends on the available data. In this section, the different rehabilitation levels are described followed by the discussion of their impact on overlay performance.

Each of the three rehabilitation levels requires different inputs for estimating the existing pavement damage. It should be noted that regardless of the selected rehabilitation level, there are always three levels for characterizing the HMA mixture and binder. The Level 1 characterization requires in-situ field cores to obtain the undamaged dynamic modulus master curve for the existing HMA layer. Nondestructive deflection testing (NDT) data are needed for estimating the layer back-calculated modulus to characterize damage for the existing HMA layer. The back-calculated dynamic modulus from NDT is used to obtain the initial damage level and damaged modulus master curve. From standard forensic tests on field cores (in-situ properties), the parameters needed for the dynamic modulus predictive equation are (*11*):

- Air void content
- Asphalt content
- Gradation
- A and VTS parameters for the ASTM viscosity temperature susceptibility relationship as determined from recovered binder.

These in-situ HMA volumetric properties and recovered binder parameters are then used in the dynamic modulus predictive equation to establish the undamaged master curve for the existing HMA layer. The damaged modulus is obtained directly from NDT analysis. Knowing the damaged and undamaged dynamic modulus values, fatigue damage is calculated using Equation (3) (*11*) and the process is shown schematically in Figure 2-5.

$$E^*_{dam} = 10^{\delta} + \frac{E^* - 10^{\delta}}{1 + e^{-0.3+5*\log(d_{AC})}} \tag{3}$$

where:

E^*_{dam} = damaged modulus, psi.

δ = regression parameter, representative of minimum value of E^*
E^* = undamaged modulus for a specific reduced time
d_{AC} = fatigue damage in the HMA layer

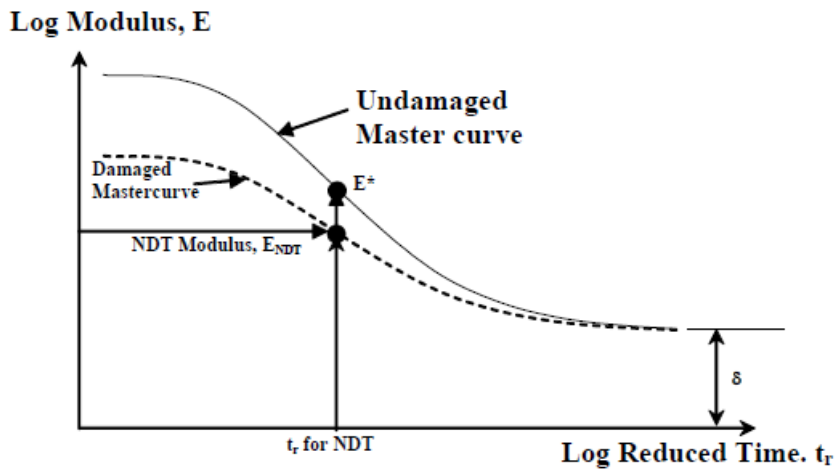


Figure 2-5 Existing HMA layer damaged E* mastercurve computation (*11*)

In level 2 rehabilitation, characterization for an existing asphalt layer uses field cores to obtain the undamaged modulus similar to rehabilitation level 1. The level 2 rehabilitation combine the use of correlations between modulus and measured material characteristics with pavement surface condition data (% cracking and rutting). The initial damage and the damaged modulus master curve are then developed from an estimate of fatigue damage obtained from pavement surface condition data. The amount of alligator cracking measured at the pavement surface is used to solve for the HMA damage using Equation (4).

$$C_{AC} = \frac{100}{1+e^{c+d(d_{AC})}} \tag{4}$$

where:
C_{AC} = percent alligator cracking in the existing HMA layer
d_{AC} = damage computed in the existing HMA layer
c, d = field calibration fitting parameters

Having the undamaged dynamic modulus master curve and field damage, the damaged modulus master curve is calculated from Equation (3). The level 3 rehabilitation uses typical published or recommended values for modulus and information from pavement condition ratings for estimating damage. For level 3 rehabilitation, no HMA and binder testing are required. The undamaged modulus is obtained from the dynamic modulus predictive equation using typical HMA volumetric and binder properties for the existing pavement mixture type. The current damage,d_{AC}, is obtained from the pavement surface condition rating as shown in Table 2-16 (*11*). Pavement condition can also be represented by the pavement surface cracking area as shown in Table 2-17. Having the undamaged modulus master curve and current damage known, the damaged modulus master-curve is obtained from Equation (3).

Table 2-16 Damage based on pavement condition rating (*11*)

Category	Damage
Excellent	0.00-0.20
Good	0.20-0.40
Fair	0.40-0.80
Poor	0.80-1.20
Very Poor	>1.20

Table 2-17 Description of existing pavement condition rating (*13*)

Category	Percent cracked area
Excellent	<5%
Good	5-15%
Fair	15-35%
Poor	35-50%
Very Poor	>50%

CHAPTER 3 - CHARACTERIZING THE EXISTING PAVEMENT LAYERS

3.1 INTRODUCTION

Several issues were encountered while running the MEPDG/DARWin-ME rehabilitation options. These concerns were related to certain structural and material properties. In addition, reasonableness of certain inputs was investigated whenever some unusual results were encountered during the analyses. These concerns are related to the following topics:

- Existing concrete elastic modulus to characterize damage
- Design subgrade modulus
- Impact of interlayer thickness and modulus on the existing PCC slab equivalent thickness
- Discrepancy in performance prediction for thin PCC unbonded overlay
- Layer structure in composite pavement

3.2 EXISTING PCC ELASTIC MODULUS LIMITATIONS

As mentioned in Chapter 2, the maximum value of the existing PCC slab modulus is recommended to be 3,000,000 psi in the MEPDG/DARWin-ME. Based on the existing backcalculated results from LTPP database (General Pavement Studies, GPS-9), where the existing PCC elastic modulus ranged between 3,000,000 psi and 10,000,000 psi with most of the sections around 5,000,000 psi. To verify that the maximum value entered in the MEPDG/DARWin-ME should not exceed 3,000,000, a trial analysis was performed by varying the existing PCC slab elastic modulus to determine its impact on the predicted pavement performance. A sensitivity analysis was performed and the time to reach 20 percent slabs cracked was determined. Figure 3-1 shows the results for different existing PCC elastic moduli for both MEPDG and DARWin-ME. It can be seen that a concrete pavement with a E_{PCC} greater than 3,000,000 psi reaches the distress threshold limit faster. These results are counterintuitive because PCC with higher elastic modulus should perform better than PCC with a lower elastic modulus. Therefore, the recommended maximum limit of 3,000,000 psi for the elastic modulus was used in all analyses in the study.

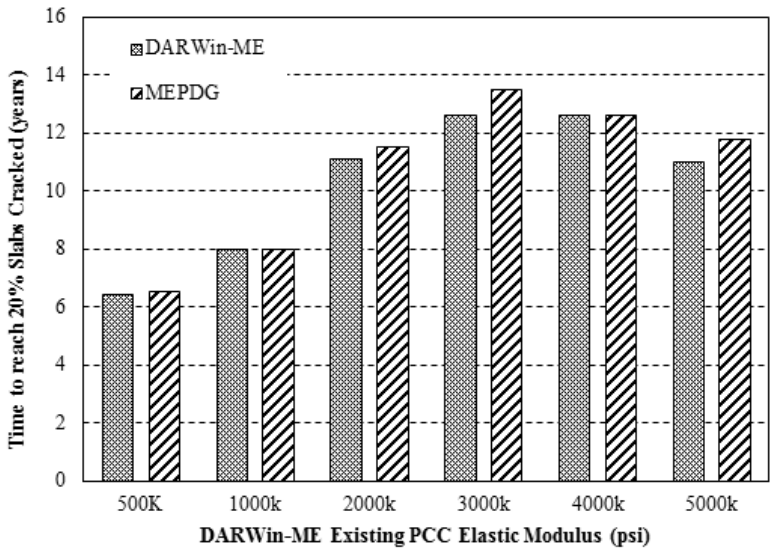


Figure 3-1 Comparison between DARWin-ME and MEPDG for time to failure by varying the elastic modulus of the existing PCC pavement

3.3 DESIGN SUBGRADE MODULUS

MDOT inquired about the use of appropriate MR values to represent soils resilient moduli in Michigan. In general, the values recommended by the MEPDG/DARWin-ME are significantly larger than those being used in MDOT practice. It should be noted that the subgrade moduli values used in the MEPDG/DARWin-ME are based on back-calculated subgrade modulus values from the LTPP database. However, the subgrade modulus values are internally reduced by a factor of 0.55 or 0.67 (*1*) depending on whether the soil type is fine or coarse grained in order to convert the moduli values from field to laboratory. Table 3-1 shows the backcalculated MR (from the Subgrade MR Study) and the DARWin-ME internally reduced MR values. This investigation shows that even though a higher MR value is used as the input for design in the MEPDG/DARWin-ME, the software reduces the values by a fixed factor. Thus, the MEPDG/DARWin-ME factored MR values reflects laboratory determined MR. For level 1 rehabilitation , the reduction factor can be specified by the user. The internal reduction factor cannot be adjusted for levels 2 and 3 analyses. Furthermore, at a project level the backcalculated subgrade MR is recommended for use in rehabilitation design. If backcalculated MR is not available for an overlay or a new project, the unadjusted laboratory MR value from the MDOT subgrade MR study should be used as an input to characterize subgrade.

It should be noted that the MR values reported by Baladi et.al (Subgrade MR Study) were recommended to be used in the AASHTO 93 and the MEPDG designs. However, at the time when the subgrade study was conducted, the information regarding the subgrade modulus internal reduction in the MEPDG was not known and was not considered. Therefore, the MR values suggested in that report should only be considered for AASHTO 93 design procedure. The DARWin-ME design methodology is entirely different from an empirical design approach such as AASHTO 93. The DARWin-ME performance models were nationally calibrated using backcalculated subgrade MR values from the LTPP

database. Those backcalculated values are much greater than typical AASHTO 93 design MR values. However, further investigation will be conducted during the local calibration of the performance models (Part 3 of the study) to evaluate the appropriateness of both backcalculated and design subgrade MR values.

Table 3-1 Internal MR reduction factors for various soil types in DARWin-ME

Roadbed Type		Average MR			DARWin-ME Reduced MR	
USCS	AASHTO	Back-calculated (psi)	Design value (psi)	Recommended design MR value (psi)	Reduced MR (psi)	Factor
SM	A-2-4, A-4	24,764	5,290	5,200	17,261	0.70
SP1	A-1-a, A-3	27,739	7,100	7,000	18,724	0.68
SP2	A-1-b, A-2-4, A-3	25,113	6,500	6,500	16,198	0.65
SP-SM	A-2-4, A-4	20,400	7,000	7,000	13,586	0.67
SC-SM	A-2-6, A-6, A-7-6	20,314	5,100	5,000	8,552	0.42
SC	A-4, A-6, A-7-6	21,647	4,430	4,400	9,113	0.42
CL	A-4, A-6, A-7-6	15,176	4,430	4,400	6,389	0.42
ML	A-4	15,976	4,430	4,400	5,384	0.34
SC/CL/ML	A-2-6, A-4, A-6, A-7-6	17,600	4,430	4,400	7,157	0.41

3.4 EQUIVALENT THICKNESS CONCEPT

In unbonded overlays for rigid pavement, a thin HMA interlayer is generally used to separate the two PCC slabs (i.e., existing and overlay slabs). The research team investigated the impact of interlayer thickness and modulus on the equivalent thickness of the existing PCC slab. The main objective was to verify the impact of interlayer thickness on the predicted performance. For both new PCC design and unbonded overlay design, the MEPDG uses the concept of equivalent thickness to reduce the multilayer system into one equivalent slab. The equivalent slab is then analyzed as a slab on grade. Equation (1) is used within the software to calculate the equivalent thickness for a newly designed PCC pavement where the PCC slab is above the granular base (*2, 3*).

$$h_{eff} = \sqrt[3]{h_{PCC}^3 + \frac{E_{base}}{E_{PCC}} h_{base}^3} \tag{1}$$

where:
h_{eff} = equivalent slab thickness
E_{PCC} = PCC slab modulus of elasticity
E_{base} = base modulus of elasticity
h_{PCC} = PCC slab thickness
h_{base} = base thickness

The equation was modified to incorporate the structural aspects of the asphalt interlayer and the existing PCC layer to determine its impact on the equivalent thickness. Equation (2) was used to account for the existing PCC and the asphalt interlayer.

$$h_{eff} = \sqrt[3]{h_{PCC}^3 + \frac{E_{existingPCC}}{E_{PCC}} h_{existingPCC}^3 + \frac{E_{asphalt}}{E_{PCC}} h_{asphalt}^3} \quad (2)$$

where:
H_{eff} = equivalent slab thickness
E_{PCC} = PCC overlay modulus of elasticity
$E_{existingPCC}$ = existing PCC modulus of elasticity
$E_{asphalt}$ = asphalt interlayer elastic modulus
h_{PCC} = PCC overlay thickness
$h_{existingPCC}$ = existing PCC thickness
$h_{asphalt}$ = asphalt interlayer thickness

One-at-a-time sensitivity analysis was performed on the existing PCC elastic modulus, existing PCC thickness, asphalt interlayer modulus and the asphalt interlayer thickness. The following ranges were used for each input variable:

- PCC elastic modulus:
  - 1,000,000 – 10,000,000psi
- PCC thickness:
  - 5 – 13 inches
- Asphalt interlayer elastic modulus:
  - 100,000 – 600,000 psi
- Asphalt interlayer thickness:
  - 0 – 5 inches

The pavement structure for the sensitivity analysis is illustrated in Figure 3-2.

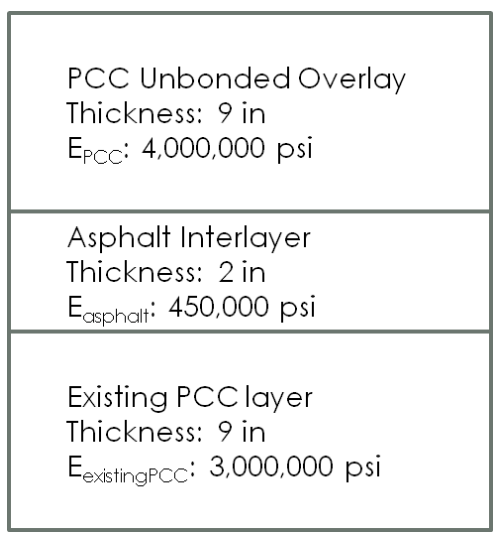


Figure 3-2 Equivalent slab thickness base case structure

The results from the equivalent slab thickness calculations can be seen in Figure 3-3. It is observed that the greatest effect comes from the existing PCC layer properties, while the

asphalt interlayer has very little effect on the equivalent thickness. The reason for such a trend is that the PCC elastic modulus is much greater compared to the asphalt interlayer elastic modulus. Therefore, the interlayer modulus and thickness have insignificant impact on the equivalent thickness. This also implies the interlayer thickness and stiffness will not have much impact on the predicted performance. These results regarding the impact of the asphalt interlayer on the equivalent thickness are intuitive and follow the conventional wisdom in rigid pavement overlay designs.

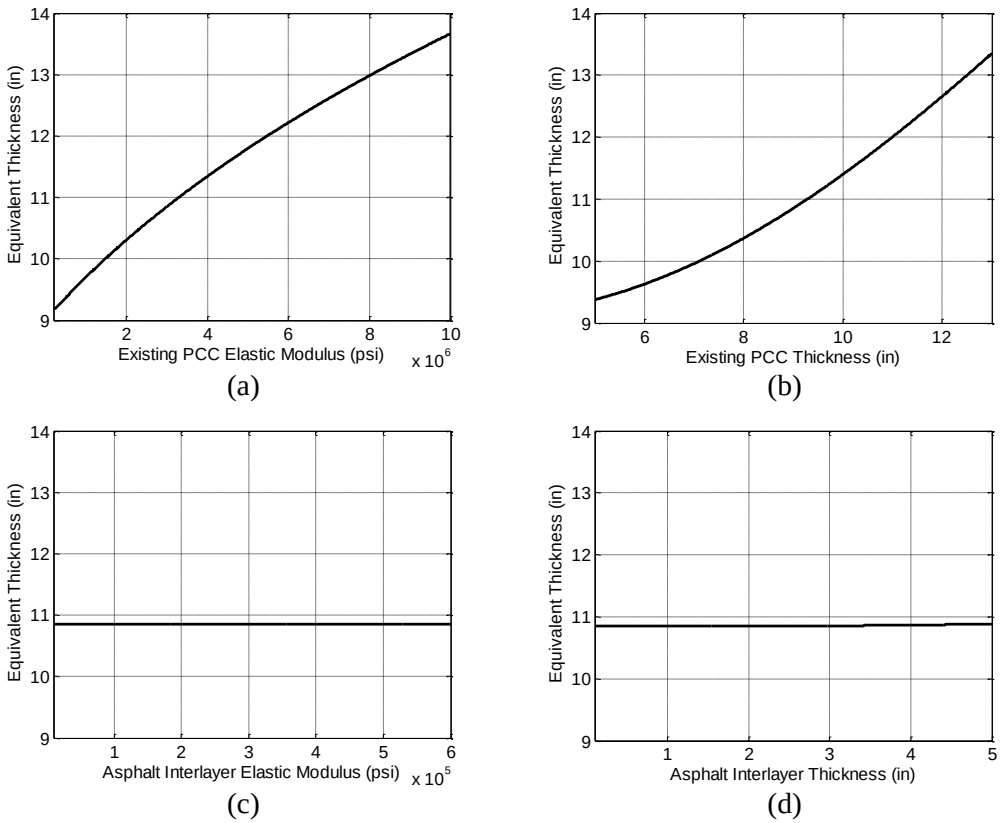


Figure 3-3 Sensitivity analysis based on modified equivalent slab calculations (a) effect of existing PCC elastic modulus, (b) effect of existing PCC thickness, (c) effect of HMA interlayer elastic modulus, (d) effect of HMA interlayer thickness on equivalent thickness

3.5 UNBONDED OVERLAY THICKNESS LIMITATIONS

During the sensitivity analysis, it was found that the MEPDG (version 1.1) software does not allow the user to input any PCC design thickness less than 7 inches. While the DARWin-ME allows for thickness inputs less than 7 inches, caution is advised when running the software beyond a practical design life (i.e. 40+ years) for unbonded overlays thinner than 7 inches. As an example, one unbonded pavement section was analyzed with different thicknesses. A design life of 80 year was chosen in the DARWin-ME in order to ensure failure (i.e., 15% slabs cracked) of the unbonded overlays. The cracking prediction results in Figure 3-4 shows

that a 6 inch unbonded overlay yields less cracking than an 8 inch unbonded overlay at 80 years design life. However, within the practical range of design life (20-40 years), the transverse cracking trends are as one would expect.

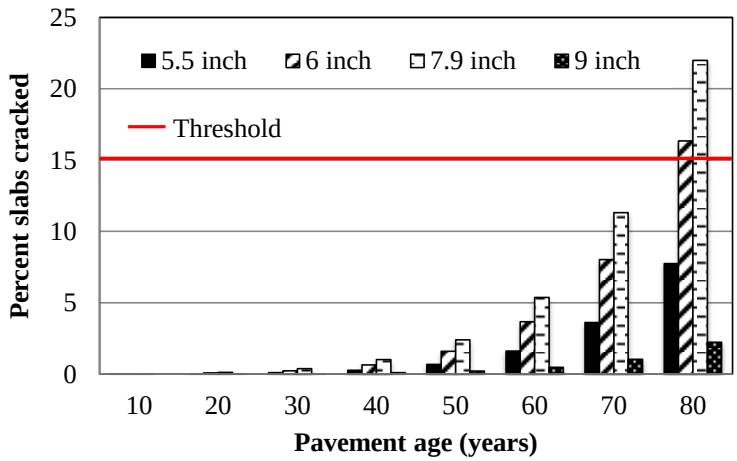


Figure 3-4 Effect of pavement thickness on distress when analyzed until failure

3.6 LAYER STRUCTURE IN COMPOSITE PAVEMENTS

The MSU research team encountered several issues when performing the validation of composite pavements. The MEPDG (version 1.1) software would stop working when the existing base and subbase layers were beyond a certain thickness. It is critical that the most representative section needs to be used in order to provide the most accurate validation results. However, this issue did not occur in the DARWin-ME and the actual pavement cross-sections were used.

3.7 USE OF FWD IN THE MEPDG/DARWIN-ME

The rehabilitation options available in the MEPDG/DARWin-ME suggest using falling weight deflectometer (FWD) deflection data to backcalculate the existing pavement layer moduli. The FWD information is used to characterize the existing condition of both flexible and rigid pavements. This section outlines the needs for FWD testing in the MEPDG/DARWin-ME.

3.7.1 Flexible Pavements

3.7.1.1. HMA

For new HMA pavements, the various input levels used to characterize the properties of the HMA layer is documented in the literature review. The dynamic modulus (E^*) is the most important parameter to characterize the HMA pavement layer. While FWD testing is not necessary for newly designed HMA pavements, such testing is highly recommended for rehabilitation design because it provides a better estimate of the existing in-situ conditions.

Based on backcalculated modulus, the damaged E^* master curve for rehabilitation design is determined for various input levels as mentioned below (*4*):

- For level 1 input, the MEPDG/DARWin-ME requires the following procedure:
  1. Conduct FWD tests in the outer wheelpath and determine the backcalculated HMA modulus. Record the HMA layer temperature at the time of testing and determine the layer thickness from coring or ground penetrating radar testing.
  2. Determine HMA mix volumetric and asphalt viscosity parameters from cores.
  3. Develop an undamaged E^* mastercurve using the modified Witczak equation and the data from step 2 at the same temperature recorded in the field and at an equivalent frequency corresponding to the FWD pulse duration.
  4. Estimate the fatigue damage in the HMA layer using the damaged E^* obtained from step 1 and the undamaged E^* from step 3.
  5. Calculate $\alpha' = (1 - d_{ac})\alpha$; where α is a function of mix gradation parameters.
  6. Determine the field-damaged E^* mastercurve using α' instead of α.
- For levels 2 and 3 inputs, FWD testing is not required.

It should be noted that based on steps 1 and 2, the MEPDG/DARWin-ME software determines the damaged E^* mastercurve using steps 3 through 6.

3.7.1.2. Unbound materials

The DARWin-ME flexible pavement rehabilitation design characterizes the unbound material as follows:

- For level 1 Rehabilitation
  - The backcalculated resilient modulus for each unbound layer (including the subgrade) is used as a direct input
- Otherwise
  - Level 2 input consists of correlations with strength data
  - Level 3 input consists of typical modulus values for different soil classifications

3.7.2 Rigid Pavements

The input parameters needed for the design of an overlay on top of a PCC pavement using the MEPDG/DARWin-ME that can be determined from FWD data. These inputs are: (a) elastic modulus of the existing PCC and base layers, (b) the subgrade k-value, and (c) the PCC flexural strength. The following recommendations need to be considered when determining these inputs based on FWD data.

Effective k-Value

As previously discussed, the suggested method for characterizing the in-situ subgrade condition in the MEPDG/DARWin-ME is by backcalculating the effective k-value, which represents the stiffness of all layers beneath the base. It is important to correctly enter in the

other material characterization properties, such as the gradations of these layers, because this information is used along with the EICM to estimate the seasonal effects on the k-value. When entering the k-value, the designer must also enter the month in which the k-value was measured. Seasonal corrections are then applied to the k-value based on the moisture conditions predicted through the EICM.

It is important to note that the subgrade k-value determined from backcalculation of FWD data is a dynamic k-value, which may be two to three times higher than a static value (*4*).

PCC Elastic Modulus

The elastic modulus of the existing slab must be determined for overlay designs. The elastic modulus can be determined by taking a core and measuring the chord modulus based on ASTM C 469 or by using FWD data to backcalculate the modulus. A backcalculated modulus must be multiplied by 0.8 to convert from a dynamic to a static elastic modulus (*4*).

For an unbonded overlay, the static elastic modulus of the PCC pavement that is determined using backcalculation or laboratory testing must be adjusted to reflect the overall condition of the pavement. The modulus is adjusted based on the condition of the pavement by multiplying it by the appropriate condition factor. Condition factors for a range of pavement conditions are provided in the explanation of Equation (2) in Chapter 2.

3.7.3 Composite Pavements

The MEPDG evaluates HMA/PCC pavements in two steps. First, the pavement system is analyzed as a rigid pavement to model continued cracking of the underlying PCC pavement. The HMA distresses are then modeled, including thermal cracking, fatigue cracking, and rutting, as well as IRI. For a HMA overlay on existing PCC, the key input parameters for this analysis obtained from FWD data are the subgrade *k*-value, E_{PCC}, and PCC modulus of rupture. Although, the PCC modulus of rupture can be estimated from backcalculated E_{PCC} using an empirical correlation (*4*), limited core testing is highly recommended to verify the values.

The backcalculation results for HMA/PCC pavements may contain greater variability than those for other pavement types, largely because the data may contain the results for tests conducted over joints or cracks in the underlying PCC pavement. For valid results, the locations of the joints in the underlying pavement should be identified and the testing conducted should be performed at mid-slab. Any significant deviations from the representative values may be an indication that the testing was conducted too close to underlying cracks or joints, and those results should be excluded in determining the average *k* and *E* values. For the evaluation of the structural adequacy of the underlying PCC pavement, the elastic modulus determined over the intact portion of the slab is needed.

The composite pavements in the MEPDG/DARWin-ME include: (a) HMA over PCC, and (b) PCC over HMA. In the first case when PCC is the existing pavement, the MEPDG/DARWin-ME allows the dynamic backcalculated *k*-value to be entered directly. Both the representative *k*-value and month of testing are needed. However, the backcalculated *k*-value is an optional input; the user is still required to enter resilient moduli for all unbound layers and subgrade. The MEPDG/DARWin-ME processes the input as usual (similar to new design) and determines the seasonal *k*-values based on EICM results and

using the E-to-*k* conversion procedure. For the second case when HMA is the existing pavement, the seasonal resilient moduli are used, but no adjustment is made to account for any difference between the *k*-value from the E-to-*k* conversion process and the backcalculated *k*-value.

3.7.4 Summary of FWD Data Usage in the MEPDG/DARWin-ME

Table 3-2 summarizes the use of deflection data for different existing pavements in the rehabilitation option for the MEPDG/DARWin-ME. The procedure outlines information necessary to determine the measure outside/inside of the MEPDG/DARWin-ME for all existing pavement types.

Table 3-2 Use of deflection data in the MEPDG/DARWin-ME (*5*)

Existing Pavement Layer	Measure	Procedure
All pavement types	Determine pavement condition uniformity.	• Evaluate deflections (e.g., using center deflection or deflection basin parameter) over length of project to determine if subsection is necessary subsections may require different overlay thicknesses based on level of deflection/distress).
HMA	Dynamic modulus, E_{HMA}	• Backcalculate existing (damaged) layer moduli (E_{dam}) from deflection testing. • Determine undamaged layer moduli (E^*) through laboratory testing of field cores. • ***Calculate damage factor (d_{ac}).*** • ***Determine α'.*** • ***Determine field master curve for existing layer, adjust for rate of loading and surface temperature at time of NDT testing.***
PCC	Elastic modulus, $E_{BASE/DESIGN}$	• Backcalculation of PCC-layer modulus (E_{TEST}). • Multiply E_{TEST} by 0.8 to convert from a dynamic to a static elastic modulus. • Determine condition of existing pavement and select a pavement condition factor (C_{BD}) • Calculate $E_{BASE/DESIGN} = (C_{BD})(E_{TEST})$.
	PCC flexural strength, E_c	• MEPDG highly recommends laboratory testing of field obtained beams or correlation with splitting tensile strength from cores for JPCP; and indirect tensile strength for CRCP.
	Effective k-value	• Use backcalculation procedures that directly produce the effective dynamic k-value. k-value determination by rehabilitation strategy • HMA over HMA – not used in MEPDG. • Bonded PCC overlay – backcalculated k-value can be used directly if existing PCC is on a stabilized base. For PCC over unstabilized base, use PCA method to negate the effects of the unstabilized base (PCA 1984). In addition, select a typical value for the base elastic modulus if unstabilized, and if stabilized, use the method proposed by Ioannides and Khazanovich (1994). • Unbonded PCC overlay – use same procedure as outlined for bonded PCC overlay. • PCC overlay of HMA – determine existing layer moduli as described for HMA pavements.

Table 3-2 Use of deflection data in the MEPDG/DARWin-ME (*5*) (Continued…)

PCC	Joint (LTE)	• LTE is not an MEPDG input; however, it can be used for determining the need for retrofit dowels in JPCP and controlling punchout-related longitudinal cracking.
	Loss of support under corner (void detection)	• The presence of voids is not a direct input for the MEPDG; however, the MEPDG assumes that voids are addressed prior to overlay placement.
Chemically stabilized materials (lean concrete, cement stabilized base, lime/cement/flyash stabilized soils)	Modulus E_{CTB}	• Backcalculate existing (damaged) layer moduli (E_{CTB}) from deflection testing. If layer is less than 150 mm (6 in) in depth, backcalculation may be problematic and laboratory testing to determine layer moduli may be required. • Determine intact modulus (E_{max}) of intact (undamaged) cores from compressive strength testing. • Determine damage level (d_{CTB}). • Adjust E_{CTB} for layer and surface condition.
Unbound Materials	Resilient modulus, M_R	• Backcalculate existing layer modulus (E_R) from deflection testing. • Apply modulus ratio (M_R/E_R) to adjust backcalculated to laboratory-obtained values. MEPDG suggests adjustment factors of 0.40 for subgrade soils and 0.67 for granular bases and subbases

3.8 LABORATORY VERSUS BACKCALCULATED MODULI

In terms of potential compatibility between field derived and laboratory measured parameters for the HMA material, it can be stated that fundamentally, field FWD test results and the indirect tensile test (IDT) results under haversine pulse loading should be similar. In addition, assuming that the boundary conditions are appropriately defined, the moduli values from lab and field testing should be similar, provided that (*6*):

1. The pulse duration is the same in both tests;
2. The effective temperature of the HMA mix is the same;
3. The effect of confinement is minimal;
4. The effect of anisotropy is minimal;
5. The effect of loading mode (compression versus tension) is minimal.
6. The effect of the backcalculation technique (in terms of the effect of error propagation in the inverse problem from other backcalculated layer moduli, namely, subgrade and base/subbase layers) is minimal.

The first two issues (pulse duration and temperature) are believed to be the most important in explaining the difference between laboratory and field derived HMA moduli using the current test protocols: (1) the pulse duration in the field is typically 0.035 sec to 0.050 sec, whereas it is 0.1 sec in the standard resilient modulus (MR) test (AASHTO P31, NCHRP 1-28A, and ASTM 4123); (2) the HMA temperature in the field is variable, and is therefore generally different from the standard MR test temperature in the laboratory.

Based on the current practices used to characterize the existing pavement materials, there is a need to determine fundamental material properties. These are the relaxation modulus, *E(t)*, for the HMA and the stress-dependent elastic moduli for base and subgrade layers.

3.9 SELECTION OF APPROPRIATE FREQUENCY FOR BACKCALCULATED MODULUS

It should be noted that since the MEPDG/DARWin-ME uses the dynamic modulus (as opposed to the resilient modulus), it assumes that the ratio of backcalculated to laboratory-measured HMA modulus is one as long as the HMA mixture is identical and the equivalent loading frequency is the same. The equivalent frequency is essentially the dominant frequency imposed by a loading pulse of certain duration. In reality, a transient pulse contains a spectrum of frequencies, so the equivalent frequency is an attempt to determine the one frequency that would best represent the frequency spectrum or the dominant range of frequencies. This equivalent loading frequency is taken as the inverse of the FWD load pulse duration, or 1/t; i.e., for a 33 ms FWD pulse load, the equivalent frequency is taken as 30 Hz. It has been reported that this equivalency frequency is incorrect, and that a more reasonable equivalent frequency should be about 1/2t, or 15 Hz in this example (*4*). For level 1 rehabilitation in flexible rehabilitation options, the software needs direct user input for the backcalculated modulus, temperature and frequency. Therefore, the load pulse of the MDOT FWD equipment should be used to calculate the frequency based on the $f = \frac{1}{2t}$.

3.10 FWD TESTING GUIDELINES

The guidelines discussed in the following section are related to the physical testing equipment configuration (such as sensor locations and load levels) as well as the type and location of deflection data that are obtained during FWD testing (*5*). A recent FHWA study outlined the overall testing procedures and guidelines for flexible and rigid pavements. These guidelines are related to the following aspects of FWD testing:

- Sensor configuration
- Number of drops and load levels
- Testing locations
- Testing increments
- Temperature measurements
    - Air and surface temperature
    - Temperature gradient
- Joint/Crack opening
- Safety guidelines

Table 3-3 summarizes the recommended FWD testing guidelines for both HMA and PCC pavements.

Table 3-3 Recommended FWD testing guidelines (*5*)

Testing Component	Recommendation								
Sensor Configuration (mm):	0	207	305	457	610	914	1219	1524	-305
(in):	0	8	12	18	24	36	48	60	-12
Load level, kN (kips)	Seating			26.7 (6)		40 (9)		53.4 (12)	
Number of drops									
HMA	1			1		1		1	
PCC	1			---		1		1	
Testing locations	Testing in outer traffic lane on multiple lane facilities. Possible directionally staggered testing on two-lane facilities								
HMA	Mid-lane and outer wheelpath								
PCC	Mid-lane, outer wheelpath and transverse joint								
Testing increments	12 to 15 tests per uniform pavement section								
General testing	30 to 150 m (100 to 500 ft)								
Project level	7.6 to 15.2 m (25 to 50 ft)								
Temperature measurements									
Air and surface	Measured at each test location								
Gradient	Measured during testing at 1-hour intervals								
Depth, mm (in)	25 (1)		50 (2)		100 (4)		200 (8)		300 (12)

CHAPTER 4 - REHABILITATION SENSITIVITY ANALYSES

4.1 INTRODUCTION

As outlined in Chapter 2, the MEPDG/DARWin-ME offers several different design options for flexible and rigid pavement rehabilitation. Based on discussions with the MDOT Research Advisory Panel (RAP), rehabilitation fixes used by MDOT were identified and are summarized in Table 4-1. Currently, MDOT does not construct any continually reinforced concrete pavement (CRCP); however, the CRCP options in the MEPDG/DARWin-ME are considered in the preliminary sensitivity analysis only.

Table 4-1 MDOT Rehabilitation options

Asphalt Concrete Overlay	PCC Overlay
AC over AC	JPCP over JPCP (unbonded)
AC over JPCP	
AC over JPCP (Fractured)	

This chapter summarizes the sensitivity analyses for the rehabilitation design options in the MEPDG according to Task 2-3 of the approved work plan. The main objective of this task was to evaluate the impact of inputs specific to various rehabilitation options on the predicted pavement performance. To accomplish this goal, the following analyses techniques were performed:

1. Preliminary sensitivity
2. Detailed sensitivity
3. Global sensitivity

Each methodology has a unique contribution to the overall understanding in determining the impact of design inputs on the predicted pavement performance. The outcome of the preliminary sensitivity is the identification of the significant inputs related to the existing pavement layers. Subsequently, these inputs were combined with the significant inputs for the new pavement layer (overlay) identified in the previous MDOT study (*1*) to conduct the detailed sensitivity. The outcome from the detailed sensitivity analyses include the significant main and interactive effects between the inputs related to the existing and overlay layers.

Finally, the global sensitivity analysis was performed based on the results from the detailed sensitivity analysis. The GSA is more robust because of the following reasons:

a. Main and interaction results are based on the entire domain of each input variable.
b. The importance of each input can be quantified using the Normalized Sensitivity Index (NSI).
c. Relative importance of each design input can be determined.

The details of each sensitivity type are presented in this chapter.

4.2 PRELIMINARY SENSITIVITY ANALYSIS

While the AASHTO 1993 Design Guide requires limited data information for the structural design of pavements, the MEPDG pavement analysis and design procedure requires a large number of design inputs related to layer materials, environment, and traffic. Ideally all the input variables should be studied together to determine their impacts on the predicted pavement performance (*2*). However, performing such an analysis including all these input variables is not efficient. Therefore, in this study the inputs specific to rehabilitation options in the MEPDG were considered along with some important inputs related to the new pavement layer.

In order to further reduce the list of important input variables, a preliminary sensitivity analysis was performed. Results of the analysis were used to identify sensitive and non-sensitive inputs for various rehabilitation options and predicted pavement performance types. Subsequently, the significant input variables identified through preliminary analysis are included in detailed and global sensitivity analyses for further evaluations. The MEPDG design inputs in rehabilitation modules can be divided into two categories:

a. Inputs that are specific to rehabilitation modules and are not part of new design, and
b. Inputs that are similar to new pavement design and are addressed in previous studies (*1, 3*).

The preliminary sensitivity analysis was performed for the current Michigan rehabilitation practices as presented above. The methodology and the results are discussed below for each rehabilitation option.

4.2.1 HMA over HMA Analysis and Results

Only level 3 design inputs specific to rehabilitation for HMA overlays were considered in this analysis (see section 4.4.1.2 to see reasons for using level 3 design inputs):

- milled thickness,
- total rutting in the existing pavement, and
- existing pavement condition rating

The design inputs for characterizing the existing HMA pavement are shown in Table 4-2. Practical ranges for the inputs were needed for the sensitivity analysis and these ranges were determined in consultation with MDOT and the Long-term Pavement Performance (LTPP) experiments as shown in Table 4-2.

Table 4-2 Design inputs for HMA over HMA

Input	Min	Base case	Max
Existing thickness (in)	2.5	6	12
Existing rating	Very poor	Fair	Excellent
Milled thickness (in)	1.5	2	3.5
Total rutting in existing (in)	0	0.5	1
Binder type	Mix 24	Mix 37 & 44	Mix 204
Asphalt mix aggregate gradation	Type 1	Type 2	Type 3

It should be noted that the inputs used in this analysis correspond to MDOT practices. For example, mixtures 24, 37 and 44 in Table 4-2 are surface courses while mixture 204 is a leveling course. The properties of these mixture numbers are explained in the Part 1 final report (*4*). The aggregate mix gradations were plotted, and the extreme bands (i.e. the upper and lower band) of the gradations were selected as the minimum and maximum of the range.

The base traffic and pavement structure for analysis are presented in Table 4-3. More details about aggregate gradation, and mix types are presented in Appendix A.

Table 4-3 HMA over HMA base case

Traffic		
AADTT	3500	20.18 million ESALS*
Other traffic data	Level 3 Statewide averages	
Climate	Lansing	
Layer properties		
Structure (layers)	Material	Thickness
1-Asphalt layer	HMA	6
2-Existing asphalt layer	HMA (existing)	6
3-Granular base	A-1-b	10
4-Subgrade	A-4	semi-infinite

* Internally estimated 20 years ESAL by the MEPDG using the default axle load spectra. The higher AADTT was used to ensure some level of distresses for sensitivity analysis.

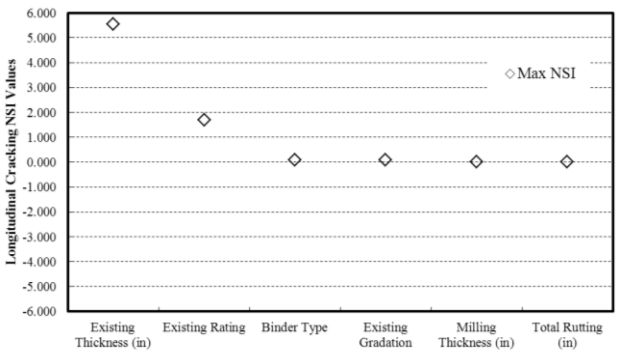
To evaluate the effect of the design inputs on the predicted pavement distresses, the inputs were varied one at a time over their ranges. Based on the predicted distress (longitudinal cracking, alligator cracking, total rutting, and IRI), the Normalized Sensitivity Index (NSI) was calculated for each input-distress combinations using Equation (1) in Chapter 2. The inputs were ranked based on the NSI (absolute) magnitude. Table 4-4 shows the calculated NSI values and Figure 4-1 presents NSI values for all inputs. An input variable with absolute NSI value greater than one was identified as a significant input. It can be seen from the results in Table 4-4, that existing pavement condition rating and existing pavement thickness are important inputs for longitudinal cracking prediction.

In addition, to verify the effect of the existing pavement condition rating, the predicted distresses at the end of pavement life were evaluated as shown in Figure 4-2. Results were compared with the threshold values shown with red dotted line. It should be noted that all distresses must be compared to the performance threshold to evaluate the significance of an input. Figure 4-2 visually shows the impact of significant inputs on the predicted performance.

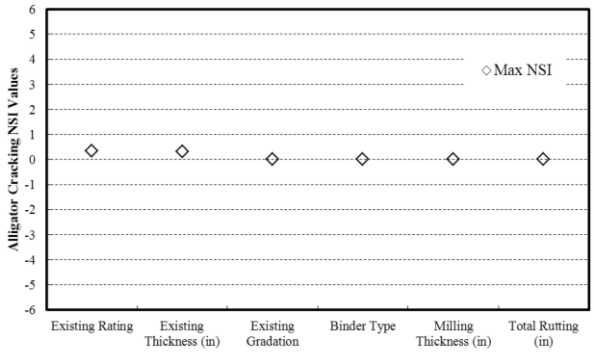
Table 4-4 Summary of NSI values for each design input for HMA overlay

Input	Longitudinal cracking	Alligator cracking	Total rutting	IRI
	Maximum NSI	Maximum NSI	Maximum NSI	Maximum NSI
Existing gradation	0.04	0.01	0	0
Milling thickness	0.01	0	0.01	0
Binder type	0.08	0.01	0	0
Existing condition rating	1.69	0.34	0.01	0.01
Existing HMA thickness	5.56	0.32	0.15	0.05
Total surface rutting	0	0	0.21	0.049

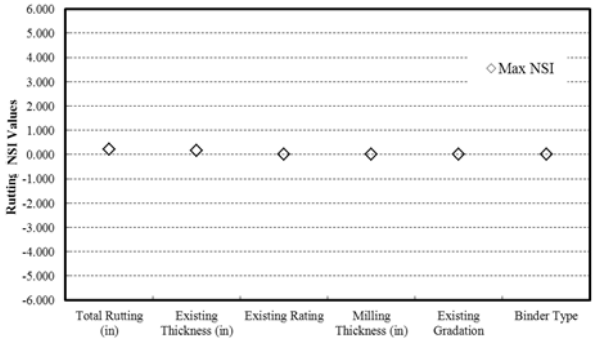
Note: Highlighted cells indicate the significant design inputs (|NSI| >1). The absolute NSI values are reported in the table.



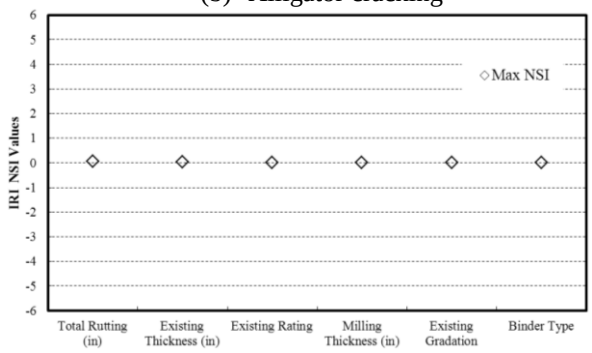
(a) Longitudinal Cracking



(b) Alligator cracking

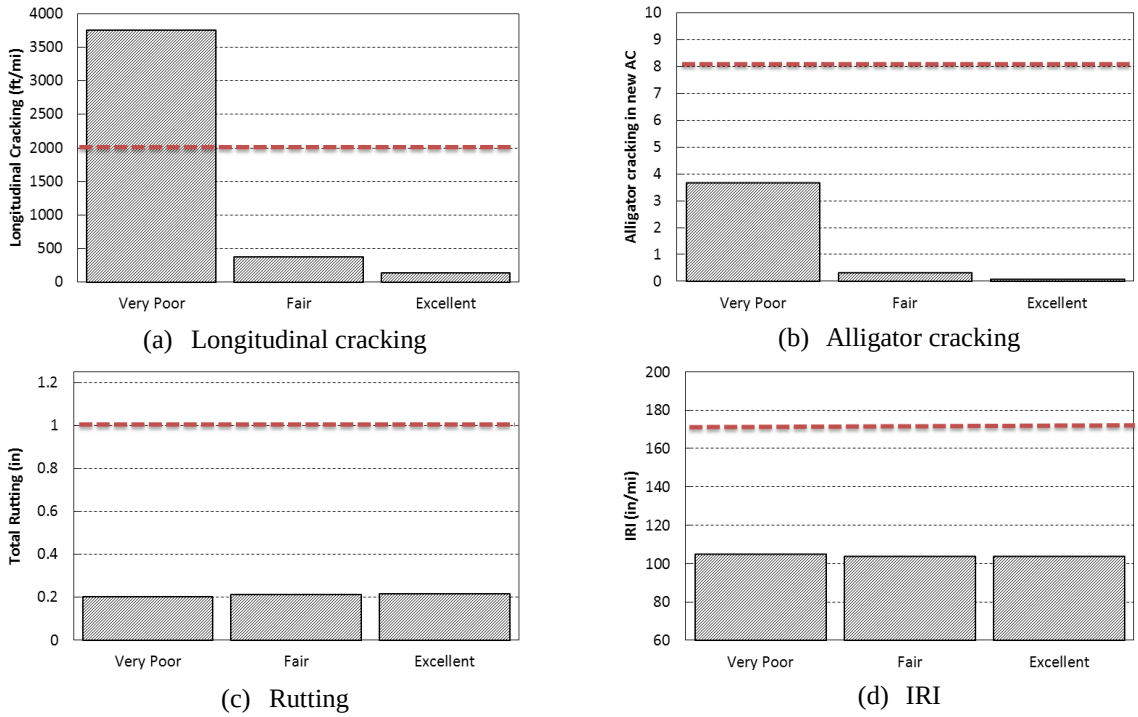


(c) Rutting



(d) IRI

Figure 4-1 NSI plots for HMA overlay



(a) Longitudinal cracking (b) Alligator cracking

(c) Rutting (d) IRI

Figure 4-2 Overlay distresses for HMA over HMA based on different levels of existing pavement condition rating at 20th year

It should be noted that reflective cracking was not included in the results. In the MEPDG software, the empirical reflective cracking model is not accessible. For example, the software does not allow the user to define a design limit (or threshold) for reflective cracking. Additionally, the transverse cracking model predicts minimal cracking when the appropriate binder grade is selected. The binder types for the analyses were selected based on MDOT practices. In order to induce more transverse cracking, binders 2 to 3 grades warmer should be used in the sensitivity analysis (*3*). In this study no thermal cracking was observed because of appropriate PG binder grade selection. Therefore, thermal cracking was not predicted by the model and no further analysis could be conducted on thermal cracking.

4.2.2 Composite (HMA over JPCP) Analysis and Results

Table 4-5 presents the list of inputs needed to characterize the existing pavement for the composite rehabilitation option in the MEPDG. Input ranges were determined in consultation with MDOT and using LTPP databases. Table 4-6 shows the traffic and pavement structure for the base case.

Table 4-5 Input variable values for composite pavements

Input variable	Min	Base case	Max
PCC existing thickness (in)	7	9	11
PCC existing strength (psi)	450	550	900
PCC CTE (per °F x 10^{-6})	4	5.5	7
Cement content (lb/yd^3)	402	556	686
Water/cement ratio	0.3	0.47	0.7

Table 4-6 Composite pavement base case

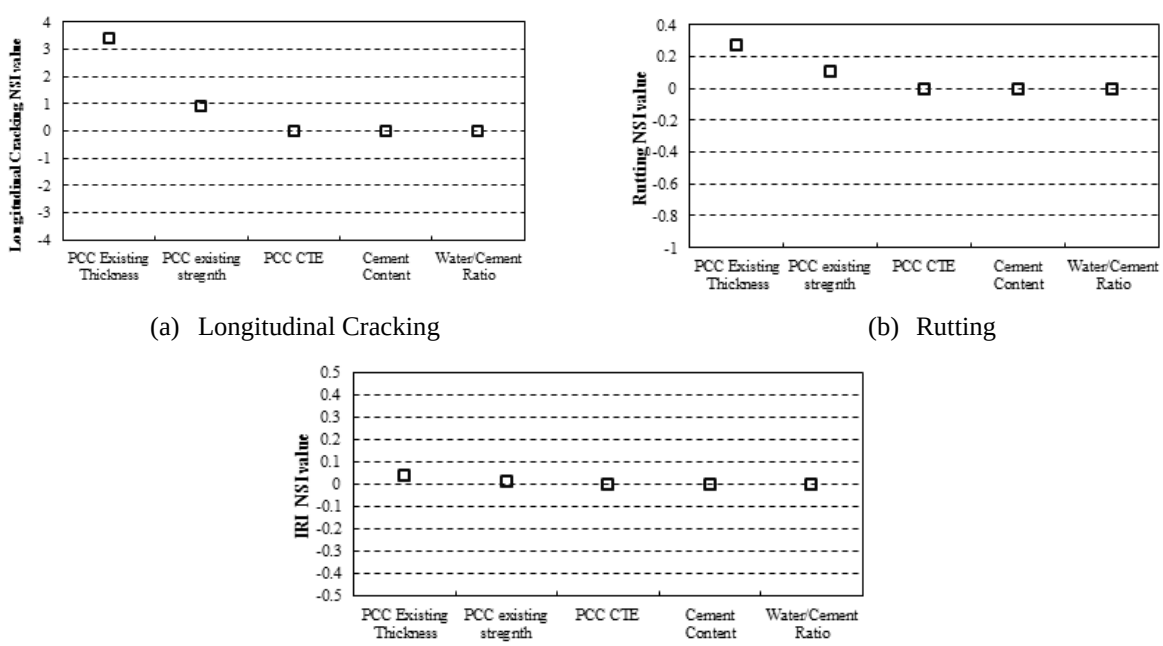
Traffic		
AADTT	15000	86.49 million ESALs*
Other traffic data	Level 3 Statewide averages	
Climate	Lansing	
Layer properties		
Structure (layers)	Material	Thickness (in)
1 - Surface layer	HMA	6
2 - Existing pavement	PCC	9
3 - Base	Crushed stone	7
4 - Subgrade	A-4	semi-infinite

* Internally estimated 20 years ESAL by the MEPDG using the default axle load spectra. The higher AADTT was used to ensure some level of distresses for sensitivity analysis.

Table 4-7 summarizes the calculated NSI for different performance measures. Figure 4-3 illustrates the calculated NSI values for various inputs and different distresses. The data in the figure indicate that only the existing PCC slab has a significant effect on predicted longitudinal cracking. The existing PCC thickness and PCC flexural strength (MOR) were considered for use in the subsequent analysis. It should be noted that no alligator cracking was predicted in this case. This is consistent with expectations, given the stiff underlying PCC base.

Table 4-7 Summary of NSI values for each design input for composite pavement

Input	Longitudinal cracking	Rutting	IRI
	Maximum NSI	Maximum NSI	Maximum NSI
Existing PCC thickness	3.40	0.37	0.04
Existing PCC flexural strength	0.90	0.14	0.01
PCC CTE	0	0	0
Cement content	0	0	0
Water/cement ratio	0	0	0



(a) Longitudinal Cracking

(b) Rutting

(c) IRI

Figure 4-3 NSI plots for composite pavements

4.2.3 Rubblized (HMA over Fractured PCC) Pavement Analysis and Results

Table 4-8 presents the range of existing pavement inputs that are specific to this rehabilitation option. The base case traffic and pavement structure information are presented in Table 4-9. As mentioned before, the inputs for the overlay layer will be held constant in order to determine the significant inputs specific to the existing pavement layers.

Table 4-8 Input variable values for rubblized pavement

Input Variable	Min	Base case	Max
Existing rubblized PCC thickness (in)	7	9	11
Existing rubblized PCC elastic modulus (psi)	200,000	400,000	1,500,000

Table 4-9 Base case values for rubblized pavement analysis

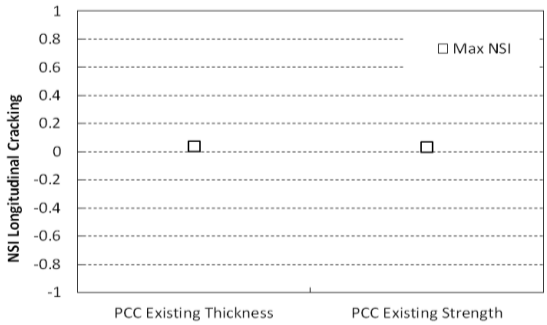
Traffic		
AADTT	15,000	86.49 million ESALs*
Other traffic data	Level 1: Statewide averages	
Climate	Lansing	
Layer properties		
Structure (layers)	Material	Thickness (in)
1 - Surface layer	AC	6
2 - Existing pavement	PCC (fractured)	9
3 - Base	Crushed stone	7
4 - Subgrade	A-4	semi-infinite

* Internally estimated 20 years ESAL by the MEPDG using the default axle load spectra. The higher AADTT was used to ensure some level of distresses for sensitivity analysis.

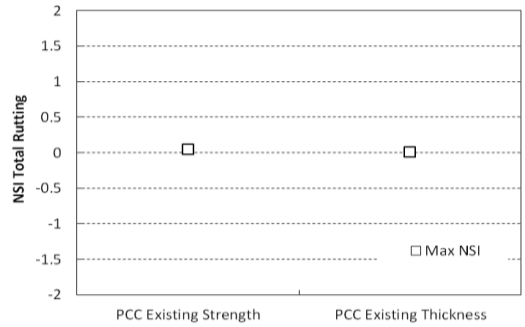
For this rehabilitation option, no input variable related to the existing pavement condition is needed. Therefore, only input variables for characterization of the existing materials and thickness were included in the analysis. Table 4-10 shows the NSI values for different performance measures and these values were plotted in Figure 4-4. Similar to composite pavements, no alligator cracking was predicted. Based on the NSI values, it was determined that the existing fractured PCC thickness and elastic modulus don't significantly affect the predicted performance. Nevertheless, they were still considered for subsequent analysis to study their interactions with overlay design inputs.

Table 4-10 Summary of NSI values for each design input for rubblized pavements

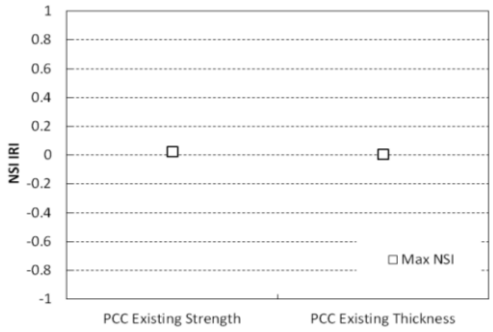
Input	Longitudinal cracking	Rutting	IRI
	Maximum NSI	Maximum NSI	Maximum NSI
PCC Existing thickness	0.04	0.01	0.01
PCC Existing strength	0.03	0.05	0.02



(a) Longitudinal Cracking



(b) Rutting



(c) IRI

Figure 4-4 NSI plots for rubblized

4.2.4 Unbonded PCC overlay Analysis and Results

The basic structure of an unbonded overlay cross-section is shown in Figure 4-5. For unbonded overlay design, an interlayer needs to be considered. The separator (or interlayer) layer consists of an asphalt material that breaks the bond between the existing PCC layer and the new overlay.

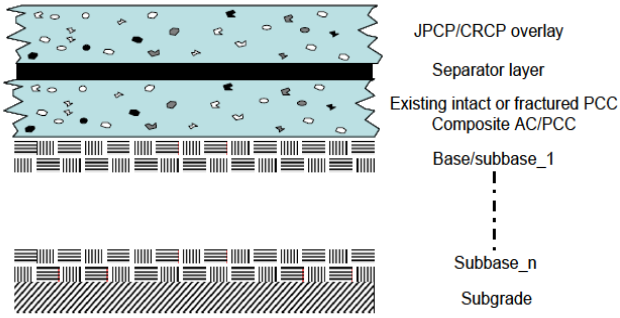


Figure 4-5 Typical unbonded overlay cross section (*5*)

The inputs specific to the asphalt interlayer include:

- Interlayer asphalt mixture data
  - Level 1: Complete dynamic modulus data (E*)
  - Level 2 & 3: Aggregate gradation
- Asphalt Binder data

    - Level 1 & 2: G* and δ values at specific temperatures and angular frequencies
    - Level 3: Select the high and low temperature PG grade
- General asphalt properties
    - Reference temperature
    - Effective binder content
    - Air voids
    - Total unit weight
    - Poisson's ratio
    - Thermal conductivity
    - Heat capacity

Another input specific to rehabilitation design is the foundation support. The dynamic modulus of subgrade reaction (k-value) can be selected as a standalone input within the unbonded overlay rehabilitation option. To characterize the existing pavement, the existing PCC elastic modulus, and PCC thickness were included in the analysis. For existing PCC modulus and thickness, the software gives a range from 200,000 to 5,000,000 psi and 1.5 to 20 inch, respectively. However, due to the software issues discussed in Chapter 3, the inputs and their range used for the analysis were limited to the minimum and maximum values that the software allows, and are shown in Table 4-11. The inputs in Table 4-11 are only related to pavement structure and strength properties of the existing PCC layer and asphalt interlayer in the MEPDG. The base case traffic and pavement structure are presented in Table 4-12.

Table 4-11 List of input variables for unbonded overlay option

Main input	Min	Base case	Max
Interlayer thickness (in)	1	2	3
Interlayer PG grade	Mix 37	Mix 24	Mix 204
Existing thickness (in)	7	9	11
Existing elastic modulus (psi)	500000	1000000	3000000

Table 4-12 Base case values for unbonded overlay

Site Factors		
AADTT	3500	20.18 Million ESALS*
Other traffic data:	Level 1: Statewide averages	
Climate	Lansing	
Layer Properties		
Structure (layers)	Material	Thickness (in)
1-PCC	PCC	9
2-Asphalt interlayer	HMA	1.5
3-Existing PCC	JPCP (existing)	9
4-Granular base	Crushed stone	7
5-Subgrade	A-4	semi-inf

* Internally estimated 20 years ESAL by the MEPDG using the default axle load spectra. The higher AADTT was used to ensure some level of distresses for sensitivity analysis.

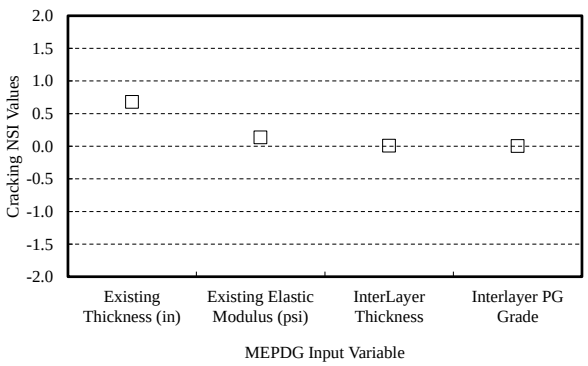
Table 4-13 summarizes the maximum calculated NSI for all of the distresses. The NSI values close or larger than 1 in Table 4-13 show the significant inputs. The NSI values

are graphically displayed in Figure 4-6 for all inputs related to both existing and overlay layers.

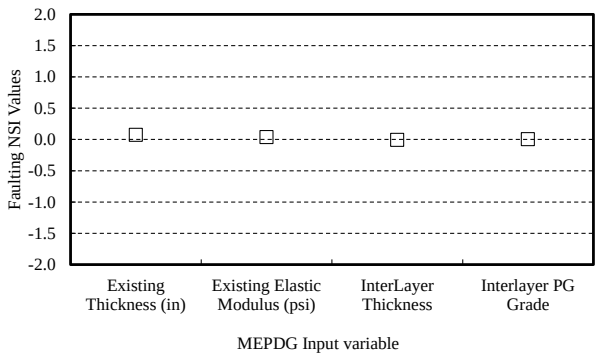
Table 4-13 Summary of NSI values for each design input for unbonded overlay

Input	Cracking	Faulting	IRI
	Maximum NSI	Maximum NSI	Maximum NSI
Existing thickness	1.41	0.07	0.16
Existing elastic modulus	0.68	0.04	0.09
Interlayer thickness	0.14	0.01	0.08
Interlayer PG grade	0.01	0	0

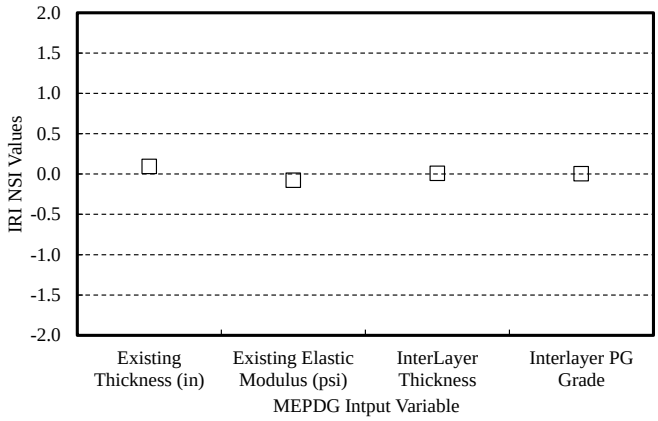
Note: Inputs related to existing pavements are only shown in the table.



(a) Cracking



(b) Faulting



(c) IRI

Figure 4-6 NSI plots for unbonded overlay

4.2.5 CRCP over HMA

Table 4-14 presents the range of existing pavement inputs for this rehabilitation option. The base case traffic and pavement structure information are presented in Table 4-15. As mentioned before, the inputs for the overlay layer were held constant in order to determine the significant inputs specific to the existing pavement layers. Again, mixtures 24, 37 and 44

in Table 4-14 are surface courses. The properties of these mixture numbers are explained in the Part 1 final report (*4*) .

Table 4-14 Input variable values for CRCP over HMA pavement

Input variable	Min	Base case	Max
Existing Gradation	Type 1	Type 2	Type 3
Milling Thickness (in)	0	3	4
Binder Type	Mix 37	Mix 24	Mix 44
Existing Rating	Very Poor	Fair	Excellent
Existing Thickness (in)	2	6	12
Ultimate Shrinkage (days)	30	35	50

Table 4-15 Base case values for CRCP over HMA pavement analysis

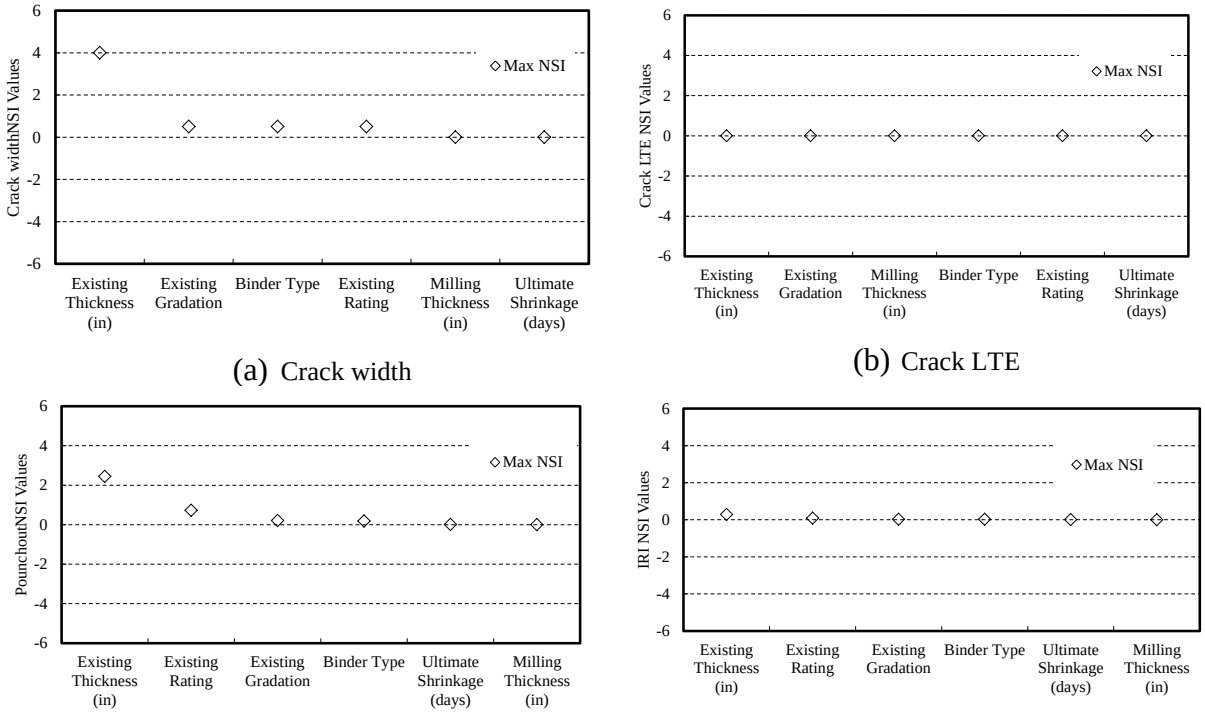
Site Factors		
AADTT	3,500	20.18 million ESALs*
Other traffic data	Level 1: Statewide averages	
Climate	Lansing	
Layer properties		
Structure (layers)	Material	Thickness (in)
1 - PCC	PCC (CRCP)	7
2 - Asphalt interlayer	AC	6
3 - Base	Crushed gravel	5
4 - Subgrade	A-7-6	semi-infinite

* Same as Table 4-3

Table 4-16 shows the NSI values for different performance measures and these values were plotted in Figure 4-7. Based on the NSI values, it was determined that the existing HMA thickness affects the predicted performance significantly.

Table 4-16 Summary of NSI values for each design input for CRCP over HMA pavements

Input	Crack width	Crack LTE	Punchout	IRI
	Max NSI	Max NSI	Max NSI	Max NSI
Existing gradation	0.50	0.00	0.21	0.02
Milling thickness (in)	0.00	0.00	0.00	0.00
Binder type	0.50	0.00	0.18	0.02
Existing rating	0.50	0.00	0.72	0.08
Existing thickness (in)	4.00	0.00	2.45	0.28



(a) Crack width

(b) Crack LTE

(c) Punchout

(d) IRI

Figure 4-7 NSI plots for CRCP over HMA

4.2.6 CRCP over JPCP

Table 4-18 presents the range of existing pavement inputs for CRCP over JPCP. The base case traffic and pavement structure information are presented in Table 4-17. As mentioned before, the inputs for the overlay layer were held constant in order to determine the significant inputs specific to the existing pavement layers.

Table 4-17 Base case values for CRCP over JPCP pavement analysis

Site factors		
AADTT	10000	
Other Traffic Data	Level 1: Statewide Averages	
Climate	Lansing	
Layer properties		
Structure (layers)	Material	Thickness (in)
1 - Surface Layer	CRCP	7
2 - AC Interlayer	AC	2
3 - Existing Pavement	PCC JPCP	9
4 - Base	Crushed Stone	7
5 - Subgrade	A-4	semi-inf

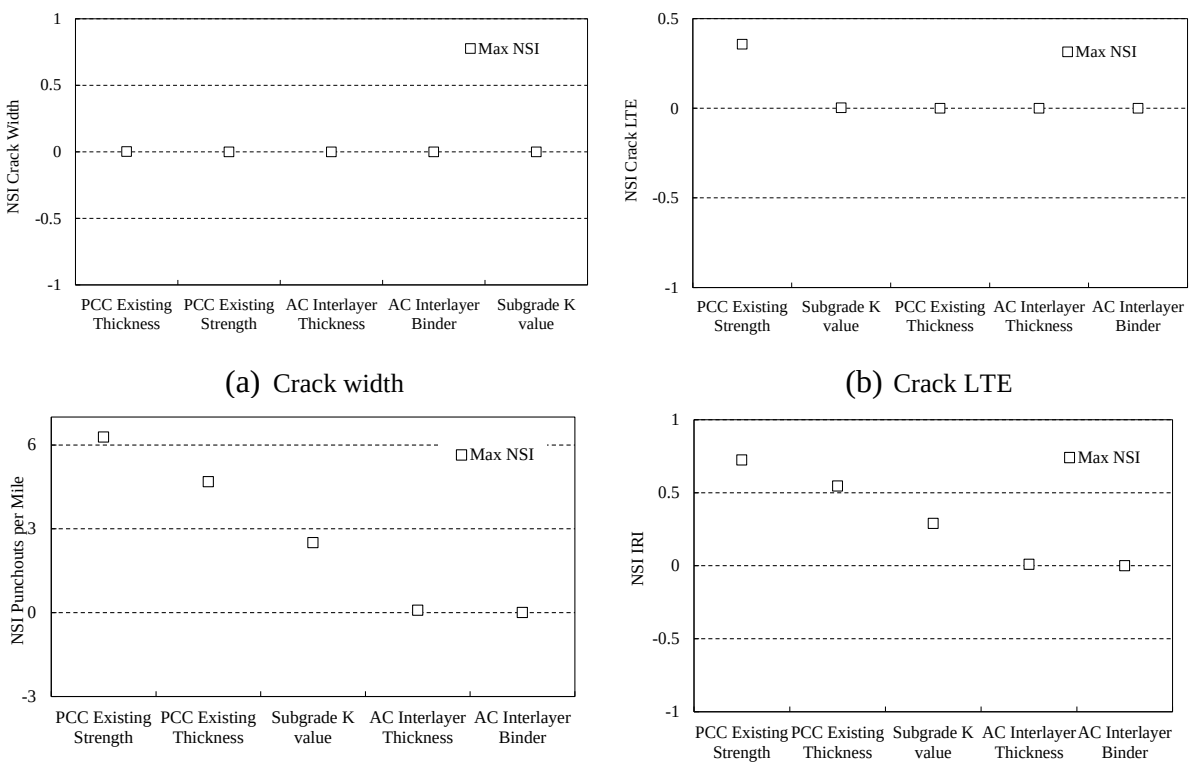
Table 4-18 Input variable values for CRCP over JPCP pavement

Input Variable	Min	Base case	Max
PCC Existing Strength (psi)	500000	1000000	3000000
PCC Existing Thickness (in)	7	9	11
AC Interlayer Thickness (in)	1	2	4
AC Interlayer Binder	52-10	PG 58-22	64-28
Subgrade K value (psi/in)	100	250	400

Table 4-19 shows the NSI values for different performance measures and these values were plotted in Figure 4-8. Based on the NSI values, it was determined that the existing PCC thickness and modulus, and subgrade *k*-value affect the predicted performance significantly.

Table 4-19 Summary of NSI values for each design input for CRCP over JPCP pavements

Input Value	Crack Width	Crack LTE	Punchouts	IRI
	Max NSI	Max NSI	Max NSI	Max NSI
PCC existing strength	0.00	0.36	6.28	0.72
PCC existing thickness	0.00	0.00	4.68	0.55
AC interlayer thickness	0.00	0.00	0.08	0.01
AC interlayer binder	0.00	0.00	0.00	0.00
Subgrade k- value	0.00	0.00	2.50	0.29



(a) Crack width

(b) Crack LTE

(c) Punchout

(d) IRI

Figure 4-8 NSI plots for CRCP over JPCP

4.2.7 CRCP over CRCP

Table 4-20 presents the range of existing pavement inputs specific to this rehabilitation option. The base case traffic and pavement structure information are presented in Table 4-21.

Table 4-20 Input variable values for CRCP over CRCP pavement

Input variable	Min	Base case	Max
Existing thickness (in)	7	8	10
Existing strength (psi)	2,000,000	3,000,000	5,000,000
Base thickness (in)	2	5	10
Base Poisson's ratio	0.25	0.35	0.4
Base resilient modulus (psi)	20000	25000	30000
Subgrade modulus (psi)	8000	13000	13500
Rehab k-value (psi/in)	50	200	300

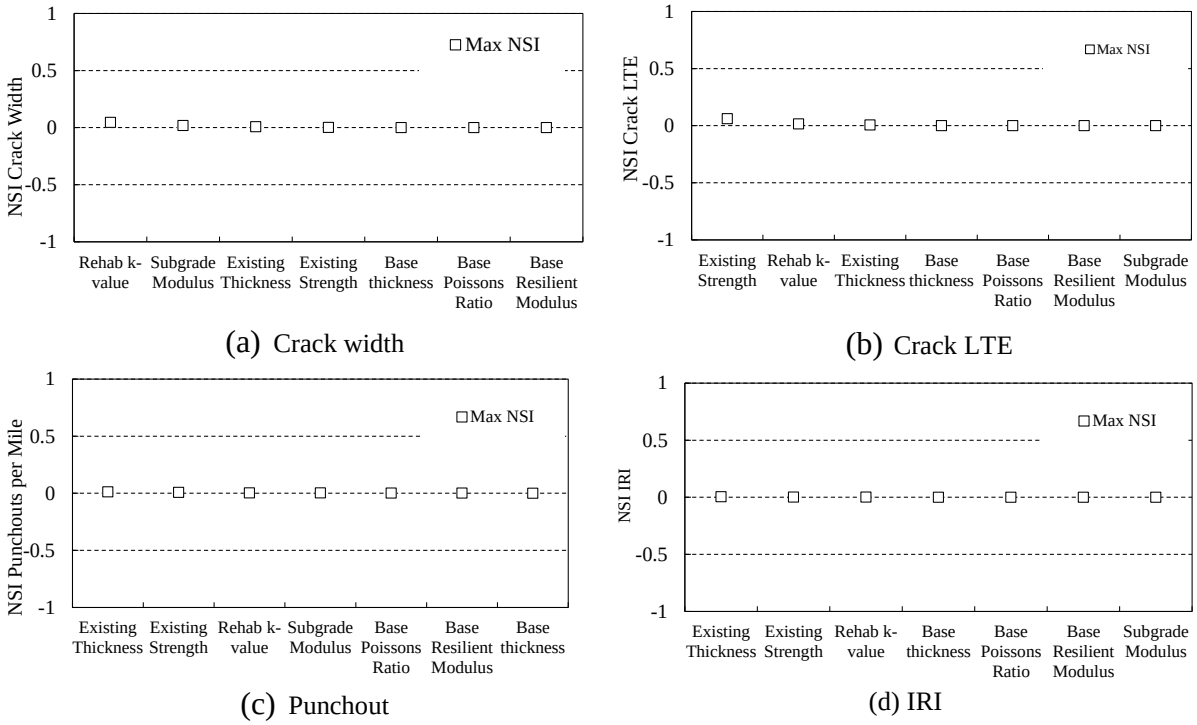
Table 4-21 Base case values for CRCP over CRCP pavement analysis

Site factors		
AADTT	20,000	
Other traffic data	Level 1: Statewide averages	
Climate	Lansing	
Layer properties		
Structure (layers)	Material	Thickness (in)
1 - Surface layer	CRCP	8
2 - HMA interlayer	HMA	2
3 - Existing pavement	PCC CRCP	8
4 - Base	Crushed stone	5
5 - Subgrade	A-4	semi-inf

Table 4-22 shows the NSI values for different performance measures and these values were plotted in Figure 4-9. Based on the preliminary analysis, none of the existing pavement inputs affect the predicted performance significantly based on the NSI values. More detailed analysis is required to analyze the effect the existing pavement has on the predicted performance of the rehabilitated pavement because of the probable interaction between different inputs.

Table 4-22 Summary of NSI values for each design input for CRCP over CRCP pavements

Input Value	Crack With	Crack LTE	Punchouts	IRI
	Max NSI	Max NSI	Max NSI	Max NSI
Existing Thickness	0.01	0.00	0.01	0.00
Existing Strength	0.00	0.06	0.01	0.00
Base thickness	0.00	0.00	0.00	0.00
Base Poisson's Ratio	0.00	0.00	0.00	0.00
Base Resilient Modulus	0.00	0.00	0.00	0.00
Subgrade Modulus	0.02	0.00	0.00	0.00
Rehab k-value	0.04	0.01	0.00	0.00



(a) Crack width (b) Crack LTE

(c) Punchout (d) IRI

Figure 4-9 NSI plots for CRCP over CRCP

4.2.8 Summary of Results

Table 4-23 summarizes the significant inputs from the preliminary sensitivity analyses for each rehabilitation option. These inputs only characterize existing pavement. The results show that existing surface layer thickness and existing pavement structural capacity are the most important inputs for all rehabilitation options. Table 4-24 presents the input levels to characterize the existing surface layer structural capacity. It should be noted that only level 3 inputs were used in the preliminary sensitivity analysis. Further, some of these inputs related to existing layer were not significant based on the preliminary sensitivity; however, those were retained in the analysis for investigating interactions in the subsequent analyses. Since, the preliminary sensitivity was conducted only for inputs related to the existing layers, it is

necessary to investigate their potential interactions with inputs related to the overlay layer. The following insignificant input variables were retained for the detailed sensitivity analysis:

- Rubblized (existing PCC thickness and elastic modulus)
- Composite (Existing PCC flexural strength)
- Unbonded overlay (existing PCC modulus)

Table 4-23 List of significant inputs from preliminary sensitivity analysis

Rehabilitation option	Significant inputs
HMA over HMA	Existing HMA condition rating Existing HMA thickness
Composite	Existing PCC thickness
Unbonded overlay	Existing PCC thickness
CRCP over HMA	Existing HMA thickness
CRCP over JPCP	Existing PCC thickness Existing PCC strength Subgrade k-value

Note: For rubblized rehabilitation option, no input was significant based on the preliminary sensitivity

Table 4-24 Inputs levels for characterizing existing pavement

Rehabilitation option	Input levels for characterizing existing condition
HMA over HMA	Existing HMA condition • Level 1: NDT Modulus, frequency, temperature • Level 2: Milled thickness, fatigue cracking, rut depth • Level 3: Pavement condition rating, milled thickness, total rut depth
Composite	Strength inputs • Level 1: Existing PCC modulus of rupture or elastic modulus • Level 2: Compressive strength • Level 3: MOR, or compressive strength or elastic modulus from historical records Percent of distressed slabs before restoration Percent of distressed slabs after restoration
Rubblized	Existing rubblized PCC elastic modulus
Unbonded overlay	Existing PCC thickness

4.3 DETAILED SENSITIVITY ANALYSIS

Section 4.2 presented the results and findings of the preliminary sensitivity analyses for various rehabilitation options. The main purpose of the analyses was to identify significant input variables related to the existing pavement layers materials and condition. Since the performance prediction models for rehabilitation module are similar to those for new designs, it can be concluded that the significant input variables related to the overlay (i.e. the new layer) are similar to those for a new pavement design. Such significant inputs were identified in the previous MDOT study (*1*) for both flexible and rigid pavements. Therefore, in the detailed sensitivity both types of input variables (for existing and new (overlay) pavements) were considered to identify the important main and interaction effects.

In the detailed sensitivity analysis, a full factorial design matrix was considered and includes several inputs related to existing and overlay layers for each rehabilitation option. The factorial matrices were used to generate pavement scenarios for various MEPDG runs. These runs were executed to capture pavement performance curves .The predicted performance measures at 20 years were used to conduct Analysis of Variance (ANOVA). In this analysis all main effects and possible two-way interactions were considered between input variables. Once all the desired MEPDG runs were accomplished, a database was prepared to evaluate the impact of input variables on various pavement performance measures. The detailed statistical analyses were conducted for each predicted performance measure. Two levels (values) were considered for each input and these levels were based on the ranges from the preliminary sensitivity analysis and the previous MDOT study (*1, 2*).

ANOVA was performed on the performance data at 20 years for each distress to: (a) obtain the design inputs main effects with some level of confidence, (b) explore the interactive effects between various input variables, (c) provide conclusions to distinguish between practical and statistical significance. The results of these for each rehabilitation option are discussed next.

4.3.1 HMA over HMA Analysis and Results

The input variables for HMA over HMA factorial matrix are summarized in Table 4-25. The full factorial matrix for HMA over HMA consists of 11 input variables at 2 levels each and a total of 2048 MEPDG runs (see Table A-3 in Appendix A). This list consists of the potential significant design inputs from preliminary sensitivity analysis as well as the significant inputs for new pavement design. Generally, full-factorial experiments such as the one considered in this study can be analyzed using fixed-effect models employing ANOVA. This type of statistical analyses can help identify the main and the interactive effects between variables. However, it should be noted that if certain variables are interacting with each other, their main effect alone should not be considered while making conclusions. Therefore, conclusions in this case will be based on the interactive effects. As an example, the summary results from ANOVA for longitudinal cracking at 20 years are given in Table 4-26. A *p-value* less than 0.05 (i.e. a confidence level of 95%) is used to identify a statistically significant effect. The highlighted rows are significant main or interactive effects of input variables. The ANOVA results for other distresses are presented in Appendix A.

The results show that for HMA over HMA, most of the main effects are significant while significant interactions differ for different distress types. It should be noted that interaction effects are critical in such analysis since the impact of one input variable can be

highly dependent on the value of another input variable. In addition, the significant interactions identified by ANOVA are based on statistics. However, in order to verify the practical significance of an effect, visual inspection combined with FHWA criteria (*6*) and engineering judgment was employed. For example, Figure 4-10 shows two interactions that are statistically significant based on ANOVA. However, as the plots indicate, only the interaction shown in Figure 4-10a is of practical significance. The results in the figure show that for a thin overlay, existing pavement condition has a significant effect on surface rutting while it may not be important in the case of a thick overlay. On the other hand Figure 4-10b shows no interaction between existing pavement thickness and overlay binder PG grading. In other words, existing thickness controls the difference in surface rutting irrespective of overlay binder PG.

Table 4-25 List and range of design inputs for HMA over HMA

No.	Input variables		Lower limit	Upper limit	Comments
1	Overlay thickness (inch) (OLTH)		2	8	This range might be larger than the typical overlay thickness used in Michigan; however a wider range is used for sensitivity purposes.
2	Overlay effective binder (% by volume) (OLEB)		7	14	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
3	Overlay PG (OLPG)		PG 58-22	PG 76-28	Based on the MDOT mix types (tested in the Part 1 of this study), largest and smallest range is chosen
4	Overlay AV (%) (OLAV)		5	12	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
5	Overlay aggregate gradation (%) (OLAGG)	3/4" sieve	100	100	Based on the MDOT mix types (tested in the Part 1 of this study)
		3/8" sieve	86.8	88.6	
		#4 sieve	79.2	73.2	
		passing # 200	5.6	4.9	
6	Existing condition rating (EXCON)		Very poor	Excellent	Two possible extremes of the MEPDG are selected
7	Existing HMA thickness (inch) (EXTH)		4	12	Considering the overlay thickness and previous MDOT study, this range is chosen
8	Existing base modulus (psi) (BMOD)		15000	40000	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
9	Existing Sub-base modulus (psi) (SBMOD)		15000	30000	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
10	Subgrade modulus (psi) (SGMOD)		2500	25000	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
11	Climate		Pellston	Detroit	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"

Note: The shaded cells show the inputs related to the overlay layer.

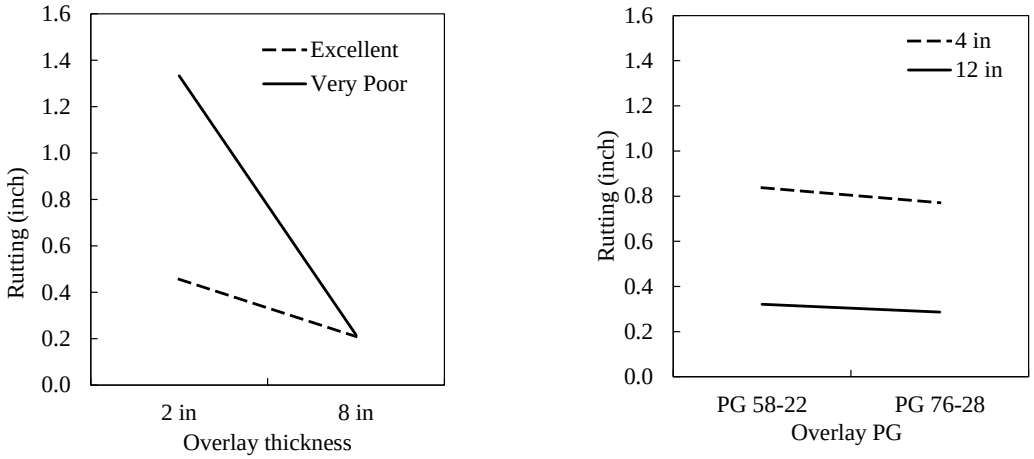
Figures 4-11 to 4-13 show the FHWA criteria based on different performance measures. This criterion documents the analysis and findings of a study to identify the site conditions and design/construction features of flexible pavements that lead to good and poor pavement performance. Data from the Long-Term Pavement Performance (LTPP) pavement sections were used. Separate criteria were developed for each performance measure including roughness (IRI), rutting, and fatigue cracking. These criteria were used to obtain the practical significance of inputs for different performance measures. It should be noted that these

criteria are not available for longitudinal cracking. Table 4-27 summarizes performance criteria developed by the FHWA (*6*).

Table 4-26 HMA over HMA longitudinal cracking ANOVA Results

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	33374980919.535	56	595981802.135	221.480	.000
Intercept	23091314591.350	1	23091314591.350	8581.248	.000
OLTH	15332796877.727	1	15332796877.727	5698.010	.000
OLEB	368936830.134	1	368936830.134	137.105	.000
OLPG	3252647.869	1	3252647.869	1.209	.272
OLAV	1983679431.092	1	1983679431.092	737.180	.000
OLAG	2479152.113	1	2479152.113	.921	.337
EXCON	4477631784.047	1	4477631784.047	1663.988	.000
EXTH	3487966887.913	1	3487966887.913	1296.206	.000
BMOD	133832100.750	1	133832100.750	49.735	.000
SBMOD	236874.143	1	236874.143	.088	.767
SGMOD	878139393.840	1	878139393.840	326.336	.000
Climate	2752504.654	1	2752504.654	1.023	.312
EXCON * BMOD	60543223.968	1	60543223.968	22.499	.000
EXTH * BMOD	272603632.116	1	272603632.116	101.306	.000
OLAG * BMOD	474.686	1	474.686	.000	.989
OLAV * BMOD	1224265.290	1	1224265.290	.455	.500
OLEB * BMOD	2806218.200	1	2806218.200	1.043	.307
OLPG * BMOD	425157.258	1	425157.258	.158	.691
OLTH * BMOD	20966345.571	1	20966345.571	7.792	.005
BMOD * SBMOD	87689.129	1	87689.129	.033	.857
BMOD * SGMOD	1023030.126	1	1023030.126	.380	.538
EXCON * EXTH	535687513.647	1	535687513.647	199.073	.000
OLAG * EXCON	107406.276	1	107406.276	.040	.842
OLAV * EXCON	100875494.134	1	100875494.134	37.488	.000
OLEB * EXCON	10145350.215	1	10145350.215	3.770	.052
OLPG * EXCON	80696.258	1	80696.258	.030	.863
OLTH * EXCON	2796705580.783	1	2796705580.783	1039.318	.000
EXCON * SBMOD	9590125.087	1	9590125.087	3.564	.059
EXCON * SGMOD	389200.176	1	389200.176	.145	.704
OLAG * EXTH	345354.255	1	345354.255	.128	.720
OLAV * EXTH	323975489.726	1	323975489.726	120.397	.000
OLEB * EXTH	21408876.072	1	21408876.072	7.956	.005
OLPG * EXTH	20016069.524	1	20016069.524	7.438	.006
OLTH * EXTH	962088193.870	1	962088193.870	357.533	.000
EXTH * SBMOD	4405402.445	1	4405402.445	1.637	.201
EXTH * SGMOD	502947530.966	1	502947530.966	186.907	.000
OLAV * OLAG	32218.166	1	32218.166	.012	.913
OLEB * OLAG	1766.817	1	1766.817	.001	.980
OLPG * OLAG	26521.348	1	26521.348	.010	.921
OLTH * OLAG	231816.235	1	231816.235	.086	.769
OLAG * SBMOD	14.841	1	14.841	.000	.998
OLAG * SGMOD	6690.281	1	6690.281	.002	.960
OLEB * OLAV	140439906.866	1	140439906.866	52.191	.000
OLPG * OLAV	48273651.829	1	48273651.829	17.940	.000
OLTH * OLAV	420262650.377	1	420262650.377	156.179	.000
OLAV * SBMOD	1166039.157	1	1166039.157	.433	.510
OLAV * SGMOD	3038505.372	1	3038505.372	1.129	.288
OLEB * OLPG	36442959.078	1	36442959.078	13.543	.000
OLTH * OLEB	302338706.749	1	302338706.749	112.356	.000
OLEB * SBMOD	1017.653	1	1017.653	.000	.984
OLEB * SGMOD	4593425.563	1	4593425.563	1.707	.192
OLTH * OLPG	48360207.191	1	48360207.191	17.972	.000
OLPG * SBMOD	22047.638	1	22047.638	.008	.928
OLPG * SGMOD	15622114.522	1	15622114.522	5.806	.016
OLTH * SBMOD	73283.472	1	73283.472	.027	.869
OLTH * SGMOD	33878122.174	1	33878122.174	12.590	.000
SBMOD * SGMOD	16450.146	1	16450.146	.006	.938

Note: Shaded cells indicate a statistical significant effect.



(a) Overlay thickness vs. existing pavement condition (↓)

(b) Overlay PG vs. existing pavement thickness

Figure 4-10 Interaction plots (a) overlay thickness and existing condition rating, (b) overlay PG and existing HMA thickness

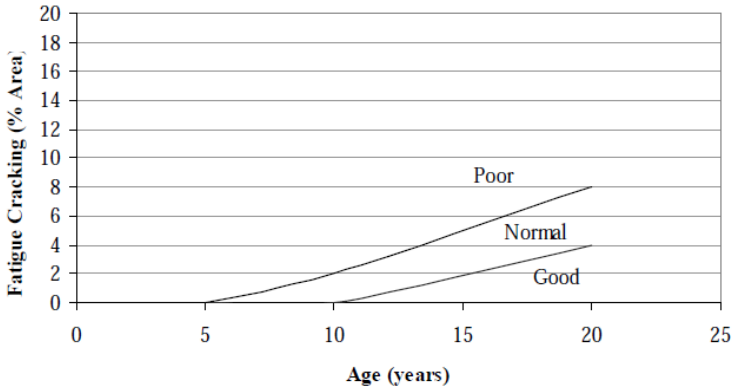


Figure 4-11 Pavement performance criteria for fatigue cracking (*6*)

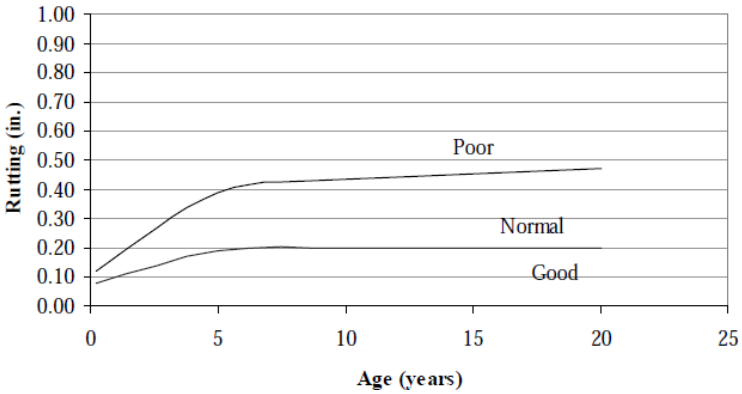


Figure 4-12 Pavement performance criteria for rutting (*6*)

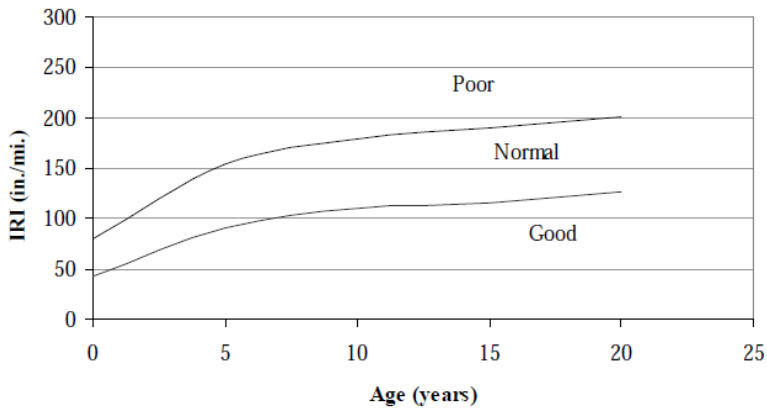


Figure 4-13 Performance criteria for IRI (*6*)

Table 4-27 Pavement performance criteria after 20 years – flexible pavements

Performance measure	Criteria after 20 years
Longitudinal cracking	500 ft/mile
Alligator cracking	4%
Rutting	0.3 in
IRI	75 in/mile

Table 4-28 summarizes the interactions that are of statistical and practical significance for HMA over HMA pavements. These interactions only involve existing pavement and overlay related inputs. Several important interactions were identified for HMA over HMA designs; however, this interdependence between variables varies among different distress types. The results of the sensitivity analyses show that the existing pavement condition rating and thickness for the HMA over HMA rehabilitation option are critical for all performance measures. In addition, several overlay layer related inputs interact with existing pavement properties. These interactions will have significant impact on the predicted pavement performance. Figure 4-14 shows examples for interpreting the interactions for any performance measure. Appendix A contains similar plots for all other performance measures within different rehabilitation options.

For example, higher percent air voids in the HMA overlay causes higher longitudinal and alligator cracking, and higher rutting and IRI, especially when the existing pavement condition is poor. The interaction between existing pavement condition and overlay effective binder content indicates that higher effective binder may reduce alligator cracking difference between poor and excellent existing pavement conditions. However, as expected, increases in the effective binder content cause an increase in surface layer rutting, especially when the existing pavement condition is poor. The overlay thickness will assist in reducing all the pavement distresses; this effect for the thicker HMA overlay is independent of the existing conditions.

The interaction between existing pavement thickness and overlay effective binder content indicates that higher effective binder may reduce both longitudinal and alligator cracking difference between thin and thick existing pavement. However, as expected, such increase in effective binder content will increase surface rutting, especially when the existing

pavement is thinner. A higher overlay thickness will assist in reducing all the pavement distresses.

Table 4-28 Summary of significant interactions (HMA over HMA) – Existing and overlay layers

Existing pavement inputs	Overlay inputs	Longitudinal cracking	Alligator cracking	Rutting	IRI
Existing pavement condition *(Very poor and excellent)*	Overlay air voids *(5% and 12%)*	↑	↑	↑	↑
	Overlay effective binder *(7% and 14%)*		↓	↑	↓
	Overlay PG *(PG 58-22 and PG 76-28)*		↑		
	Overlay thickness *(2in and 8in)*	↓	↓	↓	↓
Existing pavement thickness *(4in and 12in)*	Overlay air voids *(5% and 12%)*	↑		↑	
	Overlay effective binder *(7% and 14%)*	↓	↓	↑	
	Overlay PG *(PG 58-22 and PG 76-28)*	↑			
	Overlay thickness *(2in and 8in)*	↓	↓	↓	
Base modulus *(15000 psi and 40000 psi)*	Overlay thickness *(2in and 8in)*	↓			
Subgrade modulus *(2500 psi and 25000 psi)*	Overlay PG *(PG 58-22 and PG 76-28)*	↑			
	Overlay thickness *(2in and 8in)*	↓			

Note:

↓ Interaction is statistically and practically significant, and the difference in distress magnitude is higher at the lower level than the difference at the higher level of the input variables (see Figure 4-10).

↑ Interaction is statistically and practically significant, and the difference in distress magnitude is lower at the lower level than the difference at the higher level of the input variables.

The blank cell means no practically interaction exists. All interaction are shown graphically in Appendix A

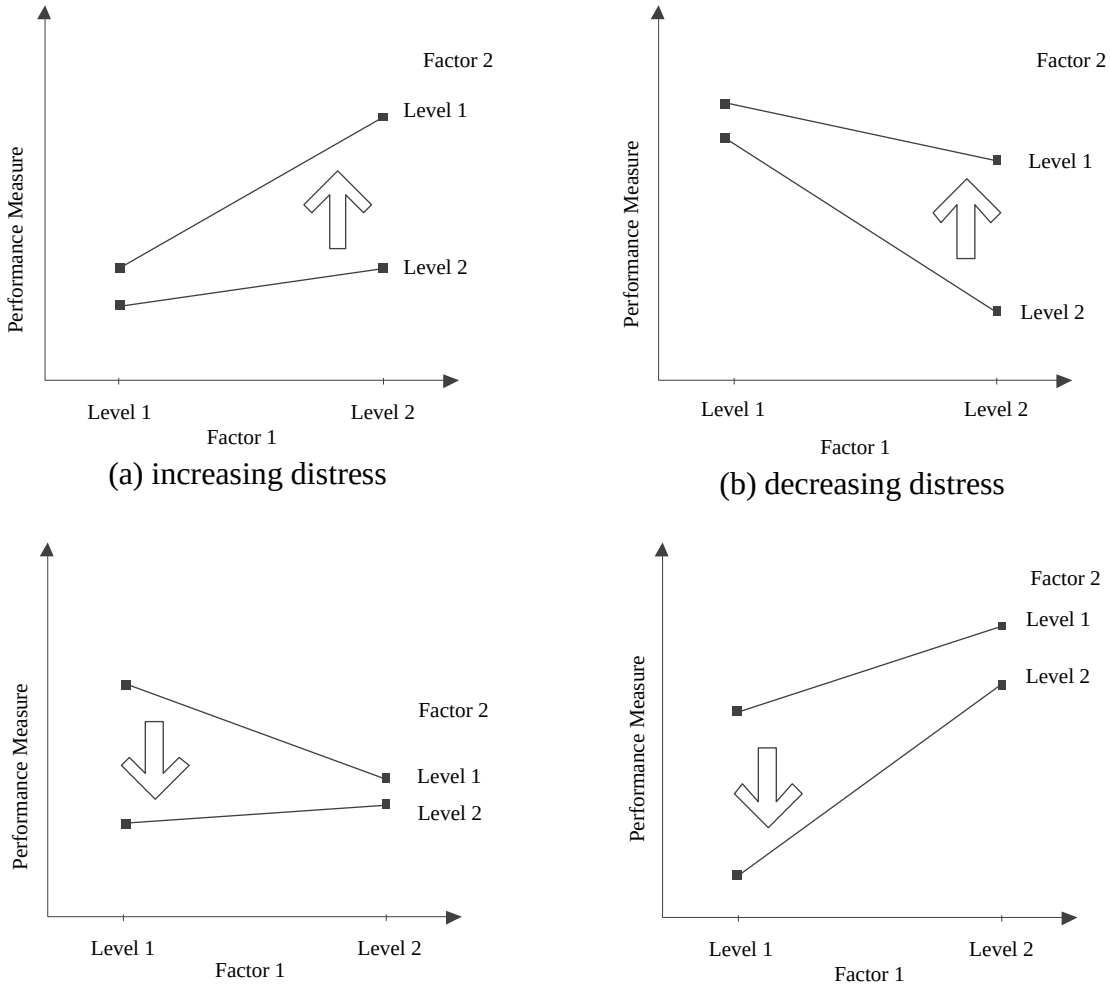


Figure 4-14 Interpretation of interactions for rutting

The interactions between the existing and overlay layer inputs were investigated and presented above. The interactions between the overlay design inputs are identical to the inputs for new pavement (as addressed in the previous MDOT study). In addition, the interactions between the existing pavement layer inputs may not be of practical importance because designer may not have a control on these inputs. However, possible interaction between inputs related to all layers (i.e., within overlay and within existing) were evaluated and are summarized in Table 4-29. For interaction between the inputs within existing layers, the results show that higher base modulus will reduce the impacts of existing condition and thickness on longitudinal cracking. Also, for thicker existing HMA layers, existing conditions will have higher impact on longitudinal cracking while for thinner existing HMA, existing conditions will have higher impact on alligator cracking and surface rutting. The higher subgrade modulus with thinner existing HMA layer has higher longitudinal cracking.

For interactions between the inputs within overlay layer, higher effective binder will have higher effect on longitudinal cracking for different air void levels while it has lower

effect on alligator cracking for different air void levels. Stiffer binder PG will have higher effect on longitudinal cracking for different overlay air voids and effective binder. Thicker overlay will have lower effect on longitudinal cracking for different overlay air void or effective binder. Thicker overlay will also have lower effect on alligator cracking and IRI for various effective binder levels. Finally, thicker overlay will have higher effect on longitudinal cracking for different levels of binder PG.

Table 4-29 Summary of significant interactions (HMA over HMA) – Within existing and within overlay layers

<table>
<tr><th>Interaction type</th><th>Longitudinal cracking</th><th>Alligator cracking</th><th>Rutting</th><th>IRI</th></tr>
<tr><td rowspan="6">Existing - Existing</td><td>BMOD * EXCON (↓)</td><td>BMOD * EXCON</td><td>BMOD * EXCON</td><td>EXCON * BMOD</td></tr>
<tr><td>BMOD * EXTH (↓)</td><td>BMOD * EXTH</td><td>BMOD * EXTH</td><td>EXTH * BMOD</td></tr>
<tr><td>EXCON * EXTH (↑)</td><td>EXCON * EXTH (↓)</td><td>EXCON * EXTH (↓)</td><td rowspan="4">EXCON * EXTH</td></tr>
<tr><td rowspan="3">EXTH * SGMOD (↑)</td><td rowspan="3">EXCON * SGMOD</td><td>EXCON * SGMOD</td></tr>
<tr><td>EXTH * SBMOD</td></tr>
<tr><td>EXTH * SGMOD</td></tr>
<tr><td rowspan="6">Overlay - Overlay</td><td>OLAV * OLEB (↑)</td><td>OLAV *OLEB (↓)</td><td>OLAV * OLEB</td><td>OLAV*OLEB (↓)</td></tr>
<tr><td>OLAV * OLPG (↑)</td><td>OLAV * OLPG</td><td>OLEB * OLPG</td><td>OLAV * OLTH</td></tr>
<tr><td>OLAV * OLTH (↓)</td><td>OLAV * OLTH</td><td rowspan="4">OLEB * OLTH</td><td rowspan="4">OLEB * OLTH (↓)</td></tr>
<tr><td>OLEB * OLPG (↑)</td><td>OLEB * OLPG</td></tr>
<tr><td>OLEB * OLTH (↓)</td><td rowspan="2">OLEB * OLTH (↓)</td></tr>
<tr><td>OLPG * OLTH (↑)</td></tr>
</table>

Note:
The interactions with an arrow are statistically and practically significance. The interactions without an arrow are only statistically significance. Blank cells indicate no statistically significant interaction exists.

4.3.2 Composite (HMA over JPCP) Pavement Analysis and Results

The input variables for composite factorial matrix are summarized in Table 4-30. The full factorial matrix consists of a total of 9 input variables at 2 levels each and a total of 512 MEPDG runs. The factorial matrix and the ANOVA tables for all the distresses are presented in Appendix A.

Based on the existing back-calculated results from LTPP database, an existing PCC elastic modulus of 3,000,000 psi is very low compared to the observed elastic moduli values for existing concrete pavements. However, as mentioned in Chapter 2, the maximum value of the existing PCC slab modulus is recommended to be 3,000,000 psi in the M-E PDG (MEPDG predictions become erratic when using a higher PCC modulus).

In order evaluate the operational (practical) importance; statistical significant interactions from ANOVA are assessed using the FHWA pavement performance criteria listed in Table 4-27. The performance difference within the levels of each input was compared with the values shown in the table. For example, in Figure 4-10a, the rutting difference between poor and excellent condition at 2-inch overlay thickness is 0.85-inch while for 8-inch overlay the difference is zero. Therefore, the total difference is 0.85-inch which is more than 0.3-inch as suggested in Table 4-27. Table 4-31 summarizes the interactions that are of statistical and practical significance for HMA over JPCP. Existing

PCC elastic modulus and thickness are important in determining the performance of an HMA overlay over an intact JPCP. For a given existing condition of the existing pavement, HMA overlay volumetric properties, binder type and amount, and thickness may play an important role. Also HMA volumetrics, binder type and amount, and thickness can be carefully selected for the overlays to mitigate various distresses when the existing pavement is an intact JPCP.

Table 4-30 List and range of design inputs for composite pavement

No.	Input variables		Lower limit	Upper limit	Comments
1	Overlay thickness (inch) (OLTH)		2	8	This range might be larger than the typical overlay thickness used in Michigan; however a wider range is used for sensitivity purposes
2	Overlay effective binder (% by volume) (OLEB)		7	14	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
3	Overlay PG (OLPG)		PG 58-22	PG 76-28	Based on the MDOT mix types (being tested in this study), largest and smallest range is chosen
4	Overlay AV (%) (OLAV)		5	12	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
5	Overlay aggregate gradation (%) (OLGRAD)	3/4" sieve	100	100	Based on the PG, the corresponding MDOT mix type and aggregate gradation are used
		3/8" sieve	86.8	88.6	
		#4 sieve	79.2	73.2	
		passing # 200	5.6	4.9	
6	Existing PCC thickness (inch) (EPCCTH)		7	11	Based on previous MDOT study
7	Existing PCC elastic modulus (psi) (EMOD)		500,000	3,000,000	The MEPDG limits the value of the existing pavement elastic modulus to ensure reliable results at 3,000,000 psi.
8	Subgrade reaction modulus (psi/in) (EK)		50	300	This input over-rides the calculation of the modulus of subgrade reaction. The lower bound value within the MEPDG is 50 and an upper value of 300 psi/in was selected
9	Climate		Pellston	Detroit	Based on previous MDOT study

Note: The shaded cells show the inputs related to the overlay layer

Table 4-31 Summary of significant interactions composite pavement

Existing pavement inputs	Overlay inputs	Longitudinal cracking	Alligator cracking	Rutting	IRI
Existing pavement modulus *(500000 psi to 3000000 psi)*	Overlay air voids *(5% and 12%)*	↑			
	Overlay thickness *(2in and 8in)*	↑			
Existing pavement thickness *(7 in to 11 in)*	Overlay air voids *(5% and 12%)*	↑			
	Overlay PG *(PG 58-22 and PG 76-28)*	↑			
	Overlay thickness *(2in and 8in)*	↑			
Climate *(Pellston and Detroit)*	Overlay air voids *(5% and 12%)*	↑			
	Overlay thickness *(2in and 8in)*	↑			

Note:

↓ Interaction is statistically and practically significant, and the difference in distress magnitude is higher at the lower level than the difference at the higher level of the input variables (see Figure 4-10).

↑ Interaction is statistically and practically significant, and the difference in distress magnitude is lower at the lower level than the difference at the higher level of the input variables.

The blank cell means no practically interaction exists. All interaction are shown graphically in Appendix A

Possible interactions between inputs related to all layers (i.e., within overlay and within existing) were evaluated and are summarized in Table 4-32. No practically significant interaction was found within the existing layer. Within the overlay layer, higher overlay air voids will have higher effect on longitudinal cracking for different overlay thicknesses. Also thicker overlay will have higher effect for different binder PGs. Finally, stiffer binder will have lower effect for different overlay air void levels.

Table 4-32 Summary of significant interactions (Composite) – Within existing and within overlay layers

Interaction type	Longitudinal cracking	Alligator cracking	Rutting	IRI
Existing - Existing	EXCON * BMOD		EMOD * EPCCTH	EMOD * EPCCTH
	EXTH * BMOD			
	EXCON * EXTH			
Overlay - Overlay	OLEB * OLAV		OLEB * OLAV	OLEB * OLAV
	OLTH * OLAV (↑)		OLGRAD * OLAV	OLGRAD * OLAV
	OLTH * OLEB		OLTH * OLAV	OLTH * OLAV
			OLPG * OLAV	OLPG * OLAV
	OLPG * OLTH (↑)		OLGRAD * OLEB	OLGRAD * OLEB
			OLTH * OLEB	OLTH * OLEB
	OLAV * OLPG (↓)		OLPG * OLEB	OLPG * OLEB
			OLTH * OLGRAD	OLTH * OLGRAD
			OLPG * OLGRAD	OLPG * OLGRAD
			OLTH * OLPG	OLTH * OLPG

Note:
The interactions with an arrow are statistically and practically significance. The interactions without an arrow are only statistically significance. Blank cells indicate no statistically significant interaction exists.

4.3.3 Rubblized (HMA over Fractured PCC) Pavement Analysis and Results

The input variables for the factorial matrix of HMA over fractured (rubblized) PCC pavement are summarized in Table 4-33. The full factorial matrix for rubblized designs contains a total of 8 input variables at 2 levels each and a total of 256 MEPDG runs. The factorial matrix and the ANOVA tables for all the distresses are presented in Appendix A.

Table 4-33 Input variable ranges for HMA over fractured JPCP

No	Input variables		Lower limit	Upper limit	Comments
1	Overlay thickness (inch) (OLTH)		2	8	This range might be larger than the typical overlay thickness used in Michigan; however a wider range is used for sensitivity purposes
2	Overlay effective binder (% by volume) (OLEB)		7	14	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
3	Overlay PG (OLPG)		PG 58-22	PG 76-28	Based on the MDOT mix types (being tested in this study), largest and smallest range is chosen
4	Overlay AV (%) (OLAV)		5	12	Based on the report, "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavement"
5	Overlay aggregate gradation (%) (OLAG)	3/4" sieve	100	100	Based on the PG, the corresponding MDOT mix type and aggregate gradation are used
		3/8" sieve	86.8	88.6	
		#4 sieve	79.2	73.2	
		passing # 200	5.6	4.9	
6	Existing PCC thickness (inch) (EPCCE)		7	11	Based on previous MDOT study
7	Existing PCC elastic modulus (psi) (EPCCTH)		35,000	1,500,000	The MEPDG limits the value of the existing pavement elastic modulus to ensure reliable results at 3,000,000 psi.
8	Climate		Pellston	Detroit	Based on previous MDOT study

Note: The shaded cells show the inputs related to the overlay layer

Table 4-34 summarizes the interactions that are of statistical and practical significance for the rubblized rehabilitation option. The existing PCC rubblized modulus and thickness are important in determining the performance of HMA overlay over rubblized JPCP. HMA volumetrics, binder type and amount, and thickness can be selected for the overlays to mitigate various distresses when the existing pavement is rubblized JPCP.

As shown in Table 4-34 and Appendix A, the results show that higher air voids in the HMA overlay will produce higher longitudinal and alligator cracking, especially for the weaker existing rubblized pavement. While higher rutting should be expected with higher air voids in the HMA layer, the impact of existing rubblized layer moduli is lower for rutting performance relative to other pavement performance measures. The overlay thickness will assist in reducing all the pavement distresses; this effect for the thicker HMA overlay is independent of the existing conditions.

Table 4-34 Summary of significant interactions (HMA over fractured JPCP)

Existing pavement inputs	Overlay inputs	Longitudinal cracking	Alligator cracking	Rutting	IRI
Existing pavement modulus *(35000 psi to 1500000 psi)*	Overlay air voids *(5% and 12%)*	↑	↑	↓	↑
	Overlay effective binder *(7% and 14%)*		↓	↓	↓
	Overlay PG *(PG 58-22 and PG 76-28)*	↑		↑	
	Overlay thickness *(2in and 8in)*	↓	↓	↓	↓
Existing pavement thickness *(7 in to 11 in)*	Overlay thickness *(2in and 8in)*	↑			

Note:

↓ Interaction is statistically and practically significant, and the difference in distress magnitude is higher at the lower level than the difference at the higher level of the input variables (see Figure 4-10).

↑ Interaction is statistically and practically significant, and the difference in distress magnitude is lower at the lower level than the difference at the higher level of the input variables.

The blank cell means no practically interaction exists. All interaction are shown graphically in Appendix A

Possible interactions between inputs related to all layers (i.e., within overlay and within existing) were evaluated and are summarized in Table 4-35. No practically significant interaction was found within overlay or within the existing layers.

Table 4-35 Summary of significant interactions (Rubblized) – Within existing and within overlay layers

Interaction type	Longitudinal cracking	Alligator cracking	Rutting	IRI
Existing - Existing	EPCCE * EPCCTH		EPCCE * EPCCTH	
Overlay - Overlay	OLTH * OLAV		OLTH * OLAG	OLEB * OLAV
	OLTH * OLPG		OLEB * OLAV	OLTH * OLAV
			OLPG * OLAV	OLTH * OLEB
			OLTH * OLAV	
			OLPG * OLEB	
			OLTH * OLEB	
			OLTH * OLPG	

Note:

The interactions with an arrow are statistically and practically significance. The interactions without an arrow are only statistically significance. Blank cells indicate no statistically significant interaction exists.

4.3.4 Unbonded PCC Overlay Analysis and Results

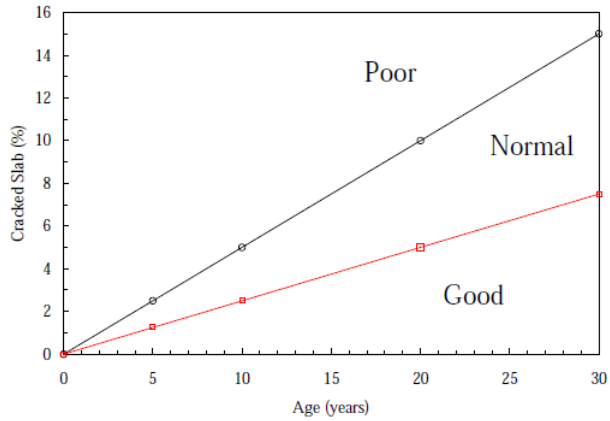
The input variables for unbonded PCC overlay factorial matrix are summarized in Table 4-36. The full factorial matrix for unbonded PCC overlay contains 9 input variables at 2 levels each and a total of 256 MEPDG runs. The factorial matrix and the ANOVA tables for all the distresses are presented in Appendix A.

Table 4-36 Input variable ranges for JPCP over JPCP (unbonded overlay)

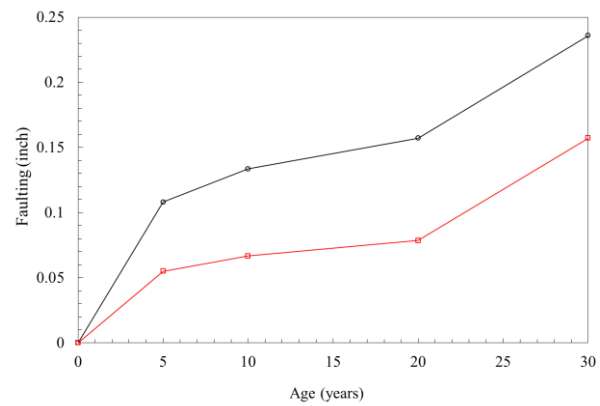
No.	Input variable	Lower limit	Upper limit	Comments
1	Overlay PCC thickness (inch) (OLTH)	7	10	The minimum thickness for an unbonded concrete overlay within MEPDG is 7 inches. The upper bound was selected based on LTPP unbonded overlay thicknesses and to ensure that it is lower than the existing pavement layer
2	Overlay PCC CTE (per °F x 10^{-6}) (OLCTE)	4	7	The overlay PCC CTE was selected based on the values from the previous MDOT study
3	Overlay joint spacing (feet) (OLJS)	10	15	Joint spacing was selected based on MDOT's unbonded overlay joint spacing of 12 feet. 10 and 15ft were selected for the lower and upper bound values.
4	Overlay PCC MOR (psi) (OLMOR)	550	900	Based on typical values
5	Modulus of subgrade reaction, *k* (psi/in) (SGMOD)	50	300	This input over-rides the calculation of the modulus of subgrade reaction. The lower bound value within the MEPDG is 50 and an upper value of 300 psi/in was selected
6	Existing PCC thickness (inch) (EXTH)	7	11	Based on previous MDOT study
7	Existing PCC elastic modulus (psi) (EXMOD)	500,000	3,000,000	The MEPDG limits the value of the existing pavement elastic modulus to ensure reliable results at 3,000,000 psi.
8	Climate (CL)	Pellston	Detroit	Based on previous MDOT study

Note: The shaded cells show the inputs related to the overlay layer

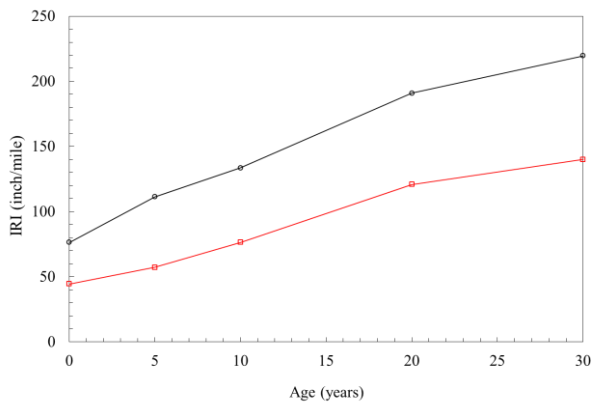
For PCC overlay in this investigation, performance criteria developed by the FHWA (*7*), were modified to reflect MDOT practices and were used to ascertain the practical significance of an effect on cracking, faulting, and IRI. The details of modifying the performance criteria can be found elsewhere (*1*). Figure 4-15 shows the performance criteria for the PCC overlay performance measures and Table 4-37 summarizes the performance thresholds for practical significance.



(a) Percent slab cracked



(b) Joint or crack faulting



(c) Roughness in terms of IRI

Figure 4-15 Adopted performance criteria for JPCP (*7*)

Table 4-37 Pavement performance criteria after 20 years – Rigid pavements

Performance measure	Threshold after 20 years
Percent slabs cracked	5%
Faulting	2 mm
IRI	70 in/mile

The predicted performance data were analyzed using ANOVA and only the interactions between existing and overlay pavement layers were further investigated. The statistically significant results were further analyzed to determine the practical significance of the interaction. Table 4-38 summarizes the practically significant interactions for unbonded PCC overlay rehabilitation option.

The results of the sensitivity analyses show that the existing pavement condition (in terms of *E*) for unbonded overlays is critical for their cracking performance. Higher MOR and thickness of overlay will limit the cracking. However, if the existing foundation is weak, a better strategy to improve the unbonded overlay cracking performance would be to increase MOR and thickness and use concrete with lower CTE within the practical range used in Michigan.

Table 4-38 Interaction summary table (unbonded overlay)

Interactions and input values		Cracking	Faulting	IRI
Existing elastic modulus *(500,000 and 3,000,000 psi)*	Overlay MOR *(550 and 900 psi)*	↓		
	Overlay thickness *(7 and 9 in)*	↓		
	Overlay CTE *(4 and 7 per °F x 10^{-6})*			
	Overlay joint spacing *(10 and 15 ft)*			
Existing thickness *(9 and 11 in)*	Overlay MOR *(550 and 900 psi)*	↓		
	Overlay thickness *(7 and 9 in)*			
	Overlay CTE *(4 and 7 per °F x 10^{-6})*			
	Overlay joint spacing *(10 and 15 ft)*			
Modulus of subgrade reaction *(50 and 300 psi/in)*	Overlay MOR *(550 and 900 psi)*	↓		
	Overlay thickness *(7 and 9 in)*	↓		
	Overlay CTE *(4 and 7 per °F x 10^{-6})*	↓		
	Overlay joint spacing *(10 and 15 ft)*			

Note:
↓ Interaction is statistically and practically significant, and the difference in distress magnitude is higher at the lower level than the difference at the higher level of the input variables.
↑ Interaction is statistically and practically significant, and the difference in distress magnitude is lower at the lower level than the difference at the higher level of the input variables.

Possible interactions between inputs related to all layers (i.e., within overlay and within existing) were evaluated and are summarized in Table 4-39. Within the existing layer, for cracking, thicker existing PCC will have higher effect for various existing PCC moduli values while higher subgrade modulus will have lower effect in interacting with existing PCC modulus. Thicker overlays will lessen the effect of joint spacing, MOR and CTE on transverse cracking in unbonded overlays. The same effect can be verified while MOR is interacting with CTE and joint spacing. Finally, higher joint spacing will have higher effect on cracking for different levels of CTE.

Table 4-39 Summary of significant interactions (Unbonded overlay) – Within existing and within overlay layers

Interaction type	Cracking	Faulting	IRI
Existing - Existing	EXMOD * EXTH (↑)	EXMOD * EXTH	
	EXMOD * SGMOD (↓)	EXMOD * SGMOD	
Overlay - Overlay	OLCTE * OLJS (↑)	OLCTE * OLJS	OLCTE * OLJS
	OLCTE * OLMOR (↓)	OLCTE * OLMOR	OLTH * OLCTE
	OLCTE * OLTH (↓)	OLCTE * OLTH	OLJS * OLMOR
	OLJS * OLMOR (↓)	OLJS * OLMOR	OLTH * OLMOR
	OLJS * OLTH (↓)	OLJS * OLTH	
	OLMOR * OLTH (↓)	OLMOR * OLTH	

Note:
The interactions with an arrow are statistically and practically significance. The interactions without arrow are only statistically significance. Blank cells indicate no statistically significant interaction exists.

4.3.5 Summary Results

Only four of the seven rehabilitation options considered in preliminary sensitivity analysis were considered in the detailed sensitivity analyses based on the MDOT practices. This section evaluated the impact of various design inputs on the predicted performance for the three flexible pavement rehabilitation options. The detailed sensitivity analyses included the significant variables identified in OAT analyses in addition to the significant inputs previously identified for new pavement layers *(1)*. Full factorials were designed to determine statistically significant main and two-way interaction effects. The results of the sensitivity analyses show that the existing pavement condition rating and existing thickness for HMA over HMA overlays is critical for all performance measures. On the other hand, existing PCC modulus and thickness are important in determining the performance of HMA overlay over intact and rubblized JPCP. For a given condition of the existing pavement, HMA overlay volumetric properties, binder type and amount, and thickness may play an important role. In addition, HMA volumetrics, binder type and amount, and thickness can be carefully selected for the overlays to mitigate various distresses whether the existing pavement is intact or rubblized JPCP.

For unbonded overlays, the results of the sensitivity analyses show that the existing pavement condition (in terms of *E*) is critical for their cracking performance. Higher MOR and thickness of overlay will limit the cracking. However, if the existing foundation is weak, a better strategy to improve the unbonded overlay cracking performance would be to increase MOR, thickness and concrete with lower CTE.

The detailed sensitivity produced a list of important inputs for different rehabilitation options. However, more rigorous analysis was conducted in the next section; therefore, a list of significant inputs will be presented subsequently.