AMERICAN UNIVERSITY OF BEIRUT

# IMPLEMENTATION OF PAVEMENT-ME IN THE MIDDLE EAST

by
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AMERICAN UNIVERSITY OF BEIRUT

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# AN ABSTRACT OF THE THESIS OF

Sarjoun Hassan for Master of Engineering
Major: Civil Engineering

Title: IMPLEMENTATION OF PAVEMENT-ME IN THE MIDDLE EAST

The Mechanistic-Empirical Pavement Design Method through AASHTOWare Pavement-ME software is a tool that helps make pavement design tailored to the specific material, climatic and loading conditions of the road, giving it a great advantage over its predecessor, AASHTO 1993 method. Despite the great implications of utilizing Pavement-ME on the performance and lifetime of the pavement, highway agencies around the world are shying away from implementing it due to the lack of expertise, technologies and data needed. In order for Pavement-ME to predict the performance of the pavement in real time conditions, it employs detailed input parameters on truck traffic and climate, and the proper experimental characterization of materials. In addition, it requires empirical distress prediction functions that are able to translate strains and deformations into quantified distresses.

Considering the countries of the Middle East, namely Kingdom of Saudi Arabia, United Arab Emirates and Qatar, their economies are witnessing fast growth accompanied by an expansion of their road infrastructure. The desert nature of this region alongside the very hot temperatures and the expected high truck volumes, are supporting reasons for a transfer towards Pavement-ME in pavement design.

Very few attempts to implement Pavement-ME were taken outside the United States of America and none of those attempts resulted in a full implementation of the software. Since limited data is available for local highway agencies, there is great need to present a specific implementation roadmap that utilizes available easily collected data. This research addresses the above need by utilizing Pavement-ME runs to perform sensitivity analysis on important software input parameters. This analysis will result in recommending the level of accuracy needed for certain input parameters, and catalogue values, specific for the region, for other input parameters. The research utilizes a case study from Iraq to assess the need for a local calibration of the above mentioned empirical distress prediction functions. Such calibration proved to be needed. The framework for the calibration process as part of the implementation is presented and it relies heavily on data from road observation programs available at certain highway agencies.

This research aims to help agencies reduce the amount of data they have to collect and well direct their resources and efforts where it is most necessary and effective.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

The wellbeing of the highway network has a large effect on the economic development of countries and states. This justifies the significant investments by governments and the private sector towards improving it. Aiming at decreasing life cycle costs of pavements, and building them in a more sustainable and eco-friendly manner, researchers and practitioners have developed new methods and technologies for the design, construction, maintenance and rehabilitations of paved roads.

Asphalt is the world's most used paving material, around 90% of Europe's and the U.S. paved roads are asphalt concrete pavements (European Asphalt Association, 2011). As a visco-elastic material, asphalt's behavior is a function of the climate, loading conditions, pavement structure and the asphalt mixture properties. Due to the high level of uncertainty associated with multiple variables affecting the asphalt material behavior, research in asphalt has been oriented towards the in depth understanding and accurate characterization of the material behavior, enhancing the mixture properties and altering the pavement structural design to better predict future road performance and reduce the associated variability of such predictions.

Currently, the most commonly adopted pavement design method is the AASHTO 1993 method. It is an empirical design procedure that builds on experimental data from the AASHO road test sections constructed in Ottawa, Illinois in the late 1950’s (Huang, 1993). The design equations use statistical regression models applied to observations and performance measurements of the test sections. However, material properties in addition to other critical design input variables, such as climate, traffic and subgrade properties are not properly incorporated (Lu et al., 2017). In an attempt to better understand the behavior of the constitutive materials of asphalt mixes and structures through research, the first Strategic Highway Research Program (SHRP) was formed. In 1984, the program launched the Long Term Pavement Performance test sections (LTPP) that lead to the introduction of the Superpave (SHRP, 1994) system for asphalt binder specifications and mix design methodology (Elkins, et al. 2003). In the 1990's, multiple National Cooperative Highway Research (NCHRP) projects were done and that led to introducing new asphalt mix characterization techniques and simple performance tests (Witczak et al., 2002).

## 1.2 Background

In 1998, The American Association of State Highway and Transportation Officials (AASHTO) Joint Task Force on Pavements (JTFP) started (NCHRP) Project 1-37A titled; Development of the Guide for Design of New and Rehabilitated Pavement Structures (ARA, 2004). This project resulted in developing a mechanistic-based design procedure for new and rehabilitated pavements, and in 2004, it delivered the ***Mechanistic-Empirical Pavement Design Guide*** **(MEPDG)**. The project was set to deliver, a guide for mechanistic-empirical pavement design and analysis, an accompanying software, a user manual, and implementation and training materials. Following project NCHRP 1-37A, projects 1-40A, 1-40B, 1-40D and 20-07 were undertaken to help in developing software tools and implementation guides (Darter, 2006).

Currently, the commercial version software tool based on the MEPDG design and analysis principles is the ***AASHTOWare Pavement-ME, version 2.3.1***. This software tool allows the users to perform the design and analysis of new pavement projects and rehabilitation projects. The intrinsic characteristic of Pavement-ME is that it addresses the major input variables that would affect the pavement performance such as:

- Traffic traversed and material and structural properties of the pavement.
- Temperature and moisture conditions within the pavement structure and subgrade through EICM (Enhanced Integrated Climatic Model).
- Time and climate dependent paving material properties.

Based on the input parameters, the software calculates the pavement responses to applied loads using *linear elastic finite element analysis***.** After computing the pavement response, the pavement damage and distresses are predicted using *empirical distress prediction models.*

The *distress prediction models* used in Pavement-ME are nationally calibrated for Northern America using data from the Federal Highway Administration (FHWA) Long-Term Pavement Performance (LTPP) program, which comprises of hundreds of surveyed pavement test sections from all over North America. States that were interested in implementing the Pavement-ME in their locality performed as a part of their implementation process local calibrations of some or all of the distress prediction models. For an authority to decide whether a local calibration is necessary in their context, a verification process must be undertaken (Chapter 2) and a decision should be made accordingly.

## 1.3 Research Problem

Many countries in the Middle East specially the Arabian Countries bordering the Arabian Gulf have witnessed a huge expansion in their road network in the last two decades as a way to support and diversify their economies. While the pavement design method adopted has been the AASHTO 1993 method, some authorities, especially those of KSA, UAE and Qatar, are interested in implementing mechanistic-empirical pavement design through the use of Pavement-ME. Such initiatives are being faced by the following major obstacles:

1- Absence or deficiency of pavement design inputs database that are necessary for insuring accurate and realistic results for this new design methodology.

2- Absence of test road sections to aid in the software distress prediction functions calibration process.

3- Absence of machines and technologies that could measure critical input parameters such as dynamic modulus and Weigh-in-Motion (WIM) stations.

4- Financial cost incurred with the efforts of implementation, which will require utilization of huge resources.

5- Absence or deficiency of logged historic climatic data.

6- Absence of human resources that are knowledgeable and trained on Pavement-ME.

Given the current situation, there is an urgent need for research and technology transfer that focuses on ways to render the adoption of mechanistic-empirical pavement design tools more appealing to countries other than the U.S.A and Canada.

## 1.4 Research Motive

The economies of KSA, UAE and Qatar are growing relatively better and more consistently than neighboring countries in the Middle East. Such growth is reflected in the expansion of infrastructure and in an increase of truck sales (Mathyssek et al., 2016). Saudi Arabia is in the process of diversifying its economy to reduce its dependence on oil, the country has witnessed a doubling in its truck sales in the last decade. The United Arab Emirates has a diversified economy with only one-quarter of its GDP being generated by oil and gas and that is mainly due to the country's openness to foreign investments. Qatar is experiencing growth in its oil and gas sector, manufacturing, construction and financial services, and is preparing for the 2022 World Cup by building a new port, roads and sports related infrastructure (Mathyssek et al., 2016). This growth and the need to diversify economies through consistent steps should be accompanied by building better, highly reliable, durable, less costly roads.

## 1.5 Research Objective

The objective of this research is to set the road map that authorities of KSA, UAE and Qatar should follow for the implementation of Pavement-ME in their practices, and that is through:

- Reviewing previous and ongoing implementation strategies.
- Identifying critical and sensitive input parameters.
- Recommending value ranges and sources for certain critical input parameters in Pavement-ME.
- Advising on how funds should be directed as per importance of certain data that should be collected.

- Assessing and proposing, if needed, a software empirical distress functions' calibration procedure.

## 1.6 Thesis Outline

The thesis is divided into 9 chapters; Chapter 1 introduces Pavement-ME, and the motive and objective behind implementing its use in KSA, UAE and Qatar in the Middle East.

Chapter 2 discusses the detailed functionality of Pavement-ME, the data needed for it and the way analysis it performs analysis. In addition, literature on how successful implementation processes, and attempts towards implementation from states in the United States and countries globally is reviewed.

Chapter 3 introduces the scope of the research and the methodology that will be followed.

Chapter 4 characterizes the Middle East and the current practice in pavement engineering in the countries understudy. In addition, this chapter compiles necessary data that characterizes sub-grade material, traffic, climate and acceptable road performance.

Chapter 5 presents the experimental plan followed and the Pavement-ME runs performed.

Chapter 6 discusses the results of statistical and sensitivity analysis performed on important input parameters.

Chapter 7 verifies whether a calibration of the empirical distress functions is needed for the Middle East.

Chapters 8 proposes a framework to calibrate distress functions as part of the implementation process.

Chapter 9 concludes on the findings of the thesis and recommends a roadmap for the implementation.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter presents an overview of the mechanistic-empirical pavement design method and the functionality of its associated software Pavement-ME. It also presents the Pavement-ME implementation attempts of state highway agencies in multiple states within the U.S.A., as well as other attempts from around the globe.

## 2.2 Mechanistic-Empirical Pavement Design Method

Mechanistic-empirical pavement design procedure requires advanced material characterization, comprehensive traffic characterization, and a history of the climatic data. The software uses those input parameters to mechanistically calculate the pavement responses in terms of stresses, strains and deflections then, using empirical transfer functions, predicts the actual distresses and performance in terms of International Roughness Index (IRI), cracking and rutting.

The software mechanistically computes the pavement response through the pavement response model based on the interaction between traffic, material used, pavement structure and climate. The computed response of the pavement is then translated into quantified distresses through the distress prediction model (Figure 2.1).

The reliability of this method is heavily dependent on the availability and accuracy of traffic, climate, pavement structure and materials input data that serve as reliable inputs for the models.

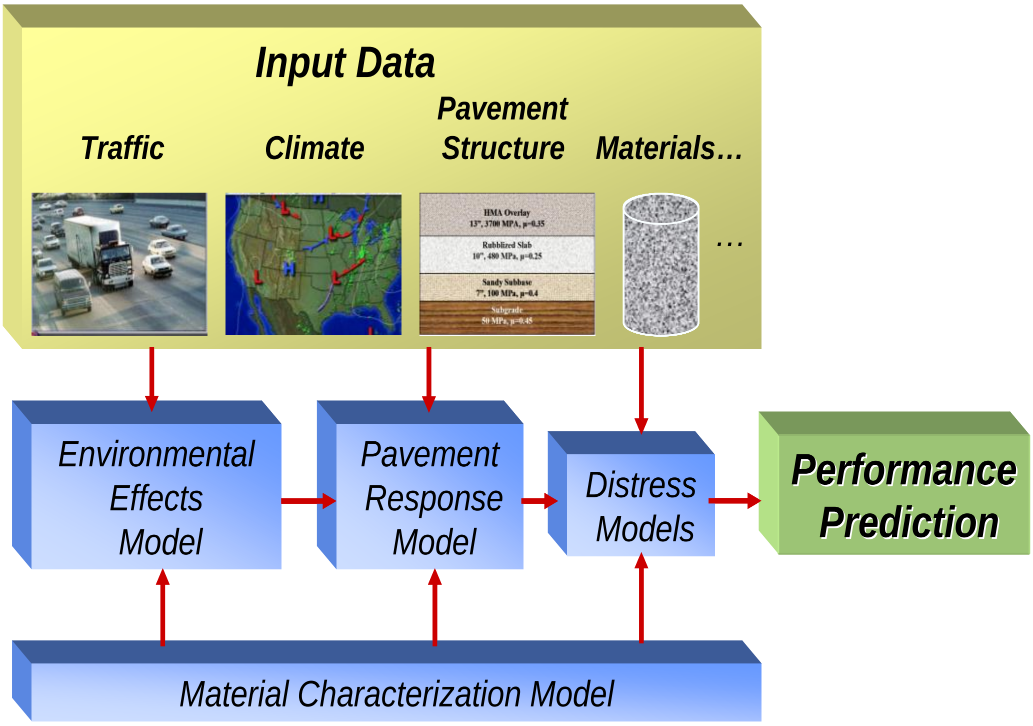
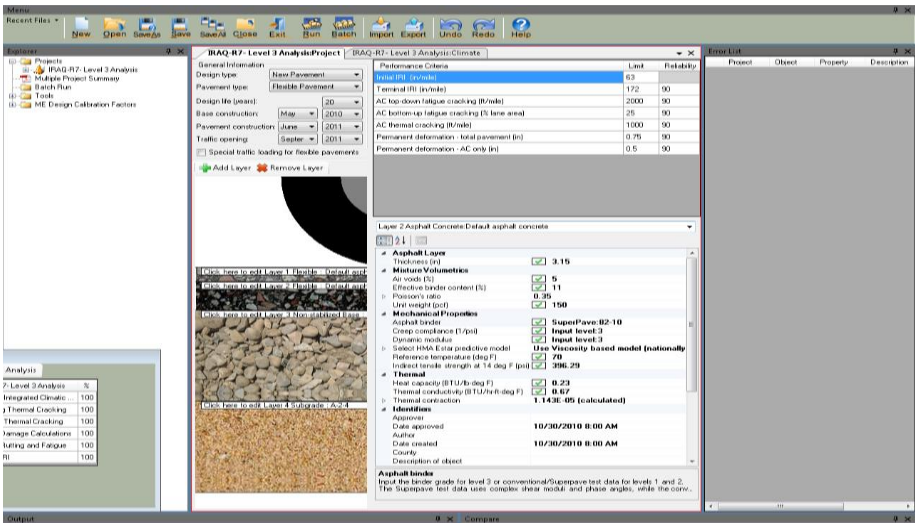


Figure 2.1: Performance Prediction Models in Pavement-ME (Daniel et al, 2012)

## 2.3 Software Interface & Input Parameters

When designing a flexible pavement using Pavement ME, the user has to define the characteristics of the four controlling categories: Climate, Traffic, Structure and Material (Figure 2.2).



General Information

Design type: New Pavement
Pavement type: Flexible Pavement
Design life (years): 20
Base construction: May 2010
Pavement construction: June 2011
Traffic opening: Septer 2011
☐ Special traffic loading for flexible pavements

| Performance Criteria | Limit | Reliability |
|---|---|---|
| Initial IRI (in/mile) | 63 | |
| Terminal IRI (in/mile) | 172 | 90 |
| AC top-down fatigue cracking (ft/mile) | 2000 | 90 |
| AC bottom-up fatigue cracking (% lane area) | 25 | 90 |
| AC thermal cracking (ft/mile) | 1000 | 90 |
| Permanent deformation - total pavement (in) | 0.75 | 90 |
| Permanent deformation - AC only (in) | 0.5 | 90 |

Layer 2 Asphalt Concrete:Default asphalt concrete

| | |
|---|---|
| **Asphalt Layer** | |
| Thickness (in) | ☑ 3.15 |
| **Mixture Volumetrics** | |
| Air voids (%) | ☑ 5 |
| Effective binder content (%) | ☑ 11 |
| Poisson's ratio | 0.35 |
| Unit weight (pcf) | ☑ 150 |
| **Mechanical Propeties** | |
| Asphalt binder | ☑ SuperPave:82-10 |
| Creep compliance (1/psi) | ☑ Input level:3 |
| Dynamic modulus | ☑ Input level:3 |
| Select HMA Estar predictive model | Use Viscosity based model (nationally |
| Reference temperature (deg F) | ☑ 70 |
| Indirect tensile strength at 14 deg F (psi) | ☑ 396.29 |
| **Thermal** | |
| Heat capacity (BTU/lb-deg F) | ☑ 0.23 |
| Thermal conductivity (BTU/hr-ft-deg F) | ☑ 0.67 |
| Thermal contraction | 1.143E-05 (calculated) |
| **Identifiers** | |
| Approver | |
| Date approved | 10/30/2010 8:00 AM |
| Author | |
| Date created | 10/30/2010 8:00 AM |
| County | |
| Description of object | |

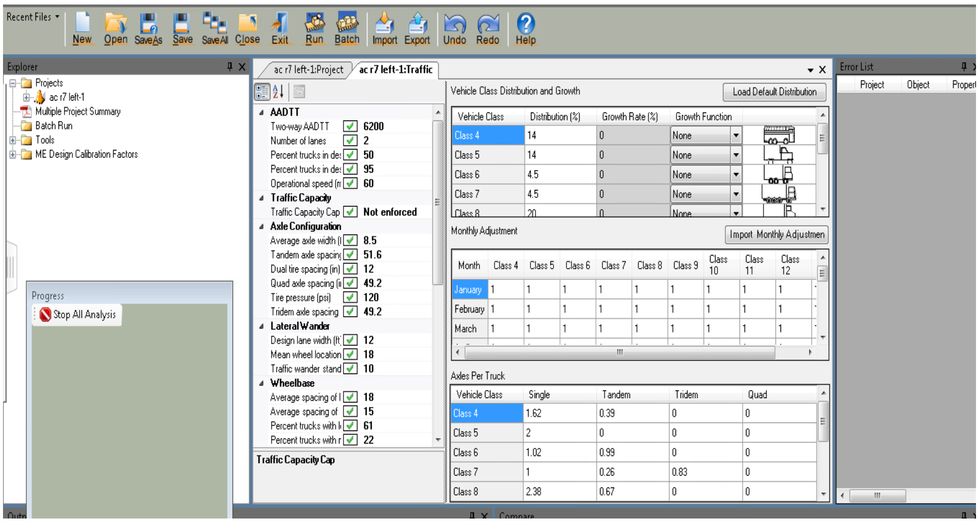
**Asphalt binder**
Input the binder grade for level 3 or conventional/Superpave test data for levels 1 and 2. The Superpave test data uses complex shear moduli and phase angles, while the conv...

Analysis

| 7- Level 3 Analysis | % |
|---|---|
| Integrated Climatic ... | 100 |
| g Thermal Cracking | 100 |
| Thermal Cracking | 100 |
| Damage Calculations | 100 |
| Rutting and Fatigue | 100 |
| RI | 100 |

Figure 2.2: Pavement-ME Main Interface

With more than 60 defined variables to consider while designing new Hot Mix Asphalt (HMA) pavements, the reliability of the design depends on how well do the default input parameters or the user defined ones reflect the reality of the traffic loading (i.e. Figure 2.3), climatic conditions, road structure and material properties in a certain country.



**AADTT**
Two-way AADTT ☑ 6200
Number of lanes ☑ 2
Percent trucks in de ☑ 50
Percent trucks in de ☑ 95
Operational speed (n ☑ 60
**Traffic Capacity**
Traffic Capacity Cap ☑ Not enforced
**Axle Configuration**
Average axle width (I ☑ 8.5
Tandem axle spacin ☑ 51.6
Dual tire spacing (in) ☑ 12
Quad axle spacing (i ☑ 49.2
Tire pressure (psi) ☑ 120
Tridem axle spacing ☑ 49.2
**Lateral Wander**
Design lane width (ft ☑ 12
Mean wheel location ☑ 18
Traffic wander stand ☑ 10
**Wheelbase**
Average spacing of I ☑ 18
Average spacing of ☑ 15
Percent trucks with I ☑ 61
Percent trucks with r ☑ 22
**Traffic Capacity Cap**

Vehicle Class Distribution and Growth

| Vehicle Class | Distribution (%) | Growth Rate (%) | Growth Function |
|---|---|---|---|
| Class 4 | 14 | 0 | None |
| Class 5 | 14 | 0 | None |
| Class 6 | 4.5 | 0 | None |
| Class 7 | 4.5 | 0 | None |
| Class 8 | 20 | 0 | None |

Monthly Adjustment

| Month | Class 4 | Class 5 | Class 6 | Class 7 | Class 8 | Class 9 | Class 10 | Class 11 | Class 12 |
|---|---|---|---|---|---|---|---|---|---|
| January | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| February | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| March | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

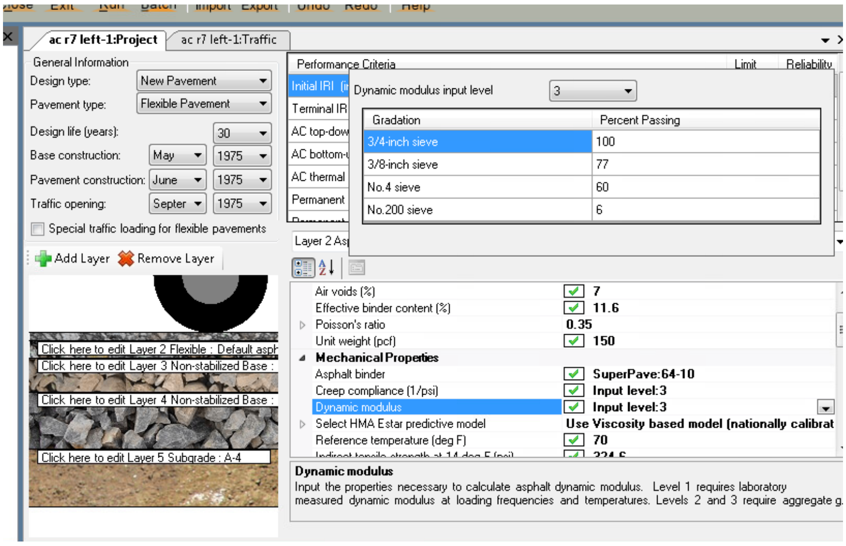
Axles Per Truck

| Vehicle Class | Single | Tandem | Tridem | Quad |
|---|---|---|---|---|
| Class 4 | 1.62 | 0.39 | 0 | 0 |
| Class 5 | 2 | 0 | 0 | 0 |
| Class 6 | 1.02 | 0.99 | 0 | 0 |
| Class 7 | 1 | 0.26 | 0.83 | 0 |
| Class 8 | 2.38 | 0.67 | 0 | 0 |

Figure 2.3: Input Parameters For Traffic Characterization

To solve the issue of lack of data in certain cases, the ME software provides three different levels of analysis:

- Level 3 which is the lowest level of analysis and reliability, the input values are software default values (Figure 2.4).
- Level 2, which is the intermediate level of analysis, users at this level might use default values and specific data together.
- Level 1 is the highest level of analysis and reliability that requires location specific parameters and lab testing for material properties (Figure 2.5).



General Information

Design type: New Pavement

Pavement type: Flexible Pavement

Design life (years): 30

Base construction: May 1975

Pavement construction: June 1975

Traffic opening: Septer 1975

☐ Special traffic loading for flexible pavements

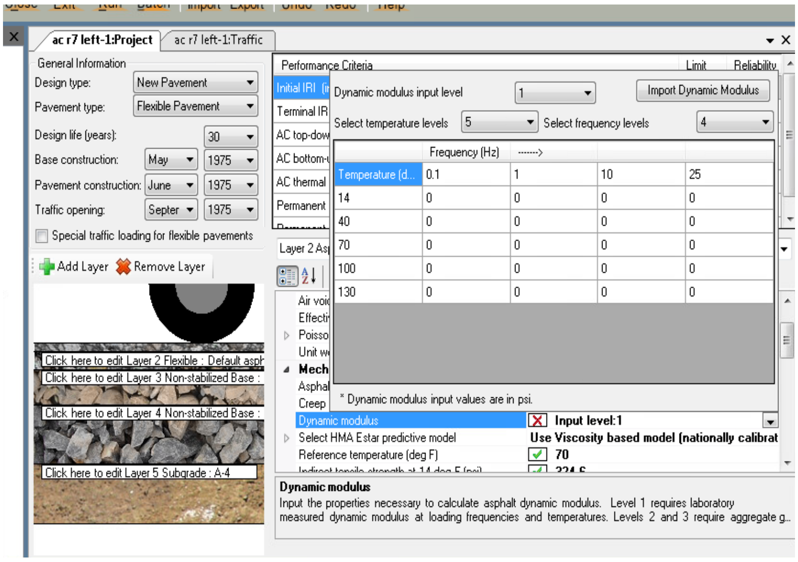
Dynamic modulus input level: 3

| Gradation | Percent Passing |
|---|---|
| 3/4-inch sieve | 100 |
| 3/8-inch sieve | 77 |
| No.4 sieve | 60 |
| No.200 sieve | 6 |

| | |
|---|---|
| Air voids (%) | ☑ **7** |
| Effective binder content (%) | ☑ **11.6** |
| Poisson's ratio | **0.35** |
| Unit weight (pcf) | ☑ **150** |
| **Mechanical Properties** | |
| Asphalt binder | ☑ **SuperPave:64-10** |
| Creep compliance (1/psi) | ☑ **Input level:3** |
| Dynamic modulus | ☑ **Input level:3** |
| Select HMA Estar predictive model | **Use Viscosity based model (nationally calibrat** |
| Reference temperature (deg F) | ☑ **70** |

**Dynamic modulus**
Input the properties necessary to calculate asphalt dynamic modulus. Level 1 requires laboratory measured dynamic modulus at loading frequencies and temperatures. Levels 2 and 3 require aggregate g

Figure 2.4: Characterizing HMA for Level 3 Analysis



General Information

Design type: New Pavement

Pavement type: Flexible Pavement

Design life (years): 30

Base construction: May 1975

Pavement construction: June 1975

Traffic opening: Septer 1975

☐ Special traffic loading for flexible pavements

Dynamic modulus input level: 1

Select temperature levels: 5

Select frequency levels: 4

| | Frequency (Hz) | -------> | | |
|---|---|---|---|---|
| Temperature (d... | 0.1 | 1 | 10 | 25 |
| 14 | 0 | 0 | 0 | 0 |
| 40 | 0 | 0 | 0 | 0 |
| 70 | 0 | 0 | 0 | 0 |
| 100 | 0 | 0 | 0 | 0 |
| 130 | 0 | 0 | 0 | 0 |

* Dynamic modulus input values are in psi.

| | |
|---|---|
| Dynamic modulus | ☒ **Input level:1** |
| Select HMA Estar predictive model | **Use Viscosity based model (nationally calibrat** |
| Reference temperature (deg F) | ☑ **70** |

**Dynamic modulus**
Input the properties necessary to calculate asphalt dynamic modulus. Level 1 requires laboratory measured dynamic modulus at loading frequencies and temperatures. Levels 2 and 3 require aggregate g...

Figure 2.5: Characterizing HMA for Level 1 Analysis

## 2.4 Types of Pavement Distresses

In order to expand the life of pavements to the fullest while maintaining high service and safety levels, roads should be properly surveyed and managed. The basis for any road management system is the definition of proper measurable performance criteria, and the availability of a decision making procedure that can conclude, from the collected data, the appropriate measures that should be taken.

The road performance indicators are measurable deformations that occur after road construction. Some deformations are due to varying issues such as structural design, chosen materials, construction, loading conditions, and maintenance plans. Such road surface deformations are manifested in the following:

1- Fatigue Cracking (FHWA, 2003): Measured in square meters in Long Term Pavement Performance Projects (LTPP) protocol and Pavement-ME. It occurs in areas subjected to repeated traffic loadings (wheel paths). It can be a series of interconnected cracks in early stages of development. It develops into many-sided, sharp-angled pieces, usually less than 0.3 m on the longest side, characteristically with a chicken wire/alligator pattern in later stages (Figure 2.6).

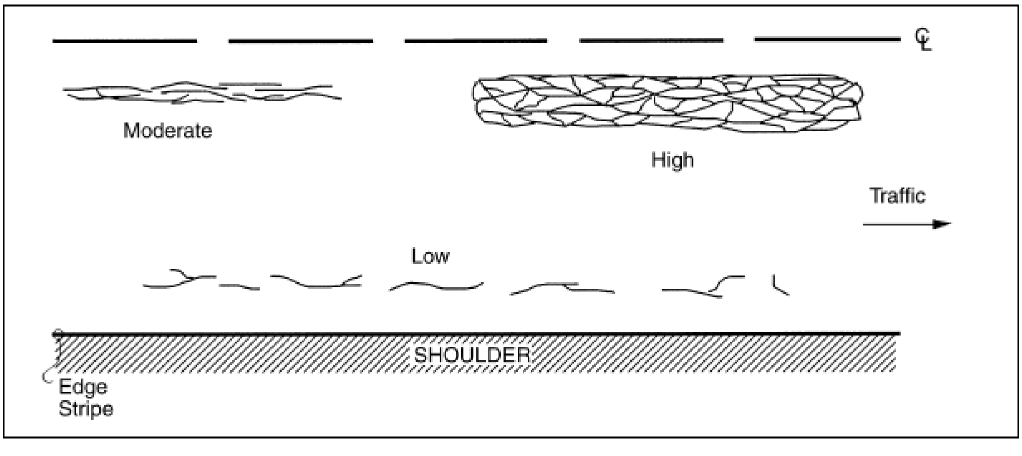


Figure 2.6: Fatigue Cracking Intensity (FHWA, 2003)

2- Longitudinal Cracking (FHWA, 2003): It measured in meter in LTPP protocol and Pavement-ME. Cracks predominantly are parallel to pavement centerline. Location within the lane (wheel path versus non-wheel path) is significant (Figure 2.7).

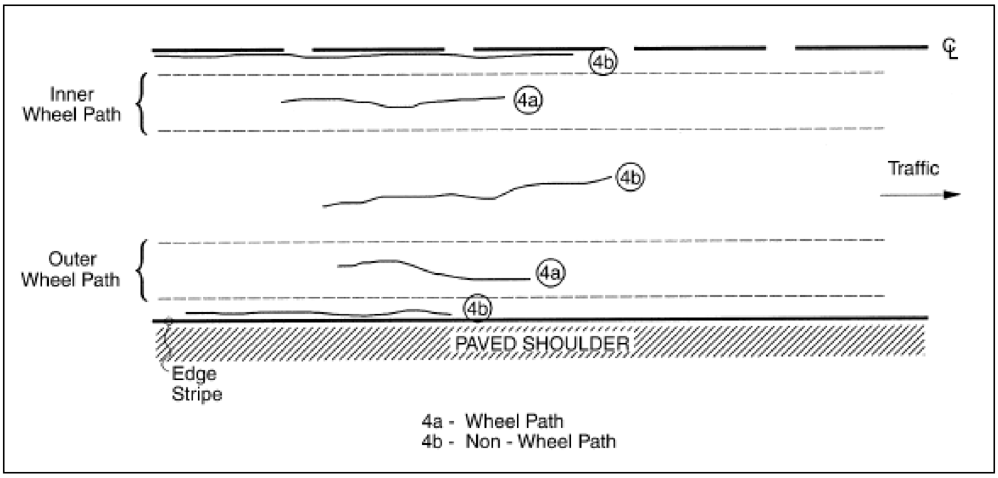


Figure 2.7: Longitudinal Cracking (FHWA, 2003)

3- Transverse Cracking (FHWA, 2003): It is measured in terms of the number of cracks per meter. Cracks that are predominantly perpendicular to pavement centerline, also known as thermal cracking, occur at low temperatures (Figure 2.8).

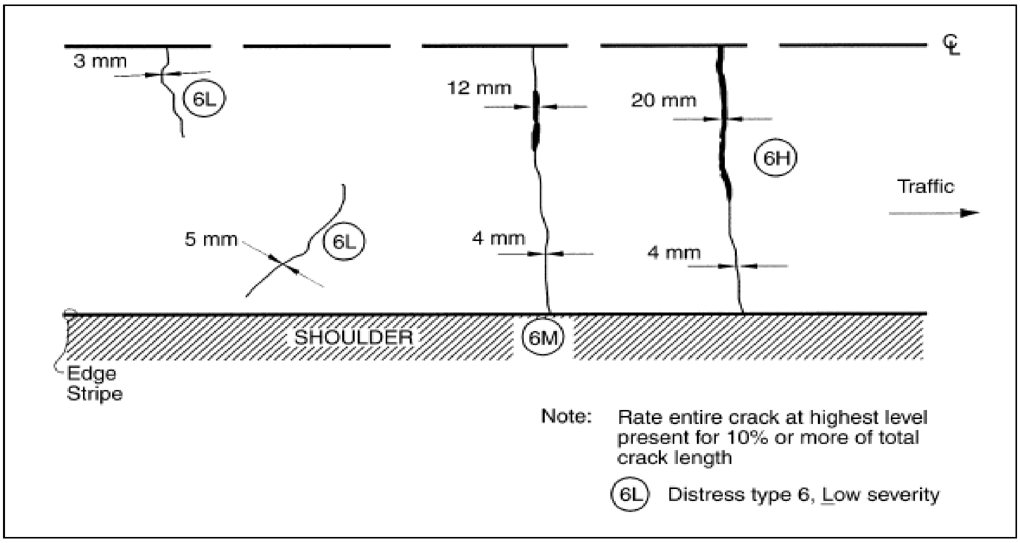


Figure 2.8: Transverse Cracking (FHWA, 2003)

4- Rutting (FHWA, 2003): It is measured in millimeters by a wire or straight edge in LTPP protocol and Pavement-ME. These are longitudinal surface depressions in the wheel path. It may have associated transverse displacement, usually occuring under high temperature or slow loading (Figure 2.9).

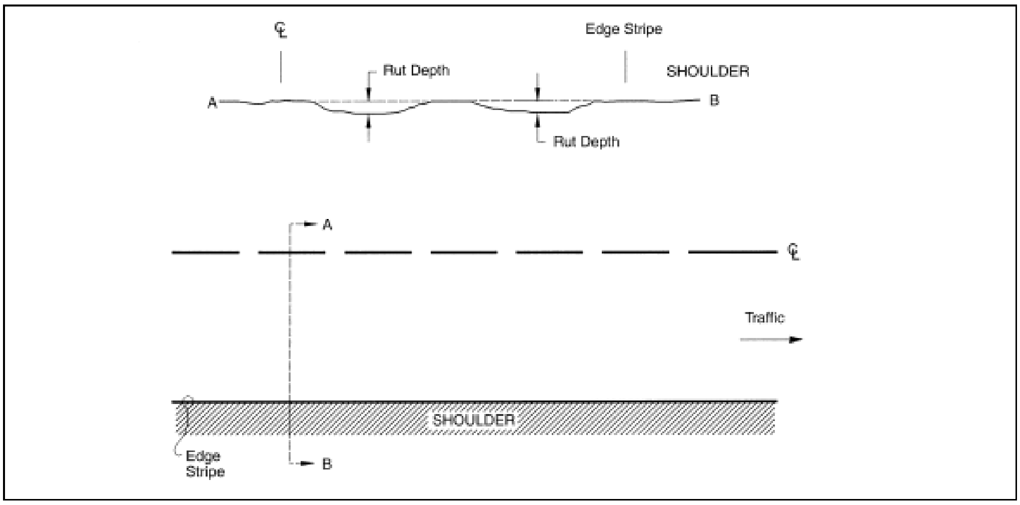


Figure 2.9: Rutting (FHWA, 2003)

Pavements could suffer from other defects such as bleeding, polished aggregate and raveling. All of those distresses impose a huge risk on the road’s level of service and safety. However, according to Huang (1993), it is generally agreed that fatigue cracking, rutting and low-temperature cracking are the three principal distress types effecting asphalt pavements.

In mechanistic empirical pavement design, the pavement is assessed based on:

- Terminal IRI (in/mile): Representative of the depressions and elevations in the surface of the road.
- Permanent Deformation- Total Pavement (inch)
- AC Bottom Up Fatigue Cracking (% of lane area)
- AC Thermal Cracking (ft/mile)

- AC Top Down Fatigue Cracking (ft/mile)
- Permanent Deformation- AC Only (inch)

## 2.5 Road Performance Indicators

The performance of the road is assessed based on the amount of distresses (rutting, cracks and IRI) and whether those predicted distresses will still be within the acceptable ranges during the service life of the pavement. The ranges of distresses are set to classify roads as very good, good, fair, poor or very poor. It is up to every road authority to classify those ranges, and decide on the thresholds that would trigger an act of maintenance or rehabilitation to sustain the road's level of service, comfort and most importantly, safety.

Based on performance surveys and this research's initial software simulations that reflect typical pavement engineering practices in the area understudy, major distresses due to the loading and climate context of the Middle East are *asphalt rutting* and *top down fatigue cracking*.

Various countries around the world manage their roads based on the distresses criteria mentioned in *section 2.3,* and more importantly, several countries are revolutionizing the way road projects are being delivered to be based on performance-based contracts. This type of contracts doesn't specify the process and specifications for building the road, the only thing that is agreed upon is the needed results and expectations. Such contracts are usually long term and can go up to 30 years (Gajurel, N.A.). The road owner will agree with one entity that will design, build and maintain the road on a set of measurable performance criteria, and specify the actions that should be taken upon faulting.

Some performance indicators, from Argentina and Uruguay, which contractors should abide by are presented in Table 2.1.

Table 2.1: Threshold Distress/IRI Values to Initiate Treatment

| **Country** | **IRI (in/mile)** | **Rutting Treatment (in)** | **Potholes** | **Cracks** |
|---|---|---|---|---|
| **Argentina** | 127 | 0.47 | No potholes | Always Sealed |
| **Uruguay** | 177 | 0.4 | No potholes | Always Sealed |

In the USA, instead of having long-term performance based contracts, state's departments of transportation take the responsibility of maintaining and rehabilitating the road network. Table 2.2 shows how multiple states assess their roads based on measurable criteria in order to prioritize acts of maintenance and rehabilitation. The optimal objective of every state is to rate all its roads at a good condition.

Table 2.2: Performance Thresholds for U.S. States

| **State** | **IRI (in/mile)** | **Rutting Treatment (in)** | **Cracks** |
|---|---|---|---|
| **Federal Highway Agency (FHWA)** | 170 | N/A* | N/A* |
| **Arizona** | 170 | N/A* | N/A * |
| **California** | 224 | N/A* | <30% wheel path area |
| **Indiana** | 170 | N/A* | N/A* |
| **Washington State** | 170 | 0.47 | N/A* |

**N/A might indicate that the indicator is not used in maintenance decision making, or that this condition is not binding by itself and the measured value of rutting is factored in an equation to come up with a full road rating.*

Based on the Ministry of Municipalities and Rural Affairs in KSA (MOMRA) Distress Identification Manual and Pavement Management Manual, the pavement condition rating is defined as shown in Table 2.3.

Table 2.3: Road Rut Rating by MOMRA KSA

| **Rutting (in)** | **Pavement Condition Rating** |
|---|---|
| 0.23-0.51 | Low |
| 0.51-0.98 | Medium |
| >0.98 | High |

In Abu Dhabi, the municipality has its own road rating based on performance measures. The roads are classified as shown in Table 2.4 (Al-kathairi, 2014).

Table 2.4: Road Performance Rating by Abu Dhabi Municipality

| **Road Condition** | **IRI (in/mile)** | **Rut Depth (in)** |
|---|---|---|
| Good | <126 | <0.38 |
| Fair | 126-190 | 0.19-0.38 |
| Poor | 190-240 | 0.38-0.78 |
| Very Poor | >240 | >0.78 |

## 2.6 Input Parameters as a Function of Level of Analysis

Table 2.5 compiles all the input parameters needed by Pavement-ME for the design of a new Hot Mixed Asphalt (HMA) pavement, and specifies the needed data to perform analysis at the three defined levels of analysis. Based on Table 2.5, two types of input parameters are differentiated; those that are independent of the level of analysis, and those that change based on the hierarchical level of analysis (Level 1, 2 or 3).

Table 2.5: Required Input for Parameters as a Function of Level of Analysis

| | | **Level 3** | **Level 2** | **Level 1** |
|---|---|---|---|---|
| **HMA** | Thickness (in) | Same data required | | |
| | As Constructed Air Voids (%) | Same data required through lab testing | | |
| | Effective Binder Content by volume (%) | Same data required through lab testing | | |
| | Poisson Ratio | Same data required | | |
| | Unit weight (pcf) | Same data required | | |
| | Asphalt Binder | Superpave performance grade or viscosity grade or penetration grade | Measure complex modulus and phase angle | Same as level 2 |
| | Creep compliance (1/psi) | ME design will calculate values | Measured creep compliance at 14 degree F | Lab measured creep compliance at -4 degree F, 14 degree F and 32 degree F |
| | Dynamic Modulus | Mix rock gradation | Mix rock gradation | Lab measured (E*) values |
| | Reference Temperature (deg F) | Same data required | | |
| | Indirect tensile strength (at $14^0$F in psi) | Same data required | | |
| | Heat Capacity (BTU/lb.deg F) | Selected based on agency historically measured values | | |
| | Thermal Conductivity | User selects based on historical values | | |
| | Thermal Contraction | Calculated | | |
| **Base,sub-base and sub-grade** | Coefficient of lateral earth pressure (k0) | Default value is used | | |
| | Layer Thickness (in) | Same data required | | |
| | Poisson's ration | Default value used 0.35 | | |
| | Resilient modulus (psi) | Annual representative value or software changes valuesbased on temperature/moisture | Monthly values | Not available |
| | Gradation and engineering properties | AASHTO classification, Sieve Analysis, PI, LL, Maximum dry unit weight (pcf), Saturated hydraulic conductivity (ft/hr),Specific gravity of solids, Water content (%), User-defined soil water characteristics curve | | |
| **Traffic** | Two-way AADTT | Same data required (design capacity) | | |
| | Number of lanes | Required User Input | | |
| | Percent trucks in design direction | Required User Input | | |
| | Percent trucks in design lane | Required User Input | | |
| | Operational speed (mph) | Required User Input | | |
| | Traffic capacity cap | Required User Input | | |
| | Average axle width (ft) | Required User Input | | |
| | Tandem axle spacing (in) | Required User Input | | |

| | | |
|---|---|---|
| | Dual tire spacing (in) | Required User Input |
| | Quad axle spacing (in) | Required User Input |
| | Tire pressure (psi) | Required User Input |
| | Tridem axle spacing (in) | Required User Input |
| | Design lane width (ft) | Required User Input |
| | Mean wheel location (in) | Required User Input |
| | Traffic wander standard deviation (in) | Required User Input |
| | Average spacing of long axles (ft) | Required User Input |
| | Average spacing of medium axles (ft) | Required User Input |
| | Percent trucks with long axles | Required User Input |
| | Percent trucks with medium axles | Required User Input |
| | Percent trucks with short axles | Required User Input |
| | Average spacing of short axle | Required User Input |
| | Vehicle class distribution and growth | Required User Input |
| | Monthly traffic adjustment | Required User Input |
| | Axles per trucks of a certain truck | Required User Input |
| **Climate** | Hourly climate data | Required User Input |
| | Station elevation (ft) | Required User Input |
| | Climate station name | Required User Input |
| | Latitude decimals degrees) | Required User Input |
| | Longitude (decimal degrees) | Required User Input |
| | Depth of water table (ft) | Required User Input |

The collection of the needed data requires numerous tests to characterize materials, and laborious field work. Those efforts need huge financial and human resources, a thing that would make authorities hesitant, and shy away from progressing in a real transformation towards mechanistic-empirical software. A lot of research was put in determining the input parameters with the most importance, so that authorities could utilize their resources in the most efficient ways. The most critical parameters as a function of the distress types are presented in Table 2.6 (Ayyala et al., 2009):

Table 2.6: Critical Input Variables as a Function of Distress Type

| **Pavement Type** | **Distress Type** | **Critical Input Variables** |
|---|---|---|
| **New HMA** | Longitudinal (top-down) cracking in the wheel path | HMA mix stiffness<br>Foundation support (base/subgrade resilient modulus)<br>HMA thickness |
| | Transverse (thermal) cracking | Binder type<br>HMA thickness<br>HMA strength<br>HMA creep compliance<br>Coefficient of thermal contraction |
| | Fatigue (bottom-up) cracking | HMA thickness<br>Binder content<br>HMA mix stiffness<br>Percent air voids |
| | Rutting | HMA gradation<br>HMA mix stiffness<br>HMA thickness<br>Base/sub-grade resilient modulus |

## 2.7 Pavement-ME Software Implementation Initiatives

### 2.7.1 *The United States of America*

Many states in the U.S.A. are far ahead in the implementation of the Pavement-ME design software and that is due to the availability of a reliable data base needed for input, in addition to hundreds of test sections that are used for the calibration of the distress models. Pavement-ME software is globally calibrated under NCHRP 1-37A and 1-40 projects using a representative database of test sections monitored by the Long Term Pavement Performance (LTPP) project only in North America. But due to the huge variation of the climate, materials, construction and maintenance practices across North America, local authorities have to do local software calibration of the transfer functions for the best prediction of the road performance based on “Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide”. Even though this experimental procedure is identified as "local calibration", this process usually involves local verification, followed by calibration, followed by validation of the software (Robbins et al., 2017).

**Verification:** “Verification of a model examines whether the operational model correctly represents the conceptual model that has been formulated.” It should also be noted that field data are not needed in the verification process, as it is “primarily intended to confirm the internal consistency or reasonableness of the model. The issue of how well the model predicts reality is addressed during calibration and validation” (Von Quintus, 2011).

**Calibration:** “A systematic process to eliminate any bias and minimize the residual errors between observed or measured results from the real world (e.g., the measured mean rut depth in a pavement section) and predicted results from the model (e.g., predicted mean rut depth from a permanent deformation model). This is accomplished by modifying empirical calibration parameters or transfer functions in the model to minimize the differences between the predicted and measured results. These calibration parameters are necessary to compensate for model simplification and limitations in simulating actual pavement and material behavior" (Von Quintus, 2011).

**Validation:** "A systematic process that re-examines the recalibrated model to determine if the desired accuracy exists between the calibrated model and an independent set of measured data. The calibrated model required inputs such as the pavement structure, traffic loading, and environmental data. The simulation model must predict results (e.g., rutting, fatigue cracking) that are reasonably close to those measured in the field. Separate and independent data sets should be used for calibration and validation. Assuming that the calibrated models are successfully validated, the models can then be recalibrated using the two combined data sets without the need for additional validation to provide a better estimate of the residual error" (Von Quintus, 2011).

#### 2.7.1.1 Indiana

The state of Indiana (INDOT) began evaluating the Pavement-ME in 2002 and reached a full implantation in 2009 (Timm et al., 2014). According to Pierce and McGovern (Pierce et al, 2014), the implementation plan of Indiana, which is the only state up until 2014 who has fully adopted Pavement-ME, included the following:

- Review current state of knowledge in pavement engineering and management
- Review and document hierarchical design input parameters for each level of design accuracy.

- Review and document relevant data contained in the Indiana DOT and LTPP databases
- Review the readiness of laboratory and field equipment needed for quantifying higher level Pavement-ME inputs.
- Acquire needed equipment and develop a testing program.
- Develop and execute a plan to establish:
    - Local calibration and validation of distress prediction models
    - Regions and segments for traffic input module
    - Populate software with additional climatic data
- Establish "mini LTPP" program to more accurately calibrate Pavement-ME performance prediction models
- Develop correlations and equations for soil resilient modulus, load spectra regions and segments based on existing WIM (weigh-in-motion) and AVC (automated vehicle classification) data and a process to aid designers in easily migrating traffic data into the software
- Provide technology and knowledge transfer and Pavement-ME training to other divisions, district, local agencies, contractors and consultants
- Revise INDOT Design Manual Chapter 52, Pavement and Underdrain Design Element

#### 2.7.1.2 Georgia

The U.S. state of Georgia proposed a plan to implement Pavement-ME and that was done through three consecutive task orders (Von Quintus et al, 2016):

- Task Order 1:
  - Task 1: Literature Search/Synthesis and two draft verification work plans
  - Task 2: Verification using LTPP Test Sections located in Georgia
- Task Order 2:
  - Task 3: Development of a Sampling Matrix and Selection of Non-LTPP sites for calibration
  - Task 4: Calibration of the distress transfer functions
- Task Order 3:
  - Task 5: Validation of the distress transfer function
  - Task 6: Design manual
  - Task 7: Final Report

The action plan used by these two states is similar and represents the proper methodology for the implementation of the ME pavement design, such an action plan could be summarized as follows:

1- Reviewing the current state of knowledge, practice and maintenance.

2- Reviewing the design input parameters and the level of accuracy that could be provided.

3- Verifying whether the set calibration of the transfer functions could be dependable under the prevailing conditions.

4- Pursuing calibration of certain or all distress transfer functions.

5- Validating the new distress functions.

#### 2.7.1.3 Other States

The state of Virginia developed a catalogue for the aggregate base layer resilient modulus, for two aggregate gradations specified by the VDOT, for aggregates from mining sites used for construction in the state. The catalogue values could be used for level 1 or level 2 types of input in the Pavement-ME software (Hossein et al. 2015). The state of Texas (Lee et al., 2017) also generated a database of material properties and performance data in order to be used in the ME models. Data collected was extensive and included laboratory results for asphalt binder, HMA mix, base and sub-grade soils, climatic data, traffic data, and test sections field performance data. Most of the U.S. states pursued or are pursuing efforts to enhance their databases of important input parameters, in addition, many states stepped to the next level of the implementation process and initiated efforts towards the calibration and validation of Pavement-ME, examples on that are Indiana, Texas (Lee et al, 2017), Kansas (Sun et al. 2015), Georgia (Von Quintus et al. 2016) etc.

### 2.7.2 *Outside Northern America*

Though many countries do use mechanistic empirical methods for pavement design (Costa Rica (Avila-Esquivel et al, 2017), South Africa (Theyse et al, 2007)…), the tools used are not Pavement-ME. Initiatives on implementing Pavement-ME itself are still focused in Northern America and in many regions globally such as Latin America, and countries in Europe and the Middle East.

In the KSA, Khattab et al., (2014) evaluated the Witczak Dynamic Modulus (E*) predictive models for the evaluation of the Pavement-ME design in KSA. The report concluded that NCHRP 1-37A provided better (E*) predictions compared to NCHRP 1-40D and that most accurate results and least biased ones were when level 3 binder characterization input was used (Khattab et al., 2014). Efforts for the collection of a database in KSA are supported by governmental interests in the fast implementation of the ME design. The KSA already has its Superpave specifications since 2005 (KSA Ministry of Transport, 2006) and research is moving forward to support the ambitions of the government.

Caliendo, (2012) noted that no papers explained how to use Pavement-ME in countries other than Northern America, and this was the motivation for an implementation study in Italy. The author worked on defining the trucks available on Italian roads and aggregated them in a way that is suitable with the Pavement-ME classification. For the climate conditions, and due to the unavailability of detailed Italian climatic files, it was decided that the weather file of Huntsville, Alabama in the U.S. represented the climate of central Italy. For binder characteristics, volumetric compositions and material specifications were used from the Italian Standard and conventional penetration grade was used for the prediction of (E*). Since test sections were not available in Italy, the Pavement-ME calibration of distress models was performed through comparison between the pavement performances predicted from the Pavement-ME and those predicted from theoretical equation/assumptions prevalently made in Italy.

Efforts were done in Egypt to collect a proper database suitable for Pavement-ME input from 16 different climate stations around Egypt (Elshaeb et al., 2014). And surveys and recommendations were done regarding truck tire pressure (Ebrahim et al., 2013). Sadek et al. (2014) also showed that Qatar is putting efforts into better understanding the input parameters that are best suited to their actual conditions, and Pavement-ME is being put into practice accordingly, using relevant material input.

# CHAPTER 3

# REASERCH SCOPE AND METHODOLOGY

## 3.1 Introduction

The conducted research to achieve the objective stated in Chapter 1 divides the implementation into two very important tasks as illustrated in Figure 3.1. Task one discusses the software input parameters through two sub-tasks that are recommending the hierarchical level of input for the most important parameters and highlighting the special considerations that are unique to the regions understudy in the Middle East. Two of the objectives of this task as well are; (1) ability to provide catalogue value or value ranges for certain parameters when possible, and (2) advising on the testing procedure that should be utilized by agencies to generate input parameters, when catalogue values can't be used as is.

The second task discusses the calibration of Pavement-ME distress prediction models, which might prove to be a necessary part of the implementation effort by agencies.

If research showed that calibration is required, one of the objectives of this task will be to provide a framework for calibration, based on the resources that could be utilized in the Middle East countries.

Those research tasks will control the type of data collected and the research scope and methodology will be coherent with the explained outline.

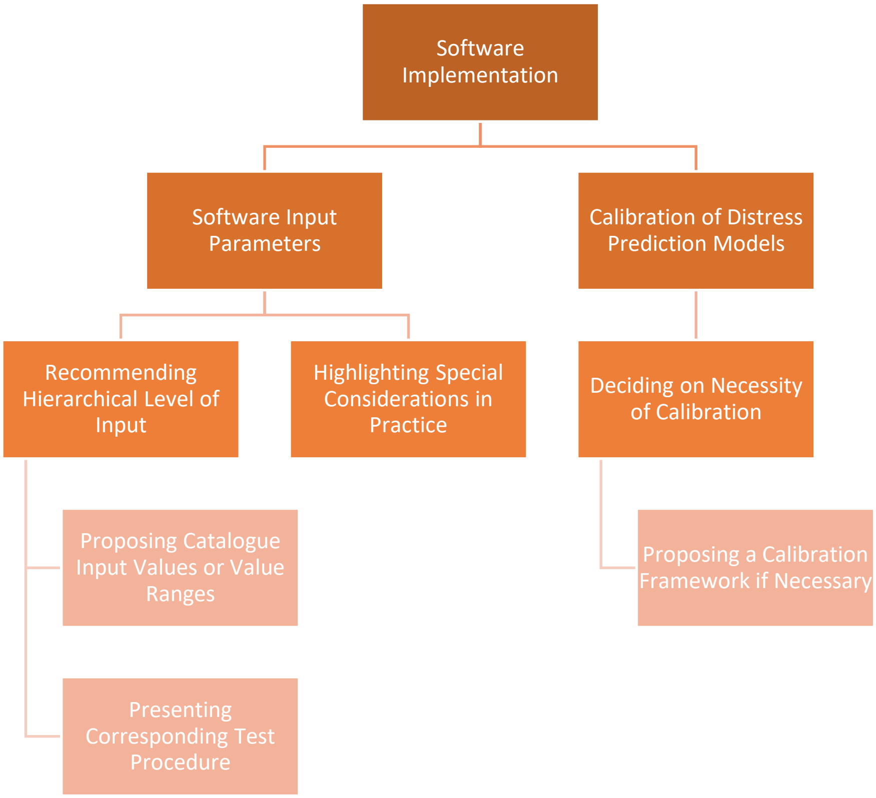


Figure 3.1: Outline of Research Approach

## 3.2 Research Scope

This research utilizes Pavement-ME to perform simulations that will allow statistical and sensitivity analysis on the variation of the predicted distresses as a function of Pavement-ME input parameters. In addition to that, the need for the calibration of distress prediction models will be verified.

### 3.2.1 *Pavement-ME Simulations*

The simulations are based on data acquired from research in the American University of Beirut and from a database of a pavement design consulting firm active in the Middle East.

Available data used in the research are:

- Four HMA mixes characterized at the materials lab in the American University of Beirut for the values of their dynamic modulus and the shear modulus of the binder used, two of those mixes use PG82-10 binders and one mix uses a PG88-10 binder. Dynamic modulus of mixes A, B and shear moduli of mixes A, B and C are attached in appendix A.

Table 3.1: Mix Designation and Type of Binder

| Mix Designation | Mix Description | Binder Grade | NMAS (mm) |
|---|---|---|---|
| **Mix A** | Polymer modified HMA mix | PG82-10 | 19 |
| **Mix B** | Polymer modified HMA mix | PG82-10 | 19 |
| **Mix C** | Polymer modified HMA mix | PG88-10 | 19 |
| **Mix D** | Unmodified Binder | PG64-10 | 19 |

- Structural details, material used, traffic volumes and types in addition to recorded distresses of multiple segments of Freeway 1 in Iraq (Appendix B).
- Traffic configurations by type of truck from multiple locations in KSA, Iraq and Lebanon. (Appendix B)

The simulations generated reflect the *structural design* of roads capable of withstanding, without any of the distressing reaching failure limits, a truck traffic of up to 15 million Equivalent Single Axle Load (ESALs) for road A (Figure 3.1), 30 million ESALs for road B (Figure 3.2) and 45 million ESALs for road C (Figure 3.3) in the climatic conditions of the East of the Arabian Peninsula, which is the hottest.

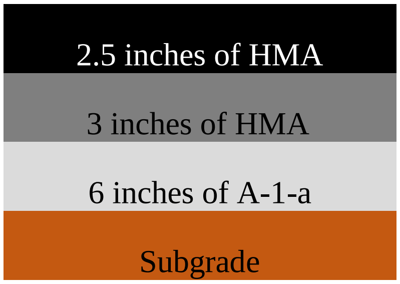


Figure 3.2: Road Structure for 15 million ESAL Traffic

Figure 3.3: Road Structure for 30 million ESAL Traffic

Figure 3.4: Road Structure for 45 million ESAL Traffic

#### 3.2.1.1 Tolerable Distress Limits

As for identifying the tolerable distress limits. Based on the global and local practices and performance measures discussed in Chapter 2, the distress limits that will be considered as a road failure when reached are:

Table 3.2: Acceptable Distress Limits

| | |
|---|---|
| **IRI (in/mile)** | **170** |
| **Rutting- Total Pavement (in)** | 0.75 |
| **Top Down Fatigue Cracking (ft/mile)** | 2000 |
| **Bottom Up Fatigue Cracking (% lane area)** | 25 |
| **Rutting- Asphalt Layer (in)** | 0.5 |

### 3.2.2 *Statistical Tools Used*

The set of statistical tools that will be used include:

1) t-test to assess the effect of each variable on AC rutting and top down fatigue cracking. An alpha (ɑ) of 0.05 was used to test for statistical significance.

2) The one way ANOVA was used to assess the effect of certain variable on AC rutting and top down fatigue cracking under different road structures, materials and traffic scenarios. Similar to the t-test, an (ɑ) of 0.05 was adopted to test for statistical significance.

*Sensitivity Analysis:*

A- If a change in a certain parameter produced results that are statistically the same, the parameter is identified as having a low impact on the distress understudy. Consequently, a set of predetermined values or a value range could be prescribed as input parameters.

B- If the change in a certain parameter produced results that are statistically different, sensitivity analysis will be performed as per *section 5.2.3*.

### 3.2.3 *Sensitivity Analysis Tools*

If the statistical analysis between two samples showed a statistical difference, it was assessed whether the change in predicted distresses has an implication on the lifetime of the pavement. Thus, sensitivity analysis was needed to decide if the input parameter value should be determined, or if generic catalogue values could be used.

It is acceptable in pavement engineering to have a certain road reach its distress limits after operating for 90% of the lifetime it was designed for. So if a pavement is designed to reach 0.5 inches of asphalt rutting after 20 years of operation, it is not considered a failure if this 0.5 inches occurred after 18 years. In other words, road designers are willing to accept rutting reaching 0.5 inches and an addition margin. Due to the damage not being linear, Pavement-ME runs will be generated in order to define the AC rutting and top down fatigue cracking values at 20 years, if limits are reached at 18 years. The percentage error accepted is then calculated.

Based on Pavement-ME runs, a damage of 0.5 inches at 18 years will increase to be 0.527 at 20 years which means the allowable error for rutting is 6%. If a change in a certain input parameter causes more than 6% change in rutting, the parameter will be considered as a sensitive parameter and will require accurate characterization.

Similarly, a damage of 2000 ft/mile of top down fatigue cracking at 18 years will increase to be 2082 ft/mile after 20 years of operations, which means that the allowable error for top down fatigue cracking is 5%. If a change in a certain input parameter causes more than 5% change in top down fatigue cracking, the parameter will be considered as a sensitive parameter and will require accurate characterization.

## 3.3 Research Methodology

The methodology adopted was comprised of three steps: **(1)** Establishing an experimental plan of Pavement-ME simulations to recommend the hierarchical level of characterization of input parameters and propose catalogue input values. **(2)** Assessing whether a calibration of the empirical transfer functions is necessary for the region understudy, and that is through a set of Pavement-ME simulations. **(3)** Establishing a step by step framework for road authorities to calibrate Pavement-ME to their conditions. To fulfill these goals, the following steps were followed:

A- Conducting literature review to build a database of:

- Current pavement construction specifications and mix designs by respective highway agencies in KSA, UAE and Qatar.
- Climate data and variation in the Middle East.
- Traffic conditions, classifications and growth in K.S.A., U.A.E. and Qatar.
- Material selections and sub-grade conditions.

B- Deciding on the acceptable distress limits by the end of the pavement lifetime.

C- Performing a set of Pavement-ME simulations using Road B mentioned above in order to select, the truck classification causing most and least damage in terms of top down fatigue cracking and AC rutting. Those runs will be used to select the two traffic classification that will be employed in the experimental plan using Pavement-ME below.

D- Running Pavement-ME simulation on the specified roads in *section 3.2.1,* at a level 1 hierarchical characterization of HMA, based on the experimental plan shown in Figure 3.5.

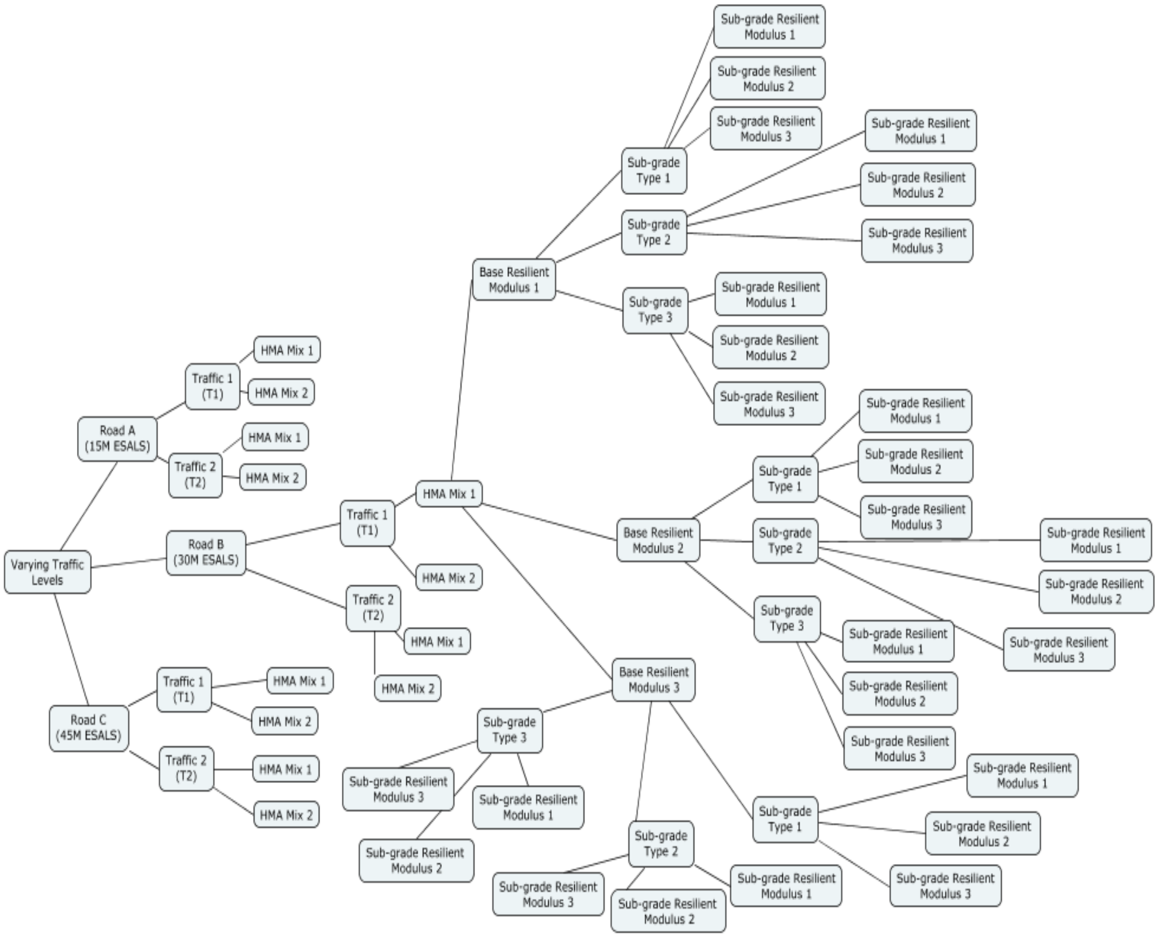


Figure 3.5: Experimental Plan of Pavement-ME Simulations

E- Certain simulations are selected in order to perform the same analysis but under a hierarchical level 2 HMA characterization:

1. The three best performing roads of every mix type and of every traffic type are selected.

2. Every road should have a different type of sub-grade soils.

F- Statistical and sensitivity analysis is performed to assess input parameters in accordance with the experimental plan discussed in *section 5.4*.

**Details of the second step**:

A- Simulating the surveyed test sections from Iraq while using the real structural, material, traffic and climatic conditions as described in section 3.2 above.

B- Comparing results predicted by Pavement-ME with surveyed distresses from the field.

C- Comparing the surveyed distresses to calibrated Pavement-ME transfer functions from:

- The hottest regions of the U.S.A state of Texas which has a climate similar to the one prevailing in the actual location of the road in parts of it.
- The state of Virginia which shared its data and distress surveys with researchers at the American University of Beirut making it easily available. This state will be used to prove the importance of local calibration even in some regions of northern America.

D- Recommending whether a specific calibration of the transfer functions is a must or if calibrated models from these two U.S. states could be used or if no calibration is needed at all.

E- Proposing local calibration coefficients for the AC rutting prediction model, as an example of how calibration should take place.

**Details of the third step:**

A- Reviewing literature on Pavement-ME calibration attempts using Pavement Management Systems (PMS).

B- Checking the state of pavement management practices used by authorities under study.

C- Establishing the step by step guide for a proper Pavement-ME calibration effort using Pavement Management Systems (PMS).

# CHAPTER 4

# THE MIDDLE EAST AND LOCAL ENGINEERING PRACTICE

## 4.1 Introduction

This chapter discusses the geopolitics, climate, soil land cover and traffic properties of the Middle East that will serve as input parameters for Pavement-ME. In addition, the current way of practice used for pavement design and construction by local highway agencies is presented.

## 4.2 The Middle East

The Middle East is defined as the area encompassing the countries of Western Asia (Lebanon, Syria, Jordan, Palestine, Iraq and Iran) the Arabian Peninsula (Kingdom of Saudi Arabia, United Arab Emirates, Qatar, Kuwait, Oman and Yemen) and North Eastern Africa (Egypt).

The dominant climate in the region is illustrated in Figure 4.1. The Koppen-Geiger Climate classification of countries vary between a hot desert climate dominant in the Arabian Gulf, Iraq, Southern Syria and coastal parts of Iran, Semi-arid climates in interior regions of Iraq, Syria and Iran and a warm Mediterranean climate in Lebanon, Palestine, and the coast of Syria.

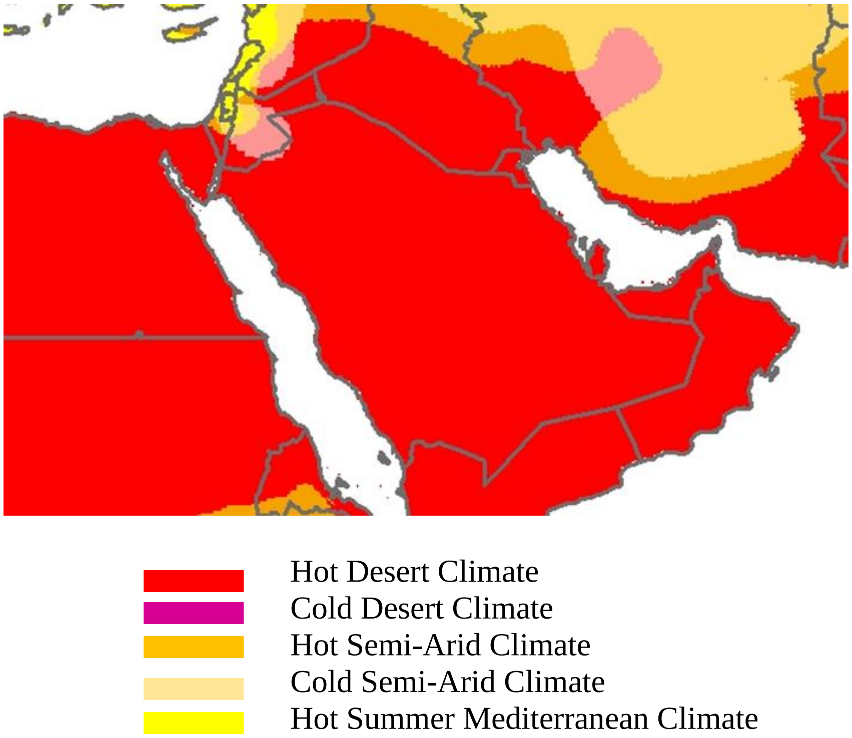


Figure 4.1: Koppen Climate Classification of the Middle East

The main focus of this study is the area of the Arabian Peninsula which is formed of 3 main sandy terrains: An-Nafud desert in the north, Al Rub' Al Khali (empty quarter) desert in south and south eastern KSA, both are connected by a sandy corridor named Ad-Dahna desert. According to Ehlen (1992) soil analysis showed that sand in the desert areas is fine sand. The western region of the Arabian Peninsula is dominated by the Tuwaiq escarpment and valleys. The eastern region is formed of sandy plains, classified by Ehlen (1992) as coarse sand in some areas, gravelly sand in other areas in addition to some gravelly loamy sands towards the northern borders with Iraq and Jordan Ehlen (1992). The geopolitical map of the Arabian Peninsula is shown in Figure 4.2.

Figure 4.2: Geopolitical Map of Arabian Peninsula

## 4.3 Climate of the Arabian Peninsula

The climate in the Arabian Peninsula is an arid desert climate characterized by high temperatures during the summer and very cold nights during the colder periods of the year.

Average daily temperatures during the relatively hottest months of June, July and August are between $40^0$C and $45^0$C with a record high of $53^0$C reached.

Average daily temperatures of the colder months of November, December, January and February range between $9^0$C and $11^0$C with the record lowest temperature reaching -$1^0$C.

Rainfall varies between areas of the Peninsula, but in general, it receives very few rain year round.

## 4.4 Sub-Grade Material in Arabian Peninsula

It is a necessity to characterize the top soils that are going to perform as a sub-grade material for the asphaltic pavements. A major initiative was taken in 1992 by King Abdulaziz City for Science and Technology (KACST) aiming at:

1- Investigating typical resilient modulus values of various roadbed soils encountered in different regions of Saudi Arabia.

2- Correlating Resilient Modulus ($M_r$) values with other physical and mechanical properties of soil.

3- Addressing the effect of soil classification, moisture content, relative compaction, anticipated loading and confining pressure on ($M_r$) values for these roadbed soils.

According to Al-Suhaibani et al. (2001) who summarized the project findings, samples were collected from all over the major Saudi Highways in intervals of 40 km over a total length of 6440 km of roads, pits were excavated 20 meters away from the edge of the pavement. 54% of the samples collected were classified as AASHTO type A-2-4 soil while other soil samples spanned over multiple soil types. Al Refai et al. (2001) aimed at studying the effect of moisture on the resilient modulus of KSA soils and collected a set of samples from near the edge of Saudi highways 0.5 m below the ground surface in 40 km intervals. Results of the corresponding AASHTO classifications are shown in Figure 4.3.

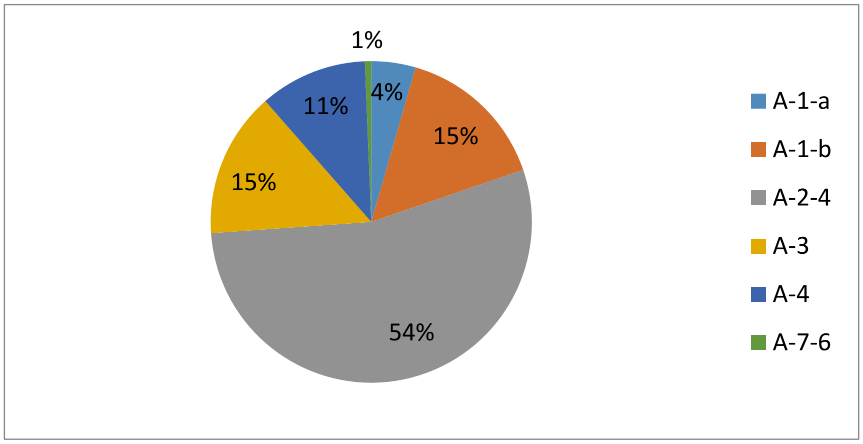


Figure 4.3 Top Soil AASHTO Classification of KSA

Similar reports from the state of Qatar indicate that the most prevalent natural top soils are of type A-2-4 and A-1-b (Sadek et al., 2014). The sub-grade in addition to its composition, Atterberg limits and CBR for the KSA based on the Al Suhaibani et al. (1999) study were shown in Appendix E.

While all soil types were available, the most dominant sub-grade is the A-2-4 type. It is shown from the table that the California Bearing Ratio (CBR) for every soil type varies; CBR of soil type A-2-4, for example, varies between 21 and 46. CBR is an indication of the resilient modulus (Mr) and (Mr) can be calculated from CBR as follows Mr= 2555 x (CBR)^0.64. (FHWA, 2006)

### 4.4.1 ***Special Considerations: Sabkha and Expansive Soils***

#### 4.4.1.1 Sabkha Soil

Sabkha is an Arabic term that describes silt, clay, muddy, Aeolian sand that is saturated with brine and is salt encrusted (Powers et al, 1966). It is very common in the coastal regions of the Arabian Peninsula and in some inland areas as described in Figure 4.4. Though it is not right to assume that all of the Sabkha sand is of a low bearing capacity, studies from Saudi Arabia showed that Sabkha sand in many areas could be loose and might not even support one story buildings without huge settlements that exceed tolerable limits. The main setback of Sabkha is its chemical properties and the general observation of high water table in regions of Sabkha (Ali et al, 2015). In the context of pavement engineering, the chemical composition of Sabkha is not going to cause any problems as asphalt pavements are not prone to corrosion, what is concerning is the depth of the water table and the sub-grade’s bearing capacity.

Figure 4.4: Regions Having Sabkha Soil

### 4.4.1.2 Expansive Soils

The arid desert and semi-arid regions of the Middle East such as the Arabian Peninsula suffers greatly from damage due to expansive soils, research from Saudi Arabia located multiple areas with dominant expansive soils and classified these soils into four different types (Daffala et al., 2012):

- Shale material: fine grained weak rock made of clay or silt, oriented and laminated and flaky in nature. Encountered in central and northern regions of the Peninsula.
- Calcareous clay material: calcium carbonate rich clay encountered at eastern regions of the Peninsula.
- Greenish silt clay: encountered in the West and North West regions of the Peninsula.

- Reddish silt clay: encountered in the southern regions of Saudi Arabia.

Those soils will cause failure of toping structures by uplifting and twisting, and are associated with the presence of water due to rain, leakage, waste disposal or ground water table rise (Daffala et al., 2012).

## 4.5 Truck Traffic and Roads in Arabian Peninsula

Important information about Saudi arterials and traffic data were collected from the General Directorate of Operations and Maintenance in the KSA by Alqaili, (2017). The data included the number of trucks and their types.

Most of the main arterials follow the following design considerations:

- The number of lanes usually is 3 lanes per direction.
- Percent of trucks in design direction is taken as 50%.
- Lane distribution factors as to identify number of trucks on the outermost lanes are as follows:
    - Single-lane roadway in one direction, LDF=1.00
    - Two lane roadway in one direction, LDF=0.9
    - Three lane roadway in one direction, LDF=0.6
    - Four lane roadways in one direction, LDF=0.45
- Roads connecting Riyadh to the major cities are three lane highways in each direction so the LDF is 0.6
- The operational speed is 60 mph.

The traffic growth factor averaged at 1.06 which implies a 6% yearly growth in traffic. This average is nationwide in KSA and was obtained after observing the traffic on the four most important roads mentioned above between the years 2011 and 2015 (Alqaili et al., 2017). According to Alqaili, (2017) as well, the applicable vehicle class distribution for trucks in the Riyadh region is as shown in Figure 4.5.

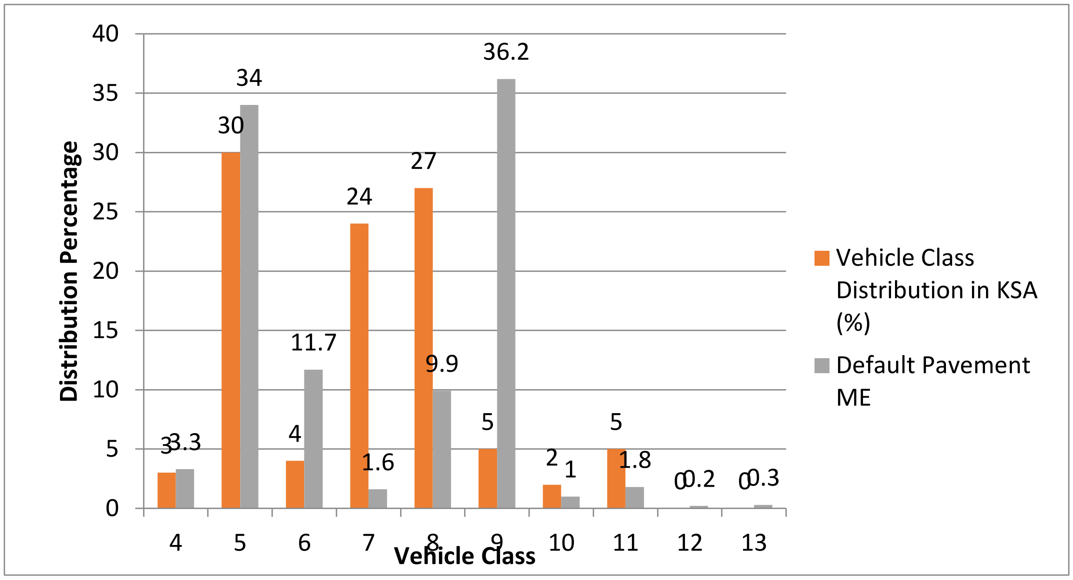


Figure 4.5: Truck Classification in KSA vs Default Pavement-ME Classification

Similar studies from UAE and Qatar are not available but it is fair to assume that given the similar type of economies, distances travelled and cross trading between KSA, UAE and Qatar that the truck characterization profile is relatively similar. Nevertheless, the effect of truck traffic characterization will be assessed in Chapter 6.

Other surveyed and measured traffic properties that could serve as Pavement-ME input parameters are as follows:

- Tire pressure: conducted research by Al-Mansour (1995) found that the pressure range is between 120 and 130 psi.
- Short trucks are Class 5, medium single unit trucks are Class 6 and Class 7, and long trucks are classes 8 to 13. The percent of trucks was: short trucks 32.75%, medium trucks 35.74%, and long trucks 31.51%.
- Lane width in Riyadh is 3.65 m.

## 4.6 Catalogue Based Pavement Design Methods

The method used to design bitumen paved roads in the countries understudy are based on a catalogue of pre-set road structures and bitumen types based on the traffic levels and region.

### 4.6.1 *Structural Design*

According to Chehab, (2016) and based on interviews conducted with personnel from the KSA Ministry of Transport (MOT) in 2015, MOT uses two pre-determined structural designs (Figure 4.6), one for low traffic and one for high traffic, yet there is no indication on what is considered low and what is considered high. The dimensions of lifts are shown, the aggregate base course layer is usually set at 12 cm (4.8 in) (Abdul Wahab et al., 1995). Figure 4.7 similarly shows the typical pavement's structural design used by highway agencies in UAE.

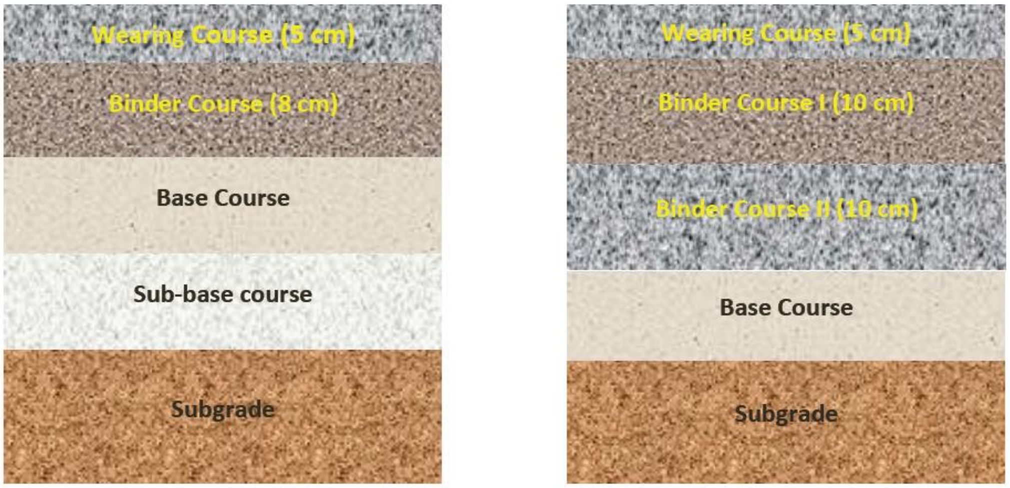


Figure 4.6: Typical Cross Section of Roads KSA (low, high) (Chehab, 2016)

Figure 4.7: Typical Pavement Cross-Section for roads in Abu Dhabi (left) and roads in Dubai (right) (Chehab, 2016)

Typical pavement cross sections in Qatar are shown in Figure 4.8 below (Sadek et al., 2014).

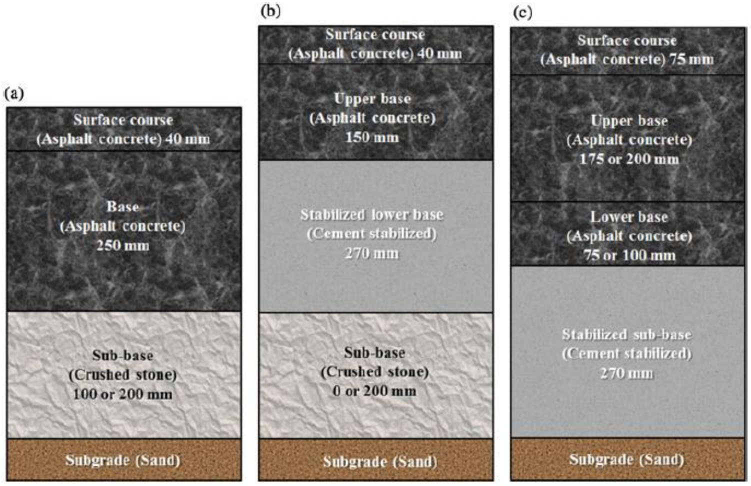


Figure 4.8: Typical Cross Sections for Asphalt Pavement Designs in Qatar: (a) AC design, (b) Flexible Composite Design, (c) Perpetual Pavement Design (Sadek et al., 2014)

### 4.6.2 *Bitumen Grade Selection*

The Arabian Peninsula is divided into three different temperature zones and the binder type applicable for each zone is specified in Figure 4.9 (Abdul Wahab et al., 1996).

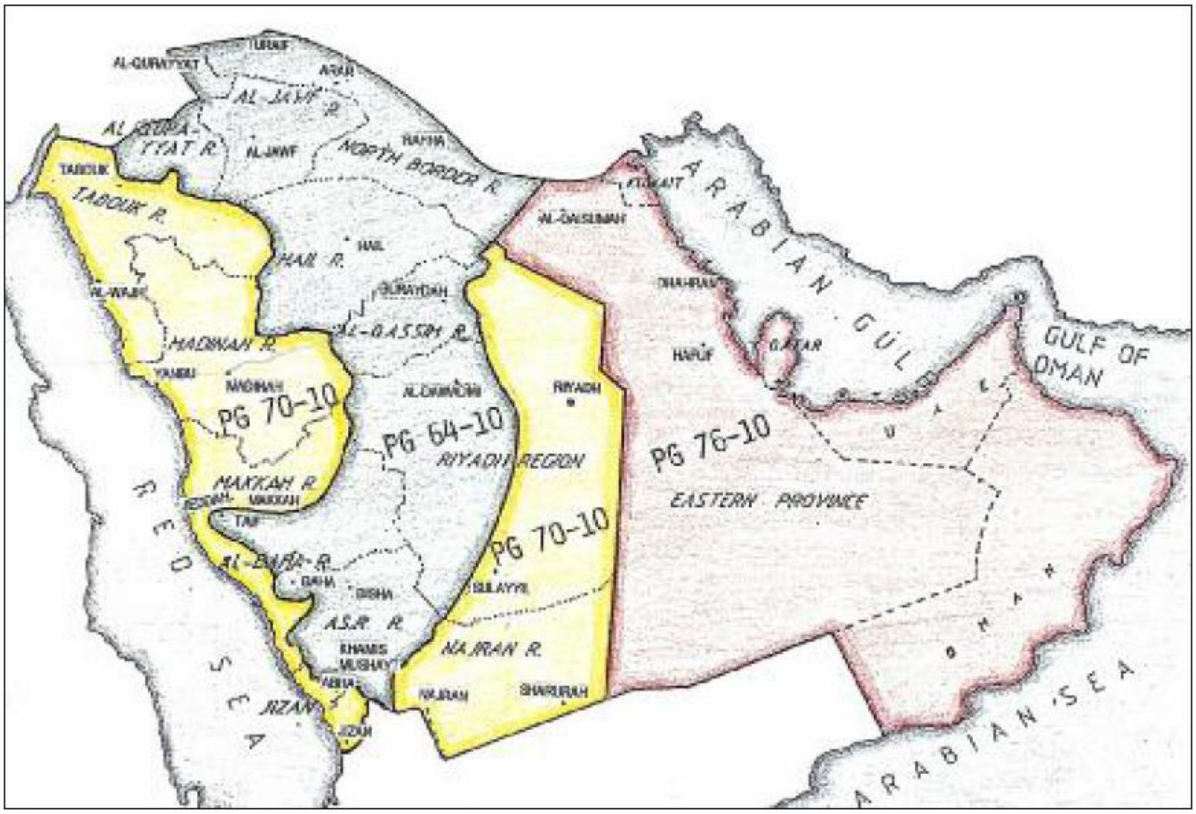


Figure 4.9: Binder Types Zoning As a Function of Climate Conditions in Arabian Peninsula (Abdul Wahab et al., 1995)

During the selection of the binder grade, the traffic volume and speed are taken into consideration and the PG grade chosen by the temperature zoning should be modified according to the conditions detailed in Table 4.2.

Table 4.1: Adjustment to Binder Type Based on Traffic Conditions in the KSA

| **Speed** | **Traffic Class Designation (or ESAL, million)** | | | | |
|---|---|---|---|---|---|
| | VL(<0.3) | L(0.3 TO 3) | M(3 to <10) | H(10 to <30) | VH (>30) |
| **Standing(Average speed <20 km/h)** | Note 2 | 2 | 2 | 2 | 2 |
| **Slow(average speed 20 to 70 km/h)** | No Adjustment | 1 | 1 | 1 | 1 |

<table>
<tr><td><b>Standard (average speed>70 km/h)</b></td><td>No Adjustment</td><td>No Adjustment</td><td>No Adjustment</td><td>Note 2</td><td>1</td></tr>
<tr><td colspan="6">Notes: (1) Increase the high temperature grade by one grade equivalent (i.e. 6 oC). Do not adjust the low temperature grade<br>(2) Consideration should be given to increasing the high temperature grade by one grade equivalent (i.e. $6^{0}$C)<br>(3) Practically, performance grade binders higher than PG 82-XX should be avoided. In case the required adjustment to account for traffic volume and speed would result in a grade higher than PG 82-XX, considerations should be given to specifying a PG 82-XX and increasing the design ESALs by one level (e.g.10 to <30 million increased to ≥30 million)</td></tr>
</table>

In addition, if the project spans over more than one zone, the design should take place according to the highest PG recommended or considerations to two multiple designs for every zone might be taken into consideration.

The location of the pavement layer also should be taken into consideration when designing. The top 100 mm of the pavement or any layer that falls entirely, or more than 75% of it, in the top 100 mm is considered as a top layer and should have the binder grade selected accordingly.

## 4.7 Climate Files Applicable for Pavement-ME

### 4.7.1 *Available Climate Data Sources*

Climate data is an essential parameter to well reflect the actual site conditions of the project. The more detailed the climate data is the more realistic the expected distresses will be. Pavement-ME requires climate files of “.hcd” (Hourly Climatic Database) type file format, those climatic files are available for the United States of America and Canada and their possessions. Files are archived online and can be downloaded from the following site (http://me-design.com/MEDesign/ClimaticData.html), which also has instructions on how to import the downloaded file to Pavement-ME.

Climatic data in “.hcd” file format are logged by weather stations mainly at airports all around Northern America. Those files hold the following information in the following format:

YYYYMMDDHH, Temperature (F), Wind Speed (mph), % Sun Shine, Precipitation, Relative Humidity.

An example on that is:

2018061512,60,4,100,0.1,97: which indicates that on 15th of June, 2018 at 12:00 P.M., air temperature was 60° F, wind speed was 4 mph, percent sunshine was 100%, precipitation is at 0.1 inches and relative humidity is at 97%.

In countries understudy, hourly climatic data files are not openly available and might not be available at all.

A globally recognized source for properly logged and readily available “.hcd” files for anywhere in the world is the MERRA (Modern-Era Retrospective Analysis for Research and Applications) database by NASA.

The retrospective analyses integrates satellite-based data and conventional observations into a modeling framework to provide earth system datasets that are continuous in space and time (https://gmao.gsfc.nasa.gov/pubs/docs/Bosilovich803.pdf). Data is given per cubed sphere grid of a latitude length of 50 km.

### 4.7.2 *Procedure to Obtain Climate File*

In order to obtain the climate file of an area that is of interest, a user has to:

1- Access the website, (https://infopave.fhwa.dot.gov/Tools/MEPDGInputsFromMERRA)

2- Click (By Map) above the Map.

3- Pin point the location where you wish to acquire the climate file.

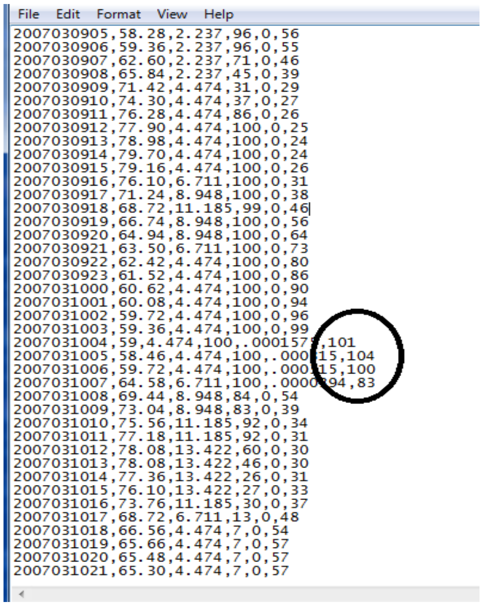
4- At the bottom of the page select the unit (US customary) to be compatible with Pavement-ME.

5- Press Download MERRA Climate Data File (.hcd).

### 4.7.3 *Shortcomings of MERRA Climate Files in Middle East*

Data from MERRA climate files might be subject to some errors that have to be assessed in further research.

1- Relative Humidity Values Above 100%: Though some experts say that relative humidity might be above 100% which means that the atmosphere is even over-saturated (http://articles.chicagotribune.com/2011-07-20/news/ct-wea-0720-asktom-20110720_1_relative-humidity-condensation-nuclei-supersaturated-air) , Pavement-ME doesn’t accept such values and 100% has to be the maximum. Maximum values found was 125% while relative humidity values between 101% and 109% where very frequent.



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2007030905,58.28,2.237,96,0,56
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2007030909,71.42,4.474,31,0,29
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2007030917,71.24,8.948,100,0,38
2007030918,68.72,11.185,99,0,46
2007030919,66.74,8.948,100,0,56
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2007031010,75.56,11.185,92,0,34
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2007031017,68.72,6.711,13,0,48
2007031018,66.56,4.474,7,0,54
2007031019,65.66,4.474,7,0,57
2007031020,65.48,4.474,7,0,57
2007031021,65.30,4.474,7,0,57
```

Figure 4.10: Relative Humidity Values Above 100%

2- Percent Sunshine: it was noticed in very few random instances that there was sunshine during night time hours. Those values aren't considered as errors by Pavement-ME and will not obstruct the file from running.

### 4.7.4 *Shortcomings of Climate File Input*

Trying to add the properties of the stations from ".dat" file for regions from the Middle East was not possible even after following the procedure recommended in (http://me-design.com/MEDesign/ClimaticData.html). The only way to incorporate the climate files from the regions understudy was by replacing the climatic file data from a U.S. city that is already available in the software's database by the data from the city understudy.

# CHAPTER 5

# EXPERIMENTAL PLAN & SOFTWARE RUNS

## 5.1 Introduction

The experimental plan employs the results of the simulations shown in Figure 3.4 and aims at assessing the following Pavement-ME input parameters:

- Recommending hierarchical level of HMA input parameters, and evaluating, if Level 1 is recommended, whether a set of generic dynamic modulus values for mixes could be used.
- Evaluating the significance of base layer resilient modulus dictated in construction specification, and proposing better alternatives.
- Evaluating the distress sensitivity to prevailing sub-grade types and resilient modulus. Special consideration is given to Sabkha Soils and Expansive Soils.
- Evaluating the distress sensitivity to prevailing truck traffic characterization and to truck overweight.

The set of 480 simulations (Figure 3.4) will serve the purpose of assessing the following parameters using the following set of statistical analysis tools mentioned in section 3.2 (Table 5.1). The basis of the analysis are the top down fatigue cracking and the AC rutting.

Table 5.1: Statistical Tools Used for Parameter Assessment

| **Parameter Assessed** | **Statistical Tool Used** |
|---|---|
| **HMA Dynamic Modulus** | T-test Between Level 1 and Level 2 HMA Characterization. |
| **Base Layer Resilient Modulus** | One Way ANOVA. |
| **Subgrade Resilient Modulus** | One Way ANOVA. |
| **Truck Class Distribution** | One Way ANOVA |

## 5.2 HMA Input Parameters

The dynamic modulus is one of the most important quantified characteristic of an asphalt mix. When performing analysis at a hierarchical level 1 in Pavement-ME, the user has to input values of a lab calculated dynamic modulus (E*) of the mix and binder's shear modulus (G*). On the contrary, if the performance prediction is done at hierarchical level 2 binder characterization, the user has to input the shear modulus of the binder (G*) and the aggregate gradation of the mix. Expertise and lab testing equipment required for performing the dynamic modulus test are not widely available nor accessible in the Arabian Peninsula yet. For that, the importance of obtaining a mix's dynamic modulus has to be assessed.

To recommend the hierarchical level that should be used, three different road structures capable of holding 15 million ESALS, 30 million ESALS and 45 million ESALS without having distresses reaching the limits were used, along with multiple, traffic, mix and binder, base and sub-grade configurations. One set was analyzed using both Mix A and Mix B at Level 1 characterization. Another set was analyzed using both Mix A and Mix B but at Level 2 characterization (Appendix C). Two sample t-tests are performed to compare both sets statistically and for sensitivity.

If the analysis proved that using Level 1 has a great added value, a comparison between the results produced from Mix A and Mix B which both use a binder designated as a PG82-10 will be done.

The objective of this comparison is to check how sensitive distresses are to a change in mix characterization, and to decide whether it is possible to recommend catalogue dynamic modulus values for mixes or not.

### 5.2.1 *Special Considerations for Binders in the Middle East*

Since the global calibration coefficients of Pavement-ME are based on test sections from northern America, binders that are used in the Middle East should have their performance checked in comparison with the default level three analysis through binders from Pavement-ME library. For this reason, mixes using binder designated as PG88-10 which could be widely used in the heavy trafficked hot regions of the Middle East and is not available in Pavement-ME binder's database will be assessed.

Mixes using a PG64-10 binder will be compared at the three different levels of analysis to assess the performance of the binder which is widely used, under hierarchical levels one, two and three.

## 5.3 Base Layer Input Parameters

According to the Saudi Highway Materials Manual, the soil classification of the granular base should be "A-1-a" based on the AASHTO Soil Classification System. The value of modulus of the base layer should be a minimum of 48,700 psi. The Plastic Index is a maximum of six (Alqaili et al, 2016).

The impact of the base resilient modulus on top down fatigue cracking is investigated based on changes in traffic level, road structure, type, and modulus of the sub-grade.

## 5.4 Sub-base Layer Input Parameters

The impact of the type and resilient modulus of sub-base on top down fatigue cracking and AC rutting will be statistically assessed under the three road structures, and two traffic scenarios. Sub-base characteristics should not have an effect on the AC rutting and statistical analysis is expecting to show that as well.

Sabkha soils and expansive soils widely available in the Arabian Peninsula have a change in performance under high water table levels and already have high plastic and liquid limits. A set of simulations will be conducted in Pavement-ME to check whether the predicted distresses are shown to be more severe under conditions of Sabkha and Expansive Soils.

The parameters that will be studied, and that vary hugely in the case of expansive soils are:

- Liquid Limit
- Plasticity Index
- Max Dry Unit Weight
- Specific Gravity
- Water Content

The expansive soil properties that will be used are provided by Daffala et al. (2012) and the simulations framework will account for the combinations presented in Table 5.2.

Table 5.2: Combinations of Expansive Soil Properties as Simulated in Pavement-ME

| | **LL** | **PI** | **Max Dry Unit weight (pcf)** | **Specific Gravity** | **Water Content Avg Max (%)** | **Water Table Depth (m)** |
|---|---|---|---|---|---|---|
| **Soil 1** | 65 | 40 | 120 | 2.7 | 15 | 2 |
| **Soil 1** | 65 | 40 | 120 | 2.7 | 15 | 5 |
| **Soil 1** | 65 | 40 | 120 | 2.7 | 15 | 20 |
| **Soil 2** | 120 | 50 | 120 | 2.75 | 60 | 2 |
| **Soil 2** | 120 | 50 | 120 | 2.75 | 60 | 5 |
| **Soil 2** | 120 | 50 | 120 | 2.75 | 60 | 20 |
| **Soil 3** | 59 | 34 | 130 | 2.75 | 25 | 2 |
| **Soil 3** | 59 | 34 | 130 | 2.75 | 25 | 5 |
| **Soil 3** | 59 | 34 | 130 | 2.75 | 25 | 20 |

## 5.5 Traffic Input Parameters

Truck traffic characterization for multiple regions in the Middle East mainly KSA, Iraq and Lebanon were collected (Appendix B). In order to assess the sensitivity of top down fatigue cracking and AC rutting to changes in truck classification, two scenarios will be chosen out of the set classifications observed (Table 5.3). The basis of the selection will be simulations having the highest IRI value and the lowest IRI value under the same basis of comparison.

Table 5.3: Road Distresses as a Function of Traffic Scenario

| **Traffic Simulation** | **Terminal IRI (in/mile)** | **Total Rutting (in)** | **Bottom Up Fatigue Cracking (% lane area)** | **Top Down Fatigue Cracking (ft/mile)** | **AC Rutting** |
|---|---|---|---|---|---|
| **1** | 155.01 | 0.51 | 9.24 | 1028.51 | 0.45 |
| **2** | 156.06 | 0.53 | 9.27 | 1115.87 | 0.48 |
| **3** | 156.16 | 0.53 | 9.28 | 1085.81 | 0.49 |

| | | | | | |
|---|---|---|---|---|---|
| **4** | 155.66 | 0.52 | 9.26 | 1065.24 | 0.47 |
| **5** | 155.66 | 0.52 | 9.26 | 1125.66 | 0.47 |
| **6** | 155.92 | 0.53 | 9.26 | 1130.57 | 0.48 |
| **7** | 155.68 | 0.52 | 9.24 | 914.92 | 0.47 |
| **8** | 155.87 | 0.53 | 9.26 | 988.61 | 0.48 |

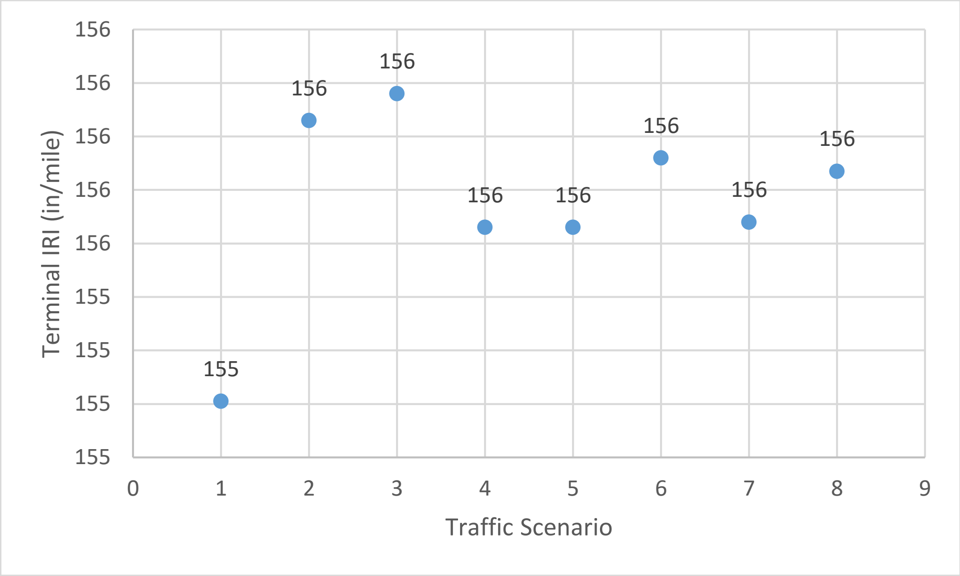

Figure 5.1: Variation of Terminal IRI as a Function of Traffic Scenario

Based on the above graph, the selected scenarios are Traffic scenario 1 and Traffic scenario 3, designated as T1 and T2 in all the future runs.

Table 5.4: Traffic Scenarios Selected for Sensitivity Analysis as Per Pavement-ME Truck Classes

| | **Class 4** | **Class 5** | **Class 6** | **Class 7** | **Class 8** | **Class 9** | **Class 10** | **Class 11** | **Class 12** | **Class 13** |
|---|---|---|---|---|---|---|---|---|---|---|
| **T1** | 3 | 30 | 4 | 24 | 27 | 5 | 2 | 5 | 0 | 0 |
| **T2** | 2.8 | 31 | 7.3 | 0.8 | 9.3 | 44.8 | 2.3 | 1 | 0.4 | 0.3 |

## 5.6 Experimental Plan Summary

Experimental plan is summarized in Figure 5.2.

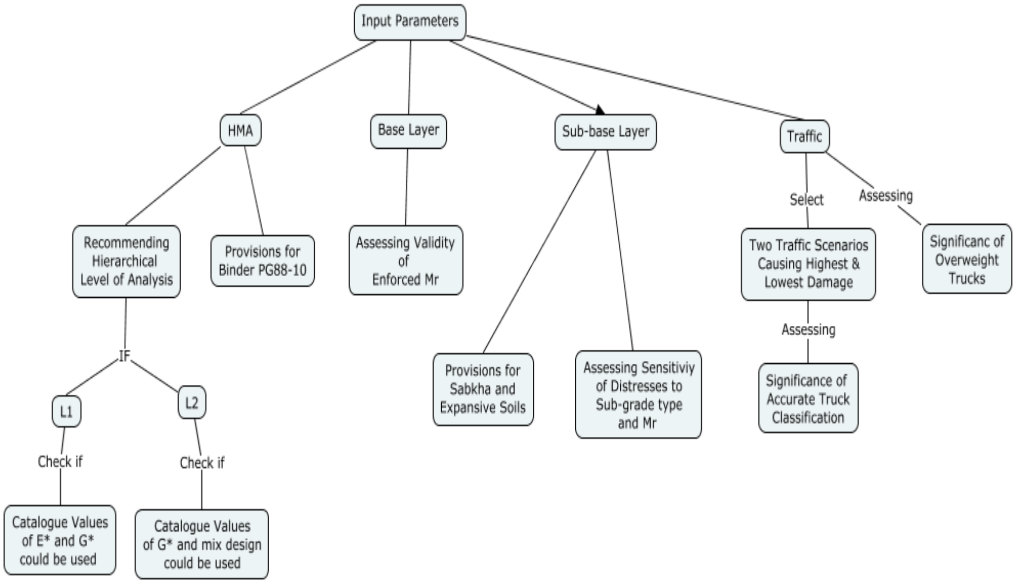

Figure 5.2: Summary of Experimental Plan

# Chapter 6

# RESULTS AND ANALYSIS

## 6.1 Materials' Section Input Parameters

### 6.1.1 *HMA Dynamic Modulus Testing*

Figures 6.2 through 6.5 show the variation in top down fatigue cracking and AC rutting resulting from analysis at level 2 versus analysis at level 1. 36 simulations were utilized for the analysis of Mix A level of characterization (Figure 6.1 & 6.3), 18 of them had their top HMA layer of type Mix A at level 1 HMA characterization and the other 18 had their top HMA layer of type Mix A but characterized at level 2. A similar set of simulations was selected to assess the significance of the hierarchical level of characterization while using Mix B (Figures 6.2 & 6.4). Analysis at Level 1 mix characterization proved to produce lower predictions of distresses. To check whether this variation in distress prediction is statistically significant, a two sample paired t-test was performed as per section 5.4.1. P-value from t-test in Table 6.1 prove that the results produced by analysis at level 1 and those at level 2 are statistically different.

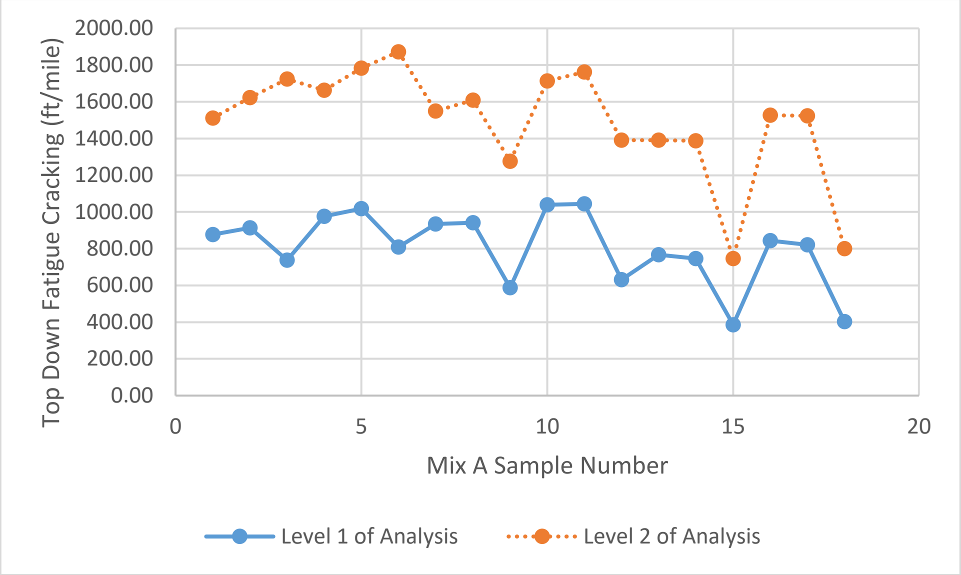

Figure 6.1: Top down Fatigue Cracking at Levels 1 and 2 of Analysis for Mix A

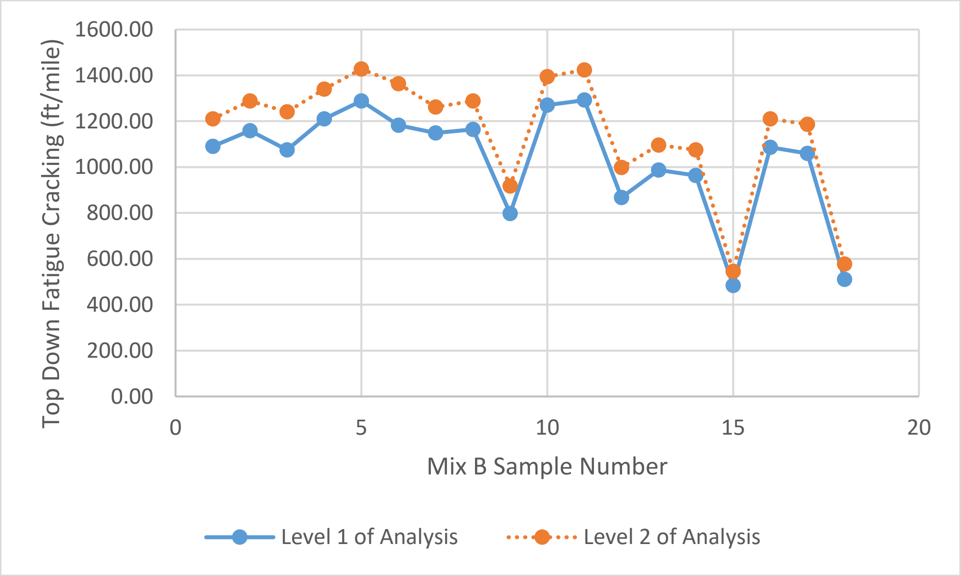

Figure 6.2: Top down Fatigue Cracking at Levels 1 and 2 of Analysis for Mix B

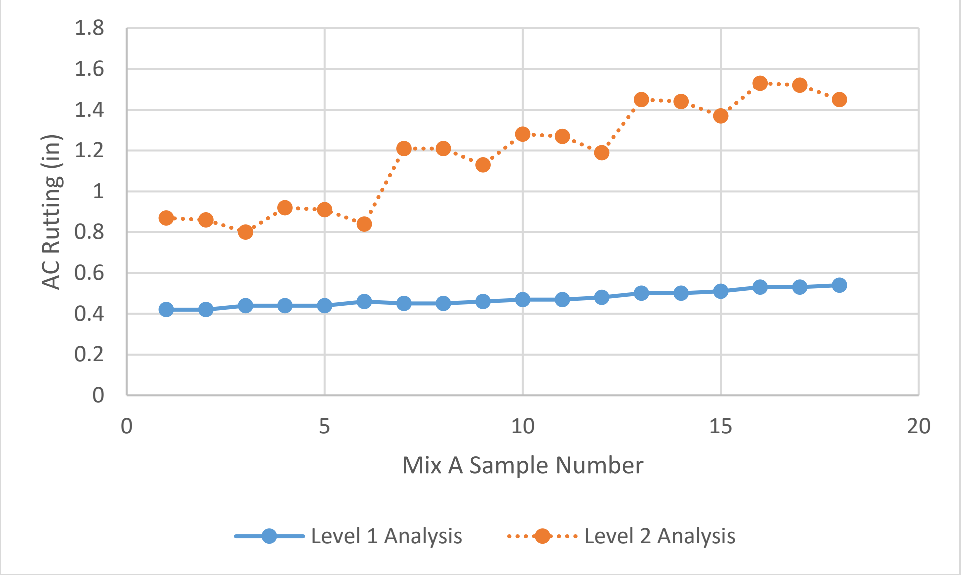

Figure 6.3: AC Rutting at Levels 1 and 2 of Analysis for Mix A

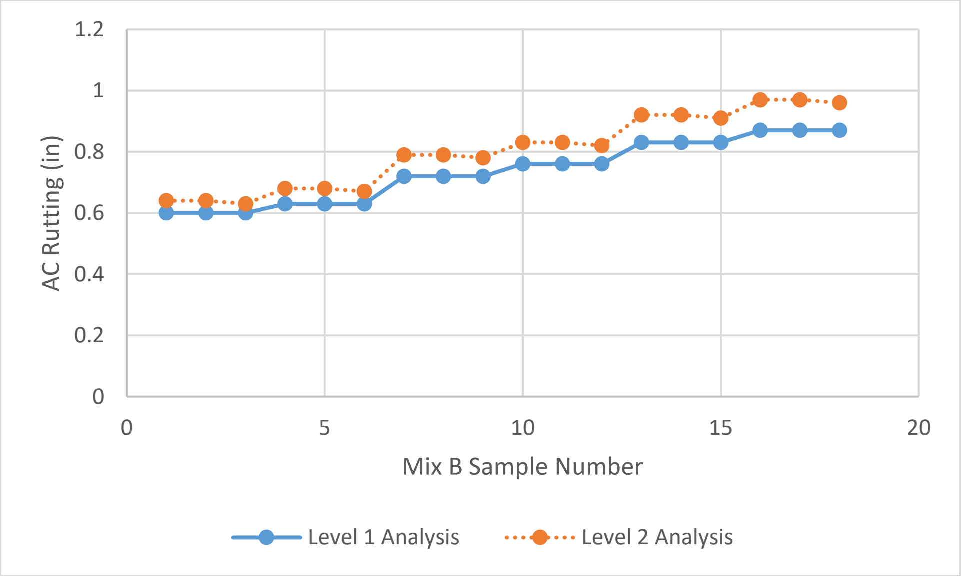

Figure 6.4: AC Rutting at Levels 1 and 2 of Analysis for Mix B

Table 6.1: T-test on Level 1 Mix Characterization versus Level 2 Binder Characterization for Top down Cracking and AC Rutting

| | **Top Down Fatigue Cracking** | **AC Rutting** |
|---|---|---|
| **p-value** | 9.38E-08 | 2.52E-10 |

Another comparison between the means of the samples was performed to check whether the difference in results is actually significant when reflected on the lifetime of the pavement (Table 6.2). Since the change in the mean value for the top down fatigue cracking is 44% which is much greater than the accepted 5% change, and since the change in the AC rutting is similarly greater than 6%, performing analysis at level 1 is recommended.

Table 6.2: Sensitivity Analysis on Level of Mix Characterization

| | **Top Down Fatigue Cracking** | | **AC Rutting** | |
|---|---|---|---|---|
| | Level 1 | Level 2 | Level 1 | Level 2 |
| **Mean Value** | 919.91 | 1324.99 | 0.61 | 0.98 |
| **Percent Change in Distress** | 44 % | | 64% | |

### 6.1.2 *Specific Testing for Mix's Dynamic Modulus*

The purpose of this set of statistical and sensitivity analysis is to decide whether it is possible to recommend a set of values or value ranges that could be used as input for the E* parameter at level 1 analysis. This step is necessary since lab testing for dynamic modulus (E*) is still a complicated process that needs advanced lab equipment not widely available in the region understudy.

Results of distresses resulting from using two mixes (Mix A and Mix B) which have the same binder designation (PG82-10) and different aggregate gradations are compared under the exact same conditions (Figure 6.5 and Figure 6.6). To check whether the results of the two samples are statistically different, the t-test is performed three times for the three different road structures. P-values resulting from the t-tests are shown in the following Table 6.3.

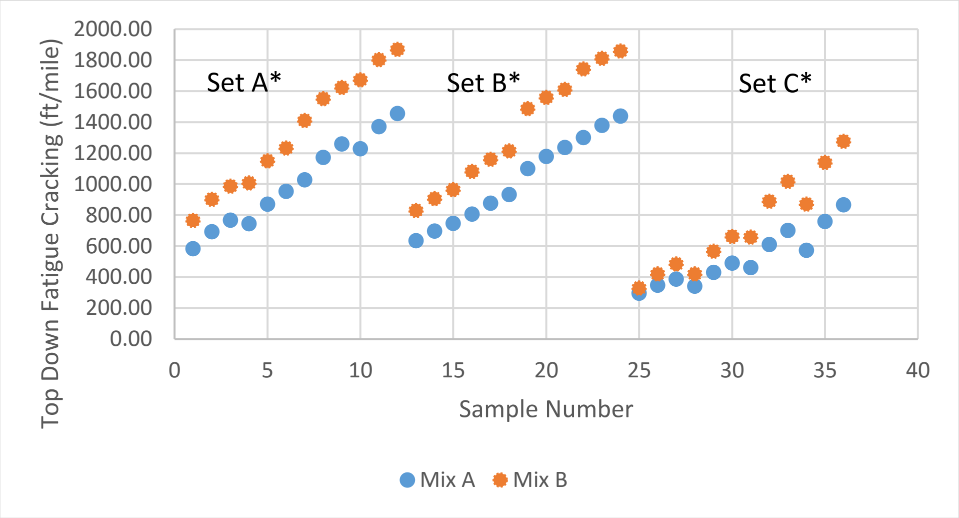

Figure 6.5: Variation of Top down Fatigue Cracking between Mix A and Mix B at Level 1 of Analysis in Road R3

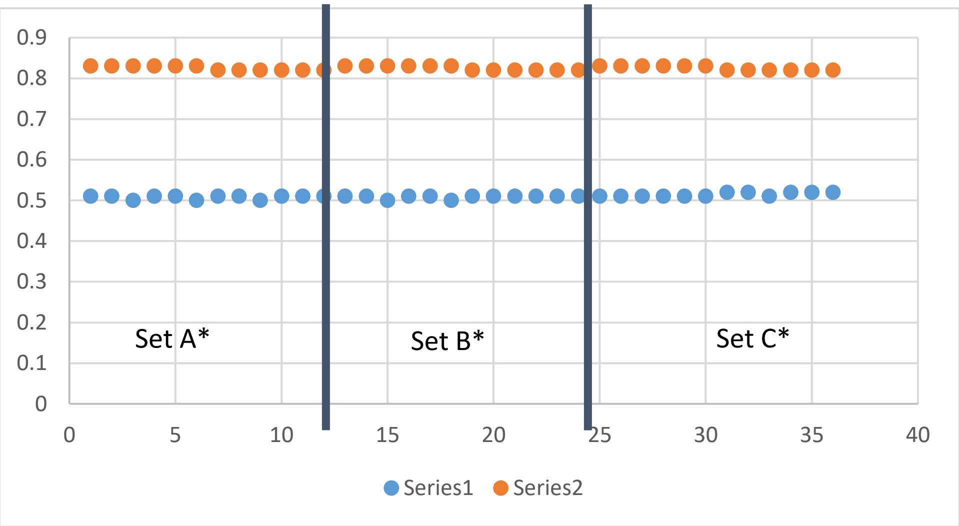

Figure 6.6: Variation of AC Rutting Between Mix A and Mix B at Level 1 of Analysis in Road R3

*{*Set A corresponds to a set of simulations having variations in the Sub-grade resilient modulus and base resilient modulus while keeping the type of sub-base the same (A-2-4); Set B correspond to a set of simulations having variations in the Sub-grade resilient modulus and base resilient modulus while keeping the type of sub-base the same (A-1-b); Set C correspond to a set of simulations having variations in the Sub-grade resilient modulus and base resilient modulus while keeping the type of sub-base the same (A-7-6)}*

Table 6.3: T-test on Predicted Distresses of Mix A versus those of Mix B for Top down Cracking and AC Rutting

| **Road Type** | **p-test for top down** | **p-value for AC rut** |
|---|---|---|
| **R1** | 5.32E-12 | 1.47E-98 |
| **R2** | 3.38E-06 | 9.6E-127 |
| **R3** | 4.36E-05 | 1.3E-135 |

The presented p-values imply that results generated from the two cases are not the same statistically. Sample means where similarly calculated and the percent change between results are documented in table 6.4 and are more than the 5% threshold value:

Table 6.4: Sensitivity Analysis on Importance of Proper E* Characterization

| | **Mean For Top Down Fatigue Cracking** | | **Mean For AC Rutting** | |
|---|---|---|---|---|
| **Road Type** | Mix A | Mix B | Mix A | Mix B |
| **R1** | 1162.59 | 1527.17 | 0.45 | 0.62 |
| **R2** | 1161.99 | 1486.89 | 0.47 | 0.74 |
| **R3** | 892.90 | 1204.66 | 0.52 | 0.85 |
| **Average Value** | 1072.493 | 1406.24 | 0.48 | 0.73 |
| **Percent Change** | 31% | | 53 % | |

The results show that it is not possible to recommend generic values that could be used as (E*) input for mixes with a PG82-10 binder. It is a must that (E*) is tested on a case by case basis for any mix.

#### 6.1.2.1 Special Consideration: Binder PG88

It is very important to note that the mix named R8 mentioned in chapter 2 above contains a binder that is designated as PG88-10 binder. It was noticed that such a binder isn't available in the default database of binders that is available for Level 3 analysis. This binder could be used on many heavy trafficked roads in the hot regions of the Middle East.

In order to check the performance of this binder as a special case binder the following simulations were done on Pavement-ME using the road structure of Road R3. The table compares the performance of the mix under characterization at Level 1, Level 2 and Level 3 (using the default PG82-10 binder since PG88-10 binder is not available at level 3 and PG82-10 is the binder with the closest performance). Results are tabulated in Table 6.5.

Table 6.5: Predicted Distresses When Using a Mix with a PG88-10 Binder at Different Hierarchical Levels of Characterization

| **Hierarchal Level** | **Terminal IRI (in/mile)** | **Total Rutting (in)** | **Bottom Up Fatigue Cracking (% lane area)** | **Top Down Fatigue Cracking (ft/mile)** | **AC Rutting (in)** |
|---|---|---|---|---|---|
| **1** | 172.57 | 0.63 | 8.16 | 901.74 | 0.59 |
| **2** | 190.87 | 1.08 | 9.15 | 1245.37 | 1.04 |
| **3** | 189.01 | 1.03 | 9.09 | 1227.75 | 0.99 |

Results show that the PG88-10 binder has a great improvement in performance when compared to the PG82-10 binder as AC rutting was reduced by around 40% and top down fatigue cracking by 30%. The results also show that it is a must that the mix is characterized at Level 1 using both (E*) and (G*) values as using only the (G*) values at

Level 2 analysis didn't reflect the true capabilities of this mix and the results obtained were even worse than those from level 3 analysis.

#### 6.1.2.2 Hierarchical Levels of Analysis for Mixes Using PG64-10

A mix using PG64-10 binder (Appendix A) was assessed at low traffic conditions (2 million ESALs) at Levels one, two and three of analysis. The results presented in Table 6.6 show that even while using the widely available and used PG64-10 binder, performing analysis at level 3 showed a huge degradation in the mix's performance as compared to analysis at level 1 using the actual dynamic modulus of mixes used in the Middle East area.

As a results, it is possible to conclude that even though PG64-10 binder is used globally, and many of the test sections used for the calibration of Pavement-ME were paved by mixes using such a binder, the discrepancy between the levels of analysis cannot be ignored. As with regards to analysis at level 2, results are always showing consistency with regards analysis at level 2 are worse than results at level 3, which is consistent with literature.

Table 6.6: Predicted Distresses When Using a Mix with a PG64-10 Binder at Different Hierarchical Levels of Characterization

| **Hierarchal Level** | **Terminal IRI (in/mile)** | **Total Rutting (in)** | **Bottom Up Fatigue Cracking (% lane area)** | **Top Down Fatigue Cracking (ft/mile)** | **AC Rutting (in)** |
|---|---|---|---|---|---|
| **1** | 142.58 | 0.27 | 3.3 | 288.37 | 0.19 |
| **2** | 147.9 | 0.4 | 3.21 | 312.77 | 0.32 |
| **3** | 145.6 | 0.34 | 3.28 | 306.7 | 0.26 |

### 6.1.3 *Sensitivity Analysis on Aggregate Base Input Parameters*

This section will investigate how significant is the impact of the base resilient modulus on top down fatigue cracking based on changes in traffic level, road structure, type and modulus of the sub-grade.

The p-values mentioned in Table 6.7 indicate that the resilient modulus of the base layer has an effect on the top down fatigue cracking. On the other hand, and as suggested by engineering knowledge and practice, the statistical analysis confirmed that the resilient modulus of the base layer has no effect on the severity of the AC layer rutting.

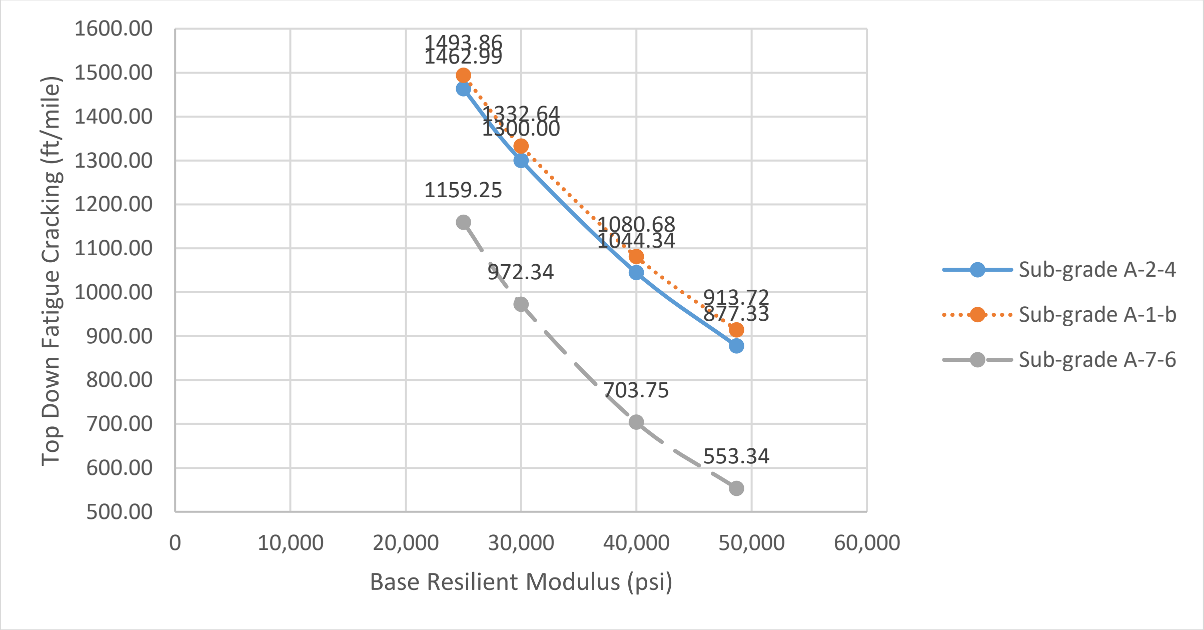

Figure 6.7: Variation of Top down Fatigue Cracking as a Function of Change in Base Layer Resilient Modulus under Multiple Sub-grade Material Scenarios

Table 6.7: One Way ANOVA on Predicted Distresses under Multiple Base Layer Resilient Moduli for Top down Cracking and AC Rutting

| **Road Structure** | **Type of sub-grade** | **p-value top down fatigue cracking** | **p-value for AC rutting** |
|---|---|---|---|
| **R1** | A-2-4 | 5.95E-10 | 0.99 |
| | A-1-B | 7.55E-10 | 0.99 |
| | A-7-6 | 3.03E-08 | 0.93 |
| **R2** | A-2-4 | 1.05E-13 | 0.98 |
| | A-1-b | 9.3E-14 | 0.99 |
| | A-7-6 | 1.33E-10 | 0.99 |
| **R3** | A-2-4 | 6.83E-10 | 0.99 |
| | A-1-b | 9.07E-13 | 0.99 |
| | A-7-6 | 1.83E-09 | 0.99 |

As to check for whether the binding specs by the Saudi authorities, on the base resilient modulus being at least 48,700 psi, have a positive or a negative impact on the pavement design practice, plots in Figures 6.8 and 6.9 are generated.

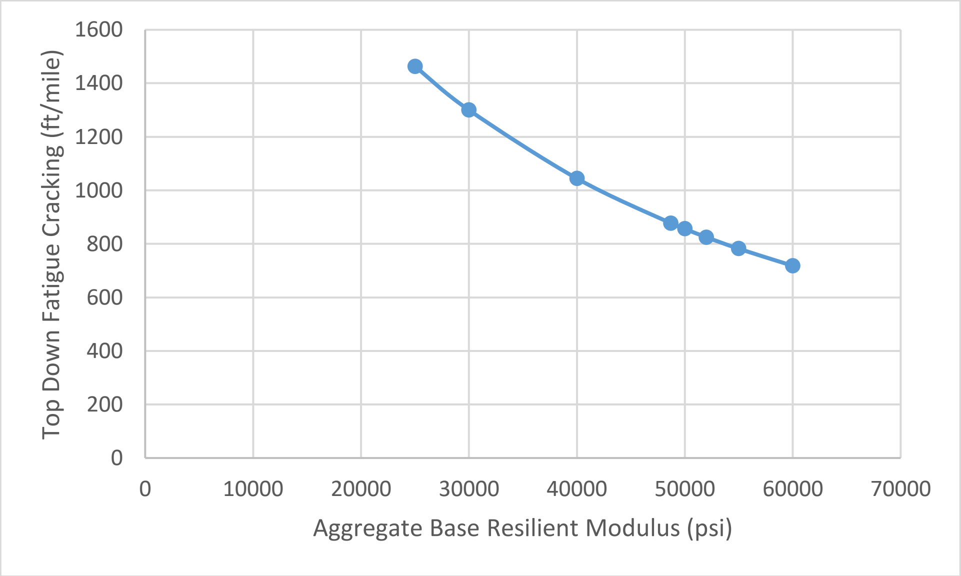

Figure 6.8: Variation of Top down Fatigue Cracking as a Function of Aggregate Base Layer Resilient Modulus

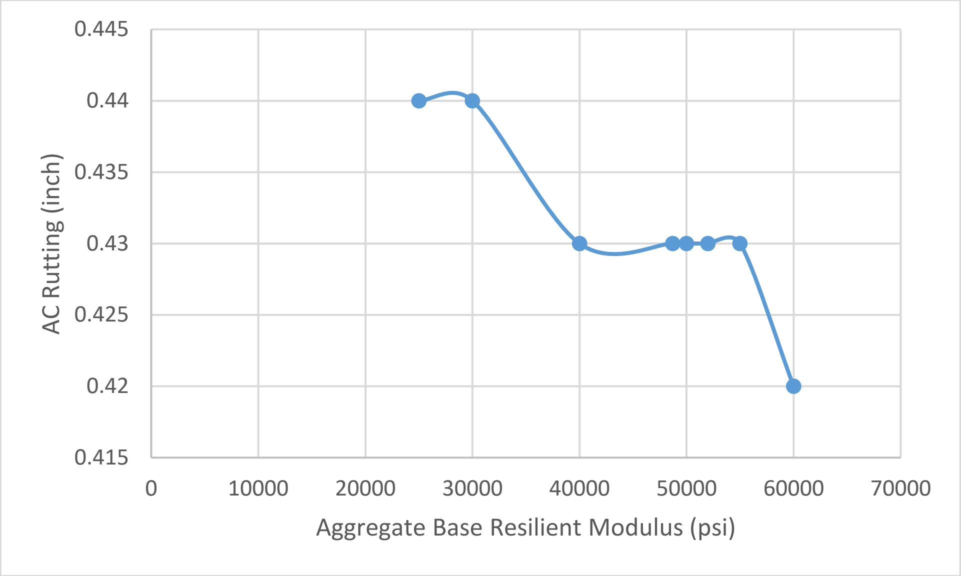

Figure 6.9: Variation of AC Rutting as a Function of Aggregate Base Layer Resilient Modulus

Trends from the above graphs show that setting the minimum value of the base resilient modulus at 48,700 psi is a reasonable recommendation as the top down fatigue cracking reached lower values as the base resilient modulus increased. Increasing the resilient modulus of the aggregate base further might be necessary in certain situations, but such an increase requires aggregate to be treated with bitumen or cement which will cause an increase in the cost.

### 6.1.4 *Sensitivity Analysis on Sub-Grade Material Input Parameters*

#### 6.1.4.1 Significance of Accurate Sub-Grade Resilient Modulus Characterization

Statistical analysis on the effect of the sub-grade resilient modulus showed that results for both top down fatigue cracking and AC rutting are statistically the same, meaning that there is no need for an accurate lab tested value of the subgrade resilient modulus and the user can use an average value approved through practice or the calculated resilient moduli collected from KSA available in Table 4.1. The p-values for the single way ANOVA test performed are shown in Table 6.8 below:

Table 6.8: One Way ANOVA on Predicted Distresses under Multiple Sub-base Resilient Moduli for Top down Cracking and AC Rutting

| Road Type | p-value for top down fatigue cracking | p-value for AC rutting |
|---|---|---|
| **R1** | 0.89 | 0.90 |
| **R2** | 0.24 | 0.98 |
| **R3** | 0.13 | 0.99 |

### 6.1.4.2 Special Consideration: Sabkha and Expansive Soils

As mentioned in Chapter 4, the sabkha and expansive soils are widely available in the Arid and Semi-Arid regions and might cause structural problems due to their low bearing capacities, chemical properties, high liquid and plastic limits and the way they perform under different water saturation levels.

Table 6.9: Variation of Distresses as a Function of Soil Type and Water Table Depth

| Run Number | LL | PI | Max Dry Unit weight (pcf) | Specific Gravity | Water Content Avg Max (%) | Water Table Depth (ft) | Terminal IRI (in/mile) | Total Rutting (in) | Bottom Up Fatigue Cracking (% lane area) | Top Down Fatigue Cracking (ft/mile) | AC Rutting |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soil 1** | 65 | 40 | 120 | 2.7 | 15 | 2 | 191.62 | 0.69 | 12.85 | 1916.38 | 0.61 |
| **Soil 1** | 65 | 40 | 120 | 2.7 | 15 | 5 | 191.53 | 0.69 | 12.75 | 1894.6 | 0.61 |
| **Soil 1** | 65 | 40 | 120 | 2.7 | 15 | 20 | 191.46 | 0.69 | 12.75 | 1914.42 | 0.61 |
| **Soil 2** | 120 | 50 | 120 | 2.75 | 60 | 2 | 189.65 | 0.64 | 11.12 | 1723.73 | 0.6 |
| **Soil 2** | 120 | 50 | 120 | 2.75 | 60 | 5 | 189.67 | 0.64 | 11.12 | 1723.73 | 0.6 |
| **Soil 2** | 120 | 50 | 120 | 2.75 | 60 | 20 | 189.67 | 0.64 | 11.12 | 1723.73 | 0.6 |
| **Soil 3** | 59 | 34 | 130 | 2.75 | 25 | 2 | 188.22 | 0.65 | 11.12 | 1723.83 | 0.6 |
| **Soil 3** | 59 | 34 | 130 | 2.75 | 25 | 5 | 188.23 | 0.65 | 11.11 | 1723.73 | 0.6 |
| **Soil 3** | 59 | 34 | 130 | 2.75 | 25 | 20 | 188.25 | 0.65 | 11.12 | 1723.73 | 0.6 |

The results of the experimental plan detailed in Chapter 5 show that:

1- The variation of water table depth was insignificant and caused a negligible change in distresses.

2- The Atterberg limits and average water content of sub-grade soils are important and should be quantified.

It could be concluded that, the devastating effect actually observed on structures in the arid and semi-arid desert regions in the Middle East is not well reflected in Pavement-ME, even when the exact properties of the soil are being input. This inability of Pavement-ME of reflecting damage caused by expansive soil is due to the unavailability of distress models that could predict such a damage. The main form of damage in structures on top of such problematic soils is heaving, and such a phenomenon is not accounted for in Pavement-ME.

## 6.2 Sensitivity Analysis on Traffic Input Section

### 6.2.1 *Significance of Accurate Truck Class Distribution*

Characterizing the truck traffic very accurately is very difficult for authorities in the region due to the absence of the Weigh in Motion (WIM) stations. Based on the methodology in Chapter 5, a t-test was performed to check whether distresses caused by two probable truck distributions (T1 and T2 which were chosen as worst case scenarios) for the Middle East region are statistically different. The results are shown in Table 6.10.

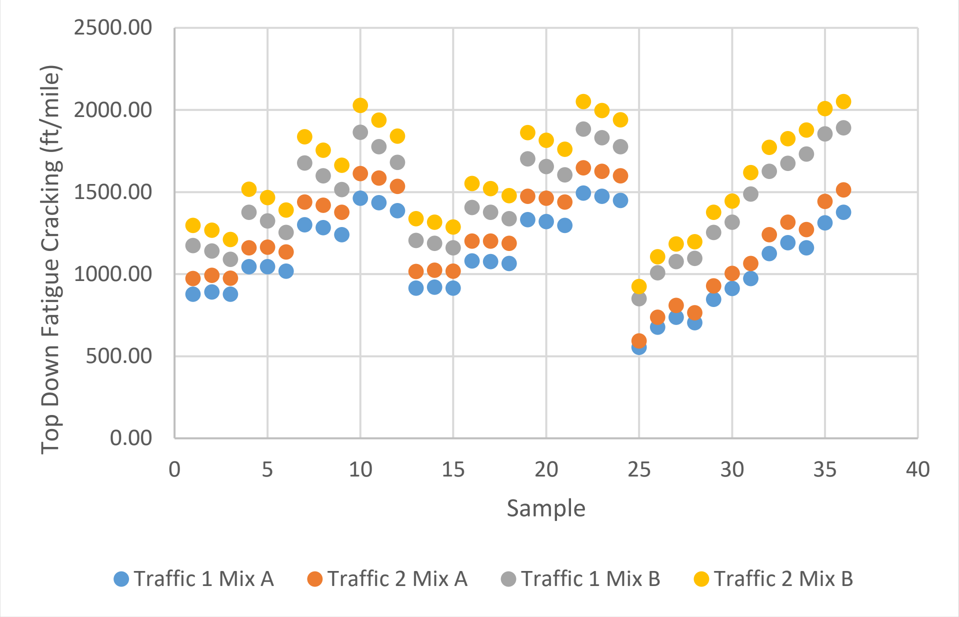

Figure 6.10: Variation of Top down Fatigue Cracking as a Function of Traffic Classification in Structure Road R1

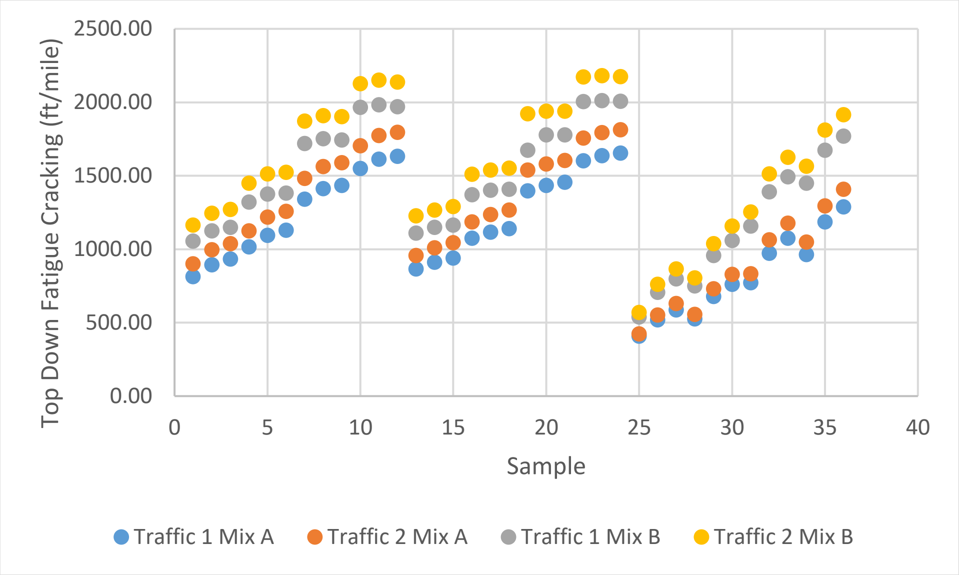

Figure 6.11: Variation of Top down Fatigue Cracking as a Function of Traffic Classification in Structure Road R2

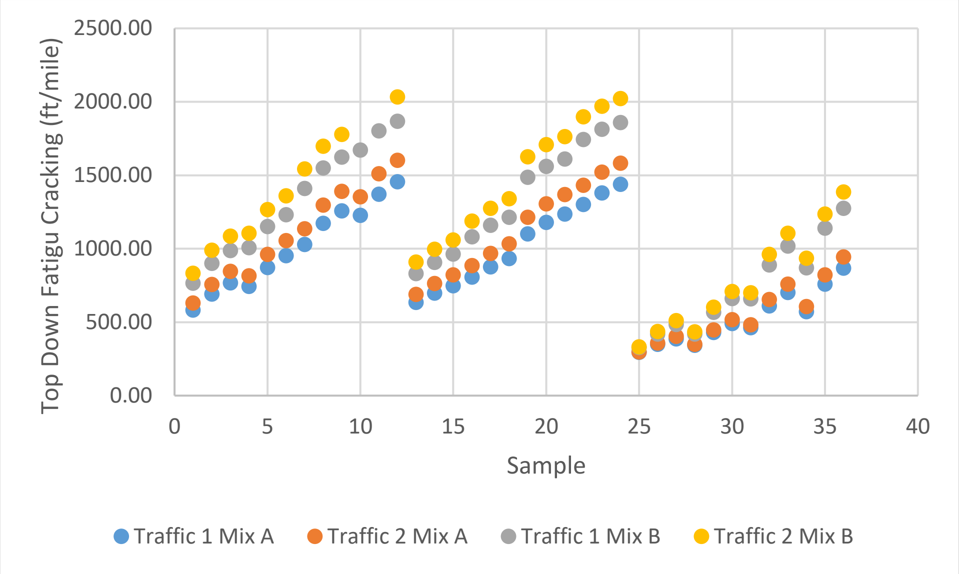

Figure 6.12: Variation of Top down Fatigue Cracking as a Function of Traffic Classification in Structure Road R3

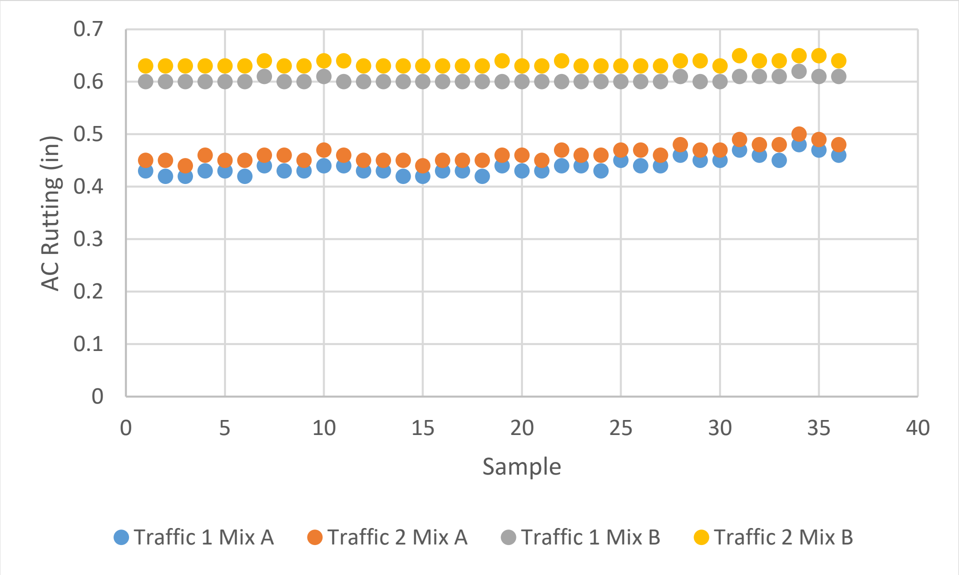

Figure 6.13: Variation of AC Rutting as a Function of Traffic Classification in Structure Road R1

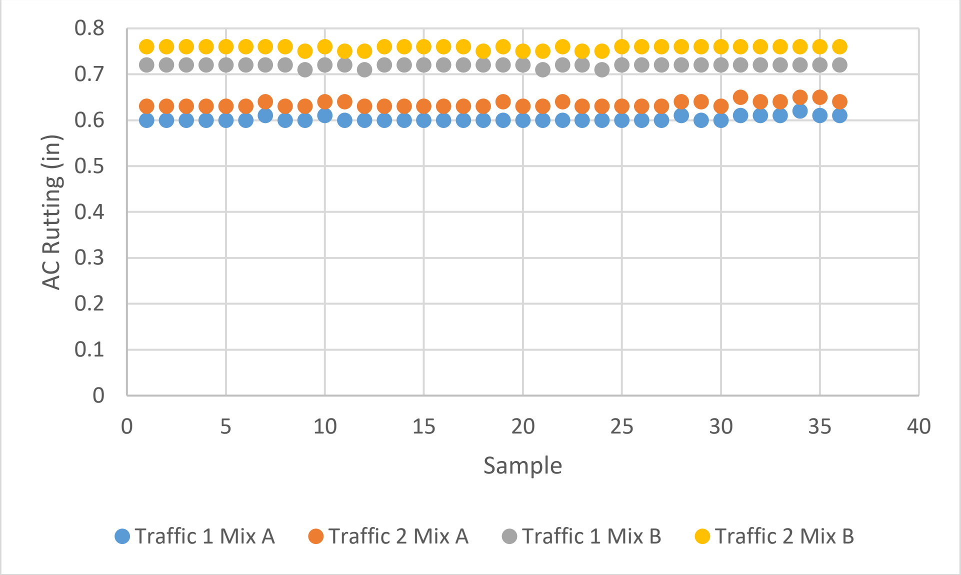

Figure 6.14: Variation of AC Rutting as a Function of Traffic Classification Structure Road R2

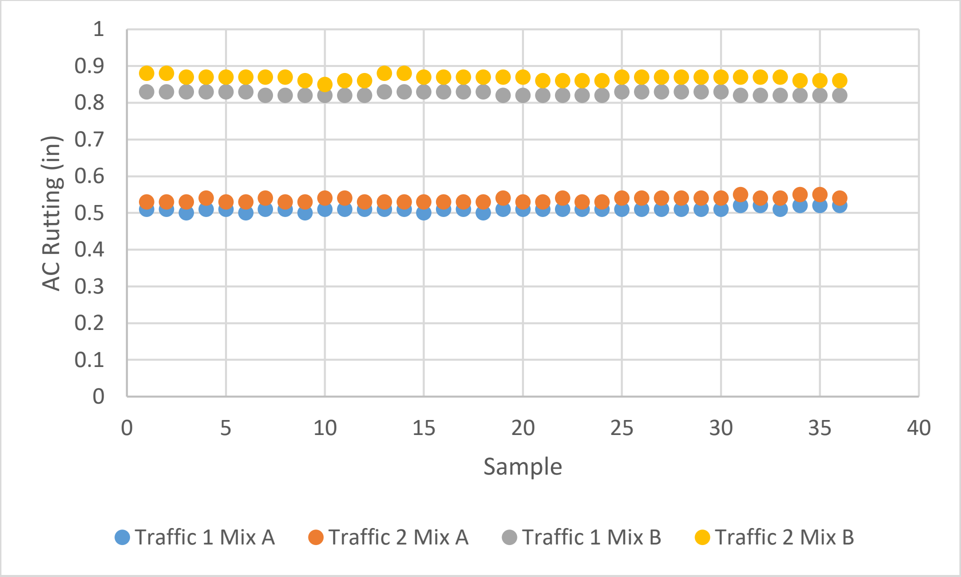

Figure 6.15: Variation of AC Rutting as a Function of Traffic Classification in Structure Road R3

Table 6.10: T-test Performed for Two Traffic Scenarios under Multiple Road Structures and Mixes

| Road Designation | Traffic (ESALS) | Mix Used | p-value (top down cracking) | p-value (AC rutting) |
|---|---|---|---|---|
| **R1** | 15M | A | 0.07 | 8.09E-09 |
| **R2** | 30M | A | 0.21 | 3.16E-34 |
| **R3** | 45M | A | 0.36 | 1.44E-28 |
| **R1** | 15M | B | 0.05 | 3.16E-34 |
| **R2** | 30M | B | 0.19 | 7.67E-53 |
| **R3** | 45M | B | 0.26 | 2.98E-41 |

It is shown that the variation in AC rutting caused by the two traffic scenarios is significant while variation in top down fatigue cracking is not. Thus sensitivity analysis will be performed to check if this change in predicted rutting is significant from the perspective of the lifetime of the pavement (Table 6.11).

Table 6.11: Sensitivity of AC Rutting to the Traffic Configuration

| Road Designation | Traffic (ESALS) | Mix Used | Mean Value for AC rutting at T1 | Mean Value for AC rutting at T2 | Percent Change |
|---|---|---|---|---|---|
| **R1** | 15M | A | 0.43 | 0.46 | 5 |
| **R2** | 30M | A | 0.60 | 0.63 | 5 |
| **R3** | 45M | A | 0.51 | 0.53 | 5 |
| **R1** | 15M | B | 0.60 | 0.63 | 5 |
| **R2** | 30M | B | 0.71 | 0.75 | 5 |
| **R3** | 45M | B | 0.82 | 0.86 | 5 |

All of the samples understudy showed that the change in the value of AC rutting incurred upon choosing two different traffic configurations, though statistically different, does not exceed the acceptable limit of 6% defined in section 5.2.3, chapter 5 for it to be practically significant in the road design. Thus, road designers could use the recommended traffic configuration in Chapter 9.

# CHAPTER 7

# NEED FOR LOCAL CALIBRATION: IRAQ CASE STUDY

## 7.1 Introduction

The objective of this chapter is to use readings from surveyed densely trafficked sections of Freeway 1 in Iraq to evaluate how predicted Pavement-ME results differ from surveyed distresses. Obtaining data on distresses and traffic evolvement is very hard in countries of the Middle East. That is due to the unavailability of such data, or for it being private and only at the disposal of governmental agencies. The data available in this study is extremely important and will serve as a tool to infer the need of calibration of the Pavement-ME functions as a necessary part of the implementation.

## 7.2 Test Sections of Iraq Freeway 1

The two sections (A and B described below) under study are sections of Freeway 1 connecting the Iraq’s coastal region of Umm Qasr (Umm Qasr Port) in Basra Governorate to Iraq’s capital city of Baghdad, to continue then to Rutba city in Al Anbar Governate before reaching the Syrian and Jordanian borders. (Figure 7.1).

The road is 1,200 km long and was open to traffic in 1990. Most of Iraq’s sea shipments pass through this road, in addition to many military transport operations during the many Iraqi wars.

Figure 7.1: Location of Iraqi Road Understudy

In 2017 there was a plan to rehabilitate the road through the removal of the top asphalt layer (wearing coarse) and replacing it by a new one. For this purpose, two small trial sections (R7 and R8) were investigated for their structural design and material properties, had their top layer pulverized and a new layer constructed. The investigation of the structural design and material properties for R7 is shown in Figure 7.2

Figure 7.2: Section R7 Road Structure

Wearing Course was 1.5 inch. No details on the HMA mix are available, but based on the technologies available during the time of construction, HMA of designation PG70-

10 is assumed to be used. The binder course was 3 inch. No details on the HMA mix are available, but based on the technologies available during the time of construction, HMA of designation PG64-10 is assumed to be used. The bitumen Treated Aggregate Base Course was 5.5 in with a modulus of elasticity of 50,000 psi. The sub-base was 10 in with a modulus of 30,000 psi. Finally the sub-grade is of type A-4 and a resilient modulus of 15,000 psi.

Road section (R8) structural and material characterization are shown in Figure 7.3.

Figure 7.3: Section R8 Road Structure

Wearing Course was 1.5 inch. No details on the HMA mix are available, but based on the technologies available during the time of construction, HMA of designation PG70-10 is assumed to be used. The binder course was 3 inch. No details on the HMA mix are available, but based on the technologies available during the time of construction, HMA of designation PG64-10 is assumed to be used. The bitumen Treated Aggregate Base Course was 5.5 in with a modulus of elasticity of 50,000 psi. The sub-base was 14 in with a modulus of 30,000 psi. Finally the sub-grade is of type A-4 and a resilient modulus of 15,000 psi.

Each section of the road had different levels of traffic based on its location and direction. Appendix B shows the multiple test sections, the traffic characterization in each, in addition to the measured asphalt rutting and cracking in the road after a service life of 30 years.

## 7.3 Pavement-ME Predicted Distresses

The ME predicted distresses here are only for the fatigue cracking, which is assumed to be top down and is represented as a percentage of the lane area.

The surveyed distresses from the test sections in Iraq were compared to predictions of:

1- Un-calibrated Pavement-ME

2- Virginia Calibration Factors: Calibration factors of the state of Virginia were chosen due to their availability at the disposal of researchers at the American University of Beirut. Virginia's Department of Transportation shared its data from test sections with pavement researchers at the American University of Beirut and this data was used in multiple research. In this thesis, data from Virginia only serves the purpose of highlighting the importance of local calibration, as even in North America, multiple states have to perform such a calibration due to the discrepancy between their surveyed distresses and the predicted ones using the global calibration coefficients of Pavement-ME.

3- Texas Rutting Calibration Factors (Benerjee et al., 2009): Some areas of the state of Texas are hot arid regions very similar to the dominating climate of the studied regions in the Middle East. The local calibration coefficients of the AC rutting distress prediction model of western Texas were selected. Only rutting was checked as hot weather is the major contributor in the formation of asphalt rutting.

Comparing actual results from Iraq to calibrated models from U.S. states holds two main objectives:

1- Showing the variation in how distresses are predicted by the software based on the calibration coefficients of the distress prediction functions.

2- Ensuring the necessity of a local calibration since even though certain conditions might be similar between two localities, this is not enough to assume that already calibrated empirical transfer functions could suit the conditions of the area understudy.

The following figures show the variation in predicted results based on different calibrated models. The results highlight that a local calibration is necessary to capture the actually surveyed road performance.

### 7.3.1 *Asphalt Rutting*

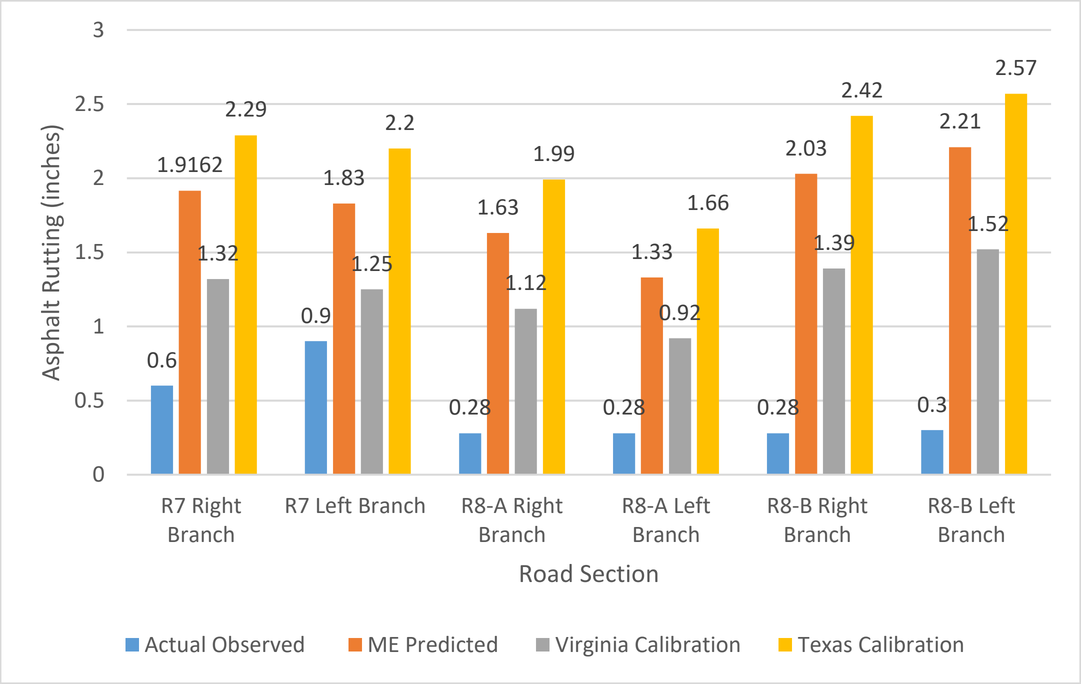

Figure 7.4: Measured Asphalt Rutting Compared with Predicted Under Multiple Calibration Conditions

With regards to asphalt rutting, it is apparent that the calibrated transfer functions of Virginia and Texas were very consistent in their discrepancy from the predicted distress by the uncalibrated Pavement-ME functions. For Virginia, the uncalibrated model over-predicted rutting by a consistent multiple of 1.45 which means:

$$Uncalibrated\ Distress\ =\ 1.45\ x\ Virginian\ Calibrated\ Distress$$

The standard variation is 0.0064 about the average value of 1.45.

For Texas, the uncalibrated models under-predicted rutting by an average factor of 0.83 and a standard deviation of 0.019.

$$Uncalibrated\ Distress\ =\ 0.83\ x\ Texas\ Calibrated\ Distress$$

On the other hand, such consistency wasn't shown when comparing the actual measured distress from Iraq and the Pavement-ME predictions. Pavement-ME was always over-predicting rutting by huge factors that have an average of 5.07 and a standard deviation of 2.16.

$$Uncalibrated\ Distress\ =\ 5.07\ x\ Actual\ Measured\ Distress$$

### 7.3.2 *Top Down Fatigue Cracking*

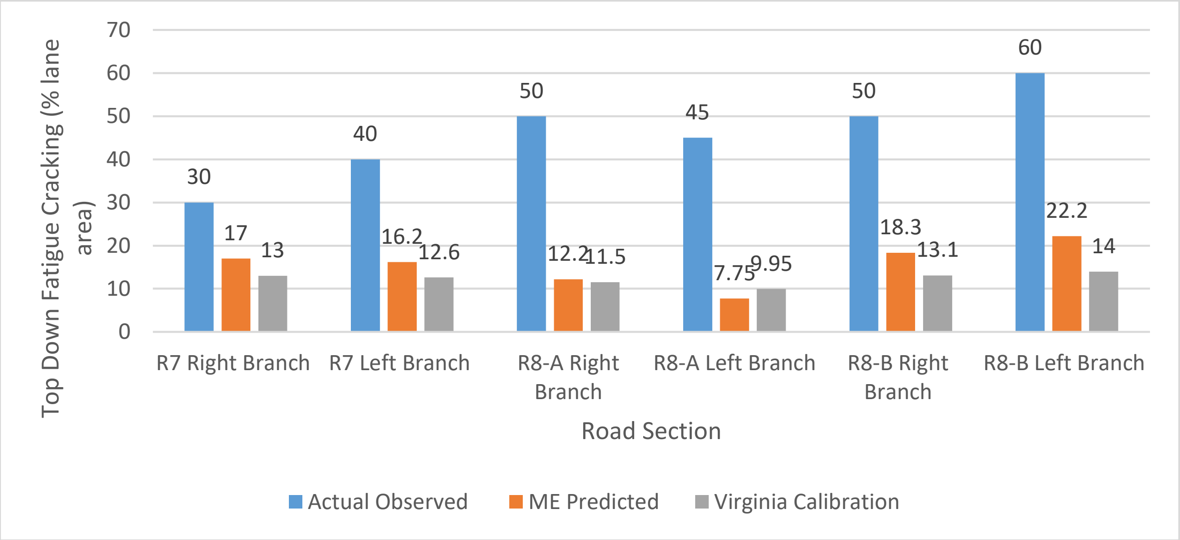

Figure 7.5: Measured Cracking Compared with Predicted Under Multiple Calibration Conditions

With regards to Top down Fatigue Cracking as well, when comparing the calibrated model of Virginia with the un-calibrated Pavement-ME model, there is consistency in how Pavement-ME over-predicts cracking. The average factor is 1.23 and the standard deviation is 0.28.

$$Uncalibrated\ Distress\ =\ 1.23\ x\ Virginian\ Calibrated\ Distress$$

On the other hand, Pavement-ME under-predicted rutting by a factor of 0.35 but that has value spreading around it with a standard deviation of 0.136.

$$Uncalibrated\ Distress\ =\ 0.35\ x\ Actual\ Observed\ Distress$$

### 7.3.3 *Assessment*

Based on the statistics above it is shown that:

1- Pavement-ME predictions for rutting are greatly over-predicting.

2- Pavement-ME predictions for cracking are slightly under-predicting.

3- Pavement-ME predictions show no consistency at all when compared with the surveyed test section distresses and that is visible in the huge standard deviation of values around the average.

Thus, it is proven that neither the default calibration model of Pavement-ME nor the calibrated models of areas having a similar climate zone were able to even closely capture the actual distresses surveyed. As a results, there is a necessity that resources be directed to calibrating the distress prediction models as part of the implementation process.

The following chapter will introduce the tools and the framework on how such a calibration could take place in the local conditions of the Middle East.

## 7.4 Local Calibration Coefficients for AC Rutting Predictive Model

Though not enough distress measurements from test sections are available, an example on how the AC rutting predictive model could be calibrated using the available data will be presented.

Since there are only six distress measurement points available, six calibration models were obtained. Every calibrated model is able to make Pavement-ME predict a value that is very close to the recorded distress for rutting. The six different calibration coefficients are then averaged and the resulting calibration coefficients are considered as the local calibration coefficients for the AC rutting distress prediction function.

The calibration factors are presented in Table 7.1.

Table 7.1: Local Calibration Coefficients of AC Rutting Equation

| **Road Section** | **Calibration Factors** | | | | | |
|---|---|---|---|---|---|---|
| | k1 | k2 | k3 | br1 | br2 | br3 |
| **R7 Right Branch** | -3.3541 | 1.5606 | 0.4791 | 0.4163 | 0.9932 | 0.9810 |
| **R7 Left Branch** | -3.3541 | 1.5606 | 0.4791 | 0.6284 | 0.9996 | 0.9810 |
| **R8-A Right Branch** | -3.3541 | 1.5606 | 0.4791 | 0.4173 | 0.9803 | 0.9601 |
| **R8-A Left Branch** | -3.3541 | 1.5606 | 0.4791 | 0.3041 | 0.9996 | 0.9810 |
| **R8-B Right Branch** | -3.3541 | 1.5606 | 0.4791 | 0.2027 | 0.9996 | 0.9810 |
| **R8-B Left Branch** | -3.3541 | 1.5606 | 0.4791 | 0.1824 | 0.9996 | 0.9810 |
| | | | **Average** | 0.3586 | 0.9953 | 0.9775 |

The coefficients that need to be changed are:

**Br1:** 0.3586; **Br2:** 0.9953; **Br3:** 0.9775.

The new predicted distresses after the calibration are shown in Figure 7.6.

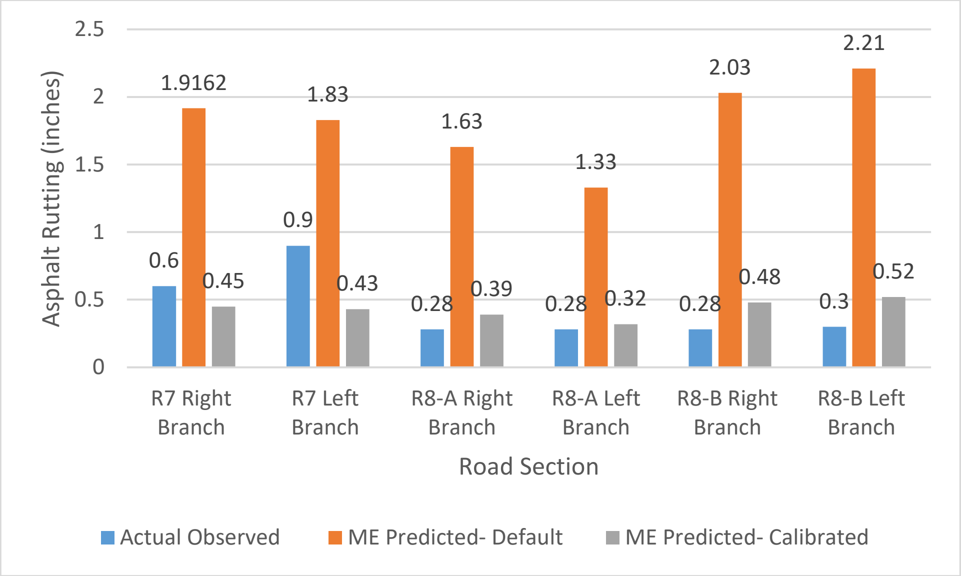

Figure 7.6: Predicted Pavement-ME Distress after Locally Calibrating AC Rutting Distress Prediction Model

# CHAPTER 8

# FRAMEWORK FOR LOCAL CALIBRATION OF DISTRESS PREDICTION MODELS

## 8.1 Introduction

Since there is no LTPP sites to be used for implementation in KSA, UAE and Qatar, the only available data on pavement distresses is from the Pavement Management Systems (PMS). The highway agencies of KSA, Abu Dhabi and Qatar have pavement management systems and use equipment with the latest technologies of Automatic Road Analyzers, falling weight deflectometers and regularly perform the needed observations for their road networks.

Authorities have to follow the calibration procedure recommended by the proceedings of project NCHRP 1-40b, but with some variation as to suit the specific conditions and data available in Middle East.

## 8.2 Challenges Facing Calibration of Pavement-ME Using PMS Data

According to (Titus-glover, 2014) PMSs are typically designed to administer a pavement program at the network level using data and models at a lower-level of granularity than those required for project level analysis. Some initial trials to use data from PMS to validate or calibrate MEPDG led to disappointing results and that’s due to multiple challenges that should be accounted for. The following sections will discuss four major challenges that might hinder the ability to implement Mechanistic-Empirical design through data from PMS independently.

### **8.2.1** ***Lack of Pavement-ME Design Specific Information in PMS Databases***

This challenge is faced due to the entity responsible for the PMS not having data on the design, maintenance, traffic, climate, geotechnical and construction conditions of the section understudy. All of this information might not reside in one place, and since all of this data is necessarily needed for the implementation effort, a strong collaboration between multiple entities from the transportation authority itself is a must. To overcome such a challenge, a comprehensive database, that could be very similar or even modeled as the LTPP IMS (information management system) should be formed. The PMS database should include:

- Library information; which contains:
    - Advanced material testing information from literature, lab testing or field testing
- Calibration information; which contains:
    - Inventory
    - Design
    - Specification (check others from inventory database)
    - Testing
    - Traffic
    - Site information

### **8.2.2** ***Inadequate Number of Pavement Sections to Cover Experimental Factorial***

A proper calibration process requires a certain number of roads to be surveyed, and have their observations properly logged. The required number of roads might not be always available.

### 8.2.3 *Inadequate Performance History*

This could take place when:

- The nominated sections are younger and have not developed appreciable pavement distress amount for the pavement distress type of interest. Such cases could be mitigated by using non-statistical approaches such as the one suggested by NCHRP 1-40b project in order to verify the model accuracy in the short-term.
- The data captured by the PMS is not of adequate quality; e.g., large fluctuations in captured distress. This can introduce large errors in the final calibrated model, and could be mitigated through a paramount quality control procedure that would insure clean usable data.

### 8.2.4 *Consistency of PMS Data with LTPP Distress Collection Protocol*

- There is a mismatch between the units of PMS-recorded data and unit used by Pavement-ME for predicting distresses, cracking is measured as a linear quantity in PMS while Pavement-ME predicts it as an area.
- A different methodology is used to capture certain distresses between Pavement-ME and PMS and this introduces bias.
    - Rutting is calculated using 3-point or 11-point based laser measurement in PMS while Pavement-ME models are based on the LTPP protocol which logs rut depths through wireline measurements.

In the case of the mismatch in the units of recording, it is necessary that data is re-recorded in accordance with Pavement-ME. This is a labor and time consuming step and might require field visits. Videos from the road will also be used in order to achieve this objective. If there is a difference in the data collection protocol similar to the case of rutting, statistical correlations can be established to develop regression equations to convert data reasonably. Examples on how the states of Arizona, Missouri and Colorado performed such calibration is attached in Appendix D.

## 8.3 Recommended Practice for Data Adjustment in Middle East

### 8.3.1 *AC Rutting*

In the states of the Middle East, and given that a history of PMS data is available, procedure that should be followed requires authorities collecting actual AC rut depth by rod and comparing it the measured PMS data. Correction factors are then applied.

### 8.3.2 *Fatigue Cracking*

The Middle East Countries could use the same methodology as to utilize the videos from ARANs that they currently utilize in order to quantify the road distress in the correct way that they need them for a calibration process for the transfer functions of alligator cracking. Inadequate number of Pavement Sections to Cover Experimental Factorial: It might be hard for agencies to find enough road sections having the design features, time period of relevance and historical performances to cover the experimental factor space.

## 8.4 NCHRP 1-40B Project Calibration Procedure of Distress Prediction Models

Under NCHRP Project 1-40B, the AASHTO Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide (2010) was developed, the report provides an 11-step roadmap for calibration of Pavement-ME software to the local conditions, policies, and materials. (Von Quintus, 2011). The steps are as follows:

- Step 1: Select hierarchical input levels.
- Step 2: Develop experimental factorial design and matrix or sampling template.
- Step 3: Estimate minimum sample size (number of pavement projects) required for each distress/international Roughness Index (IRI) prediction model validation and local calibration.
- Step 4: Select projects to populate sampling template.
- Step 5: Extract and assess distress and project data.
- Step 6: Conduct field and forensic investigations.
- Step 7: Assess local bias: validation of global calibration values to local conditions, policies, and materials.
- Step 8: Eliminate local bias of distress and IRI models.
- Step 9: Assess the standard error of the estimate.
- Step 10: Reduce standard error of the estimate.
- Step 11: Interpret results and determine adequacy of regional MEPDG locally calibrated models.

This process is what should be adopted by highway agencies in the Middle East countries but with certain modifications for it to be suitable for local conditions.

### 8.4.1 *Step 1: Select Hierarchical Input Levels*

The process of calibration of the Pavement-ME distress prediction functions comprises of changing the calibration coefficients in the empirical distress prediction functions so that the predicted distresses from the software simulated model are as close as possible to the actual distresses measured on field.

Since level 1 input parameters might not be always available for agencies, so they have to select the level at which they want to perform the calibration.

### 8.4.2 *Step 2: Develop Local Experimental Plan and Sampling Template.*

In step 2 of the local calibration effort, there should be a statistical experimental procedure to verify that the Pavement-ME global models and procedures are adequate to the local conditions and practices, and to calibrate the global models if deemed inadequate. To meet those objectives, a pavement population should be defined, sampling needs determined and the experimental design established.

The sampling template is a matrix of sample roads that reflect the different characteristics of built pavements in the region understudy (Table 8.2). Pavement are characterized based on, what is defined by (NCHRP 1-40B), as primary and secondary tiers, that are based on local standard practice and specifications.

The primary tier parameters that roads are sampled according to, should be distress dependent such as:

- Pavement type
- Surface layer type and thickness
- Subgrade soil type

Secondary parameters should include:

- Climate
- Traffic

- Design features that are dependent on pavement type.

Defining the parameters mentioned above requires a thorough review of past and current pavement design and construction practices in the areas under study which are KSA, UAE and Qatar.

- Past and current design and construction practices that should be observed:
    - Pavement types (new and rehabilitation).
    - Material types
    - Site properties (sub-grade, climate, and traffic)
    - Design features.
    - Types of rehabilitation practices employed.
    - Construction practices.
- Future design and construction practices:
    - New materials.
    - Incentive-based construction.
    - New construction techniques and equipment.

Based on this information, the pavement population and properties to include in the current and past practices in the countries understudy can be defined:

- New pavement types (AC/granular)
- Rehabilitated pavement types (AC/AC)
- Materials:

    - AC (conventional and Superpave mixes)
    - Granular base materials: A-1-a
    - Sub-grade
- Climate
- Traffic (Vehicle class distributions representative of all the main arterial roads as recommended by Chapter 6)

Traffic and climate, for example, are secondary tier parameters which means that they are reflected in the design of the pavement without the need of having them as part of the matrix. As an example; traffic if heavy would be traversing a road of higher thickness while roads of lower thicknesses will be built to service low traffic volumes.

In the case of the climate, it could be part of the matrix and that is based on how the authority choses to classify its climate and geography.

The following Table 8.2 could be a possible sampling matrix for KSA where the specifications, practices and soil type are represented. Table 8.3 shows a probable matrix that could be used by Qatari authorities based on their standard practices that are shown in (Figure 4.7) (Sadek et al., 2014).

Table 8.1: Possible Sampling Matrix for KSA

| **HMA Thickness (in)** | **Granular Base Thickness (in)** | **Subgrade type** | |
|---|---|---|---|
| | | Excellent to good soils ( A-1 through A-2) | Fair to bad soils (A-4 through A-7) |
| <15 cm | <12 cm | Number of Projects | Number of Projects |

| | | | |
|---|---|---|---|
| | >12 cm | Number of Projects | Number of Projects |
| >15 cm | <12 cm | Number of Projects | Number of Projects |
| | >12 cm | Number of Projects | Number of Projects |

Table 8.2: Possible Sampling Matrix for Qatar

| **HMA Thickness (in)** | **Stabilized Lower Base (cement stabilized) in** | **Granular Base Thickness (in)** | **Subgrade type** | |
|---|---|---|---|---|
| | | | Excellent to good soils ( A-1 through A-2) | Fair to bad soils (A-4 through A-7) |
| 29 cm | 0 | <20 | Number of Projects | Number of Projects |
| 19 cm | 27 cm | <20 cm | Number of Projects | Number of Projects |
| >30 cm | 27 cm | 0 cm | Number of Projects | Number of Projects |

There is no need to fill all the matrix cells by road sections as there might be some relations that are not feasible or not practiced.

### 8.4.3 *Step 3: Estimate Sample Size for Specific Distress Prediction Models*

The number in each cell of the sampling template should include replicate projects (projects of the same characteristics based on the matrix). This step is used to estimate the sample size or number of roadway segments to confirm the adequacy of the global calibration coefficients and determine, if needed, the local calibration coefficients for a specific distress prediction model.

The sample size needed is for evaluating both the bias and precision.

Bias: is the average residual error; therefore, the confidence interval on the mean can be used to relate the sample size and the bias.

In order to set the number of projects needed for the validation and calibration, the required information is the model error (i.e., standard error estimate [SEE]); confidence interval for statistical analysis; and performance indicators' threshold values depended by the departments of transportation in the country or emirate.

The following parameters assumed conform to the global norms and practices and apply to the local distress thresholds.

Design reliability level: 90%.

Confidence interval: 90%.

SEE for the global Pavement-ME models as presented in the following table which is meant to define the minimum number of projects required for the calibration of a certain type of distress.

Table 8.3: Identifying Road Samples Needed for Calibration

| **Pavement Type** | **Distress/IRI** | **Distress/IRI Threshold (90% reliability)** | **SEE** | **Minimum Number of Projects Required for Validation and Local Calibration** | **Minimum Number of Projects Required for each Pavement type (n)*** |
|---|---|---|---|---|---|
| **New HMA and HMA** | Alligator Cracking | 20% lane area | 5.01% | 16 | 18 |

| | | | | | |
|---|---|---|---|---|---|
| **overlaid HMA** | Transverse Thermal Cracking | Crack Spacing >100 ft of 630 ft/mile | 150 ft/mi ** | 18 | |
| | Rutting | 0.5 inch | 0.107 inch | 22 | |
| | IRI | 169 inch/mi | 18.9 inch/mi | 80 | |

$*n = \left(\frac{Z\propto/2\times\sigma}{E}\right)^2$ where $Z_{\alpha/2}$ = 1.601 (for a 90% confidence interval), $\sigma$ = performance indicator threshold (design criteria), E= tolerable bias at 90% reliability (1.601*SEE).

** Estimated from other Pavement-ME implementation projects.

Since the accuracy of the performance indicator IRI depends on the accuracy of other pavement distress predictions, it will not be calibrated itself.

Transverse cracking as well will not be calibrated since it is not one of the distress types applicable to the region understudy and it never happens.

### 8.4.4 *Step 4: Select Roadway Segments*

**Identifying Projects for Local Calibration/Validation database**

The selected projects to populate the sampling templates should be based on the recommendations from the *Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (Von Quintus, 2011)*:*

- Projects should be representative of local pavement design and construction practices.
- Projects should be representative of typical pavement conditions (i.e., poor, moderate, and good).
- Projects age should span the range typical of local practice (i.e., newly constructed, older existing, and rehabilitated)

- Projects must be located throughout the area set under calibration.

Based on the NCHRP 1-40B report (Von Quintus, 2011), although three types of experimental test sections can be used in the local validation-calibration refinement plan, roadway segment or long-term field experiments need to be used to determine the standard error of the estimate for each distress simulation model.

Since well-defined and continuously surveyed roads similar to LTPP project sites in the U.S. are not available in any of the Middle East countries, the primary source of data should be the pavement management system (PMS) database.

### 8.4.5 *Step 5: Extract and Evaluate Distress and Project*

Researchers and practitioners performing the implementation in the locality should identify all the potential projects that met the recommendation, and are included in the PMS observation program.

This system is able to provide data on the road distresses but has to be supported by a proper traffic characterization technique which up to this moment is not available by highway agencies, thus it is recommended to employ data mentioned throughout this report and other research projects in order to expedite the implementation process.

It is very important to compare the maximum measured distress values to the trigger value or design criteria used by the authority for each distress. The average maximum distress values from the sampling template should exceed 50 percent of the design criteria, as a minimum. This consideration becomes important when evaluating the bias and standard error terms of the prediction model in the following steps.

Based on the pool of projects identified above, the researchers should determine the roads where sufficient input data (such as traffic, material, and construction) and distress/IRI data in Pavement-ME required format are available. Once the projects are identified:

1- Extracted Pavement-ME input data will be reviewed to identify, correct and eliminate anomalies and outliers.

After selecting the set number of projects, researchers should extract the necessary data to serve as Pavement-ME input data; Construction, Design, Climate, Materials, Traffic. Real data specific to the project understudy should be obtained, if available. If not available, this report comprehensively characterizes to an extent very similar to the real situation in the gulf area, all of the needed parameters.

The data extracted and reviewed should be on the following parameters:

- Project Construction/Rehabilitation Year
- Project Location
- Project Functional Class (Principal Arterial, Rural….)
- Volumetrics of HMA
- Air Voids of Projects
- Aggregate Base and Subgrade Liquid Limit
- Aggregate Base and Subgrade Plasticity Index
- Aggregate Base and Subgrade Maximum Dry Density
- Subgrade Type (Coarse or Fine-Grained)
- New HMA Pavement Thickness of Projects

- Existing HMA Thickness for HMA Overlaid HMA Pavement Projects
- HMA Overlay Thickness of HMA Overlaid HMA Pavement Projects

The aggregated projects should be classified based on the above parameters in order to find the mean value and standard deviation of every parameter mentioned above. All project databases should be revised based on engineering judgement. Questionable data should be removed or replaced with typical values or project specific info from other sources.

2- Extracted distress/IRI data will be reviewed to identify and correct or eliminate anomalies and outliers.

If the collected data from PMS is compatible with Pavement-ME type of input then it can be used directly. Then, the means and standard deviation of the maximum distress and IRI (Alligator, rutting, IRI) values should be obtained.

Collected time series plots of distresses and IRI should be inspected to check if values are reasonable or if there is anything to question. Outliers and erroneous errors should be removed.

3- Distress/IRI magnitudes will be compared to the design threshold values.

4- The local Pavement ME calibration and validation database is assembled.

Following data assembly, review and cleanup, the researchers should select the projects with adequate detailed information. The road names are then tabulated in the template presented in Table 8.2.

### 8.4.6 *Step 6: Conduct Field and Forensic Investigations*

1- Agency should develop a materials' sampling and testing plan to determine any missing data element or to validate key inputs for the roadway segments selected. The *MEPDG Manual of Practice* provides recommended guidelines for field investigation.

2- Road authority has to decide whether forensic investigations are required to confirm assumptions embedded in the Pavement-ME. An example on that is the classification of rutting and the wheel path crack type (bottom up or top down).

If the authority accepts model's assumptions for layer rutting and location of crack initiation, then there is no need for a forensic investigation and agency should restrict the calibration to total rut depth and total load related cracking- combining longitudinal and alligator cracks and calibrating alligator cracking function only as per section 2.4 of NCHRP 1-40B (Von Quintus, 2011) report.

Agency should confirm that the roadway segments remaining with all the data needed is sufficient based on the needed number of segments mentioned above. If not more sections have to be sourced.

### 8.4.7 *Steps 7 through 11: Assess and Eliminate/Reduce Local Bias and Standard Error of the Estimate from Global Calibration Factors*

The procedure for those steps should be followed as per the procedure and guidelines of chapter 6 of the NCHRP 1-40B report "Guide for the Local Calibration of the Mechanistic-Empirical Pavement Design Guide" (Von Quintus, 2011).

# Chapter 9

# CONCLUSIONS AND ROADMAP OF IMPLEMENTATION

## 9.1 Introduction

There are multiple obstacles that face the process of implementing the use of Pavement-ME in the countries of the Middle East.

The methodology that the Mechanistic Empirical Pavement Design is based on requires a lot of data to be collected. Some of this data needs to be acquired by lab testing and site visits, other types of data are collected by road observations which also requires technologies, expertise and proper management.

This thesis was able through sensitivity analysis to recommend the hierarchical level of analysis and catalogue input values of certain parameters (Table 9.1). The thesis also highlighted the need for local calibration of the empirical distress prediction models and proposed a framework for such calibration based on current pavement management practices in KSA, UAE and Qatar.

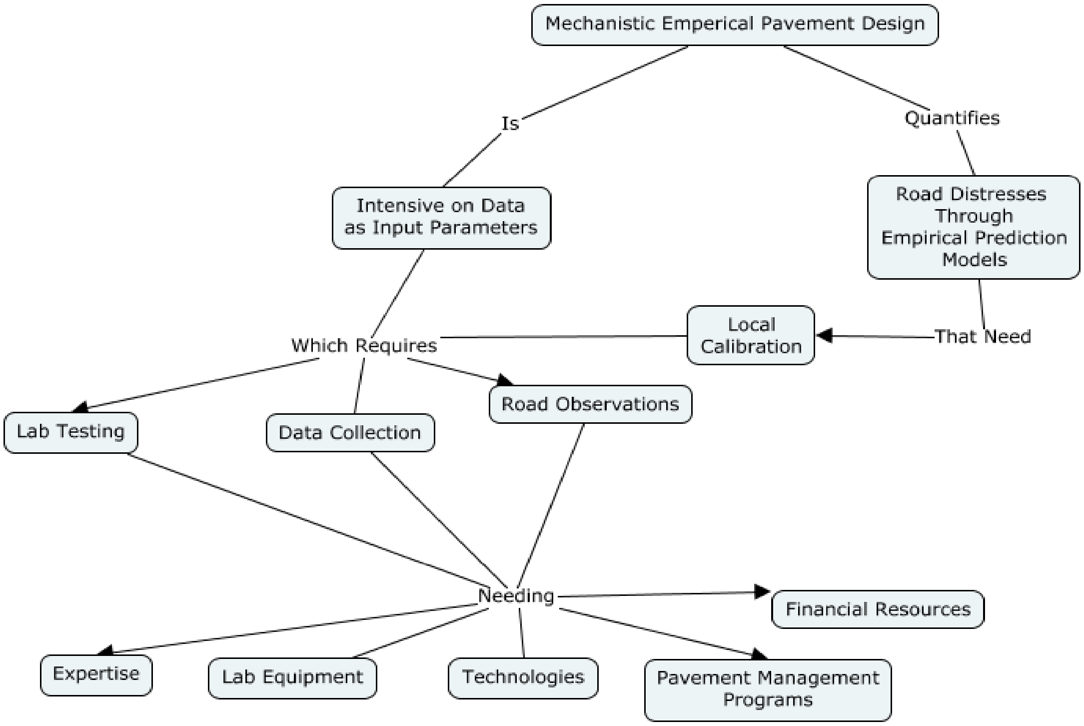

Figure 9.1: Resources Needed for Pavement-ME Implementation

## 9.2 Significance of Overweigh Trucks

It is highly expected from observations and how truck carriages are modified in the Arabian countries that trucks are being overloaded. This is a huge problem that might not be easily considered due to the lack of a single entry point that grabs the user’s attention where he could specify an average weight for every truck traffic class. The only way to reflect the actual weights of trucks is by reflecting this additional weight into a larger number of standard axles per truck or by increasing the input value of AADTT.

Multiple research has showed how critical the issue of truck overweight is. Mulyono and Antameng (2010) and Zhao et al. (2012) Showed that 80% of the trucks in countries like China and Indonesia are overweight, and that a very usual, often percentage of overloaded trucks is 10% to 30%. In his research Pais et al. (2013) indicated that the per vehicle calculated maintenance cost increases by 100% for vehicles that are overloaded.

Zhao et al. (2012) identified that the distress types highly effected by overloaded traffic are bottom up and top down cracks while rutting is less sensitive. De Beer et al. (1997) on the other hand argued that overloaded axles cause a non-uniformity of the tire contact stress which will result in an increase in the plastic deformation of asphalt mixes. As a way to quantify how much the pavement fatigue life decreases as a result of overloading, Rys et al. (2016) employed data from WIM stations in Poland and concluded that overloaded vehicles significantly affect fatigue life of the pavement, only a percentage of up to 20% of trucks being overloaded could cause a reduction of the pavement's fatigue life by around 50%.

Based on such literature, any pavement design practice that doesn't take the quantification of overloaded trucks into consideration is flawed and could highly impact the expected service life of the pavement.

Employing WIM stations on the most important arterials is a necessity to enforce proper truck loading and preserve the serviceability of the pavement structure. Being able to obtain better truck class characterization is an added value for implementing WIM stations, but as indicated in the section above, shouldn't be the main reason.

## 9.3 Catalogue Values and Lab Tests Needed

The sensitivity of distresses understudy to certain input parameters along with lab tests and catalogue values are presented in Table 9.1.

Table 9.1: Sensitivity of Distresses to Certain Input Parameters and Recommended Catalogue Values and Lab Tests

| **ME Input Variable** | **Sensitivity to predicted distress** | | **Current Possible Level of Implementation** | **Technique Needed to go to a better level of Analysis** | **Recommended Hierarchical Input Level** | **Catalogue Values** |
|---|---|---|---|---|---|---|
| | Alligator Cracking | Rutting | | | | |
| **HMA Thickness** | XXX | XX | Level 1 | | Level 1 | None |
| **HMA dynamic modulus** | XXX | XXX | Level 3 | Dynamic Modulus Test | Level 1 | None |
| **HMA Creep Compliance** | XX | XXX | Level 3 | Direct shear Test | Level 1 | None |
| **Base type/modulus** | XXX | XX | Level 3 | | Level 3 | Type A-1-a, Mr = 48,000 psi |
| **Subgrade type/modulus** | XX | XX | Level 1 | | Level 1 | A-1-a/ 25,000 psi<br>A-1-b/ 18,000 psi<br>A-2-4/ 22,000 psi<br>A-3/ 24,000 psi<br>A-4/ 8,000 psi<br>A-7-6/ 7,000 psi |
| **Climate** | XX | XXX | Required Input | | | None |
| **Truck Volume** | XXX | XXX | Level 2 | WIM stations installation | Level 1 | None |
| **Truck Class Distribution** | X | XX | Level 2 | WIM stations installation | Level 2 | Class 4, 2.8%; Class 5, 31%, Class 6, 7.3%; Class 7, 0.8%, Class 8, 9.3%, Class 9, 44.8%, Class 10, 2.3%, Class 11, 1%; Class 12, 0.4%, Class 13, 0.3%. |

**X: Low Sensitivity.**
**XX: Medium Sensitivity**
**XXX: High Sensitivity**

## 9.4 Recommendations on Implementation

The added benefits of designing in accordance with the mechanistic empirical pavement design method should encourage highway agencies to invest in the implementation of Pavement-ME. Though such a process might be lengthy due to the lack of basic elements as shown in Figure 9.1, provisions towards implementation could be set and the track towards implementation started.

Based on the findings of the thesis research and literature, the plan of action could be divided into three aspects:

- Administrative and Law Enforcement Aspect
- Managerial Aspect
- Technical and Technological Aspect

### 9.4.1 *Administrative and Law Enforcement Aspect*

Administrative aspect is controlled by decision makers in countries pushing forward towards the transformation into mechanistic empirical design. Changing the type of pavement construction contracts into performance based contracts will force contractors and designers into adopting a more scientific and reliable practice.

Law enforcement has a great role in controlling the truck traffic and not allowing overweight trucks due to the great damage that they cause on the lifetime of the pavement.

### 9.4.2 *Managerial Aspect*

Highway agencies have a great responsibility to, first pave the way towards implementation and second keep up with how the industry progresses and changes. Actions that should be taken by highway agencies are:

- Building a library of the commonly used and innovated mixes and extracting their Dynamic Modulus and Shear Moduli of binders.
- Better characterizing the weight of trucks either by:

▪ Regulatory measures to prohibit overloading or

▪ Through the installation of Weigh in Motion (WIM) stations to keep better track of overloaded trucks.

- Assigning human resources for the task of:

▪ Collecting asphalt rutting measure as per LTPP protocol from roads under observation.

▪ Watching video records collected in order to quantify the longitudinal cracks.

### 9.4.3 *Technical and Technological Aspect*

Both legal, law enforcement and managerial aspects have to be supported by the proper technical and technological infrastructure such as:

- Lab equipment to test for:
    - Dynamic Modulus Test
    - Shear Modulus Test
- Weigh in Motion Stations
- Automatic Road Analyzers

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# APPENDICES

# APPENDIX A

## Asphalt Mixes Properties

The asphalt mixes are characterized as follows:

Mix A- Which uses a binder designated as PMB PG (76-10)V available through Woqod company in Qatar, this mix is designed to hold a traffic up to 30 million ESALS in the tough climatic conditions of Eastern Arabian Peninsula. The dynamic modulus (E*) and complex modulus (G*) values are represented in tables 5.2 and 5.3 below.

Table 10.1: Dynamic Modulus of Mix A

| **Temperature (deg F)** | **0.1** | **0.5** | **1** | **5** | **10** | **25** |
|---|---|---|---|---|---|---|
| **14** | 3208099 | 3522599 | 3647269 | 3910542 | 4012657 | 4137506 |
| **40** | 2117522 | 2496374 | 2657080 | 3016684 | 3163665 | 3349119 |
| **70** | 930637 | 1230921 | 1373608 | 1728913 | 1889364 | 2105179 |
| **100** | 262275 | 392797 | 462902 | 661646 | 763410 | 912928 |
| **130** | 58000 | 82100 | 100938 | 160878 | 195271 | 250385 |

Table 10.2 Binder Shear Modulus of Binder PMB (PG76-10)V used in Mix A- Angular Frequency= 10 rad/sec

| **Temperature ( deg F)** | **Binder G* (Pa)** | **Phase angle** |
|---|---|---|
| **168.8** | 1948.05 | 66.058 |
| **179.6** | 1212.26 | 64.151 |
| **190.4** | 808.26 | 60.891 |

In case analysis at Levels 2 or 3 is required, the (E*) input values from Table 5 above have to be replaced by the aggregate gradation that is requested by Pavement-ME, the corresponding aggregate gradation of Mix A is as follows:

Table 10.3 Aggregate Gradation of Mix A

| Gradation | Percent Passing |
|---|---|
| **¾ inch sieve** | 96 |
| **3/8 inch sieve** | 69 |
| **No. 4 sieve** | 47 |
| **No. 200 sieve** | 4.2 |

Mix B- uses a binder designated as PG82-10 and is designed to hold the heavy traffic conditions (30 to 40 million ESALS) in the climatic conditions of southern Iraq, properties are presented in tables 5.5 and 5.6 below.

Table 10.4: Dynamic Modulus of Mix B

| Temperature (deg F) | 0.01 | 0.1 | 0.5 | 1 | 5 | 10 |
|---|---|---|---|---|---|---|
| **23** | 2553855 | 3136098 | 3488527 | 3633502 | 3948160 | 3998300 |
| **51** | 876195.9 | 1422688 | 1859293 | 2043814 | 2511156 | 2677892 |
| **68** | 272525.9 | 599219 | 934650.6 | 1119869 | 1599635 | 1801801 |
| **100** | 42786.13 | 107105.7 | 192430.2 | 244419.8 | 440890.4 | 561374.7 |
| **130** | 28726.5 | 35713.9 | 65664.6 | 86169.6 | 162289 | 211914 |

Table 10.5: Shear Modulus of Binder PG82-10 used in Mix B

| Temperature ( deg F) | Binder G* (Pa) | Phase angle |
|---|---|---|
| **168.8** | 4019.495 | 78 |
| **179.6** | 2085.83 | 81.2 |
| **190.4** | 1124.135 | 83.45 |
| **201.19** | 628.47 | 84.75 |

Mix C, uses a binder designated as PG88-10 properties are presented in Tables 5.7 and 5.8 below.

Table 10.6: Dynamic Modulus of Mix C

| **Temperature (deg F)** | **0.01** | **0.1** | **0.5** | **1** | **5** | **10** |
|---|---|---|---|---|---|---|
| **40** | 2309510 | 3119294 | 3650497 | 3863785 | 4315884 | 4490920 |
| **51** | 1600730 | 2265842 | 2764083 | 2982870 | 3468810 | 3641167 |
| **68** | 567402 | 1135940 | 1679575 | 1889053 | 2432671 | 2662844 |
| **100** | 82635 | 225548 | 401788 | 507753 | 822116 | 1002319 |
| **130** | 25323.9 | 75502.51 | 152944.2 | 203116.1 | 372299.3 | 472008.2 |

Table 10.7: Shear Modulus of Binder PG88-10 used in Mix C

| **Temperature ( deg F)** | **Binder G* (Pa)** | **Phase angle** |
|---|---|---|
| **168.8** | 3369.53 | 82.83 |
| **179.6** | 1687.14 | 85.26 |
| **190.4** | 888.152 | 86.82 |
| **201.19** | 493.01 | 87.65 |

Table 10.8: Dynamic Modulus of Mix Using PG64-10

| **Temperature (deg F)** | **0.01** | **0.1** | **1** | **5** | **10** |
|---|---|---|---|---|---|
| **23** | 2240516.4 | 3071755.847 | 3727567.089 | 4063681.675 | 4180218.527 |
| **51** | 375083.6 | 854708.2854 | 1607801.786 | 2219777.233 | 2482745.976 |
| **68** | 93620.2 | 238802.6357 | 582866.0438 | 992140.1509 | 1210613.346 |
| **100** | 20787.6 | 39657.68514 | 91370.50367 | 175267.1668 | 232866.3959 |
| **130** | 12861.4 | 19767.24592 | 36986.29236 | 64466.71192 | 83920.3653 |

Table 10.9: Shear Modulus of Binder PG64-10

| **Temperature ( deg F)** | **Binder G* (Pa)** | **Phase angle** |
|---|---|---|
| **125.6** | 5940.29 | 86.3 |
| **136.4** | 2578.88 | 87.5 |
| **147.2** | 1176.28 | 88.3 |
| **158** | 569.84 | 88.9 |
| **168.8** | 294.42 | 89.1 |

# APPENDIX B

## Surveyed Truck Classification and Performance Survey of Iraq

Table 10.10: Multiple Traffic and ESAL Scenarios Simulated

| | **Source** | **AADTT** | **ESALS** | **Truck Class 4** | **Truck Class 5** | **Truck Class 6** | **Truck Class 7** | **Truck Class 8** | **Truck Class 9** | **Truck Class 10** | **Truck Class 11** | **Truck Class 12** | **Truck Class 13** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Recorded data from KSA ESALS | 7000 | 14M | 3 | 30 | 4 | 24 | 27 | 5 | 2 | 5 | 0 | 0 |
| **2-A** | Pavement-ME library no 13 mix- default; equal percentages of single unit and single trailer trucks. | 7000 | 12.22M | 0.8 | 33.6 | 6.2 | 0.1 | 7.9 | 26 | 10.5 | 1.4 | 3.2 | 10.3 |
| **2-B** | Same class distribution as 2-A | 8020 | 14M | 0.8 | 33.6 | 6.2 | 0.1 | 7.9 | 26 | 10.5 | 1.4 | 3.2 | 10.3 |
| **3-A** | Pavement-ME library no 6 mix -default; mixed truck traffic with higher percentage of single unit trucks | 7000 | 10.51M | 2.8 | 31 | 7.3 | 0.8 | 9.3 | 44.8 | 2.3 | 1 | 0.4 | 0.3 |
| **3-B** | Same class distribution as 3-A | 9325 | 14M | 2.8 | 31 | 7.3 | 0.8 | 9.3 | 44.8 | 2.3 | 1 | .4 | 0.3 |
| **4-A** | Pavement-ME library no 16 mix -default; mixed truck traffic with predominantly single unit trucks. | 7000 | 11.7 | 1.3 | 48.4 | 10.8 | 1.9 | 6.7 | 13.4 | 4.3 | 0.5 | 0.1 | 12.6 |
| **4-B** | Same class distribution as 4-A | 8377 | 14 | 1.3 | 48.4 | 10.8 | 1.9 | 6.7 | 13.4 | 4.3 | 0.5 | 0.1 | 12.6 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **I1-A** | Iraq, Baghdad-Basra connection. | 7000 | 14.53 M | 3 | 22 | 5 | 16 | 15 | 20 | 15 | 1 | 1 | 2 |
| **I1-B** | Iraq, Baghdad-Basra connection | 6745 | 14 | 3 | 22 | 5 | 16 | 15 | 20 | 15 | 1 | 1 | 2 |
| **I2-A** | Iraq, Baghdad-Basra connection. | 7000 | 14.38 | 2.5 | 16.5 | 4 | 12 | 21 | 21 | 21 | 1 | 0 | 1 |
| **I2-B** | Iraq, Baghdad-Basra connection | 6815 | 14 | 2.5 | 16.5 | 4 | 12 | 21 | 21 | 21 | 1 | 0 | 1 |
| **L1-A** | Lebanon, Beirut-Tripoli Connection. | 7000 | 9.26 | 45.8 | 2 | 11.3 | 0.8 | 4.5 | 2.3 | 8.1 | 4.0 | 21.2 | 0 |
| **L1-B** | Lebanon, Beirut-Tripoli Connection | 10580 | 14 | 45.8 | 2 | 11.3 | 0.8 | 4.5 | 2.3 | 8.1 | 4.0 | 21.2 | 0 |
| **L2-A** | Lebanon, Beirut-Beqaa Connection. | 7000 | 9.89 | 29.3 | 7.1 | 17.9 | 0.4 | 12.9 | 3.3 | 12.2 | 2.2 | 14.7 | 0 |
| **L2-B** | Lebanon, Beirut-Bekaa Connection | 900 | 14 | 29.3 | 7.1 | 17.9 | 0.4 | 12.9 | 3.3 | 12.2 | 2.2 | 14.7 | 0 |

Table 10.11: Traffic Characterization and Measured Distresses on Freeway 1 Surveyed Sections

| | | **Truck Class Distribution by %** | | | | **Measured Distresses** | |
|---|---|---|---|---|---|---|---|
| **Section** | AADTT | 4 and 5 | 6 and 7 | 8,9 and 10 | 11,12 and13 | AC Rutting (mm) | Cracking (%) |
| **R7- Right Branch** | 3524* | 30 | 7 | 59 | 5 | 15 | 30 |
| **R7- Left Branch** | 3129* | 28 | 9 | 57 | 6 | 23 | 40 |
| **R8- A- Right Branch** | 2313* | 23 | 33 | 40 | 4 | 7 | 50 |
| **R8- A- Left Branch** | 1610* | 31 | 31 | 34 | 5 | 7 | 45 |
| **R8- B- Right Branch** | 3664* | 19 | 16 | 63 | 2 | 7 | 50 |
| **R8- B- Left Branch** | 4235* | 15 | 26 | 53 | 5 | 8 | 60 |

*** The AADTT in Pavement-ME model is multiplied by 2 to account for the proven overloaded truck traffic traversing the road.**

# Appendix C

## Sample of Simulation's Properties

Table 10.12: A Sample of the Simulations

| **Traffic MESALS** | **Traffic Classification** | **Road Structure** | **Mix Type** | **Level of Analysis** | **Type of Base** | **Resilient Modulus of Base** | **Type of Subgrade** |
|---|---|---|---|---|---|---|---|
| **10** | T1 | R1 | A | L1 | A-1-a | 48,700 | A-2-4 |
| **10** | T1 | R1 | A | L1 | A-1-a | 48,700 | A-1-b |
| **10** | T1 | R1 | A | L1 | A-1-a | 48,700 | A-7-6 |
| **10** | T1 | R1 | B | L1 | A-1-a | 48,700 | A-2-4 |
| **10** | T1 | R1 | B | L1 | A-1-a | 48,700 | A-1-b |
| **10** | T1 | R1 | B | L1 | A-1-a | 48,700 | A-7-6 |
| **10** | T2 | R1 | A | L1 | A-1-a | 48,700 | A-2-4 |
| **10** | T2 | R1 | A | L1 | A-1-a | 48,700 | A-1-b |
| **10** | T2 | R1 | A | L1 | A-1-a | 48,700 | A-7-6 |
| **10** | T2 | R1 | B | L1 | A-1-a | 48,700 | A-2-4 |
| **10** | T2 | R1 | B | L1 | A-1-a | 48,700 | A-1-b |
| **10** | T2 | R1 | B | L1 | A-1-a | 48,700 | A-7-6 |
| **30** | T1 | R2 | A | L1 | A-1-a | 48,700 | A-2-4 |
| **30** | T1 | R2 | A | L1 | A-1-a | 48,700 | A-1-b |
| **30** | T1 | R2 | A | L1 | A-1-a | 48,700 | A-7-6 |
| **30** | T1 | R2 | B | L1 | A-1-a | 48,700 | A-2-4 |
| **30** | T1 | R2 | B | L1 | A-1-a | 48,700 | A-1-b |
| **30** | T1 | R2 | B | L1 | A-1-a | 48,700 | A-7-6 |
| **30** | T2 | R2 | A | L1 | A-1-a | 48,700 | A-2-4 |
| **30** | T2 | R2 | A | L1 | A-1-a | 48,700 | A-1-b |
| **30** | T2 | R2 | A | L1 | A-1-a | 48,700 | A-7-6 |
| **30** | T2 | R2 | B | L1 | A-1-a | 48,700 | A-2-4 |
| **30** | T2 | R2 | B | L1 | A-1-a | 48,700 | A-1-b |
| **30** | T2 | R2 | B | L1 | A-1-a | 48,700 | A-7-6 |
| **45** | T1 | R3 | A | L1 | A-1-a | 48,700 | A-2-4 |
| **45** | T1 | R3 | A | L1 | A-1-a | 48,700 | A-1-b |
| **45** | T1 | R3 | A | L1 | A-1-a | 48,700 | A-7-6 |
| **45** | T1 | R3 | B | L1 | A-1-a | 48,700 | A-2-4 |
| **45** | T1 | R3 | B | L1 | A-1-a | 48,700 | A-1-b |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **45** | T1 | R3 | B | L1 | A-1-a | 48,700 | A-7-6 |
| **45** | T2 | R3 | A | L1 | A-1-a | 48,700 | A-2-4 |
| **45** | T2 | R3 | A | L1 | A-1-a | 48,700 | A-1-b |
| **45** | T2 | R3 | A | L1 | A-1-a | 48,700 | A-7-6 |
| **45** | T2 | R3 | B | L1 | A-1-a | 48,700 | A-2-4 |
| **45** | T2 | R3 | B | L1 | A-1-a | 48,700 | A-1-b |
| **45** | T2 | R3 | B | L1 | A-1-a | 48,700 | A-7-6 |

# Appendix D

## Calibration Examples Using PMS Data

The following sections will show case studies for how some states overcame the challenge of inconsistency between PMS and LTPP protocols in order to use the PMS data for calibration.

**Arizona State Method to Adjust Rutting Measurements**

According to (Titus-glover, 2014) a comparison between the rut depth using three point laser equipment, usually used by automatic road analyzers traversing roads, showed discrepancy from the LTPP measured data by wire or straight-edge measurements. To ensure that rut depth from both sources were compatible, the Arizona DOT (ADOT) followed the following steps:

- Obtain Sample Data: This was done using rut depth measures from the Arizona LTPP flexible pavement projects as baseline and obtain ADOT PMS rut depth measurements for the same projects within the same measurement timeframe).
- Plot rut depth measurements from LTPP and ADOT PMS (Figure X below)
- Determine Extent of Bias Present: Bias was defined as the consistent under- or over estimation of rut depth by ADOT when compared to baseline LTPP measurements. Bias was determined by performing linear regression using 11 Arizona measured and LTPP measured rut depth and performing the following two hypothesis tests (assumed a significance level, α, of 0.05 or 5 percent):

- Hypothesis 1: Paired t-test. This test determined whether the Arizona and LTPP measured rut depth represented the same population. The paired t-test consisted of the following:
  - Assume the following null and alternative hypothesis:
    - $H_0$: mean measured ADOT measured rut depth = mean LTPP measured rut depth.
    - $H_A$: mean measured ADOT measured rut depth ≠ mean LTPP measured rut depth.
    - Compute test p-value. Compare computed p-value to predetermined level of significance for this test of 0.05. The null hypothesis $H_0$ was rejected if the p-value was less than 0.05. Rejecting $H_0$ implied that the Arizona and LTPP measured rut depth were essentially from different populations at the 5 percent significance level. Belonging to different populations indicates bias in the ADOT measured rut depth data as the LTPP measurements were considered the "ground truth" for this test analysis.
- Hypothesis 2. This set of paired t-test determined whether a linear regression model (ADOT Rut Depth = α*LTPP Rut Depth) has a slope (α) of 1.0 and Intercept of 0 at the 5 percent significance level. The test consisted of the following steps:
  - Using the results of the linear regression analysis, test the following null and alternative hypotheses to determine if the linear regression model Slope is 1.0, Intercept = 0:
    - $H_o$: model slope (α) = 1.0 and Intercept = 0.
    - $H_A$: model slope (α) ≠ 1.0 and Intercept ≠ 0.
  - Compute test p-value for both situations.

- Compare computed p-value to predetermined level of significance for this test and interpret as done for Hypothesis 1.

The outcome of the hypothesis testing are presented below

To eliminate bias in measured ADOT rut depth measurements the correction factor below was applied.

$$ADOT\_RUTADJ = 0.1544 * 2.918(2.4273*ADOT-RUT) \quad (1)$$

where

ADOT_RUTADJ = ADOT rut depth measurement adjusted to be compatible with LTPP ADOT-RUT = ADOT measured rut depth

Figure 4 presents the relationship between LTPP adjusted ADOT and LTPP rutting measurements. The adjusted ADOT and LTPP rutting measurements were tested for bias.

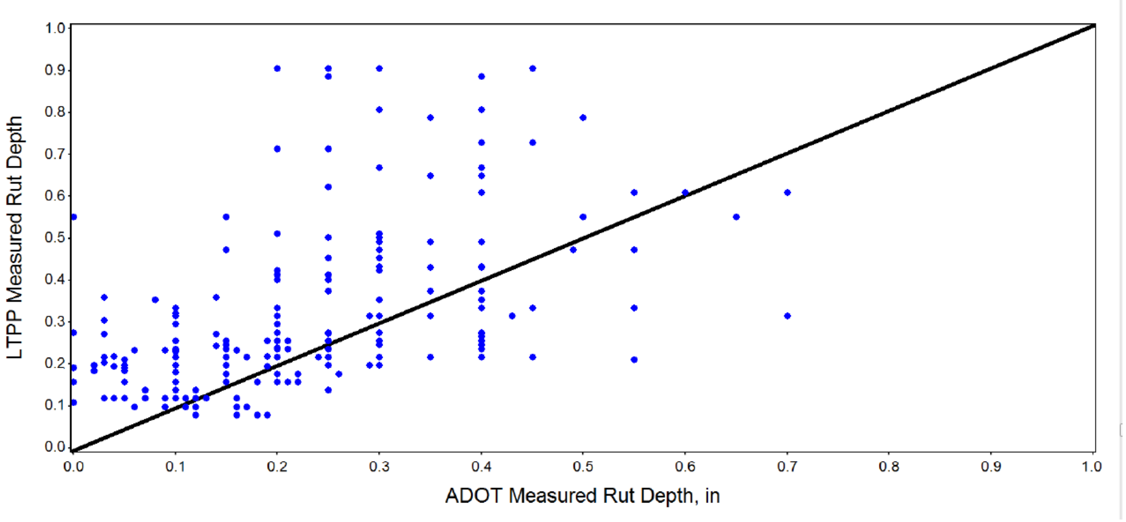
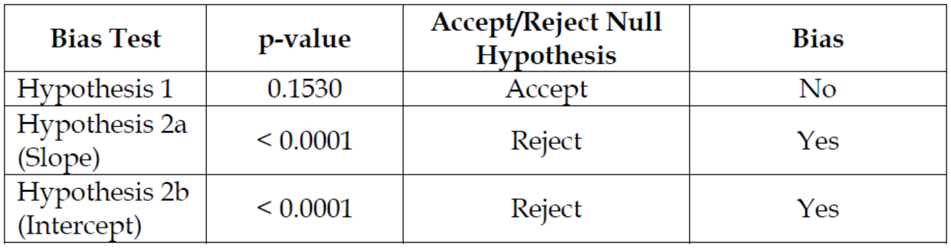


Figure 10.1: Relationship Between ADOT and LTPP Rutting Measurements



| Bias Test | p-value | Accept/Reject Null Hypothesis | Bias |
|---|---|---|---|
| Hypothesis 1 | 0.1530 | Accept | No |
| Hypothesis 2a (Slope) | < 0.0001 | Reject | Yes |
| Hypothesis 2b (Intercept) | < 0.0001 | Reject | Yes |

Figure 10.2: Summary of Outcome of Hypothesis Testing

### Colorado State Method to Adjust Rutting Measurements

Colorado state Department of Transportation (CDOT) intended to use the PMS data it collects in the calibration process of MEPDG. But similar to ADOT rut depth is also collected using 3-point laser equipment and should be adjusted to be significant and used to complement readings from LTPP.

The methodology used was as follows:

1- Perform field measurement of rut depth as per LTPP measurement protocol.
2- Compared field measured rut depth measurement to PMS measurements.
3- Apply correction factors as need to adjust PMS rut measurements.

Examples of the adjustment procedure for two PMS projects is presented below.

- Example 1: A plot of CDOT PMS rut depth versus age is presented in figure X for PMS Project 10-12393. Superimposed on this plot is the field measured rut depth (at age = 9 years). A comparison of field measured and PMS rut depth for ages 5, 7, and 9 shows that the PMS data follow a trend that approximately fits the field measure value reasonably. Thus the PMS rut depth values was deemed reasonable and no adjustment was needed. An adjustment factor of 1.0 was thus assumed.

- Example 2: A plot of CDOT PMS rut depth versus age is presented in figure 6 for PMS Project 27-13959. Superimposed on this plot is field measured rut depth at 13 age a section age of 8 years. A comparison of field measured and PMS rut depth for at 8 years shows a PMS rut value of 0.51 in and a field measured value of 0.85 in. The difference in these measures was deemed significant. The plot of PMS rut depth versus age shows that the PMS rut measurement at 8 years was not an anomaly or outlier as it fitted trends from previous measurements well. Thus there was a need to adjust the PMS rut depth to field measurements. This was done by determining an adjustment factor equal to field rut depth divided by PMS rut depth (at age = 8). For this PMS project the ratio was 0.85/0.51 = 1.66667. The adjustment factor was used to adjust PMS rut measurements for this project as shown in figure X below.

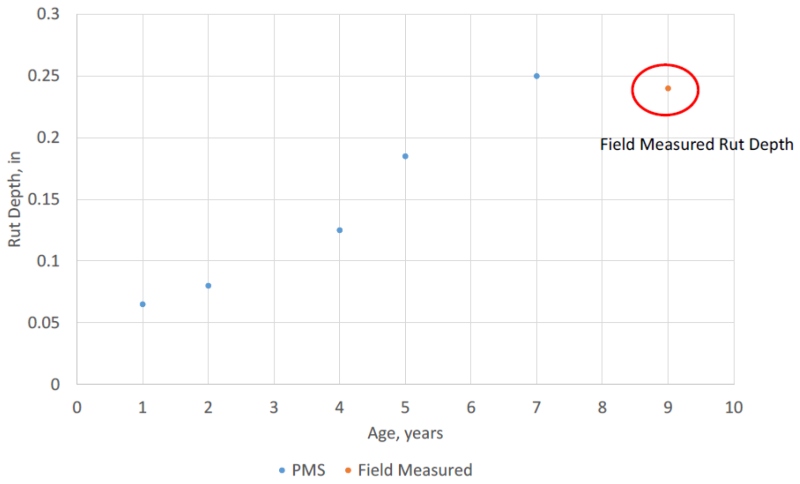


Figure 10.3: Relationship Between Field Measured and CDOT PMS Rut Depth for Project 10-12393

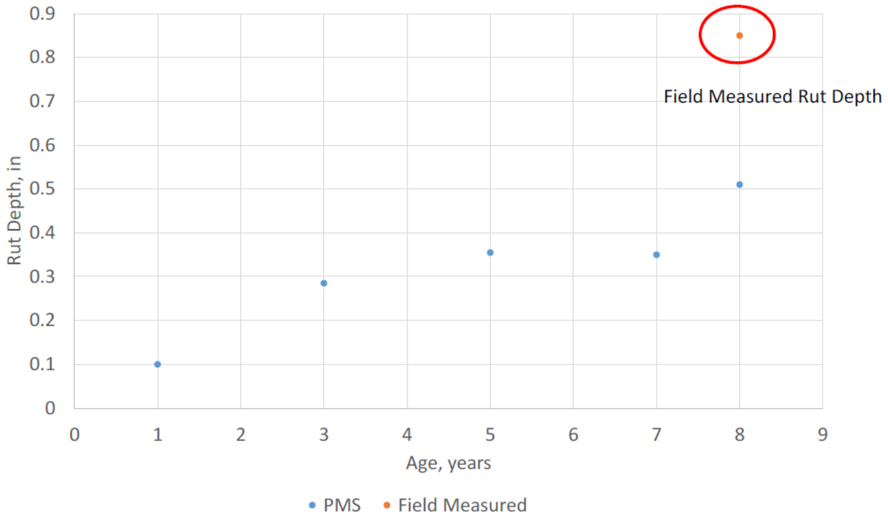


Figure 10.4: Relationship Between Field Measured and CDOT PMS Rut Depth for Project 27-13959

**Missouri State Utilization of PMS for Alligator Cracking Quantification.**

Missouri DOT wanted to augment the LTPP projects with some PMS projects as to fully cover the sampling space for the calibration process. Historical alligator and transverse cracking quantification was needed as per LTPP distress survey protocols. PMS in Missouri employs the Automated Road Analyzer (ARAN) to calculate the IRI and to capture through video the cracks on the roads. Those videos are then manually interpreted and cracks recorded and classified. The methodology followed by Missouri DOT was as follows:

- Identify the highway ID (route, direction, lane number, and begin/end milepost) for each project of interest.
- Identify sample sections within the project of interest.
- Retrieve distress videos from the MoDOT video archives.

- Review distress on the archived distress video and quantify alligator cracking and transverse cracking as per LTPP protocol.
- Develop records of distress patterns and locations on LTPP distress maps.
- Compute alligator cracking and transverse cracking as per MEPDG requirements.

# Appendix E

## Soil Properties in Arabian Peninsula

Table 10.13: Soil Properties in Arabian Peninsula

| **Sample** | **Soil Classification** | | **Gs** | **Sand %** | **Silt %** | **Clay %** | **Atterberg Limits** | | | **Compaction Test** | | **CBR** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AASHTO | Unified | | | | | LL | PL | PI | MDD | OMC | |
| **B-09** | A-1-a | SP | 2.711 | 53.9 | 3.3 | 1.6 | | | NP | 2.136 | 8 | 53 |
| **H-01** | A-1-a | GP-GM | 2.764 | 38 | 8 | 2.8 | | | NP | 2.118 | 10.3 | 17 |
| **A-03** | A-1-b | SMSC | 2.663 | 55.5 | 14.3 | 7 | 22.7 | 17.5 | 5.2 | 2.048 | 8.9 | 9 |
| **B-19** | A-1-b | SM | 2.669 | 69 | 10.4 | 3.5 | | | NP | 2.04 | 9.5 | 36 |
| **B-08** | A-2-4 | SP-SM | 2.721 | 70.7 | 19.9 | 7 | | | NP | 1.915 | 12.6 | 21 |
| **F-04** | A-2-4 | SP-SM | 2.695 | 71.8 | 7.5 | 4 | 15.5 | 15.3 | NP | 2.06 | 9.2 | 26 |
| **I-03** | A-2-4 | SM | 2.811 | 75.3 | 18.3 | 4 | | | NP | 2.054 | 9 | 46 |
| **K-12** | A-2-4 | SMSC | 2.645 | 59.2 | 18.4 | 8 | 21.7 | 17.5 | 4.2 | 1.944 | 10.8 | 26 |
| **K-05** | A-3 | SP-SM | 2.613 | 91.4 | 5.7 | 2.9 | | | NP | 1.883 | 0 | 37 |
| **N-02** | A-3 | SP-SM | 2.717 | 82.9 | 6.5 | 3.3 | .3 | | NP | 1.843 | 0 | 30 |
| **E-06** | A-4 | SC | 2.769 | 27.9 | 24.4 | 17 | 31.5 | 22.4 | 9.1 | 1.863 | 15 | 5 |
| **H-02** | A-4 | SM | 2.807 | 19.8 | 29.2 | 8 | 25.6 | 23 | 2.6 | 1.924 | 13 | 7 |
| **D-06** | A-7-6 | SC | 2.751 | 43.6 | 18.2 | 27 | 42.3 | 25.3 | 17 | 1.773 | 15.5 | 5 |