

Utilizing the Canadian Long-Term
Pavement Performance (C-LTPP)
Database for Asphalt Dynamic Modulus
Prediction

by

Richard Christopher Korczak

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada, 2013

©Richard Christopher Korczak 2013

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

In 2007, the Mechanistic-Empirical Pavement Design Guide (MEPDG) was successfully approved as the new American Association of State Highway and Transportation Officials (AASHTO) pavement design standard (Von Quintus et al., 2007). Calibration and validation of the MEPDG is currently in progress in several provinces across Canada. The MEPDG will be used as the standard pavement design methodology for the foreseeable future (Tighe, 2013).

This new pavement design process requires several parameters specific to local conditions of the design location. In order to perform an accurate analysis, a database of parameters including those specific to local materials, climate and traffic are required to calibrate the models in the MEPDG.

In 1989, the Canadian Strategic Highway Research Program (C-SHRP) launched a national full scale field experiment known as the Canadian Long-Term Pavement Performance (C-LTPP) program. Between the years, 1989 and 1992, a total of 24 test sites were constructed within all ten provinces. Each test site contained multiple monitored sections for a total of 65 sections. Each of these sites received rehabilitation treatments of various thicknesses of asphalt overlays. The C-LTPP program attempted to design and build the test sections across Canada so as to cover the widest range of experimental factors such as traffic loading, environmental region, and subgrade type. With planned strategic pavement data collection cycles, it would then be possible to compare results obtained at different test sites (i.e. across traffic levels, environmental zones, soil types) across the country.

The United States Long-Term Pavement Performance (US-LTPP) database is serving as a critical tool in implementing the new design guide. The MEPDG was delivered with the prediction models calibrated to average national conditions. For the guide to be an effective resource for individual agencies, the national models need to be evaluated against local and regional performance. The results of these evaluations are being used to determine if local calibration is required. It is expected that provincial agencies across Canada will use both C-LTPP and US-LTPP test sites for these evaluations. In addition, C-LTPP and US-LTPP sites provide typical values for many of the MEPDG inputs (C-SHRP, 2000).

The scope of this thesis is to examine the existing data in the C-LTPP database and assess its relevance to Canadian MEPDG calibration. Specifically, the thesis examines the dynamic modulus parameter ($|E^*|$) and how it can be computed using existing C-LTPP data and an Artificial Neural

Network (ANN) model developed under a Federal Highway Administration (FHWA) study (FHWA, 2011).

The dynamic modulus is an essential property that defines the stiffness characteristics of a Hot Mix Asphalt (HMA) mixture as a function of both its temperature and rate of loading. $|E^*|$ is also a primary material property input required for a Level 1 analysis in the MEPDG. In order to perform a Level 1 MEPDG analysis, detailed local material, environmental and traffic parameters are required for the pavement section being analyzed. Additionally, it can be used in various pavement response models based on visco-elasticity.

The dynamic modulus values predicted using both Level 2 and Level 3 viscosity-based ANN models in the ANNACAP software showed a good correlation to the measured dynamic modulus values for two C-LTPP test sections and supplementary Ontario mixes. These findings support previous research findings done during the development of the ANN models. The viscosity-based prediction model requires the least amount data in order to run a prediction. A Level 2 analysis requires mix volumetric data as well as viscosity testing and a Level 3 analysis only requires the PG grade of the binder used in the HMA. The ANN models can be used as an alternative to the MEPDG default predictions (Level 3 analysis) and to develop the master curves and determine the parameters needed for a Level 1 MEPDG analysis. In summary, Both the Level 2 and Level 3 viscosity-based model results demonstrated strong correlations to measured values indicating that either would be a suitable alternative to dynamic modulus laboratory testing.

The new MEPDG design methodology is the future of pavement design and research in North America. Current MEPDG analysis practices across the country use default inputs for the dynamic modulus. However, dynamic modulus laboratory characterization of asphalt mixes across Canada is time consuming and not very cost-effective. This thesis has shown that Level 2 and Level 3 viscosity-based ANN predictions can be used in order to perform a Level 1 MEPDG analysis. Further development and use of ANN models in dynamic modulus prediction has the potential to provide many benefits.

Acknowledgements

I would like to sincerely thank Dr. Susan Tighe for all of her help and guidance as my graduate supervisor over the past two years. Her constant encouragement and motivation, especially during the writing of this thesis, was greatly appreciated.

I would also like to thank everyone in the Infrastructure Management and Pavement Engineering (IMPE) department at Stantec Consulting, especially Gabe Cimini, Amir Abd El Halim and Frank Meyer. This could not have been done without their support, understanding and being able to work around my academic schedule.

Finally, I would like to thank the love of my life, Marie Bucaro for her patience, support and understanding over the past two years. She gave me the motivation to both start and finish my graduate degree and sacrificed many weekends and nights with me so that I could get my work done. I love you with all my heart.

Dedication

I would like to dedicate this thesis to my family, friends and my future wife Marie. Their encouragement and support during the past two years during my studies is greatly appreciated and I could not have completed this without them.

Table of Contents

AUTHOR'S DECLARATION	ii
Abstract	iii
Acknowledgements	v
Dedication	vi
Table of Contents	vii
List of Figures	xii
List of Tables	xiii
Chapter 1 Introduction.....	1
1.1 Background	1
1.2 Scope	2
1.3 Objectives.....	3
1.4 Thesis Methodology	3
Chapter 2 Literature Review	5
2.1 Pavement Design.....	5
2.1.1 History of Test Roads in the United States.....	5
2.1.2 History of Test Roads in Canada.....	6
2.1.3 Pavement Design Methods	7
2.1.4 Current Status of Pavement Design in North America.....	8
2.1.5 Mechanistic-Empirical Pavement Design Guide (MEPDG)	9
2.1.6 Comparison between AASHTO 1993 and the MEPDG.....	10
2.2 Pavement Performance Databases.....	10
2.2.1 United States Long-Term Pavement Performance (US-LTPP) Database	10
2.2.2 Canadian Long-Term Pavement Performance (C-LTPP) Database	11
2.2.3 Importance of Pavement Performance Databases	14
2.3 Dynamic Modulus	15
2.4 Dynamic Modulus Testing	16
2.4.1 Dynamic Modulus Master Curves.....	17
2.5 US-LTPP Computed Parameter: Dynamic Modulus.....	18
2.5.1 Witczak Equation (NCHRP 1-37A)	19
2.5.2 Modified Witczak Equation Based on $ G^* $ (NCHRP 1-40D)	19
2.5.3 Hirsch Model.....	20

2.5.4 Law of Mixtures Parallel Model	20
2.5.5 ANN Models	21
2.6 Viscosity-Based Supplementary Functions	22
2.6.1 Sigmoidal Function	22
2.6.2 Time-Temperature Shift Factor Function	22
2.6.3 Study Results – Model Prioritization and Decision Tree Development	23
2.7 Summary	24
Chapter 3 Comprehensive C-LTPP Database Review	25
3.1 Database Overview	26
3.2 Descriptive Module	27
3.2.1 ASBUILT Database	28
3.2.2 EXP_CODE Database	28
3.2.3 GLOSSARY Database	28
3.2.4 TABLEDEF Database	28
3.3 Historic Module	29
3.3.1 CLIM_HST Database	29
3.3.2 TRAF_HST Database	29
3.4 Materials Module	30
3.4.1 AC_Tst 1	31
3.4.2 AC_Tst 2	32
3.4.3 Base_Tst	32
3.4.4 Core_Tst 1	32
3.4.5 Core_Tst 1	32
3.4.6 Dyn_Tst (AC)	32
3.4.7 Log_Core	33
3.4.8 Log_Bore	33
3.4.9 Log_Shoulder	33
3.4.10 Log_Test Pit	33
3.4.11 MrDyn_Sampling	33
3.4.12 Mr_Tst (FGS)	34
3.4.13 Mr_Tst (GM)	34
3.4.14 MrSamples_FGS	34

3.4.15 MrSamples_GM	34
3.4.16 Rehabcast	35
3.4.17 Subbase_Tst.....	35
3.4.18 Subgrade_Tst.....	35
3.4.19 Tpit_Tst	35
3.5 Monitoring Module	36
3.5.1 Benkelman Beam Database	36
3.5.2 Climate Database.....	37
3.5.3 Descriptive Database	37
3.5.4 FWD Database.....	38
3.5.5 L-Profiles Database	39
3.5.6 IRI Database	39
3.5.7 Maintenance Database.....	39
3.5.8 Rut Depth Database.....	40
3.5.9 Skid Database	41
3.5.10 Surface Distress Database	42
3.5.11 Traffic Database	43
3.6 Summary of C-LTPP Database Gaps in Data	44
3.6.1 Descriptive Module	44
3.6.2 Historic Module.....	45
3.6.3 Materials Module.....	45
3.6.4 Monitoring Module	45
3.7 C-LTPP Database Recommendations	46
3.8 Data Sources Extracted For Thesis.....	48
3.9 Summary	48
Chapter 4 ANNACAP Version 1.2	49
4.1 M_R -Based ANN Model.....	49
4.2 $ G^* $ -Based ANN Model	50
4.2.1 Level 1 Analysis	50
4.2.2 Level 2 Analysis	50
4.2.3 Level 3 Analysis	50
4.3 Viscosity-Based ANN Model.....	51

4.3.1 Level 1 Analysis.....	53
4.3.2 Level 2 Analysis.....	54
4.3.3 Level 3 Analysis.....	54
4.4 Summary	54
Chapter 5 Data Analysis	55
5.1 Data Extraction from the C-LTPP Database.....	55
5.1.1 C-LTPP Dynamic Modulus Testing	55
5.1.2 Extraction of Measured Dynamic Modulus Values	57
5.1.3 Data Extraction for Viscosity-Based Prediction	58
5.2 Quality Control (QC) Checks	60
5.2.1 QC Check #1	61
5.2.2 QC Check #2.....	61
5.2.3 QC Check #3.....	61
5.2.4 QC Check #4.....	62
5.2.5 QC Check #5.....	62
5.2.6 QC Check #6.....	62
5.2.7 QC Check #7.....	62
5.3 Predicted Dynamic Modulus Results, $ E^* $	63
5.4 Summary	64
Chapter 6 Comparison Results.....	66
6.1 Measured Dynamic Moduli – C-LTPP Database.....	66
6.2 Predicted Dynamic Moduli - ANNACAP	67
6.3 Measured and Predicted Dynamic Moduli Comparison	68
6.3.1 Section 830403 – Dynamic Modulus Master Curves	69
6.3.2 Section 890503 – Dynamic Modulus Master Curves	72
6.4 Additional Viscosity-Based ANN Model Verification	74
6.4.1 Dynamic Modulus Prediction of Supplementary Mixture Data.....	75
6.5 Summary	76
Chapter 7 Conclusions and Recommendations.....	78
7.1 Summary	78
7.2 Recommendations.....	80
Appendix A Extracted C-LTPP Data.....	82

Appendix B Supplemental Mix Statistical Analysis	87
References	91

List of Figures

Figure 1: Overview of Research Methodology	4
Figure 2: AASHO Road Test Configuration (Pavement Interactive 2007)	6
Figure 3: Stress and Strain in Dynamic Loading (Clyne et al., 2003)	16
Figure 4: Sample Dynamic Modulus Master Curve	17
Figure 5: ANN Schematic Structure (FHWA 2011).....	21
Figure 6: ANN Model Decision Tree (FHWA 2011)	23
Figure 7: C-LTPP Test Site Locations (C-SHRP 1990)	25
Figure 8: C-LTPP Database Hierarchy (C-SHRP 1990).....	26
Figure 9: Descriptive Module Hierarchy (C-SHRP 1990).....	27
Figure 10: Historic Module Hierarchy (C-SHRP 1990)	29
Figure 11: Materials Module Hierarchy (C-SHRP 1990)	31
Figure 12: Monitoring Module Hierarchy (C-SHRP 1990).....	36
Figure 13: Descriptive Files Hierarchy (C-SHRP 1990)	38
Figure 14: Maintenance Database Hierarchy (C-SHRP 1990)	40
Figure 15: Rut Depth Database Hierarchy (C-SHRP 1990)	40
Figure 16: Surface Distress Hierarchy (C-SHRP 1990)	42
Figure 17: Traffic Database Hierarchy (C-SHRP 1990).....	44
Figure 18: Kinematic Viscosity Test Equipment (Koehler 2006)	51
Figure 19: Absolute Viscosity Capillary Tube (Koehler 2006)	52
Figure 20: Ring and Ball Apparatus (OSU 2012).....	52
Figure 21: Asphalt Penetration Test Equipment (Pavement Interactive 2007).....	53
Figure 22: Four Point Flexural Beam Test Diagram (TAC 2004)	56
Figure 23: Section 830403 – Measured Master Curve.....	70
Figure 24: Section 830403 - Predicted Master Curve.....	70
Figure 25: Section 830403 - Measured vs. Predicted Master Curves	71
Figure 26: Section 890503 – Measured Master Curve.....	72
Figure 27: Section 890503 – Predicted Master Curve	73
Figure 28: Section 890503 - Measured vs. Predicted Master Curves	73

List of Tables

Table 1: Flexible Pavement Design Methods (C-SHRP 2002, Tighe 2013).....	8
Table 2: Summary of C-LTPP Test Sections and Climatic Zones (C-SHRP 1990)	13
Table 3: Project Activities and Responsibilities (C-SHRP 1997)	27
Table 4: Compressive and Flexural Testing Frequencies.....	56
Table 5: Compressive and Flexural Testing Temperatures	57
Table 6: Sample C-LTPP Dynamic Moduli Data.....	57
Table 7: Sample Queried C-LTPP Data for ANN Analysis	58
Table 8: C-LTPP Sections Containing Sufficient Data for E* Prediction	58
Table 9: QC Check Summary.....	60
Table 10: QC#1 - Input Data Ranges (FHWA 2010).....	61
Table 11: QC#1 - Input Data Ranges (FHWA 2010).....	62
Table 12: C-LTPP Sections with “A” Grade Predicted E*	64
Table 13: C-LTPP Dynamic Modulus Master Curve Parameters (TAC 2004).....	66
Table 14: C-LTPP Time-Temperature Shift Factor Regression Parameters (TAC 2004)	67
Table 15: ANNACAP Dynamic Modulus Master Curve Parameters	68
Table 16: ANNACAP Time-Temperature Shift Factor Fitting Coefficients	68
Table 17: Master Solver Master Curve Statistics	69
Table 18: Supplementary Measured Dynamic Modulus Mix Data.....	74
Table 19: Statistical Analysis of Supplementary Mix Predictions	75

Chapter 1

Introduction

1.1 Background

In 2007, the Mechanistic-Empirical Pavement Design Guide (MEPDG) was successfully approved as the new American Association of State Highway and Transportation Officials (AASHTO) pavement design standard (Von Quintus et al., 2007). Calibration and validation of the MEPDG is currently in progress in several provinces across Canada. The MEPDG will be used as the standard pavement design methodology for the foreseeable future (Tighe, 2013). There are many advantages to the MEPDG published in several research papers over the last few years. The MEPDG has several improvements over the previous AASHTO empirical design methods; the MEPDG: uses newly developed mechanistic-empirical design procedures, contains performance prediction models for common distresses (fatigue cracking, faulting, rutting, etc.), material characterization, the addition of environmental inputs, more accurate categorization of traffic loading and measures of performance (Ali, 2005). However, the main disadvantage of the new pavement design process is that it requires several parameters specific to local conditions of the design location. In order to perform an accurate analysis, a database of parameters including those specific to local materials, climate and traffic are required to calibrate the models in the MEPDG.

The United States Long-Term Pavement Performance (US-LTPP) program began in 1987 as part of the Strategic Highway Research Program (SHRP) (FHWA, 2010). The main goal of this program was to promote pavement research and improved pavement performance by establishing a national long-term pavement performance database. In 1992, SHRP ended as planned, however the Federal Highway Administration (FHWA) took ownership of the US-LTPP program. The FHWA encouraged highway agencies in all 50 States, the District of Columbia, Puerto Rico, and 10 Canadian Provinces to participate and provide feedback for the program. Since 1989, the US-LTPP program has monitored nearly 2,500 pavement test sections throughout the United States and Canada (FHWA, 2010). In addition, a separate C-LTPP program was designed in a similar manner as the Strategic Highway Research Program (SHRP) in the United States during the late 1980's. This program was directed specifically at rehabilitation.

In 1989, the Canadian-Strategic Highway Research Program (C-SHRP) launched a national full scale field experiment known as the Canadian Long-Term Pavement Performance (C-LTPP) program. Between the years, 1989 and 1992, a total of 24 test sites were constructed within all ten

provinces. Each test site contained multiple monitored sections for a total of 65 sections. The C-LTPP program attempted to design and build the test sections across Canada to cover the widest range of pavement design factors including traffic loading, environmental region, and subgrade type. This ensured that the C-LTPP would encompass the majority of conditions under which pavements are designed and constructed in Canada.

The overall goal of the C-LTPP program was to “increase pavement life through the development of cost-effective pavement rehabilitation procedures, based upon a systematic observation of in-service pavement performance” (C-SHRP, 1997). The test sections were monitored over time and the various input factors of design, construction and service conditions would be measured and analyzed so that improvements could be achieved. In short, extension of pavement life and cost reductions for constructing and maintaining pavements to produce better designs and to devise better maintenance and rehabilitation practices would be the outcome. Data was collected annually at the C-LTPP sites from 1990, immediately following the overlay and has continued either, until the end of the service life of the section, or until the end of the program in 2009. It has now been 24 years since the program began and all of the collected data has been combined into multiple databases.

The US-LTPP database is serving as a critical tool in implementing the new MEPDG. The MEPDG was delivered with the prediction models calibrated to average national conditions. For the guide to be an effective resource for individual agencies, the national models need to be calibrated and validated to local and regional conditions. The results of these evaluations are being used to determine if local calibration is required. It is expected that provincial agencies across Canada will use both C-LTPP and US-LTPP test sites for these evaluations. Both, C-LTPP and US-LTPP programs contain Canadian test sites with over a decade of performance data which can be used for MEPDG analyses (C-SHRP, 2000).

1.2 Scope

The scope of this thesis is to examine the existing data in the C-LTPP database and assess its relevance to Canadian MEPDG calibration. Specifically, the thesis examines the dynamic modulus parameter ($|E^*|$) and how it can be computed using existing C-LTPP data and an Artificial Neural Network (ANN) model developed under an FHWA study (FHWA, 2011).

The dynamic modulus is an essential property that defines the stiffness characteristics of a Hot Mix Asphalt (HMA) mixture as a function of both its temperature and rate of loading. $|E^*|$ is also a

primary material property input required for a Level 1 analysis in the MEPDG. In order to perform a Level 1 MEPDG analysis, detailed local material, environmental and traffic parameters are required for the pavement section being analyzed. Additionally, it can be used in various pavement response models based on visco-elasticity.

1.3 Objectives

The objectives of this thesis are:

- Conduct a literature review on the role of a pavement database in pavement design and management;
- Review existing Canadian pavement design practices and the future of pavement design;
- Evaluate the existing data in the C-LTPP
- Calculate the dynamic modulus, $|E^*|$, for all existing C-LTPP experimental pavement sections using existing laboratory data;
- Discuss the importance of dynamic modulus in the use of the MEPDG; and
- Draw conclusions from the lessons learned in this process and propose how other existing data elements can be used by provincial agencies in the calibration of MEPDG models to local conditions.

1.4 Thesis Methodology

The second chapter of this thesis includes a literature review that provides details on the current state-of-practice in national and international pavement engineering including pavement design, data collection and pavement performance databases.

The third chapter of this thesis features a comprehensive review that was performed on the C-LTPP database, which was the primary source of pavement data used in the data analysis in this thesis. Any data gaps in the database are identified and recommendations are provided to address any identified issues.

The fourth chapter of this thesis provides a brief overview of the ANNACAP software used for dynamic modulus prediction.

The fifth chapter provides details on the data that was extracted from the C-LTPP database on asphalt mixture laboratory tests and used for input into two different artificial neural network (ANN) prediction models for the dynamic modulus parameter.

The sixth chapter provides a summary of the data analysis performed and any comparisons between the measured and predicted dynamic modulus data.

The final component of this research draws conclusions from the analyses performed and outlines other valuable elements that can be used for calibrating local MEPDG models by provincial agencies.

The various steps to accomplish the objectives are illustrated in Figure 1.

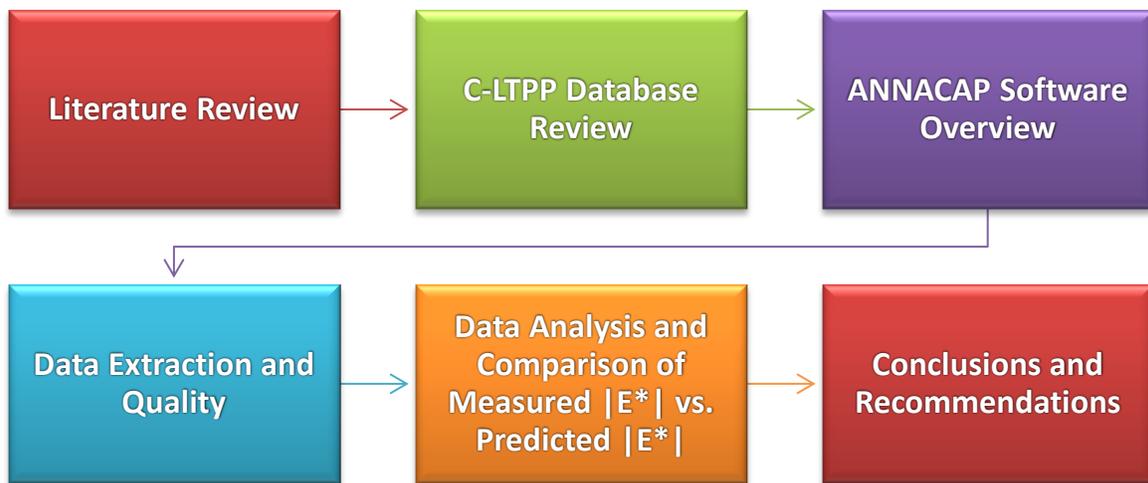


Figure 1: Overview of Research Methodology

Chapter 2

Literature Review

2.1 Pavement Design

2.1.1 History of Test Roads in the United States

The American Association of State Highway Officials (AASHO) Road Test was composed of a series of road experiments starting in the 1920s with the last major experiment carried out in the late 1950s (AASHTO, 1972). The purpose of these studies was to determine how traffic contributes to the deterioration of pavements. Construction of the AASHO Road Test site in Ottawa, Illinois began in 1956 with the final studies concluding in 1961 (AASHTO, 1972). The findings from this study were the basis of the 1972 AASHTO Guide for Design of Pavement Structures. Major revisions to the guide were published in 1986 and 1993 (AASHTO, 1986, 1993).

The AASHO Road Test was an empirical study in which each road section was subjected to repeated loading by a specific vehicle type and weight. A total of six 2-lane test loops were constructed. Loop 1 was not subjected to any traffic loading as it was used as a control section to test environmental effects. Loops 2 to 6 were subjected to various combinations of truck traffic. A limitation of this type of empirical study is that its data is only valid under the specific conditions of the experiment. More specifically, the environmental conditions and materials used in the experiment will vary geographically. The AASHO Road Test configuration is illustrated in Figure 2.

Several reviews and studies have been conducted that have identified deficiencies in the current design process. These deficiencies are related to the limitations in the Road Test experiment. The data collected from the Road Test experiment was highly dependent on the limitations related to the location selected for the experiment. Data was collected on one subgrade soil type and road construction material with unique environmental and traffic conditions (NCHRP, 2004). In the mid-1990s, a shift from a strictly empirical design method to a mechanistic-empirical approach was realized.

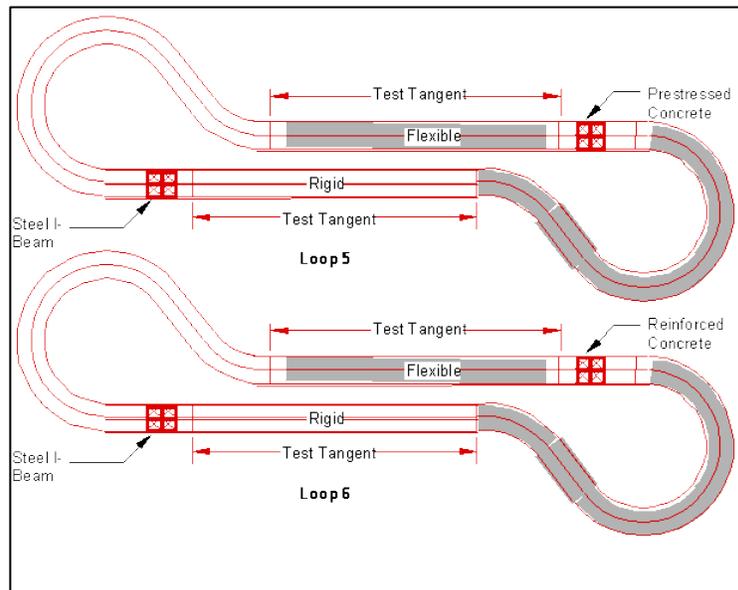


Figure 2: AASHO Road Test Configuration (Pavement Interactive 2007)

2.1.2 History of Test Roads in Canada

Transportation agencies in Canada took notice of the research studies being performed in the United States and wanted to conduct similar experiments using local materials and conditions. In 1965, the Ministry of Transportation Ontario (MTO) began collecting data on 36 newly constructed pavement test sections. These test sections were located on Highway 10 near Brampton, Ontario. The main goals of these experiments were to: correlate the results of the AASHO Road Test to Ontario materials and conditions; evaluate the performance of standard pavement designs; and to document the performance of various base materials (Phang and Stott, 1981).

In the late 1980s, additional research was initiated by C-SHRP to study the effect of climatic conditions on roadway performance. The primary goals of this study were to: document current paving practices in Canada; and further the understanding of AC properties that influence low temperature performance (Gavin et al., 2003).

A total of three C-SHRP test sites were constructed in three different locations across Canada. The test sites were constructed in the vicinity of the following cities: Lamont, Alberta; Hearst, Ontario; and Sherbrooke, Quebec. The test site located near Lamont in Alberta was the only full-scale experiment, while the test sites in Ontario and Quebec were considered as smaller scale satellite experiments (Gavin et al., 2003).

2.1.3 Pavement Design Methods

There are four primary types of pavement design methodologies used throughout North America (Tighe, 2013):

- Experience-based;
- Empirical;
- Mechanistic; and
- Mechanistic-Empirical (M-E)

Experience-based pavement design methods use standard pavement sections that are based on past performance experience. Designs are typically organized in matrices and will vary based on subgrade type, traffic conditions and road classification. Due to its simplicity, it is still used by several agencies throughout North America for the design of low volume roads. However, the main disadvantage of this method is that it is not able to account for changes in loading, material types and climate change (Tighe, 2013).

Empirical pavement design methods are based on the results of a measured response. A number of observations are made to define the relationships between input variables and observed results (Pavement Interactive, 2008). For example, the AASHO Road Test as described above was an empirical-based experiment. The AASHTO 1993 Design Guide is an empirically-based design method based on empirical equations which were derived from the various experiments (Pavement Interactive, 2008).

Mechanistic pavement design methods are based on the theoretical analysis of stresses and strains at critical locations within the pavement structure (Tighe, 2013). An example of a mechanistically-based method is the Boussinesq method of evaluating a layered elastic model of a pavement system (Pavement Interactive, 2008). The main disadvantage of mechanistic design methods is that they are purely theoretical and do not incorporate results from the field.

Lastly, M-E pavement design methods are becoming increasingly popular as they combine the advantages of empirically-based and mechanistically-based design methods without any of their disadvantages. However, M-E based methods have their own unique disadvantages in that they require model calibration and validation which is an intensive process.

2.1.4 Current Status of Pavement Design in North America

In 1996, a survey was conducted as part of the NCHRP Project 1-32. The survey determined that approximately 80% of state agencies in the United States use the 1972, 1986, or 1993 AASHTO Design Guides (NCHRP, 2003). A similar survey, conducted in 2002, across Canada determined that approximately 70% of all provincial agencies use a portion of the 1993 AASHTO Design Guide (C-SHRP, 2002).

In the United States, the FHWA is responsible for funding pavement construction, rehabilitation and setting design standards. However, in Canada each provincial agency is free to use a design procedure for pavement design and rehabilitation of their own choice. A summary table presenting the distribution of design methods and parameters used throughout Canada is presented in Table 1.

Table 1: Flexible Pavement Design Methods (C-SHRP 2002, Tighe 2013)

Agency	General Design Method(s)	Type of Design Method
British Columbia	AASHTO 1993	Empirical
Alberta	AASHTO 1993	Empirical
Saskatchewan	Shell Method	Mechanistic-Empirical
	Asphalt Institute	
Manitoba	AASHTO 1993	Empirical
	Asphalt Institute	Mechanistic-Empirical
Ontario	AASHTO 1993	Empirical
	Asphalt Institute	Mechanistic-Empirical
Quebec	AASHTO 1993	Empirical
	CHAUSEE 1.1	
New Brunswick	AASHTO 1993	Empirical
	Rebound Values	
Prince Edward Island	Asphalt Institute	Mechanistic-Empirical
	Thickness Design	
Nova Scotia	AASHTO 1993	Empirical
	Correlation Charts using AADT & grain size of subgrade	
Newfoundland	Standard Section Used	Experience-based
Public Works and Government Services Canada	AASHTO 1993	Empirical
	State of Alaska Design Method	

From examining Table 1, it is clear that design methodology varies through Canada. In 2008, AASHTO adopted an interim pavement design guide titled Mechanistic-Empirical Pavement Design Guide (MEPDG). The new design guide is the culmination of NCHRP Projects 1-37A and 1-40D. It is expected that there will be widespread adoption of the mechanistic-empirical design methodology across all Canadian provincial agencies.

2.1.5 Mechanistic-Empirical Pavement Design Guide (MEPDG)

The MEPDG was developed and funded by the NCHRP Project 1-37A initiative. The new guide “provides a uniform basis for the design of flexible, rigid and composite pavements, using mechanistic-empirical approaches that more realistically characterize in-service pavement and improve the reliability of designs” (FHWA, 2006). The MEPDG will eventually replace the AASHTO 1993 Design Guide, which was based on empirical equations derived from the AASHTO Road Test.

Advancements in computers and technology in general combined with pavement performance databases, have allowed researchers to develop more robust software applications capable of running thousands of iterations of a design to find the best solution. DARWin-ME, the next generation of pavement design software, which was built upon the MEPDG principles allows users to take advantage of the MEPDG models in a software package.

The MEPDG performance models were calibrated using data from the SHRP US-LTPP program database. However, there are several general performance parameters that need to be calibrated to local conditions for a Level 1 analysis. The MEPDG is based on a hierarchical structure with three different levels of analysis. A Level 1 analysis requires detailed project specific inputs obtained through direct testing or field measurement. A Level 2 analysis uses correlations to determine the necessary inputs. Finally, a Level 3 analysis can be run with the default regional inputs, and as a result it also provides the lowest accuracy of the three levels. Additionally, it is also possible for the user to mix and match the levels of input for each data element (Olidis and Hein, 2004).

In addition to the hierarchical material level inputs, another major change introduced by the MEPDG is changes in material properties due to climate and load. A master climate database is used to model the variation in the properties of the pavement and subgrade materials. These models allow engineers to determine the impact of a change in environmental conditions on a specific material property. For example, hot mix asphalt (HMA) is considered a visco-elastic material which is affected

by temperature change. As the temperature increases the HMA modulus decreases. Similarly, precipitation and various environment conditions can negatively impact subgrade strength. The MEPDG is able to model these changes based on environmental condition.

The traffic characterization method used in the MEPDG also differs significantly from the 1993 Design Guide. Rather than using the conventional Equivalent Single Axle Load (ESAL) technique adopted by previous guides, the MEPDG has adopted an axle load spectra method. Detailed traffic data, including truck count by class, direction and lane are required for traffic characterization. Axle load spectra distributions are then obtained for each vehicle class from known axle weight data. The traffic volumes are then forecasted by vehicle class over the selected design period.

2.1.6 Comparison between AASHTO 1993 and the MEPDG

A review of the AASHTO 1993 design method and the MEPDG method was conducted by a National Research Council (NRC) Canada study in 2005 (Ali, 2005). The report highlighted several significant improvements in the MEPDG design process. This list describes the MEPDG improvements:

- Capable of designing for a wide range of pavement structures for both new construction and for rehabilitation. For example, composite pavement structures can now be analyzed and an engineer can evaluate rehabilitation options of overlaying with either asphalt or concrete;
- New traffic characterization methods including the use of tire pressure, axle load and traffic distribution parameters;
- Environmental impact on pavement structure materials;
- Mechanistic material characterization allows assessing newly developed materials such as engineered binders and recycled materials; and
- Introduction of distress prediction models promotes performance-based designs rather than typical stress and strain (mechanistic) based designs.

2.2 Pavement Performance Databases

2.2.1 United States Long-Term Pavement Performance (US-LTPP) Database

The US-LTPP program was established by SHRP in 1987 to collect and store pavement performance data. The US-LTPP program is the largest pavement performance research program in existence and contains data on more than 2,500 test sections located on in-service highways throughout the United

States and Canada. Since 1992, the FHWA has assumed the management duties as well as the funding obligations for the project (FHWA, 2010).

The US-LTPP program is divided into two fundamental classes of pavement studies, General Pavement Studies (GPS) and Specific Pavement Studies (SPS). The pavement data collected by the program is stored in seven different data modules: Inventory, Maintenance, Monitoring, Rehabilitation, Materials Testing, Traffic and Climate. Data has been collected since 1989 and although the number of in-service pavement sections has decreased significantly since inception, new experiments are being planned and will be implemented in the next few years.

All of the data is stored in a central FHWA database called the LTPP Information Management System (IMS). The database has undergone several updates since its creation in 1988, and continues to be improved. Currently anyone in the public can access the data through the Internet by using the web-based tool known as DataPave Online through ltpm-products.com (FHWA, 2011).

2.2.2 Canadian Long-Term Pavement Performance (C-LTPP) Database

The Canadian Strategic Highway Research Program (C-SHRP) was funded by the Council of Deputy Ministers responsible for transportation and highway safety and, on behalf of the Council of Deputy Ministers, was managed by the C-SHRP Executive Committee. The program's objective was to improve the performance and durability of highways and to make them safer for motorists and highway workers by extracting the benefits of the United States SHRP. In addition, the program strove to solve highway problems, which are of a high priority in Canada, that are related to, but not duplicates of, SHRP research projects.

In 1989, C-SHRP launched a national full scale field experiment known as the C-LTPP program. Between the years, 1989 and 1992, a total of 24 test sites were constructed within all ten provinces. Each test site contained multiple monitored sections for a total of 65 sections. Each of these sites received rehabilitation treatments of various thicknesses of asphalt overlays. The majority of the overlays used Hot-Mix Asphalt Concrete (HMAC). Several sections used HMAC with the addition of a polymer-modified binder, or a high friction mix, and several others used Reclaimed Asphalt Pavement (RAP). The C-LTPP program attempted to design and build the test sections across Canada so as to cover the widest range of experimental factors such as traffic loading, environmental region, and subgrade type. The environment types include Wet-No Freeze, Wet-Freeze and Dry-Freeze. This ensured that the C-LTPP would encompass the majority of conditions under which pavements are

constructed in Canada. It would then be possible to compare results obtained at different test sites (i.e. across traffic levels, environmental zones, soil types) by using a statistical analysis of the factorial population.

The C-LTPP program was modelled after a similar program established by SHRP in the 1980's. The US-LTPP program began in 1987 as part of SHRP (FHWA, 2010). The main goal of this program was to promote pavement research and improved pavement performance by establishing a national long-term pavement performance database. In 1992, SHRP ended as planned, however the FHWA took ownership of the US-LTPP program. The FHWA encouraged highway agencies in all 50 States, the District of Columbia, Puerto Rico, and 10 Canadian Provinces to participate and provide feedback for the program.

The overall goal of the C-LTPP program was to “increase pavement life through the development of cost-effective pavement rehabilitation procedures, based upon a systematic observation of in-service pavement performance” (C-SHRP, 1997). The belief was that as the test sections were monitored over time, the underlying mechanism, which related the input factors of design, construction and service conditions to the measured performance, would become known. Extension of pavement life and cost reductions for constructing and maintaining pavements would result from application of these mechanisms to produce better designs and to devise better maintenance and rehabilitation practices.

Data was collected annually at the sites from 1990, immediately following the overlay and has continued either, until the end of the service life of the section, or until the end of the program in 2009. It has now been 24 years since the program began and all of the collected data has been combined into multiple databases. A summary of the C-LTPP test sections as well as the location, environmental zone and overlay type are presented in Table 2.

Table 2: Summary of C-LTPP Test Sections and Climatic Zones (C-SHRP 1990)

Province	C-SHRP ID	Highway	Environment	Overlay
Alberta	810404	Hwy 16:06	Dry-Freeze	HMAC/RAP
British Columbia	820205	Hwy 19	Wet-No Freeze	HMAC
	820502	Hwy 99	Wet-No Freeze	RAP
	820605	Hwy 99	Wet-No Freeze	HMAC
Manitoba	830403	PTH 2	Dry-Freeze	HMAC
	830801	Hwy 1	Dry-Freeze	HMAC/RAP
New Brunswick	840101	Hwy 15	Wet-Freeze	HMAC/RAP
	840204	Hwy 101	Wet-Freeze	HMAC
	840604	Hwy 2	Wet-Freeze	HMAC/RAP
Newfoundland	850201	Route 1	Wet-Freeze	HMAC
	850206	Route 1	Wet-Freeze	HMAC
	850601	Route 1	Wet-Freeze	HMAC
Nova Scotia	860501	Hwy 102	Wet-Freeze	HMAC (high friction mix)
	860603	Hwy 103	Wet-Freeze	HMAC
Ontario	870102	Hwy 80	Wet-Freeze	HMAC
	870504	Hwy 11	Wet-Freeze	HMAC
	870505	Hwy 57	Wet-Freeze	HMAC/RAP
	870701	Hwy 31	Wet-Freeze	HMAC
Prince Edward Island	880203	Route 2	Wet-Freeze	HMAC
Quebec	890503	Autoroute 40	Wet-Freeze	HMAC/ HMAC with Polymer
	890702	Autoroute 73	Wet-Freeze	HMAC
Saskatchewan	900402	Hwy 5-06	Dry-Freeze	HMAC
	900802	Hwy 10-03	Dry-Freeze	HMAC
	900803	Hwy 1-06B	Dry-Freeze	HMAC

It should be noted that the US-LTPP program has a total of 127 Canadian test sections and are similarly distributed across ten of Canada's provinces. The US-LTPP program also has sections located throughout Canada that have been rehabilitated through the use of asphalt overlays. However, the C-LTPP program's sections are representative of typical pavements found throughout Canada.

The C-LTPP “experiment was not designed as a rigorous statistical study, but rather intended to complement and extend the SHRP studies to include more typically Canadian pavement conditions” (SHRP, 1994). There have recently been discussions of including the C-LTPP database in Standard Data Releases (SDR) along with the US-LTPP database. This would provide an opportunity for the exposure to C-LTPP data to a much more global audience.

2.2.3 Importance of Pavement Performance Databases

Since the late 1990s, one of the pavement research community's single largest investments has been in the development of the Mechanistic-Empirical Pavement Design Guide (MEPDG) and for usage in DARWin-ME. Development of the new guide required detailed information about pavements located across North America and representing a wide range of loading, climate, and subgrade conditions with varying structural compositions. At the time, the US-LTPP database was critical to the development of the MEPDG, as it was the only source of comprehensive pavement data representative of national conditions. In fact, the MEPDG could not have been completed without the type and national extent of data provided by the US-LTPP studies. All of the traffic loading defaults provided in the MEPDG, for example, were derived from the US-LTPP traffic database using Weigh-in-Motion (WIM) sites across the United States and Canada, and all of the distress and smoothness models in the MEPDG were calibrated using US-LTPP data (NCHRP, 2004).

The MEPDG models evaluate the impact of traffic, climate, materials, and subgrade stiffness on performance and account for the interactions among these components. The MEPDG predicts individual performance measures (i.e., transverse cracking, fatigue, smoothness, rutting) based on site condition input for a given trial pavement section. These prediction techniques can be used in pavement evaluation studies, as well as in forensic investigations.

The US-LTPP database is serving as a critical tool in implementing the new design guide. The MEPDG was delivered with the prediction models calibrated to average national conditions. For the guide to be an effective resource for individual agencies, the national models need to be evaluated against local and regional performance. The results of these evaluations are being used to determine if local calibration is required. It is expected that provincial agencies across Canada will use both C-LTPP and US-LTPP test sites for these evaluations. In addition, C-LTPP and US-LTPP sites provide typical values for many of the MEPDG inputs.

The objectives of the NCHRP 1-40B project (Local Calibration Guidance for the Recommended Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures) were to develop a user guide and a manual on local calibration of the MEPDG (NCHRP, 2009). Local validation and calibration will rely heavily on the C-LTPP and US-LTPP databases as many agencies do not otherwise have the data necessary to complete this endeavor.

2.3 Dynamic Modulus

The dynamic modulus, ($|E^*|$), is the absolute value of the complex modulus (E^*) and is an essential property that defines the stiffness characteristics of an HMA mixture as a function of both its temperature and rate of loading (Yoder and Witczak, 1975).

“The complex modulus, (E^*), is defined as the ratio of the amplitude of the sinusoidal stress and sinusoidal strain that results in a steady state response” (Garcia and Thompson, 2007). Equation 2.1 exhibits this relationship:

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_0 \cdot e^{i\omega t}}{\varepsilon_0 \cdot e^{i(\omega t - \delta)}} = \frac{\sigma_0 \cdot \sin(\omega t)}{\varepsilon_0 \cdot \sin(\omega t - \delta)} \quad (2.1)$$

Where:

- E^* = complex modulus
- σ_0 = peak (maximum) stress
- ε_0 = peak (maximum) strain
- δ = phase angle (degrees)
- ω = angular velocity
- t = time (seconds)
- i = imaginary component of the complex modulus

The dynamic modulus, $|E^*|$, can therefore be presented as the following relationship in Equation 2.2:

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (2.2)$$

The stress and strain relationship in dynamic loading is illustrated in Figure 3.

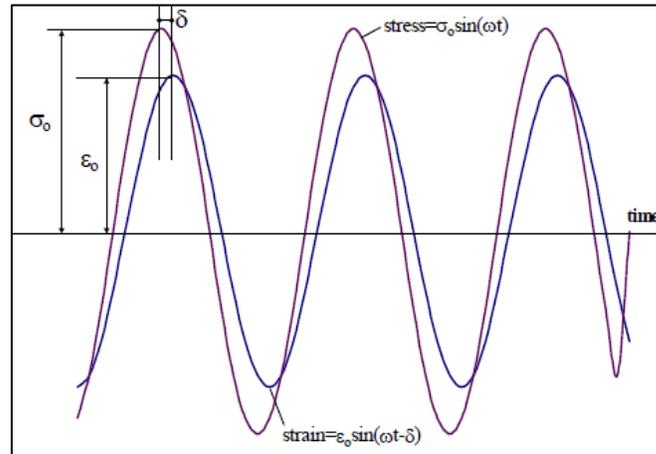


Figure 3: Stress and Strain in Dynamic Loading (Clyne et al., 2003)

2.4 Dynamic Modulus Testing

The dynamic modulus test uses a sinusoidal axial compressive stress which is applied to an asphalt concrete core sample at a constant temperature and loading frequency. The applied stress and the axial strain response of the core sample are measured and used to calculate the dynamic modulus and phase angle of the bituminous mixture. These calculated parameters can be used as performance criteria for HMA design (AASHTO TP 62-07, 2007). The dynamic modulus of a bituminous mixture has become an important pavement design parameter within the last 10 years; however, the dynamic modulus test method has been around for more than 50 years. In the early 1960s, Papazian was one of the first to research visco-elastic testing on bituminous mixtures (Papazian 1962, Clyne et al., 2003).

Further research was done on the dynamic modulus of asphalt mixtures and multiple test methods were developed that considered different loading procedures. Loading the test specimens in compression, tension and a combination of the two were evaluated. Bonnaure et al. determined the dynamic modulus of a trapezoidal test specimen using a 2-point bending test (Bonnaure et al., 1977). The flexural test method considers that the bituminous layer acts in flexion, or as a beam since it is a bound layer. The compression test method considers the bituminous layer acts only in compression similar to the underlying pavement layers (TAC, 2004). However, Witczak and Root concluded that a tension-compression test method is more representative to actual field conditions (Witczak and Root, 1974).

As of 2012, the most widely accepted dynamic modulus test method is the compressive dynamic modulus method, ASTM D3497-79, as specified by the NCHRP 1-37A project (Andrei et al., 1999).

Comparisons between the flexural and compression testing of dynamic modulus have been researched by several engineers. Di Benedetto and De la Roche (1998) as well as Witczak et al. (2001) found that the flexural dynamic modulus tests generally provide lower dynamic modulus values than the dynamic compressive tests. Giuliana et al. confirmed these results during their research on dynamic modulus testing of high air void content mixtures (Giuliana et al., 2012).

2.4.1 Dynamic Modulus Master Curves

A dynamic modulus master curve is defined as “a composite curve constructed at a reference temperature (21.1°C) by shifting dynamic modulus data from various temperatures along the log frequency axis” (AASHTO PP 62-09, 2009). The curve can be used for bituminous mixture evaluation and for the characterization of HMA moduli in the MEPDG.

The development of the dynamic modulus master curve typically follows the AASHTO PP 62-09 method (AASHTO PP 62-09, 2009). Usually, the master curve is constructed using a reference temperature of 21.1°C (70°F). Once the curve is created, it is possible to compare linear visco-elastic materials using different frequencies and temperatures (Garcia and Thompson, 2007). Dynamic moduli of a sample mix tested at multiple temperatures and frequencies as well as the resultant master curve and the shifted dynamic moduli are illustrated in Figure 4.

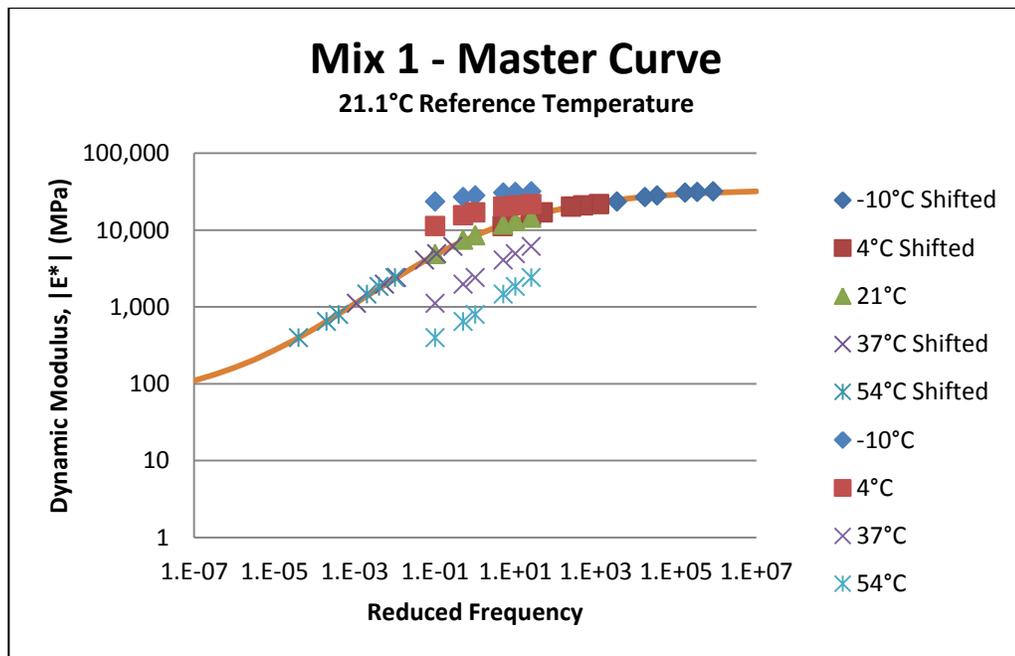


Figure 4: Sample Dynamic Modulus Master Curve

2.5 US-LTPP Computed Parameter: Dynamic Modulus

The dynamic modulus, $|E^*|$, of a HMA mixture is a fundamental property that defines the stiffness characteristics as a function of temperature and loading rate. It is also one of the primary material inputs in the MEPDG and DARWin-ME software developed under NCHRP Projects 1-37A and 1-40D. In 2011, an FHWA funded research study was published in which researchers evaluated existing models used to estimate the dynamic modulus of a HMA mixture as well as additional models that were developed as part of the study (FHWA, 2011).

In total, seven models were evaluated as part of this study:

1. Original Witczak equation (NCHRP 1-37A)
2. Modified Witczak dynamic shear ($|G^*|$) equation (NCHRP 1-40D)
3. Hirsch Model
4. Law of mixtures parallel model
5. Resilient modulus (M_R)-based ANN model
6. Viscosity-based ANN model
7. Binding shear modulus ($|G^*|$)-based ANN model

Models 1 through 4 were the existing models evaluated. The additional models, 5 through 7, developed during the study were based on the use of artificial neural networks (ANNs).

When the US-LTPP database structure was initially conceived in the 1980s, the importance of the dynamic modulus was not yet known and thus no testing was done on any samples in the database. Due to time and budget limitations, it was not feasible to perform dynamic modulus tests on US-LTPP material samples. As a result, the primary objective of the 2011 FHWA study was to “develop estimates of the dynamic modulus of HMA layers on US-LTPP test sections following the models used in the MEPDG” (FHWA, 2011). This was determined to be feasible; since the existing US-LTPP database contains HMA mixture and binder laboratory test data that could be used as inputs in the models.

The following sections present the four existing models that were evaluated by this study.

2.5.1 Witczak Equation (NCHRP 1-37A)

The original Witczak equation was revised by Andrei et al. (1999) based on data collected from 205 HMA mixtures (Andrei et al., 1999). The revised equation is as follows:

$$\log_{10} |E^*| = -1.249937 + 0.02923p_{200} - 0.001767(p_{200})^2 - 0.002841p_4 - 0.05809V_a - 0.082208 \frac{V_{beff}}{V_{beff}+V_a} + \frac{3.871977-0.0021p_4+0.003958p_{3/8}-0.000017(p_{3/8})^2+0.00547p_{3/4}}{1+\exp(-0.603313-0.313351 \log f-0.393532 \log \eta)} \quad (2.3)$$

Where:

- p_{200} = Percentage of aggregate passing #200 sieve
- p_4 = Percentage of aggregate retained in #4 sieve
- $p_{3/8}$ = Percentage of aggregate retained in 3/8-inch sieve
- $p_{3/4}$ = Percentage of aggregate retained in 3/4-inch sieve
- V_a = Percentage of air voids (by volume of mix)
- V_{beff} = Percentage of effective asphalt content (by volume of mix)
- f = Loading frequency (hertz)
- η = Binder viscosity at temperature of interest (10^6 Poise)

The Witczak model is currently one of two options for a Level 3 analysis using the MEPDG. This model incorporates asphalt mixture volumetrics and aggregate gradations.

2.5.2 Modified Witczak Equation Based on $|G^*|$ (NCHRP 1-40D)

Witczak reformulated his original model to include the binder dynamic shear modulus, $|G^*|$. The equation is as follows:

$$\log_{10} |E^*| = -0.349 + 0.754(|G^*|_b^{-0.0052}) \left(6.65 - 0.032p_{200} + 0.0027(p_{200})^2 + 0.011p_4 - 0.0001(p_4)^2 + 0.006p_{3/8} - 0.00014(p_{3/8})^2 - 0.08V_a - 1.06 \left(\frac{V_{beff}}{V_{beff}+V_a} \right) \right) + \frac{2.558+0.032V_a+0.713 \left(\frac{V_{beff}}{V_{beff}+V_a} \right) + 0.0124p_{3/8} - 0.0001(p_{3/8})^2 - 0.0098p_{3/4}}{1+\exp(-0.7814-0.5785 \log |G^*|_b+0.8834 \log \delta_b)} \quad (2.4)$$

Where:

$|G^*|_b$ = Dynamic shear modulus of asphalt binder (psi)

δ_b = Binder phase angle associated with $|G^*|_b$ (degrees)

The modified Witczak model is the second of two options for a Level 3 analysis in the MEPDG (FHWA, 2011).

2.5.3 Hirsch Model

The Hirsch Model was developed by Christensen et al. (2003) by examining four individual models based on the law of mixtures parallel model. It was determined that the most accurate results were yielded from the model that used the binder modulus, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) (FHWA, 2011). The Hirsch model is made up of three equations as follows:

$$|E^*|_m = P_c \left[4,200,000 \left(1 - \frac{VMA}{100} \right) + 3|G^*|_b \left(\frac{VFA \times VMA}{10,000} \right) \right] + \frac{(1-P_c)}{\frac{(1-VMA/100)}{4,200,000} + \frac{VMA}{3|G^*|_b(VFA)}} \quad (2.5)$$

$$\phi = -21(\log P_c)^2 - 55 \log P_c \quad (2.6)$$

$$P_c = \frac{(20+33|G^*|_b(VFA)/(VMA))^{0.58}}{650+(3|G^*|_b(VFA)/(VMA))^{0.58}} \quad (2.7)$$

Where:

$|E^*|_m$ = Dynamic modulus of HMA (psi)

P_c = Aggregate contact volume

ϕ = Phase angle of HMA

It is important to note that a small data set, 206 data points, was used to determine the coefficients used in the Hirsch model. The Witczak and modified Witczak models used significantly larger data sets to determine their coefficients with 2,750 and 7,400 data points respectively (FHWA, 2011).

2.5.4 Law of Mixtures Parallel Model

The law of mixtures parallel model, also known as the Al-Khateeb model, was developed by Al-Khateeb et al. based on findings from the Hirsch model (FHWA, 2011). The equation is as follows:

$$|E^*|_m = 3 \left(\frac{100-VMA}{100} \right) \left(\frac{(90+10,000(|G^*|_b/VMA))^{0.66}}{1,100+(900(|G^*|_b/VMA))^{0.66}} \right) |G^*|_g \quad (2.8)$$

Where:

$|G^*|_g =$ Dynamic shear modulus of asphalt binder at the glassy state (assumed to be 145 ksi)

2.5.5 ANN Models

An Artificial Neural Network (ANN) “is a mathematical or computational model that tries to simulate the structure and functional aspects of biological neural networks. It consists of an interconnected group of artificial neurons and processes information using a connectionist approach to computation” (Sakhaeifar et al., 2010). A neural network can be considered a nonlinear statistical modeling tool and is mostly used to model complex relationships between the inputs and the outputs and can also be used to find patterns in data. The most distinct characteristic of an artificial neural network is its ability to act as an adaptive system and is able to change its structure during a “learning” phase (Sakhaeifar et al., 2010). ANNs have the ability to “learn” by using a set of observations to find the most optimal solution (Anderson, 1995).

The network structure used for training the artificial neural networks is presented in a schematic in Figure 5.

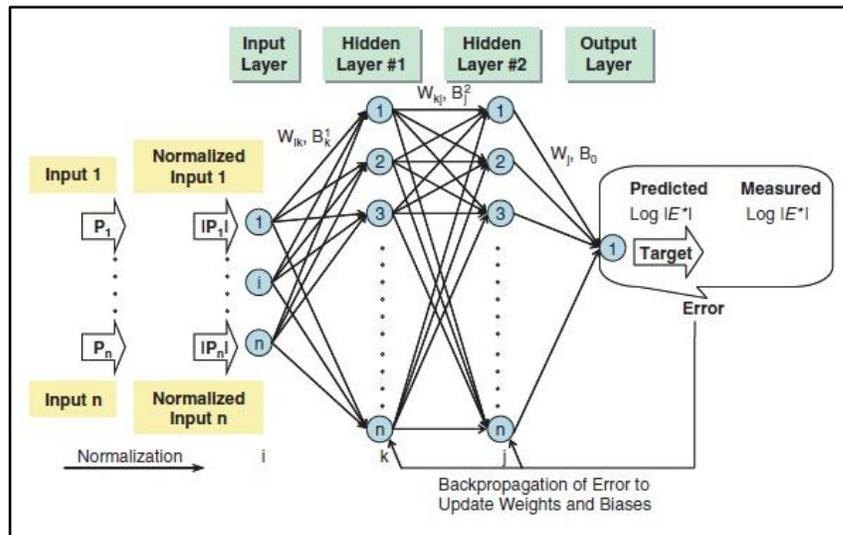


Figure 5: ANN Schematic Structure (FHWA 2011)

The ANN models developed under the 2011 FHWA study were based on supervised learning using a feed-forward back-propagation method with the sigmoidal function used as a transfer function

(Sakhaeifar et al., 2010). The three ANN models developed in the study were created by using three different primary input parameters:

1. M_R ANN – used resilient modulus as the primary input;
2. VV ANN – used binder viscosity as the primary input; and
3. $|G^*|$ ANN – used the binder shear modulus as the primary input.

The above primary input parameters were selected for different reasons. The resilient modulus input was selected because as part of the US-LTPP program, resilient modulus was collected as the primary mixture stiffness for the majority of the layers in the experimental sections. Therefore, a significant amount of resilient moduli data was readily available for analysis in the US-LTPP database. The binder viscosity and shear modulus parameters were selected after evaluation of the Hirsch model indicated better statistical predictions than both of the Witczak models (FHWA, 2011).

2.6 Viscosity-Based Supplementary Functions

The following functions can be used to determine the reduced frequency as well as the time-temperature shift factor for the dynamic modulus using the ANNACAP predicted fitting coefficients.

2.6.1 Sigmoidal Function

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log(t_R)}} \quad (2.9)$$

Where:

t_R = The inverse of the reduced frequency of loading (Hz)

δ , α , β , and γ = Fitting coefficients (determined by linear regression)

2.6.2 Time-Temperature Shift Factor Function

$$\log a_T = \alpha_1 T^2 + \alpha_2 T + \alpha_3 \quad (2.10)$$

Where:

α_T = Mixture time-temperature shift factor

T = Temperature of interest

α_1 , α_2 , and α_3 = Fitting coefficients (determined by linear regression)

2.6.3 Study Results – Model Prioritization and Decision Tree Development

As part of the 2011 FHWA study, the existing models (Witczak, Hirsch, etc.) were compared to the three ANN models. Overall, the ANN models were found to provide more accurate predicted values than all four of the existing models. Based on these results, the US-LTPP database was populated with dynamic modulus values predicted from all three ANN models (FHWA, 2011).

The ANN models, developed as part of this study, were also compared to each other and ranked based on their respective performance. As a result, a decision tree was created and is presented in Figure 6.

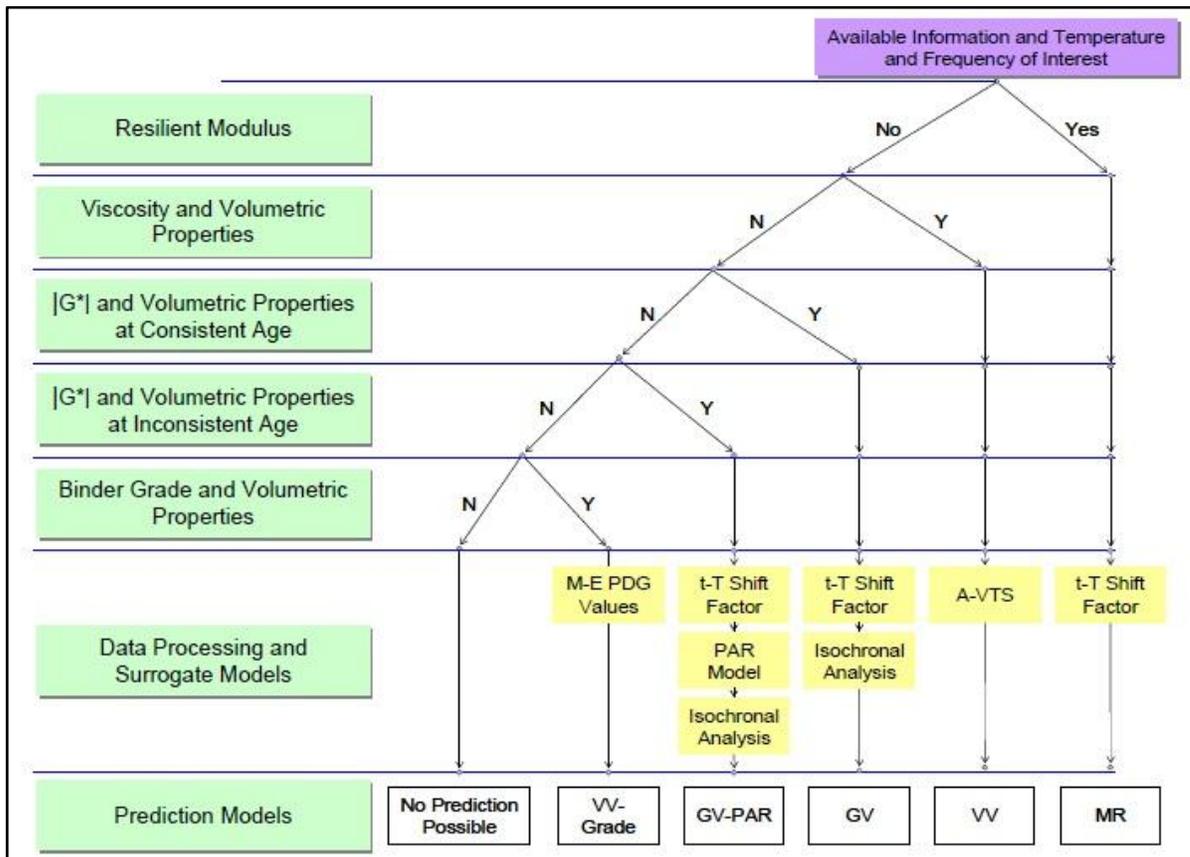


Figure 6: ANN Model Decision Tree (FHWA 2011)

As shown in Figure 6, the preferred ANN model is the resilient modulus (M_R) based model. If no resilient modulus data is available, the next preferred model is the viscosity-based (VV) ANN model.

A software program named Artificial Neural Networks for Asphalt Concrete Dynamic Modulus Prediction (ANNACAP) was also developed under the 2011 FHWA study. ANNACAP can be used to predict dynamic modulus values using any of the three ANN models developed. The ANNACAP software was used to predict dynamic modulus values of all C-LTPP pavement sections in the database and will be discussed in detail in the following sections of this thesis.

2.7 Summary

This literature review examined the history of pavement design in North America and explained the direction it is heading in the near future. The MEPDG will be required for pavement design practices for the foreseeable future. Several Canadian provincial agencies are currently in the process of transitioning to this new design method. However, a huge level of effort is still required to calibrate and validate the existing MEPDG models to local conditions. The importance of the role of pavement performance databases in MEPDG calibration was also discussed. There is an abundance of existing data in existing pavement databases, more specifically the US-LTPP and C-LTPP databases.

Research on the dynamic modulus, $|E^*|$, of HMA mixtures were summarized and discussed as it is the most important material characterization property when running an MEPDG analysis on an asphalt pavement section. It is not economically feasible for provincial agencies to perform large-scale dynamic modulus testing on HMA mixtures, thus the ANN dynamic modulus prediction models detailed in this chapter will be evaluated as part of this thesis. The ANN prediction models can be a potential data source of dynamic modulus data to aid with MEPDG calibration.

Chapter 3

Comprehensive C-LTPP Database Review

The research in this thesis is also part of a study which involved a comprehensive review of the C-LTPP database on behalf of the Transportation Association of Canada (TAC). The project involved identifying gaps in the C-LTPP database and preparing a summary of the available data (Korczak et al., 2011).

This review and the subsequent use of the C-LTPP database to calculate parameters for the MEPDG are presented in this thesis. This chapter summarizes the available data and data gaps in the C-LTPP database. Furthermore, this chapter describes how data can be extracted for the analyses in the following chapters. It should be noted that all database module and table names used in this chapter are as they appear in the C-LTPP database. Figure 7 illustrates and summarizes the C-LTPP test site locations across Canada.

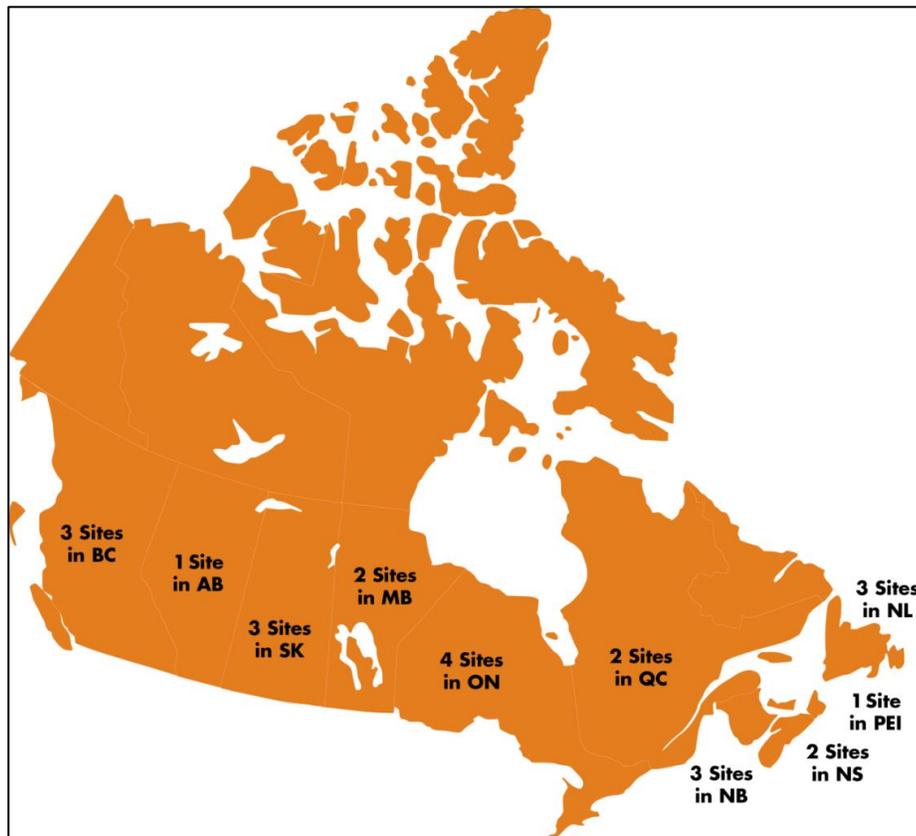


Figure 7: C-LTPP Test Site Locations (C-SHRP 1990)

3.1 Database Overview

This section will present and describe the general C-LTPP database structure. In total, the database contains 62 tables distributed throughout four major data modules or databases in Microsoft Access (.mdb file type) format:

- Descriptive
- Historic
- Materials
- Monitoring

Figure 8, illustrates the overall database hierarchy.

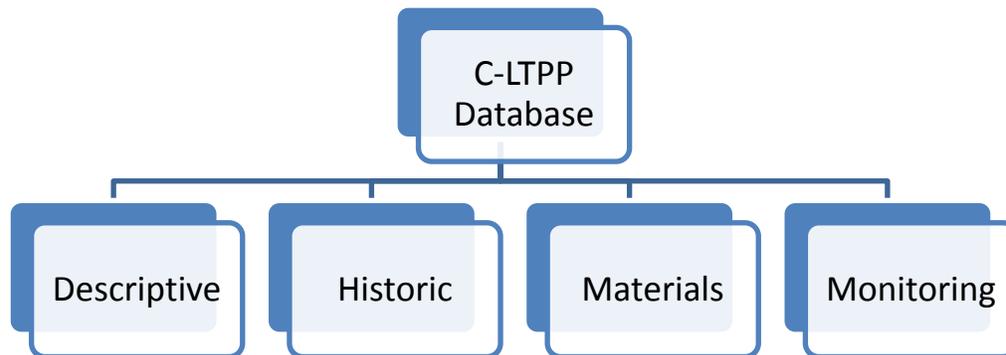


Figure 8: C-LTPP Database Hierarchy (C-SHRP 1990)

As part of the C-LTPP program, the individual provincial Departments of Transportation (DOTs) were responsible for nearly all aspects of data gathering, testing and reporting. The role of C-SHRP staff was limited to coordination and management of the individual activities and some contracting of special activities (SHRP, 1994). Table 3 outlines the project activities and responsibilities.

Table 3: Project Activities and Responsibilities (C-SHRP 1997)

ACTIVITY	FREQUENCY	RESPONSIBILITY
Test Site Identification	one-time	Agency
Pavement Rehabilitation	one-time	Agency
Material Sampling & Testing	prior, during, and immediately after the overlay	Agency
Surface Distress Survey	prior to overlay, yearly	Agency
Longitudinal & Transverse Profile	prior to overlay, yearly	Agency
Benkelman Beam - Long-Term Changes	prior to overlay, yearly (up to 1995)	Agency
Benkelman Beam - Seasonal Variations	monthly, in one year	Agency
Benkelman Beam - Spring Factor	weekly, in three different years	Agency
Falling Weight Deflectometer	every 2nd year	C-SHRP/Agency
Environmental Data ¹	historical, yearly	C-SHRP
Traffic Data ²	historical, yearly	Agency
Skid Resistance	every 2nd year	Agency
Pavement Maintenance	as required	Agency
Video Logging	one-time	Agency

1 Climatic data is obtained from the Canadian Climate Centre, Environment Canada

2 Traffic Data includes continuous Weigh-In-Motion (WIM) or continuous Automatic Vehicle Classification (AVC) when available, as well as agency estimates of major traffic parameters.

3.2 Descriptive Module

Figure 9, illustrates the hierarchy of the Descriptive Module. As noted below, it is composed of four databases including: ASbuilt, Experiment Code, Glossary and Table Definitions. As noted, some short forms are used in this figure and these relate to the actual names of the databases.

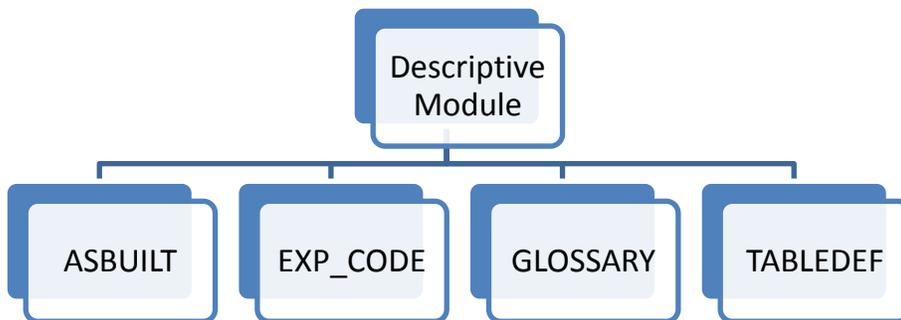


Figure 9: Descriptive Module Hierarchy (C-SHRP 1990)

3.2.1 ASBUILT Database

This database currently consists of a single table called Site Description. As the table name implies, this table consists of section identification, location and description of the experimental test sites, including as-built information on the pavement structure.

The location data includes: C-SHRP site identification number, province where the test site is located, a brief description of the site location, elevation above sea level, a station used by the provincial highway agency and geographic coordinates.

The Site Description table also includes essential data on the as-built properties of each test section. This includes: highway classification, total number of through lanes, lane widths, shoulder types, shoulder widths, date of original construction, layer thicknesses and material codes.

In addition, the Site Description table contains some key environmental data such as: environment type, freeze index, annual precipitation, annual freeze-thaw cycles and temperature gradient.

Overall, the Site Description table contains most key data elements required to perform any kind of analysis.

3.2.2 EXP_CODE Database

This database contains only one table called Explanatory Codes. It is a basic table containing the various codes used throughout the C-LTPP database and their descriptions.

3.2.3 GLOSSARY Database

This database also contains a single table called Glossary of Data Elements. The table contains a definition of each data element in the C-LTPP database organized by table.

3.2.4 TABLEDEF Database

Again, this database contains a single table called Database Tables Definitions. The table contains a summary of the C-LTPP database including table definitions.

3.3 Historic Module

Figure 10, illustrates the hierarchy of the Historic Module. As noted below it is composed of two databases including: Historical Climatic Data and Historical Traffic Data. As noted, some short forms are used in this figure and these relate to the actual names of the databases.

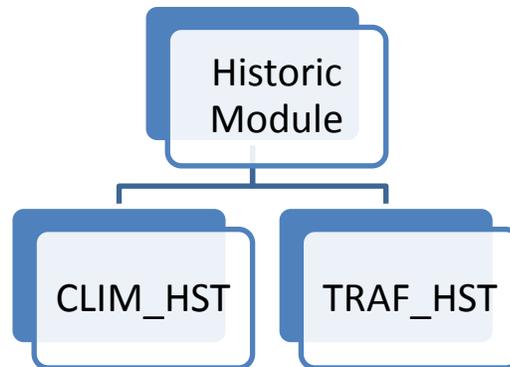


Figure 10: Historic Module Hierarchy (C-SHRP 1990)

3.3.1 CLIM_HST Database

This database contains a table called Historical Climatic Data and includes historical monthly climatic data. The climatic data originated from Environment Canada weather stations in the vicinity of the test site.

More specifically, this table includes minimum, maximum and mean daily temperatures, total precipitation, number of hours of sunshine and average wind speed summarized by month. Also included are annual summaries of the same data, described above, as well as an annual average temperature gradient, total annual number of days with precipitation, average annual freeze-thaw cycles, highest monthly mean Global Solar Radiation and lowest monthly mean Global Solar Radiation.

3.3.2 TRAF_HST Database

This database contains a table called Historical Traffic Data and includes annual summaries of traffic variables from original highway construction to the time of rehabilitation. This traffic data is based on provincial highway agency records.

More specifically, this table includes the year of original pavement construction, range of years of traffic records, average daily traffic in year of original construction, Directional Distribution Factor (DDF) on the highway in the vicinity of the C-SHRP test site in year of original construction, percentage of trucks in traffic stream in year of original construction, Lane Distribution Factor (LDF) on the highway in the vicinity of the C-SHRP test site, average daily traffic of all reported years, DDF for all reported years, average percentage of trucks in the traffic stream for all reported years, LDF on the highway for all reported years, estimated total Equivalent Single Axle Loads (ESAL) in the C-SHRP lane only for the reported years and the method used to compute ESALs.

3.4 Materials Module

The overall C-LTPP project goal was to increase pavement life through the development of cost effective pavement rehabilitation procedures, based upon a systematic observation of in-service pavement performance. To complete this goal, the C-LTPP program would provide a viable linkage between material properties and long-term pavement performance.

Each individual provincial agency was responsible for field sampling, field testing, sample handling and laboratory tests of materials (C-SHRP, 1990).

Figure 11, illustrates the hierarchy of the Materials Module. As noted below it is composed of nineteen databases including: Asphalt Concrete Test Results 1, Asphalt Concrete Test Results 2, Base Test Results, Asphalt Concrete Core Test Results 1, Asphalt Concrete Core Test Results 2, Dynamic Modulus Test Results, Log of Pavement Cores, Log of Shoulder Probe, Log of Pavement Test Pit, Resilient and Dynamic Modulus Materials Sampling, Resilient Modulus Fine Grained Soil Samples, Resilient Modulus Granular Material Samples, Resilient Modulus Test Results – Fine Grained Soils, Resilient Modulus Test Results – Granular Materials, Pavement Rehabilitation Construction Data, Subbase Test Results, Subgrade Test Results and In-Situ Test Results. As noted, some short forms are used in this figure and these relate to the actual names of the databases.

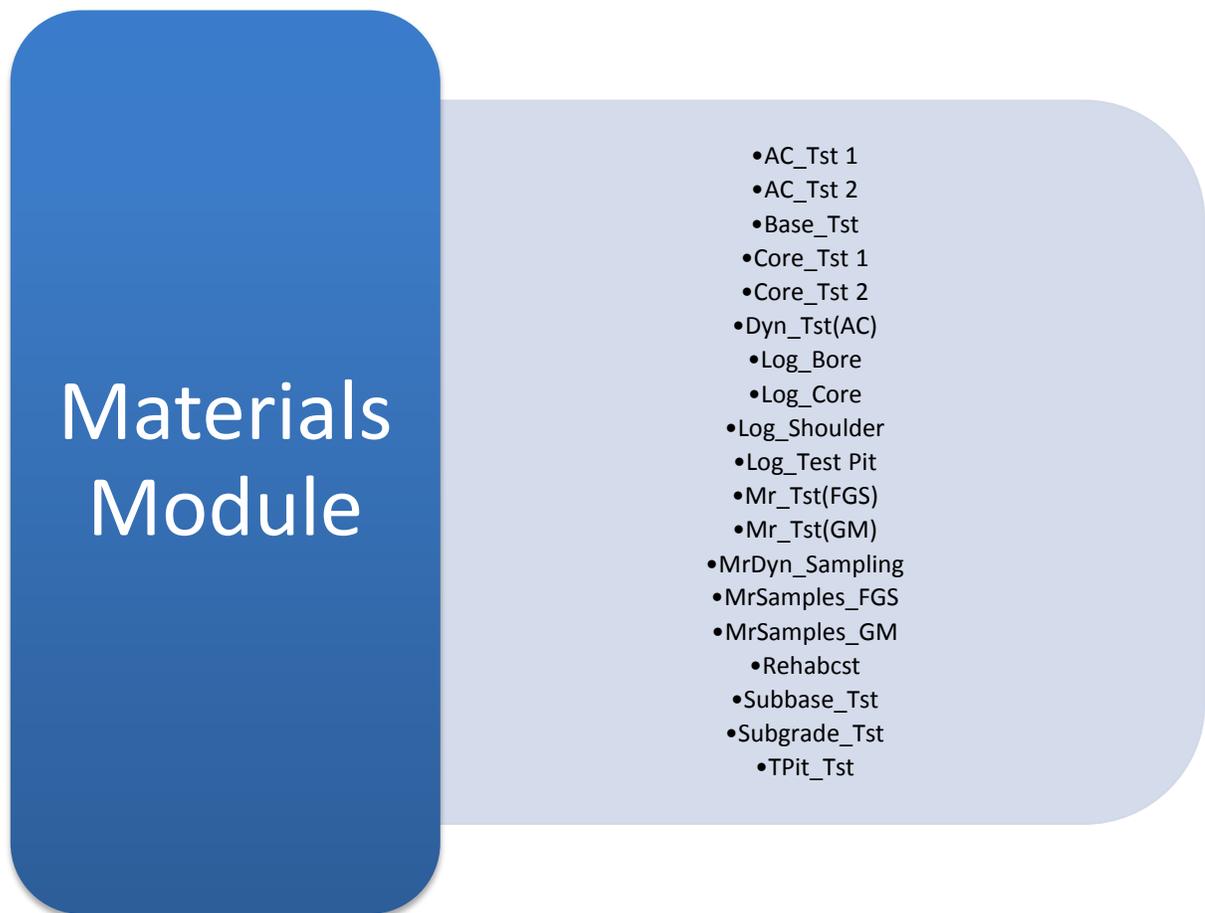


Figure 11: Materials Module Hierarchy (C-SHRP 1990)

3.4.1 AC_Tst 1

The Asphalt Concrete Test Results 1 table includes laboratory tests conducted on asphalt concrete cores and on bulk uncompacted AC samples retrieved before and after rehabilitation. More specifically, this table contains the following data elements: grade of bitumen, source of AC, description of asphalt crude source, specific gravity of AC, kinematic and coefficient of viscosity of the AC at different temperatures, penetration of AC at different temperatures, ductility of AC at different temperatures and a grain size analysis of the aggregate in the asphalt sample.

3.4.2 AC_Tst 2

The Asphalt Concrete Test Results 2 table includes laboratory tests conducted on bulk uncompacted AC samples retrieved from either the paver or the asphalt plant during rehabilitation. More specifically, this table contains the following data elements: average, minimum and maximum bulk specific gravity and theoretical maximum specific gravity tests, as well as asphalt mix volumetric and gravimetric information on the bulk uncompacted AC samples.

3.4.3 Base_Tst

The Base Test Results table includes a classification and physical properties of the base material. More specifically, this table contains the following data elements: thickness of layer, material classification and AASHTO classification codes, results of Atterberg Limits tests, maximum dry density, optimum moisture content, in-situ and laboratory moisture contents, in-situ density, in-situ and laboratory bearing ratio and a grain size analysis on the base material samples.

3.4.4 Core_Tst 1

The Asphalt Concrete Core Test Results 1 table includes laboratory tests conducted on asphalt concrete cores retrieved before and after rehabilitation. More specifically, this table contains the following data elements: asphalt core thickness, average, minimum and maximum bulk specific gravity and theoretical maximum specific gravity, asphalt mix volumetric and gravimetric information and a grain size analysis on the aggregate from the recovered asphalt core samples.

3.4.5 Core_Tst 2

The Asphalt Concrete Core Test Results 2 table includes laboratory tests conducted on asphalt concrete cores retrieved after rehabilitation. More specifically, this table contains the following data elements: asphalt core thickness, average, minimum and maximum bulk specific gravity of the recovered asphalt cores.

3.4.6 Dyn_Tst (AC)

The Dynamic Modulus Test Results table includes physical properties and results of dynamic modulus tests on asphalt concrete samples. More specifically, this table contains the following data elements: bulk and maximum specific gravity, percent air voids, test temperature, test frequency, average dynamic modulus and average phase angle of tested sample.

3.4.7 Log_Core

The Log of Pavement Cores table includes thickness, material description and condition of all extracted cores. More specifically, this table contains the following data elements: date, location and diameter of recovered asphalt core, as well as thickness measurements for each identified layer in the recovered asphalt core.

3.4.8 Log_Bore

The Log of Pavement Bore Holes table includes description of depths and strata changes from the top of pavement surface before rehabilitation, including identification of samples removed. More specifically, this table contains the following data elements: date, location, number, diameter and depth of boreholes, as well as Standard Penetration Test (SPT) blow count and a general description of material observed during drilling.

3.4.9 Log_Shoulder

The Log of Shoulder Probe table includes a description of depths and strata changes from the top of the shoulder. More specifically, this table contains the following data elements: date, location of borehole as well as depth to bedrock, depth of strata change and a general description of the material observed during drilling.

3.4.10 Log_Test Pit

The Log of Pavement Test Pit table includes a physical description of pavement structure before rehabilitation as observed in test pit, including identification of samples removed. More specifically, this table contains the following data elements: date, location and depth of strata change in the test pit as well as a classification code of the material observed in the test pit.

3.4.11 MrDyn_Sampling

The Resilient and Dynamic Modulus Materials Sampling table includes thickness, physical properties, classifications and gradations of pavement materials recovered for resilient and dynamic modulus tests. More specifically, this table contains the following data elements: component layer of pavement structure, depth from pavement surface to top of layer, in-situ dry density from nuclear gauge measurement, in-situ moisture content from nuclear gauge measurement, gradation of recovered sample, results of Atterberg Limits testing, curvature coefficient, uniformity coefficient,

AASHTO classification, specific gravity, percent moisture absorption, maximum dry density and geological origin of the sampled material.

3.4.12 Mr_Tst (FGS)

The Resilient Modulus Fine Grained Soil Samples table includes physical properties and gradations of fine grained soil samples prepared for resilient modulus tests. More specifically, this table contains the following data elements: component layer of pavement structure, method of compaction used to prepare sample, number of layers of fine grain material used, moisture content, dry density and grain size analysis of the prepared sample.

3.4.13 Mr_Tst (GM)

The Resilient Modulus Granular Material Samples table includes physical properties and gradations of granular material samples prepared for resilient modulus tests. More specifically, this table contains the following data elements: component layer of pavement structure, specific gravity, moisture absorption, moisture content, dry density, volume of voids, degree of saturation and grain size analysis of the prepared sample.

3.4.14 MrSamples_FGS

The Resilient Modulus Test Results – Fine Grained Soils table includes the results of the resilient modulus tests on fine grained soils. More specifically, this table contains the following data elements: component layer of pavement structure, moisture content, dry density, applied confining pressure, applied deviator stress, average radial strain and resilient modulus of the prepared sample.

3.4.15 MrSamples_GM

The Resilient Modulus Test Results – Granular Materials table includes the results of the resilient modulus tests on granular materials. More specifically, this table contains the following data elements: component layer of pavement structure, saturation state of sample, moisture content, degree of saturation, suction level, applied confining pressure, applied seating deviator stress, applied deviator stress, average vertical strain, average radial strain, resilient modulus and computed Poisson's Ratio of the prepared sample.

3.4.16 Rehabcst

The Pavement Rehabilitation Construction Data table includes construction records of the rehabilitated pavements. More specifically, this table contains the following data elements: classification code of overlay, overlay lift identification, thickness of overlay lift, asphalt plant used for construction, identification and percent usage of anti-stripping agent, identification and percent usage of recycling agent, measurement of temperature immediately after placement, air temperature, compaction equipment and method of compaction used, as well as the date of rehabilitation.

3.4.17 Subbase_Tst

The Subbase Test Results table includes classifications and physical properties of the subbase material. More specifically, this table contains the following data elements: thickness of layer, material classification and AASHTO classification codes, results of Atterberg Limits tests, maximum dry density, optimum moisture content, in-situ and laboratory moisture contents, in-situ density, in-situ and laboratory bearing ratio and a grain size analysis on the base material samples.

3.4.18 Subgrade_Tst

The Subgrade Test Results table includes classifications and physical properties of the subgrade material. More specifically, this table contains the following data elements: material classification and AASHTO classification codes, results of Atterberg Limits tests, maximum dry density, optimum moisture content, California Bearing Ratio (CBR), frost susceptibility, in-situ and laboratory moisture content, in-situ density, in-situ and laboratory bearing ratio and a grain size analysis on the subgrade material samples.

3.4.19 Tpit_Tst

The In-Situ Test Results table includes the results of in-situ tests conducted in the test pit at each distinct layer of the pavement structure. More specifically, this table contains the following data elements: in-situ density and moisture testing on each layer of the pavement structure using a nuclear density gauge, as well as bearing ratios for the unbound pavement layers in the test pit.

3.5 Monitoring Module

The Monitoring Module contains all of the data collected using non-destructive test methods. Figure 12, illustrates the hierarchy of the Monitoring Module.

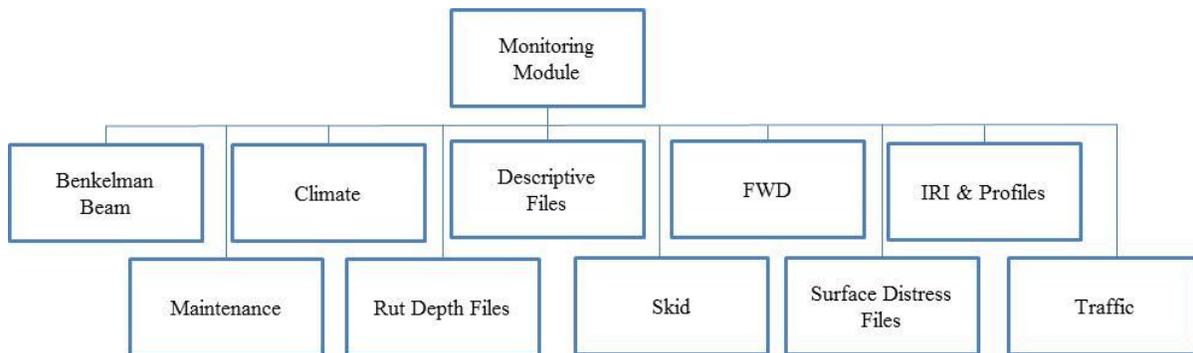


Figure 12: Monitoring Module Hierarchy (C-SHRP 1990)

3.5.1 Benkelman Beam Database

This database contains only one table called Benkelman Beam Rebounds and contains all Benkelman Beam readings and computed rebound values.

The Benkelman Beam was developed in 1953 to measure pavement deflection under typical test-wheel loadings. The Benkelman Beam deflection readings were used for two key portions of the study. The Benkelman Beam was used to characterize the strength parameter before and after rehabilitation.

According to the C-LTPP Database User's Guide, the collection of Benkelman Beam data followed three different guidelines (C-SHRP, 1997). When testing for the Spring Factor, Benkelman Beam data was to be collected weekly in three different years. For Seasonal Variation, data was collected monthly for one year. Finally, to analyze long-term changes in the pavement, data was collected yearly up to the year 1995.

As specified in the "C-LTPP Database User's Guide" document, Benkelman Beam data was the responsibility of the provincial highway agencies (C-SHRP, 1997).

3.5.2 Climate Database

Climatic data is considered mandatory for the C-LTPP program. The data is needed to adjust design and construction standards, to update materials specifications and to assist in analyzing pavement performance.

This database contains only one table called Annual Climate. This table includes an annual summary, by month, of climatic variables from weather stations in the vicinity of each test site.

Similar to the historical table, this table includes the following data elements: weather station identification, average monthly temperature, average maximum daily temperature by month, average minimum daily temperature by month, average monthly precipitation, average monthly percent sunshine, average monthly wind speed, climatic zone, average annual number of wet days, frost penetration, average number of freeze-thaw cycles, freezing index, average annual de-icing chemical application, highest monthly mean solar radiation, lowest monthly mean solar radiation, moisture index and load ban period.

According to the C-LTPP Data User's Guide, climatic data was to be collected yearly after rehabilitation and was the responsibility of C-SHRP. All of the climatic data was obtained from the Canadian Climate Centre operated by Environment Canada (C-SHRP, 1997).

3.5.3 Descriptive Database

Figure 13, illustrates the hierarchy of the Descriptive Files database.

This element contains three separate tables: "Main ID", "Provinces" and "Sections". The "Main ID" table includes a summary of all provinces participating in data collection for the C-LTPP program. The "Provinces" table also includes a list of all provinces participating in the data collection for the C-LTPP program. The "Sections" table includes the individual test sections for the different test sites of the C-LTPP program.

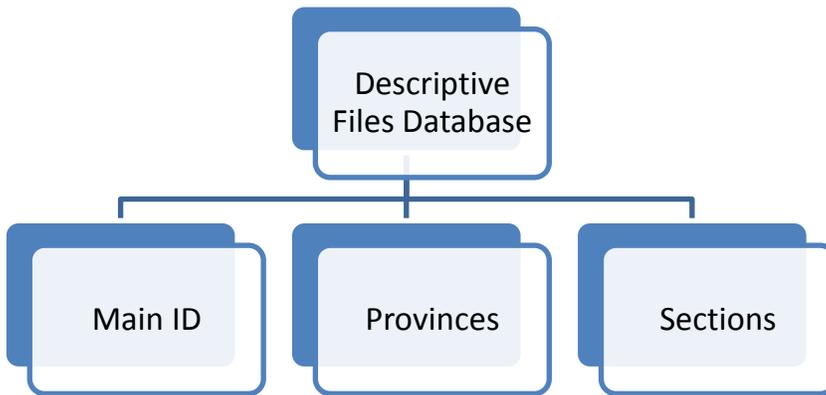


Figure 13: Descriptive Files Hierarchy (C-SHRP 1990)

3.5.4 FWD Database

This database currently contains a table named “FWD”, abbreviated for Falling Weight Deflectometer. This table includes all Dynatest FWD peak deflection readings collected every second year since rehabilitation.

The FWD is an automated device used to rapidly and non-destructively measure pavement deflection. An impulse load which reasonably simulates traffic loading is applied to a spring loaded baseplate on the pavement surface. Deflections are measured at the centre of the baseplate and at six other pre-determined radial points from the baseplate by geophones.

When the C-LTPP program began, the Benkelman Beam was considered an industry standard for measuring pavement deflections. In the early 1990s the FWD was gaining wide acceptance across North America and has now become the industry standard for collecting pavement deflection data. Foresightedly, FWD testing was included in the C-LTPP program in the likely event that the Benkelman Beam would be replaced by the FWD as the deflection measuring device. Consequently, it is understandable that the Benkelman Beam database has more extensive data sets as no seasonal testing was ever done using the FWD units during the time of the study.

The majority of test sections were first tested by the FWD units in either 1991 or 1992. As stated in the C-SHRP document, “C-LTPP Database User’s Guide” (C-SHRP, 1997), FWD data was to be

collected every second year and was the responsibility of the provincial highway agencies. However, there were instances where C-SHRP had retained a private sector consultant to collect FWD data.

3.5.5 L-Profiles Database

This database contains a single table called Longitudinal Profiles. This table includes longitudinal Inner Wheel Path (IWP) and Outer Wheel Path (OWP) elevations from annual Dipstick surveys.

Ride quality is a primary response measurement used as a basis for many pavement management systems and performance models. Ride quality is measured in many different ways and in different forms. Ride, roughness and profile are all methods of characterizing the longitudinal deformation in pavement structures.

The uniform method of measurement for C-LTPP is profile determination using the digital incremental profiler Dipstick. The Dipstick allows a sample interval of 300cm and has the advantage of determining elevations from which roughness coefficients can be calculated for each section.

As specified in the “C-LTPP Database User’s Guide” document, longitudinal profile data was to be collected prior to rehabilitation and then yearly after rehabilitation and was the responsibility of the provincial highway agencies (C-SHRP, 1997).

3.5.6 IRI Database

This database contains a single table called Pavement Roughness Index (IRI) and includes annual IRI values in the IWP and OWP computed from the longitudinal elevation profiles.

In 1996 and 1997, a series of data insight projects were initiated to establish performance trends and to carry out comparative analyses and diagnostic evaluations as well as test the integrity of the C-LTPP database. A report titled “Roughness Trends at C-SHRP LTPP Sites” concluded “that the IRI values in the C-LTPP database are valid” (C-SHRP, 1999).

Since the IRI values are computed using the longitudinal profile data, IRI was also required to be available yearly coinciding with every Dipstick survey.

3.5.7 Maintenance Database

Maintenance performed on the C-LTPP monitoring sites will influence the results of the pavement performance studies. However, it is recognized that necessary maintenance work may be carried out

on the monitoring sections to keep the pavements in a safe and serviceable condition. It is essential that an accurate record of all maintenance activities and occurrences be kept.

Figure 14, illustrates the hierarchy of the Maintenance database.

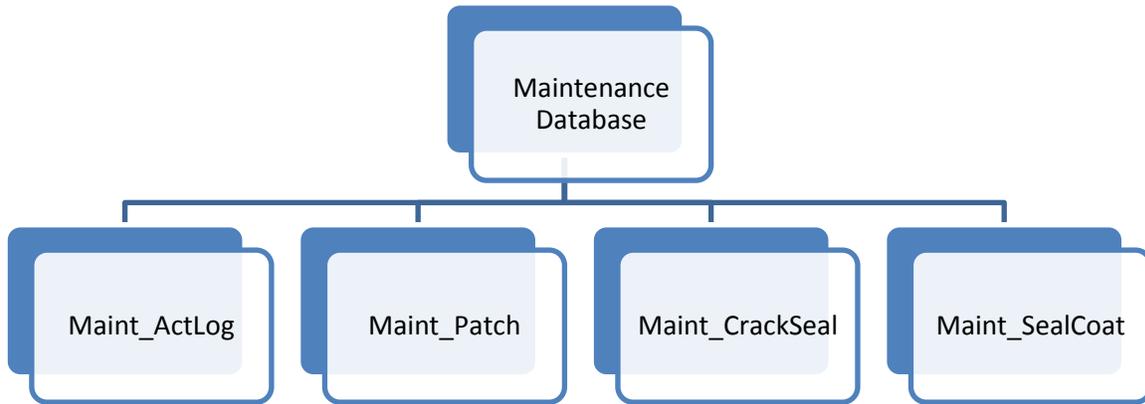


Figure 14: Maintenance Database Hierarchy (C-SHRP 1990)

This database contains four different tables: Maintenance Activity Log, Maintenance Crack Seal, Maintenance Patch and Maintenance Seal Coat. These tables include summary data for annual maintenance activities, crack sealing operations, patching activities and seal coat applications respectively.

3.5.8 Rut Depth Database

The Rut Depth database contains all of the rutting data collected for each test section. Figure 15, illustrates the hierarchy of the Rut Depth database.

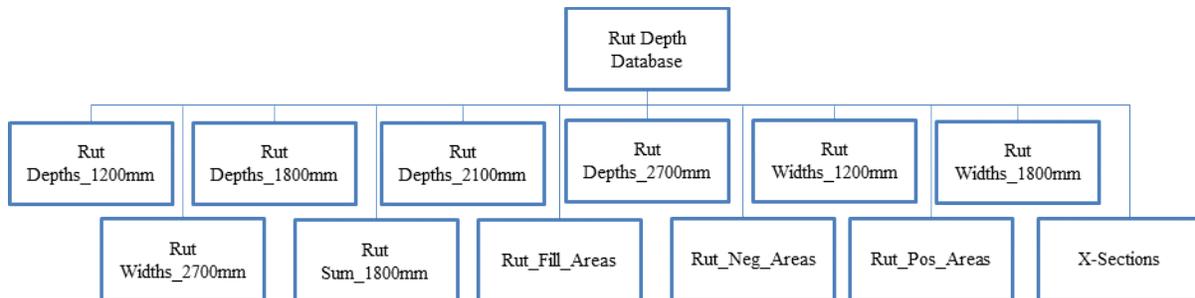


Figure 15: Rut Depth Database Hierarchy (C-SHRP 1990)

This database contains twelve different tables: “RutDepths_1200mm”, “RutDepths_1800mm”, “RutDepths_2100mm”, “RutDepths_2700mm”, “Rut Widths_1200mm”, “Rut Widths_1800mm”, “RutWidths_2700mm”, “RutSum_1800mm”, “Rut_Fill_Areas”, “Rut_Neg_Areas”, “Rut_Pos_Areas” and “X-Sections”.

The Rut Depth tables include a summary of rut depths under the given straight edge length and are derived from the transverse elevation profiles. The Rut Width tables include a summary of rut widths associated with the rut depths and are also derived from the transverse elevation profiles. The Rut Sum table includes a summary of IWP and OWP rut depths under an 1800 mm straight edge. The Rut Fill table includes calculated areas between the transverse elevation profile and chords extending from lane centreline to lane edge. “Rut_Neg_Areas” table includes calculated areas above the transverse elevation profile and a chord extending across the lane width. The “Rut_Pos_Areas” table includes calculated areas below the transverse elevation profile and a chord extending across the lane width. Finally, the “X-Sections” table includes transverse profile elevations from the annual Dipstick surveys.

Since the rut depth data are computed using the longitudinal profile data, rut depths were also required to be available annually coinciding with every Dipstick survey.

3.5.9 Skid Database

Skid resistance is the force created when a tire that is prevented from rotating slides along the surface of the pavement. Although skid resistance is often thought of as a pavement property, it is actually a property of both the pavement surface characteristics and the vehicles’ tires. Skid resistance is measured and reported in the C-LTPP database using a Skid Number (SN).

This database contains a single table called Skid Resistance and includes skid resistance measurements obtained since rehabilitation. More specifically, this table includes the following data elements: weather description, air temperature, pavement temperature, test method, equipment used, tire type, tire size, tire pressure, SN, test speed, pavement type and pavement condition.

As specified in the “C-LTPP Database User’s Guide” document, skid testing data was to be collected every second year after rehabilitation and was the responsibility of the provincial highway agencies (C-SHRP, 1997).

3.5.10 Surface Distress Database

Surface distress is a key measurement within the C-LTPP program as it is one of the most commonly used measures of pavement response. Difficulties arise in achieving consistent details of surface distress because of the subjective nature of the identification process.

A report titled “C-LTPP Surface Distress Variability Analysis” identified major sources of error and suggested potential improvements to C-SHRP’s surface distress mapping process and data entry process (C-SHRP, 2000).

The objective in the C-LTPP program was to capture as much quantitative data for distress as possible since any number of qualitative assessments could then be accommodated.

Each test section and its distresses were manually mapped, coded and photographed in 30m intervals.

Figure 16, illustrates the hierarchy of the Surface Distress Database.

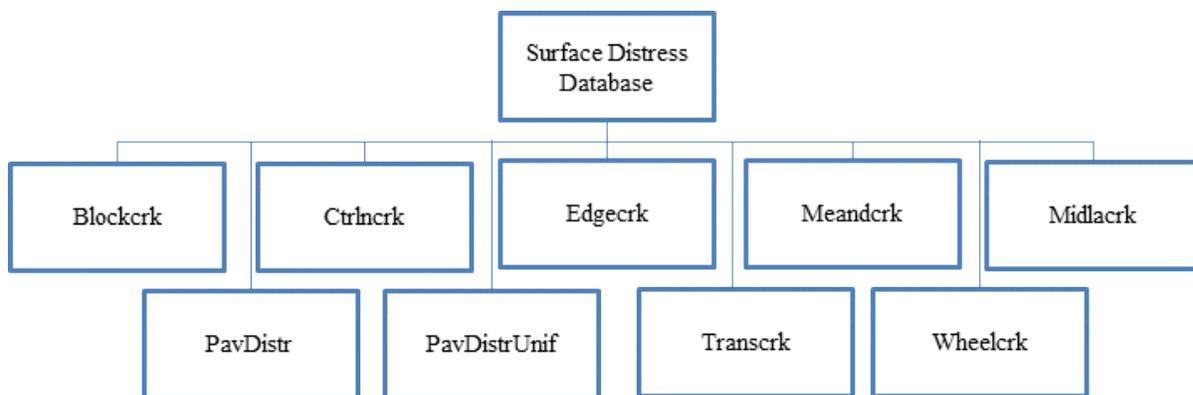


Figure 16: Surface Distress Hierarchy (C-SHRP 1990)

This database contains nine different tables: Block Cracking Summary, Centreline Cracking Summary, Pavement Edge Cracking Summary, Meander Cracking Summary, Midlane Cracking Summary, Pavement Surface Distress, Uniform Pavement Surface Distress, Transverse Cracking Summary and Wheel Path Cracking Summary.

The Block Cracking Summary table includes an annual summary of the extent of block cracking by severity level. The Centreline Cracking Summary table includes an annual summary of the extent of longitudinal centreline cracking by severity level. The Pavement Edge Cracking Summary table includes an annual summary of the extent of longitudinal pavement edge cracking by severity level.

The Meander Cracking Summary table includes an annual summary of the extent of meander cracking by severity level. The Midlane Cracking Summary table includes an annual summary of the extent of midlane cracking by severity level. The Pavement Surface Distress table includes the results of the annual pavement surface condition surveys. The Uniform Pavement Surface Distress table includes information on uniform surface defects that cover more than 75% of the pavement surface. The Transverse Cracking Summary table includes an annual summary of the extent of transverse cracking by severity level. Finally, the Wheel Path Cracking Summary table includes an annual summary of the extent of wheel path cracking by severity level.

All of the tables providing a summary of the various types of cracking, which can occur on an asphalt pavement surface, are computed using the annual distress data populated in the Pavement Surface Distress table.

As specified in the “C-LTPP Database User’s Guide”, pavement distress surveys were to be conducted once prior to the overlay and on a yearly basis after rehabilitation and were the responsibility of the provincial highway agencies (C-SHRP, 1997).

3.5.11 Traffic Database

Traffic data is a fundamental component for all pavement design and performance models. The models are used to design new pavements and overlays to predict performance, to evaluate investment costs and benefits, and to schedule construction and maintenance operations.

The prohibitive cost of Weigh-In-Motion (WIM) equipment, the limits of existing technology and the need to minimize cost have influenced but not compromised the type and quantity of data required for each site. The collection of historic traffic data since construction and the continuous monitoring of traffic at each test site will provide the information to estimate the total ESAL applications on the pavement.

Site specific information for traffic volumes, vehicle classification and axle loads are required for each C-LTPP test section. The data was required to be collected in the vicinity of each test location to ensure that any change in traffic patterns as a result of economic conditions, seasonal variations or enforcement activity were accounted for.

Traffic data collection for the C-LTPP program requires the use of Automatic Vehicle Classification (AVC) and portable or permanent WIM equipment.

Figure 17, illustrates the hierarchy of the Traffic Database.

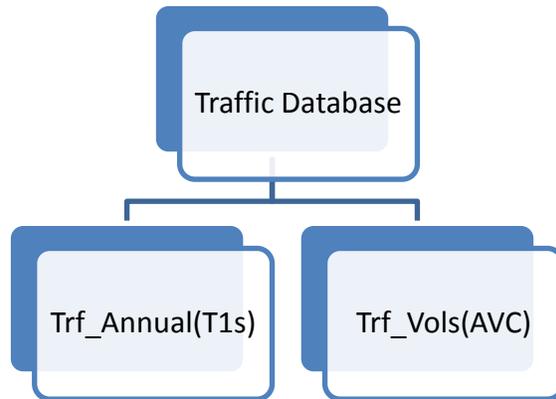


Figure 17: Traffic Database Hierarchy (C-SHRP 1990)

This database contains two separate tables: Annual Traffic Parameters and Automatic Vehicle Classifier Traffic Volumes. The Annual Traffic Parameters table includes an annual summary of traffic variables since rehabilitation and is based on provincial highway agency records. The Automatic Vehicle Classifier Traffic Volumes table includes a summary of traffic volume records from AVC surveys.

As specified in the “C-LTPP Database User’s Guide”, only annual traffic data was required to be collected yearly. Traffic volume records from the AVC systems were populated when available (C-SHRP, 1997).

3.6 Summary of C-LTPP Database Gaps in Data

Several gaps in data were identified throughout the C-LTPP database. Some of the gaps were due to a lack of user-friendliness and several others were due to the provincial agency not collecting data for consecutive years during an experiment’s service life (Korczak et al., 2011). The data gaps will be summarized by data module.

3.6.1 Descriptive Module

Only a few gaps were identified in the Descriptive module:

1. The Asbuilt table was missing proper GPS coordinates in degrees minutes and seconds (DMS).

2. The Site Description table was missing a description of how the pavement thickness was determined (average measured core thickness).
3. Lastly, the database in general would benefit from a Master Layer Table summarizing the layer thicknesses. It is not essential; however it would make the database more user-friendly.

3.6.2 Historic Module

Only one data gap was identified in the Historic module. The TRAF_HST table is missing detailed traffic data for several experimental sites in multiple provinces.

3.6.3 Materials Module

Several data gaps were identified in the Materials module. The gaps were mostly associated with missing sampling data such as sample location (station, offset, etc.), date of sampling as well as material type.

3.6.4 Monitoring Module

The Monitoring module had the highest number of data gaps. These gaps can be attributed to not following the collection schedule as identified in Table 3 which resulted in missing monitoring data for consecutive years.

All monitoring data elements were missing data for several test sections in every province. These data elements included:

- Benkelman Beam;
- Climate Data;
- Falling Weight Deflectometer (FWD);
- Longitudinal Profile;
- Skid Data;
- Pavement Distress; and
- Traffic Data.

3.7 C-LTPP Database Recommendations

In general, all data modules require improvements. The Monitoring and Materials data modules require the most significant amount of effort to improve data quality and data usability.

The data gaps requiring immediate attention are:

Descriptive Module

- Obtain full geographic coordinates for each test section
- Add a column field for an Out of Study Date and populate for each test section

Materials Module

- Add a column field to include sampling dates for all samples in the test results tables
- Populate the sampling location field for "Log_Core" and "Log_Bore" tables using "Pavement Research Technical Guidelines" document and raw field sampling sheets
- Quality Control check on "orphan" sample numbers

Monitoring Module

- Populate missing Climate Data fields using Environment Canada's historical database
- Populate critical data gaps identified in the FWD database using correlated Benkelman Beam data
- Populate missing Traffic Data fields identified as well as all sections labeled as having critical data gaps using provincial agency data
- Add a column field called "Lane_Loc" to the FWD table and populate with either "IWP" or "OWP"

Suggestions have also been made for improvements to accessibility for every module currently in the C-LTPP database. The following is a summary of the suggestions made in the report:

Descriptive Module

- Create a program similar to the US-LTPP Table Navigator program to help users browse through the different data elements
- Add design overlay thicknesses to the Site Description table

Historic Module

- Merge the Historic Climate table with the Annual Climate table, and then remove the Historic Climate table from the database

Materials Module

- Create a Master Layer Table using thickness data from both the Site Description and Core Log tables
- Create a Master Sampling table to resolve the "orphan" sample numbers issue
- Merge the "Base_Tst" and "Subbase_Tst" tables into one table called "Unbound_Layer_Tst"
- Merge the "AC_Tst 1" and "AC_Tst 2" tables into a single table called "AC_Tst"

Monitoring Module

- Remove the Main Identification, Provinces and Test Site Sections tables from the database
- Convert all distress codes to their respective full terms
- Change the format of the Pavement Surface Distress table to have each pavement distress represented by a column in the table to improve functionality (optional)

General Accessibility

- Update the C-SHRP website, or create a new web page in the current TAC website
- Distribute the C-LTPP database and all necessary supporting documents on digital media such as DVDs, thumb drives etc. at all major transportation conferences and events
- Create an auxiliary database where researchers can access the raw data files and sheets from data collection in the field
- Create a new up-to-date C-LTPP User's Manual

3.8 Data Sources Extracted For Thesis

The data used for analysis in this thesis were extracted from the AC_Tst 1, AC_Tst 2 and Dyn_Tst (AC) tables from the Materials Module in the C-LTPP database.

A query was created in Microsoft Access in order to extract volumetric data from the AC_Tst 1 and AC_Tst 2 tables for input into the ANNACAP software. The Dyn_Tst table contains dynamic modulus test results from the asphalt concrete samples collected at each C-LTPP section.

A dynamic modulus sample was collected at a minimum of one test section in each province. As a result, each province has dynamic modulus test results for at least one asphalt mix. Some provinces have multiple data sets. The measured dynamic modulus results were extracted in order to compare to the predicted results calculated using the ANNACAP ANN models. The comparison results are included in the following sections of this thesis.

It is important to note that the binder type for the majority of the mixes used for dynamic modulus testing is unknown. The sample records in the Materials module indicate that the majority of samples were coded with a material code translating to a binder type of “Other”.

3.9 Summary

This chapter provided a summary of the contents of the C-LTPP database as well as any gaps identified as part of a TAC research project completed for the C-LTPP steering committee in 2011. The database contains several types of data elements spread throughout several modules; however the data needed for this thesis were sourced from the Materials module. The lack of binder material classification, identified as one of the gaps in the Material module, effects the analysis results as typical dynamic moduli for specific mix types was desired.

The C-LTPP database contains other data that may also be used for local calibration such as climate and traffic data.

Chapter 4

ANNACAP Version 1.2

The Artificial Neural Networks for Asphalt Concrete Dynamic Modulus Prediction (ANNACAP) software was developed under an FHWA contract in order to process large amounts of data in a batch mode using existing data in the FHWA's US-LTPP database (FHWA, 2011). The benefits of using artificial neural networks to predict dynamic modulus values were presented in the literature review. In summary, it is not financially feasible to perform laboratory dynamic modulus testing on material samples that are being stored in the US-LTPP Materials Reference Library (MRL). However, it is recognized that this data is very important for the calibration and validation of the MEPDG.

Similarly, many provincial agencies do not have the funds or the equipment available for dynamic modulus testing or both. However, both the US-LTPP and C-LTPP databases contain other laboratory data that can be used to estimate or predict the $|E^*|$ master curve and shift factors, the dynamic modulus at specific load durations and temperatures as well as develop inputs for the MEPDG models in DarWIN-ME.

The ANNACAP software contains three different models that can be used to predict dynamic modulus: M_R -based ANN, $|G^*|$ -based ANN and Viscosity-based ANN.

4.1 M_R -Based ANN Model

The first of the three ANN models in ANNACAP is the M_R -based model. A material's resilient modulus (M_R) is an estimate of its modulus of elasticity. The resilient modulus of an asphalt material is determined using a triaxial test. Essentially, the test applies a repeated axial cyclic stress of fixed magnitude, load duration and cycle duration to a cylindrical test specimen (eg. Asphalt core, etc.). This cyclic load is supposed to simulate traffic loading. While the specimen is subjected to this dynamic cyclic stress, it is also subjected to a static confining stress provided by a triaxial pressure chamber (NCHRP, 2004).

The ANNACAP user must enter M_R values at three specific temperatures (5°, 25° and 40°C) in the units of Gigapascals (GPa) into the software for it to predict the dynamic modulus using the M_R -based ANN model.

4.2 |G*|-Based ANN Model

The second of the three ANN models in ANNACAP is the |G*|-based model. The complex shear modulus (G^*) can be considered the sample's total resistance to deformation when repeatedly sheared (AASHTO T 315-12, 2012). The shear modulus is typically measured using a dynamic shear rheometer (DSR). The DSR is used to characterize the viscous and elastic behavior of asphalt binders at medium to high temperatures and follows the AASHTO T 315 procedure.

Similar to the MEPDG levels of input, the |G*|-based ANN model in the ANNACAP software has three different levels of analysis: Level 1, Level 2 and Level 3.

4.2.1 Level 1 Analysis

For a Level 1 analysis, the user requires access to a complete dataset of |G*| values at multiple temperatures and loading frequencies. The data can be loaded into the software using a tab delimited text file.

4.2.2 Level 2 Analysis

A Level 2 analysis requires the user to have access to |G*| values at multiple temperatures but can be at a fixed frequency of 10 rad/s and a load time of 60 seconds. However, the aging levels of the samples tested are required to be constant.

4.2.3 Level 3 Analysis

Similar to Level 2, a Level 3 analysis requires the user to have access to |G*| values at multiple temperatures and a fixed frequency of 10 rad/s and a load time of 60 seconds. However, the aging levels of the samples tested can be a mixture of rolling thin-film oven (RTFO) and pressure aging vessel (PAV) samples.

The PAV procedure exposes the asphalt binder to heat and pressure to simulate in-service aging over a 7 to 10 year period (AASHTO R 28-12, 2012). The RTFO procedure exposes the asphalt binder to elevated temperatures to simulate manufacturing and placement aging (AASHTO T 240-09, 2009). In general, binder tests concerned with in-service pavement performance are performed on samples first aged in a rolling thin-film oven and then in a pressure aged vessel.

4.3 Viscosity-Based ANN Model

Asphalt can be classified as a visco-elastic-plastic material. The viscous property of asphalt is an important part of asphalt material research as it is one of the parameters which controls rutting in a pavement structure (Uzarowski, 2006).

Prior to the implementation of the Superpave mix design method, the viscosity of asphalt binders was the key measure in asphalt mix designs. Asphalt is viscous by nature and its viscosity can be measured by using a Brookfield Viscometer. Over the years, the viscosity of asphalt has been measured using four test methods which measure kinematic viscosity, absolute viscosity, softening point and penetration (Oregon State University, 2012).

Kinematic viscosity is measured by following ASTM D2170 and is essentially the absolute viscosity divided by the density of the asphalt at the temperature of measurement. Kinematic viscosity is measured at a temperature of 135°C which is the typical laydown temperature during paving (ASTM Standard D2170, 2010). Figure 18 illustrates the Kinematic viscosity testing equipment.

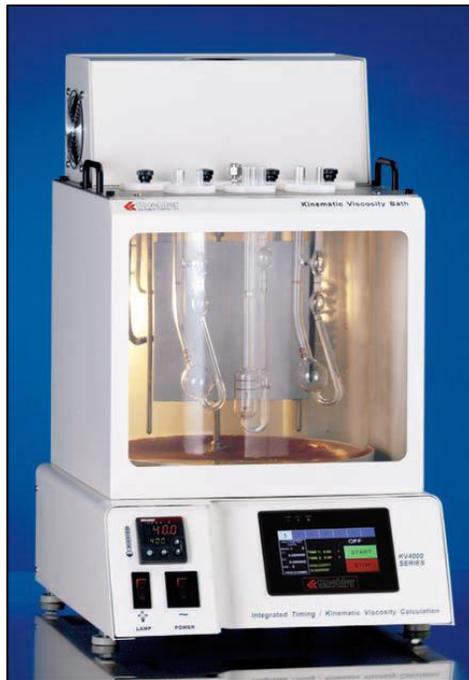


Figure 18: Kinematic Viscosity Test Equipment (Koehler 2006)

The absolute viscosity test method (ASTM D2171) measures the time it takes for a fixed volume of asphalt binder to be drawn up a capillary tube by a vacuum (ASTM Standard D2171, 2010). The

absolute viscosity is typically measured at a temperature of 60°C because it is the maximum pavement surface temperature during the hot summer months in North America. Figure 19 illustrates the absolute viscosity test equipment.



Figure 19: Absolute Viscosity Capillary Tube (Koehler 2006)

The softening point (ring and ball apparatus) temperature method follows ASTM D36 and measures the softening point of an asphalt binder sample. The softening point is reported as the mean of the temperatures at which two disks of bitumen soften enough to allow a 3.5 gram steel ball to fall a distance of 25 mm (ASTM Standard D36, 2012). Figure 20 illustrates the ring and ball apparatus.

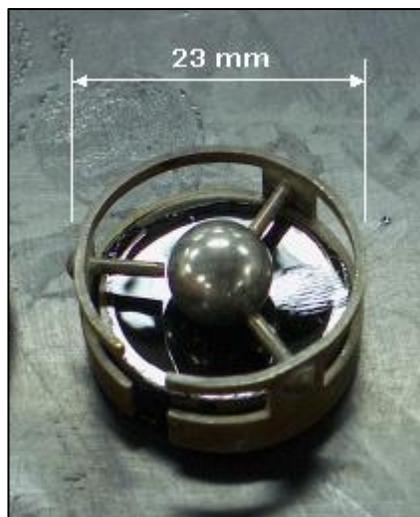


Figure 20: Ring and Ball Apparatus (OSU 2012)

Finally, one of the oldest asphalt tests is the penetration test. The penetration test follows ASTM D5 and essentially measures the depth of penetration of a standard needle into an asphalt binder sample at a fixed temperature and load (ASTM Standard D5, 2006). Figure 21 illustrates the asphalt penetration test equipment.



Figure 21: Asphalt Penetration Test Equipment (Pavement Interactive 2007)

Similar to the G^* -based ANN models, there are three levels of analysis: Level 1, Level 2 and Level 3.

4.3.1 Level 1 Analysis

For a Level 1 analysis, the user is required to enter the intercept of temperature susceptibility relationship (A) and slope of temperature susceptibility relationship (VTS) values into the software. Binder viscosity research has shown that a linear relationship exists when proper transformations are made to temperature and viscosity. This relationship is commonly referred to as the A-VTS relationship (FHWA, 2011).

4.3.2 Level 2 Analysis

If the temperature susceptibility and slope of temperature susceptibility (A-VTS) relationship is unknown, a Level 2 analysis can be performed by entering viscosity measures. Accepted viscosity measurements include: kinematic viscosity, ring and ball temperature and penetration. At least two measures of viscosity must be entered for the software to compute the A and VTS parameters.

4.3.3 Level 3 Analysis

If no viscosity measurements are available, the user can compute the A-VTS relationship using the binder grade of the asphalt. The binder grades can either be Superpave-based, viscosity-based or penetration-based.

4.4 Summary

This chapter provided a summary of the ANNACAP software as well as the three models and various levels of analysis within the program which are capable of predicting dynamic modulus. The three models available in the software are:

- M_R -based
- G^* -based
- Viscosity-based

Each method has different levels of analysis available to the user. Similar to the MEPDG, a Level 1 analysis will be more accurate as specific data is required in order to predict the dynamic modulus of the sample mixture.

No resilient modulus or shear modulus data is available in the C-LTPP database, thus only the Viscosity-based ANN model can be used to predict dynamic modulus using the C-LTPP data. However, provincial agencies may have access to existing resilient modulus or shear modulus data for the mix types typically used.

Chapter 5

Data Analysis

5.1 Data Extraction from the C-LTPP Database

The data used for the ANNACAP analysis was extracted from the C-LTPP database. In its current form, the C-LTPP database is divided into several tables across multiple Microsoft Access databases. The tables relevant to this research were combined into one Access database and queries were developed to extract data from every C-LTPP test section in the database. The data extracted included: measured dynamic modulus results, measured absolute and kinematic viscosity, mix volumetrics, ring and ball softening points and any other data that would help describe a specific asphalt mix design.

The purpose of this data extraction was to be able to obtain enough data in order to perform dynamic moduli predictions using the ANNACAP models and compare the predicted results to the measured dynamic moduli for each C-LTPP test section.

The ANNACAP software allows the user to use three different dynamic modulus prediction models, M_R -based, G^* -based and Viscosity-based. Since the C-LTPP database does not contain any resilient modulus or shear modulus data, the Viscosity-based ANN model was selected for dynamic modulus prediction.

5.1.1 C-LTPP Dynamic Modulus Testing

The C-LTPP database currently contains measured dynamic modulus data for at least one test section in every province. The C-LTPP dynamic modulus testing was completed at the University of Laval (Laval) in partnership with Transports Quebec (MTQ). The test method chosen by Laval was the four points flexural beam test method. The flexural $|E^*|$ values tend to be smaller than the compressive $|E^*|$ as the temperature increases and the loading rate decreases (Witczak et al., 2001). Figure 22 illustrates the test setup.

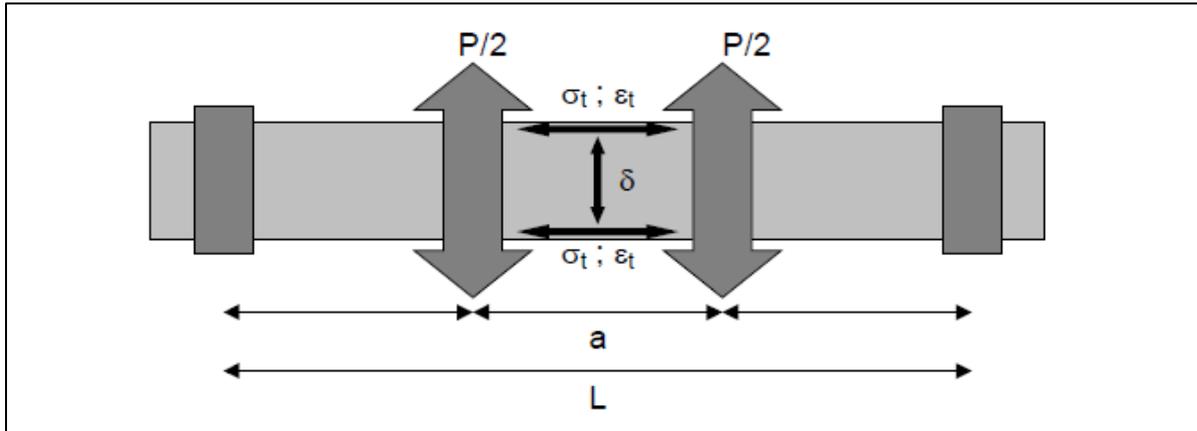


Figure 22: Four Point Flexural Beam Test Diagram (TAC 2004)

All dynamic modulus test samples were extracted in accordance with the “Instruction for Materials Sampling and Shipping for Resilient Modulus Characterization” (C-SHRP, 1999).

The testing frequencies selected differ from the compressive testing frequencies because of the instability of the test setup. Table 4, presents the typical testing frequencies used in the compressive test method and the testing frequencies used in the flexural test method.

Table 4: Compressive and Flexural Testing Frequencies

Compressive Test Frequency (Hz)	Flexural Test Frequency (Hz)
0.1	0.01
0.5	0.03
1	0.1
5	0.3
10	1
25	3
-	10

The test temperatures for both methods also vary and are presented in Table 5.

Table 5: Compressive and Flexural Testing Temperatures

Compressive Test Temperature (°C)	Flexural Test Temperature (°C)
-10	0
4	15
21	30
37	-
54	-

The ANNACAP models predict the dynamic modulus based on the compressive test method, while the measured dynamic modulus results from the C-LTPP database were determined using the flexural test method. Although several testing parameters differ between the two methods, the results can be compared by analyzing the master curves developed from the laboratory test results of each method.

5.1.2 Extraction of Measured Dynamic Modulus Values

The Dynamic Modulus Test Results table (Dyn_Tst) includes physical properties and results of dynamic modulus tests on asphalt concrete samples. Also included in this table are the following data elements: bulk and maximum specific gravity, percent air voids, test temperature, test frequency, average dynamic modulus and average phase angle of tested sample.

A sample of the measured dynamic modulus data extracted from the C-LTPP database is presented in Table 6.

Table 6: Sample C-LTPP Dynamic Moduli Data

C-SHRP ID	Bulk Specific Gravity	Max. Specific Gravity	Air Voids (%)	Test Temperature (°C)	Test Frequency (Hz)	Dynamic Modulus, E* (MPa)	Phase Angle (degrees)
890503	2.340	2.470	5.30	0.05	0.10	7,461	9.5
890503	2.340	2.470	5.30	0.01	1.00	9,120	7.6
890503	2.340	2.470	5.30	0.05	10.00	10,852	6.1
890503	2.340	2.470	5.30	15.08	0.10	3,114	24.0
890503	2.340	2.470	5.30	15.15	1.00	5,247	19.4
890503	2.340	2.470	5.30	30.08	0.10	653	39.1
890503	2.340	2.470	5.30	29.91	1.00	1,496	35.4
890503	2.340	2.470	5.30	30.35	10.00	2,955	27.0

5.1.3 Data Extraction for Viscosity-Based Prediction

The Viscosity-based ANN prediction model was chosen because the C-LTPP database does not contain any resilient or shear modulus data. The Viscosity-based ANN model has three different levels of analysis.

A Level 2 analysis was selected because the temperature susceptibility relationship coefficients were not known. The Level 2 analysis requires at least two measures of viscosity. The C-LTPP database contains data results from all four of the standard viscosity test methods; however, not every asphalt sample was tested using all four methods.

A query was developed to join data from lab samples tested using two tables, AC_Tst 1 and AC_Tst 2. The AC_Tst 1 table contains laboratory test results from asphalt cores and bulk samples taken before and after rehabilitation. The AC_Tst 2 table contains laboratory test results from bulk samples collected directly from the paver during rehabilitation or directly from the plant.

A sample of the query results is presented in Table 7.

Table 7: Sample Queried C-LTPP Data for ANN Analysis

C-SHRP ID	Section	Layer Location	Viscosity @ 60°C (Pa-s)	Kinematic Viscosity @ 135°C (mm ² /sec)	Penetration @ 25°C (mm X 1/10)	Penetration @ 4°C (mm X 1/10)	Ring & Ball Softening Point (°C)
890503	1	Surface	2,219.7	924.3	25	5	59.7
890503	2	Surface	25,674.4	2,046.3	27	5	69.8
890503	3	Surface	2,219.7	924.3	25	5	59.7
890503	4	Surface	25,674.4	2,046.3	27	5	69.8

It is important to note that not every experimental section had sufficient data to be able to run the ANN analysis. Table 8, summarizes the experimental sections that had a sufficient amount of data for input into the ANNACAP software.

Table 8: C-LTPP Sections Containing Sufficient Data for |E*| Prediction

Provincial Agency	C-SHRP ID	Section	Rehabilitation Treatment	Layer Location	Aging Type
British Columbia	820205	1	overlay	Surface	TFOT
British Columbia	820205	2	overlay	Bottom	Unknown
British Columbia	820205	2	overlay	Surface	TFOT
British Columbia	820502	1	overlay	Bottom	Unknown
British Columbia	820502	1	overlay	Surface	TFOT

Provincial Agency	C-SHRP ID	Section	Rehabilitation Treatment	Layer Location	Aging Type
British Columbia	820502	2	overlay	Bottom	Unknown
British Columbia	820502	2	overlay	Surface	TFOT
British Columbia	820605	1	overlay	Surface	TFOT
British Columbia	820605	2	overlay	Surface	TFOT
Manitoba	830403	1	overlay	Surface	TFOT
New Brunswick	840204	1	overlay	Bottom	TFOT
New Brunswick	840204	1	overlay	Bottom	TFOT
New Brunswick	840204	1	overlay	Bottom	TFOT
New Brunswick	840204	1	overlay	Surface	TFOT
New Brunswick	840204	1	overlay	Surface	TFOT
New Brunswick	840204	1	overlay	Surface	TFOT
New Brunswick	840204	1	overlay	Surface	TFOT
New Brunswick	840204	1	overlay	Surface	TFOT
New Brunswick	840204	1	overlay	Surface	TFOT
New Brunswick	840604	4	overlay	Surface	TFOT
New Brunswick	840604	4	overlay	Surface	TFOT
New Brunswick	840604	4	overlay	Surface	TFOT
Nova Scotia	860501	2	overlay	Surface	Unknown
Nova Scotia	860501	3	overlay	Surface	Unknown
Nova Scotia	860603	1	overlay	Surface	Unknown
Nova Scotia	860603	2	overlay	Surface	Unknown
Nova Scotia	860603	3	overlay	Surface	Unknown
Ontario	870102	1	overlay	Bottom	Unknown
Ontario	870505	1	overlay	Surface	Unknown
Ontario	870505	3	overlay	1st Intermediate	Unknown
Ontario	870505	3	overlay	Surface	Unknown
Ontario	870505	4	overlay	Bottom	Unknown
Ontario	870505	4	overlay	Surface	Unknown
Ontario	870701	2	overlay	Surface	Unknown
Quebec	890503	1	overlay	Surface	Unknown
Quebec	890503	2	overlay	Surface	Unknown
Quebec	890503	3	overlay	Surface	Unknown
Quebec	890503	4	overlay	Surface	Unknown
Quebec	890702	1	overlay	Surface	Unknown

The data contained in the “Aging Type” column in Table 8, specifies whether to use a lab-aged or field-aged analysis. Several samples were lab-aged using the thin-film oven test (TFOT) and as a result were run through the ANNACAP software using the lab-aged data inputs.

Since the ANNACAP software was developed in the United States, there are several fields requiring the data to be in Imperial units. All data requiring imperial units were converted and entered into the ANNACAP software and subsequently converted back to metric units for presentation purposes.

5.2 Quality Control (QC) Checks

Currently, the C-LTPP database does not have a data quality rating system. However, it is understood that all data resident in the C-LTPP database has passed a rudimentary QC check prior to data entry. All collected C-LTPP data was checked against typical ranges and any data field that did not meet the requirements was nulled prior to entry.

The ANNACAP software includes built-in Quality Control (QC) checks used to verify data quality. There are seven built-in QC levels. After each QC check, each line of data is assigned one of three output values: “A”, “C” or “F”.

An “A” grade is given to data that has successfully passed the QC check. A “C” grade is only given to the predicted dynamic moduli and denotes a questionable prediction. Data with a “C” grade can still be used; however, the data should be used with caution. Finally, an “F” grade is given to data that has not passed the QC check. Table 9 summarizes the quality control checks in the ANNACAP software.

Table 9: QC Check Summary

QC Check#	Summary
1	Checks user inputs against standard ranges
2	Assesses the predicted $ E^* $ trend as a function of temperature and frequency
3	Checks the percentage difference of the predicted $ E^* $ at the same temperature but varying frequencies
4	Assesses the predicted $ E^* $ trend as a function of temperature at a constant frequency
5	Compares the time-temperature shift factors to typical values
6	Compares the predicted $ E^* $ values to a typical range
7	Calculates fitting statistics for the master curve and compares them to AASHTO requirements ($R^2 > 0.99$ and $S_e/S_y < 0.05$)

The following sections will provide the details of the ANNACAP QC checks.

5.2.1 QC Check #1

Similar to several other initial data quality checks, the first QC check considers the typical input range and inspects for violations to that range. The input ranges for the viscosity-based model, used for $|E^*|$ predictions, are shown in Table 10.

Table 10: QC#1 - Input Data Ranges (FHWA 2010)

Model	Range	f_R (Hz)	Viscosity (10^9 P)	VMA (%)	VFA (%)	Log $ E^* $ (kPa) [psi]
Viscosity-based	Min	0.01	1.99E-06	9.51	32.82	24.27 [3.52]
	Max	25	2.70E+01	34.64	95.07	47.02 [6.82]

5.2.2 QC Check #2

The second QC check assesses the trends of the dynamic modulus, $|E^*|$, as a function of temperature and frequency. In general, the dynamic modulus will decrease with an increase in temperature and a decrease in loading frequency. Any predicted values that violate this trend will fail the QC check.

5.2.3 QC Check #3

The third QC check uses an equation to calculate the percentage of difference of the predicted dynamic modulus between 0.1 Hz at one temperature and 25 Hz at the next warmest temperature. The equation used is as follows:

$$\% \text{ Difference} = \frac{\text{Lower Temperature @ 0.1 Hz} - \text{Higher Temperature @ 25 Hz}}{\text{Higher Temperature @ 25 Hz}} \quad (5.3)$$

The acceptable percentage differences for specific temperatures are as follows:

- From -10°C to 4.4°C – $\pm 25\%$;
- From 4.4°C to 21.1°C – $+50\%$ and -75% ;
- From 21.1°C to 37.7°C – $+50\%$ and -75% ; and
- From 37.7°C to 54.4°C – $+50\%$ and -75%

5.2.4 QC Check #4

Similar to QC Check #2, the fourth QC check assesses the trends of the predicted dynamic modulus as temperature increases, but at a constant loading frequency of 0.1 Hz. The dynamic modulus tested at the same frequency should decrease with an increase in temperature.

5.2.5 QC Check #5

The fifth QC check compares the predicted time-temperature shift factors to typical values. The goal of this QC check is to anticipate issues with the master curve generation process, therefore only shift factors at the extreme testing temperatures are evaluated. The typical time-temperature shift factor ranges are shown below at the two extreme testing temperatures:

- At -10°C – $3 < \log(a_T) < 7$
- At 54.4°C – $-5 < \log(a_T) < -2$

5.2.6 QC Check #6

The sixth QC check compares the predicted dynamic modulus value to a typical range. Table 11 presents the limiting dynamic modulus values used for this QC check.

Table 11: QC#1 - Input Data Ranges (FHWA 2010)

Model	Upper Limit (MPa) [psi]	Lower Limit (MPa) [psi]
Viscosity-based	40,600 [5,888,437]	22.830 [3,311.311]

5.2.7 QC Check #7

Similar to QC Check #5, the seventh QC check attempts to anticipate issues with the master curve generation process. The ANNACAP software calculates fitting statistics every time a master curve is generated. According to AASHTO PP-62, the explained variance (R^2) should be greater than 0.99. The ratio of the standard error to standard deviation (S_e/S_y) should be less than 0.05 (AASHTO PP 62-09, 2009). The equations used to calculate these fitting statistics are as follows:

$$S_e = \frac{1}{23} \sum_1^n \sqrt{[(\log|E^*|_{ANN})_i - (\log|E^*|_{fit})_i]^2} \quad (5.4)$$

Where:

23 = number of temperature/frequency combinations used minus the number of fitting parameters minus 1.

$(\log|E^*|_{ANN})_i$ = logarithm of the modulus determined from the ANN models at a particular temperature frequency combination.

$(\log|E^*|_{fit})_i$ = logarithm of the modulus determined from the optimized sigmoidal fit.

$$S_y = \frac{1}{29} \sum_{i=1}^n \sqrt{[(\log|E^*|_{ANN})_i - (\log|E^*|)_{avg}]^2} \quad (5.5)$$

Where:

29 = number of temperature/frequency combinations used minus 1.

$(\log|E^*|_{avg})_i$ = logarithm of the average modulus determined from the ANN models for a given layer.

$$R^2 = 1 - \frac{(23)S_e^2}{(29)S_y^2} \quad (5.6)$$

5.3 Predicted Dynamic Modulus Results, |E*|

As shown in Table 8, not every test section had sufficient data for input into the ANNACAP prediction models. Test sections determined to have sufficient data were extracted from the C-LTPP database and formatted for input into the software. The ANNACAP software returned approximately 4,200 records. However, only a small percentage of that data received an “A” grade indicating successful completion of all QC level checks. Less than 20% of the records were given a data quality grade of “A”.

The majority of records failed QC Checks #5 and #7. Both of these checks verify the quality of the master curve and thus are the most important quality checks. Approximately 60% and 80% of the total records failed QC Checks #5 and #7, respectively. Only data with a grade level of “A” was used for further data analysis and comparisons to the measured dynamic modulus values in the C-LTPP database.

A total of four test sections had useable predicted dynamic modulus data. The test sections with predicted dynamic moduli values that successfully passed all quality control checks are presented in Table 12.

Table 12: C-LTPP Sections with “A” Grade Predicted |E*|

Provincial Agency	C-SHRP ID	Section	Rehabilitation Treatment	Layer Location	Aging Type
British Columbia	820205	1	overlay	Surface	TFOT
Manitoba	830403	1	overlay	Surface	TFOT
Quebec	890503	1	overlay	Surface	Unknown
Quebec	890503	3	overlay	Surface	Unknown

5.4 Summary

Viscosity and volumetric data were extracted from the Materials module in the C-LTPP database and used for a Level 2 analysis using the Viscosity-based ANN model. The goal of this data analysis is to compare the predicted dynamic modulus values to the measured dynamic modulus values in the C-LTPP database to verify accuracy of the ANN models.

An issue with the measured dynamic modulus data was identified. The existing measured data was tested using a non-standard flexural beam dynamic modulus test method. The ANN models were developed and calibrated with the dynamic modulus compressive test method. However, the data can still be compared by comparing the master curves for each sample.

After data extraction, it was noted that not all test sections had sufficient amounts of data to be able to run the prediction models. Test sections in British Columbia (820205, 820502 and 820605), Manitoba (830403), New Brunswick (840204), Nova Scotia (860603), Ontario (870102, 870505 and 870701), and Quebec (890503 and 890702) were the only sections in the C-LTPP database to have sufficient data for analysis.

The analysis was completed using the ANNACAP software and its built-in QC checks. Only data receiving a grade of “A” would be accepted. However, only four sections received acceptable data quality grades:

- Section 820205-1, located in British Columbia;
- Section 830403-1, located in Manitoba;

- Section 890503-1, located in Quebec; and
- Section 890503-3, located in Quebec.

Unfortunately, only two of these four sections (830403-1 and 890503-1) had measured dynamic modulus data available in the C-LTPP database for comparison. Sampling for dynamic modulus testing was only carried out on one test section per province due to a fixed budget. The following sections present the methods and results of the comparisons between the measured and predicted dynamic modulus for sections 830403-1 and 890503-1.

Chapter 6

Comparison Results

6.1 Measured Dynamic Moduli – C-LTPP Database

A project named, the “Dynamic and Resilient Modulus Characterization of C-LTPP Pavement Materials”, was completed in January of 2004 by Laval in partnership with the MTQ. In addition to the sampling and testing performed as part of this project, master curve parameters were determined for every test section at a reference temperature of 15°C. Delta, alpha, beta and gamma (δ , α , β , and γ) are the sigmoidal function regression parameters from equation 2.9 in Chapter 2. These parameters are presented in Table 13. This table also provides the coefficient of determination, or explained variance, of the models (R^2) as well as the root of mean square errors (RMSE) for the dynamic modulus master curve relationship.

Table 13: C-LTPP Dynamic Modulus Master Curve Parameters (TAC 2004)

Section	δ	α	β	γ	R^2	RMSE
810404	1.69	2.50	-1.44	-0.69	1.00	0.024
820605	0.50	3.94	-1.43	-0.46	1.00	0.040
830403	0.75	3.35	-1.45	-0.50	1.00	0.030
830801	0.99	3.18	-1.62	-0.57	1.00	0.019
840604	-0.16	4.34	-1.88	-0.41	1.00	0.011
850601	0.69	3.51	-1.59	-0.47	1.00	0.021
870701	0.73	3.46	-1.66	-0.45	1.00	0.015
880203	0.94	3.20	-1.51	-0.55	1.00	0.020
890503	1.14	2.97	-1.89	-0.53	1.00	0.020
890702	0.95	3.23	-1.76	-0.46	1.00	0.033
900803	0.73	3.52	-1.59	-0.51	1.00	0.018

An R^2 equal to 1 indicates that the sigmoidal model sufficiently defines the relationship between the dynamic modulus and the testing frequency (TAC, 2004). The RMSE is a good indication of how well the tested dynamic moduli fit the master curve for each data set. The RMSE for all mixes tested is less than 5% and indicates a good fit.

The time-temperature shift factor regression parameters were also calculated at a reference temperature of 15°C and are presented in Table 14. Again, the “a” and “b” parameters are determined by regression analysis of the shift factor equation.

Table 14: C-LTPP Time-Temperature Shift Factor Regression Parameters (TAC 2004)

Section	a	b	R ²	RMSE
810404	0.14	-2.11	1.00	0.05
820605	0.16	-2.61	1.00	0.24
830403	0.15	-2.33	1.00	0.18
830801	0.14	-2.25	1.00	0.12
840604	0.15	-2.48	0.99	0.23
850601	0.16	-2.54	0.99	0.24
870701	0.16	-2.68	0.99	0.26
880203	0.16	-2.44	1.00	0.11
890503	0.14	-2.17	1.00	0.04
890702	0.15	-2.36	1.00	0.11
900803	0.15	-2.35	1.00	0.18

Similarly, the R² equal to 1 indicates a well-defined relationship between the shift factor and the temperature. In this case, the RMSE for the majority of the tested mixes are typically between 10% and 25% indicating a greater degree of error and should be used with caution.

6.2 Predicted Dynamic Moduli - ANNACAP

The ANNACAP software predicted dynamic modulus values for three test sections:

- Section 820502 on Hwy 99 near Surrey, British Columbia;
- Section 830403 on PTH 2 near Wawanesa, Manitoba; and
- Section 890503 on Hwy 40 near Pointe aux Trembles, Quebec.

The predicted dynamic moduli for the sections above were given a data quality grade of “A” and can be considered of high quality since the data successfully passed all seven of the built-in ANNACAP quality control checks described in Chapter 5.

The master curve parameters were determined using linear regression at a reference temperature of 21.1°C and following the AASHTO PP-62 procedure. The parameters are presented in Table 15.

Table 15: ANNACAP Dynamic Modulus Master Curve Parameters

Section	δ	α	β	γ	R^2	RMSE
820502	3.54	3.18	-0.71	0.42	1.00	0.006
830403	3.55	3.15	-0.76	0.43	1.00	0.003
890503	3.52	3.18	-0.50	0.42	1.00	0.008

The time-temperature shift factor regression parameters were determined by the ANNACAP software at a reference temperature of 21.1°C and are presented in Table 16.

Table 16: ANNACAP Time-Temperature Shift Factor Fitting Coefficients

Section	α_1	α_2	α_3
820502	0.0021	-0.2340	4.004
830403	0.0015	-0.2073	3.695
890503	0.0013	-0.1727	3.064

6.3 Measured and Predicted Dynamic Moduli Comparison

The measured and predicted dynamic modulus master curve parameters are known; therefore, the master curves can be plotted for each mix. However, the measured master curve parameters were determined at a reference temperature of 15°C, while the predicted master curve parameters were determined at a reference temperature of 21.1°C. In order to compare the two master curves, the parameters need to be determined for the same reference temperature.

As part of NCHRP 09-29, the Simple Performance Tester for Superpave Mix Design Project, an Excel spreadsheet was developed, named Master Solver Version 2.2, capable of calculating the master curve parameters using a modified version of the MEPDG master curve equation (Bonaquist and Christensen, 2005). This spreadsheet allows a user to determine the required parameters at any desired temperature. Thus, this spreadsheet was used to calculate the C-LTPP measured dynamic modulus master curve parameters at a reference temperature of 21.1°C.

The Master Solver Excel spreadsheet was used to determine the master curve parameters at a reference temperature of 21.1°C. The regression statistics are presented in Table 17.

Table 17: Master Solver Master Curve Statistics

Section	R ²	S _e	S _y	S _e /S _y
830403	0.99	0.043	0.615	0.07
890503	0.98	0.049	0.489	0.10

The explained variance (R²), standard error of estimate (S_e), standard deviation of the average measured data (S_y), and the ratio of the standard error to standard deviation (S_e/S_y) are provided in Table 17 as part of the Master Solver process. As per AASHTO PP 62-09, the S_e/S_y ratio should be less than 0.05 and the R² should be greater than 0.99 (AASHTO PP 62-09, 2009).

It is important to note that Section 820502 was not included in the C-LTPP dynamic modulus characterization study performed by Laval in 2004; therefore no comparisons can be made between the measured and predicted dynamic moduli for that test section.

6.3.1 Section 830403 – Dynamic Modulus Master Curves

Dynamic modulus master curves were developed for both the C-LTPP measured samples as well as the predicted ANN data. The Master Solver master curve statistics for the measured values do not indicate a very strong relationship as the standard error to standard deviation ratio (S_e/S_y) is not less than 0.05. This may be attributed to the test method used to measure the dynamic modulus. Typically, the samples are tested at five temperatures; however the four-point flexural beam method used only measured the dynamic modulus at three different temperatures. The explained variance, R², was determined to be 0.99 and indicates a good fit, however does not meet the AASHTO standards of greater than or equal to 1.0.

The dynamic modulus master curve for the C-LTPP measured values is illustrated in Figure 23.

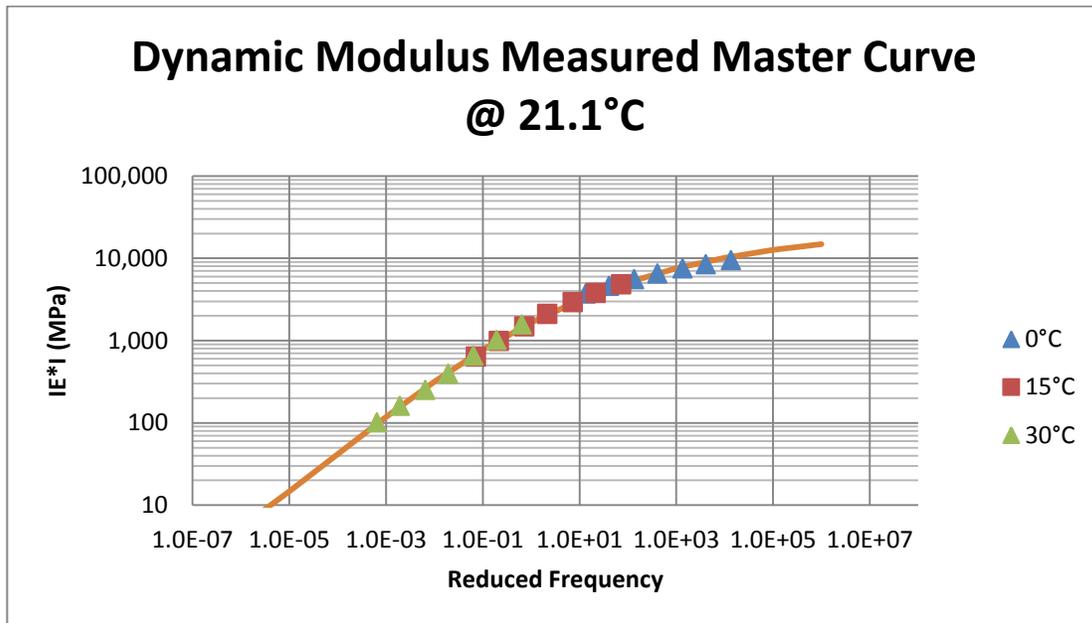


Figure 23: Section 830403 – Measured Master Curve

The dynamic modulus master curve for the ANNACAP predicted values is illustrated in Figure 24.

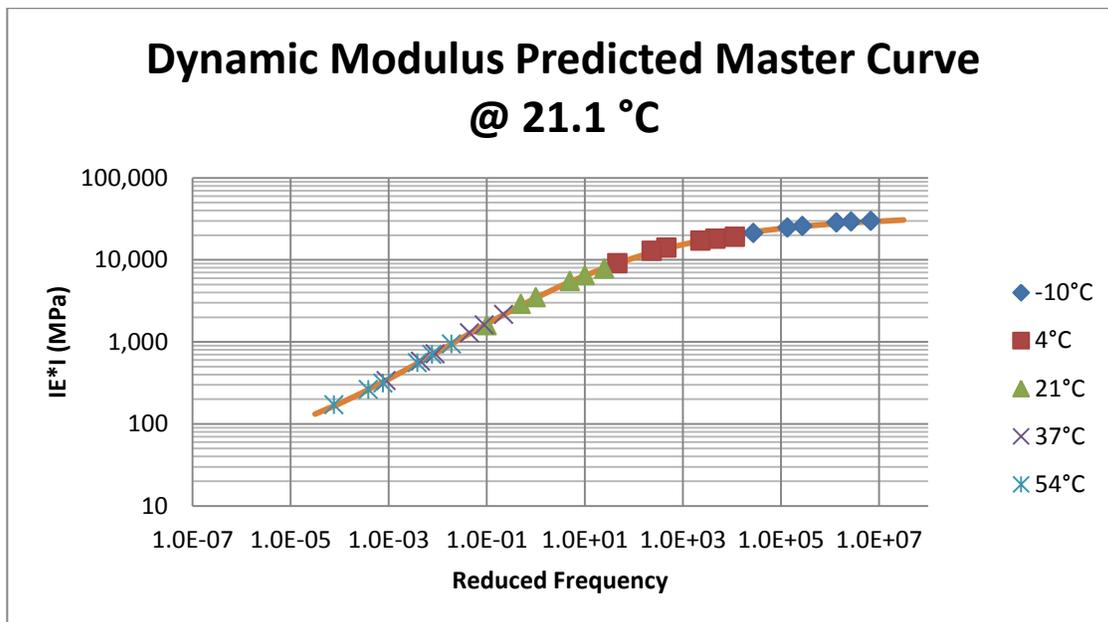


Figure 24: Section 830403 - Predicted Master Curve

Since each master curve was developed at a reference temperature of 21.1°C, they can be compared by plotting each curve on the same graph. Both master curves are illustrated in Figure 25.

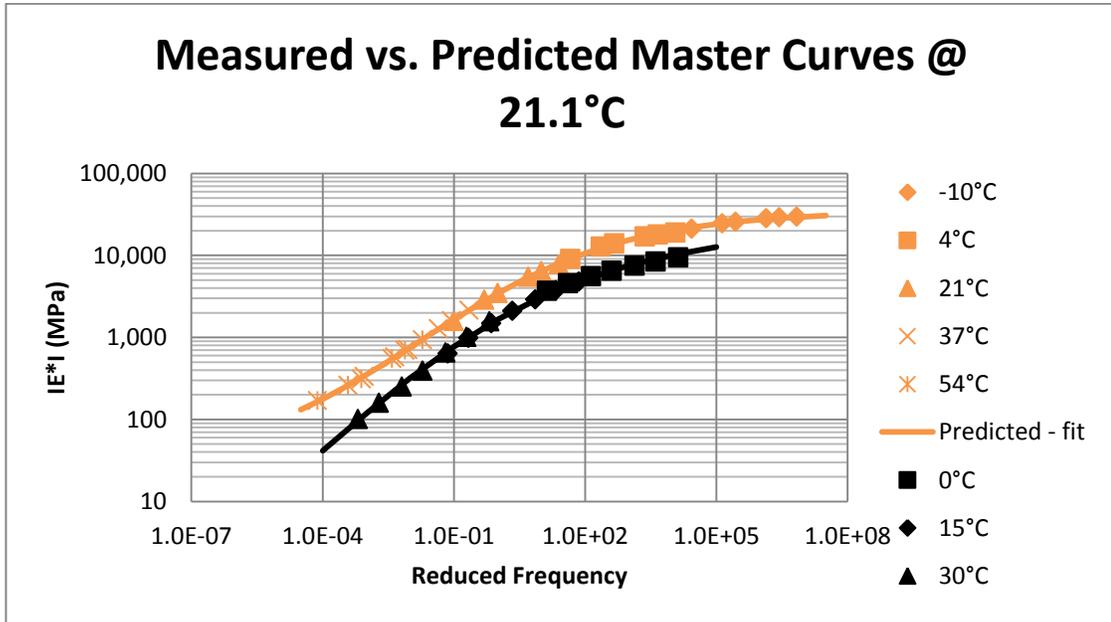


Figure 25: Section 830403 - Measured vs. Predicted Master Curves

As discussed in Section 2.3, the flexural dynamic modulus test typically produces lower dynamic moduli than the compression test. This relationship is demonstrated in Figure 25, as the predicted dynamic moduli (compression) are generally higher than the measured dynamic moduli (flexural) at the same temperature and loading frequency.

Differences in the master curve shapes can also be seen, specifically at the extreme ends of the curves. This can be attributed to the lack of measured results at the extreme testing temperatures (-10°C and 54°C).

In order to statistically compare the two sets of data, a Student's t-Test was performed on the two data sets. However, since the two data sets were tested under different conditions, temperatures and frequencies, the outlier testing temperatures (-10°C and 54°C) were excluded in an effort to limit the amount of bias in the analysis. The objective was to determine if the two data sets were statistically different from each other. In this case, the Null Hypothesis is that the means of the two data sets are equal. The alternative hypothesis is that the means of the two data sets are statistically different.

A two-sample Student's t-Test was performed assuming unequal variances and a 95% confidence interval. The results are as follows:

- Two-sample $t(23) = 2.07$, $p = 0.035$
- Reject Null-Hypothesis, the two data sets are statistically different

6.3.2 Section 890503 – Dynamic Modulus Master Curves

Similar to Section 830403, dynamic modulus master curves were developed for both the C-LTPP measured samples as well as the predicted ANN data. Also, the Master Solver master curve statistics for the measured values do not indicate a very strong relationship as the standard error to standard deviation ratio (S_e/S_y) is not less than 0.05. Additionally, the R^2 was determined to be 0.98 and indicates a reasonably good fit, but weaker than the Section 830403 data set. Similar to the previous test section, the explained variance does not meet the AASHTO standards of greater or equal to 1.0.

The dynamic modulus master curve for the C-LTPP measured values is illustrated in Figure 26.

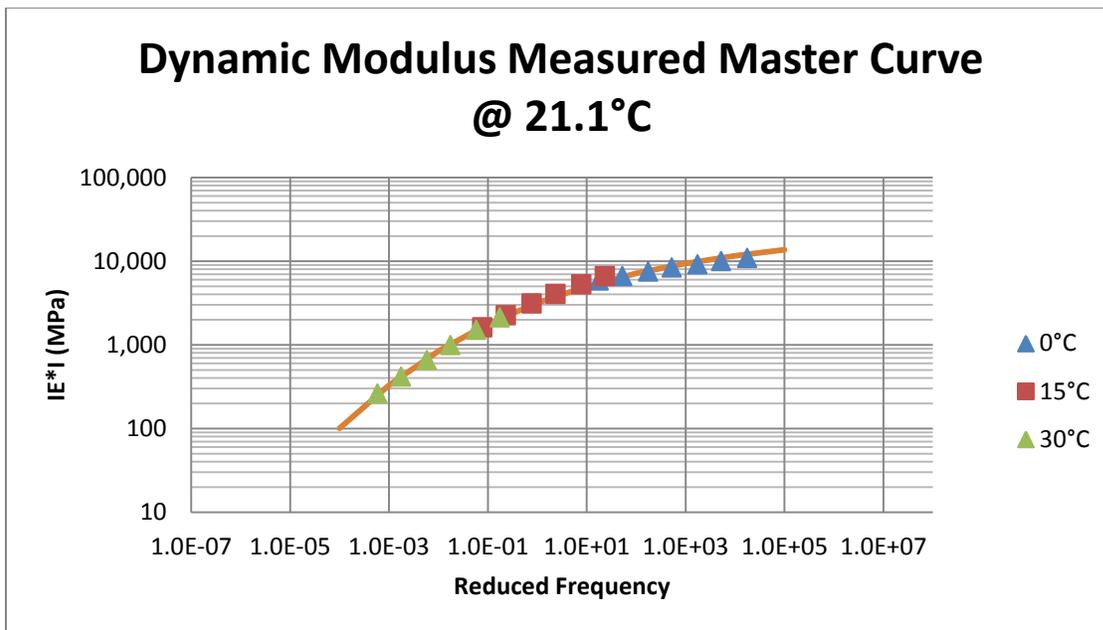


Figure 26: Section 890503 – Measured Master Curve

The dynamic modulus master curve for the ANNACAP predicted values is illustrated in Figure 27.

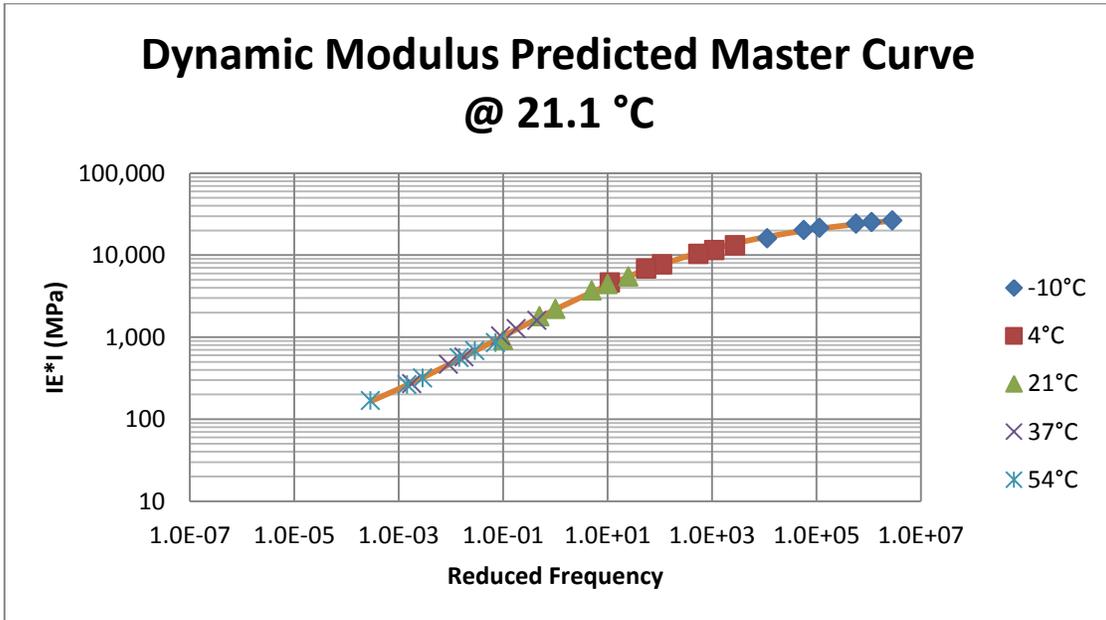


Figure 27: Section 890503 – Predicted Master Curve

Since each master curve was developed at a reference temperature of 21.1°C , they can be compared by plotting each curve on the same graph. Both master curves are illustrated in Figure 28.

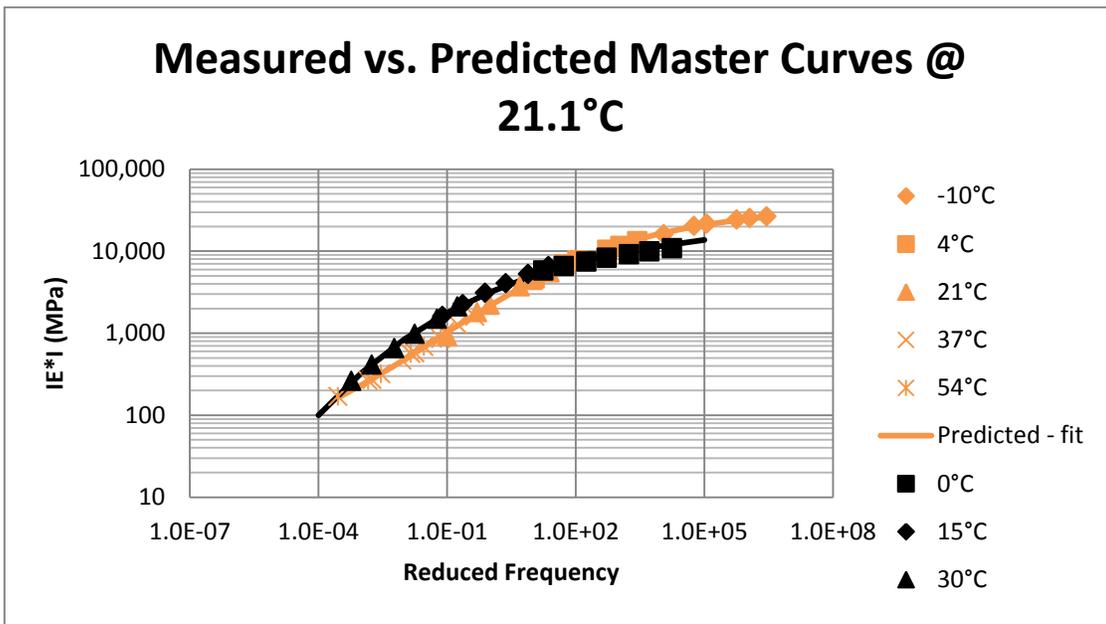


Figure 28: Section 890503 - Measured vs. Predicted Master Curves

The flexural dynamic moduli is typically lower than compression tested dynamic moduli, the measured dynamic moduli (flexural) in this case are generally higher than the predicted dynamic moduli (compression) from approximately 0°C to 30°C at the same loading frequency. However, the measured dynamic moduli are only slightly higher than the predicted values.

Similar to Section 830403, there are differences in the master curve shapes, even more so at the extreme ends of the curves. Again, this can be attributed to the lack of measured results at the extreme testing temperatures (-10°C and 54°C).

Similar to the statistical analysis of the previous test section above, the outlier testing temperatures were removed from the analysis. A two-sample Student’s t-Test was performed assuming unequal variances and 95% confidence interval. The results are as follows:

- Two-sample $t(33) = 2.03$, $p = 0.85$
- Accept Null-Hypothesis, the two data sets have statistically equal means

6.4 Additional Viscosity-Based ANN Model Verification

Supplementary measured dynamic modulus data was obtained from two University of Waterloo doctoral theses that involved extensive asphalt material testing (Uzarowski 2006, El-Hakim 2013). This additional data was used to compare to the predicted dynamic moduli from the ANNACAP viscosity-based ANN model. The measured dynamic moduli results were from six mixes commonly used in Ontario. The mixes are detailed in Table 18.

Table 18: Supplementary Measured Dynamic Modulus Mix Data

Mix Type	Binder Grade
Hot Laid 3 (HL3)	PG 58-28
Superpave 12.5 (SP 12.5)	PG 64-28
Superpave 19 (SP 19 A)	PG 64-28
Superpave 19 (SP 19 B)	PG 64-28
Superpave 19 (SP 19 C)	PG 70-28
Superpave 25 (SP 25)	PG 58-28

The first column in Table 18 describes the type of the bituminous mixture. Prior to the use of performance-graded (PG) asphalt binders used in Superpave mixes, an HL3 mix was most often used in the surface lift of the majority of asphalt pavements throughout Ontario. The remaining five mixes

are currently used throughout Ontario as part of the MTO’s Superpave program. An SP 12.5 mix is most often used in the surface lift of an asphalt pavement, while SP 19 and SP 25 mixes are most often used in the base lift of an asphalt pavement.

The binder grade, or PG-grade, of a bituminous mixture specifies the performance-based grade of the asphalt binder used in the mix (OHMPA, 1999). The PG-grades of the various mixtures are provided in Table 18.

6.4.1 Dynamic Modulus Prediction of Supplementary Mixture Data

The supplementary mixes were entered into ANNACAP for dynamic modulus prediction. The purpose of this was to compare the predicted values against the measured values using the same compression testing methodology. Asphalt mixes tested for dynamic modulus and predicted at the same testing temperatures and frequencies permits for a less biased comparison. Since no viscosity test data was available for any of the supplementary mixes, a Level 3 viscosity-based ANN model was used in the ANNACAP prediction.

The explained variance, R^2 , was determined for the measured and predicted dynamic modulus data and illustrated in graphical plots for each mixture. A two-sample Student’s t-Test assuming unequal variances was performed for each asphalt mixture at the same testing temperature at a confidence interval of 95%. The objective was to determine if the two data sets were statistically different from each other. In this case, the Null Hypothesis is that the means of the two data sets are equal. The alternative hypothesis is that the means of the two data sets are statistically different. The result of the statistical analysis is shown in Table 19. The graphical plots are included in Appendix B.

Table 19: Statistical Analysis of Supplementary Mix Predictions

Mix Type	Binder Grade	R^2	Student’s t-Test: p-value Testing Temperature				
			-10°C	4.4°C	21.1°C	37.8°C	54.4°C
Hot Laid 3 (HL3)	PG 58-28	0.95	0.10	0.31	0.82	0.10	0.062
Superpave 12.5 (SP 12.5)	PG 64-28	0.99	0.13	0.44	0.45	0.091	0.041
Superpave 19 (SP 19 A)	PG 64-28	0.99	0.043	0.32	0.61	0.16	0.77
Superpave 19 (SP 19 B)	PG 64-28	0.96	0.087	0.57	0.79	0.10	0.032
Superpave 19 (SP 19 C)	PG 70-28	0.93	0.013	0.13	0.078	0.46	0.54
Superpave 25 (SP 25)	PG 58-28	0.99	0.36	0.20	0.058	0.0039	0.0021

The results of the statistical analysis suggest a good relationship between measured and predicted dynamic modulus values, however the Student's t-Test indicated variation between sample means at several testing temperatures. This is most likely due to the fact that the samples were compared at the same testing temperature but over multiple testing frequencies. Ideally, several sample mixtures would be compared at the same temperature and frequency; however additional data was not available.

6.5 Summary

The master curves for each test section and data type were plotted. Statistical analysis on the measured and predicted dynamic modulus C-LTPP data was not conclusive and indicated large variances in the data sets. This variation was attributed to the differences in the test methods, temperatures and frequencies in the comparisons, especially at the extreme ends of the master curves.

Although it was only possible to predict dynamic moduli for two C-LTPP test sections, dynamic modulus master curves were developed for at least one test section in every province as part of the dynamic and resilient modulus characterization project carried out by Laval under a C-LTPP project. As a result of this previous research, several mixes have already been characterized and can be used for a Level 1 analysis in the MEPDG. The only caveat being that Superpave mixes were not included in this research as Superpave was not implemented nation-wide until after the C-LTPP project was underway. However, the ANN models used in the ANNACAP software were developed using several different types of mixes, including Superpave mixes as they were included in US-LTPP test sections.

In general, the predicted dynamic modulus values were difficult to statistically compare to the C-LTPP measured results due to the different testing conditions. Ideally, a more accurate comparison can be done using dynamic modulus values measured by using the compression test method to the predicted results. Supplementary data was extracted from prior research at the University of Waterloo and used for comparison purposes.

The supplementary data indicated very strong relationships between the measured and predicted values using a Level 3 viscosity-based ANN prediction. However, a Student's t-Test suggested variation between the means of the data sets analyzed.

The MTO released an interim document specifying the input values to be used for MEPDG analysis throughout the province (MTO, 2012). The document specifies the use of an "Input Level 3" selection for dynamic modulus, which is an option in the DARWin-ME software to use the program's

default values for Level 3 analysis. The Level 3 analysis uses one of two Witczak equations (Equations 2.3 and 2.4) for predicting dynamic modulus based on mixture volumetrics and aggregate gradations. As presented in Chapter 2, the ANN predicted dynamic moduli were found to be more accurate than all previously developed models, including both of Witczak's prediction models (FHWA, 2011). One of the three ANN models can be used to predict dynamic moduli, as demonstrated by using existing C-LTPP volumetric data for dynamic moduli prediction, to be used for a Level 1 analysis in the MEPDG.

Chapter 7

Conclusions and Recommendations

7.1 Summary

As part of this thesis, the literature review revealed that pavement design in North America is shifting towards a mechanistic-empirical based design methodology, specifically using the newly developed MEPDG. Pavement performance databases are an important factor in the development and calibration of the models used in the MEPDG. For example, the ANN prediction models used for dynamic modulus prediction in this thesis were developed using existing performance data in the US-LTPP database.

A comprehensive review of the C-LTPP database demonstrated that there is an abundance of performance data specific to Canadian climates, materials and traffic. With a few enhancements, as recommended in Chapter 3, the C-LTPP database can be transformed into a more user-friendly tool that could be used for future research in pavements. Several other data elements are also available for research use in the C-LTPP database which may be of interest to provincial agencies and municipalities in the on-going effort to calibrate the MEPDG to local conditions. These data elements include: climatic data, traffic data, roughness data, distress data and material testing data. The C-LTPP database contains historic climate and traffic data as well as in-service climate and traffic data during the service lives of each of the experiments. Pavement performance data collected during a section's service life such as roughness, distress and material testing data can also aid in the calibration of local models. However, the only observed limitation of the C-LTPP database is that the experiments were limited to asphalt overlays.

The US-LTPP database is an example of a more comprehensive pavement performance database which includes overlays as well as new construction and various types of construction materials and methods including both asphalt and concrete. It is important to note that the US-LTPP database has several experiments and test sections scattered throughout every province in Canada.

The dynamic modulus is an essential property that defines the stiffness characteristics of a Hot Mix Asphalt (HMA) mixture as a function of both its temperature and rate of loading. $|E^*|$ is also a primary material property input required for a Level 1 analysis in the MEPDG. In Ontario, the current practice is to use the recommended default inputs for dynamic modulus, or a Level 3 MEPDG analysis. Instead of using the default inputs, this thesis has shown that it is possible to use the ANN

prediction models to predict dynamic modulus so that a Level 1 analysis can be performed. The type of model used will depend on the available mix data: M_R -based, G^* -based or viscosity-based.

The dynamic modulus values predicted using the Level 2 viscosity-based ANN model in the ANNACAP software showed a good correlation to the measured dynamic modulus values for two C-LTPP test sections. These findings support previous research findings done during the development of the ANN models. The ANN models can be used as an alternative to the MEPDG default predictions (Level 3 analysis) and to develop the master curves and determine the parameters needed for a Level 1 MEPDG analysis.

Supplemental asphalt mixes were also analyzed using the ANNACAP Level 3 viscosity-based model and compared to measured results from other research projects. Statistical analysis indicated a very strong relationship between measured and predicted values, however the sample means were difficult to analyze due to a lack of data.

The viscosity-based prediction model requires the least amount data in order to run a prediction. A Level 2 analysis requires mix volumetric data as well as viscosity testing and a Level 3 analysis only requires the PG grade of the binder used in the HMA. In summary, Both the Level 2 and Level 3 viscosity-based model results demonstrated strong correlations to measured values indicating that either would be a suitable alternative to dynamic modulus laboratory testing.

The ANN models used in this research were released to the public in the Fall of 2011 and are still a fairly new concept in pavement research. Further research needs to be done on comparing dynamic moduli determined using the compression test method to dynamic moduli predicted using the ANN models. Further research is being done on the prediction of dynamic modulus throughout North America. At the time of writing this paper, research on the characterization of Superpave mixes is underway at the Centre for Pavement and Transportation Technology (CPATT) located at the University of Waterloo. The goal of this research is to characterize the mix properties of several standard Superpave mixes used in pavement designs throughout Ontario. In the future, this research can be used to create a better data set for comparison to ANN predicted values.

This thesis has shown that there is still valuable data that is currently stored in the C-LTPP database. Dynamic modulus testing is expensive and time-consuming; as a result there is an abundance of research on different methods of predicting dynamic modulus values for a specific mix.

Existing mix volumetric data can be used in conjunction with ANN models to develop master curve parameters and master curves for use in a Level 1 MEPDG analysis.

7.2 Recommendations

The new MEPDG design methodology is the future of pavement design and research in North America. Current MEPDG analysis practices across the country use default inputs for the dynamic modulus. However, dynamic modulus laboratory characterization of asphalt mixes across Canada is time consuming and not very cost-effective. Further development and use of ANN models in dynamic modulus prediction will have widespread benefits.

Although statistical analysis indicated strong relationships in some of the data sets analyzed, not all statistical comparisons were favorable. It is believed that if more sample data was available for analysis, statistical comparisons would be more consistent. Based on the results of this study, the following recommendations are presented and areas for future research of ANN prediction models are presented:

- The C-LTPP database contains a large amount of useful data that can be extracted and used by researchers to aid with MEPDG local calibration. More specifically, climate, traffic, roughness, distress and material testing data are available for every test section and could be used for calibration purposes.
- The C-LTPP database should be merged into a single Microsoft Access database to make it more user-friendly.
- Additional dynamic modulus testing should be completed using the standard AASHTO test method for dynamic modulus testing should the funds be available.
- Any future dynamic modulus mix characterization should have a component included for comparison of dynamic modulus prediction models. At least four to five samples of every mix should be tested to provide for a better data set than what is currently available.
- Each of the three ANN prediction models should be evaluated and compared using several different asphalt mixes to determine which model is the most effective.
- All three levels of dynamic modulus inputs in the current version of the MEPDG should be compared to the ANN prediction models by running analyses on multiple pavement sections, and possibly taking advantage of existing US-LTPP laboratory test data.

- With additional research the ANN prediction models should be considered for implementation into the MEPDG in addition to the existing Witzak models.

Appendix A
Extracted C-LTPP Data

Table A.1: C-LTPP Viscosity Data Extraction

C-SHRP ID	Section	Sample Code	Layer Location	Kinematic Viscosity @60C(mm2/sec)	Viscosity @60C(Pa-s)	Kinematic Viscosity @135C(mm2/sec)	Penetration @25C(mm X 1/10)	Penetration @4C(mm X 1/10)	Ring & Ball Softening Point(°C)
820205	1	BA60	Surface		112.9	259	72	6	45
820205	2	BA64	Bottom		118.5	267	70	7	45.5
820205	2	BA62	Surface		143.6	289	72	5	45
820502	1	BA51	Bottom		51.2	153	120	10	43.5
820502	1	BA54	Surface		108.6	277	80	5	42.5
820502	2	BA52	Bottom		329.6	345	38	3	51.5
820502	2	BA55	Surface		133	305	88	6	44
820605	1	BA57-2	Surface		146.5	293	64	7	43.5
820605	2	BA58	Surface		139.5	298	70	6	43
830403	1	BA01	Surface		398.2	535	61	9	50.5
840204	1	BA04-1	Bottom	1298		289	72	46	47
840204	1	BA06-1	Bottom	1445		283	81	50	45
840204	1	BA05-1	Bottom	1332		283	95	57	43
840204	1	BA01-2	Surface	4882		528	40	26	53
840204	1	BA02-2	Surface	6307		568	38	30	57
840204	1	BA04-3	Surface	6922		599	35	34	56
840204	1	BA05-3	Surface	6922		599	35	34	56
840204	1	BA06-3	Surface	6922		599	35	34	56
840604	4	BA08-1	Surface	1276		497	38	15	52
840604	4	BA07-1	Surface	1793		503	43	23	54
840604	4	BA09-1	Surface	1879		686	33	28	48
860501	2	CA54-56	Surface			205.6	165	26	36

C-SHRP ID	Section	Sample Code	Layer Location	Kinematic Viscosity @60C(mm2/sec)	Viscosity @60C(Pa-s)	Kinematic Viscosity @135C(mm2/sec)	Penetration @25C(mm X 1/10)	Penetration @4C(mm X 1/10)	Ring & Ball Softening Point(°C)
860501	3	CA57-59	Surface			205.6	165		36
860603	1	CA51-53	Surface			205.6	165	26	36
860603	2	CA54-56	Surface			205.6	167		36
860603	3	CA57-59	Surface			205.6	167		36
870102	1	B1,B3	Bottom		2884	427	79		49.4
870505	1		Surface		21170	1200	54	6	56
870505	3		1st Intermediate		3083	513	84	4	45
870505	3		Surface		3664	465	64	6	47.8
870505	4		Bottom		20482	451	45	8	55.3
870505	4		Surface		2638	406	71	9	51.4
870701	2	B5	Surface			477	57	6	47
890503	1	CA51-56	Surface		2219.7	924.3	25	5	59.7
890503	2	CA57-512	Surface		25674.4	2046.3	27	5	69.8
890503	3	CA51-56	Surface		2219.7	924.3	25	5	59.7
890503	4	CA57-512	Surface		25674.4	2046.3	27	5	69.8
890702	1	CA51-56	Surface		1918.8	843.3	30	4	62.3

Table A.2: C-LTPP Volumetric Data Extraction

C-SHRP ID	Section	Sample Code	Layer Location	Specific Gravity Asphalt Cement	Air Voids (%)	VMA (%)	Bulk Specific Gravity	Max Specific Gravity	Effective Asphalt Cement (%)
820205	1	BA60	Surface	1.025	3.09	14.51	2.55	2.63	4.9
820205	2	BA64	Bottom	1.023	2.43	13.75	2.56	2.62	4.8
820205	2	BA62	Surface	1.025	2.76	14.02	2.55	2.62	4.8
820502	1	BA51	Bottom	1.026	4.42	14.47	2.4	2.51	4.6
820502	1	BA54	Surface	1.018	3.71	13.79	2.41	2.51	4.5
820502	2	BA52	Bottom	1.03	6.77	15.29	2.36	2.54	3.9
820502	2	BA55	Surface	1.016	5.17	14.39	2.37	2.5	4.4
820605	1	BA57-2	Surface	1.019	3.98	14.38	2.41	2.51	4.6
820605	2	BA58	Surface	1.019	4.87	15.29	2.38	2.5	4.7
830403	1	BA01	Surface	1.061	4.28	15.52	2.34	2.45	5.25
840204	1	BA04-1	Bottom	1.029	3.52	15.27	2.41	2.5	5
840204	1	BA06-1	Bottom	1.031	3.52	15.27	2.41	2.5	5
840204	1	BA05-1	Bottom	1.029	3.52	15.27	2.41	2.5	5
840204	1	BA01-2	Surface	1.045	3.92	17.1	2.37	2.46	5.7
840204	1	BA02-2	Surface	1.044	3.92	17.1	2.37	2.46	5.7
840204	1	BA04-3	Surface	1.046	3.92	17.1	2.37	2.46	5.7
840204	1	BA05-3	Surface	1.046	3.92	17.1	2.37	2.46	5.7
840204	1	BA06-3	Surface	1.046	3.92	17.1	2.37	2.46	5.7
840604	4	BA08-1	Surface	1.048	3.54	16.7	2.41	2.5	5.7
840604	4	BA07-1	Surface	1.045	3.54	16.7	2.41	2.5	5.7
840604	4	BA09-1	Surface	1.05	3.54	16.7	2.41	2.5	5.7
860501	2	CA54-56	Surface	1.013	3.7	15.5	2.41	2.5	4.8
860501	3	CA57-59	Surface	1.013	3.9	16.1	2.4	2.49	5.3
860603	1	CA51-53	Surface	1.013	3.7	15.5	2.37	2.46	4.7

C-SHRP ID	Section	Sample Code	Layer Location	Specific Gravity Asphalt Cement	Air Voids (%)	VMA (%)	Bulk Specific Gravity	Max Specific Gravity	Effective Asphalt Cement (%)
860603	2	CA54-56	Surface	1.013	3.7	15.5	2.37	2.46	4.7
860603	3	CA57-59	Surface	1.013	3.7	15.5	2.37	2.46	4.7
870102	1	B1,B3	Bottom	1.025					
870505	1		Surface	1.034					
870505	3		1st Intermediate	1.028					
870505	3		Surface	1.031					
870505	4		Bottom	1.031					
870505	4		Surface	1.025					
870701	2	B5	Surface	1.03					
890503	1	CA51-56	Surface	1.04	2.8	13.5	2.43	2.5	
890503	2	CA57-512	Surface	1.04	2.75	13.5	2.43	2.5	
890503	3	CA51-56	Surface	1.04	2.8	13.5	2.43	2.5	
890503	4	CA57-512	Surface	1.04	2.75	13.5	2.43	2.5	
890702	1	CA51-56	Surface	1.04	3.07	19.7	2.55	2.63	

Appendix B
Supplemental Mix Statistical Analysis

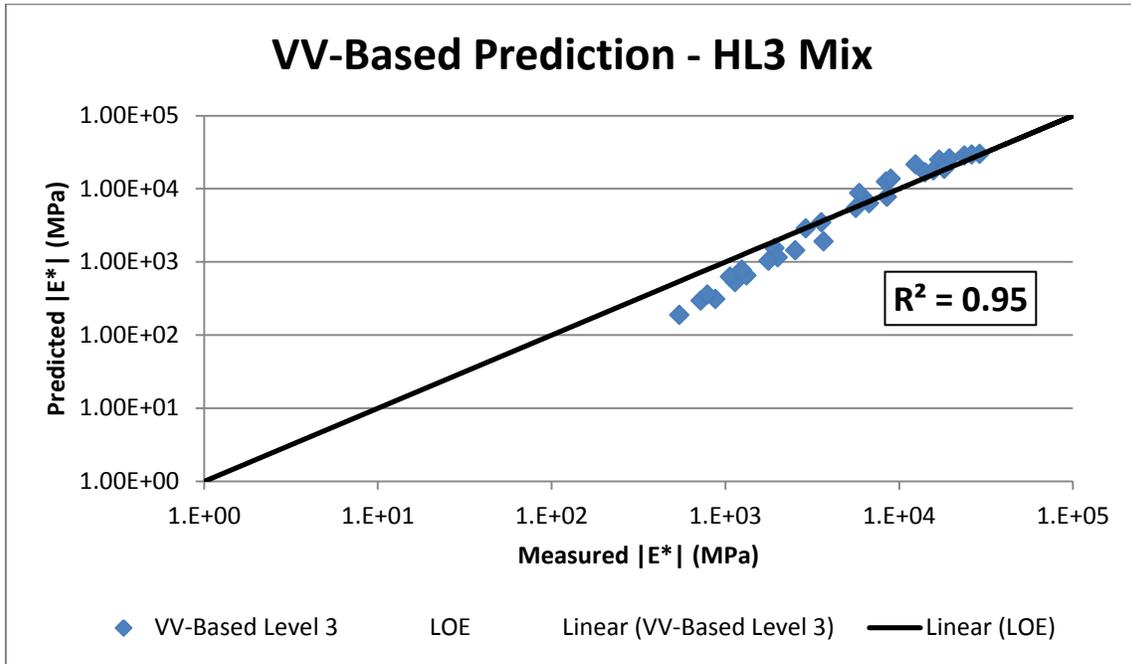


Figure B.1: HL3 Mix Measured vs. Predicted Dynamic Modulus – Logarithmic Scale

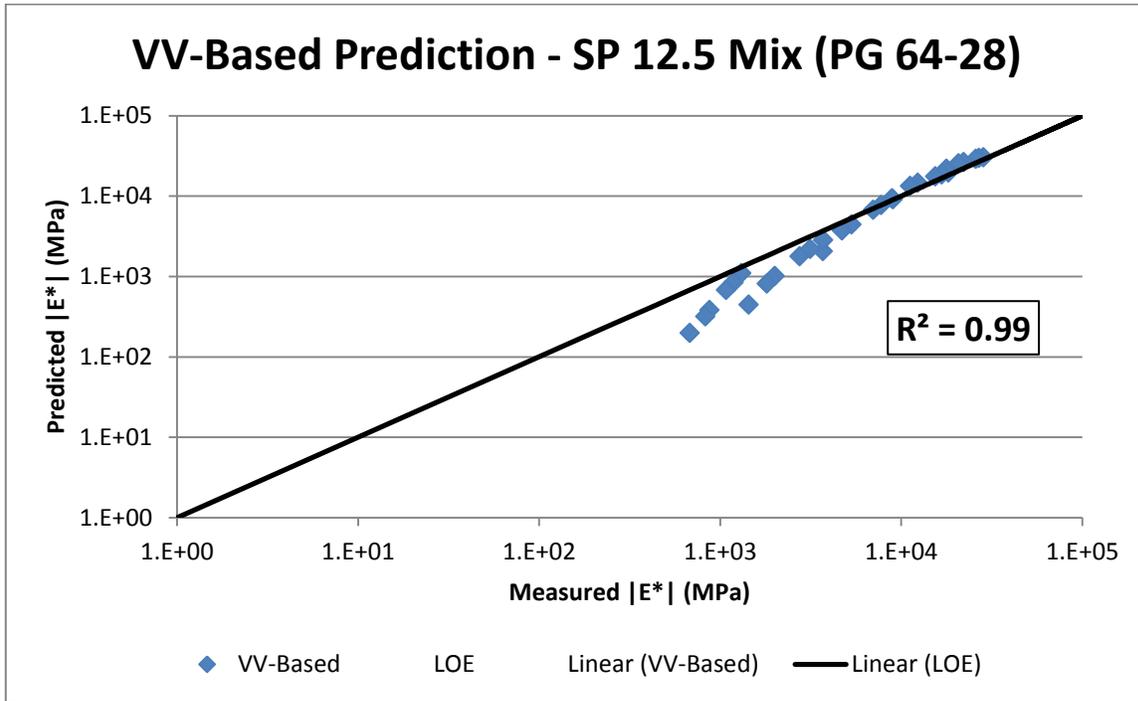


Figure B.2: SP12.5 Mix Measured vs. Predicted Dynamic Modulus – Logarithmic Scale

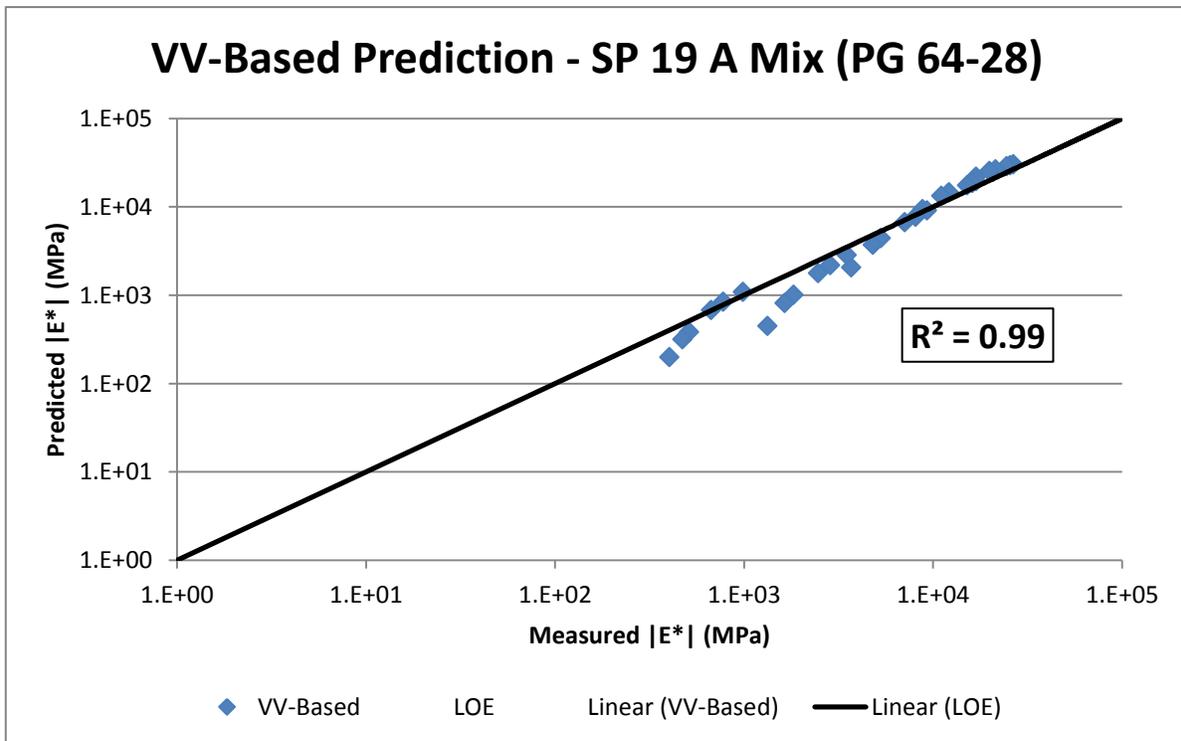


Figure B.3: SP19 A Mix Measured vs. Predicted Dynamic Modulus – Logarithmic Scale

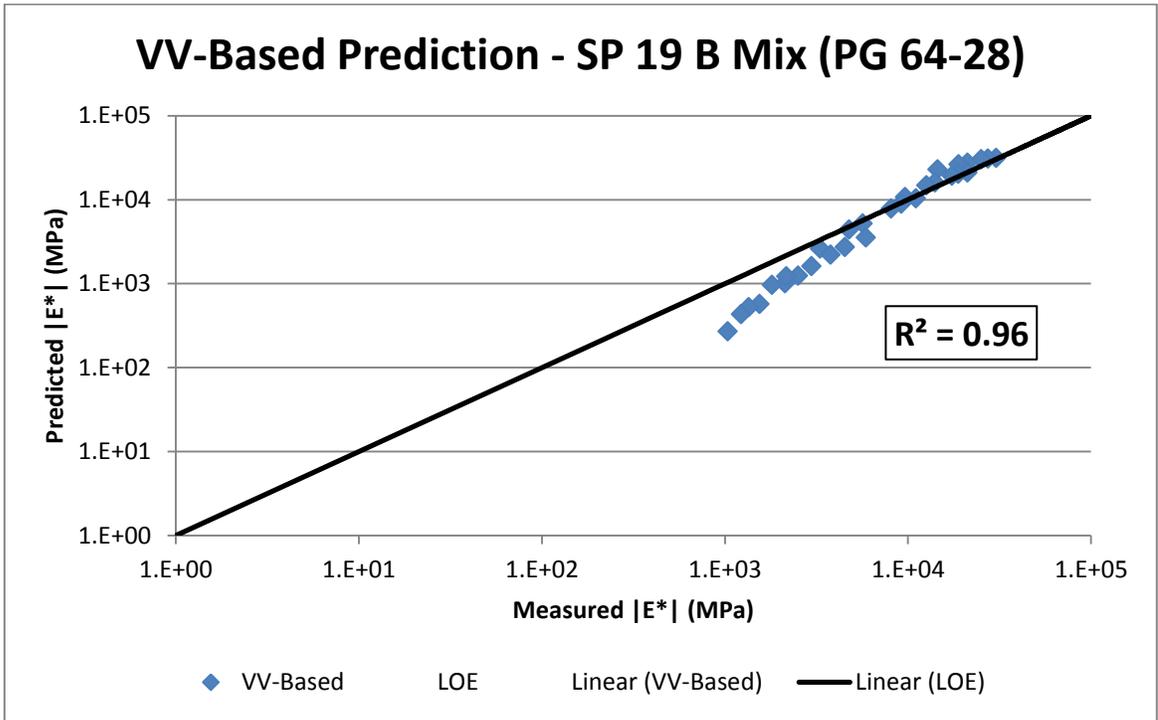


Figure B.4: SP19 B Mix Measured vs. Predicted Dynamic Modulus – Logarithmic Scale

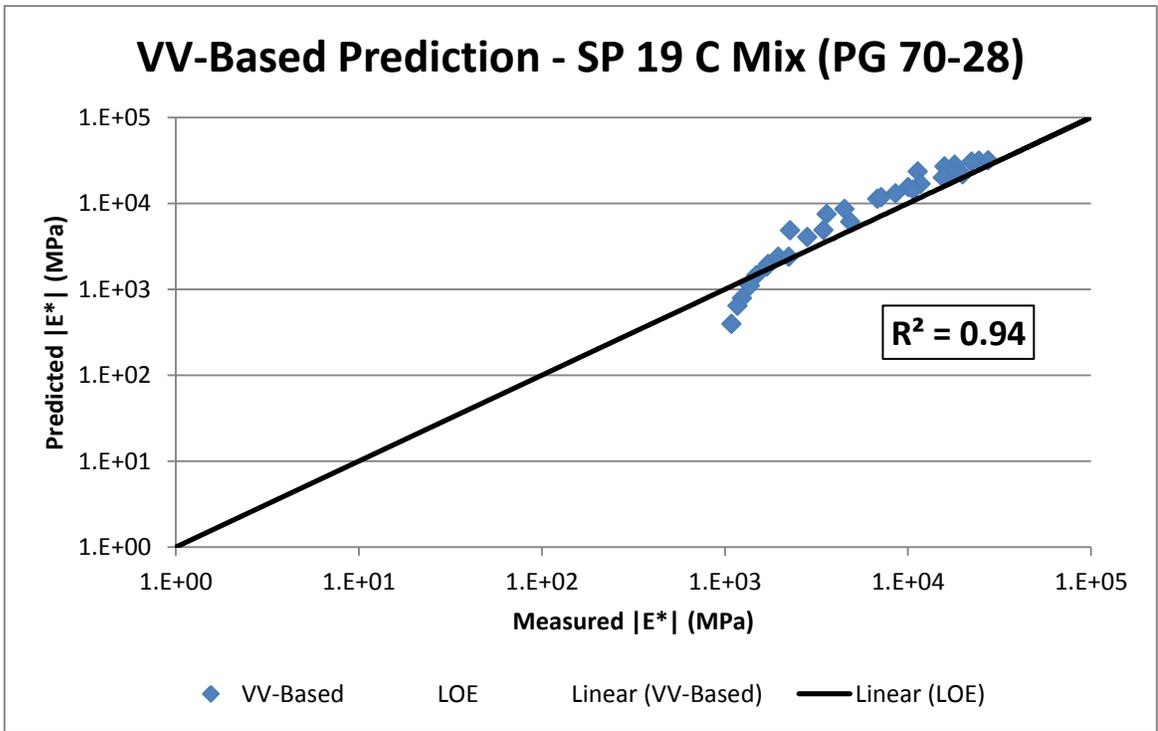


Figure B.5: SP19 C Mix Measured vs. Predicted Dynamic Modulus – Logarithmic Scale

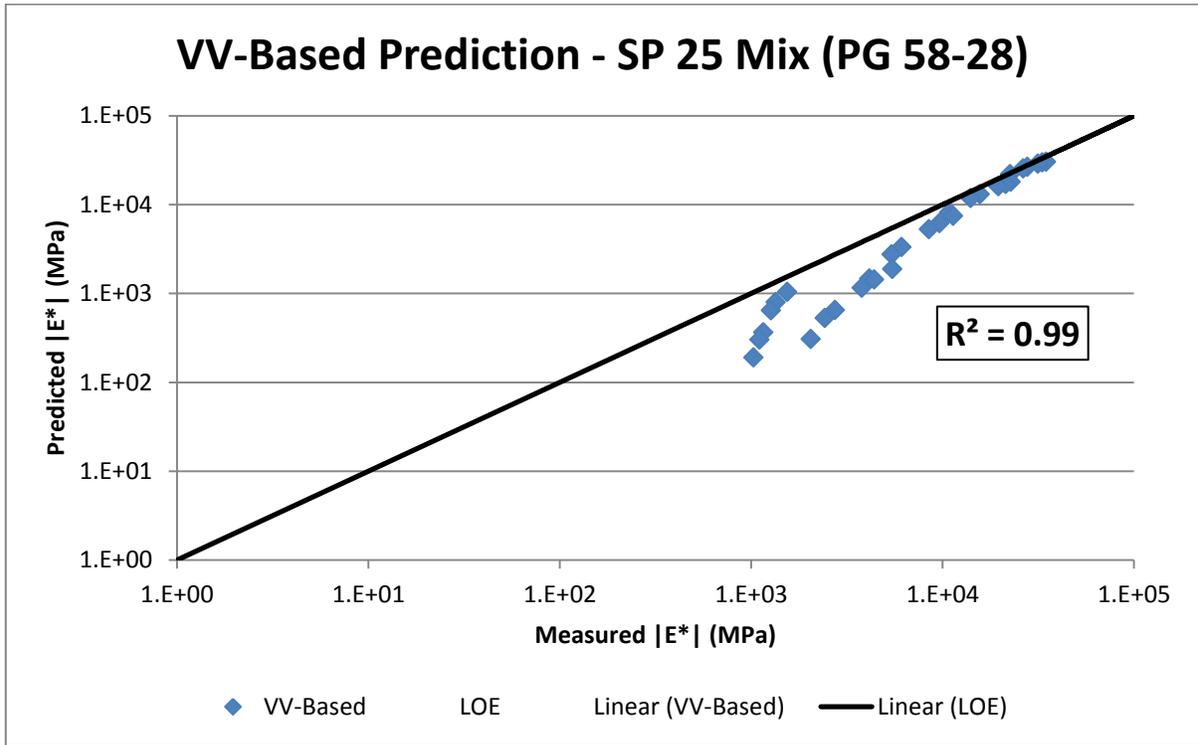


Figure B.6: SP25 Mix Measured vs. Predicted Dynamic Modulus – Logarithmic Scale

References

- AASHTO. (1972). *AASHTO Interim Guide for Design of Pavement Structures*. Washington, DC: American Association of State Highway and Transportation Officials (AASHTO).
- AASHTO. (1986). *AASHTO Guide for Design of Pavement Structures*. Washington, DC: American Association of State Highway Transportation Officials (AASHTO).
- AASHTO PP 62-09. (2009). *Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA)*. Washington, DC: American Association of State Highway Transportation Officials.
- AASHTO R 28-12. (2012). *Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)*. Washington, DC: American Association of State Highway Transportation Officials.
- AASHTO T 240-09. (2009). *Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt (RTFOT)*. Washington, DC: American Association of State Highway Transportation Officials.
- AASHTO T 315-12. (2012). *Standard Test Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*. Washington, DC: American Association of State Highway Transportation Officials.
- AASHTO TP 62-07. (2007). *Determining Dynamic Modulus of Hot Mix Asphalt (HMA)*. Washington, DC: American Association of State Highway Transportation Officials.
- Ali, O. (2005). *Evaluation of the Mechanistic Empirical Pavement Design Guide (NCHRP 1-37A)*. Ottawa: National Research Council Canada (NRC).
- American Association of State Highway and Transportation Officials (AASHTO). (1993). *AASHTO Guide for Design of Pavement Structures*. Washington, DC: American Association of State Highway and Transportation Officials (AASHTO).
- Anderson, J. (1995). *Introduction to Neural Networks*. Cambridge, MA: MIT Press.
- Andrei, D., Witczak, M., & Mirza, M. (1999). *Development of a Revised Predictive Model for the Dynamic (Complex) Modulus of Asphalt Mixtures*. Washington, DC: National Cooperative Highway Research Program (NCHRP).
- ASTM Standard D2170. (2010). *Standard Test Method for Kinematic Viscosity of Asphalts*. West Conshohocken, PA: ASTM International.
- ASTM Standard D2171. (2010). *Standard Test Method for Viscosity of Asphalts by Capillary Viscometer*. West Conshohocken, PA: ASTM International.

- ASTM Standard D36. (2012). *Standard Test Method for Softening Point of Bitumen*. West Conshohocken, PA: ASTM International.
- ASTM Standard D5. (2006). *Standard Test Method for Penetration of Bituminous Materials*. West Conshohocken, PA: ASTM International.
- Bonaquist, R., & Christensen, D. (2005). A Practical Procedure for Developing Dynamic Modulus Master Curves for Pavement Structural Design. *84th Annual Meeting of the Transportation Research Board*. Washington, DC.
- Bonnaure, F., Gest, G., Gravois, A., & Uge, P. (1977). A New Method of Predicting the Stiffness of Asphalt Paving Mixtures. *Association of Asphalt Paving Technologists*. San Antonio, Texas.
- Christensen, J. D., Pellinen, T., & Bonaquist, R. (2003). Hirsch Model for Estimating the Modulus of Asphalt Concrete. *Journal of the Association of Asphalt Paving Technologists*, 72, 97-121.
- Clyne, T. R., Li, X., Marasteanu, M. O., & Skok, E. L. (2003). *Dynamic and Resilient Modulus of MN/DOT Asphalt Mixtures*. St. Paul, Minnesota: Minnesota Department of Transportation (MNDOT).
- Corre, B. (2005). *Implementing the M-E Pavement Design Guide in Iowa*. Ames, IA: Center for Transportation Research and Education, Iowa State University.
- C-SHRP. (1990). *Pavement Research Technical Guidelines*. Ottawa: Transportation Association of Canada.
- C-SHRP. (1997). *Canadian Long-Term Pavement Performance (C-LTPP) - Database User's Guide*. Ottawa: Transportation Association of Canada.
- C-SHRP. (1999). *Resilient Modulus Testing of C-LTPP Materials*. Ottawa: Canadian Strategic Highway Research Program (C-SHRP).
- C-SHRP. (2000). *Pavement Design and Performance: Current Issues and Research Needs*. Ottawa: Canadian Strategic Highway Research Program (C-SHRP).
- C-SHRP. (2002). *Pavement Structural Design Practices Across Canada*. Ottawa: Canadian Strategic Highway Research Program (C-SHRP).
- Di Benedetto, H., & De La Roche, C. (1998). State of the Art on Stiffness Modulus and Fatigue of Bituminous Mixtures. In *RILEM Report 17, Bituminous Binder and Mixes - State of the Art and Interlaboratory Tests on Mechanical Behaviour and Mix Design* (pp. 137-179). Report of RILEM Technical Committee 152-PBM.
- El-Hakim, M. (2013). *A Structural and Economic Evaluation of Perpetual Pavements: A Canadian Perspective*. Waterloo: University of Waterloo.

- Federal Highway Administration (FHWA). (2010). *Artificial Neural Networks for Asphalt Concrete Dynamic Modulus Prediction*. McLean, VA: Federal Highway Administration (FHWA).
- FHWA. (2006, July 1). *Focus*. Retrieved September 1, 2012, from <http://www.fhwa.dot.gov/publications/focus>
- FHWA. (2010). *Long-Term Pavement Performance Program Highlights: Accomplishments and Benefits 1989-2009*. McLean, Virginia: Federal Highway Administration.
- FHWA. (2010). *LTPP Information Management System - IMS Quality Control Checks*. McLean, Virginia: Federal Highway Administration.
- FHWA. (2011). *DataPave Online*. Retrieved February 1, 2013, from LTPP Products Online: <http://www.ltpm-products.com/Default.aspx>
- FHWA. (2011). *LTPP Computed Parameter: Dynamic Modulus*. McLean, Virginia: Federal Highway Administration (FHWA).
- Garcia, G., & Thompson, M. (2007). *HMA Dynamic Modulus Predictive Models - A Review*. Springfield, IL: Illinois Center for Transportation.
- Gavin, J., Dunn, L., & Juhasz, M. (2003). Long Term Performance Monitoring of the Lamont Test Road. *2003 Annual Conference of the Transportation Association of Canada*. St. John's, Newfoundland.
- Giuliana, G., Nicolosi, V., & Festa, B. (2012). Predictive Formulas of Complex Modulus for High Air Void Content Mixes. *Transportation Research Board*. Washington, DC.
- Goodman, S. (2000). *C-LTPP Surface Distress Variability Analysis*. Ottawa: Canadian Strategic Highway Research Program (C-SHRP).
- Haas, R., Li, N., & Tighe, S. (1999). *Roughness Trends at C-SHRP LTPP Sites*. Ottawa: Canadian Strategic Highway Research Program (C-SHRP).
- Koehler Instrument Company Inc. (2006). *Catalog*. Retrieved January 31, 2013, from <http://www.koehlerinstrument.com/literature/catalog/2006/01-Viscosity.pdf>
- Korzak, R., Tighe, S., MacLeod, D., & Cimini, G. (2011). *C-LTPP Database: A Review*. Ottawa: Transportation Association of Canada.
- MTO. (2012). *Ontario's Default Parameters for AASHTOWare Pavement ME Design Final Report*. Toronto: Materials Engineering and Research Office.
- NCHRP. (2003). *Pavement Design Tools: NCHRP Project 1-32*. Washington, DC: Transportation Research Board (TRB).

- NCHRP. (2004). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures - Chapter 4: Traffic*. Washington, DC: National Cooperative Highway Research Program (NCHRP).
- NCHRP. (2004). Laboratory Determination of Resilient Modulus for Flexible Pavement Design. *Research Results Digest*(285).
- NCHRP. (2009). *User Manual and Local Calibration Guide for the Mechanistic-Empirical Pavement Design Guide and Software*. Washington, DC: Transportation Research Board.
- OHMPA. (1999). *The ABCs of PGAC*. Toronto: Ontario Hot Mix Producers Association (OHMPA).
- Olidis, C., & Hein, D. (2004). Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures Materials Characterization: Is Your Agency Ready? *2004 Annual Conference of the Transportation Association of Canada*. Quebec City.
- Oregon State University. (2012). *Materials - Asphalt*. Retrieved January 31, 2013, from http://classes.engr.oregonstate.edu/cce/winter2012/ce492/Modules/03_materials/03-3_body.htm#summary
- Papazian, H. S. (1962). The Response of Linear Viscoelastic Materials in the Frequency Domain with Emphasis on Asphaltic Concrete. *International Conference on the Structural Design of Asphalt Pavements*. Ann Arbor, Michigan.
- Pavement Interactive. (2007, August 13). *AASHO Road Test*. Retrieved January 30, 2013, from <http://www.pavementinteractive.org/article/aasho-road-test/>
- Pavement Interactive. (2007, August 16). *Penetration Test*. Retrieved January 31, 2013, from <http://www.pavementinteractive.org/article/penetration-test/>
- Pavement Interactive. (2008, March 13). *Empirical Pavement Design*. Retrieved January 31, 2013, from <http://www.pavementinteractive.org/article/empirical-pavement-design/>
- Pavement Interactive. (2008, March 13). *Flexible Pavement Mechanistic Models*. Retrieved January 31, 2013, from <http://www.pavementinteractive.org/article/flexible-pavement-mechanistic-models/>
- Phang, W., & Stott, G. (1981). *Pavement Condition and Performance Observations: Brampton Test Road*. Toronto: Ministry of Transportation Ontario.
- Sakhaeifar, M., Underwood, S., Kim, R., Puccinelli, J., & Jackson, N. (2010). Development of Artificial Neural Network Predictive Models for Populating Dynamic Moduli of Long-Term Pavement Performance Sections. *Transportation Research Record*(2181), 88-97.

- SHRP. (1994). *SHRP-LTPP International Participation: Five-Year Report*. Washington, DC: National Research Council.
- TAC. (2004). *Dynamic and Resilient Modulus Characterization of C-LTPP Pavement Materials*. Ottawa: Transportation Association of Canada (TAC).
- Tighe, S. (2013). *Pavement Design and Management Guide*. Ottawa: Transportation Association of Canada.
- Uzarowski, L. (2006). *The Development of Asphalt Mix Creep Parameters and Finite Element Modeling of Asphalt Rutting*. Waterloo: University of Waterloo.
- Von Quintus, H., Darter, M., & Mallela, J. (2007). *Manual of Practice - Interim Mechanistic Empirical Pavement Design Guide*. NCHRP Project 1-40B.
- Witczak, M. W., & Root, R. E. (1974). *Summary of Complex Modulus Laboratory Test Procedures and Results*. West Conshohocken, PA: American Society for Testing and Materials (ASTM).
- Witczak, M., Bari, J., Doucet, F., & Quayum, M. (2001). *Comparison of Dynamic Complex Modulus Tests in Repeated Load Beam Flexure and Uniaxial Compression Modes*. Washington, DC: National Cooperative Highway Research Program (NCHRP).
- Yoder, E., & Witczak, M. (1975). *Principles of Pavement Design*. J. Wiley and Sons, Inc.