USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No 011IY01

Development of a Finite Element Based Thermal Cracking Performance Prediction Model

By

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Discovery Park

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USDOT Region V Regional University Transportation Center Final Report

TECHNICAL SUMMARY

NEXTRANS Project No 011IY01 Final Report, October 2009

Development of a Finite Element Based Thermal Cracking Performance Prediction Model

Introduction

Low-temperature cracking of hot-mix asphalt (HMA) pavements continues to be a leading cause of premature pavement deterioration in regions of cold climate and/or where significant thermal cycling occurs. Recent advances in fracture testing and modeling of HMA materials have greatly aided in the understanding of the key mechanisms behind this devastating pavement distress mode. While these advances have led to new insights into cracking mechanisms and design strategies, there remains the challenge of implementing these models into a standalone program which can be easily used by other researchers and practitioners. The proposed supplemental study extends the scope of the existing pooled fund study to more explicitly capture the interactions between vehicles and the infrastructure. Following the successful first phase of the National Pooled Fund Study on Low Temperature Cracking, a second phase will be initiated in mid-2007 and continue for two to three years. While the phase II study will provide additional funding for more field sections at the Minnesota Road Research (Mn/Road) facility and other locations in the US (selected participating states), there is a need for additional research which would facilitate the development of standalone, efficient code for thermal crack prediction. The main deliverable of this project is a user-friendly, computationally efficient program called Visual LTC, which can be used to analyze and to design against thermal cracking in asphalt pavements. This tool will greatly facilitate the design of economical pavement systems and the utilization of modern material formulations and construction techniques that are environmentally friendly and sustainable, such as the use of very high amounts of recycled materials and the use of low energy/low emission warm mix technologies. Planned work in the next phase of this study will lead to the integration of this software into a more holistic asset management analysis system.

Findings

Given the nature of the proposed GUI and the nature of material database development and distribution/sharing, an object-oriented language was found to be necessary. Visual LTC is written in C# (pronounced “see-sharp”) under Microsoft’s .NET framework. Visual LTC uses an intuitive class structure to represent data (i.e. each pavement layer is a new instance of a class). Visual LTC has been demonstrated to work properly with existing thermal cracking software modules, i.e., those used in the Mechanistic Empirical Design Guide (MEPDG).

Recommendations

The following tasks are recommended for the next phase of this research project:

- Implementation of nonlinear cohesive zone model capabilities in Visual LTC
- Improvement of the user-interface of Visual LTC based upon feedback from the project panel and practitioners
- Development of a database of material properties
- Integration of Visual LTC software into a comprehensive asset management analysis system.

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background and motivation

Low-temperature cracking of hot-mix asphalt (HMA) pavements continues to be a leading cause of premature pavement deterioration in regions of cold climate and/or where significant thermal cycling occurs. Recent advances in fracture testing and modeling of hot-mix asphalt (HMA) materials have greatly aided in the understanding of the key mechanisms behind this important pavement distress, which can greatly reduce pavement lifespan and the lifespan of subsequent rehabilitation cycles. While new tests and models represent powerful tools for the design of more reliable, more sustainable flexible pavement systems, there is a need to implementation the models into a standalone program which can be readily utilized by researchers and practitioners. Moreover, the complete integration of material selection, material design, pavement design and pavement performance into a more holistic asset management system has been hampered by the lack of accurate, user-friendly performance prediction models for pavements. This research provides one of the critical links needed to move this integrated approach to the state of practice.

1.2 Relation to NEXTRANS Objectives

The scope of this work is within the vehicle-infrastructure research pillar of the NEXTRANS center. This research is geared towards development of an integrated solution scheme that incorporates short-term and long-term pavement performance solutions through advanced research. The overall objective is to deliver a stand-alone user-friendly tool to highway designers for design of thermal cracking resistant asphalt pavements. This tool will greatly facilitate the design of economical pavement systems and the utilization of modern material formulations and construction techniques that are environmentally friendly and sustainable, such as the use of very high amounts of recycled materials and the use of low energy/low emission warm mix technologies.

1.3 Objectives

The objective of this work is to develop a user-friendly interface that provides simplified access to sophisticated low-temperature cracking prediction models. This stand-alone program will greatly accelerate the transfer of this technology to practitioners and other interested scientists and engineers (pavement designers, analysts, and researchers). The program is designed to be compatible with the existing thermal cracking model used in the Mechanistic Empirical Pavement Design Guide (MEPDG), and with the new thermal cracking model being developed under the National Pooled Fund Study on Low Temperature Cracking.

1.4 Thermal-Cracking Model (TCModel)

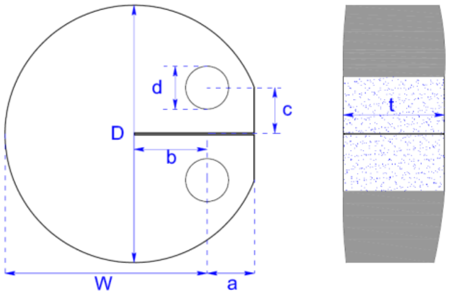
A thermal-cracking prediction model (TCModel) developed by Hiltunen and Roque (1994) is currently the most widely utilized mechanistic-empirical design tool to control thermal cracking in asphalt pavements. The model was developed in early 1990's (Lytton et al, 1993) and relies on use of material tensile strength as the key input for linking the material behavior with low-temperature cracking performance (Roque et al, 1995a, 1995b) using Linear-elastic Fracture Mechanics (LEFM). Since the development of TCModel, asphalt concrete fracture behavior has been extensively studied. Several authors, including but not limited to, Wagoner et al. (2005a and 2005b) and Li et al. (2006) have demonstrated that fracture of asphalt concrete is a highly non-linear phenomenon involving quasi-brittle and ductile failure mechanisms. TCModel does not capture these type of material failure behaviors. Furthermore, the crack propagation model in TCModel is based on Paris law (Paris et al., 1961), which is a phenomenological model for linking structural response to pavement failure.

Significant improvements in material fracture characterization and modeling over the past several years have yielded accurate testing and modeling procedures that can perform robust thermal-cracking predictions to design modern, sustainable asphalt pavement systems. Newly developed asphalt concrete fracture test procedure and a fracture mechanics-based model are proposed for use in the new performance prediction model being developed under a National Pooled Fund Study on Low Temperature Cracking.

1.5 Asphalt Concrete Fracture Testing and Modeling

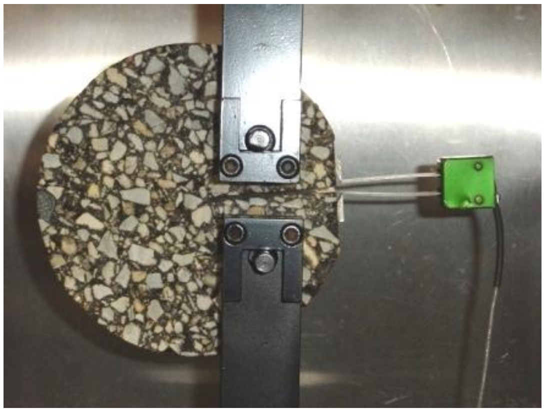
Fracture processes can be divided into three modes namely, Mode I (opening Mode), Mode II (in-plane shear), and Model III (out of plane shear). For thermal cracking the most critical of these to control is Mode I. A great deal of effort has been directed towards the development of Mode I fracture testing methods. There are three commonly used testing configurations for Mode-I fracture characterization of asphalt concrete: the Single Edge Notch Beam [SE(B)] (Wagoner et al., 2005a), the Semi-Circular Bending [SC(B)] (Li et al., 2006), and the Disk-Shaped Compact Tension [DC(T)] (Wagoner et al., 2005b).

Wagoner et al. (2005b) proposed a DC(T) test that is suited for fracture characterization of asphalt concrete. The DC(T) test has been used for variety of research studies, including the study of reflective cracking by Paulino et al. (2006), thermal cracking by Dave et al. (2008), and aging by Apeagyei et al. (2008). Above all, the test has been standardized in ASTM D7313-07 (2007). The disk-shaped compact tension geometry is a circular specimen with a single edge notch loaded in tension. Figure 1 shows the geometry and recommended dimensions for the DC(T). Due to its simple geometry, DC(T) specimens can be obtained easily from field cores or lab compacted samples. Wagoner et al. (2006) made comparisons between the indirect tensile (IDT) strength test utilized in TCModel with the fracture energies obtained from DC(T) test for variety of asphalt mixtures. The results from their study is reproduced in Figure 2. Notice that the IDT strength does not distinguish between various mixtures and this is lack of distinction is specifically apparent for mixtures manufactured with polymer-modified asphalt binders. Use of polymer-modified binders have been increasing significantly over the years and is most-prevalent in high traffic pavement surface courses. The surface of asphalt pavements are most susceptible to thermal cracking due to greater exposure to lower temperatures as well as higher cooling rates. The DC(T) test measures an intrinsic property of asphalt mixtures, i.e., the energy associated with creating a unit crack surface. This data resulting from the DC(T) test can be used in modern nonlinear fracture models as part of a system to predict low-temperature cracking performance of asphalt pavements.



DC(T), Dimensions (mm)	
D	150
W	110
a	35
b	27.5
c	25
d	25
t	50

(a) Schematic and Dimensions



(b) Test-setup at University of Illinois

Figure 1: Disk-Shaped Compact Tension Test

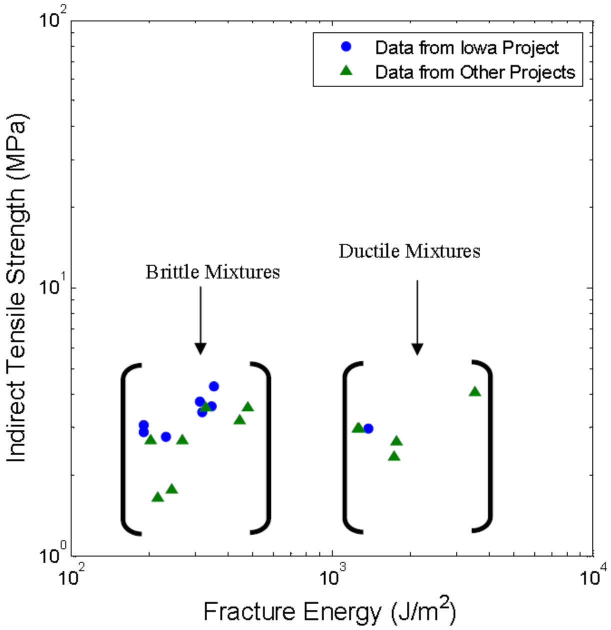


Figure 2: Comparison of Indirect Tensile Strength and Fracture Energy (reproduced from Wagoner et al., 2006)

In order to simulate the complex mechanisms underlying the thermal cracking phenomenon, a standard "strength of materials" type analysis is insufficient, due to: 1) the highly non-linear behavior in the vicinity of the crack tip in this viscoelastic, particulate composite with large aggregate particles, and 2) the importance of the crack in the overall structural response (i.e., the need to model thermal crack as a moving boundary value problem). The cohesive zone model provides a computationally efficient way to predict the damage occurring in a process zone located ahead of a crack tip in a material. This approach, which provides constitutive laws to describe displacement jump/traction behavior along crack surfaces, can capture complex fracture behavior such as crack nucleation, crack initiation and both mode-I and mixed-mode crack propagation. In other words, the cohesive zone model dictates the relationship at any material point between its capacity to transfer load (traction) and potential opening (displacement jump) due to material damage or cracking.

The cohesive zone approach readily utilizes experimentally determined fracture energy. In the cohesive fracture approach, the material begins to incur damage (softening) once the stresses exceed the limit stress of the material, which in this case is assumed to be the tensile strength. Beyond this peak, the material undergoes a stage of softening (damage) whereby its capacity to transfer load across the potential crack continuously decreases. Once the material dissipates the energy equivalent to its fracture energy, a macro-crack is developed. The region between the point of damage initiation and point of complete failure is often called the fracture process zone. Figure 3 illustrates the process zone, modeled herein as the region between the cohesive crack tip (where the traction is at a maximum and equivalent to material's tensile strength, (σ_t) and the material crack tip (where the traction is zero). Figure 3 also shows a schematic illustration of the fracture process zone or cohesive zone (hashed region) with traction forces along the potential crack faces illustrated by a series of arrows.

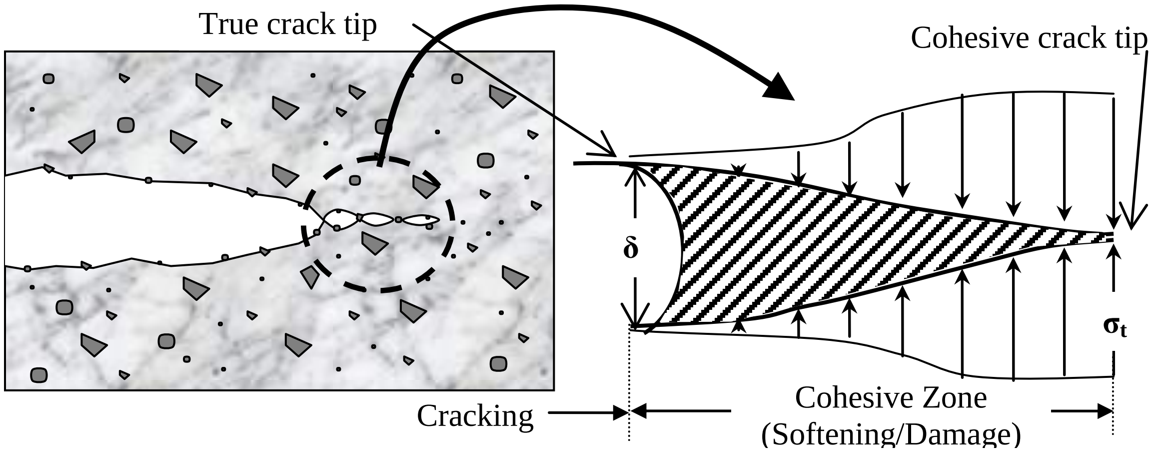


Figure 3: Schematic of Fracture Behavior near Crack Tip and the Fracture Process Zone

Song et al. (2006) and de Souza et al. (2004) have demonstrated the various capabilities of the cohesive zone model for the simulation of cracking in asphalt concrete materials. Baek and Al-Qadi (2006), and Dave et al. (2007 and 2008) have applied the cohesive zone model to simulate cracking in asphalt pavements.

In summary, it is evident from recent technical literature that for accurate prediction of thermal-cracking performance of asphalt pavements, a fracture mechanics based approach, that simulates realistic material behavior and accounts for actual material failure properties is necessary. Significant progress was made through US Department of Transportation’s Pooled Fund Study on low-temperature cracking by Marasteanu et al. (2007). However, the outcome of other studies were limited to identification of fracture tests for asphalt concrete and development and utilization of cohesive zone fracture models. In order to incorporate these into a routine pavement designs performed by state and local agency personnel, and other practitioners, it is necessary that a user-friendly design procedure be developed. The MEPDG (ARA Inc., 2004) is a good example of such an approach, where user friendly software allows the user to perform advanced pavement design through integration of several sophisticated analysis models.

1.6 <u>Proposed Low-Temperature Cracking (LTC) Model</u>

The previous section described recent developments in modeling and characterization of fracture in asphaltic materials. The new laboratory tests coupled with mechanics-based models will enable prediction of thermal cracking in pavements for a much wider variety of materials and to a level of accuracy not currently possible. The present TCModel is available to pavement design engineers only in the form of the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) Software (ARA Inc., 2004). The MEPDG software performs analysis for rutting, fatigue and thermal cracking predictions during each simulation run. This requires a large set of material, structural, and traffic inputs, with an average run taking over 30 minutes. The proposed user interface is being developed so that practitioners and researchers can perform thermal-cracking analysis with significantly fewer inputs relative to the requirements of the MEPDG, for those only wishing to obtain thermal cracking distress predictions. Table 1 summarizes the technical differences between the TCModel from MEPDG software and the LTC Model discussed herein.

Table 1: Capabilities of TCModel and the LTC Model Developed in Present Study

Capabilities	**TCMODEL (AASHTO MEPDG)**	**Pooled Fund LTC Model**
Fracture model	Based on Paris law (Linear Elastic Fracture Mechanics)	Non-linear cohesive zone fracture model (appropriate for quasi-brittle materials)
Modeling scheme	Analytical, Simplified 1-D representation	Finite-element based, 2-D representation
Pavement model representation	Single asphalt concrete layer	Multiple pavement layers
Crack propagation direction	Limited to top-down	Based on pavement response (top-down, bottom-up or both)

1.7 Organization of the Report

The remainder of the report is organized as follows. Chapter 2 introduces the standalone low-temperature cracking analysis program. Chapter 3 details the development of Visual LTC (GUI) from both the users' and programmer's perspective. The usability and implementation of the interface are described. Chapter 4 shows the functionality of Visual LTC and application is illustrated in Chapter 5 through an example run of the program. Results obtained with Visual LTC are also compared, illustrating the effectiveness of the program as an analysis and design tool. Chapter 6 summarizes this work and provides suggestions for future research.

CHAPTER 2. STAND ALONE LOW-TEMPERATURE CRACKING ANALYSIS PROGRAM

2.1 *Introduction*

This chapter introduces the a standalone, user-friendly low-temperature cracking (LTC) analysis program. The creation of a graphical user interface is the first task in the development of the improved thermal cracking model, and was the focus of this phase of the project. Chapter 1 provided a summary of recent developments in the field of fracture characterization and modeling of asphaltic materials. In order to design sustainable asphalt pavements, it is necessary that an accurate and mechanics-based prediction model be developed and used in conjunction with a user-friendly GUI that unifies several analysis modules in an intuitive, accessible manner. The key attributes of the new user inteface were determined to be:

- Minimized and enhanced organizational structure of input data for the analysis model relative to the existing MEPDG.
- The ability to access existing material databases, add and store new materials to the database, and the ability to access material databases over the internet.
- Incorporation of new model inputs, e.g., fracture properties, including local scale material strength and fracture energy, as required by the cohesive zone model.
- Streamlined and enhanced model outputs, with compatibility for use in the larger context of asset management system analysis.

2.2 *Phases of Development*

The development of the stand-alone LTC model is being performed in two phases. The first phase of development will involve the development of a user-friendly graphical user interface (GUI) called “**Visual LTC**.” The second phase involves development of the new analysis model that utilizes fracture energy as the key material input and relies on finite element analysis with cohesive zone fracture modeling.

2.3 *Graphical User Interface: Visual LTC (Phase-I)*

A GUI plays an important role in the process of design through the use of sophisticated simulation models which involve complex computations and allows integration of various design components such as, climatic modeling, determination of material viscoelastic parameters, non-linear fracture modeling, pavement structure data handling, etc. A case for the need of a GUI can be made by considering the MEPDG software. The MEPDG software integrates various pavement distress mechanisms, including rutting, fatigue cracking and thermal cracking. In order to perform mechanistic empirical analysis for each of these distresses, the GUI in MEPDG performs several thousand iterations of the structural response software. For example layered elastic analysis is performed several thousand times to predict fatigue cracking a typical MEPDG run. Furthermore, the MEPDG GUI enables integration of several different aspects of pavement design, such as integration of climatic and traffic loading with structural response codes, allowance for library of material properties and various options for providing the inputs (default properties versus user provided properties), linking of pavement distress data with pavement performance. All of these capabilities suggest that the GUI is a critical component of the design procedure, without which, a pavement designer will be faced with manually integrating several different components and repeating their use over several iterations. Lack of a GUI will not only make the design procedure extremely laborious, but will also introduce a greater probability of user error. Another key feature of the GUI is that it allows users to develop a library of material properties and pavement structures that can be quickly recalled during the design process, thereby increasing productivity and eliminating repetitive data input steps.

The development of the GUI for the proposed model is completed at this stage and a detailed description is provided in Chapters 3. Chapter 4 demonstrates the application of the GUI through use of an example. At present, the second phase of model development is under-way. Therefore, as an interim analysis engine the existing program “TCModel” from the current version of the MEPDG is being utilized to test the new GUI developed herein. Upon completion of model development in the second phase of this study, the existing TCModel program will be replaced by the finite-element based cohesive zone thermal cracking prediction model.

2.4 Finite-Element Based Analysis Model (Phase-II)

For simulation of crack initiation and propagation, a finite-element based simulation model is being developed. A cohesive zone model was selected for fracture modeling because of its accuracy and efficiency in accounting for material response ahead of the crack tip in the fracture process zone (region of micro-cracking, crack pining, crack branching, material softening, etc.). The bilinear model implementation developed by Song et al. (2006) is being utilized. This model allows for minimizing artificially-induced compliance by adjusting the initial slope of the cohesive law. The fundamental material parameters used in the cohesive fracture model are: material strength and fracture energy. The fracture energy measurements from DC(T) test (described in Section 1.4) will be utilized. A schematic of the bilinear model is shown in Figure 4.

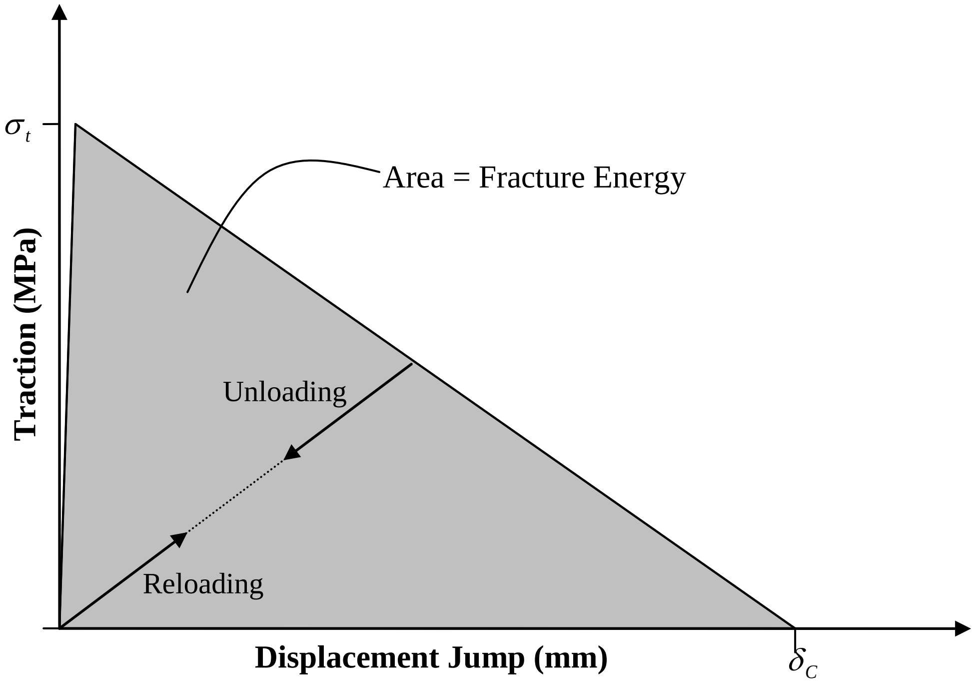


Figure 4: Schematic of Bilinear Cohesive Zone Model Governing Local Material Separation

Other key features of the analysis model include:

- Built-in mesh generator for the finite element model, which will generate the finite element model for the pavement structure input by the user through the GUI.
- Use of realistic pavement temperature profiles as the loading conditions. The temperature profiles will be determined using the Integrated Climatic Model (ICM) from the MEPDG and linked to the analysis model through the GUI.
- Viscoelastic analysis capabilities for accurate representation of the rate and temperature dependent material behavior of asphalt concrete

CHAPTER 3. VISUAL LTC DEVELOPMENT

3.1 Introduction

This chapter describes the development and implementation of Visual LTC. Section 3.1 discusses the implementation of Visual LTC in an object oriented setting. Section 3.2 discusses the class structure and organization details of the object oriented program. Section 3.3 addresses the method of data storage utilized by Visual LTC.

3.2 Implementation of Visual LTC in C#

Visual LTC is written in C# (pronounced “see-sharp”) under Microsoft’s .NET framework. C# is an object oriented language that provides some favorable attributes for software development. Given the nature of the proposed GUI and the nature of material database development and distribution/sharing, an object-oriented language appears to be necessitated. The Visual LTC uses an intuitive class structure to represent data (i.e. each pavement layer is a new instance of a class). In fact, C# provides automatic garbage collection, meaning memory accumulated during program execution is recycled. Lack of memory management can lead to leaks in which memory used by the program is not released. Ultimately, an accumulation of memory without garbage collection can diminish code performance. Given the computational intensity of the time-stepping, viscoelastic/fracture based cracking model being developed, the benefits of automatic garbage collection makes C# a good choice for Visual LTC development.

Additionally, C# utilizes exception handling, which prevents the program from ending abruptly due to an unexpected error. In the case of user error (i.e. invalid input), C# may throw an exception from one area of the source code to another. Visual LTC is programmed in such a way that the code expects such errors, informs the user of the invalid input, and allows the user to change the input. In the unlikely event of some other unexpected error, Visual LTC will display an error message indicating why the program failed.

Although there are other programming-languages with similar attributes to C#, the .NET framework made C# the clear choice for Visual LTC. The advantage of Microsoft’s .NET framework is that building and running applications are specifically supported. Programs written in C# under the .NET framework are intended for use as deployable software. Visual LTC is easily programmed, then locally executed and will be internet distributed.

3.3 Organization of Visual LTC

Visual LTC takes advantage of the object-oriented nature of C# by using an intuitive class structure to represent the data input by the user. Table 2 shows the various classes and organization of the Visual LTC code. Figure 5 shows a schematic of the pavement structure storage. Each layer is either an AsphaltLayer or BaseLayer object, stored as a list in the Project class.

Table 2: Visual LTC Classes

Class	Subclasses	Data Stored	Functions
C_sharpDatabase	n/a	• Available locations • Existing mixes, bases, subgrades • Existing projects	• Loads existing data when Visual LTC starts
Layer	AsphaltLayer	• All asphalt properties	• Gets and sets properties
	BaseLayer	• All base and subgrade properties	• Gets and sets properties
Location	n/a	• Climatic station data	• Gets and sets properties
Project	n/a	• All general project data • List of layers representing pavement structure	• Gets and sets project data
RunExecutables	n/a	• None	• Runs external executable analysis modules
TextFileHandler	n/a	• None	• Reads data in from text files • Writes data out to text files

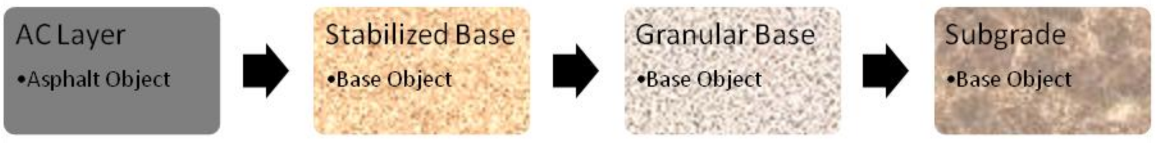


Figure 5: Schematic of storage of pavement structure in Project class

In addition to the classes list in Table 2, eight graphical user interfaces are used to collect data and run the analysis. Several analysis modules are required to conduct low temperature cracking, described in Table 3.

Table 3: Analysis tools utilized by Visual LTC

Module	**Inputs**	**Function**	**Output**
Master.exe	• Creep compliance test data • Asphalt layer properties	• Constructs master creep compliance curve	• Voight-Kelvin Model and Power Law coefficients
ICM.exe	• Location's climatic data	• Constructs temperature profile of pavement section	• Pavement temperatures at various depths with time
TCModel.exe	• Master.exe and ICM.exe output • Calibration factors	• Computes amount of cracking versus time	• Amount of cracking with time

Figure 6 shows the major operations performed by Visual LTC (further details of key operations are discussed in section 3.4). Data is entered into the Visual LTC interface by the user. Visual LTC creates 4 input files: inputmc.prm, .out, data.in, and *.icm. Files are passed to the first two analysis modules, Master.exe, which creates the master creep compliance curve, and ICM.exe which constructs the temperature profile of the pavement section. The output files of those modules are comply.in and thermal.tmp, which are then passed to the final analysis module, TCModel. The amount of cracking versus time is computed in TCModel and returned, as output file yrcrack.tcr, to Visual LTC for post processing (i.e. graphing). Notice that the only contact point for the user is with the interface; the other analysis modules and input/output files are embedded in Visual LTC.

3.4 Data storage and user accessibility

Several factors affected the way data is stored in Visual LTC. The user should have access to the following data: existing projects from previous Visual LTC runs, existing asphalt mixes from previous Visual LTC runs, default asphalt mixes packaged with Visual LTC, and climatic data files. (Climatic data files are assumed to be downloaded by the user at http://onlinepubs.trb.org/onlinepubs/archive/mepdg/home.htm).

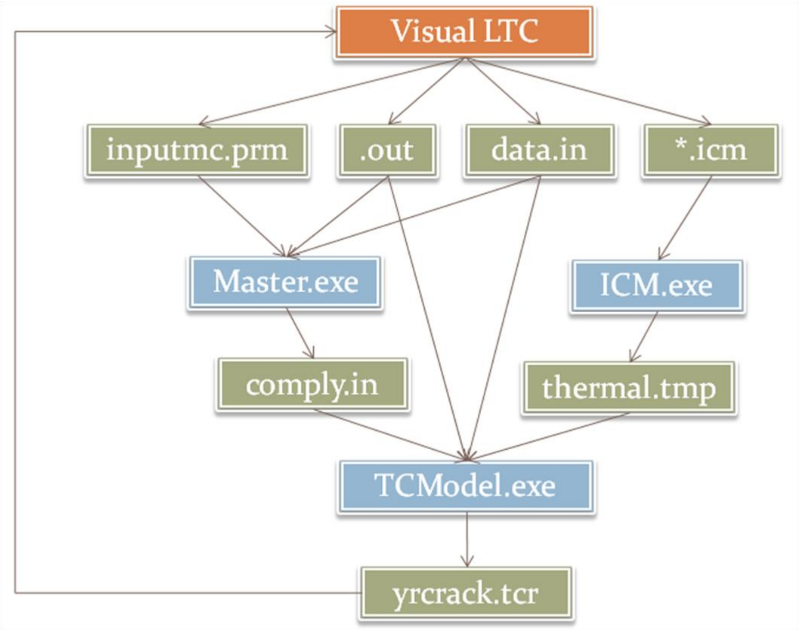


Figure 6: Operations performed by Visual LTC

Since Visual LTC is designed to allow users to conduct multiple analyses quickly, modifications to existing data and new data in one Visual LTC run should be available to the user in subsequent runs. For example, if the user creates a new mix in one run, that mix should be available in the next run.

Additionally, the data storage method was constrained in the sense that the user cannot be required to install any additional software to run the program. Hence, options such as an external database were not feasible. Based on the considerations above, data storage is handled with input files, output files and a working directory.

3.4.1 **Working Directory and Input Files**

Two types of input files hold all the information necessary to execute Visual LTC. The first file type holds all the data for a specific asphalt mix and has extension ".acinp" (for asphalt concrete input file). Table 3 shows the information stored in the *.acinp files. The units shown in Table 3 are not consistent in English or SI units; however, they were chosen to be units typically used by engineers familiar with the existing model.

Each file represents an asphalt mix that will be available to the user to assign to an asphalt layer. At the beginning of a Visual LTC run, the user selects a working directory which is immediately parsed for these *.acinp files. The user has the option of importing an *.acinp file from a different location on his/her machine. The user also has the option to save modifications to an existing mix or to add a new mix, in which case a new *.acinp file is created and saved in the working directory. (The users' ability to add and modify mixes is described in section 4.2.)

Table 4: Asphalt Concrete Input File Data

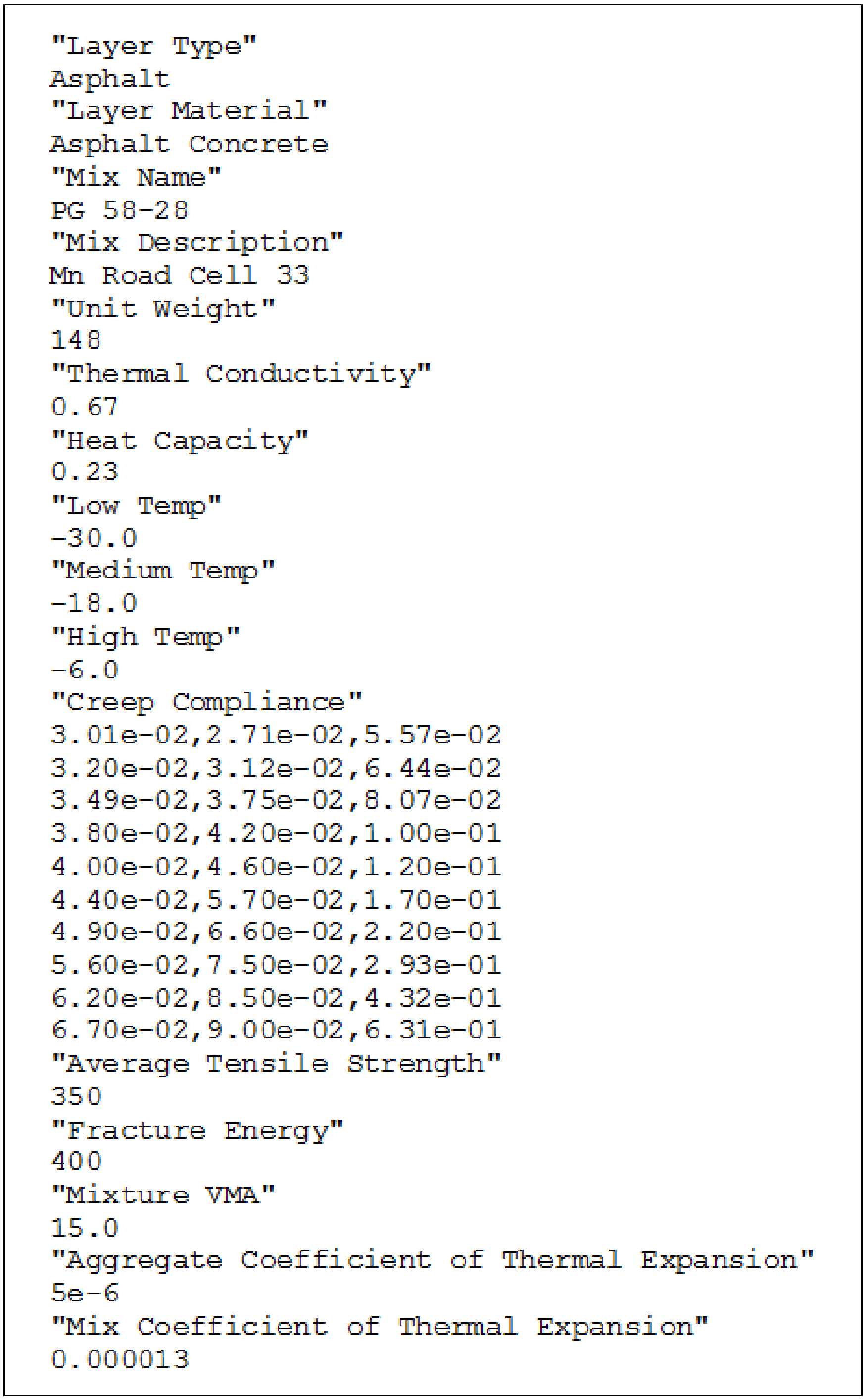
Item	**Units**
Layer Type	n/a
Layer Material	n/a
Mix Name	n/a
Mix Description	n/a
Unit Weight	g/cm^3
Thermal Conductivity	BTU/hr-ft °F
Heat Capacity	BTU/lb °F
Creep Compliance Test Low Temperature	°C
Creep Compliance Test Medium Temperature	°C
Creep Compliance Test High Temperature	°C
Creep Compliance Test Data	1/GPa
Average Tensile Strength	Mpa
Fracture Energy	J/m^2
Mixture VMA	%
Aggregate Coefficient of Thermal Expansion	mm/mm/°C
Mix Coefficient of Thermal Expansion	mm/mm/°C

Table 5: Project Input File Data

Item	**Note**
Project Name	Optional
Project Description	Optional
Analyzed By	Optional
Date	Optional
Working Directory	Directory on User's Machine
Climatic File	Climatic Station ID
Analysis Period	Length or Dates
Days	Only required if analysis period is "Length"
Start Date	Only required if analysis period is "Dates"
End Date	
Num AC Layers	1 layer currently supported
Asphalt Layer Files	File name
Num Base Layers	At least one
Base Layer Type	Repeated for each base layers
Base Layer Material	
Last Layer (t/f)	
Thickness	

The second file type, the project file (*.prj), is only required if the user is opening an existing Visual LTC project. At the beginning of a Visual LTC run, the user can start a new project, in which case no *.prj file is necessary, or work from an existing project. In the latter case, Visual LTC parses the file and populates the Visual LTC interface accordingly. Additionally, the user may choose to save a project at any time while entering data. A *.prj file is automatically generated and saved in the working directory. Table 5 shows the specific information stored in the *.prj files.

Input files are parsed in Visual LTC and stored as objects in the C_sharpDatabase class. The format of the input files are intended to be intuitive, allowing the end user to write one manually. Each data item requires a flag on the preceding line indicating what the data represents. A typical *.acinp file is shown in Figure 7. The *.prj files have a similar format.



```
"Layer Type"
Asphalt
"Layer Material"
Asphalt Concrete
"Mix Name"
PG 58-28
"Mix Description"
Mn Road Cell 33
"Unit Weight"
148
"Thermal Conductivity"
0.67
"Heat Capacity"
0.23
"Low Temp"
-30.0
"Medium Temp"
-18.0
"High Temp"
-6.0
"Creep Compliance"
3.01e-02,2.71e-02,5.57e-02
3.20e-02,3.12e-02,6.44e-02
3.49e-02,3.75e-02,8.07e-02
3.80e-02,4.20e-02,1.00e-01
4.00e-02,4.60e-02,1.20e-01
4.40e-02,5.70e-02,1.70e-01
4.90e-02,6.60e-02,2.20e-01
5.60e-02,7.50e-02,2.93e-01
6.20e-02,8.50e-02,4.32e-01
6.70e-02,9.00e-02,6.31e-01
"Average Tensile Strength"
350
"Fracture Energy"
400
"Mixture VMA"
15.0
"Aggregate Coefficient of Thermal Expansion"
5e-6
"Mix Coefficient of Thermal Expansion"
0.000013
```

Figure 7: Typical *acinp File

3.5 *Visual LTC Key Program and User Steps*

The keys programming steps of Visual LTC are illustrated in Figure 8. The operations performed by Visual LTC are shown in yellow boxes, while the user inputs are shown in rounded blue boxes.

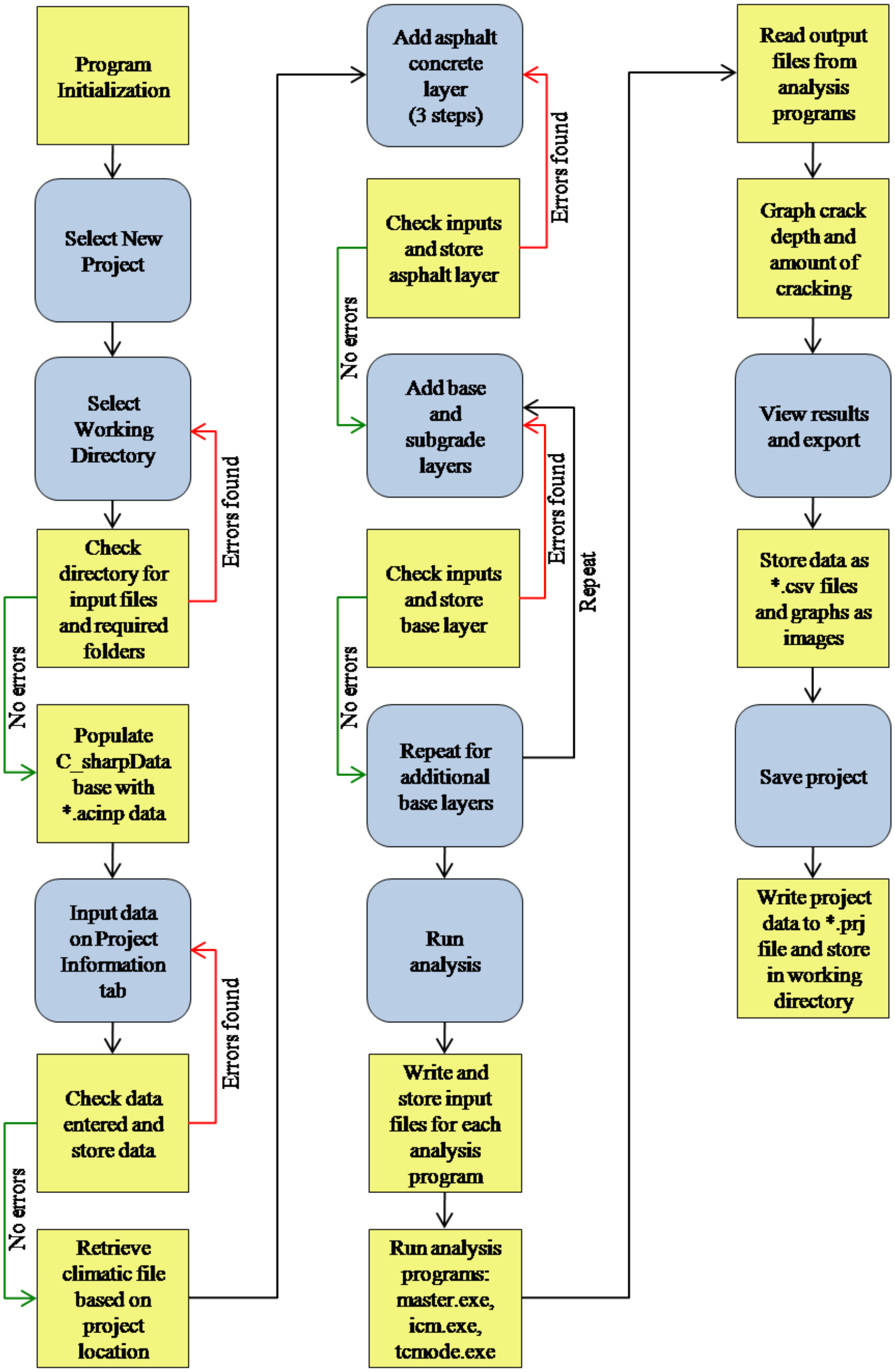


Figure 8: Key programming steps of Visual LTC

CHAPTER 4. FUNCTIONALITY OF VISUAL LTC

4.1 Introduction

This chapter describes the usability of Visual LTC from the perspective of the user. Section 4.1 describes the five main sections of the program, each of which require user input. Section 4.2 further explains the usability of Visual LTC in context of various user types.

4.2 Required User Input to Visual LTC

Visual LTC is intended to be a very user friendly and intuitive graphical user interface for conducting low-temperature cracking analysis of asphalt concrete pavements. Upon execution, the user is greeted by an interface organized into four main sections:

Section 1 – Start: The user either opens an existing project or starts a new project

Section 2 – Project Information: The user inputs general information about the project including project name, location, length of analysis, etc.

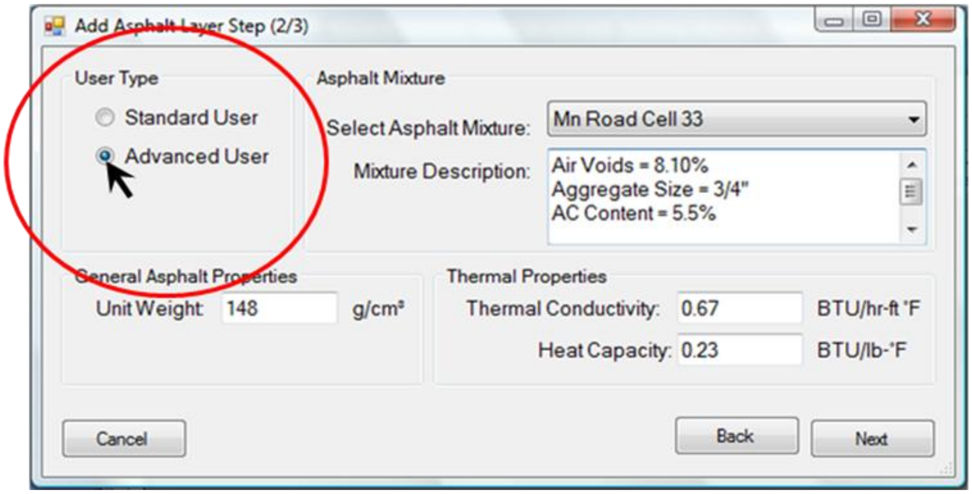
Section 3 – Pavement Materials and Structure: The user builds the pavement structure by adding layers (i.e. asphalt layer, base layers, subgrade layer). Data for each layer is entered as it is added. Properties for several materials (i.e. asphalt mixes, stabilized bases, granular bases, and subgrades) are included as default options for the user.

Section 4 – Run: User selects run and Visual LTC executes the necessary analysis modules stores results for post processing.

Section 5 – Results: Results are displayed to the in graphical form. (i.e. amount of cracking with time and feet of cracking in 500 feet of pavement) The user has options of saving graphical output as image files and of exporting raw data to .csv files for further post processing.

4.3 User types

Visual LTC is intended for use by practitioners and researchers alike. Therefore, two user types are supported: “Standard User,” and “Advanced User.” Both users have access to all functionality described in Chapter 3. However, Advanced Users have the additional capability of adding new asphalt mixes and modifying properties of existing asphalt mixes. The distinction between these user types is present so that existing properties are protected from accidental user error. The user can easily change from one user type to the other, and assumes the responsibility of entering consistent data. Figure 9 shows the option for the user to toggle between type “Standard User” and “Advanced User.”



Add Asphalt Layer Step (2/3)

User Type

○ Standard User

● Advanced User

Asphalt Mixture

Select Asphalt Mixture: Mn Road Cell 33

Mixture Description:
Air Voids = 8.10%
Aggregate Size = 3/4"
AC Content = 5.5%

General Asphalt Properties

Unit Weight: 148 g/cm³

Thermal Properties

Thermal Conductivity: 0.67 BTU/hr-ft °F

Heat Capacity: 0.23 BTU/lb-°F

Figure 9: User type selection option

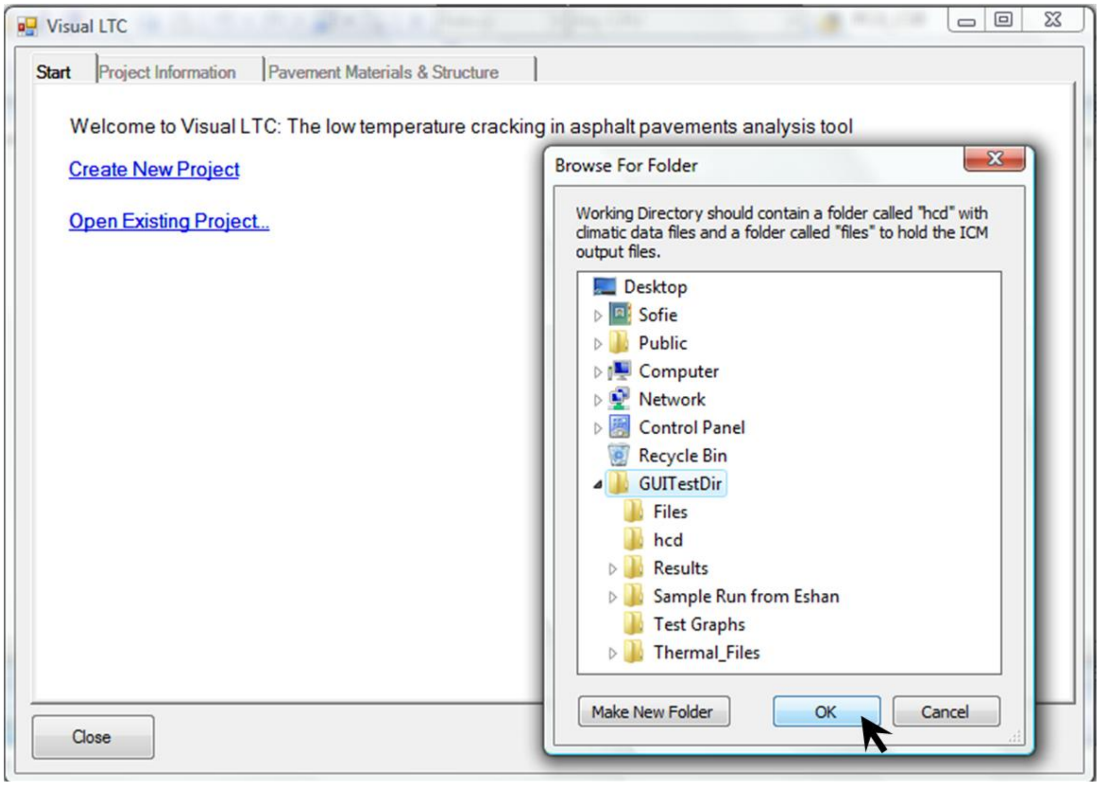
CHAPTER 5. APPLICATIONS OF VISUAL LTC

5.1 *Introduction*

Chapter 5 illustrates a sample run of Visual LTC. Section 4.1 details the execution of the program including user options and input. Section 4.2 compares results obtained with Visual LTC.

5.2 *Sample execution of Visual LTC*

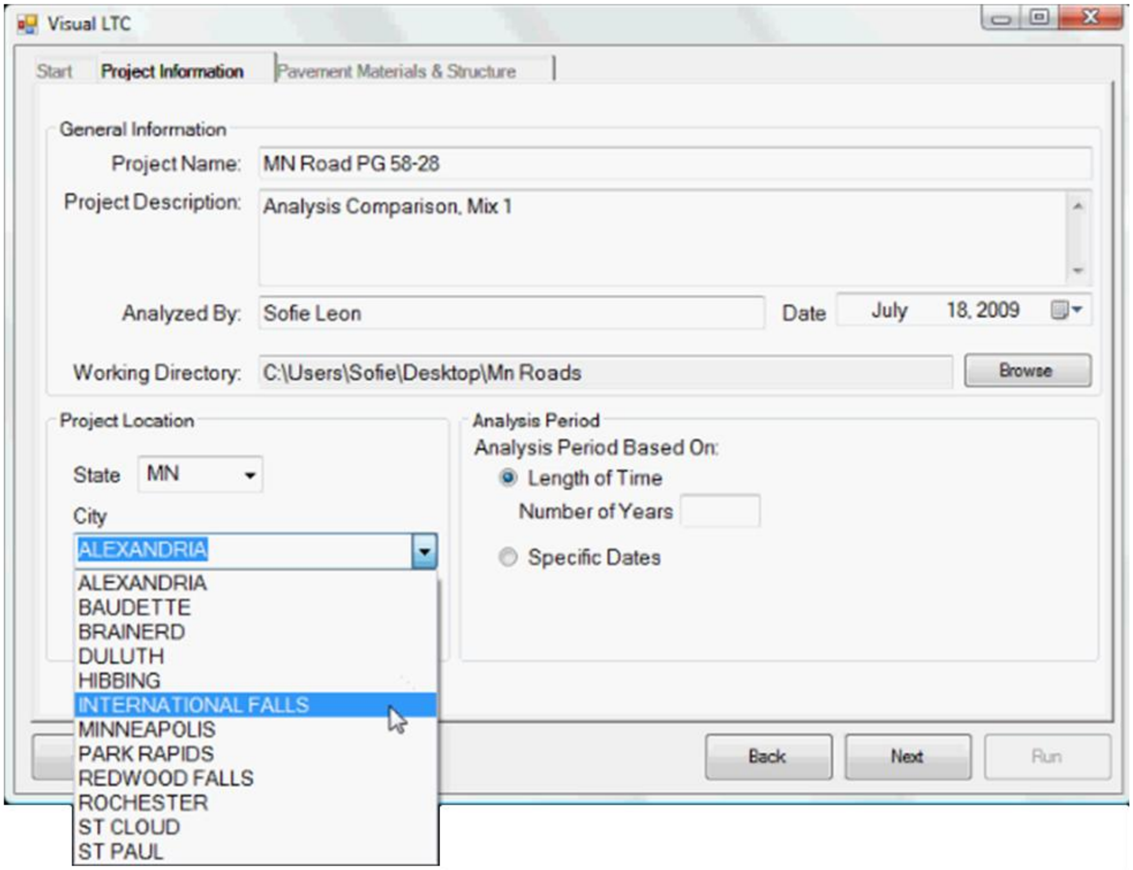
Figures 10-20 illustrate the execution of Visual LTC. This example is typical of how a "Standard User" would use Visual LTC.



Welcome to Visual LTC: The low temperature cracking in asphalt pavements analysis tool

Working Directory should contain a folder called "hcd" with climatic data files and a folder called "files" to hold the ICM output files.

Figure 10: The user creates a new project and selects working directory



General Information

Project Name: MN Road PG 58-28

Project Description: Analysis Comparison, Mix 1

Analyzed By: Sofie Leon

Date July 18, 2009

Working Directory: C:\Users\Sofie\Desktop\Mn Roads

Project Location

State MN

City ALEXANDRIA

Analysis Period

Analysis Period Based On:

● Length of Time

Number of Years

○ Specific Dates

Figure 11: The user supplies general project information, selects a location and enters analysis period

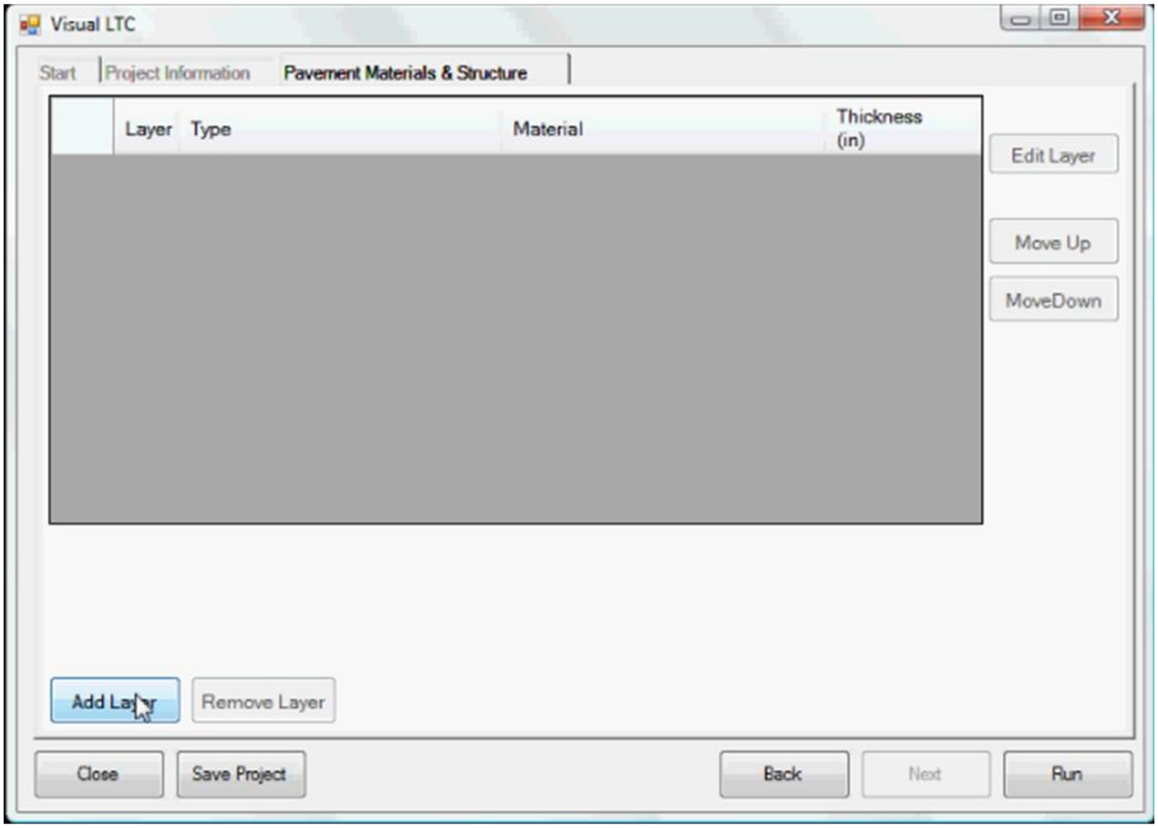
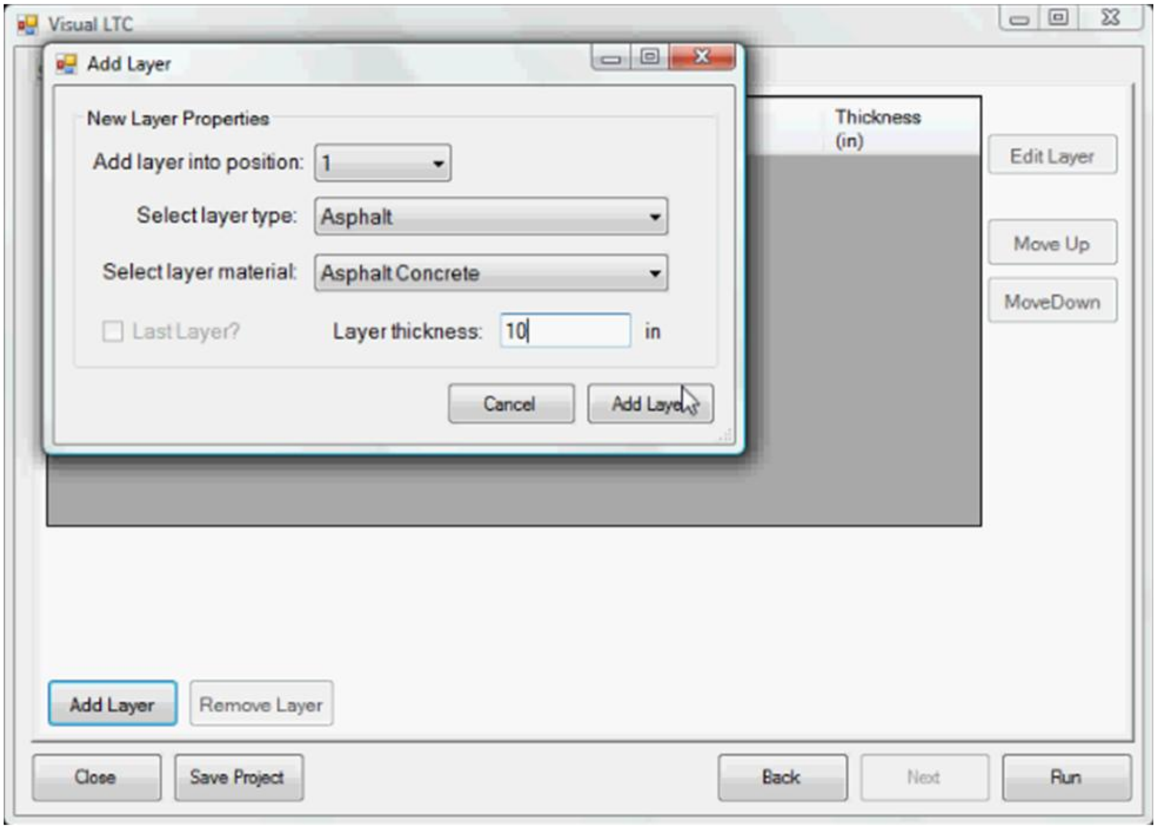


Figure 12: The user begins building the pavement structure



Add layer into position: 1

Select layer type: Asphalt

Select layer material: Asphalt Concrete

☐ Last Layer?

Layer thickness: 10 in

Figure 13: The user defines the first layer as an asphalt concrete layer

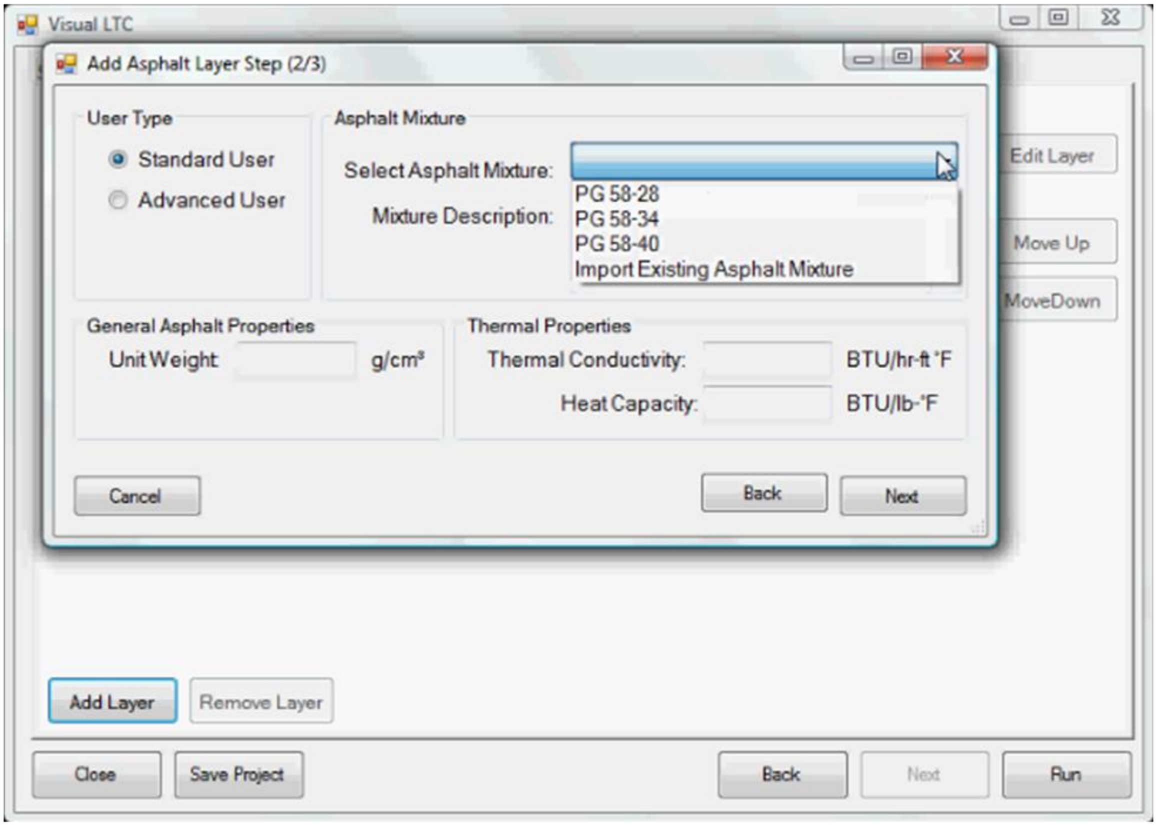
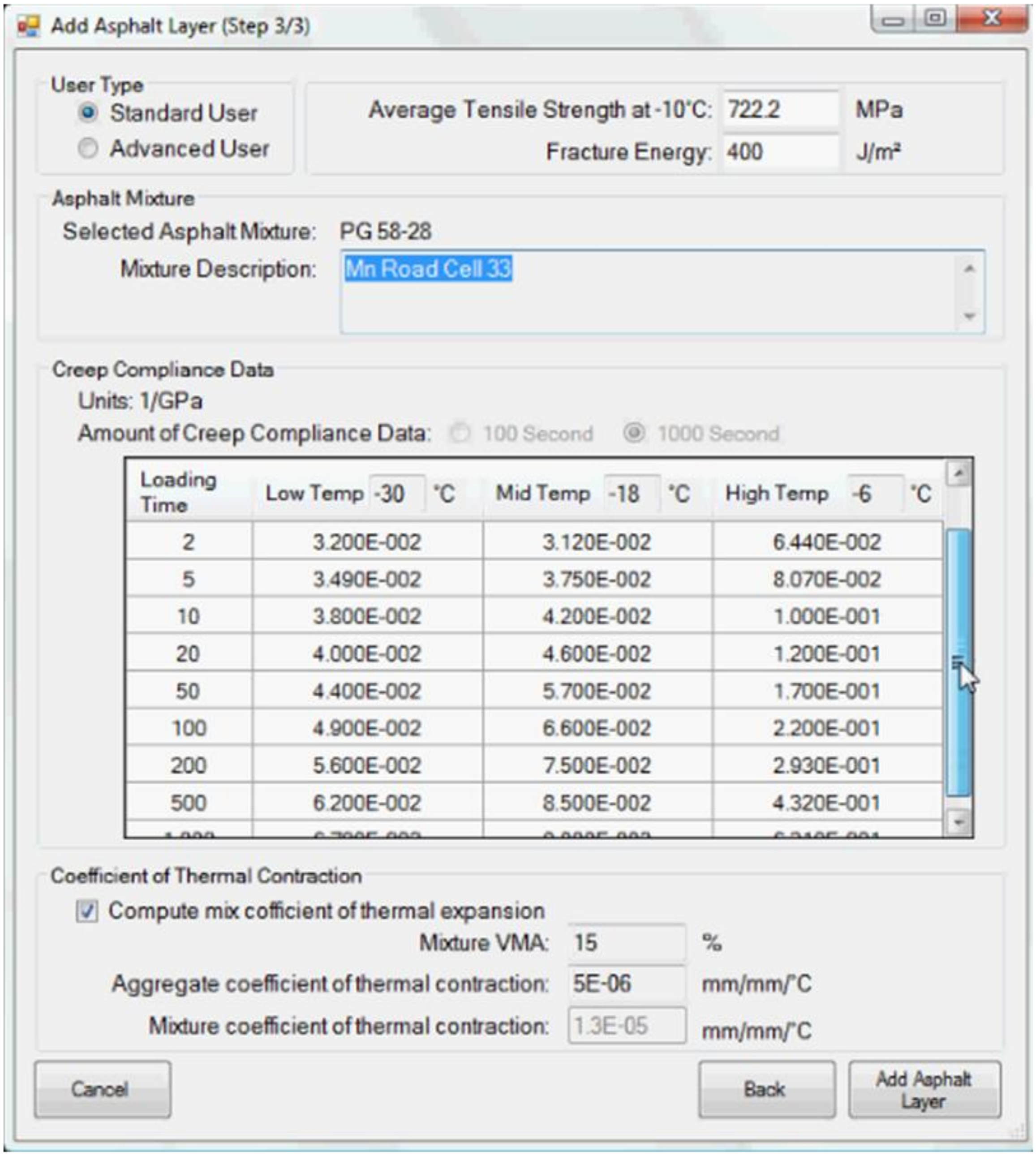


Figure 14: As a “Standard User” the user selects an existing asphalt mixture



Add Asphalt Layer (Step 3/3)

User Type

● Standard User

○ Advanced User

Average Tensile Strength at -10°C: 722.2 MPa

Fracture Energy: 400 J/m²

Asphalt Mixture

Selected Asphalt Mixture: PG 58-28

Mixture Description: Mn Road Cell 33

Creep Compliance Data

Units: 1/GPa

Amount of Creep Compliance Data: ○ 100 Second ● 1000 Second

Loading Time	Low Temp -30 °C	Mid Temp -18 °C	High Temp -6 °C
2	3.200E-002	3.120E-002	6.440E-002
5	3.490E-002	3.750E-002	8.070E-002
10	3.800E-002	4.200E-002	1.000E-001
20	4.000E-002	4.600E-002	1.200E-001
50	4.400E-002	5.700E-002	1.700E-001
100	4.900E-002	6.600E-002	2.200E-001
200	5.600E-002	7.500E-002	2.930E-001
500	6.200E-002	8.500E-002	4.320E-001

Coefficient of Thermal Contraction

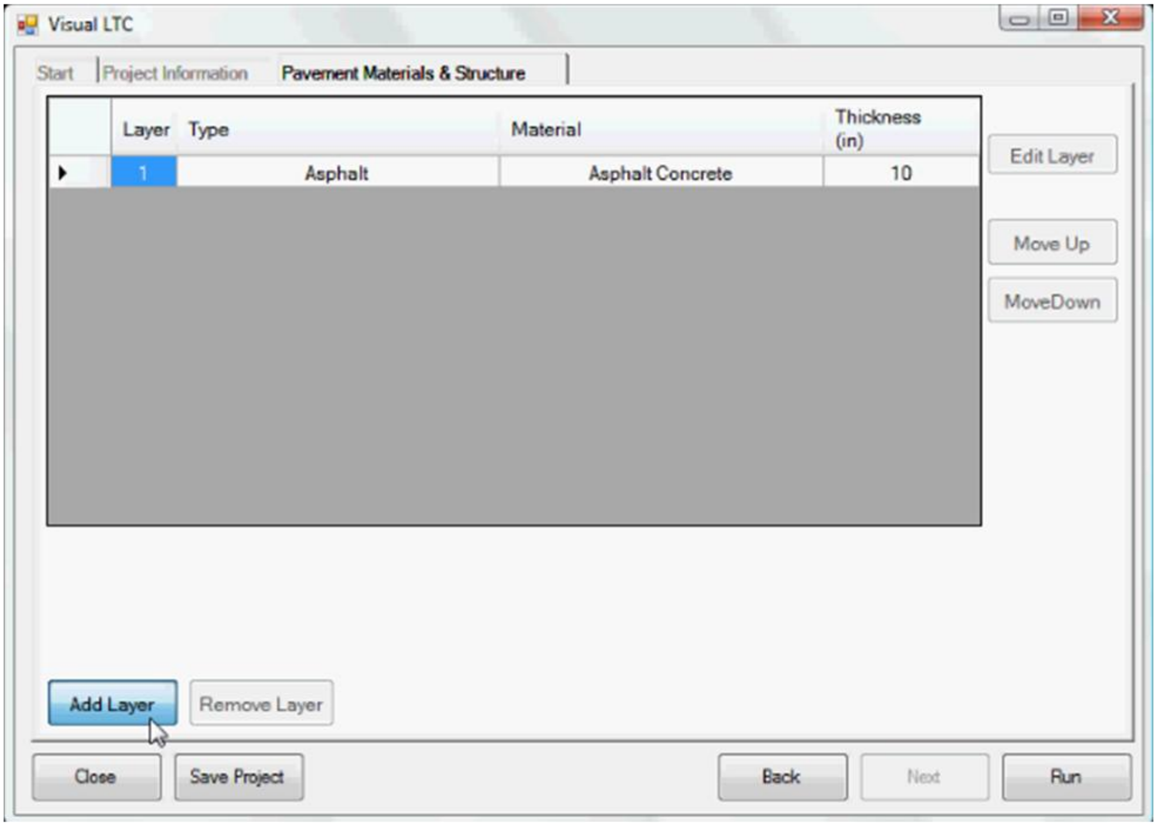
☑ Compute mix cofficient of thermal expansion

Mixture VMA: 15 %

Aggregate coefficient of thermal contraction: 5E-06 mm/mm/°C

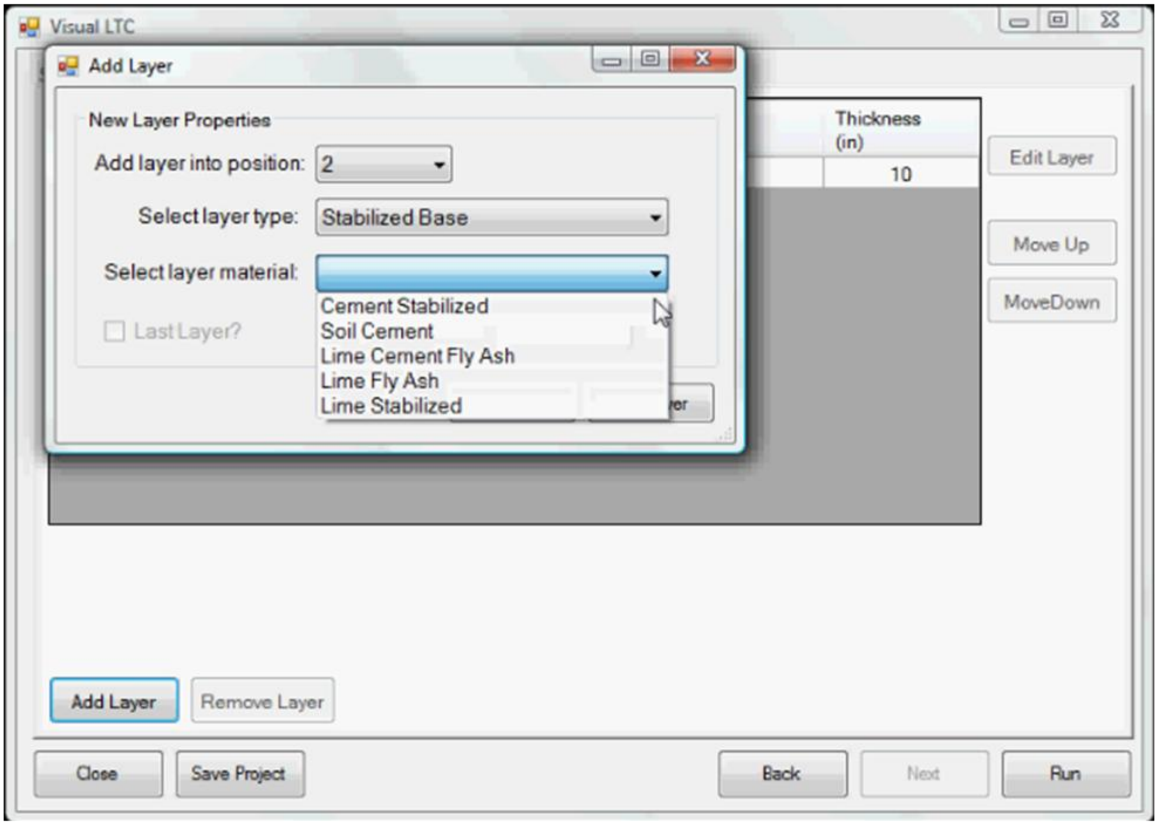
Mixture coefficient of thermal contraction: 1.3E-05 mm/mm/°C

Figure 15: The properties associated with the selected mix are default values.
(The user can change to an advanced user to modify any of the properties)



Layer	Type	Material	Thickness (in)
1	Asphalt	Asphalt Concrete	10

Figure 16: After the asphalt layer in entered, the user begins adding the base and subgrade layers.



New Layer Properties

Add layer into position: 2

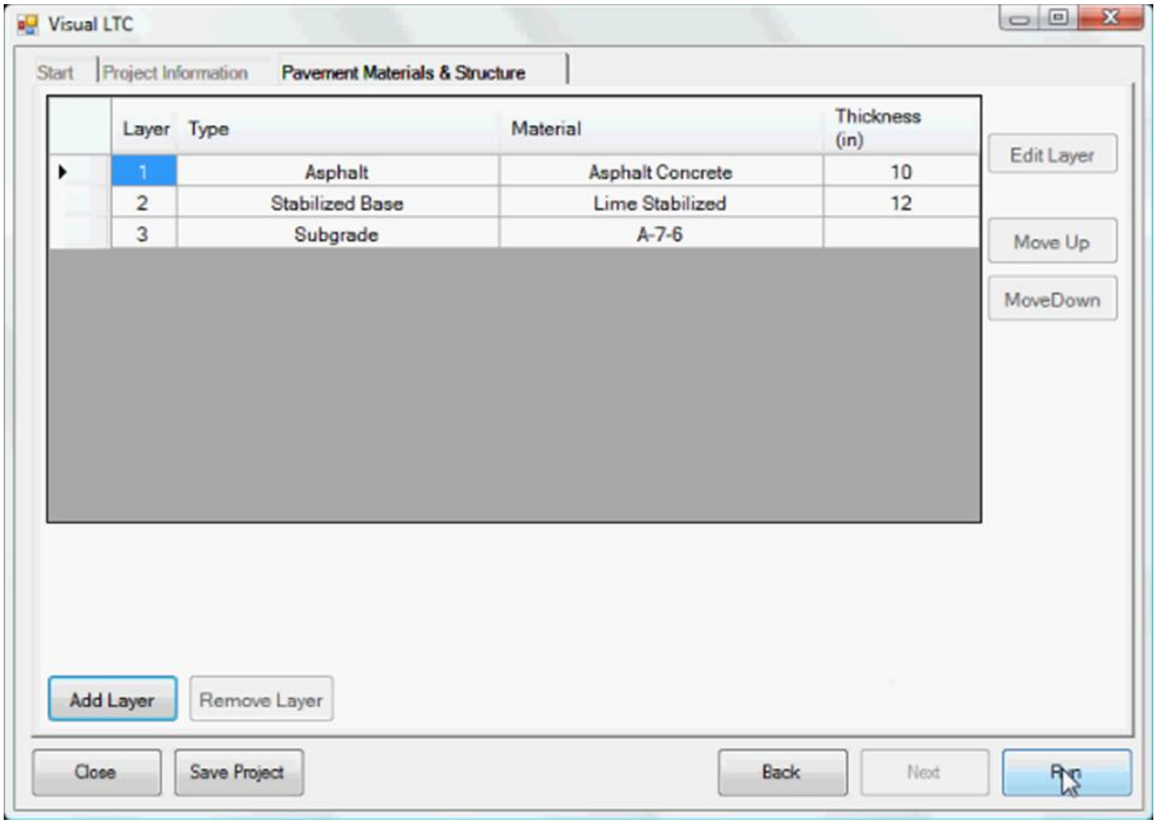
Select layer type: Stabilized Base

Select layer material:

- Cement Stabilized
- Soil Cement
- Lime Cement Fly Ash
- Lime Fly Ash
- Lime Stabilized

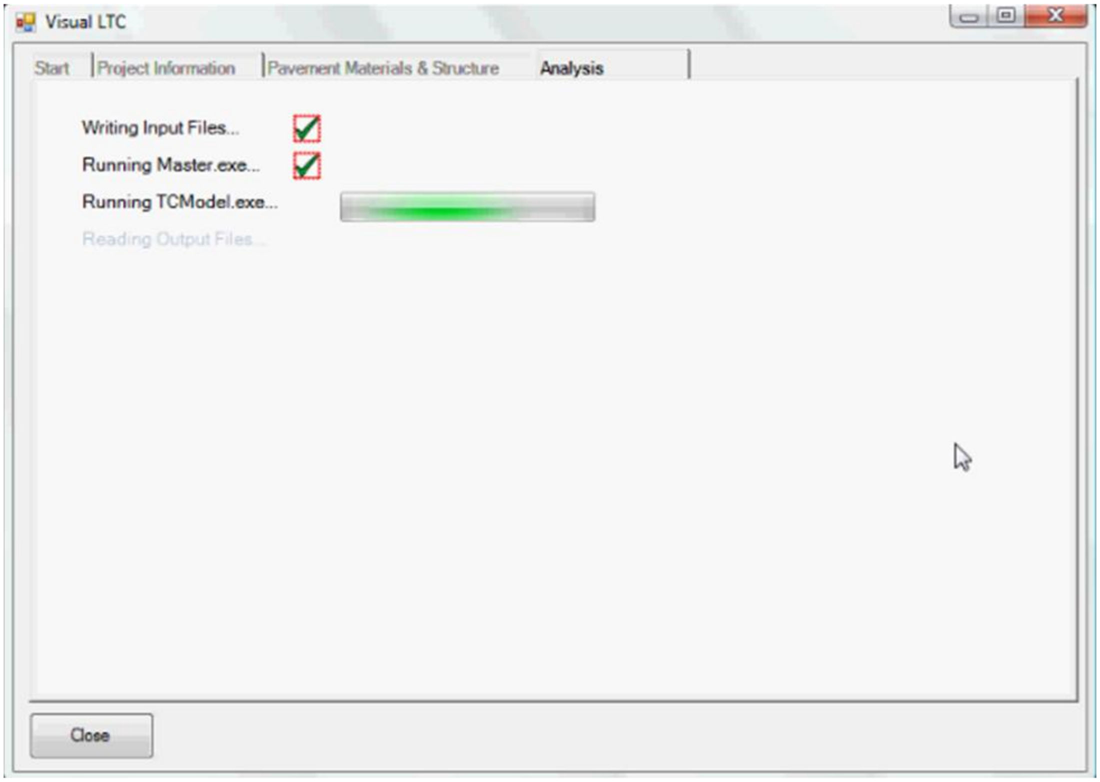
☐ Last Layer?

Figure 17: The user chooses a base layer from the list of existing stabilized bases



Layer	Type	Material	Thickness (in)
1	Asphalt	Asphalt Concrete	10
2	Stabilized Base	Lime Stabilized	12
3	Subgrade	A-7-6	

Figure 18: After adding all layers, the user is ready to run the thermal cracking analysis



Writing Input Files... ☑
Running Master.exe... ☑
Running TCModel.exe...
Reading Output Files...

Figure 19: Various analysis modules run and inform the user of progress

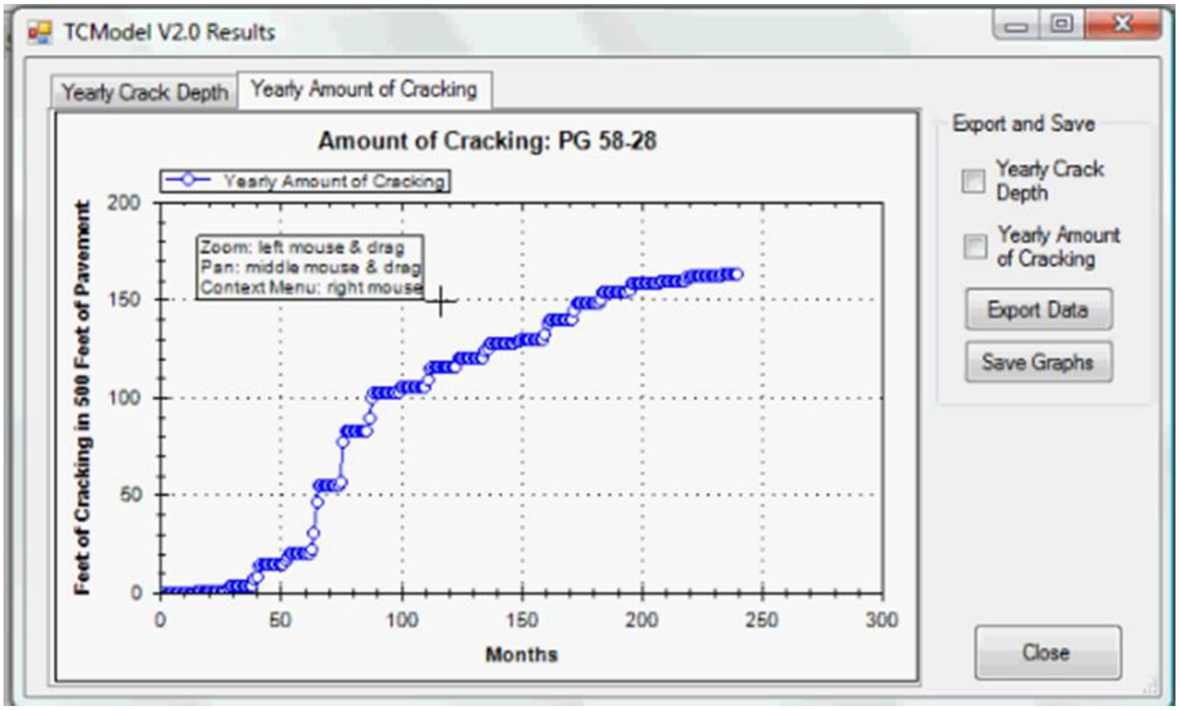


Figure 20: Results are plotted and displayed to the user. The user can export the data in comma separated variable (*.csv) format and save the graphs as images.

5.3 *Comparison of Visual LTC results*

Visual LTC was used to conduct a simple comparison of two asphalt mixes used in International Falls, MN. The user-friendly interface allows a user to conduct such a comparison quickly and effectively. Ultimately, Visual LTC can be used as a design tool; users can modify mix properties, run a sophisticated low-temperature analysis and modify their design as necessary. Figure 21 shows a comparison of the amount of cracking with time for a stiffer binder (PG58-28) and more flexible binder (PG58-40). As expected the more flexible binder shows lower cracking with time. Because this model directly outputs cracking in a physical sense, it can be directly used in a pavement management or asset management system. For instance, cracking amount can be used to compute maintenance costs, time to the next major rehabilitation, performance of subsequent overlay cycles, and to future pavement salvage values.

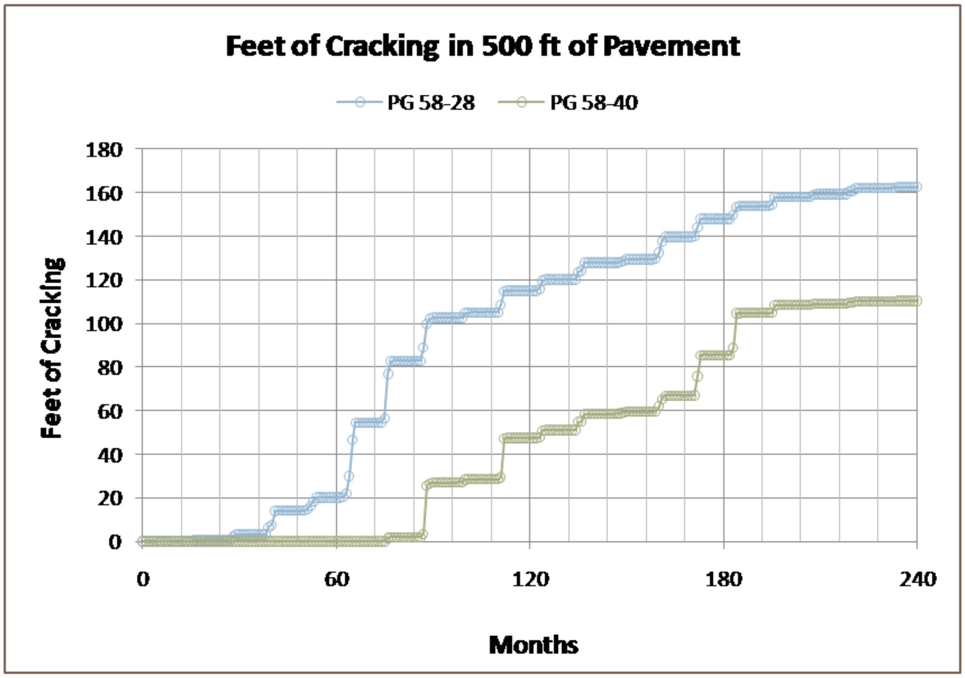


Figure 21: Performance of PG58-28 and PG58-40 binders in International Falls, MN

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

6.1 Summary

This work addresses the primary objective of making advanced low-temperature cracking models available to researchers and practitioners through a stand-alone user-friendly software tool. The first phase of the project involved the development of a graphical user interface, or GUI, calledVisual LTC. The stand-alone code is now available to practitioners and researchers, and utilizes the thermal-cracking analysis model (TCModel) currently available in the MEPDG. Currently a finite-element based analysis engine is under development, which, when complete, will be incorporated into Visual LTC. This work is planned for the next phase of this project.

6.2 Future research

- Implementation of nonlinear cohesive zone model capabilities in **Visual LTC**
- Improvement of the user-interface of **Visual LTC** based upon feedback from the project panel and practitioners
- Development of a database of material properties
- Collaboration with Professor Yanfeng Ouyang at the University of Illinois, which will lead to the integration of this software with a more holistic asset management analysis system.

6.2.1 Availability of Visual LTC

An executable file for Visual LTC will be produced, which will be made available for download by practitioners and researchers. The executable file is compatible with any modern Windows-based operating system.

Additionally, the analysis programs will be required to run Visual LTC. Therefore, master.exe, icm.exe and tcmodel.exe will also be available for download.

Existing asphalt mixtures are easily imported into Visual LTC, as described in chapter 3. When Visual LTC is made available for download several sample mixes will also be available. The existing mixes will be available in the form of *.acinp files. The user can either put these files into the working directory or import from a different location. As described in chapter 3, Visual LTC will parse the *.acinp files make the data available to assign to asphalt layers.

6.2.2 Improved Thermal Cracking Model

The current model for thermal cracking, TCModel (Hiltunen 1994) uses asphalt mixture fracture parameters, empirically derived from conventional creep and strength data obtained with the IDT, in a basic power law equation (Paris, 1961) to track thermal crack propagation. The authors acknowledged that the Paris law approach is more appropriate for shorter cracks propagating in stable fatigue and less appropriate for single event thermal cracking that has a devastating effect in very cold climates. Therefore an improved thermal cracking model that better captures the true fracture properties of asphalt concrete, is necessary. A new model (NewTCModel), based on the Cohesive Zone Model (CZM) (Song et al., 2006) tailored for fracture in HMA is currently under development. This model will take into account previously neglected effects, such as: combined thermal and mechanical loads, quasi-brittle failure mode of asphaltic materials, multiple asphalt surface layers, and aging induced material property gradients.

REFERENCES

A. K. Apeagyei, W. G. Buttlar, and B. J. Dempsey (2008). "Investigation of Cracking Behavior of Antioxidant-Modified Asphalt Mixtures." *Journal of the Association of Asphalt Paving Technologists*, Volume 77, pp. 393-430.

ARA, Inc. (2004) “Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures,” National Cooperative Highway Research Program, Project 1-37A, Final Report.

J. Baek, and I. L. Al-Qadi. (2006) “Finite Element Method Modeling of Reflective Cracking Initiation and Propagation: Investigation of the Effect of Steel Reinforcement Interlayer on Retarding Reflective Cracking in Hot-Mix Asphalt Overlay,” *Transportation Research Record: Journal of Transportation Research Board*, Record Number 1949, pp. 32-42.

E. V. Dave, S. H. Song, W. G. Buttlar, and G. H. Paulino (2007). "Reflective and Thermal Cracking Modeling of Asphalt Concrete Overlays,” Proceedings of the International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, Taylor and Francis.

E. V. Dave, A. F. Braham, W. G. Buttlar, G. H. Paulino, and A. Zofka (2008). “Integration of Laboratory Testing, Field Performance Data, and Numerical Simulations for the Study of Low-Temperature Cracking,” Proceedings of the 6th RILEM International Conference on Cracking in Pavements, Chicago, USA, Eds. Al-Qadi, Scarpas, and Loizos, CRC Press Taylor and Francis Group, New York, ISBN: 978-0-415-4757-54, pp. 369-378.

D. R. Hiltunen and R. Roque. (1994) “A Mechanics-Based Prediction Model for Thermal Cracking of Asphaltic Concrete Pavement.” *Journal of the Association of Asphalt Paving Technologists*, Volume 63, pp. 81-108.

R. L. Lytton, J. Uzan, E. G. Femando, R. Roque, D. Hiltunen, and S. M. Stoffels. (1993) “Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixes,” Final Report, Strategic Highway Research Program, Project SHRP-A357, Washington DC.

M. Marasteanu, A. Zofka, M. Turos, X. Li, R. Velasquez, X. Li, C. Williams, J. Bausano, W. Buttlar, G. Paulino, A. Braham, E. Dave, J. Ojo, H. Bahia, A. Gallistel, and J. McGraw. (2007) “Investigation of Low Temperature Cracking in Asphalt Pavements”, National Pooled Fund Study 776, Minnesota Department of Transportation, Research Services MS 330, St. Paul, MN 55155, 2007.

P. C. Paris, M. P. Gomez and W. E. Anderson. (1961) "A rational analytic theory of fatigue." The Trend in Engineering. Volume 13, pp. 9-14.

G. H. Paulino, W. G. Buttlar, P. B. Blankenship, M. P. Wagoner, S. H. Song, and E. V. Dave. (2006) "Final Report for NSF-GOALI Project - CMS:0219566," National Science Foundation, Washington, DC, 2006.

R. Roque, D. R. Hiltunen, W. G. Buttlar. (1995a) "Thermal Cracking Performance and Design of Mixtures Using Superpave(TM*)," Journal of the Association of Asphalt Paving Technologists*, Volume 64, pp. 718-735.

R. Roque, D. Hiltunen, W. Buttlar, T. Farwana. (1995b) "Engineering Properties of Asphalt Mixtures and the Relationship to their Performance," STP1265 Engineering Properties of Asphalt Mixtures and the Relationship to their Performance, ASTM International.

F. V. De Souza, J. Soares, D. H. Allen, and F. Evangelista Jr. (2004) "Model for predicting damage evolution in heterogeneous viscoelastic asphaltic mixtures. *Transportation Research Record: Journal of Transportation Research Board*, Record Number 1891, pp. 131-139.

S. H. Song, G. H. Paulino, and W. G. Buttlar. (2006) **"**A Bilinear Cohesive Zone Model Tailored for Fracture of Asphalt Concrete considering Rate Effects in Bulk Materials," *Engineering Fracture Mechanics*, Volume 73, Number 18, pp. 2829-2848.

M. P. Wagoner, W. G. Buttlar, and G. H. Paulino. (2005a) "Development of a Single-Edge Notched Beam Test for Asphalt Concrete Mixtures", *ASTM Journal of Testing and Evaluation*, Volume 33, pp. 452:460.

M. P. Wagoner, W. G. Buttlar, and G. H. Paulino. (2005b) "Disk-Shaped Compact Tension Test for Asphalt Concrete Fracture", *Experimental Mechanics*, Volume 45, pp. 270-277.

M. P. Wagoner, W. G Buttlar, G. H. Paulino and P. I. Blankenship. (2006) "Laboratory Testing Suite for Characterization of Asphalt Concrete Mixtures Obtained from Field Cores", *Journal of the Association of Asphalt Paving Technologists*, Volume 75, pp. 215-251.

X. Li, M. O. Marasteanu, N. Iverson, and J. F. Labuz, (2006) "Observation of Crack Propagation in Asphalt Mixtures with Acoustic Emission," *Transportation Research Record: Journal of Transportation Research Board*, Record Number 1970, pp 171-177.