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Development of Performance-based Specifications for Louisiana Asphalt Mixtures

by

Louay N. Mohammad, Ph.D.
Minkyum Kim, Ph.D.
Harshavardhan Challa

LTRC & LSU

4101 Gourrier Avenue | Baton Rouge, Louisiana 70808
(225) 767-9131 | (225) 767-9108 fax | www.ltrc.lsu.edu

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16. Abstract

Quality control and quality assurance (QC/QA) specifications typically define the asphalt mixtures by how close the as-built mixture meets the requirements of the as-designed mix. A common QC/QA specification for asphalt pavement construction is based on controlling the volumetric properties of compacted asphalt mixtures such as air voids, asphalt content, and aggregate gradation. However, there is no fundamental correlation to ensure that these volumetric properties are sufficient to provide satisfactory long term performance of the asphalt pavements. In order to address the issue in the current QC/QA specification, it is needed to develop a performance-based specification (PBS), which measures the mechanical and/or engineering properties of asphalt mixture as performance predictors of finished pavements. Such a PBS must be verified to actual field performance data. The objective of this study is to develop a framework for the implementation of PBS for Louisiana. To achieve this objective, nine asphalt paving projects were selected across the state. A total of 14 pavement sections that includes 21 asphalt mixtures were selected. A suite of laboratory tests using the Hamburg type loaded-wheel tester (LWT) and the semi-circular bending (SCB) device were performed to evaluate the rutting (in terms of rut depth, RD) and cracking resistance (in terms of critical strain energy release rate, Jc), respectively. In addition, indirect tensile dynamic modulus test (IDT $|E^*|$) were conducted to evaluate the viscoelastic properties of the asphalt mixtures. The dynamic modulus from IDT $|E^*|$ can be used as a material input in the Mechanistic-Empirical Pavement Design Guide (MEPDG) software to predict the 20-year projected distresses. The field distress data were obtained from Louisiana pavement management system (LA-PMS) for the selected projects and used to calibrate the 20-year projected rutting by the MEPDG simulations. From the comparison analyses, it was observed that the LWT measured rut depths of 6 mm or less and 10 mm or less can be the tentative quality limits for the Level 2 and Level 1 Louisiana asphalt pavements, respectively. Similarly, the minimum SCB Jc values of 0.6 and 0.5 kJ/m^2 for Level 2 and Level 1 asphalt pavements, respectively, seemed to serve well as the tentative criteria to avoid crack related problems. Along with the tentative rutting and cracking performance criteria, a draft sampling and testing plan of the PBS was proposed. A continued effort to collect more field and laboratory performance data in accordance with the proposed PBS is desired to validate the tentative performance criteria and to address unknown challenges for DOTD and contractors in implementing the proposed PBS

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Janice P. Williams, P.E.
DOTD Chief Engineer

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Louay N. Mohammad, Ph.D.
Professor of Civil and Environmental Engineering
Department of Civil and Environmental Engineering
Director, Engineering Materials Characterization Research Facility
Louisiana Transportation Research Center
Louisiana State University

Minkyum Kim, Ph.D.
Research Associate
Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808

Harshavardhan Challa
Graduate Research Assistant
Department of Civil and Environmental Engineering
Louisiana State University
4101 Gourrier Ave., Baton Rouge, LA 70808

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ABSTRACT

Quality control and quality assurance (QC/QA) specifications typically define the asphalt mixtures by how close the as-built mixture meets the requirements of the as-designed mixture. A common QC/QA specification for asphalt pavement construction is based on controlling the volumetric properties of compacted asphalt mixtures such as air voids, asphalt content, and aggregate gradation. However, there is no fundamental correlation to ensure that these volumetric properties are sufficient to provide satisfactory long term performance of the asphalt pavements. In order to address the issue in the current QC/QA specification, it is needed to develop a performance-based specification (PBS), which measures the mechanical and/or engineering properties of asphalt mixture as performance predictors of finished pavements. Such a PBS must be verified to actual field performance data.

The objective of this study is to develop a framework for the implementation of a PBS for Louisiana. To achieve this objective, nine asphalt paving projects were selected across the state. A total of 14 pavement sections that includes 21 asphalt mixtures were selected. A suite of laboratory tests using the Hamburg type loaded-wheel tester (LWT) and the Semi-Circular Bending (SCB) device were performed to evaluate the rutting (in terms of rut depth, RD) and cracking resistance (in terms of critical strain energy release rate, Jc), respectively. In addition, indirect tensile dynamic modulus test (IDT $|E^*|$) were conducted to evaluate the viscoelastic properties of the asphalt mixtures. The dynamic modulus from IDT $|E^*|$ can be used as a material input in the Mechanistic-Empirical Pavement Design Guide (MEPDG) software to predict the 20-year projected distresses. The field distress data were obtained from Louisiana pavement management system (LA-PMS) for the selected projects and compared with the laboratory test results.

From the comparison analyses, it was observed that the LWT measured rut depths of 6 mm or less and 10 mm or less can be the tentative quality limits for the Level 2 and Level 1 Louisiana asphalt pavements, respectively. Similarly, the minimum SCB Jc values of 0.6 and 0.5 kJ/m^2 for Level 2 and Level 1 asphalt pavements, respectively, seemed to serve well as the tentative criteria to avoid crack related problems. Along with the tentative rutting and cracking performance criteria, a draft sampling and testing plan of the PBS was proposed. A continued effort to collect more field and laboratory performance data in accordance with the proposed PBS is desired to validate the tentative performance criteria and to address unknown challenges for DOTD and contractors in implementing the proposed PBS.

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IMPLEMENTATION STATEMENT

Based on the findings and the results of this project, a simplified performance-based specification, tailored for the needs of Louisiana asphalt pavements, was developed. Tentative performance criteria, established based upon the historical performance data of Louisiana asphalt mixtures and asphalt pavements, are expected to provide a reliable means to ensure satisfactory long-term performance of new and rehabilitated Louisiana asphalt pavements. The applicability of the proposed sampling and testing plan for the PBS should be evaluated through pilot projects where continuous field construction and laboratory performance data should be collected and analyzed to identify any other challenges that have not been considered.

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INTRODUCTION

Background

In order to accomplish quality construction of asphalt pavements, an effective construction specification is essential. Such a specification should clearly state the quality goals to ensure that the as-built pavement meets the as-designed criteria. Louisiana's current construction specification for asphalt pavements adopts a quality control (QC) and quality acceptance (QA) procedure, which describes the required quality goals in terms of the volumetric and physical properties of asphalt mixtures and roadways *[1]*. Since the introduction in 1976, Louisiana's QC/QA specification has served well in numerous highway construction projects. In recent years, however, asphalt pavements built with acceptable levels of quality by the current specification have started to experience premature failures more frequently than before. Primary causes of the frequent premature failures of asphalt pavements can be attributed to the increased traffic volume on highways *[2]*. Adaptation of unconventional asphalt paving technologies, such as the use of high percentage recycling materials, polymer modified asphalt cements, warm-mix asphalt technologies, etc., can also make it challenging to adequately guarantee the long-term performance of pavements with conventional quality goals such as voids filled with asphalt (VFA), voids in mineral aggregate (VMA), air voids (AV), roadway density, and international roughness index (IRI). Therefore, it is necessary to improve the reliability of the construction specification by implementing more effective QC/QA methodologies. Coupled with the rapid decline of experienced QC/QA personnel, this lack of effective QC/QA methodologies pose a tremendous challenge to ensure long-term performance of asphalt pavements in Louisiana.

Problem Statement

Performance related specifications (PRS) and/or performance based specifications (PBS) are the two emerging approaches developed to overcome the shortcomings of the current QC/QA specifications by taking the predictable performance of pavements directly as the quality goals of the construction *[3]*. Of the two, PBS looks more promising as its primary quality measures are fundamental mechanical properties of asphalt mixtures, which are not dependent on the various innovative asphalt paving technologies. Clear understanding on the features and requirements of the PBS, however, is needed to prepare a tailored approach for the Louisiana Department of Transportation and Development (DOTD) to improve the effectiveness of current asphalt pavement specifications. This research, therefore, was conducted to investigate the applicability of key PBS principles and to develop a framework for the implementation of the tailored PBS for Louisiana asphalt pavement mixtures.

Literature Review

State of the Practice in Construction Specifications

Different types of construction specifications have been used by state highway agencies (SHAs) in the US for decades in order to guarantee quality construction of transportation infrastructures. These specifications range from the method specification to performance-based specification. Table 1 summarizes the definition, features, and advantage/disadvantage of various specifications evolved in the history of pavement construction *[3]*. Recognizing the drawbacks of the earlier types of specifications (e.g., method specifications or end-result specifications), the SHAs started to adopt quality assurance (QA) specifications in the late 1960s. According to a survey performed by Ksaibati and Butts in 2003, a majority of the SHAs adopted some variations of QA specifications for their asphalt pavement construction *[4]*. Figure 1 shows their survey result. Of the 45 SHAs that responded to the survey, 40 of them responded that they were using QA specifications while five states indicated that they did not have QA specifications for the asphalt pavements.

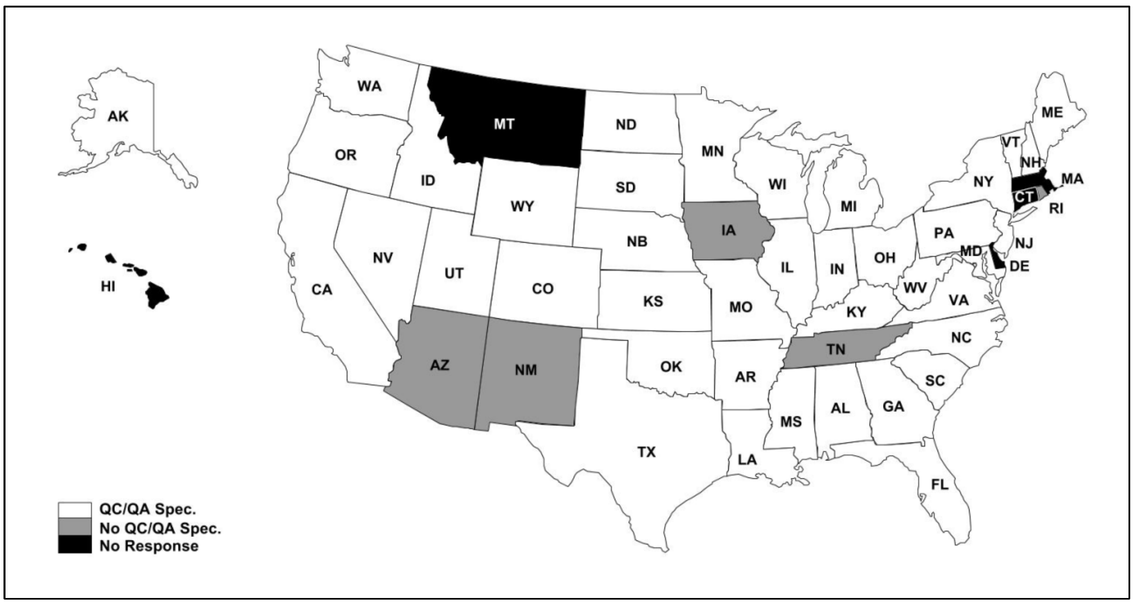

Figure 1
Use of asphalt pavement specifications *[4]*

Table 1
Types of pavement construction specifications *[3]*

Specification Type	Definition	Advantage/Disadvantage
Method Specifications	A specification that require the contractor to produce and place a product using specified materials in definite proportions and specific types of equipment and methods under the direction of the Agency	• Leaving no opportunity to the contractor to implement innovative or economical procedures and equipment. • Difficult to determine whether to correct the process, shut down production, or reject/remove material • Increased chances of disputes and confrontations
End-Result Specification (ERS)	A specification that require the Contractor to take the entire responsibility for producing and placing a product	• QC responsibility is often not clearly defined. • Difficult for timely identification and correction of work • Acceptance target values are often subjective
Quality Assurance (QA) Specification	A specification that require contractor Quality Control (QC) and Agency Acceptance (AA) activities throughout production and placement of a product	• Clearly specified sampling schedule for both QC and QA • Easier QC activity decision based on real-time monitoring of production • Require multiple measurements within an entire lot for reliability • Acceptance is based on the percentage of material within specified limits. • Provide rational mechanism to determine incentive or reduced pay
Performance-Related Specifications (PRS)	A specification that describe quantified Quality Characteristics that are related to product performance	• Acceptance based on key quality characteristics that correlate with fundamental engineering properties that predict performance • Models that predict the fundamental properties of materials using the key quality characteristics and the performance of pavements using the predicted fundamental properties are required. • Pay adjustments can be based on the expected life of the pavement.
Performance-Based Specifications (PBS)	A specification that describe the desired levels of fundamental engineering properties that are predictors of performance and appear in primary prediction relationships	• Acceptance based on fundamental engineering properties that predict performance • Performance prediction model that uses fundamental engineering properties are required. • Pay adjustments can be based on the expected life of the product.

In recent years, SHAs have become increasingly concerned on the performance of pavements and have put their efforts on implementing PRS and/or PBS. Clearly, a common benefit of implementing either of the two recently evolved types of specifications (PRS and PBS) is that they are both "performance-oriented" for the acceptance of the products.
However, distinctions among different levels of performance-oriented specifications need to be understood as discussed by Chamberlin *[5]*. Table 2 summarizes those distinctions in terms of the acceptance quality characteristics (AQCs), use of a mechanical property prediction model, use of a performance prediction model, and finally, a level of knowledge on the performance of the final product.

Table 2
Level of knowledge on the performance in various specifications

Key Features	Intuitive Specifications	PRS	PBS	Performance Spec. (PS)
Acceptance Quality Characteristic (AQC)	Non-fundamental or None	Volumetric Properties	Mechanical Properties	Performance
Mechanical Property Prediction Model	No	Yes	No	No
Performance Prediction Model	No	Yes	Yes	No
Knowledge on Performance	Intuitive	Empirical	Mechanistic-Empirical	Direct

The AQCs are the measurements of the product to be collected during the construction and the basis of quality control (QC) and quality acceptance (QA) decisions. Mechanical or volumetric properties of asphalt concrete such as the modulus, strength, asphalt content, density, etc. are examples of the AQCs. A mechanical property prediction model is the model used to estimate a mechanical property of asphalt mixtures (e.g., dynamic modulus) using other mechanical or non-mechanical properties. Witczak's predictive equation is such model which predicts the dynamic modulus of asphalt mixtures given some volumetric properties of the mixture composition *[6]*. A performance prediction model is used to forecast the long-term performance of pavements based upon the mechanical behavior of the pavement structures under specified environmental and loading conditions. The Mechanistic-Empirical Pavement Design Guide (MEPDG), commercial version of which is available as "AASHTOWare Pavement ME-Design (Pavement-ME, hereafter)," is considered as the most widely accepted performance prediction models in the recent years *[7, 8]*.

Intuitive specifications include any types of specifications that do not specify the performance criteria of the pavement, whether it is direct or indirect, as the final product quality. The method specification, which accepts the final product based only on the level of contractor's compliance to the instruction of the agency, is an example of the intuitive specification. In such a specification, the AQCs are typically not very well specified or non-fundamental properties at the most; therefore, the link from the AQC to the performance of the pavement is merely "intuitive."

On the other extreme, performance specifications (PS) describe how the built pavement should perform over time. The AQC is the pavement performance which can be described in terms of the level of distresses such as rutting, cracking, etc. or in terms of the cumulative traffic bringing the pavement to a condition defined as "failure" (e.g., service life). Hence, the link from the AQC to the performance of the pavement is "direct," and no prediction models are necessary. However, PS is not practically applicable to pavement construction projects, since the actual performance of pavements can only be determined at the end of the service life.

PRS describe the desired levels of AQC that are some volumetric properties, such as air voids, asphalt cement content, voids in the mineral aggregate, etc. PRS needs two prediction models: a material model for the AQC to mechanical property relationship and a subsequent performance model for the mechanical property to pavement performance relationship. Witczak's Predictive Equation and the Pavement-ME are examples of the material model and the performance model, respectively, *[6, 7]*. Thus, the linkage from the AQC to the performance is mostly empirical.

PBS describes the desired levels of fundamental mechanical properties of materials as the AQC. The mechanical properties, such as the dynamic modulus or creep compliance, are the key material input variables for the performance prediction models (e.g., the Pavement-ME). Its linkage from the AQC to the performance is mechanistic-empirical, since the predicted performance is based on the measured fundamental mechanical properties through empirical transfer functions between computed stress-strain and in-field performance of pavement structures. Compared to the PRS, PBS has an advantage on the AQCs that are fundamental mechanical properties of materials, and thus, eliminates the need for a material property prediction model. Yet, unlike the PS, a standard PBS procedure still requires a performance prediction model to estimate the long-term pavement performance. The prediction usually requires an extensive amount of information on the traffic, climate of the project area, structural pavement design, and material properties of sub-layers in addition to the asphalt surface course.

In fact, an alternative approach can be adopted to address the limitations of both PBS and PS. Table 3 describes the alternative approach (i.e., simplified PBS) to the standard PBS. In the simplified PBS, the AQCs can be chosen as semi-direct performance indicators of the pavement to eliminate the need for a performance prediction model. As long as the reliability of the selected performance indicators are proven by comparison analyses between field and laboratory performances, the simplified PBS can be a practical tool to ensure the long-term performance of constructed asphalt pavements.

Table 3
Alternative (simplified) PBS concept

Types of Specifications	Standard PBS	Alternative (simplified) PBS	Performance Spec. (PS)
Acceptance Quality Characteristic (AQC)	Mechanical Properties	Performance Indicator	Performance
Mechanical Property Prediction Model	No	No	No
Performance Prediction Model	Yes	No	No
Link to Performance	Mechanistic-Empirical	Semi-direct	Direct

Pavement Performance Indicators

Many laboratory and in-situ test methods have been proposed to measure the pavement performance indicators in simple and practical manners *[9-34]*. Rutting at high service temperatures and cracking at intermediate service temperatures are the two common asphalt pavement distresses, for which these test methods are developed to evaluate.

Laboratory Performance Tests

High Temperature Rut Resisting Performance Tests. At high in-service temperatures, asphalt pavements need to resist permanent deformation (or rutting) as the repetitive traffic loading passes over. Rutting in asphalt pavements can occur as a combination of progressive densification and shear deformation. Resistance to rutting used to be defined as a stability-related problem, and the stability was considered as the main property for asphalt mixture design to minimize rutting. Hubbard-Field, Marshall, and Hveem stability test methods are the examples of the stability-related mixture design *[9]*.

Witczak et al. and Witczak compared various laboratory test methods and their response parameters as the simple performance tests (SPTs) for evaluating asphalt mixtures' resistance to rutting *[10, 11]*. Reliability of discrimination, repeatability, complexity of procedure, equipment cost, testing time, and so forth were considered to select best candidate test methods and response parameters for evaluating the rut resisting performance of various asphalt mixtures. The analysis results led to a conclusion that the rut factor ($|E^*|/sin\delta$) measured at high temperatures (e.g., 38 to 54 °C), flow time (F_t), and the flow number (F_n) from triaxial tests are the three best laboratory test methods and parameters for the rutting resistance evaluations.

Other researchers have been using the Hamburg type loaded wheel tracking (LWT) device to evaluate the combined rutting and moisture damage potential (susceptibility) of asphalt mixtures *[12-17]*. According to an extensive literature review performed by Cooley et al., the correlations between the LWT measured rut depth (RD) and the actual field rutting performance are reasonably good when the loading and environmental conditions are considered, and thus, they concluded that the test methods have a potential to be used as a "pass/fail" type of criterion *[14]*.

Mohammad et al. investigated rutting performance indicators such as $|E^*|$, $|E^*|/sin\delta$, F_t, F_n, and LWT RD *[18]*. Various types of asphalt mixtures typically used in Louisiana for different levels of highways with varying traffic volume were included. Through a series of comparison analyses among the investigated performance indicators, they observed that these laboratory measured performance parameters are capable of discriminating different mixtures as different groups. This observation suggests that these parameters can be used as the asphalt mixtures' rutting performance indicators. However, their relationships to the actual pavement rutting performance have not been thoroughly investigated.

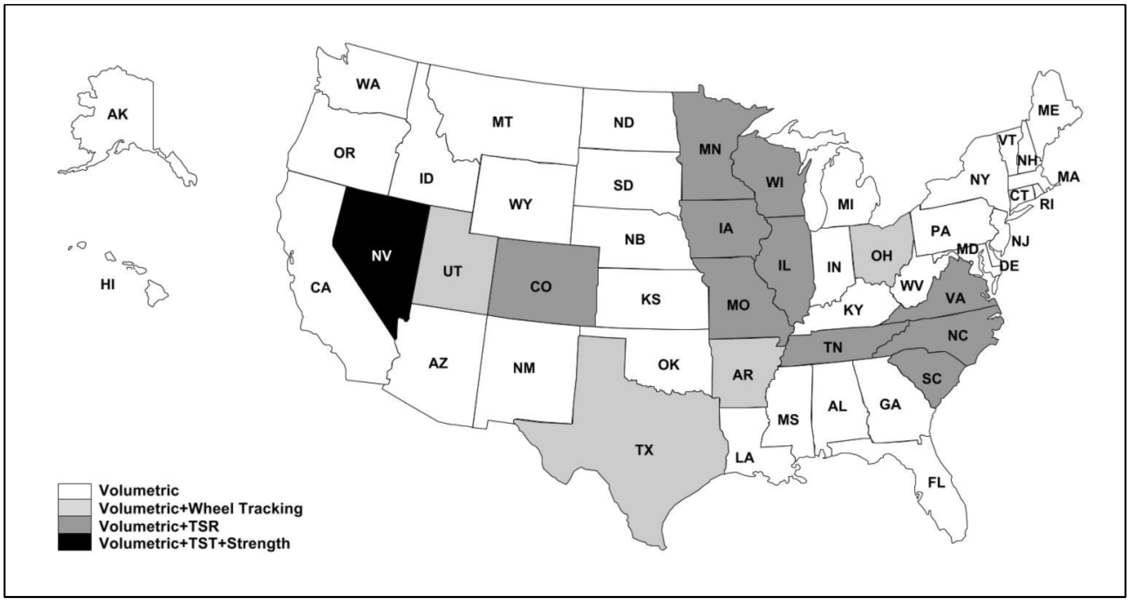

Figure 2
Types of quality characteristics used by state DOTs (2013)

As a part of the literature review of this study, an extensive survey of the asphalt pavement specifications across the US was conducted in 2013. The latest version of construction specifications of all 50 Department of Transportations (DOTs) were collected and reviewed to identify the quality requirements for asphalt pavements. Figure 2 summarizes the survey results with the types of quality characteristics adopted in the construction specifications of the state DOTs. Note that the asphalt mixture design, plant quality, and roadway quality requirements are combined all together in categorizing the states. A majority of states specify mixture volumetric properties, roadway density and roughness profile as the quality characteristics in their latest version of specifications. A number of states (11 out of 50), in addition to the volumetric properties, have included tensile strength ratio (TSR) of moisture conditioned specimen to unconditioned specimen as a performance criteria to minimize the moisture damage potential. Among them, Nevada is the only state to further specify the minimum tensile strength of unconditioned specimens as the mixture quality requirements. Four states (e.g., Arkansas, Ohio, Texas, and Utah) have implemented the Hamburg type wheel tracking tests as the rutting performance criteria.

Specific criteria and ranges of volumetric quality requirements vary from state to state as the historical performance of local pavements varies and the specific performance goals of one state differ from that of another. The wheel tracking test requirement also varies between states since it needs to be determined on the basis of historical rutting performance data of individual states.

Intermediate Temperature Crack Resisting Performance Tests. Cracking is a major distress type in asphalt pavements at intermediate service temperatures, which is caused by damage induced from repeated loadings. Formation of cracks on the pavement surface, coupled with moisture infiltration through the crack, generally expedites deterioration of the pavement structures and leads them into eventual loss of serviceability. Many laboratory test methods such as the beam fatigue, Texas overlay tester (OT), indirect tensile (IDT) strength, Asphalt Mixture Performance Tester (AMPT), and semi-circular bending (SCB) tests, to name few, have been used to characterize the resistance of asphalt mixture to cracking.

One of the most widely accepted laboratory test methods to evaluate cracking resistance of asphalt concrete at intermediate temperatures is the repeated loading beam fatigue test *[19-21]*. The typical response parameter of the test is load repetitions until failure or the constant rate of dissipated strain energy per loading cycle. Despite its popularity as a fundamental research tool among researchers, the test method has not been widely adopted by practitioners for routine use due to relatively large beam specimen size and longer testing time to complete *[22]*.

The overlay tester is one of the recently developed test methods for characterizing fatigue cracking resistance of asphalt mixtures *[23]*. Response parameters used to estimate the fatigue life of asphalt pavements are A and n, which are the fundamental fracture properties of asphalt mixtures obtained from Paris' Law. Reliability of the test method has been validated through the federal highway administration's accelerated loading facility (FHWA-ALF) fatigue tests, but because it is new, no further field validation has been conducted, yet.

The IDT test was developed early in the 1990s primarily to measure the creep compliance and tensile strength of asphalt mixtures at low temperatures *[24]*. The test method has been also used to determine the fracture properties of asphalt mixtures at intermediate temperatures *[25, 26]*. Primary response parameters measured from the test are tensile strength, strain at the peak load (or failure strain), toughness index (TI), and fracture energy. While strength and strain measures do not correlate with field cracking performance very well, TI and fracture energy have demonstrated promising relationships with the field cracking performance.

AMPT primarily measures the dynamic modulus of asphalt mixtures at broad ranges of loading frequencies and temperatures as recommended by Witczak et al. *[10]*. Witczak et al. specifically recommended the $|E^*|$ measured at low temperature ranges (e.g., 4 to 15 °C) for the fatigue cracking analysis. Some suggested benefits of the AMPT measured $|E^*|$ were compatibility with the Pavement-ME fatigue cracking prediction model and consistency in the test method for both rutting and cracking.

The SCB test method was originally used in rock mechanics and was adapted for asphalt mixture fracture property characterization during the past decades *[27]*. Fracture energy and critical *J*-integral (or critical strain energy release rate, Jc) are the two main response parameters of the test. Since its introduction, the SCB test method has been investigated by many researchers and was found to be a simple and reliable test method for estimating the fracture resistance of asphalt mixtures *[28-33]*. Some advantages of the SCB test method acknowledged by the researchers include the flexibility of specimen fabrication, quick testing time, and simplicity of the test procedure.

In-Situ Non-Destructive (NDT) Tests

Some NDT test methods, such as the light falling weight deflectometer (LFWD) and portable seismic property analyzer (PSPA), have been used to measure the modulus (or stiffness) of in-situ pavements. According to a comparison study between the in-situ and laboratory mechanical properties of asphalt mixtures conducted by Mohammad et al. *[34]*, a good relationship between the in-situ moduli measured by the LFWD and PSPA and laboratory measured moduli of asphalt mixtures was observed. It was also noted that the LFWD can be used as an alternative test device to FWD for the portability and convenience of testing. Based upon the observations, it can be expected that these in-situ test methods and response parameters (i.e., in-situ moduli) would relate to the modulus based rutting and fatigue cracking performance indicators recommended by Witczak et al. (i.e., $|E^*|/sin\delta$ at 38 to 54 °C and $|E^*|$ at 4 to 15 °C) *[10]*, and therefore, have a potential to eliminate the need for more complicated AMPT tests.

Summary

Findings of the literature review conducted in this study are summarized as follows:

- The concept of performance-based specification is plausible since it takes a more direct performance measure as the quality goal of the pavement construction. However, actual application of PBS requires somehow complicated performance predictions such as the Pavement-ME.

- An alternative simplified PBS approach can be used to improve the reliability of current QC/QA specifications while avoiding the complications of the standard PBS approach.

- Hamburg type LWT test can provide a practical means of evaluating rutting performance of asphalt mixtures in terms of the rut depth (RD).
- SCB test can be used to evaluate the cracking performance of asphalt mixtures in terms of the critical strain energy release rate (Jc).
- In-situ non-destructive test devices, such as the LFWD and PSPA, can be used to obtain the modulus based rutting and fatigue cracking performance indicators in a timely and convenient way.

OBJECTIVE

The primary objective of this research is to develop a framework for the implementation of a performance based specification (PBS) for new and rehabilitated asphalt pavements. Specific objectives of the study include:

- Identifying state-of-the-practice of PBS employed in highway agencies,
- Evaluating the applicability of key PBS principles to LA pavements,
- Developing a tailored PBS for DOTD, and
- Developing a framework of the PBS implementation in Louisiana.

SCOPE

Nine field project sites across Louisiana were selected and the approximate locations of the selected projects are shown in Figure 3. Of the nine projects, six were existing projects, which had been in service for three to eight years, and three were newly completed projects during the 2013-2014 construction season. The six existing projects consisted of 11 pavement sections with 15 asphalt mixtures, of which ten were Level 1 traffic mixtures and five were Level 2 traffic mixtures. The three new projects consisted of three pavement sections with six asphalt mixtures, all of them being Level 1 traffic mixtures. Both hot-mix asphalt (HMA) and warm-mix asphalt (WMA) technologies were used to produce these asphalt mixtures.

A suite of field and laboratory experiments were carried out to evaluate the performance of asphalt pavements in service. Laboratory tests were conducted on field core samples to evaluate rutting (permanent deformation) and cracking (fracture) resistance of asphalt mixtures at high and intermediate temperatures, respectively. Hamburg type loaded wheel tracking (LWT) test for rutting performance evaluation, semi-circular bending (SCB) test for cracking performance evaluation, and indirect tensile dynamic modulus (IDT $|E^*|$) test for full viscoelastic characterization of asphalt mixtures were conducted. In-situ non-destructive tests (NDT) were conducted where field core samples were collected. Light falling weight deflectometer (LFWD) and portable seismic property analyzer (PSPA) were used to measure the in-situ stiffness of the pavements.

METHODOLOGY

Study Approach

To achieve the aforementioned objectives of the study, the following research tasks were planned and conducted:

- Task 1 – Conducting literature review
- Task 2 – Identifying field projects and preparing samples
- Task 3 – Conducting laboratory and field experiments
- Task 4 – Performing data analyses
- Task 5 – Developing a prototype PBS
- Task 6 – Preparing a draft project report

Field Projects and Materials

Figure 3 shows the approximate locations of selected field projects across the state. A total of nine field projects were selected through a consultation with the DOTD construction and research personnel. All relevant design and construction records were collected including project design proposals and mixture design job-mix formulas (JMFs). Table 4 lists the nine field projects included in this study.

Among them, six were existing projects constructed three to eight years before the revisits during this study. Two different traffic levels are included among the existing projects. Projects I10 Egan (I10EG), I10 Vinton (I10VT), and LA964 Baker (964BK) composed of three pavement sections with five asphalt mixtures designed for Level 2 traffic volume in accordance with the 2006 LA Standard Specifications for Roads and Bridges. Projects US171 Shreveport (171SP), LA3121 Spearsville (3121SV), and LA116 Pineville (116PV) composed of eight pavement sections with 10 asphalt mixtures designed for Level 1 traffic volume. These six field projects with 11 pavement sections provided cored asphalt mixture samples brought to and tested in the Louisiana Transportation Research Center (LTRC) laboratory to measure the proposed performance indicators such as the LWT RD, SCB Jc, and dynamic modulus ($|E^*|$). Historical performance data of these pavement sections were collected from the Louisiana pavement management system (PMS) database as described in the later section, except the 116-1 section. The field performance data of 116-1 section were not found in the PMS database, and thus, no further comparisons with the laboratory performance indicators could be made.

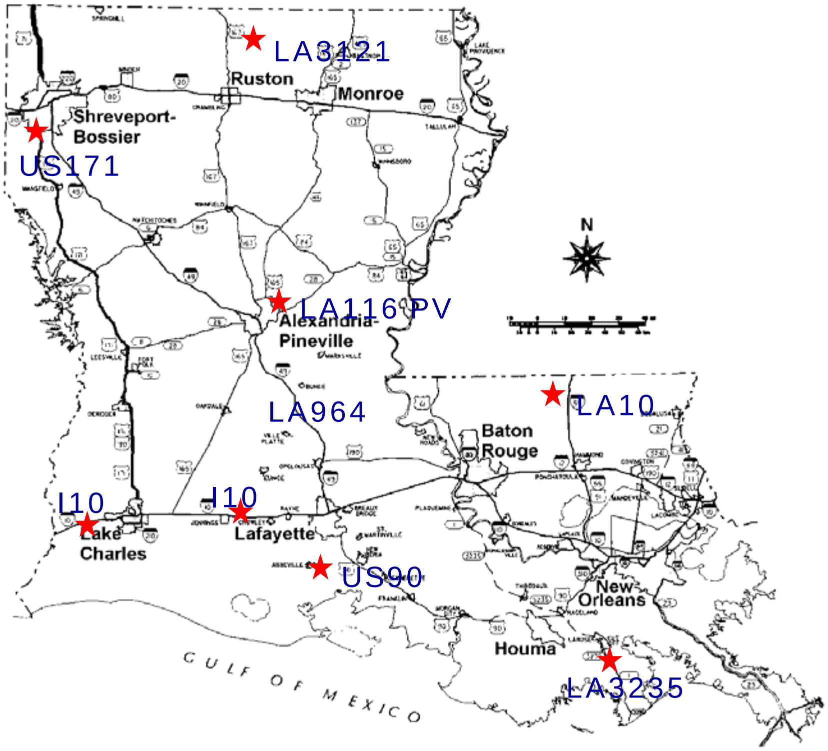

Figure 3
Approximate locations of selected field projects

In addition to the six existing projects, three new field projects in LA10 St. Helena (10SH), LA3235 Lafourche (3235LF), and US90 Iberia (90IB), which consist of three pavement sections with six asphalt mixtures, were selected to provide construction data and asphalt mixtures necessary for the verification of the proposed PBS approach. These asphalt mixtures were designed for Level 1 traffic volume.

All 21 asphalt mixtures included in this study are also shown in Table 4. Mixture IDs shown in the table are used throughout the report. Asphalt binder used for the asphalt mixtures ranged from PG70-22m to PG82-22rm where the letter “m” stands for “polymer modified” and “rm” stands for “crumb rubber modified” asphalt binders, respectively. The nominal maximum aggregate size of the mixtures ranged from 12.5 to 25.0 mm. Varying percentages of reclaimed asphalt pavement (RAP) from 0 to 30% were used in the mixtures. All mixtures were Superpave designed except L964W and LA964B, which were designed using the Marshall Mix design method.

Table 4
Field project and mixtures

	Traffic Level	Project Name (ID)	Mix Type	Section Code	Mix Layer	Mix ID	Binder Grade	NMAS (mm)	RAP (%)	Mix Design
Existing Projects	2	I10 Egan (I10EG)	HMA	I10EG	WC	I10EW	PG76-22m	12.5	0	Superpave
					BC	I10EB		25.0		
		I10 Vinton (I10VT)	HMA (SMA)	I10VT	WC	I10VW	PG76-22m	12.5	0	Superpave
		LA964 Baker (964BK)	HMA	964BK	WC	964W	PG76-22m	19.0	15	Marshall
					BC	964B		25.0	19	
	1	US171 Shreveport (171SP)	HMA	171-1	WC	171H1	PG70-22m	12.5	15	Superpave
			WMA	171-2		171W1			15	
				171-3		171W2			30	
		LA3121 Spearsville (3121SV)	HMA	3121-1	WC	3121H1	PG70-22m	12.5	14	Superpave
			WMA	3121-2		3121W1			14	
				3121-3		3121W2			29	
		LA116 Pineville (116PV)	HMA	116-1	WC	116H1	PG70-22m	12.5	14	Superpave
					BC	116H2		19.0	19	
			WMA	116-2	WC	116W1		12.5	14	
					BC	116W2		19.0	19	
New Projects	1	LA10 St. Helena (10SH)	WMA	10SH	WC	10W	PG82-22rm	12.5	15	Superpave
					BC	10B	PG70-22m	19.0		
		LA3235 Lafourche (3235LF)	HMA	3235LF	WC	3235W	PG70-22m	12.5	19	Superpave
					BC	3235B		19.0		
		US90 Iberia (90IB)	HMA	90IB	WC	90W	PG70-22m	12.5	15	Superpave
					BC	90B		19.0	19	

Laboratory and Field Experiments

A typical test section of selected field projects is shown in Figure 4. At each selected project, at least one or more test sections that were approximately 0.16-km (0.1-mile) long were selected for core sampling and in-situ NDT testing. As shown in the schematic layout, core locations were marked in order of LWT, SCB, and |*E**| cores approximately 15 m (50 ft.) away from each other. This coring order was continued to obtain 13 cores as specified in Table 6. The LTRC research team equipped with a heavy duty, rapid coring rig took all of the cores using a 150 mm (6 in.) diameter diamond core bit.

On every |*E**| core locations, LFWD and PSPA tests were conducted prior to taking the cores in order to closely compare the |*E**| measurements from the laboratory test with the in-situ measured moduli. Air and pavement surface temperatures at the time of these NDT tests were also recorded for the temperature correction of NDT measured moduli, which was necessary for the comparison with the |*E**|. The temperature correction was done by the method introduced in Li and Nazarian *[35]*.

Cored field samples were further prepared for the proposed laboratory performance tests. Standard test protocols summarized in Table 5 were followed. Detailed descriptions of the specimen preparation and test methods are provided in the Appendix A.

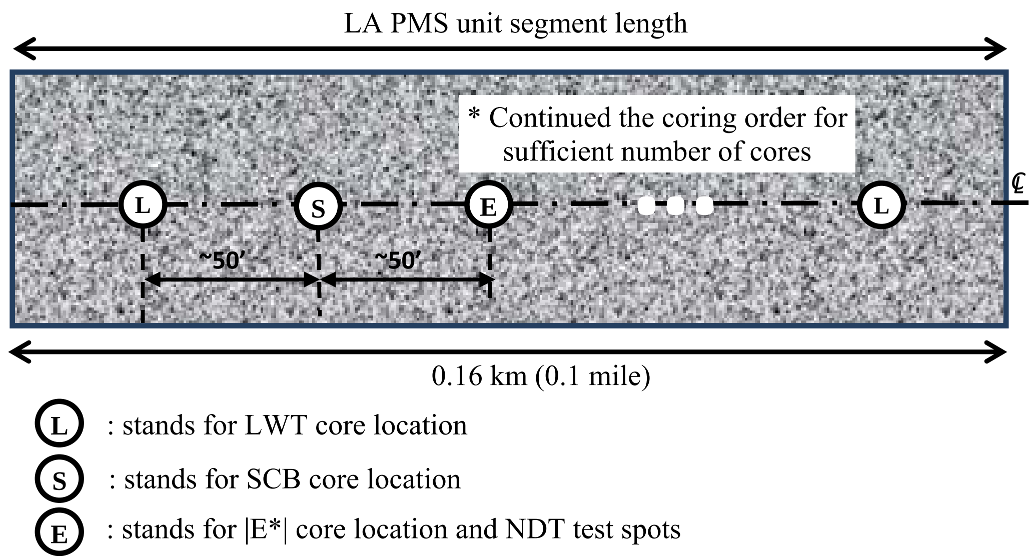

Figure 4
Typical test section layout

Table 5
Laboratory performance test parameters and protocols

Test Method	Primary Performance Indicator	Test Temperature	Test Protocol
LWT	Rut Depth (mm)	50ºC	AASHTO T 324
SCB	Jc (kJ/m^2)	25ºC	DOTD TR 330
IDT |*E**|	Dynamic Modulus	-10 to 30	Kim et al. *[26]*

Table 6 shows the number of core samples required per pavement section for a complete suite of the three laboratory tests. The LWT test uses four samples, two conjoined specimens under each of the two loaded wheels; the SCB test utilizes four replicate semi-circular (a half of a core) specimens per a single notch-depth test, and thus, a total of six cores for all three notch-depths - 25.4, 31.8, and 38.0 mm (1.0, 1.25, and 1.5 in.); and the IDT |*E**| test is conducted with three replicates. A total of 13 is the minimum number of field core samples per a pavement section.

Table 6
Dimensions and number of core samples needed per pavement section

Test Method	Specimen Dimension	No. of Cores Needed
LWT	150 mm x40mm	4 Cores
SCB	150 mm x 57mm	6 Cores
IDT |*E**|	150 mm x 38 mm	3 Cores
Total		13 Cores

Distress Survey

Louisiana PMS (LA PMS) Database

Louisiana DOTD surveys its highway network using the automatic road analyzer (ARAN) every two years and records distress data in the Louisiana PMS database. Figure 5 shows the ARAN and example distress images.

Figure 5
Automatic road analyzer (ARAN) van

For the rutting performance survey, the ARAN uses a transverse laser profiler mounted at the back of the survey van, which has 1280 measurements across a lane width (perpendicular to the driving direction), to compute the average rut depth of a location. The transverse rutting profile is continuously measured as the survey van drives on a pavement section, and then the average rutting in inches for a 0.16 km (0.1 mile) long unit segment of the pavement section is calculated as the field rutting performance indicator.

For the crack performance survey, on the other hand, a digital pavement imaging system mounted at the back of the survey van records the planar view of pavement surface for every 6.4 m (0.004 mile) long pavement area, while driving at posted highway speeds. The continuous aerial images of the pavement surface is then post processed to detect types and severity of cracks in accordance with "Louisiana Cracking and Patching Protocol for Asphalt Surface Pavements" *[36]*. The LA PMS records alligator, longitudinal, transverse, block, and random cracking in low, medium, and high severity levels, but the block cracking is not often observed nor appearing in the PMS database. Alligator and random cracking are the two most commonly observed cracking types in the LA PMS database. Note that the random cracking is the sum of longitudinal and transverse cracks. The extent of the cracks is quantified per 0.16 km (0.1 mile) unit segment. Alligator cracks are calculated as the square footage per the unit segment (ft^2/0.1mile), while longitudinal, transverse, and random cracking are counted as the linear feet per the unit segment (ft/0.1mile).

Index System

Rutting Index. The LA PMS converts the distress survey data into an index scale from 0 to 100, with 100 being the perfect condition. Table 7 shows the conversion between the rutting measured in inches and the corresponding index values. The rutting index stays at 100 until the measured rutting reaches 3.175 mm (0.125 inches), then decreases linearly as the measured rutting increases. Hence, the exact index value corresponding to a certain rutting should be calculated by the linear interpolation.

Cracking Index. The DOTD uses a "deduct point" system to calculate cracking indices. These deducts are a function of types, extent, and severity levels of cracking. As discussed earlier, the alligator and random cracking are the two most commonly observed cracking types in Louisiana asphalt pavements. Therefore, further investigation on the field cracking performance was conducted using the two types of cracking. Tables 8 and 9 presents the deduct points for alligator and random cracking, respectively.

Table 7
DOTD rutting index

No.	Rut (in.)	Rutting Index
1	0.000	100
2	0.125	100
3	0.250	90
4	0.500	70
5	0.750	50
6	1.000	30
7	1.250	10
8	1.375	0

Table 8
Deduct points for alligator cracking index (ACI)

	EXTENT ($ft.^2$)					
SEVERITY	0-50.9	51-701	701-1301	1301-2401	2401-3168	3168-9999.9
LOW	0	1-16	16-21	21-25	25-28	28
MED	0	1-21	21-29	29-36	36-49	49
HIGH	0	1-29	29-43	43-50	50-61	61

Table 9
Deduct points for random cracking index (RCI)

	EXTENT (ft.)					
SEVERITY	0-30.9	31-301	301-1601	1601-5001	5001-6001	6001-9999.9
LOW	0	1-3	3-16	16-18	18-20	20
MED	0	1-16	16-21	21-30	30	30
HIGH	0	1-26	26-28	28-42	42-48	48

A range of deduct points is given depending on the severity level and extent of cracking, then the exact deduct point corresponding to a certain extent of the cracking is calculated by the linear interpolation within the range. The alligator cracking index (ACI) and random cracking index (RCI) used to make a comparison with laboratory measured SCB Jc values are calculated using the equations (2) and (3), respectively.

$$ACI = 100 - [(AD)_L + (AD)_M + (AD)_H] \quad (2)$$
$$RCI = 100 - [(RD)_L + (RD)_M + (RD)_H] \quad (3)$$

where,

ACI and RCI: Alligator Cracking and Random Cracking Indice

$(AD)_L$ and $(RD)_L$= Alligator and Random cracking deducts for low severity level

$(AD)_M$ and $(RD)_M$= Alligator and Random deducts for medium severity level
$(AD)_H$ and $(RD)_H$= Alligator and Random deducts for high severity level

Table 10 presents examples of some maintenance and rehabilitation actions for Louisiana flexible pavements and their trigger index values. A certain type of maintenance or rehabilitation action is triggered when the distress indices exceed the set limit for a certain maintenance action. For example, a “thin overlay on interstate (action item no. 2)” is required if the rutting index of the pavement is less than 80. Likewise, rutting index 65 is the trigger for a “thin overlay on arterial.” For the “medium overlay” on Interstate and Arterial, RCI 90 and 80 are the respective triggers. For the “structural overlay” on Interstate and Arterial, ACI 65 and 60 are the respective triggers.

Table 10
DOTD maintenance triggers for flexible pavements (partial)

#	Maintenance Action Description	ACI	RCI	Rut
1	Micro surfacing on Interstate	>=98	>=98	>=80 <90
2	Thin Overlay on Interstate (Cold Plane 2 in., put 2 in. back; 0-100 sq.yds. Patching)	>=90	>=85	<80
3	Medium Overlay on Interstate (Cold Plane 2 in., put 3.5 in. back or just 3.5 in. overlay, 100-300 sq.yds Patching)	>=65 <90	<90	
4	Structural Overlay on Interstate (7 in. Overlay; 700 sq.yds. Patching)	<65		
6	Thin Overlay on Arterial (Cold Plane 2 in., put 2 in. back; 0-100 sq.yd. Patching)	>=80 <90	>=80 <95	<65
7	Medium Overlay on Arterial (Cold Plane 2 in., put 3.5 in. back or just 3.5 in. overlay, 100-300 sq.yds Patching)	>=60 <80	<80	
8	Structural Overlay on Arterial (5.5 in. Overlay; 700 sq.yds. Patching)	<60		

Data Analysis

A series of statistical and comparative analyses were conducted to identify correlations between field pavement performance indicators and laboratory measured asphalt mixture performance indicators. As discussed in the previous sections, LWT RD and SCB Jc were the primary laboratory performance indicators. The MEPDG projected terminal rutting was the field rutting performance indicator, while the 20-year projected combined cracking, ACI, and RCI were the field cracking performance indicators related to the SCB Jc. In addition to the primary laboratory performance indicators, other laboratory test parameters and some mixture properties were also included in the statistical analyses for their potential contribution to field performance predictions.

Analysis of Covariance

Analysis of covariance (ANCOVA) is a combination of analysis of variance (ANOVA) and regression analysis, but in ANCOVA, one dependent variable can be compared with multiple independent variables unlike in ANOVA. A Type III error rate (α) of 0.05 was utilized to differentiate any significant difference between the mixtures in consideration. In this analysis, every independent variable evaluates its significance with a particular dependent variable, with the secondary continuous variable effects termed as covariates being statistically controlled. This type of analysis mainly yields the p-value, which is the main indicator for significance between the potential factors. Therefore, a p-value higher than 0.05 is considered not significant and a value less than 0.05 is considered a significant variable with respect to a particular dependent variable.

Stepwise Regression (Backward Elimination)

A linear stepwise regression was conducted to reduce the subset from a larger set resulting in simple model regression with a good predictive ability. The original model was in the form of equation (5), with a single dependent variable and multiple independent variables.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon \quad (5)$$

For this analysis, a specific α value was specified for the variables to enter the model (if p-value $< \alpha$) and to exit the model (if p-value $> \alpha$). For this study, α value of 0.05 was utilized to conduct the analysis. Backward elimination in general includes all of the specified candidate independent variables, utilizes a specific model comparison criterion, and repeats the process of deleting any variable, which by doing so improves the model until no possible improvement is expected. The model comparison criteria selected for this analysis was Mallows' Cp. Based on the R^2 of the final model, the robustness of the variables included could be explained. The final model was in the form of equation (6), deleting all the independent variables which were found not significant with respect to the dependent variable.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \quad (6)$$

DISCUSSION OF RESULTS

Laboratory Performance Test Results

In this study, it was assumed that the asphalt layers were completely bonded and resisted the deformation and fracture together as a whole layer but with different contribution rates from the individual layers (e.g., different LWT and SCB test results of different asphalt mixtures). Thus, the average of wearing and binder course mixture test results (if present) should be representative of the entire asphalt pavement section's rutting or cracking resistance. Based on the assumption, laboratory test results were averaged for the wearing and binder course mixtures of I10EG, 964BK, 116-1, 116-2, 10SH, 3235LF, and 90IB to represent the overall performance of these pavement sections. Moreover, these section averages of laboratory test results enabled direct section-by-section comparisons with field distress performance obtained from the PMS.

LWT Test Results

Figure 6 shows a schematic of the LWT specimen arrangement and locations of deformation measurements on the two conjoined specimens under one of the two wheel paths of the LWT device. As shown in the schematic, two average rut depths were computed from the middle four deformation measurements in each of the two specimens separately. Therefore, from both left and right side wheels, a total of four rutting profiles were recorded for an asphalt mixture.

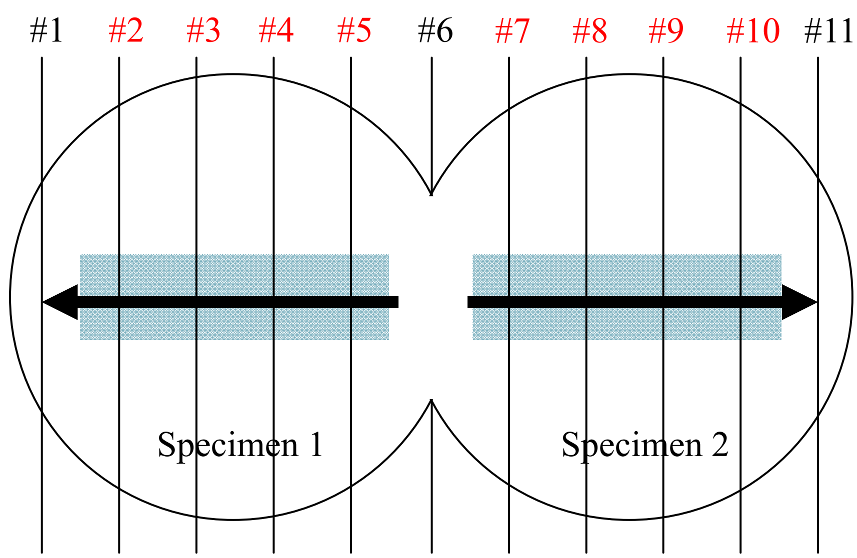

Figure 6
Schematic arrangement of LWT specimens and measurement locations

Figure 7 shows an example plot of these four rutting profiles over a number of loading passes for the I10 Egan wearing course mixture (I10EW). Rutting profiles recorded from the left and right side wheels are denoted with prefixes L and R, respectively, followed by the numbers 1 and 2, which specify the relative positions of the two conjoined specimens. Using the rutting profiles, final rut depths and post consolidations were determined as described in the test protocol (see Appendix A), and these test parameters were averaged to represent the rutting performance of a specific asphalt mixture after removing apparent outliers. The LWT rutting profile plots of all asphalt mixtures are presented in the Appendix B-1 section, and the averaged test parameters along with the averaged in-place density are summarized in Table 11.

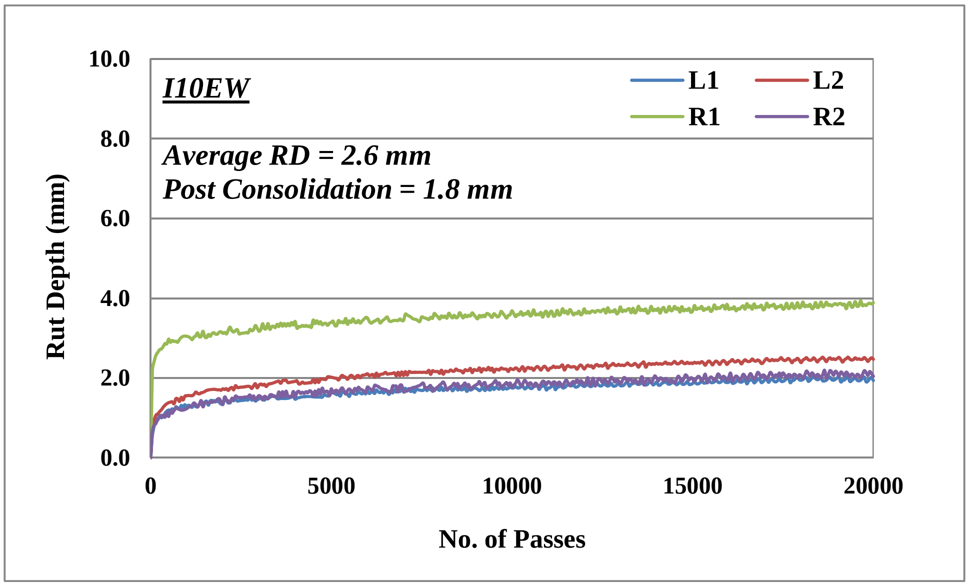

Figure 7
Mixture LWT test results

Good rutting performance of existing pavement sections were predicted by the LWT RD, ranging from 1.8 to 6.7 mm with an average of 3.8 mm, which are lower than the thin overlay trigger values of 9.5 and 14.3 mm for Interstate and Arterial roads, respectively. Sections I10EG, I10VT, 116-1, and 116-2 showed the lowest RD values of 2.5, 2.7, 1.8, and 2.5 mm, respectively, which imply that these pavement sections will develop low rutting problems. Section 10SH showed the lowest RD among the three new sections. A reasonable amount of post consolidation around 2.0 mm was measured for all existing pavement sections. In-place densities of all pavement sections were well above the minimum requirement of 92%, which would indicate that there were no abnormalities in construction of these pavement sections. Similar density, rut depth, and post consolidation results were obtained from the three new pavement sections on averages. Separate layer results, however, showed that the 90W mixture may experience an excessive rutting problem with 9.5 mm of RD.

Table 11
Summary of LWT test results

	Traffic Level	Layer Average					Section Average			
		Mix ID	Thickness[1] (mm)	Density[2] (%)	RD[3] (mm)	PC[4] (mm)	Section ID	Density (%)	RD (mm)	PC (mm)
Existing Projects	2	I10EW	50.8	95.3	2.6	1.8	I10EG	95.3	2.5	1.5
		I10EB	189.0	95.2	2.4	1.1				
		I10VW	50.8	95.4	2.7	1.3	I10VT	95.4	2.7	1.3
		964W	40.0	93.8	4.1	2.0	964BK	94.1	4.1	2.0
		964B	110.0	94.4	4.1	2.0				
	1	171H1	50.8	95.6	6.7	2.1	171-1	95.6	6.7	2.1
		171W1	50.8	96.4	4.3	2.0	171-2	96.4	4.3	2.0
		171W2	50.8	94.9	4.8	2.7	171-3	94.9	4.8	2.7
		3121H1	50.8	94.8	3.1	1.7	3121-1	94.8	3.1	1.7
		3121W1	50.8	95.3	4.5	1.4	3121-2	95.3	4.5	1.4
		3121W2	50.8	95.0	4.8	1.9	3121-3	95.0	4.8	1.9
		116H1	38.1	95.7	1.8	0.6	116-1	95.9	1.8	0.8
		116H2	50.8	96.0	1.7	0.9				
		116W1	38.1	93.0	3.2	1.4	116-2	94.3	2.5	1.1
		116W2	50.8	95.5	1.7	0.7				
New Projects	1	10W	38.1	95.1	3.7	1.5	10SH	95.2	2.7	1.3
		10B	100.8	95.3	1.7	1.0				
		3235W	38.1	95.2	4.6	1.2	3235LF	94.1	3.8	1.3
		3235B	50.8	93.0	3.0	1.4				
		90W	38.1	92.1	9.5	2.5	90IB	93.6	6.8	2.2
		90B	50.8	95.0	4.0	1.8				

[1] Layer Thickness,
[2] Density of roadway cores as percentage to the maximum density;
[3] LWT measured rut depth in mm at 20,000 passes; and
[4] LWT measured post consolidation in mm at 1,000 passes

SCB Test Results

Figure 8 shows typical load versus deformation curves obtained from the SCB test at three different notch depths. The areas under the curves up to their corresponding peak loads were computed to represent strain energies consumed by the specimens until failures. These strain energies were typically inversely proportional to the notch depths, i.e., the higher the notch depths, the lesser the strain energies.

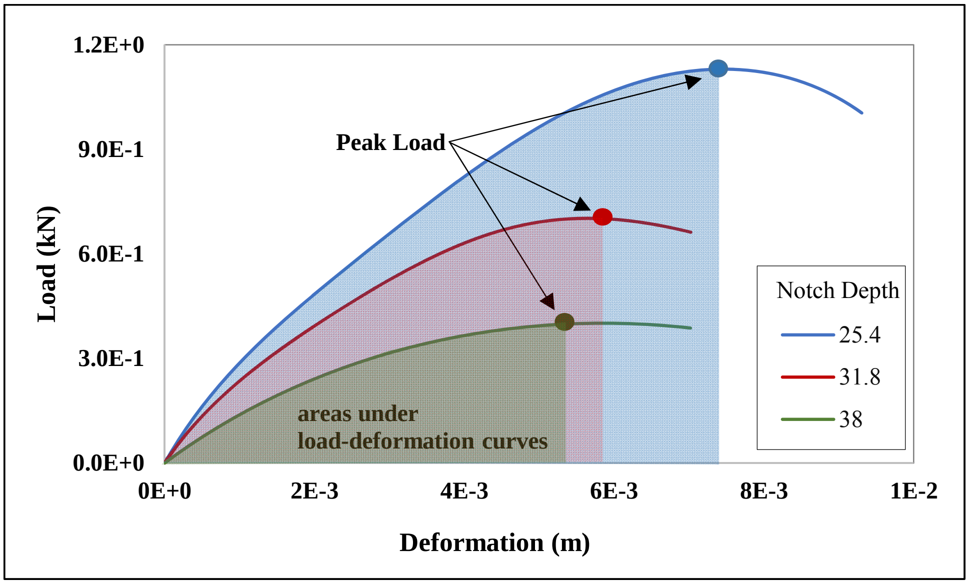

Figure 8
Typical load-deformation curves from SCB tests

Figure 9 shows the strain energies normalized by the thickness of specimens (unit strain energy in kJ/m) and plotted over the notch depths for the 116W1 mixture. In the plot, the empty circles represent individual replicated test results, while the filled circles represent the averaged unit strain energies. As explained in the test protocol section of Appendix A, the slope of a linear trend line through the unit strain energy over notch depth data points, which is Jc, was computed as the cracking performance of 116W1. The SCB test result plots of all asphalt mixtures are presented in Appendix B-2 section and the averaged test parameters along with the average in-place density are summarized in Table 12.

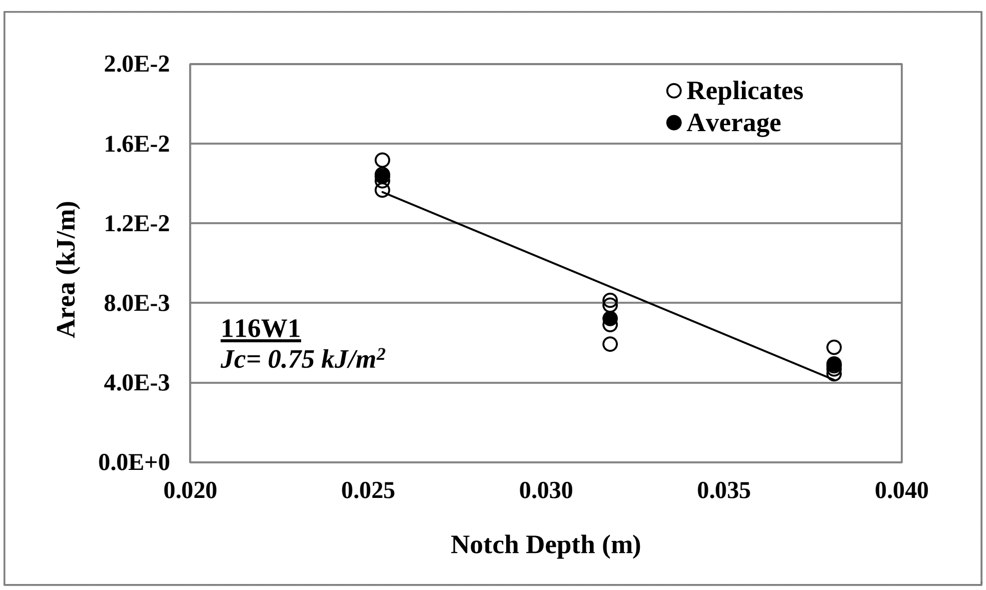

Figure 9
116W1 mixture SCB test results

The SCB Jc values of existing pavement sections range from 0.37 to 0.93 kJ/m^2. Section 964BK showed the lowest value of 0.37 kJ/m^2, while all other sections showed Jc values greater than or equal to 0.52 kJ/m^2. Among the three new pavement sections, 90IB section showed 0.30 kJ/m^2 of Jc value, while other two sections demonstrated reasonably higher values of Jc. These observations would imply that the two pavement sections (i.e., 964BK and 90IB) will likely experience cracking problems more than any other pavement sections investigated in this study.

Table 12
SCB test results summary

	Traffic Level	Layer Average			Section Average		
		Mix ID	Density (%)	Jc (kJ/m^2)	Section ID	Density (%)	Jc (kJ/m^2)
Existing Projects	2	I10EW	94.3	0.39	I10EG	94.9	0.64
		I10EB	95.5	0.88			
		I10VW	95.6	0.93	I10VT	95.6	0.93
		964W	94.3	0.30	964BK	93.9	0.37
		964B	93.5	0.43			
	1	171H1	95.7	0.52	171-1	95.7	0.52
		171W1	96.2	0.73	171-2	96.2	0.73
		171W2	94.9	0.60	171-3	94.9	0.60
		3121H1	95.2	0.66	3121-1	95.2	0.66
		3121W1	94.8	0.91	3121-2	94.8	0.91
		3121W2	96.1	0.60	3121-3	96.1	0.60
		116H1	95.7	0.71	116-1	95.9	0.54
		116H2	96.0	0.37			
		116W1	93.6	0.75	116-2	93.9	0.66
		116W2	94.2	0.57			
New Projects	1	10W	94.7	0.52	10SH	95.2	0.57
		10B	95.7	0.61			
		3235W	96.2	0.61	3235LF	95.7	0.69
		3235B	95.1	0.77			
		90W	93.6	0.28	90IB	94.5	0.30
		90B	95.3	0.31			

IDT |*E|**

Figures 10 and 11 present the dynamic modulus master curves of all 21 individual asphalt mixtures included in this study. Master curves were constructed at the reference temperature of 10 °C. A rule of thumb expectation from the master curve is that a stiffer asphalt mixture at the low reduced frequency range (approximately from 10^{-5} Hz to 10^{-3} Hz) would result in low rutting, while a softer asphalt mixture at the middle reduced frequency range (approximately from 1 Hz to 100 Hz) would result in low cracking. Among the existing pavement mixtures, 964W, 964B, 116W1, and 116W2 looked stiffer than the rest at the low reduced frequency range, while 171H1, 171W2, and I10EW looked softer than the rest at the middle reduced frequency range. Thus, existing pavement sections 964BK and 116-2 are expected to have minimal rutting, and 171-1, 171-3, and I10EG existing pavement sections are expected to have low cracking problems. Similarly, section 10SH is expected to develop the lowest rutting, and section 90IB is expected to experience the least cracking problems among the three new projects.

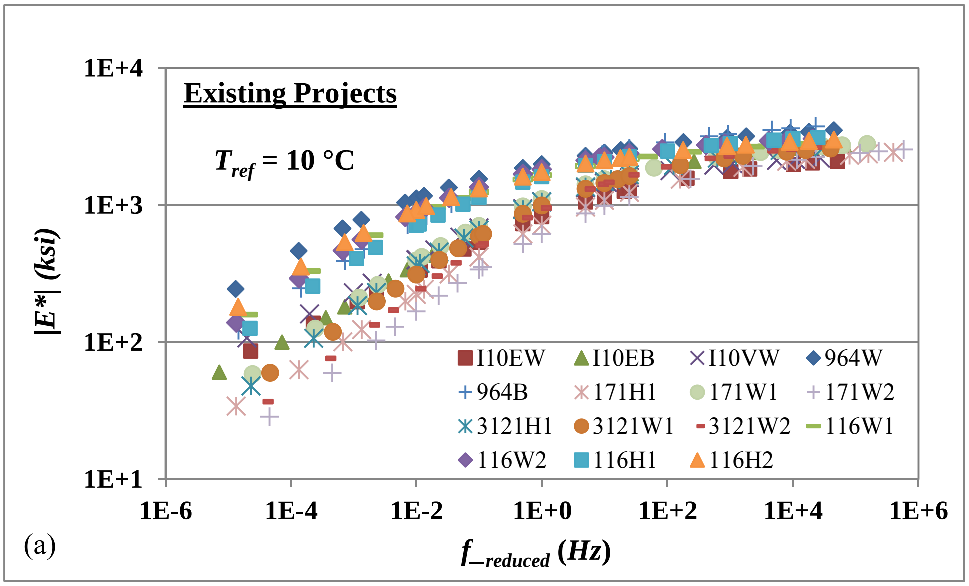

Figure 10
Dynamic modulus master curves of existing projects

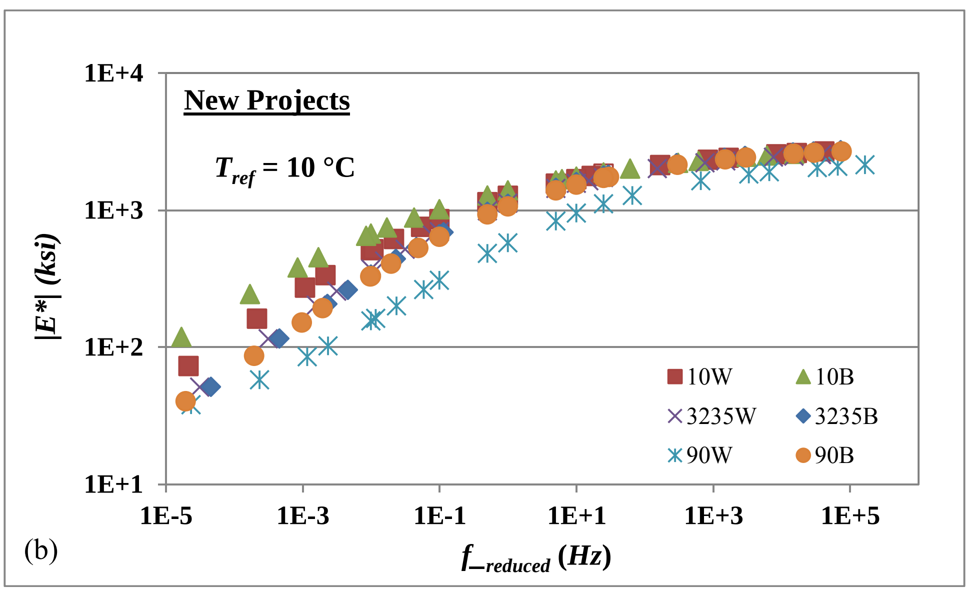

Figure 11
Dynamic modulus master curves of new projects

These dynamic modulus data were also used as material input in the AASHTOWare Pavement-ME for the field rutting performance predictions of the pavement sections.

Field Performance Evaluation Results

Two NDT tests (i.e., LFWD and PSPA) were conducted in selected number of field projects to compare the in-situ stiffness of pavement sections to the laboratory measured dynamic modulus (|*E**|) of cored field samples. In general, the LFWD and PSPA deflection measurements are very sensitive to surrounding vibration generated by external sources such as passing heavy vehicles. Therefore, it is ideal to perform these tests when there is no passing traffic. However, it was difficult to find such an ideal moment on the high volume Level 2 highways. Thus, only the low to medium volume Level 1 existing and new field projects were chosen for the NDT tests and the results are presented in this section.

NDT Test Results

LFWD. Table 13 summarizes the LFWD test results. The in-situ stiffness of pavement sections were measured in the vicinity of IDT |*E**| test cores to compare the NDT and laboratory measured modulus values. As discussed in the methodology, all of the final modulus values were normalized to 25°C. Tests were performed at six spots in the vicinity of IDT |*E**| cores. Within each spot, nine measurements were recorded around the sampling spot. The average of these nine measurements was computed as the modulus of the spot. Finally, an average of the all six modulus values was calculated as the section representative modulus value. It is noteworthy that the measurements were recorded by moving the apparatus around the coring location within a close proximity.

Figure 12 shows a graphical representation of the data summarized in the Table 13. Each vertical bar in the graph represents the final modulus value for each pavement section. A straight line indicates the average modulus value of all pavement sections which was 221 ksi. Among the existing projects, the LFWD measured pavement section moduli range from 97 ksi to 339 ksi. The two LA116 pavement sections marked the highest stiffness at over 300 ksi, while the three US171 pavement sections had the three lowest stiffness values. Among the new projects, LA10 was the stiffest and US90 was the least stiff sections with 375 ksi and 187 ksi, respectively.

Table 13
LFWD test results

	Route	Section ID	Age (yrs)	LFWD Stiffness (ksi)
Existing Project	LA 3121	3121-1	3.9	203
		3121-2	3.9	225
		3121-3	3.9	166
	LA 116	116-1	3.3	300
		116-2	3.3	339
	US 171	171-1	3.7	138
		171-2	3.7	161
		171-3	3.7	97
New Project	LA 10	10SH	0	375
	LA 3235	3235LF	0	245
	US 90	90IB	0	187

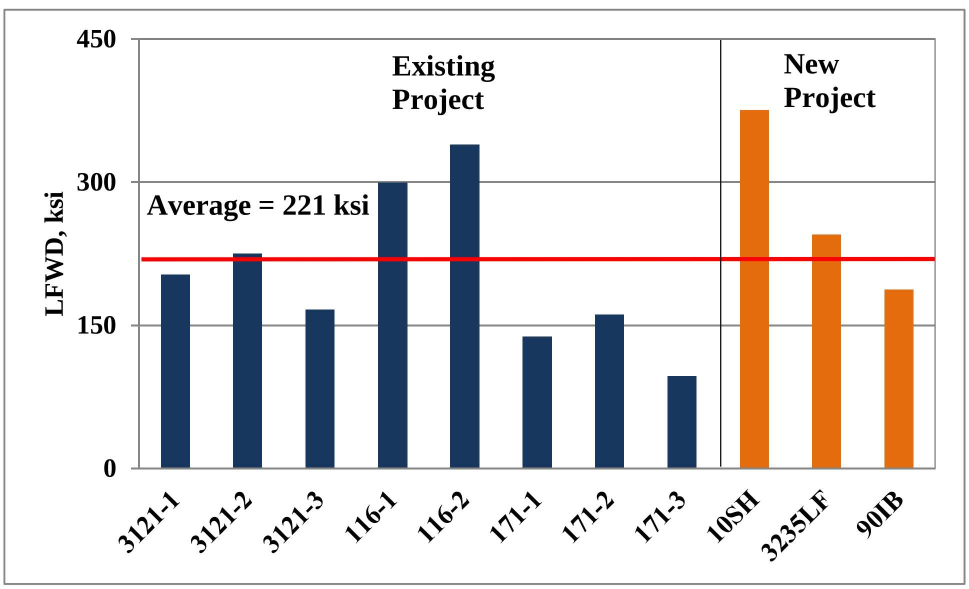

Figure 12
LFWD measured stiffness

PSPA. Table 14 summarizes the PSPA measured stiffness. Figure 13 presents the test results summarized from the table in a bar chart format. The average stiffness of all pavement sections was 1543 ksi, as shown with the red horizontal line. Among the existing projects, the PSPA stiffness ranged from 1011 ksi to 1766 ksi. Similar to the LFWD results, the two

LA116 pavement sections marked the highest stiffness at over 1700 ksi. Unlike LFWD, however, all pavement sections in LA3121 and US171 showed very similar stiffness values. Among the new projects, LA10 had the stiffest and US90 had the least stiff sections with 2393 ksi and 1725 ksi, respectively, which is consistent with the LFWD trend.

Table 14
PSPA test results

	Route	Section ID	Age (yrs)	PSPA Stiffness (ksi)
Existing Project	LA 3121	3121-1	3.9	1011
		3121-2	3.9	1268
		3121-3	3.9	1214
	LA 116	116-1	3.3	1766
		116-2	3.3	1735
	US 171	171-1	3.7	1327
		171-2	3.7	1440
		171-3	3.7	1172
New Project	LA 10	10SH	0	2393
	LA 3235	3235LF	0	1922
	US 90	90IB	0	1725

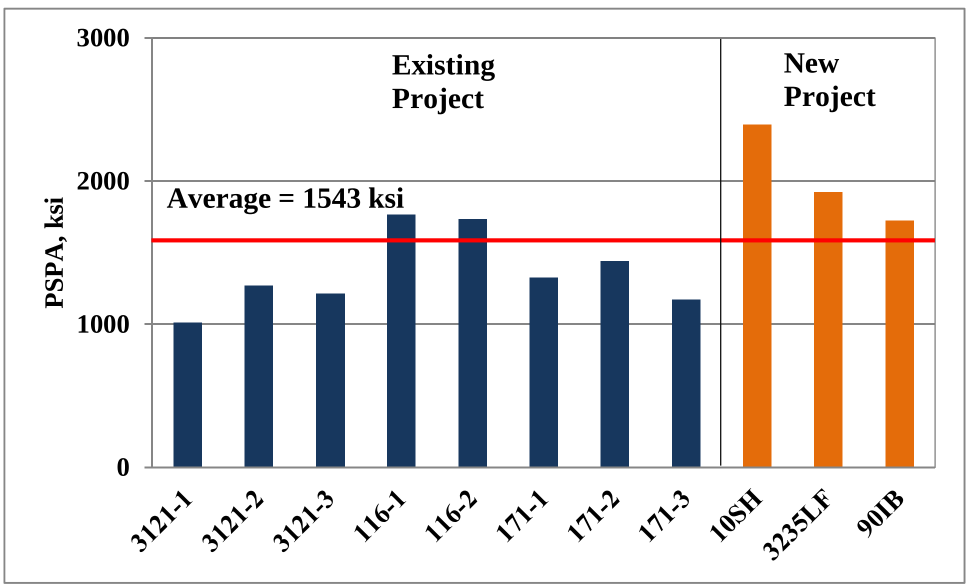

Figure 13
PSPA measured stiffness

Field Performance

PMS Rutting Performance Record. Table 15 and Figure 14 summarize the field rutting performance data recorded in the Louisiana PMS. Specific locations of the pavement sections where the rutting performance data were collected are shown with the control section log mile (CSLM). Older pavement sections (e.g., I10EG, I10VT, and 964BK) have longer records of rutting performance starting from 2007 for I10EG and I10VT and 2009 for 964BK. On the other hand, seven younger pavement sections have shorter performance records that started in the 2011 survey cycle. As noted earlier, performance data of 116-1 section was not found and could not be included.

Table 15
PMS rutting data

Pavement Sections	CSLM[1] (mile)	Age (month)	Rutting (mm), years measured			
			2007	2009	2011	2013
I10EG	7.0 - 14.9	101	2.2	2.7	2.8	3.1
I10VT	2.2 - 10.0	115	2.3	3.0	2.8	3.6
964BK	0.4 - 5.1	93	-	2.8	3.4	3.6
3121-1	0.0 - 2.2	39	-	-	2.2	2.1
3121-2	2.4 - 4.3	39	-	-	2.1	2.0
3121-3	4.4 - 5.0	39	-	-	2.2	2.1
116-2	4.7 - 6.5	33	-	-	2.2	1.5
171-1	2.8 - 3.7	36	-	-	2.7	5.6
171-2	4.2 - 6.4	36	-	-	2.6	4.6
171-3	0.8 - 2.0	36	-	-	2.6	5.9

[1] control section log mile used in PMS to identify locations of projects
- Not available

In general, gradual increases of field rutting over time can be observed except with few irregularities, such as the reversed trends observed in 3121-2, 3121-3, and 116-2. Nonetheless, given the very small magnitude of rutting in these pavement sections (e.g., only about 2 mm), the reversal in trends (e.g., 0.7 mm drop from 2.2 mm in 2011 to 1.5 mm in 2013 for 116-2) may only indicate that the rutting in these pavements over years have been very minimal. In fact, good rutting performance of the 10 existing pavement sections was consistently observed through the 2013 survey record. The highest rutting value of 5.9 mm was observed in 171-3 after 36 months in service, which is much lower than the thin overlay trigger value of 14.3 mm for arterial roads. Overall, average rutting of all 10 sections was only 3.4 mm.

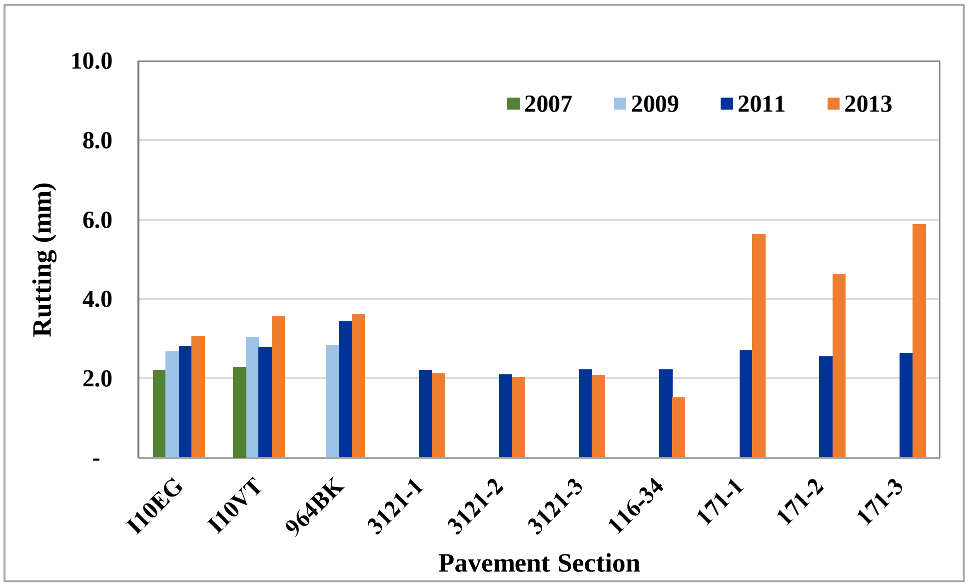

Figure 14
Field rutting trend

For better unbiased comparisons, however, these rutting data for different pavement sections at different ages needed to be projected to the terminal service life. Projections of the "terminal rutting" were made by the rutting prediction model of Pavement-ME software as shown in equation (7) through curve fittings to the rutting history data.

$$\frac{p}{r} = k_z\, \beta_{r1}\, 10^{k_1}\, T^{k_2 \;\; r2}\, N^{k_3 B_{r3}} \tag{7}$$

where,

$\varepsilon_p/\varepsilon_r$ = ratio of accumulated permanent strain to elastic strain at N^{th} loading
N = number of traffic loadings
T = pavement temperature, °F
k_z = function of asphalt layer thickness for confining pressure adjustment
k_1, k_2, and k_3 = nationally calibrated model coefficients
β_{r1}, β_{r2}, and β_{r3} = local calibration constants

A trial-and-error based, least square curve fitting approach was employed for the prediction of terminal field rutting using the Pavement-ME software. First, the local calibration constants, namely β_{r1}, β_{r2}, and β_{r3}, were initialized to a set of recommended values reported by Mohammad et al. *[18]*. An initial simulation was run for a specific pavement structure with known climate, traffic, and asphalt mixture's dynamic modulus data. Then, a sum of squared error (SSE) between the predicted and observed rut depths was computed. The calibration constants were adjusted to reduce the SSE for the second simulation. The process was iterated until the SSE was minimized. The final rutting prediction at this stage was regarded as the projected "terminal rutting" of the pavement. Figure 15 shows an example plot of the Pavement-ME based curve fitting to the rutting history data for the projection, and Table 16 summarizes the 20-year projected rutting of the 10 existing pavement sections. It should also be noted that the field rutting from PMS database is the rutting measured at the surface of pavements, which may include rutting from non-bituminous layers. For fair comparisons of rutting performance, only the asphalt layer portion of the Pavement-ME rutting prediction was further compared with the LWT measured rut depth of asphalt mixtures.

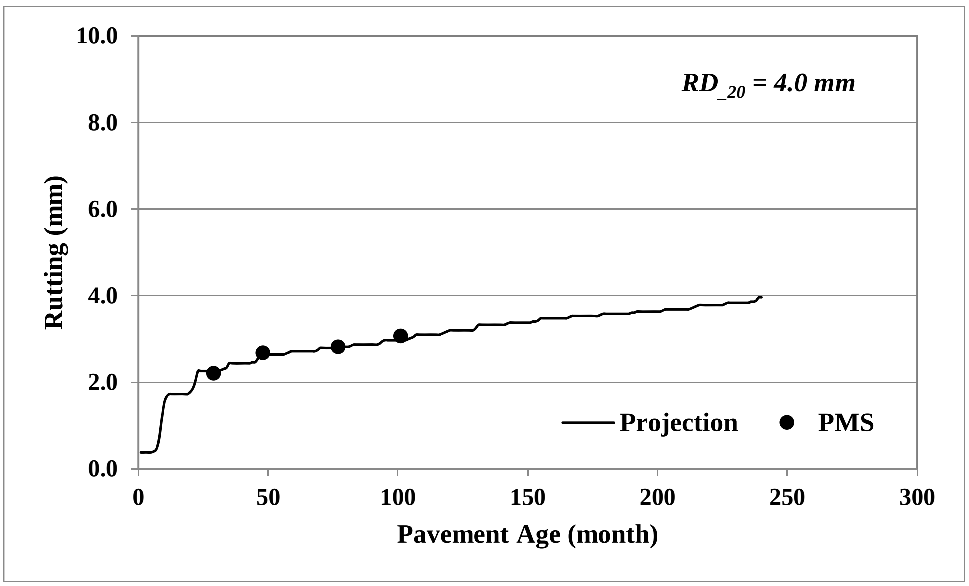

Figure 15
Example rutting projection using pavement-ME

Table 16
20-Year projected field rutting

	Project	Service Year	Field Rutting, mm	
			2013 PMS	MEPDG Projected*
Existing Sections	I10EG	6.9	3.1	4.0
	I10VT	8.1	3.6	3.7
	964BK	6.9	3.6	4.3
	3121-1	3.9	2.1	3.9
	3121-2	3.9	2.0	2.5
	3121-3	3.9	2.1	2.7
	116-2	3.3	1.5	3.1
	171-1	3.7	5.6	7.1
	171-2	3.7	4.6	5.2
	171-3	3.7	5.9	8.1

* Projected for 20-years using Pavement-ME and PMS rutting data.

PMS Cracking Performance Record. Table 17 and Figure 16 summarize the field cracking performance records of the 10 existing pavement sections. For a concise presentation of the data, three severity levels (e.g., low, medium, and high) of alligator, longitudinal, transverse, and random cracking are summed up together without weights. Either no or very little amount of alligator cracks were recorded for six pavement sections (I10EG, I10VT, 116-2, 171-1, 171-2, and 171-3), and relatively small amounts of alligator cracks were observed in three 3121SV sections (3121-1, 3121-2, and 3121-3). The 964BK section, on the other hand, showed a significantly higher amount of alligator cracks than the other sections. Similarly, the 964BK section showed the highest amount of random cracks, while the rest of the pavement sections showed some moderate amount of random cracks with reasonable growing patterns over time.

The significance of these crack counts can be more clearly demonstrated when the crack counts are converted into the index as discussed in a previous section. Table 18 presents the RCI values converted from the random crack counts at present time. It should be noted that the alligator cracking index (ACI) values are not presented nor further analyzed, hereafter, because most of the alligator crack counts remained at zero or very small resulting in the ACI values near 100 except the 964BK section.

Table 17
Field cracking performance record

Pavement Sections	Age (Month)	Alligator (ft^2/0.1 mile)	Longitudinal (ft/0.1 mile)	Transverse (ft/0.1 mile)	Random (ft/0.1 mile)
I10EG	29	0	1	0	1
	48	0	3	4	8
	77	0	4	3	7
	101	0	10	4	13
I10VT	47	0	3	1	4
	63	2	1	3	4
	89	1	7	4	12
	115	5	121	16	137
964BK	42	0	1	3	3
	70	255	58	170	228
	93	674	81	441	522
3121-1	15	7	0	0	1
	39	11	3	2	5
3121-2	15	48	10	1	11
	39	131	34	25	59
3121-3	15	96	27	1	28
	39	122	59	7	66
116-2	9	5	2	4	6
	33	9	13	67	79
171-1	9	0	9	3	12
	36	0	262	3	265
171-2	9	0	10	3	13
	36	0	92	32	124
171-3	9	0	21	0	21
	36	0	212	0	212

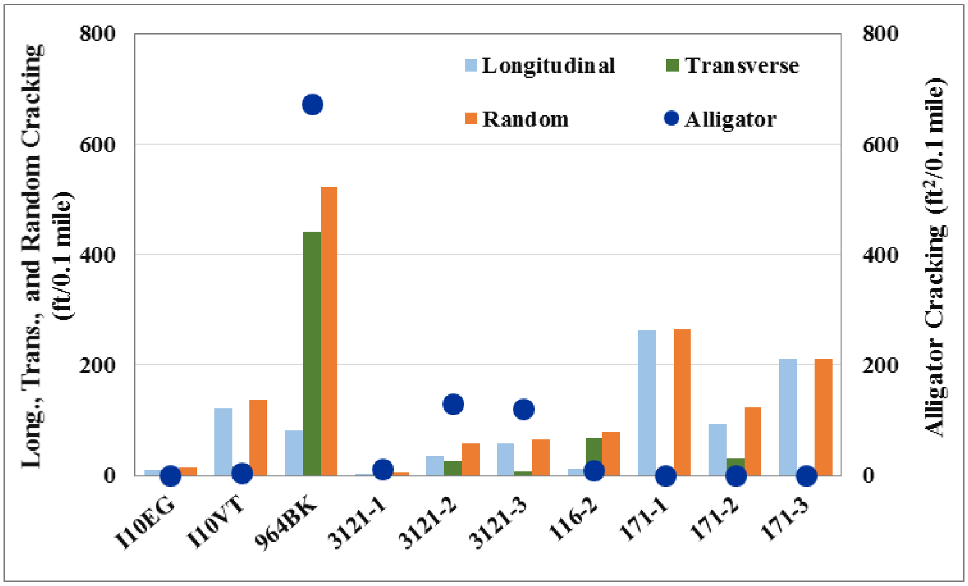

Figure 16
Field cracking measured at the last survey

Table 18
Random cracking index (RCI)

Pavement Sections	Random Cracking (ft/0.1mile)				RCI (0-100)
	L	M	H	Total	
I10EG	7	7	0	13	100
I10VT	29	107	1	137	96
964BK	165	356	1	522	82
3121-1	3	2	0	5	100
3121-2	25	34	1	59	100
3121-3	15	46	5	66	99
116-2	52	27	0	79	99
171-1	24	242	0	265	89
171-2	27	97	0	124	96
171-3	1	211	0	212	90

At present time, no pavement sections have crossed the medium overlay triggers at 90 and 80 for interstate and arterial roads, respectively, with 964BK being the only pavement section approaching the trigger. It is interesting to note that the 964BK section has been constantly rated as high chance of cracking pavement by both laboratory and field performance indicators. Therefore, the RCI values of the existing pavement sections were further compared with the SCB Jc values of corresponding asphalt mixtures to identify the potential relationship between the field and laboratory.

Field vs. Laboratory Performance Comparisons

Figure 17 presents quantitative comparisons between the field and laboratory measured performance indicators. Figure 17 (a) shows the scatter plot of projected field rutting versus the LWT RD, and Figure 17 (b) shows the scatter plot of field RCI versus the SCB Jc. The coefficient of determination (R^2) value of the linear trend line for the field rutting vs. LWT RD relationship was 0.30. The low R^2 value means that the "one-to-one" relationship between the field and lab measured rutting performance indicators are very weak. Such a weak correlation can be expected since field rutting is not only a function of asphalt mixture's rutting resistance but also a function of many other factors such as the asphalt layer thickness, asphalt mixture's density, asphalt content, etc. On the other hand, the R^2 value of the power law trend line for the RCI vs. SCB Jc was considerably higher (0.73) than the field rutting vs. LWT RD. It can be noted that the power law trend line crosses the RCI value of 80, medium overlay trigger of arterial roads, when the Jc value is around 0.37. Based upon the strong correlation between the RCI and SCB Jc, it can be expected that the asphalt mixtures with SCB Jc values of 0.37 or higher may not experience severe cracking problems to trigger a rehabilitation action. However, it should be reminded again that the field pavement performance is not only a function of a single performance indicator, such as the LWT RD or SCB Jc, but also it is a function of many other potentially influencing factors.

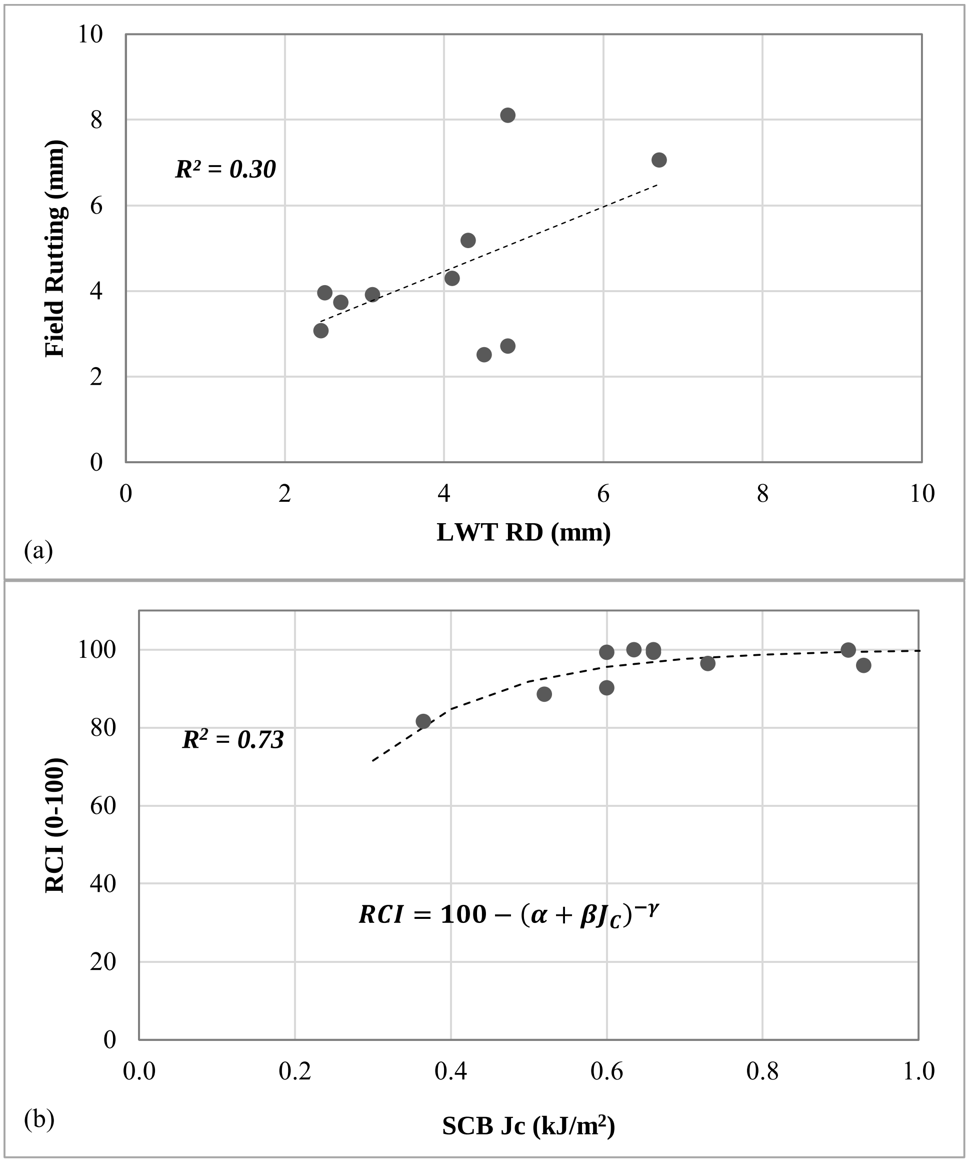

Figure 17
Field versus lab performance indicators: (a) Rutting vs. LWT RD and (b) RCI vs. SCB Jc

To further investigate the correlation between the field performance and some of these potentially influencing factors, a statistical analysis was conducted to build a linear regression model that considers these additional factors. These factors are presented in Tables 19 and 20 for field rutting and cracking, respectively.

A stepwise regression method was employed to reduce a large set of independent variables to a smaller set through either a "backward elimination" or a "forward addition" algorithm *[37]* using a commercial statistical analysis software package. The initial model includes all independent variables in the form of equation (8):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_n X_n + \varepsilon \quad (8)$$

where,

Y = the dependent variable
β's = model coefficients
X's = the independent variables
ε = regression error

Goodness of fit was assessed through the R^2 and Mallow's Cp. Mallow's Cp is a measure of the fit of a regression model based on the ordinary least squares, which is typically applied for model selection from multiple independent variables. The backward elimination algorithm takes out one independent variable at a time, computes the updated Mallow's Cp due to the removal of the variable, and compares the updated statistics to that of the immediate previous step. If the Cp decreases, then the elimination process continues until no further improvement is observed. The resulting final model will include less independent variables than the initial model.

Table 19
Factors affecting field rutting performance

Section ID	Density (%)	LWT RD (mm)	PC (mm)	AC (%)	VMA (%)	Thickness (mm)
I10EG	95.3	2.5	1.5	4.5	13.7	240
I10VT	95.4	2.7	1.3	6.0	16.6	226
964BK	94.1	4.1	2.0	4.2	13.3	150
3121-1	94.8	3.1	1.7	4.8	15.0	50.4
3121-2	95.3	4.5	1.4	4.8	15.0	50.4
3121-3	95.0	4.8	1.9	4.8	15.0	50.4
116-34	94.3	2.5	1.1	4.4	13.5	88.5
171-1	95.6	6.7	2.1	5.0	14.5	50.4
171-2	96.4	4.3	2.0	5.0	14.5	50.4
171-3	94.9	4.8	2.7	5.4	14.0	50.4

Table 20
Factors affecting random cracking index

Section ID	AC (%)	Unit Peak Load (kN/mm)	Coarse Aggregate Slope (nCA)	Film Thickness (micron)	ESAL (million)	SCB J_c (kJ/m^2)
I10EG	4.5	0.032	0.41	6.5	48.0	0.64
I10VT	6.0	0.028	0.56	7.0	48.0	0.93
964BK	4.2	0.019	0.38	8.3	1.4	0.37
3121-1	4.8	0.018	0.29	8.2	0.1	0.66
3121-2	4.8	0.016	0.29	6.0	0.1	0.91
3121-3	4.8	0.000	0.29	8.2	0.1	0.60
116-34	4.4	0.022	0.28	6.1	0.6	0.66
171-1	5.0	0.014	0.32	8.7	1.3	0.52
171-2	5.0	0.016	0.29	7.6	1.3	0.73
171-3	5.4	0.011	0.30	9.3	1.3	0.60

On the other hand, the forward addition algorithm starts from a constant function (y = constant) and adds one independent variable in every iteration until the best combination of independent variables is chosen by the minimum Cp. The final linear models selected for the field rutting from the factors presented in Table 19 and for the RCI from the factors in Table 20 are shown in equations (9) and (10):

$$R_{field} = 13.0 + 4.3(AC) + 0.6(RD_{LWT}) - 2.2(VMA) \quad (9)$$

$$RCI = 100.4 - 5.8(AC) + 34.9(SCB\ Jc) \quad (10)$$

where, R_{field} is the predicted field rutting, *RCI* is Random Cracking Index, *AC* is asphalt content, RD_{LWT} is the LWT RD, *VMA* is voids in the mineral aggregates, and *SCB* J_c is SCB measured J_c.

Figure 18 shows comparisons between the regression model predicted performance parameters, i.e., rutting by equation (9) and RCI by equation (10), and the projected field performance parameters. As shown in the figure, improved predictions of field performance indicators were achieved through the use of the linear models, which included more than one independent variable. The computed field rut depth using the linear regression model built with the three independent variables agrees very well with the field rutting performance, showing a good R^2 value of 0.87. Likewise, the computed RCI using the two-variable linear regression model agreed reasonably well with the field RCI, showing a decent R^2 value of 0.60. It is worth noting that the R^2 value of 0.60 in Figure 18 (b) is lower than that shown in

Figure 17 (b). The reduction is due to the difference in trend line functions, i.e., power model versus linear model, but not due to the addition of AC variable in equation (10).

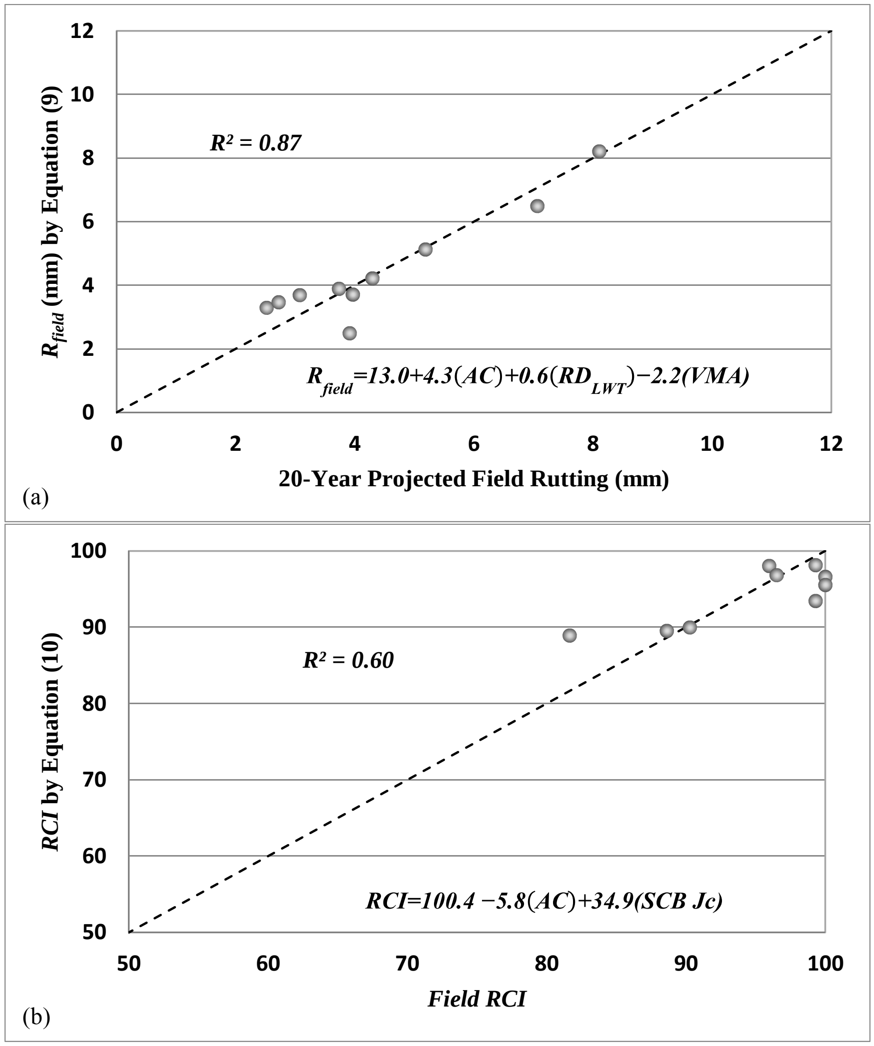

Figure 18
Regression model vs. field performance: (a) projected rutting and (b) RCI

The strong relationships between field and laboratory performance indicators observed in Figures 18 (a) and 18 (b) may be translated into an expectation that the laboratory performance indicators such as the LWT RD and SCB Jc, together with some other relevant quality characteristics of asphalt mixtures and pavement construction, can be added into the current specification as supplemental requirements to better guarantee the ultimate performance of asphalt pavements.

Figure 19 recaptures the relationship between the projected field performance indicators and the laboratory measured performance indicators previously presented in Figure 17. Although the one-to-one correlations between the field and laboratory performance indicators were not good enough, a further qualitative examination on the clustered data points showed some useful implications of their relationship. In Figure 19 (a), data points of Level 2 pavement sections are represented as dark filled circles, while the Level 1 sections are represented with light filled circles. A rectangular box with a dark solid line is drawn in the plot to show an enclosed area under 6 mm of rutting on both axes, while another rectangular box with light dotted line encloses another lager area under 10 mm of rutting on both axes. These limits of rutting values were used by Brown et al. and Cooper, respectively, *[15, 38]*. Clearly, all three Level 2 pavement sections were clustered well within the 6 mm by 6 mm enclosed area; similarly, the Level 1 sections were clustered well within the 10 mm by 10 mm enclosed area. This observation may indicate that, within the limited data presented, the RD_{LWT} of 6 mm or less can be a target quality level for the Level 2, and 10 mm or less can be a target quality level for the Level 1 Louisiana asphalt pavements, respectively. If these criteria are satisfied along with the AC and VMA requirements, the pavement sections are expected to resist rutting accumulations in the field very well.

In Figure 19 (b), on the other hand, medium overlay trigger values for the Level 2 and Level 1 pavement sections are shown with a solid lateral line at RCI 90 and with a dotted lateral line at RCI 80, respectively. Again, three Level 2 pavement sections are shown with dark filled circles, while seven Level 1 pavement sections are shown with light filled circles. In general, good cracking resistance of all pavement sections are evident, except the 964BK section that has the RCI value of 82. Similar to Figure 19 (a), two boxed zones are created and shown in Figure 19 (b), i.e., a dotted rectangular box bounded by the RCI value of 80 and higher and the SCB Jc value of 0.5 kJ/m^2 and higher for Level 1 pavements, and a solid rectangular box bounded by the RCI value of 90 and higher and the SCB Jc value of 0.6 kJ/m^2 and higher for Level 2 pavements, respectively. Two of the three Level 2 pavement sections whose Jc values are higher than 0.6 kJ/m^2 stay well within the solid rectangular box meaning that they perform well against random cracking. On the other hand, the 964BK section that has the Jc value much lower than 0.6 kJ/m^2 stays far out of the boxed area meaning that it performs poorly against random cracking. All Level 1 pavement sections whose Jc values are higher than 0.5 kJ/m^2 stay well within the dotted rectangular box showing good cracking resistance. The observation may suggest that the Jc values of 0.5 and 0.6 kJ/m^2 can be tentative performance criteria for identifying potentially crack prone pavements.

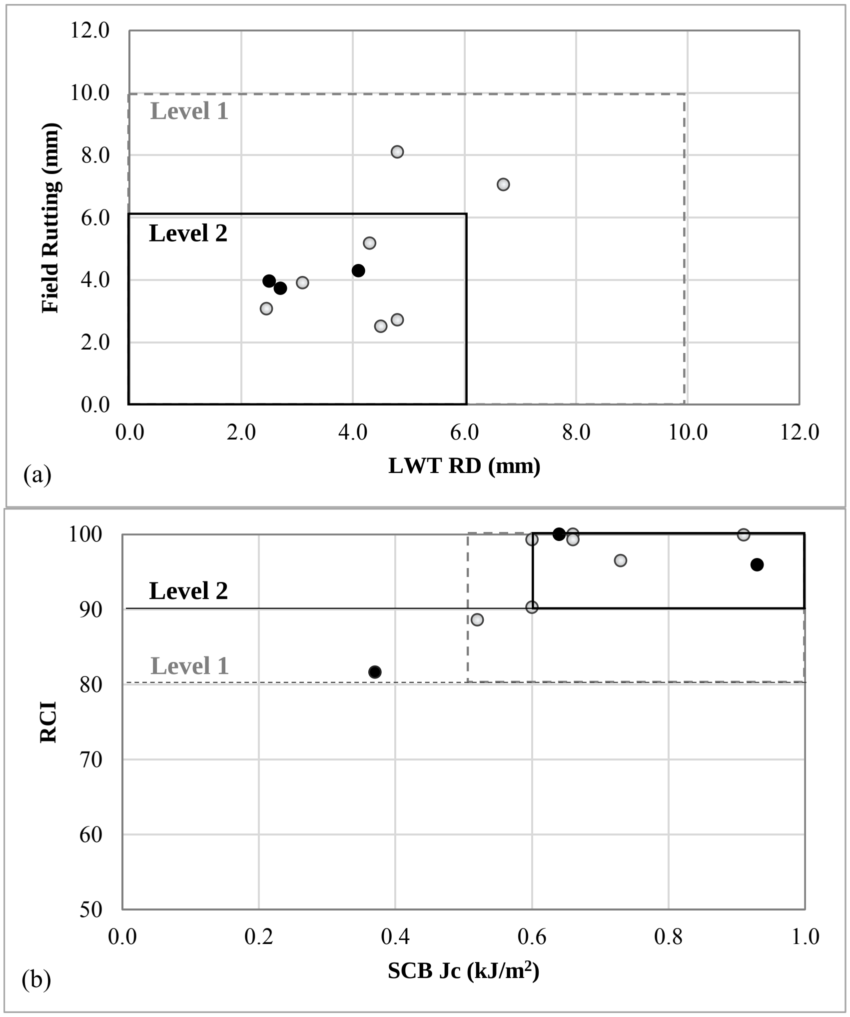

Figure 19
Tentative guidelines of laboratory performance indicators: (a) rutting and (b) random cracking

Comparisons between Standard and Simplified PBS

A brief comparison was made between standard performance based specification process and simplified performance specification process to determine advantages and disadvantages of the two different approaches. Construction details of the three new field projects were collected and field asphalt mixture samples were tested in the laboratory for input variables necessary in the comparison analysis. Figure 20 shows the flowchart of the comparison analysis. The AQC used for standard PBS were the dynamic modulus values. Along with the pavement structure, climate, and initial traffic data, the dynamic modulus values were used as key input variables in the Pavement-ME software to predict the performance of pavement sections. It should be noted that a set of locally calibrated rutting model constants were used, while the cracking models were not calibrated for local pavements *[18]*. The predicted distress values were then converted into corresponding index values to determine the acceptance of the roadways. On the other hand, the LWT RD and SCB Jc were measured as the AQCs of the simplified PBS, which were compared with the proposed performance criteria shown in Table 21. It is worth noting that a reduced SCB Jc requirement was allowed for the Level 1 traffic mixtures to account for an offset due to the potentially good alligator cracking performance of the pavement sections, which were not reflected in the determination of the proposed guideline.

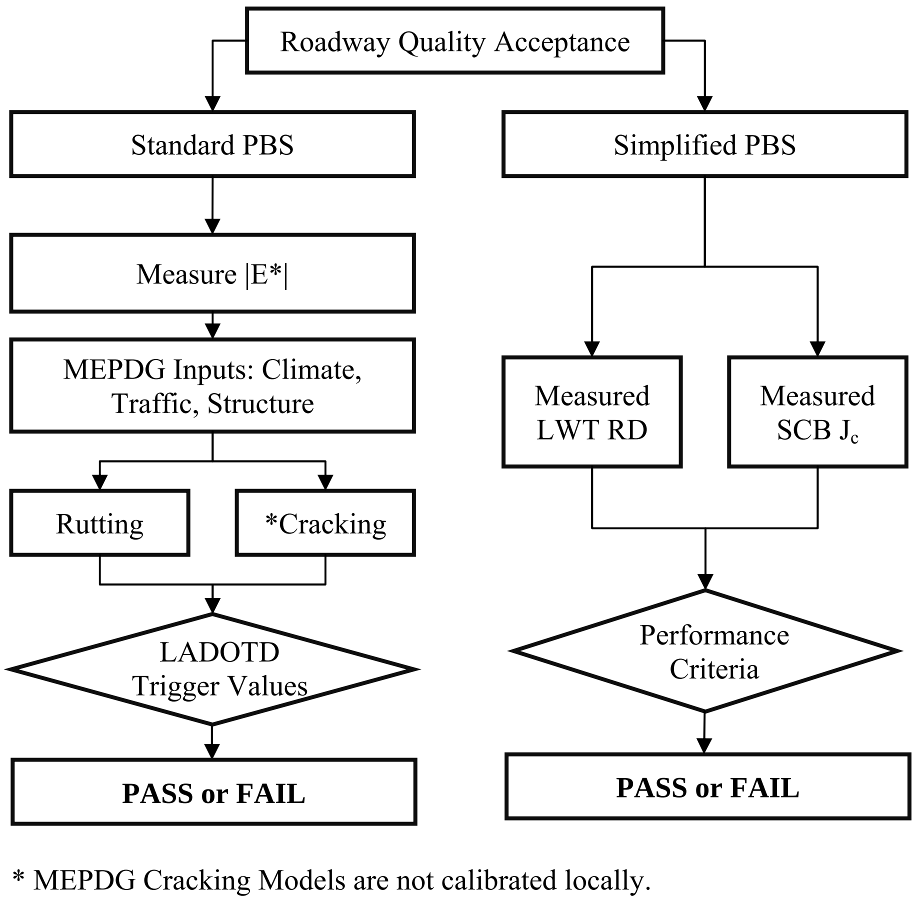

Figure 20
Standard-PBS vs. simplified-PBS

Table 21
Proposed peformance test criteria

Performance Based Tests	Level 1 Traffic	Level 2 Traffic
LWT RD @50°C, mm	10.0	6.0
SCB J_c @25°C, kJ/m^2	0.5	0.6

Table 22 presents a summary of the comparison results. For Level 1 mixtures, the thin overlay trigger is rutting index (RI) 65 or less, and the medium overlay trigger is RCI 80 or less. Meanwhile, the simplified performance criteria for rutting and cracking are 10 mm and 0.5 kJ/m^2, respectively. All three pavement sections passed rutting performance criteria for both standard and simplified specifications. Moreover, the orders of performance measures by the two approaches match exactly the same. Such a good agreement between the standard and simplified specification procedures in acceptance would support the applicability of a simplified procedure in lieu of a far more complicated and time-consuming approach. For the cracking performance acceptance, on the other hand, three pavement sections passed the standard specification performance criterion for the random cracking, while 90IB section failed the simplified cracking performance criterion of 0.5 kJ/m^2. In fact, it should be reminded that the un-calibrated cracking models of Pavement-ME were used in the performance predictions of these new pavement sections. Thus, the RCI values shown in Table 22 were not capable of discriminating different materials' performance, while the SCB Jc suggest, with relatively reasonable reliability, that the 90IB section will experience cracking related problem in the future.

Table 22
Summary of standard vs. simplified specification comparison

Pavement Section	Rutting		Random Crack	
	Standard (RI>65)	Simplified (LWT RD>10 mm)	Standard (RCI>80)	Simplified (SCB Jc > 0.5 kJ/m^2)
10SH	96	2.7	100	0.57
3235LF	92	3.8	82	0.69
90IB	89	6.8	100	0.30

Framework Development

Based on the analyses conducted in this study, a preliminary set of specification limits was proposed to ensure the long term performance of asphalt mixtures. For the rutting, 10 mm or less and 6 mm or less of average LWT rut depths for Level 1 and Level 2 asphalt pavements, respectively, seemed to guarantee acceptable field rutting performance. Similarly, for the cracking, 0.5 kJ/m^2 or higher and 0.6 kJ/m^2 or higher of the average SCB Jc values seemed to guarantee acceptable field cracking performance for Level 1 and Level 2 asphalt pavements, respectively. Table 23 presents the proposed specification limits for LWT test and SCB test categorized by the design traffic Levels for acceptance.

Table 23
Proposed specification limits for performance based tests

Performance Based Tests	Level 1 Traffic	Level 2 Traffic
Average LWT RD @50°C, mm Any single RD @50°C, mm	≤ 10.0 ≤ 12.5	≤ 6.0 ≤ 12.5
Average SCB J_c @25°C, kJ/m^2 Any single SCB Jc @25°C, kJ/m^2	≥ 0.5 ≥ 0.3	≥ 0.6 ≥ 0.3

In addition to the proposed specification limits, a detailed sampling and testing plan was also recommended in this study. Figure 21 presents the flow chart of the sampling and testing plan for the proposed PBS approach. On the roadway, a total of 25 cores per lot will be sampled from five random spots in each of the five sublots within a day after the completion of compaction for the acceptance testing. Among the 25 cores, a total of 15 cores will be selected for the acceptance testing, and the remaining ten cores will be reserved for future use in case of dispute resolution.

The 15 acceptance testing cores should include at least three cores from each sublot, and all of them will be tested for the density prior to the performance tests. After the density measurements, four cores will be used for the LWT RD and another four cores will be used for the SCB Jc measurements. It should be noted that a single run of LWT test with the four cores will result in four RD measurements as discussed earlier. On the other hand, a single run of SCB test in accordance with the standard test procedure followed in this study requires six cores for a single Jc measurement, which may not be practical. Thus, to reduce the required total number of SCB test cores, a modified test protocol was proposed by eliminating the middle notch depth test (31.8 mm notch depth). Removing the middle notch tests appeared not to affect the Jc value calculations significantly since the normalized strain energy vs. notch depth relationship (see Figure 9) is mostly linear. A detailed comparison analysis between the three-notch depth SCB Jc and the two-notch depth SCB Jc calculations is provided in Appendix C. The elimination of the middle notch depth test reduced the number of cores required for a complete set of SCB Jc test to four instead of six; the first two cores to produce four 25.4-mm notched semi-circular specimens and the remaining two cores to produce four 38.0-mm notched semi-circular specimens. Furthermore, assuming acceptable uniformity of replicate specimens, one can pair a 25.4-mm notch specimen to a 38.0-mm notch specimen randomly to obtain four sets of SCB Jc from the four cores.

As proposed in Table 23, the average of four RD measurements should be less than or equal to 10 mm and 6 mm for Level 1 and Level 2 mixtures, respectively, with all single RD values not exceeding 12.5 mm for the satisfactory rutting performance of pavements. Similarly, the average of four SCB Jc measurements should be higher than or equal to 0.5 kJ/m^2 and 0.6 kJ/m^2 for Level 1 and Level 2 mixtures, respectively, with all single Jc values not less than 0.3 kJ/m^2 for the satisfactory cracking performance of pavements.

Finished roadways will be accepted if the two performance tests pass the proposed criteria. If the criteria are not met, a resolution test by a certified independent laboratory is initiated and the reserved ten cores will be used for the resolution tests. Additional sampling, if needed, should follow a random sampling procedure that DOTD approves. Final acceptance of the roadways will be determined based upon the resolution test results. If the results fail to meet the proposed performance criteria, the mixture production should be ceased and corrective actions must be taken place until the production can be resumed.

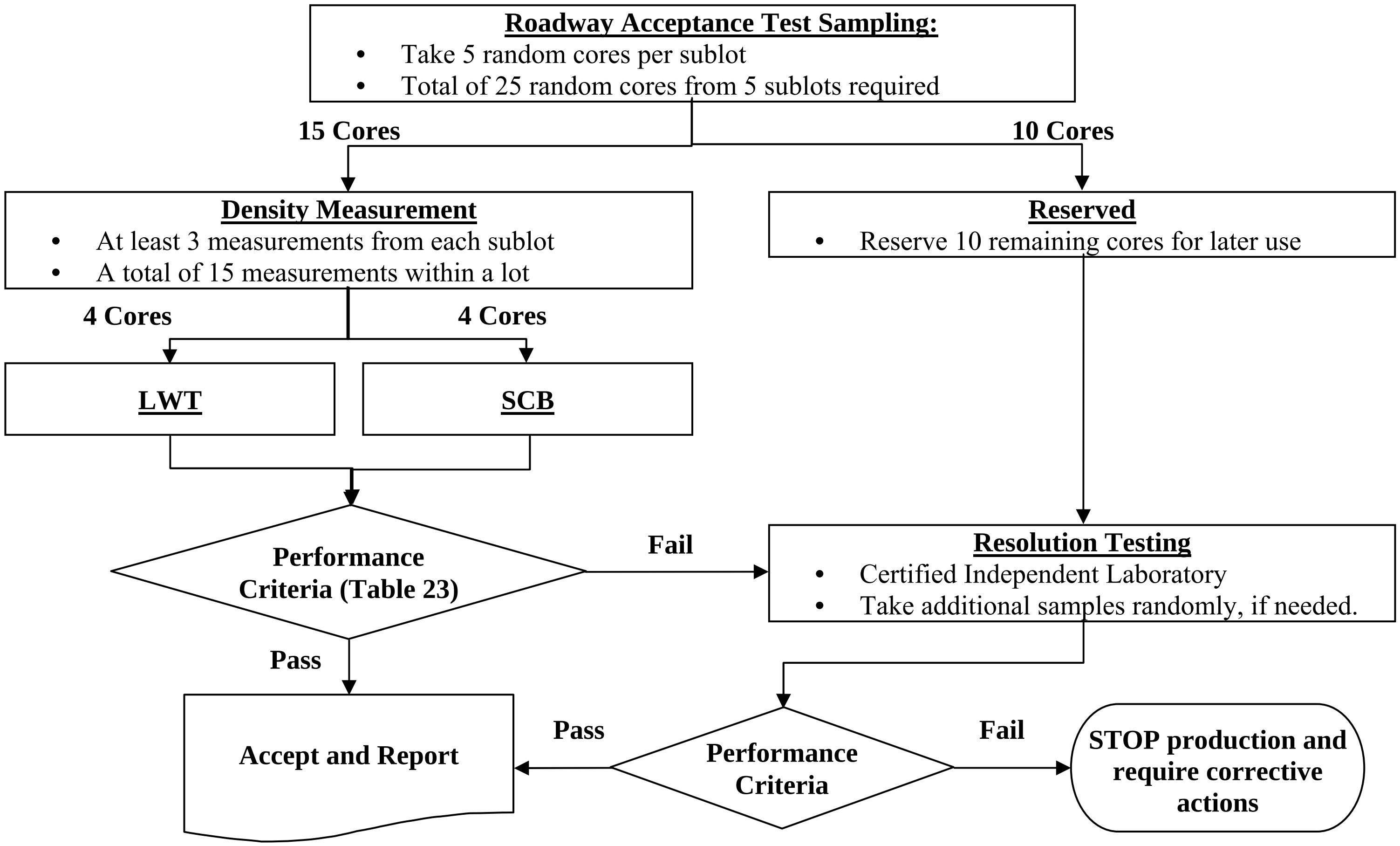

Figure 21
Proposed acceptance test plan

CONCLUSIONS

The primary objective of this research was to develop a simplified performance-oriented specification for new and rehabilitated asphalt pavements in Louisiana. Understanding the performance oriented specifications and establishing simplified performance guidelines of roadways were the two specific objectives of this study.

A total of nine field projects across Louisiana were selected, of which six were existing projects that have been in service for three to eight years and three were new projects. Hamburg type LWT device and SCB tests were conducted to measure proposed performance indicators of asphalt pavements from the field core samples for rutting and cracking performance indicators, respectively. In addition, IDT $|E^*|$ test was conducted for full viscoelastic characterization of asphalt mixtures, which were used in the performance predictions of AASHTOWare Pavement ME-Design.

Findings of the research are summarized as follows:

- The concept of performance-oriented specification is promising, since it takes more direct performance measure as the quality goal of the pavement construction. However, applications of the concept to actual projects require the use of complicated prediction models for material properties and pavement performance.

- A simplified approach to the standard performance-related or performance-based specification procedure can be attempted to improve the reliability of current QC/QA specifications, while avoiding the use of complicated prediction models.

- The LWT device can be a practical tool for evaluating rutting performance of asphalt mixtures and pavements. The LWT measured rut depths of 6 mm or less and 10 mm or less can be the tentative target quality limits for the Level 2 and Level 1 Louisiana asphalt pavements, respectively.

- SCB Jc was found to be a promising cracking performance indicator of asphalt mixtures. The minimum SCB Jc values of 0.6 and 0.5 kJ/m^2 are proposed as the cracking performance criteria in order to ensure acceptable cracking performance of Level 2 and Level 1 asphalt mixtures, respectively.

- According to the qualitative comparison between standard and simplified PBS approaches, the simplified procedure seemed to discriminate different performing asphalt pavements as effectively as the more complicated standard PBS. With the absence of locally calibrated cracking prediction models at the present time, the simplified PBS would be more effective in ensuring acceptable cracking resistance of asphalt pavements.

- A sampling and testing plan was prepared and recommended for a continued data collection effort to further validate the performance criteria and to help address unknown challenges for implementing the PBS in practice.

According to findings of this research, it can be concluded that a simplified performance based specification procedure, which include LWT and SCB tests, can be added to the current QC/QA specification to better guarantee the long term performance of Louisiana asphalt pavements. A continued research effort to collect further field and laboratory performance data is desired to validate the tentative performance criteria and to address unknown challenges in implementing the proposed PBS approach.

RECOMMENDATIONS

- This research study concluded that LWT and SCB tests can be adopted as potential laboratory test methods to better evaluate the long term pavement performance. Since this study includes a limited number of projects, it is recommended to conduct an extended monitoring of this proposed methodology. This data collection effort can identify difficulties in implementing the proposed PBS and help to make necessary modifications.
- The SCB test was conducted on partially field aged specimens in this study. It is necessary to investigate the long term performance of these pavement sections to better evaluate the aging influence on the SCB testing.

Pavement-ME cracking performance prediction models should be calibrated to continuously validate with the field cracking data.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

$(AD)_H$	high severity alligator cracking deduct value
$(AD)_L$	low severity alligator cracking deduct value
$(AD)_M$	medium severity alligator cracking deduct value
$(RD)_H$	high severity random cracking deduct value
$(RD)_L$	low severity random cracking deduct value
$(RD)_M$	medium severity random cracking deduct value
$\|E^*\|$	dynamic modulus
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt content in percentage
ACI	alligator cracking index
AMPT	Asphalt Mixture Performance Tester
ANCOVA	analysis of covariance
ANOVA	analysis of variance
AQC	acceptance quality characteristic
ARAN	automatic road analyzer
AV	air voids
β_{r1}, β_{r2}, β_{r3}	rutting model local calibration constants
cm	centimeter(s)
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation and Development
ε_p	permanent strain
ε_r	recoverable strain
ERS	End-result specification
ESAL	equivalent single axle load
FHWA-ALF	Federal Highway Administration's Accelerated Loading Facility
F_n	flow number
F_t	flow time
ft.	foot (feet)
FWD	falling weight deflectometer
HMA	hot-mix asphalt
IDT	indirect tensile
in.	inch(es)
IRI	international roughness index
Jc	critical strain energy release rate
JMF	job-mix formula

kJ	kilojoules
km	kilometer(s)
kN	kilo-Newton
k_1, k_2, k_3	nationally calibrated rutting model coefficients
k_z	function of asphalt layer thickness for confining pressure adjustment
lb.	pound(s)
LFWD	light falling weight deflectometer
LTRC	Louisiana Transportation Research Center
LWT	loaded wheel tracking
m	meter(s)
mm	millimeter(s)
MEPDG	Mechanistic-Empirical Pavement Design Guide
N	number of traffic loadings
nCA	coarse aggregate slope
NDT	non-destructive test
OT	overlay tester
PBS	performance based specification
PC	post-consolidation
PMS	pavement management system
PRS	performance related specification
PS	performance specification
PSPA	portable seismic property analyzer
QC/QA	Quality Control/Quality Acceptance
RCI	random cracking index
RD	rut depth
R_{field}	regression model predicted field rutting
RI	rutting index
SCB	semi-circular bending
SHA	State highway agency
SPT	simple performance test
T	pavement temperature in Fahrenheit
TI	toughness index
TSR	tensile strength ratio
VFA	voids filled with asphalt
VMA	voids in mineral aggregates
WMA	warm-mix asphalt

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APPENDIX A

Laboratory Tests Methods and Specimen Preparation

Sample Coring and Fabrication

Field samples were cored on random locations within the selected field projects. For every project, fifteen coring spots, of which six were for SCB test, four were for LWT test, and five were for IDT |*E**| test, were selected with a minimum spacing of 50 feet between two adjacent spots. A 6 inch inner diameter coring rig was used so that the minimum diameter of laboratory test specimens would remain close to 150 mm (6 inches). Once the cores were obtained, they were secured in a safe insulated container to prevent unwanted damage while transporting to the laboratory. The thickness of the cores varied depending on the structural designs of particular pavement sections. After transported to the laboratory, the core samples were cut into desirable thicknesses for the three mechanical tests using a heavy duty mechanical sawing machine. The desired specimen thicknesses were 57 mm (2.24 inch) for SCB test, 40 mm (1.57 inch) for LWT test, and 38 mm (1.49 inch) for IDT |*E**| test. After cutting the specimens to the desirable thickness, air voids were measured in accordance with AASHTO T-166 "Standard Specification for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimens."

Figure A.1
Fabrication of SCB test samples

Laboratory Test Methods

Loaded Wheel Tracking (LWT) Test. The loaded wheel tracking (LWT) test is conducted to determine the rutting characteristics of the asphalt mixtures considered in this study in accordance with AASHTO T 324 "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)." In this test, asphalt mixture specimens (cores or rectangular slabs) are subjected to a steel wheel weighing

703 N (158 pounds) repeatedly rolled across the top surface of the specimens, while they are submerged underwater maintained at 50^{o}C. The test completion time is predicated upon test specimens being subjected to a maximum of 20,000 cycles or attainment of 20 mm deformation; whichever is reached first. Upon completion of the test, the average rut depth (RD) for the samples tested is recorded and used in the analysis. Figure A.2 shows the test set-up. The device can test two specimens simultaneously. Specimens are pre-conditioned at 50 °C for 90 minutes before the testing starts.

Figure A.2
Hamburg loaded wheel tracking device

Two linear variable displacement transducers (LVDTs) are used to measure deformations during testing, and the subsequent test results (e.g., rut depths, number of passes, and bath temperature) are collected and recorded in an automatic data recording system. Figure A.3 presents a typical LWT test output.

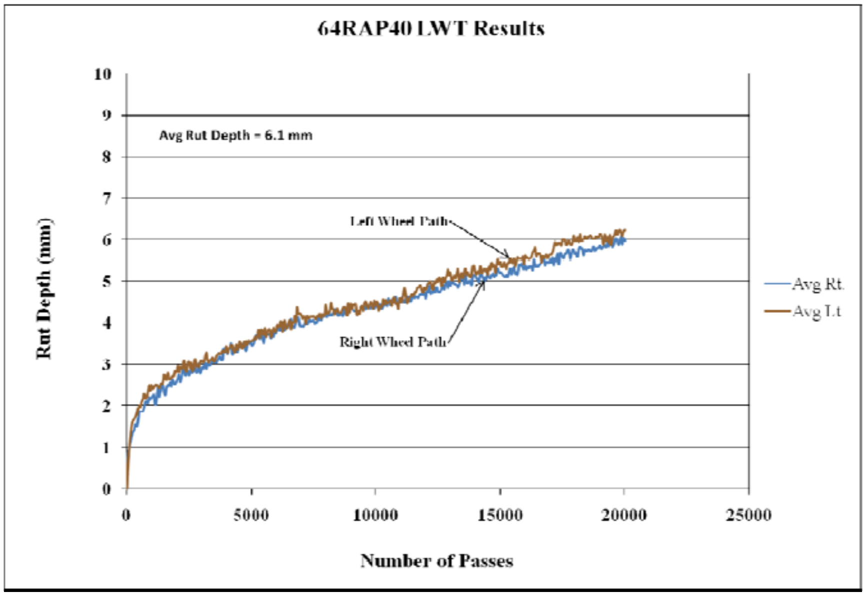


Figure A.3
Typical LWT test output

Semi-Circular Bending (SCB) Test. This test characterizes the fracture resistance of asphalt mixtures based on a fracture mechanics concept, the critical strain energy release rate also called the critical value of J-integral, or Jc. To determine the critical value of J-integral, semi-circular specimens with three notch depths (25.4, 31.8, and 38.0 mm) are tested using three replicates per notch depth. The test is conducted at 25°C. A semi-circular specimen is loaded monotonically until the fracture takes place under a constant cross-head deformation rate of 0.5 mm/min in a three-point bend load configuration, Figure A.4. The load and deformation are continuously recorded, and the critical value of J-integral is determined and used in the analysis based on the following equation:

$$Jc = -\left(\frac{1}{b}\right)\frac{dU}{da}$$

where,

Jc= critical strain energy release rate (kJ/m^2);
b = sample thickness (m);
a = notch depth (m);
U = strain energy to failure (kilo-Joule, kJ); and
dU/da = change of strain energy with notch depth, KJ/m ..

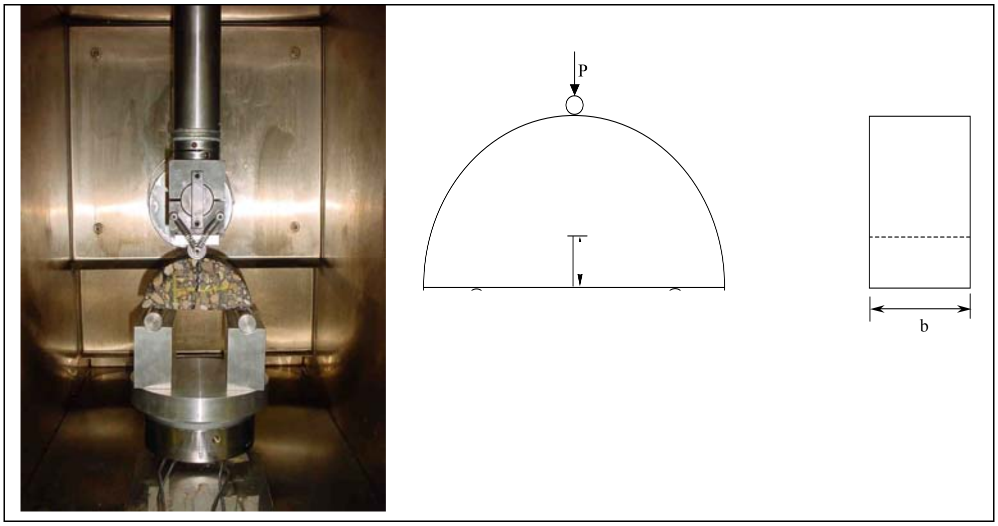


Figure A.4
Set-up of semi-circular bending test

Indirect Tension Complex Modulus (IDT |E*|) Test. Typically, dynamic modulus (The test protocol in the axial mode requires specimen to be 100 mm in diameter and 150 mm tall. However, cores obtained from the field do not meet the height requirements of 150 mm. Thus, the IDT |*E**| test can be a viable alternative to measuring the complex modulus of the asphalt specimen. The IDT |*E**| test can be performed in accordance to the dynamic modulus test protocols under uniaxial compression, but the test temperatures and loading frequencies are usually adjusted to better fit the specimen geometry and loading configuration of IDT, which are different from that of uniaxial set up *[39, 40]*. In this study IDT |*E**| tests were performed at three temperatures (i.e., -10, 10, and 30 ^{o}C) and at six frequencies (i.e., 0.01, 0.1, 0.5, 1, 5, 10 Hz). Once measured, the obtained |*E**| values at these temperature and frequency combinations were extrapolated to five standard temperatures (i.e., -10, 4, 25, 38, 54 ^{o}C) and six standard loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) required for inputs in the Pavement-ME performance prediction software following the method described in Kim et al. *[41]*.

Figure A.5 shows the IDT |*E**| specimen and test set up. Specimen dimensions are 150 mm in diameter and 38 mm in thickness. While the specimen is subjected to the varying frequencies of sinusoidal loading through the loading strip across its thickness as shown in Figure A.5 (c), the induced strain is measured using two 38.1-mm long extensometers mounted on both sides of disk shaped specimen as shown in Figure A.5 (b). The IDT |*E**| values were calculated following the procedure developed by Kim et al. *[26]*.

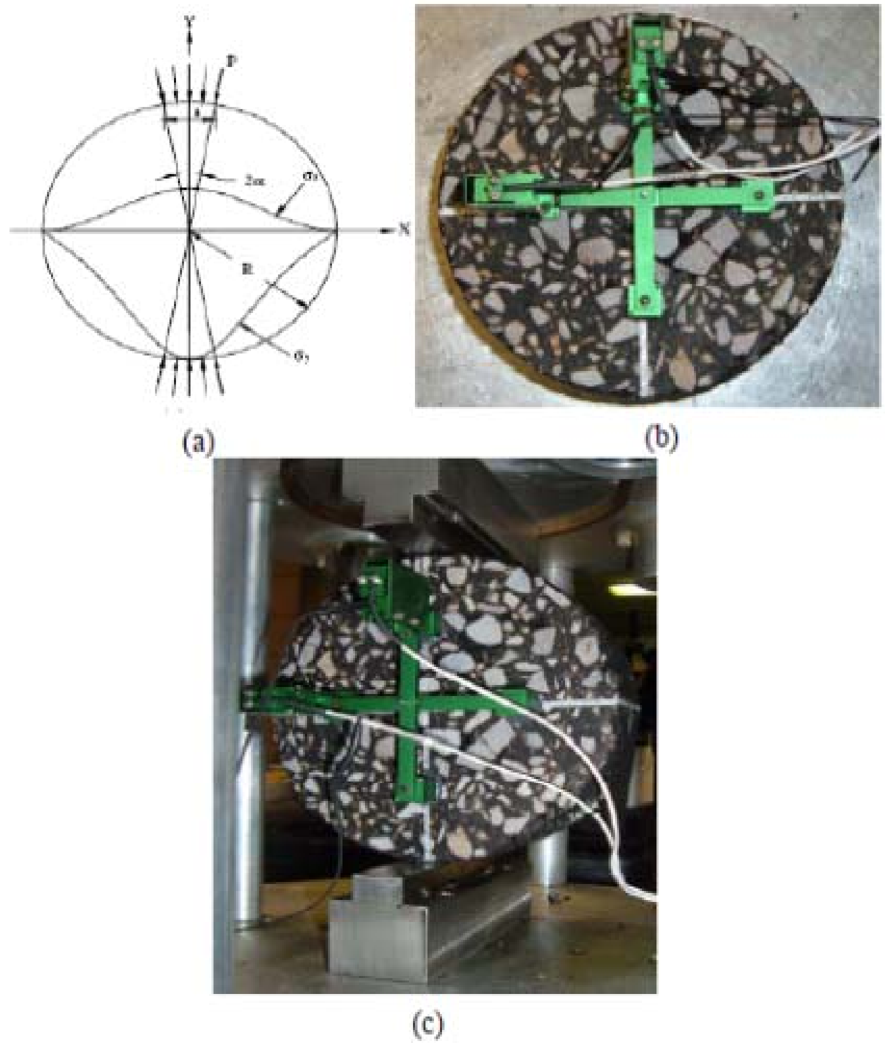


Figure A.5
(a) stress distribution in the IDT mode, (b) specimen with extensometer mounted, and (c) specimen in test position

Field Experiments

Light Falling Weight Deflectometer (LFWD). Light falling weight deflectometer (LFWD) is designed as an alternative in-situ test to the plate load test and was originally developed in Germany. This LFWD device mainly consists of a loading plate generating a lad pulse, a loading plate, and a center geophone as per Zorn. DynaTest LFWD, as shown in Figure A.6, was used in this study.

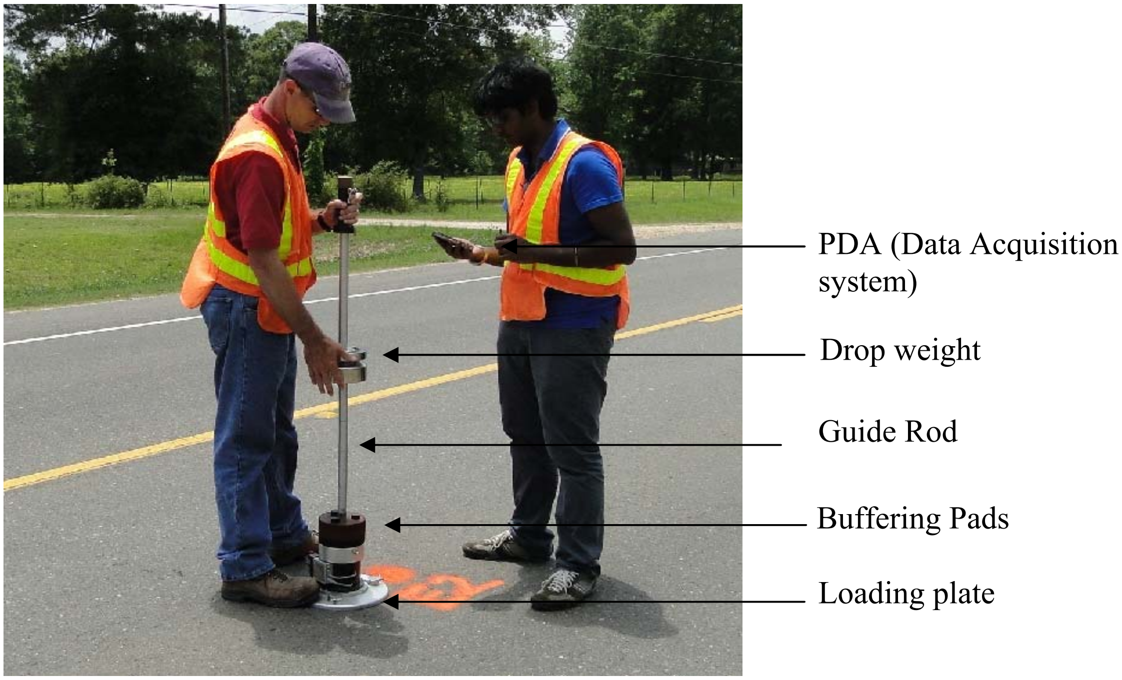


Figure A.6
LFWD device setup

The device has a falling mass of 10 kg and two extra loads, each 5 kg. The extra loads can be added according to the requirement of the pavement structure. Usually in this research, all of the tests are carried out using the mass of 10 kg. With this 10 kg mass impact on the plate, a load pulse is produced up to 15 kN of 15-25 ms duration. The center geophone measures the mass impacted deflection on the loading plate. The diameter of the loading plate varies from 150 and 300 mm (150 mm is used in this research). The deflection equation was based on Boussines for an applied load over single circular area on elastic half space. The equation used to calculate the modulus E_{LFWD}, which was used in the subsequent section of analysis, is as follows:

$$E_{LFWD} = \frac{2(1-\nu^2)\sigma \times R}{\delta_c}$$

where,

σ = applied stress, MPa
R = loading plate radius, mm
δ_c = deflection measured under the plate, mm
ν = Poisson's ratio

Portable Seismic Property Analyzer (PSPA). The portable seismic property analyzer (PSPA) is mainly used to determine the top layer stiffness (modulus) of the pavements where the effective thickness can be varied accordingly.

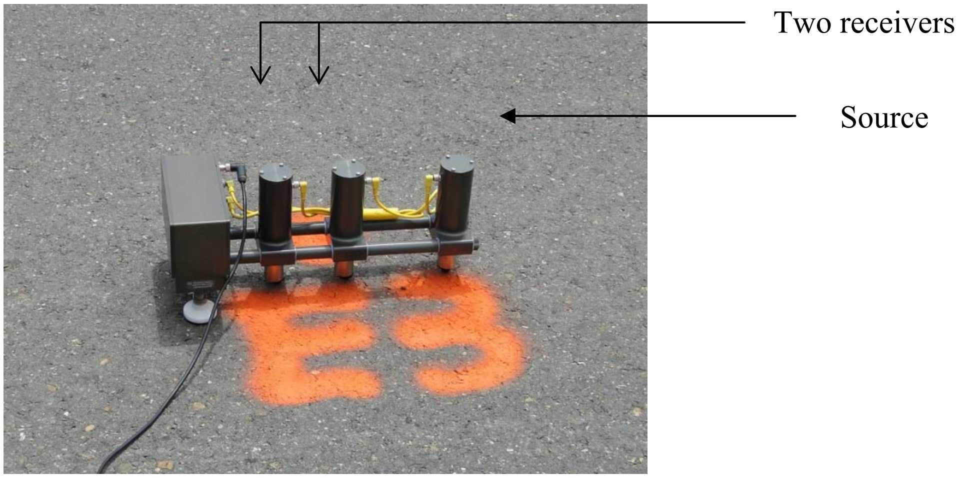


Figure A.7
PSPA setup

As shown in Figure A.7, the device consists of two receivers with a source. The whole device is connected to a laptop with control software to record the data at each impact. It can perform high frequency seismic tests.

PSPA is based on generating the stress waves and detecting them in a medium. An offset of the Spectral Analysis of Surface Wave (SASW) method, which is the Ultrasonic Surface Wave (USW) method, is used to determine the modulus of the material. The testing sequence starts with a program initiation (SPA manager) on the laptop. The source then generates seven high frequency waves on to the material. The last three impact results are saved and averaged from the output of the two receivers. Dynamic range gains are set with the other (pre-recording) impacts used to set the gains of amplifiers. The modulus of the top layer, E, can be determined from:

$$E = 2 \rho V_S^2 (1+\nu)$$

where,

V_S = velocity of shear waves
ρ = mass density
ν = Poisson's ratio.

Both of the LWD and PSPA data are corrected to 25°C using the following equation *[35]*:

$$E_{25} = \frac{E_T}{1.35 - 0.014 \times T}$$

where,

E_{25} = modulus at 25 °C, MPa
E_T = modulus at test temperature, MPa
T = pavement mid depth temperature, °C

The pavement mid depth temperature was obtained using BELLS3 model as shown in the following equation:

$$T = 0.95 + 0.892 \times IR + \{\log(d) - 1.25\}\{-0.448 \times IR + 0.621 \times (1\text{-day})$$
$$+ 1.83 \times \sin(hr18 - 15.5)\} + 0.042 \times IR \times \sin(hr18 - 13.5)$$

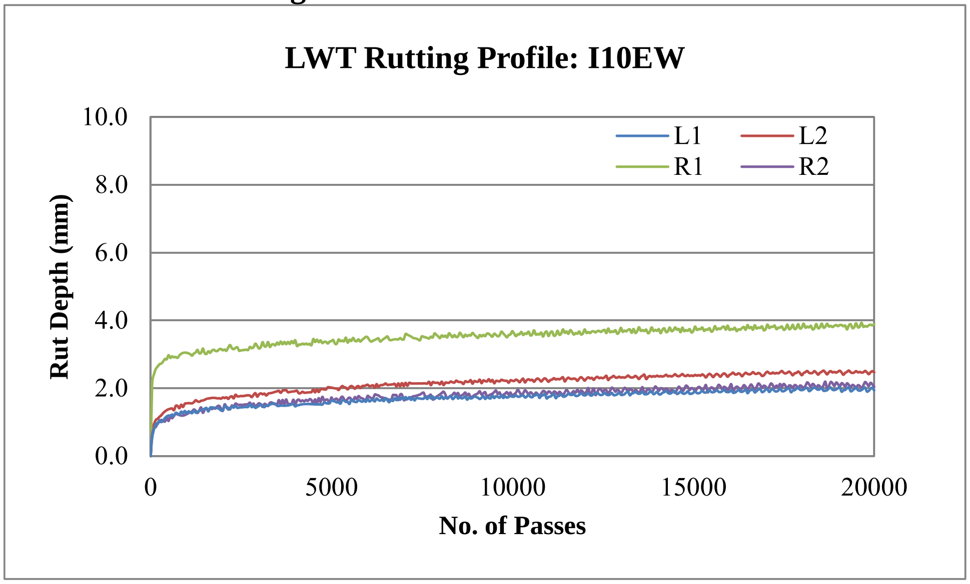
where,

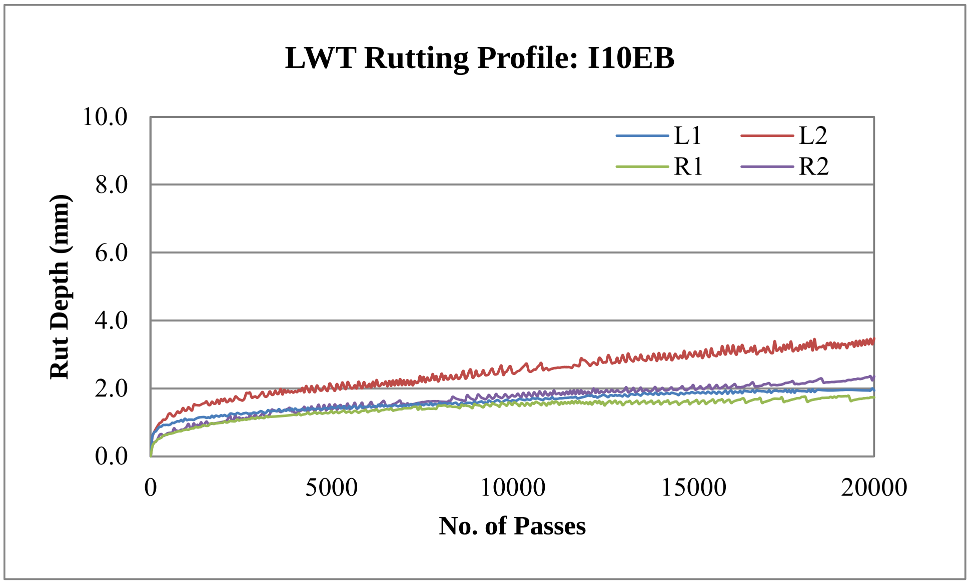
T = Pavement temperature at depth d, °C
IR = Infrared surface temperature, °C
log = Base 10 logarithm
d = Depth at which mat temperature is to be predicted, mm
1-day = Average air temperature the day before testing, °C
sin = Sine function on an 18-hr clock system, with 2π radians equal to one 18-hr cycle
hr18= Time of day, in 24-hr clock system, but calculated using an 18-hr asphalt concrete

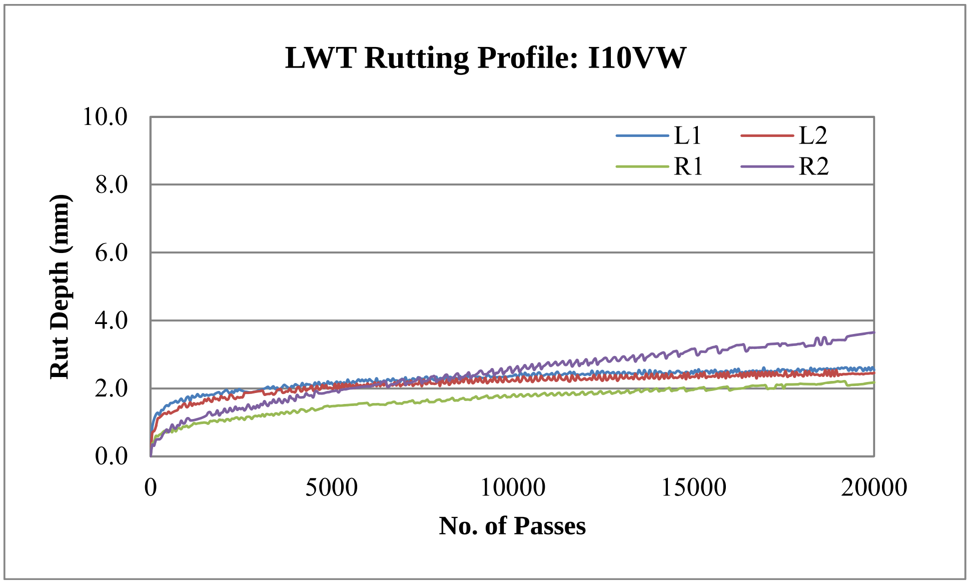
APPENDIX B

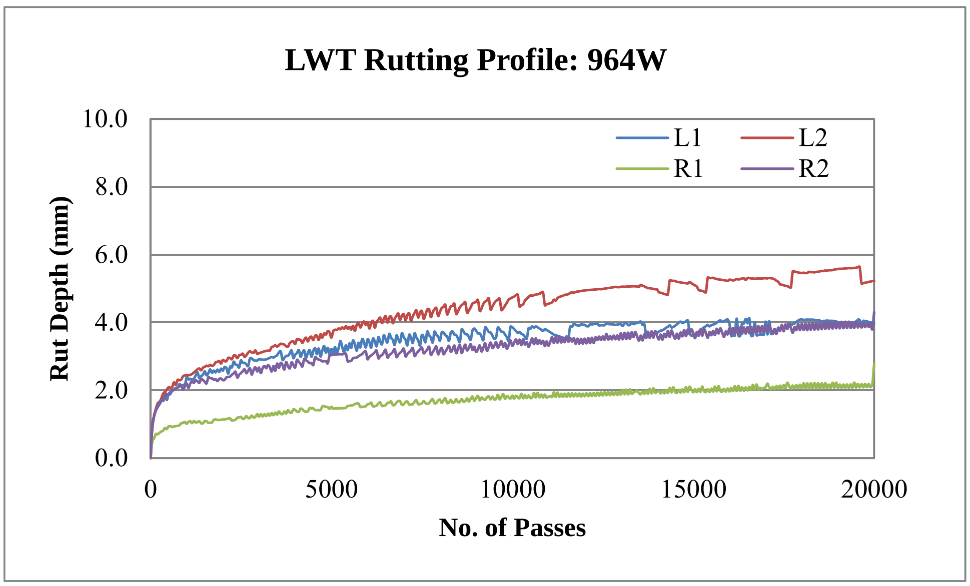
Laboratory Test Results

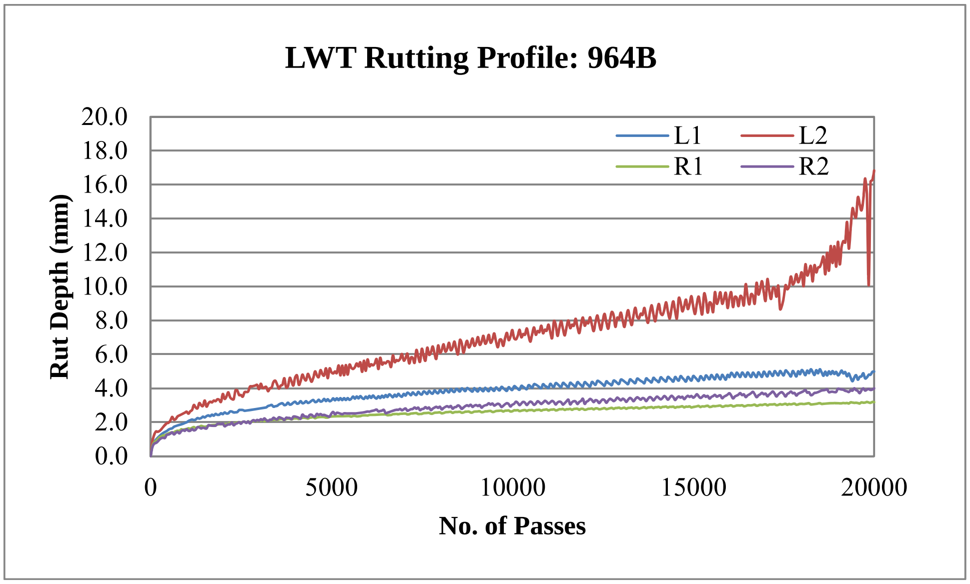
B-1. Loaded Wheel Tracking Test

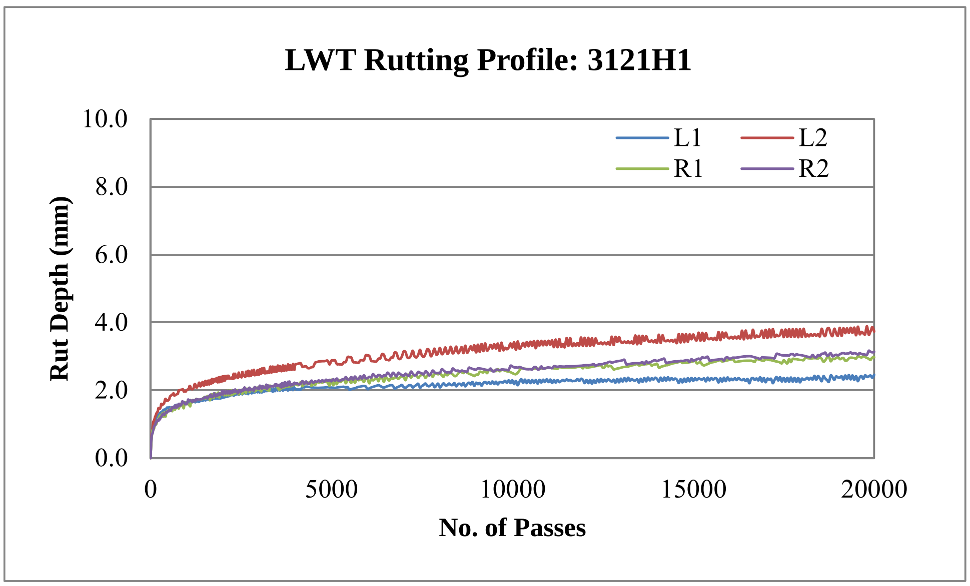


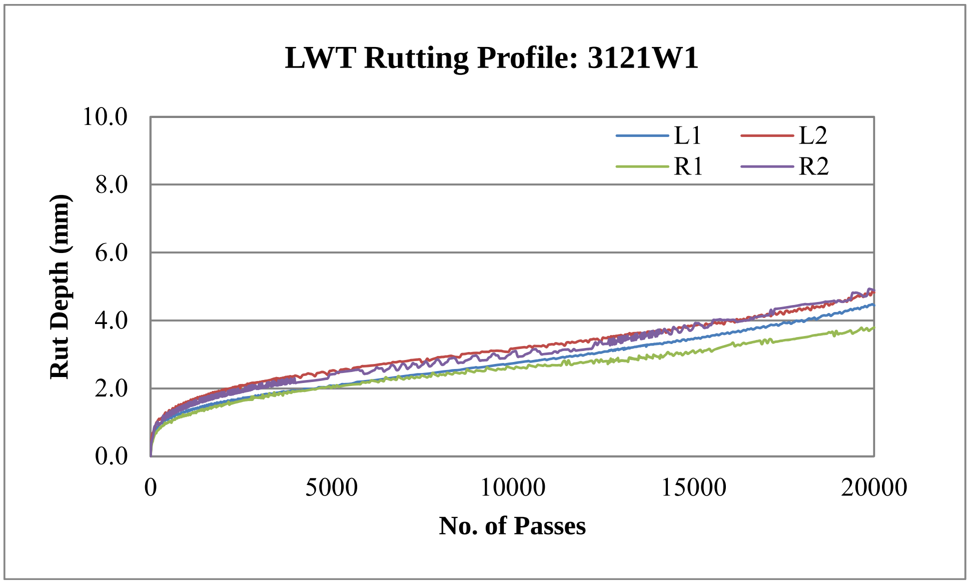


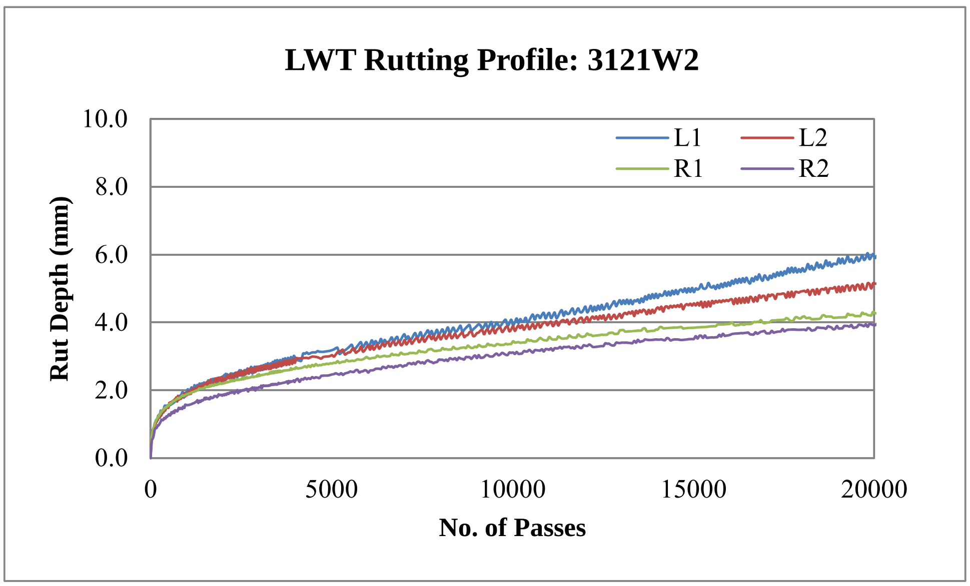

LWT Rutting Profile: I10VW
Rut Depth (mm)
No. of Passes
L1
L2
R1
R2
0.0
2.0
4.0
6.0
8.0
10.0
0
5000
10000
15000
20000

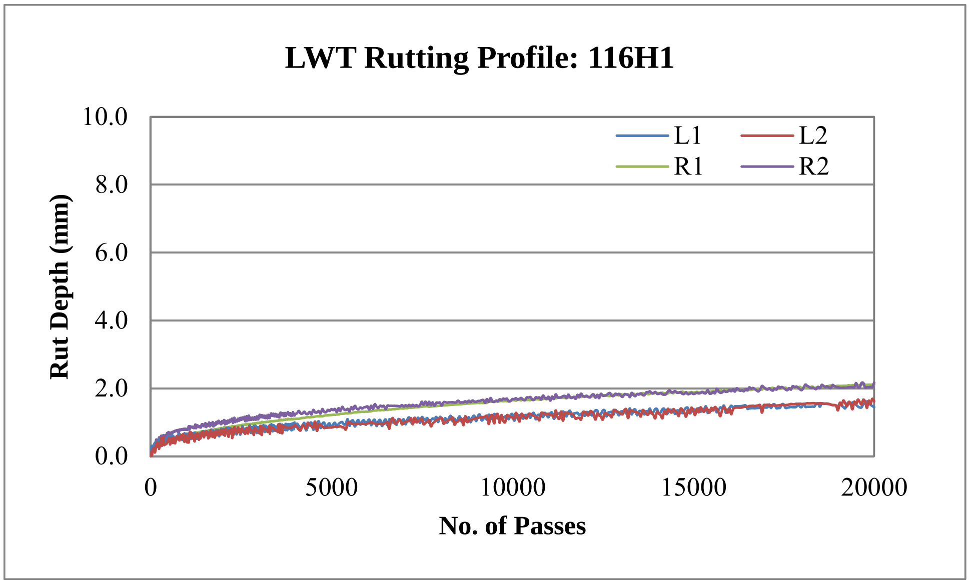

LWT Rutting Profile: 964W
Rut Depth (mm)
No. of Passes
L1
L2
R1
R2
0.0
2.0
4.0
6.0
8.0
10.0
0
5000
10000
15000
20000

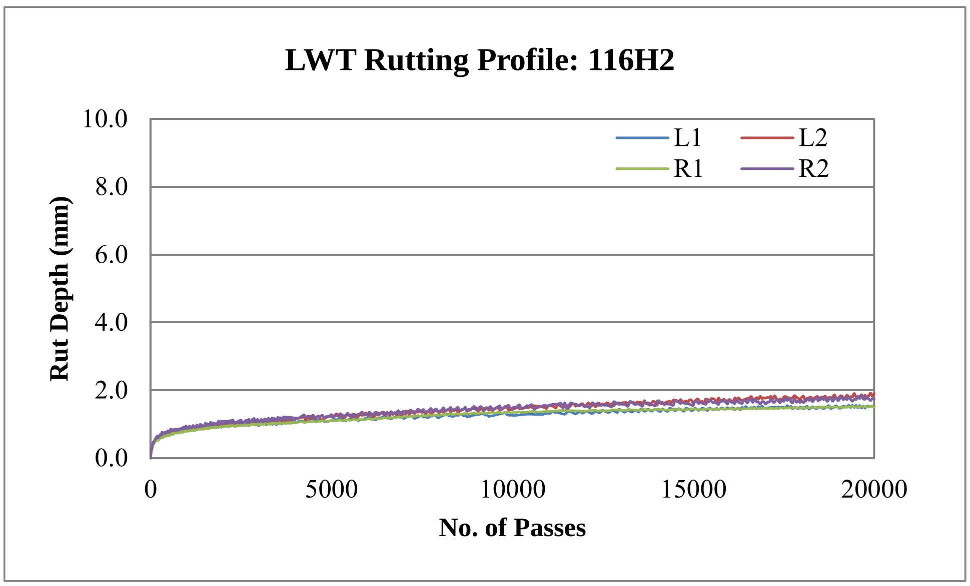

LWT Rutting Profile: 964B
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Rut Depth (mm)
L1
L2
R1
R2
0
5000
10000
15000
20000
No. of Passes

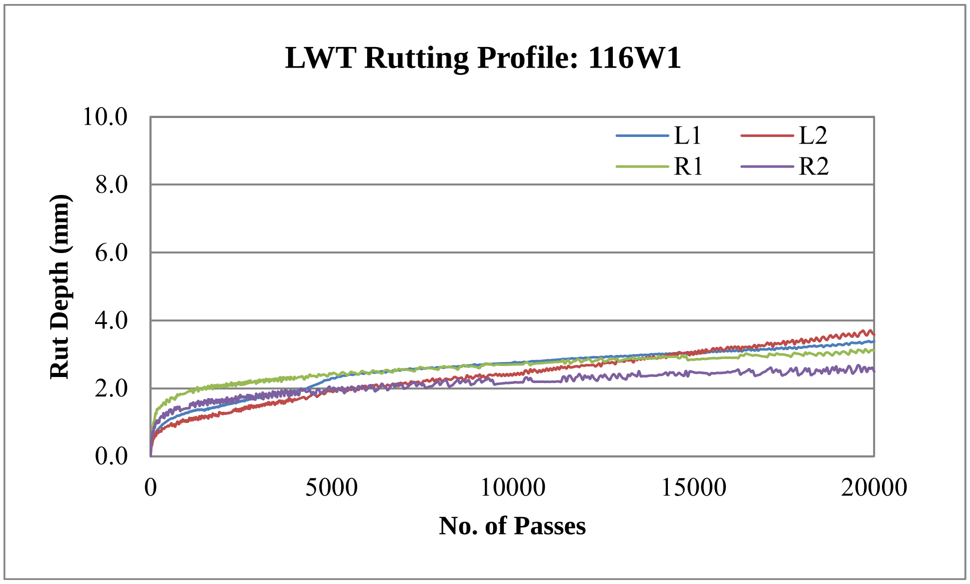

LWT Rutting Profile: 3121H1
10.0
8.0
6.0
4.0
2.0
0.0
Rut Depth (mm)
L1
L2
R1
R2
0
5000
10000
15000
20000
No. of Passes

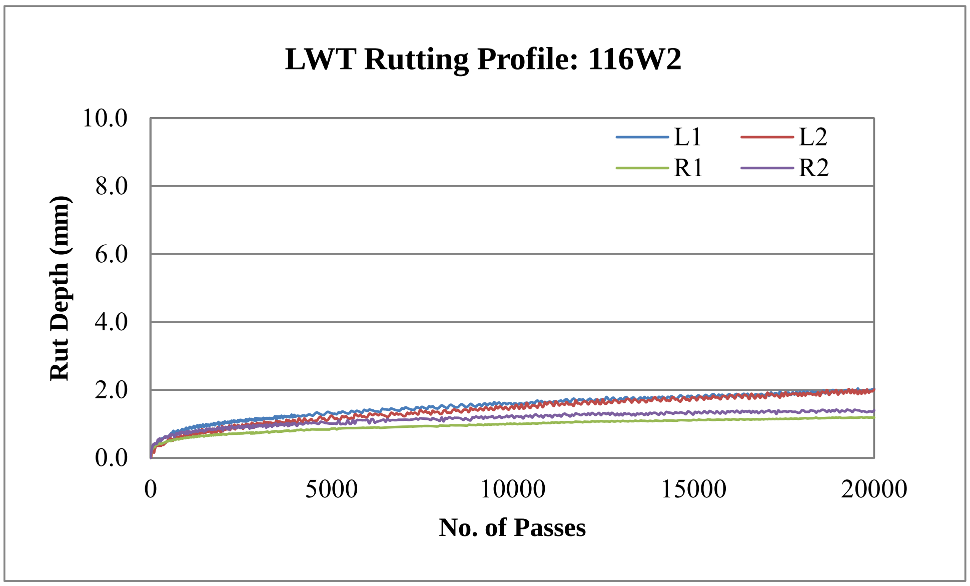

LWT Rutting Profile: 3121W1
L1
L2
R1
R2
Rut Depth (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
No. of Passes

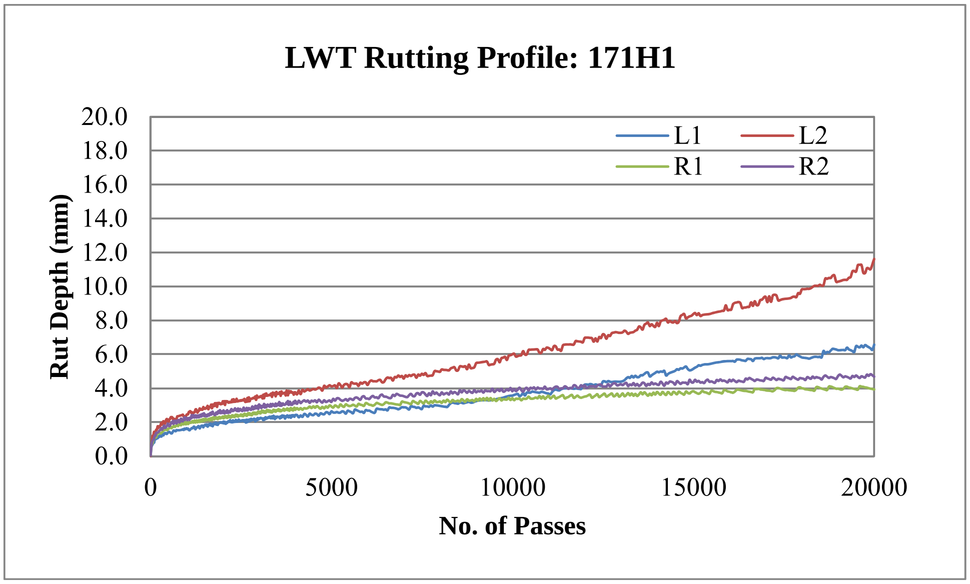

LWT Rutting Profile: 3121W2
L1
L2
R1
R2
Rut Depth (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
No. of Passes

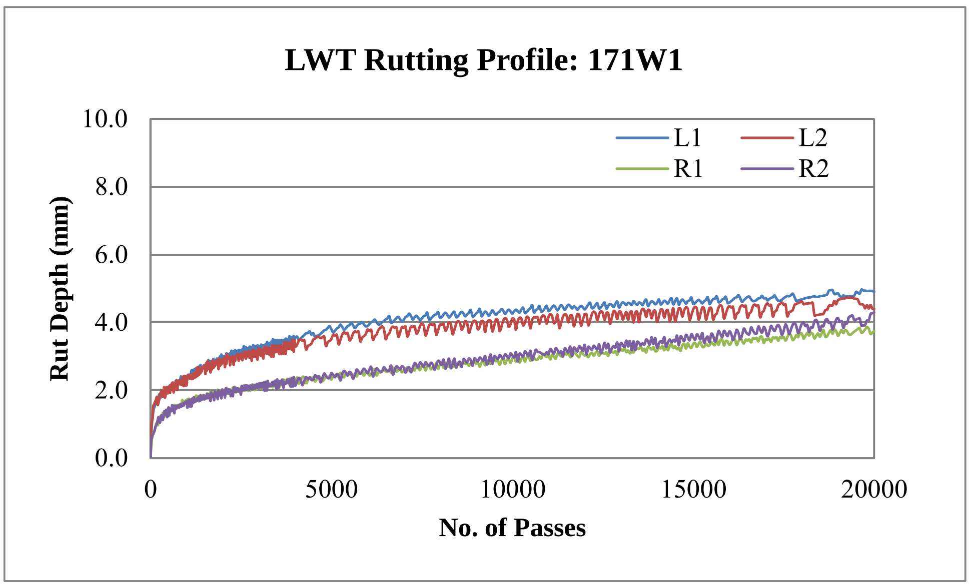

LWT Rutting Profile: 116H1
Rut Depth (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
No. of Passes
L1
L2
R1
R2

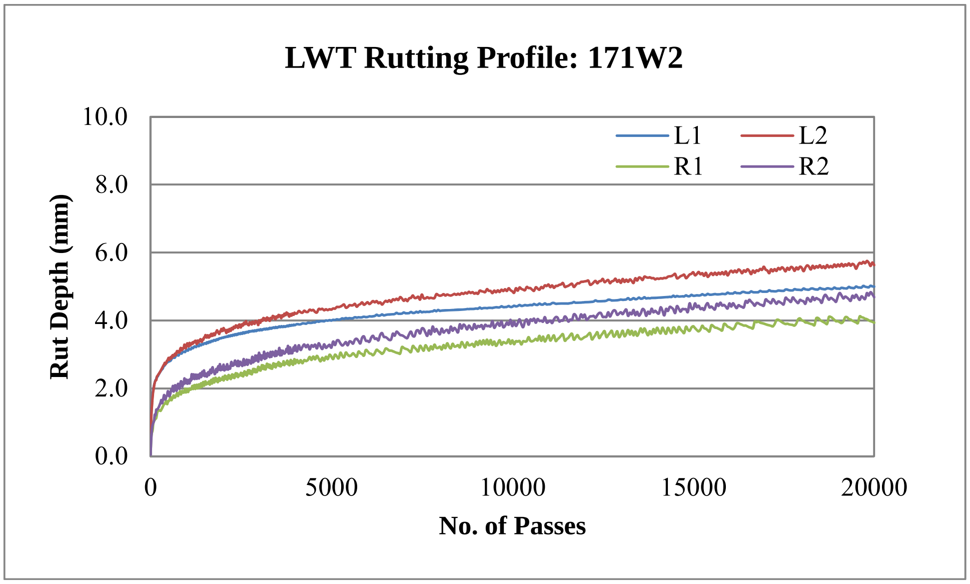

LWT Rutting Profile: 116H2
Rut Depth (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
No. of Passes
L1
L2
R1
R2

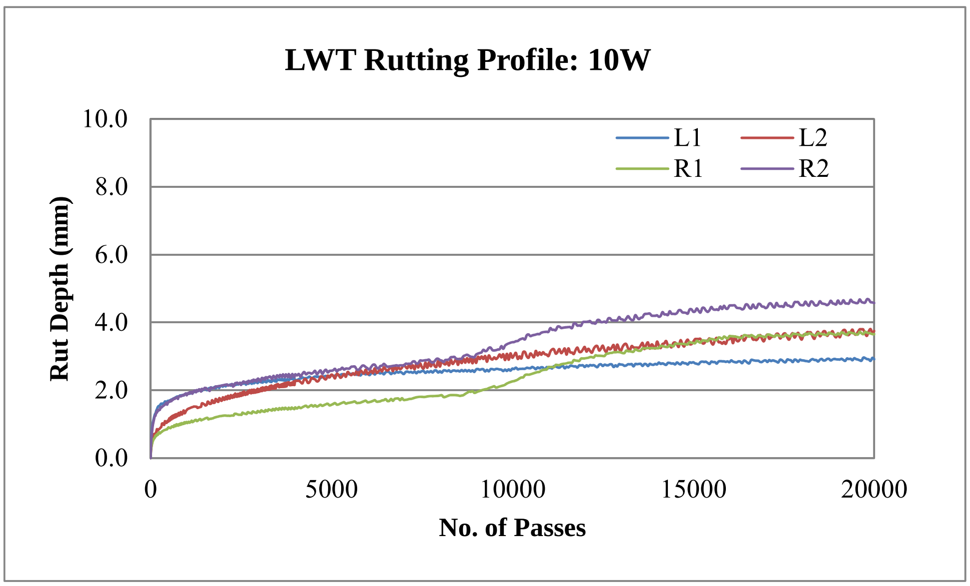

LWT Rutting Profile: 116W1
Rut Depth (mm)
No. of Passes
L1
L2
R1
R2
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000

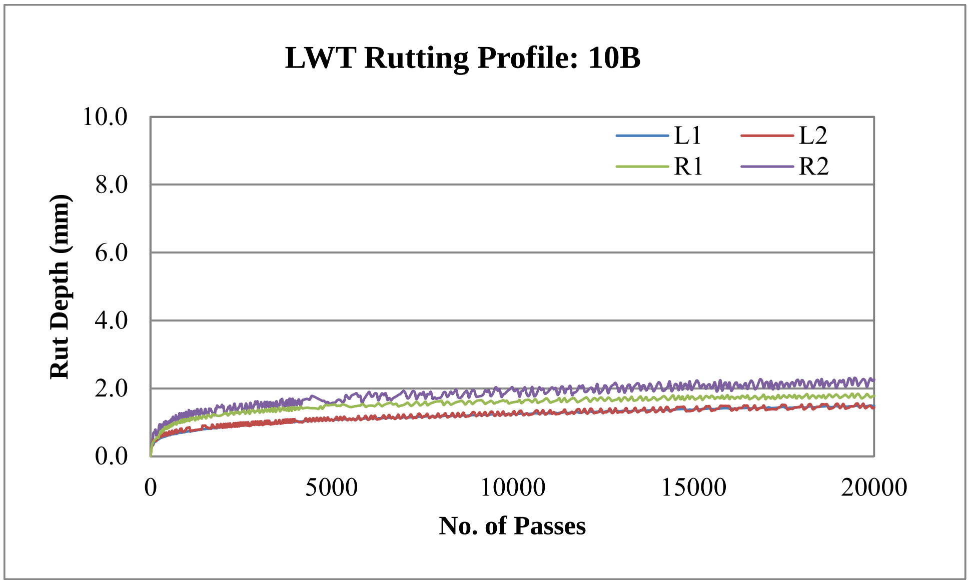

LWT Rutting Profile: 116W2
Rut Depth (mm)
No. of Passes
L1
L2
R1
R2
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000

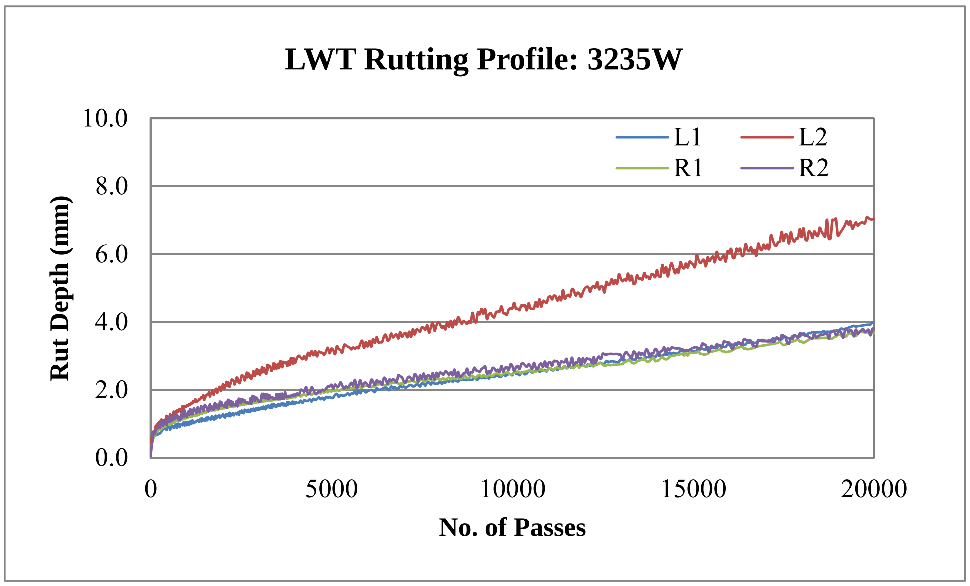

LWT Rutting Profile: 171H1
L1
L2
R1
R2
Rut Depth (mm)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
0
5000
10000
15000
20000
No. of Passes

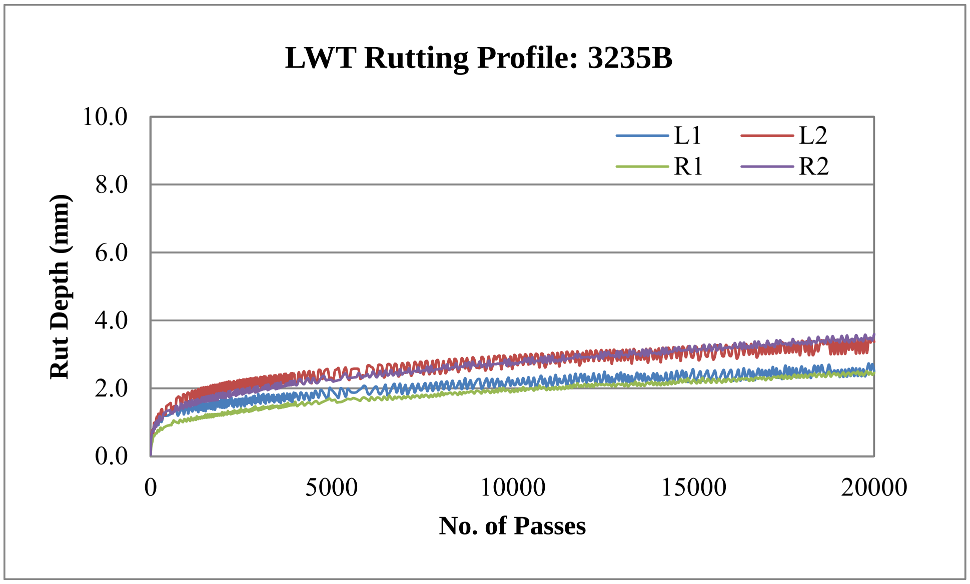

LWT Rutting Profile: 171W1
L1
L2
R1
R2
Rut Depth (mm)
0.0
2.0
4.0
6.0
8.0
10.0
0
5000
10000
15000
20000
No. of Passes

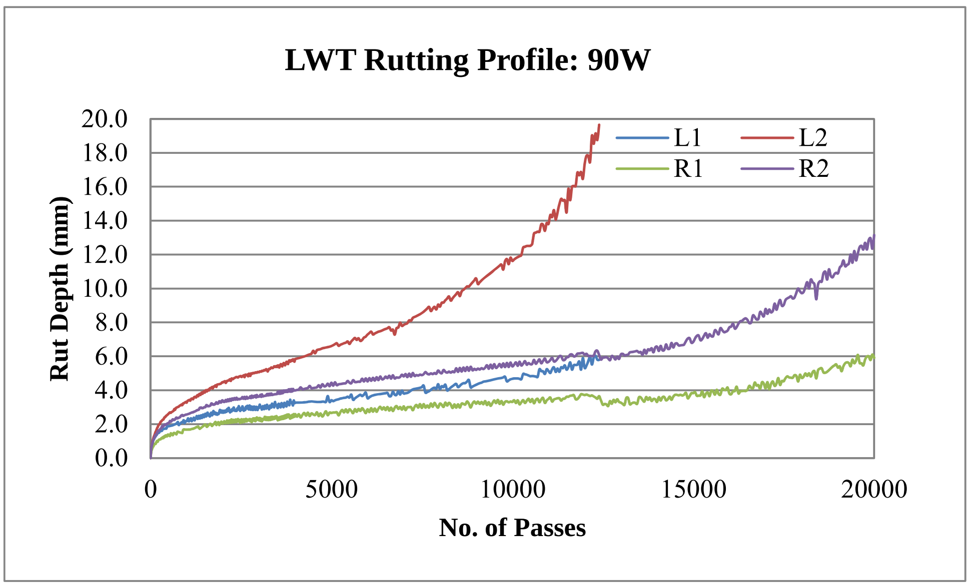

LWT Rutting Profile: 171W2
L1
L2
R1
R2
10.0
8.0
6.0
4.0
2.0
0.0
Rut Depth (mm)
0
5000
10000
15000
20000
No. of Passes

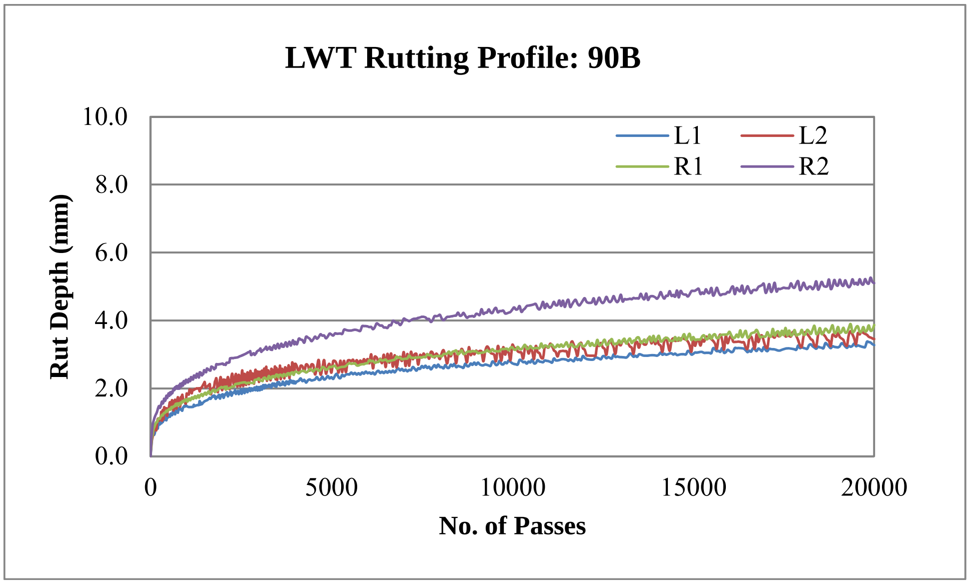

LWT Rutting Profile: 10W
L1
L2
R1
R2
10.0
8.0
6.0
4.0
2.0
0.0
Rut Depth (mm)
0
5000
10000
15000
20000
No. of Passes


LWT Rutting Profile: 10B
Rut Depth (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
No. of Passes
L1
L2
R1
R2


LWT Rutting Profile: 3235W
Rut Depth (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
No. of Passes
L1
L2
R1
R2

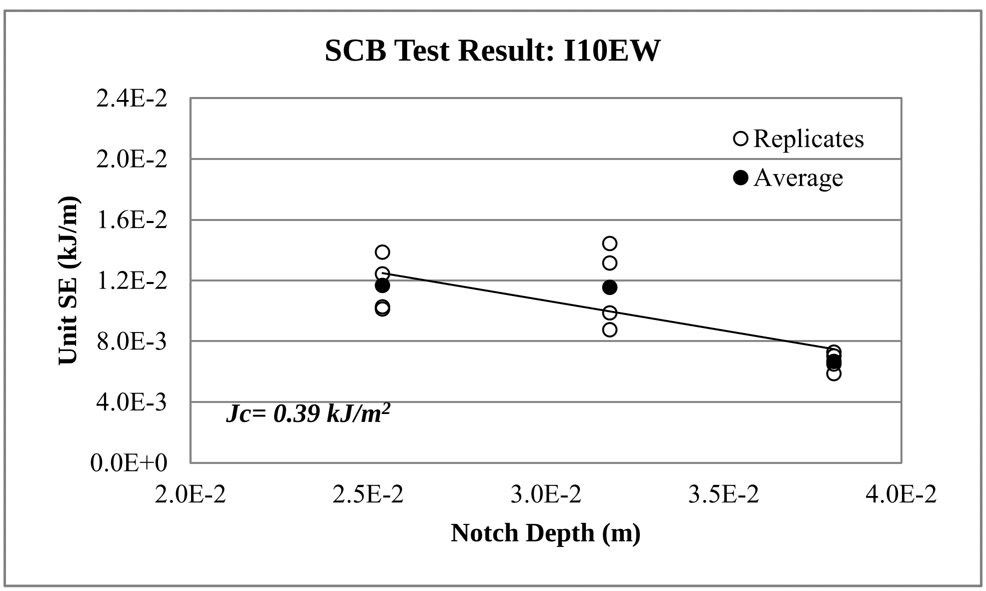

LWT Rutting Profile: 3235B
10.0
8.0
6.0
4.0
2.0
0.0
Rut Depth (mm)
0
5000
10000
15000
20000
No. of Passes
L1
L2
R1
R2


LWT Rutting Profile: 90W
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Rut Depth (mm)
0
5000
10000
15000
20000
No. of Passes
L1
L2
R1
R2

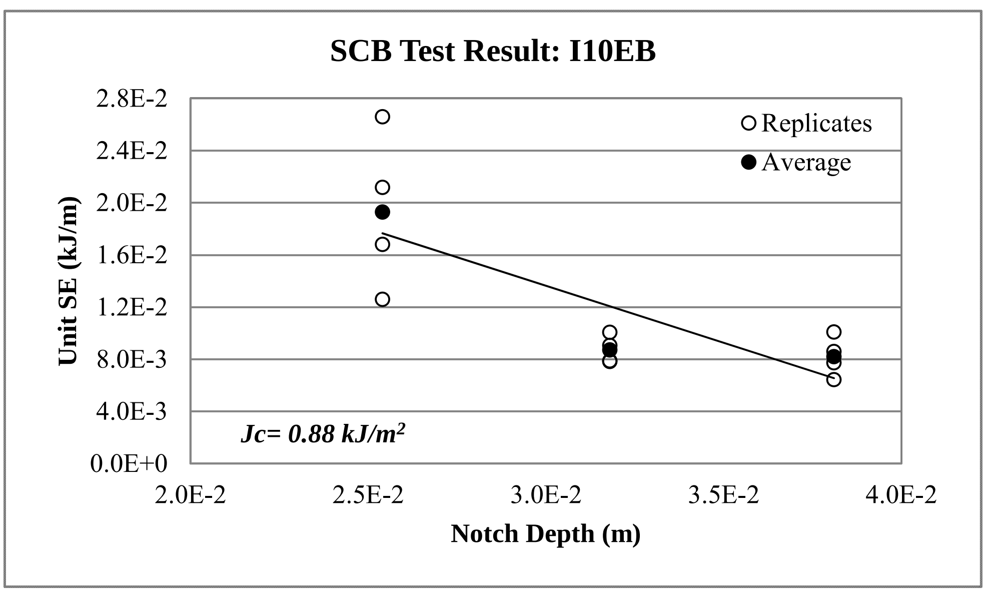

LWT Rutting Profile: 90B
Rut Depth (mm)
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
No. of Passes
L1
L2
R1
R2

B-2. Semi-Circular Bending Test

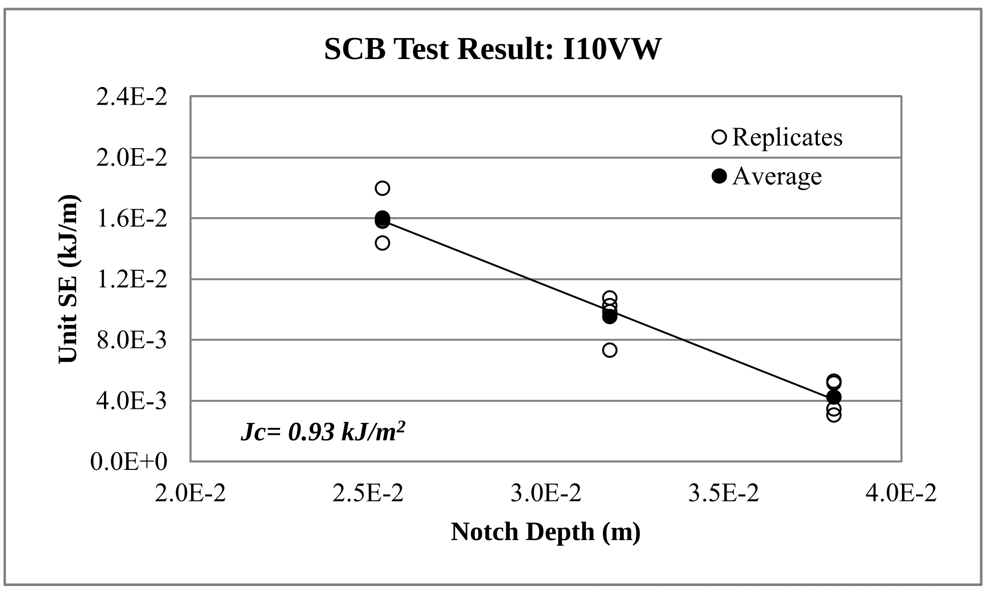
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.27	0.94	0.813	58.6	1.4E-2
	2	1.04	0.90	0.600	59.2	1.0E-2
	3	1.34	0.66	0.598	58.2	1.0E-2
	4	1.17	0.92	0.728	58.5	1.2E-2
	Average	1.21	0.85	0.685	58.6	1.2E-2
	Stdev.	0.13	0.13	0.105	0.4	1.8E-3
	COV (%)	11	15	15	1	15
31.8	1	1.07	0.76	0.556	56.3	9.9E-3
	2	0.75	0.93	0.491	56.1	8.8E-3
	3	1.12	1.05	0.725	50.2	1.4E-2
	4	1.01	0.98	0.659	50.1	1.3E-2
	Average	0.99	0.93	0.608	53.2	1.2E-2
	Stdev.	0.16	0.12	0.104	3.5	2.7E-3
	COV (%)	16	13	17	7	23
38.0	1	0.57	0.84	0.335	57.1	5.9E-3
	2	0.77	0.81	0.418	57.3	7.3E-3
	3	0.73	0.70	0.359	55.2	6.5E-3
	4	0.72	0.82	0.401	57.0	7.0E-3
	Average	0.70	0.79	0.379	56.7	6.7E-3
	Stdev.	0.09	0.06	0.038	1.0	6.3E-4
	COV (%)	12	8	10	2	9



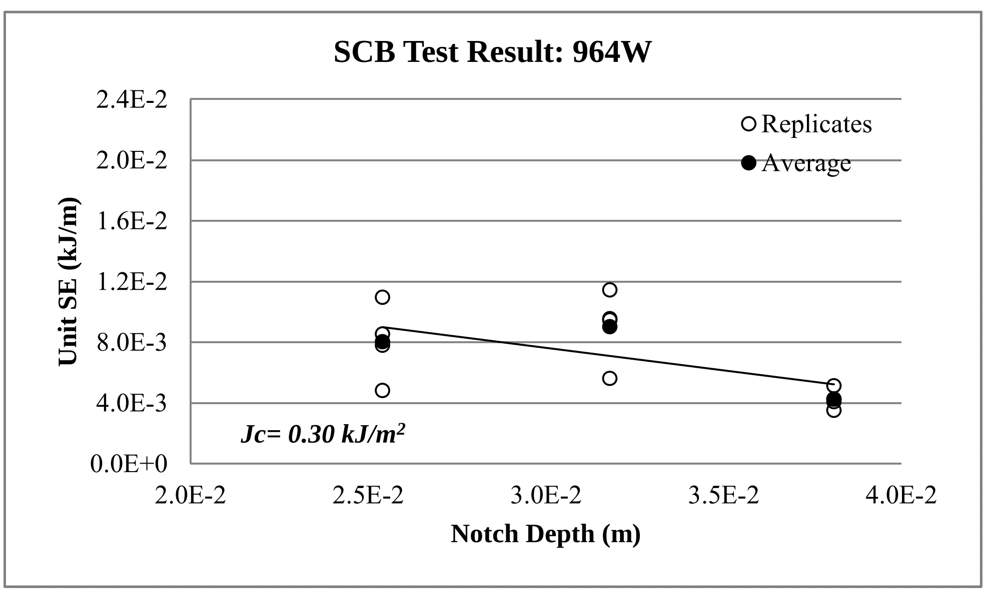
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.84	1.01	0.585	46.4	1.3E-2
	2	0.91	1.26	0.782	46.5	1.7E-2
	3	1.19	1.81	1.474	55.4	2.7E-2
	4	0.97	1.64	1.173	55.4	2.1E-2
	Average	0.98	1.43	1.004	50.9	1.9E-2
	Stdev.	0.15	0.36	0.398	5.2	6.0E-3
	COV (%)	16	26	40	10	31
31.8	1	0.71	0.94	0.526	58.1	9.1E-3
	2	0.81	0.75	0.460	58.2	7.9E-3
	3	0.91	0.81	0.544	54.0	1.0E-2
	4	0.77	0.74	0.424	54.1	7.8E-3
	Average	0.80	0.81	0.489	56.1	8.7E-3
	Stdev.	0.08	0.09	0.056	2.4	1.1E-3
	COV (%)	10	12	12	4	12
38.0	1	0.54	0.91	0.370	57.5	6.4E-3
	2	0.55	1.22	0.497	57.7	8.6E-3
	3	0.64	0.98	0.449	58.0	7.7E-3
	4	0.71	1.17	0.586	58.1	1.0E-2
	Average	0.61	1.07	0.475	57.8	8.2E-3
	Stdev.	0.08	0.15	0.090	0.3	1.5E-3
	COV (%)	14	14	19	0	19



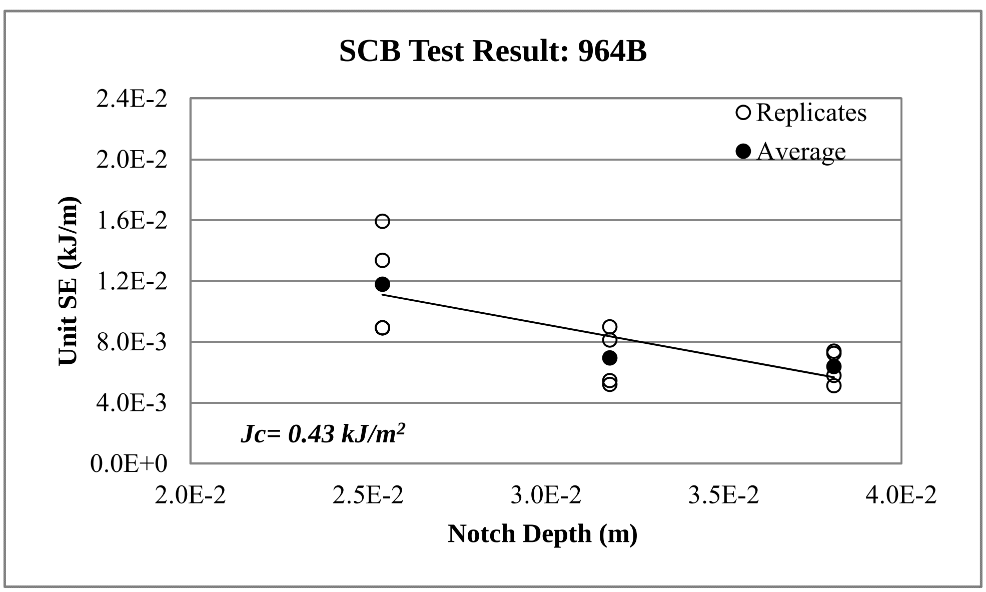
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.31	0.99	0.886	61.6	1.4E-2
	2	1.40	1.18	1.111	61.8	1.8E-2
	3	1.42	1.02	0.958	60.6	1.6E-2
	4	1.25	1.20	0.970	61.1	1.6E-2
	Average	1.34	1.10	0.981	61.3	1.6E-2
	Stdev.	0.08	0.11	0.094	0.5	1.5E-3
	COV (%)	6	10	10	1	9
31.8	1	0.92	0.83	0.567	57.5	9.9E-3
	2	1.04	0.94	0.623	57.9	1.1E-2
	3	0.83	0.73	0.391	53.3	7.3E-3
	4	0.81	1.03	0.536	52.3	1.0E-2
	Average	0.90	0.88	0.529	55.3	9.6E-3
	Stdev.	0.10	0.13	0.099	2.9	1.5E-3
	COV (%)	11	15	19	5	16
38.0	1	0.92	0.51	0.302	57.2	5.3E-3
	2	0.89	0.53	0.297	57.4	5.2E-3
	3	0.75	0.40	0.192	55.4	3.5E-3
	4	0.84	0.33	0.173	56.4	3.1E-3
	Average	0.85	0.44	0.241	56.6	4.2E-3
	Stdev.	0.08	0.10	0.068	0.9	1.1E-3
	COV (%)	9	22	28	2	27



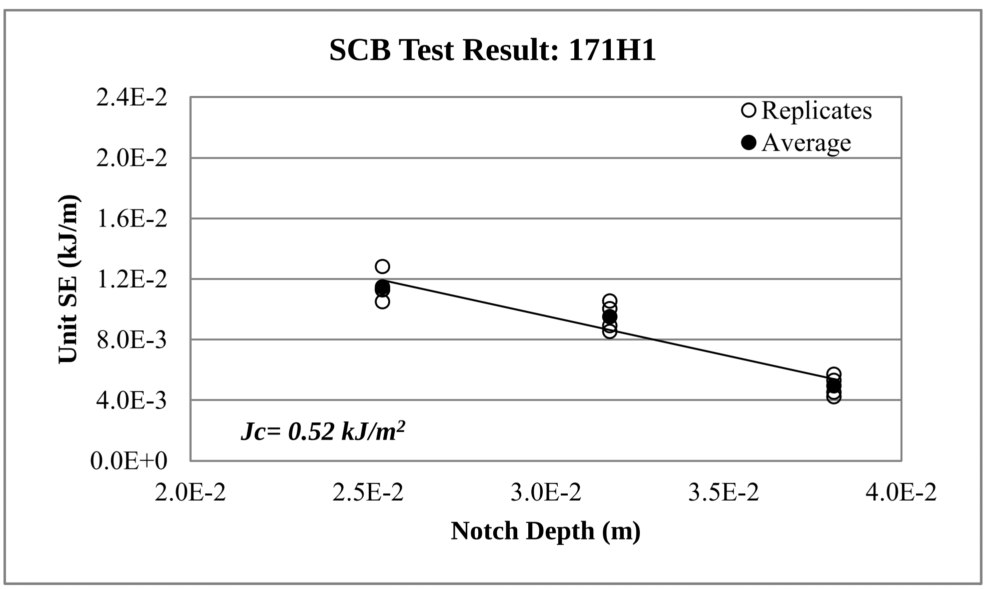
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.96	0.61	0.372	47.5	7.8E-3
	2	1.23	0.65	0.523	47.7	1.1E-2
	3	0.94	0.37	0.231	47.7	4.8E-3
	4	1.29	0.47	0.406	47.4	8.6E-3
	Average	1.11	0.53	0.383	47.6	8.0E-3
	Stdev.	0.18	0.13	0.120	0.1	2.5E-3
	COV (%)	17	24	31	0	31
31.8	1	1.94	0.42	0.470	49.1	9.6E-3
	2	1.34	0.35	0.276	48.9	5.6E-3
	3	2.46	0.45	0.715	62.4	1.1E-2
	4	2.38	0.41	0.565	59.5	9.5E-3
	Average	2.03	0.41	0.506	55.0	9.0E-3
	Stdev.	0.51	0.04	0.184	7.0	2.4E-3
	COV (%)	25	10	36	13	27
38.0	1	0.52	0.51	0.206	58.4	3.5E-3
	2	0.65	0.51	0.240	58.7	4.1E-3
	3	1.25	0.32	0.243	56.9	4.3E-3
	4	1.18	0.38	0.295	57.2	5.2E-3
	Average	0.90	0.43	0.246	57.8	4.3E-3
	Stdev.	0.37	0.10	0.037	0.9	6.8E-4
	COV (%)	41	23	15	2	16



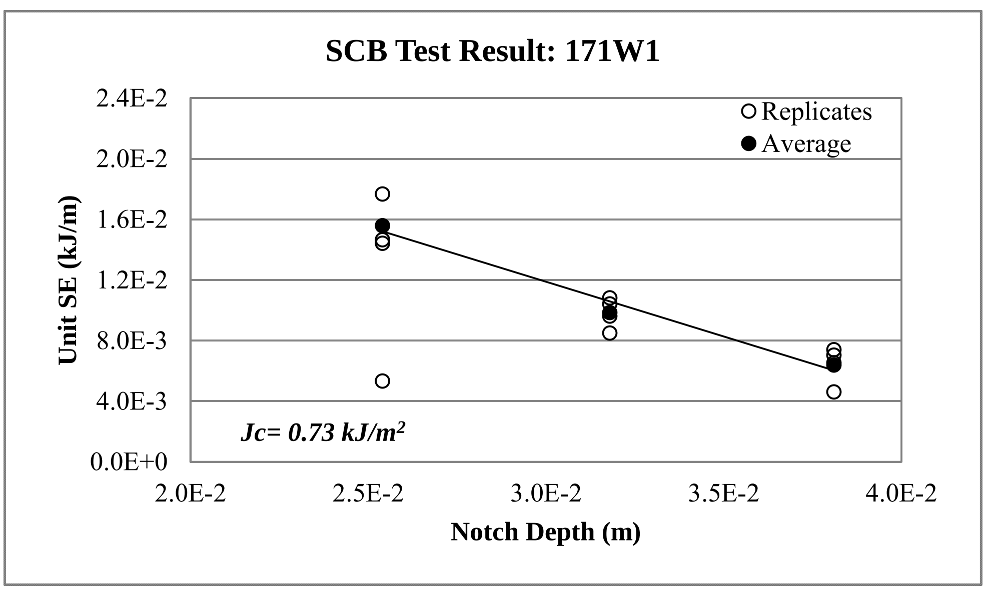
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.87	0.63	0.761	56.9	1.3E-2
	2	1.93	0.75	0.906	56.8	1.6E-2
	3	1.14	0.65	0.513	57.5	8.9E-3
	4	1.02	0.72	0.512	57.3	8.9E-3
	Average	1.49	0.69	0.673	57.1	1.2E-2
	Stdev.	0.48	0.06	0.194	0.3	3.5E-3
	COV (%)	32	8	29	1	29
31.8	1	0.68	0.59	0.309	59.2	5.2E-3
	2	0.82	0.84	0.482	59.3	8.1E-3
	3	0.89	0.90	0.561	62.4	9.0E-3
	4	1.00	0.46	0.325	59.5	5.5E-3
	Average	0.85	0.70	0.419	60.1	7.0E-3
	Stdev.	0.14	0.20	0.122	1.5	1.9E-3
	COV (%)	16	29	29	3	27
38.0	1	0.64	0.67	0.308	53.2	5.8E-3
	2	0.51	1.06	0.385	53.1	7.3E-3
	3	0.57	0.65	0.276	53.9	5.1E-3
	4	0.61	0.82	0.389	52.6	7.4E-3
	Average	0.58	0.80	0.340	53.2	6.4E-3
	Stdev.	0.05	0.19	0.056	0.5	1.1E-3
	COV (%)	9	24	17	1	17



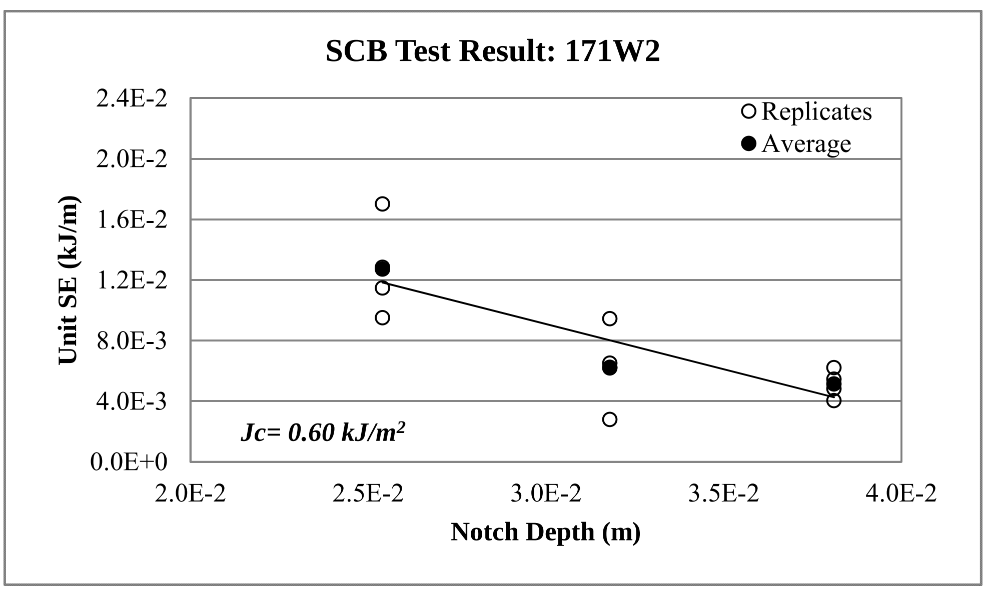
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.61	1.25	0.508	45.0	1.1E-2
	2	0.75	1.19	0.577	45.0	1.3E-2
	3	0.68	1.31	0.566	54.0	1.0E-2
	4	0.72	1.34	0.599	53.0	1.1E-2
	Average	0.69	1.27	0.562	49.3	1.1E-2
	Stdev.	0.06	0.07	0.039	4.9	9.7E-4
	COV (%)	9	5	7	10	8
31.8	1	0.57	1.23	0.414	48.5	8.5E-3
	2	0.72	1.02	0.438	49.2	8.9E-3
	3	0.69	1.22	0.521	49.5	1.1E-2
	4	0.73	1.15	0.493	49.1	1.0E-2
	Average	0.68	1.15	0.467	49.1	9.5E-3
	Stdev.	0.07	0.10	0.049	0.4	9.3E-4
	COV (%)	10	8	11	1	10
38.0	1	0.45	1.00	0.314	55.0	5.7E-3
	2	0.39	1.06	0.251	55.5	4.5E-3
	3	0.45	1.06	0.287	54.0	5.3E-3
	4	0.36	0.89	0.227	53.5	4.2E-3
	Average	0.41	1.00	0.270	54.5	4.9E-3
	Stdev.	0.04	0.08	0.039	0.9	6.8E-4
	COV (%)	11	8	14	2	14



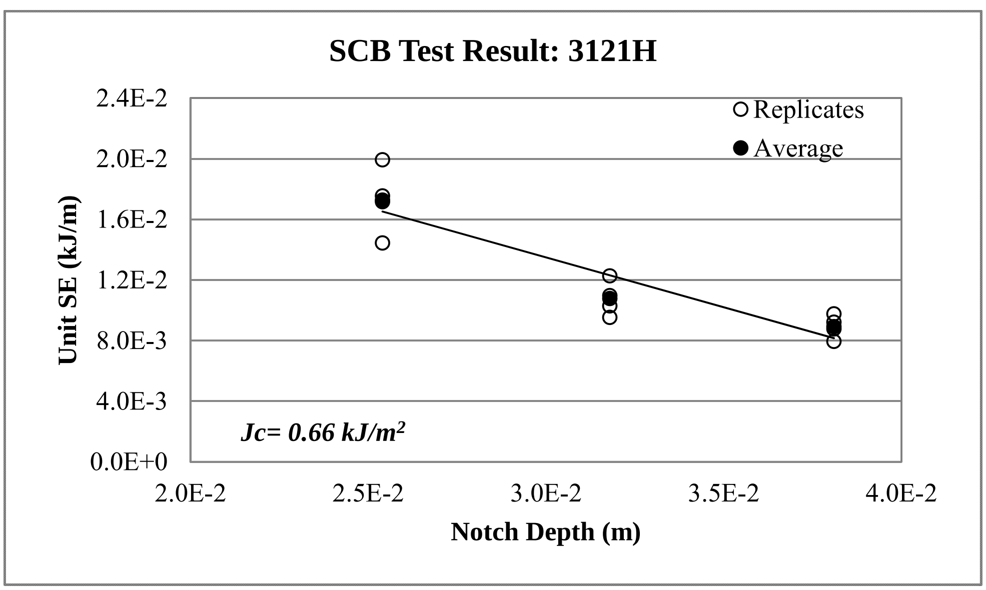
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.04	1.00	0.630	43.0	1.5E-2
	2	0.91	1.01	0.620	43.0	1.4E-2
	3	0.91	1.38	0.760	43.0	1.8E-2
	4	0.46	0.82	0.229	43.0	5.3E-3
	Average	0.83	1.05	0.560	43.0	1.3E-2
	Stdev.	0.26	0.23	0.230	0.0	5.3E-3
	COV (%)	31	22	41	0	41
31.8	1	0.71	1.33	0.584	54.0	1.1E-2
	2	0.76	1.34	0.529	55.0	9.6E-3
	3	0.67	1.43	0.553	53.0	1.0E-2
	4	0.68	1.05	0.459	54.0	8.5E-3
	Average	0.70	1.29	0.531	54.0	9.8E-3
	Stdev.	0.04	0.16	0.053	0.8	1.0E-3
	COV (%)	6	13	10	2	10
38.0	1	0.55	1.06	0.359	55.0	6.5E-3
	2	0.50	1.32	0.394	56.0	7.0E-3
	3	0.50	0.71	0.240	52.0	4.6E-3
	4	0.56	1.06	0.400	54.0	7.4E-3
	Average	0.53	1.04	0.348	54.3	6.4E-3
	Stdev.	0.03	0.25	0.075	1.7	1.2E-3
	COV (%)	6	24	21	3	19



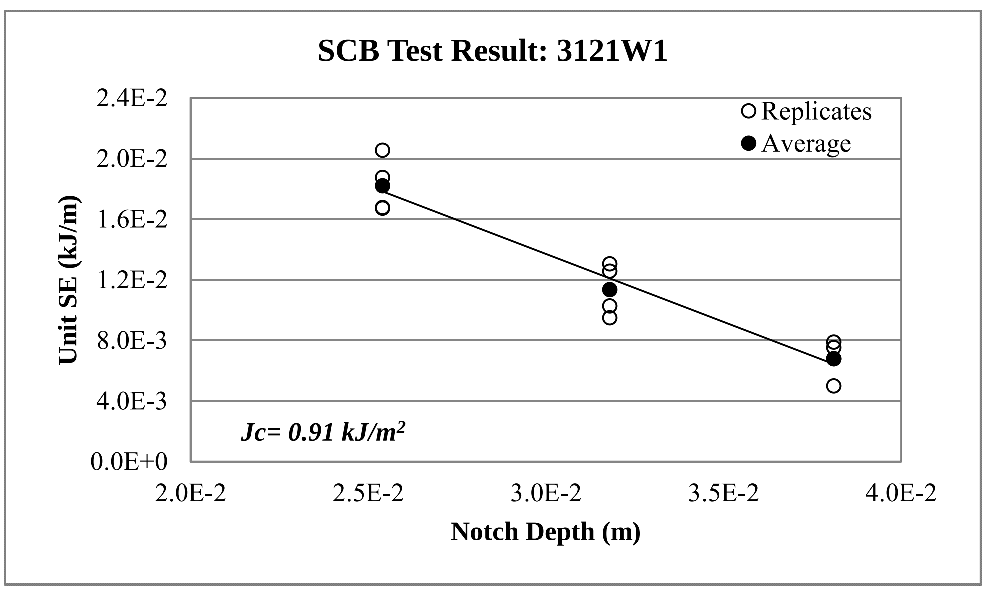
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.65	1.19	0.578	45.0	1.3E-2
	2	0.78	1.74	0.766	45.0	1.7E-2
	3	0.61	1.60	0.620	54.0	1.1E-2
	4	0.52	1.53	0.504	53.0	9.5E-3
	Average	0.64	1.52	0.617	49.3	1.3E-2
	Stdev.	0.11	0.23	0.110	4.9	3.2E-3
	COV (%)	17	15	18	10	25
31.8	1	0.39	1.36	0.352	54.0	6.5E-3
	2	0.26	0.88	0.150	53.5	2.8E-3
	3	0.40	1.25	0.328	53.0	6.2E-3
	4	0.47	1.58	0.496	52.5	9.5E-3
	Average	0.38	1.27	0.332	53.3	6.2E-3
	Stdev.	0.09	0.29	0.142	0.6	2.7E-3
	COV (%)	24	23	43	1	44
38.0	1	0.38	1.15	0.301	55.0	5.5E-3
	2	0.33	1.20	0.268	55.5	4.8E-3
	3	0.28	1.14	0.219	54.0	4.0E-3
	4	0.40	1.26	0.332	53.5	6.2E-3
	Average	0.35	1.19	0.280	54.5	5.1E-3
	Stdev.	0.05	0.05	0.049	0.9	9.2E-4
	COV (%)	16	4	17	2	18



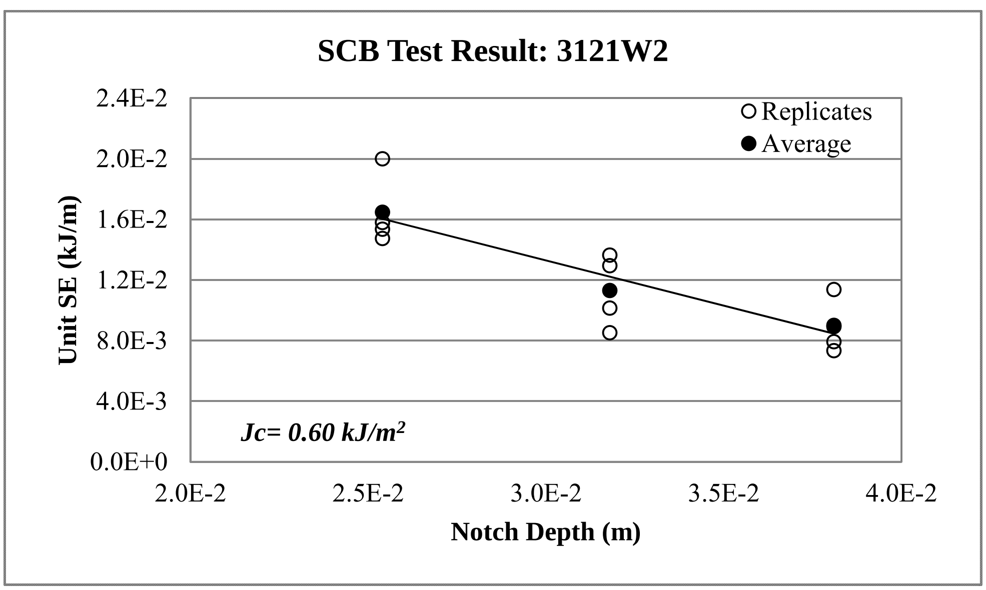
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.91	1.26	0.789	45.0	1.8E-2
	2	0.82	1.34	0.773	45.0	1.7E-2
	3	1.12	1.39	1.077	54.0	2.0E-2
	4	0.93	1.36	0.766	53.0	1.4E-2
	Average	0.94	1.34	0.851	49.3	1.7E-2
	Stdev.	0.12	0.06	0.151	4.9	2.2E-3
	COV (%)	13	4	18	10	13
31.8	1	0.72	0.95	0.467	49.0	9.5E-3
	2	0.72	1.33	0.614	50.0	1.2E-2
	3	0.73	1.24	0.516	47.0	1.1E-2
	4	0.71	1.08	0.484	47.0	1.0E-2
	Average	0.72	1.15	0.520	48.3	1.1E-2
	Stdev.	0.01	0.17	0.066	1.5	1.2E-3
	COV (%)	1	15	13	3	11
38.0	1	0.58	1.10	0.429	49.0	8.8E-3
	2	0.55	1.09	0.390	49.0	8.0E-3
	3	0.58	1.20	0.459	47.0	9.8E-3
	4	0.52	1.23	0.433	47.0	9.2E-3
	Average	0.56	1.16	0.428	48.0	8.9E-3
	Stdev.	0.03	0.07	0.028	1.2	7.6E-4
	COV (%)	5	6	7	2	9



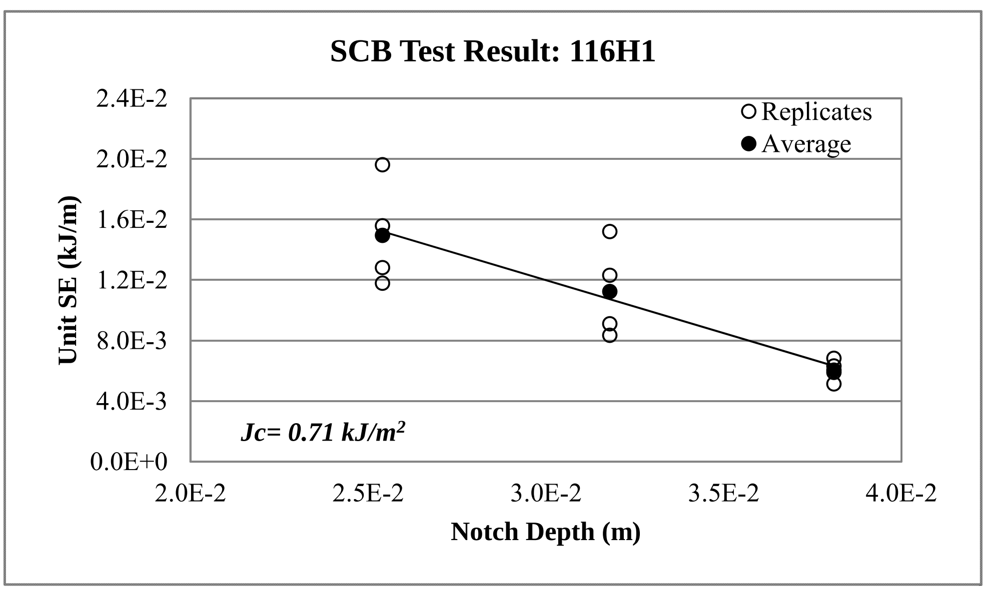
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.98	1.43	0.938	50.0	1.9E-2
	2	0.97	1.31	0.853	51.0	1.7E-2
	3	0.82	1.66	0.822	49.0	1.7E-2
	4	0.91	1.68	1.027	50.0	2.1E-2
	Average	0.92	1.52	0.910	50.0	1.8E-2
	Stdev.	0.08	0.18	0.092	0.8	1.8E-3
	COV (%)	8	12	10	2	10
31.8	1	0.59	1.72	0.666	51.0	1.3E-2
	2	0.72	1.32	0.641	51.0	1.3E-2
	3	0.67	1.21	0.493	52.0	9.5E-3
	4	0.73	1.10	0.534	52.0	1.0E-2
	Average	0.68	1.34	0.584	51.5	1.1E-2
	Stdev.	0.07	0.27	0.083	0.6	1.7E-3
	COV (%)	10	20	14	1	15
38.0	1	0.39	0.88	0.245	49.0	5.0E-3
	2	0.37	1.30	0.387	49.0	7.9E-3
	3	0.50	0.88	0.305	45.0	6.8E-3
	4	0.50	0.95	0.338	45.0	7.5E-3
	Average	0.44	1.00	0.319	47.0	6.8E-3
	Stdev.	0.07	0.20	0.060	2.3	1.3E-3
	COV (%)	16	20	19	5	19



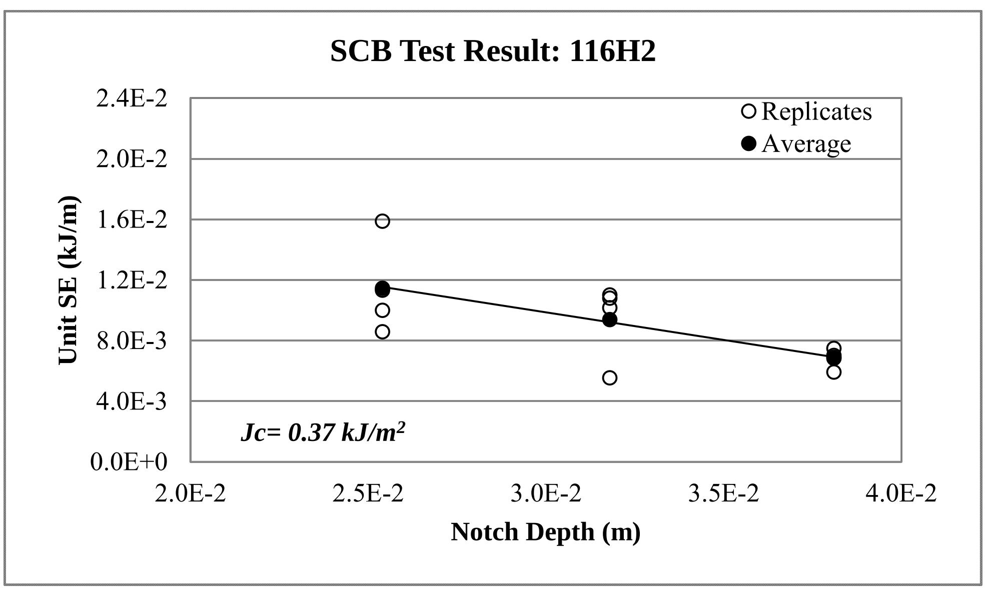
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.77	1.43	0.695	44.0	1.6E-2
	2	0.75	1.28	0.648	44.0	1.5E-2
	3	0.89	1.26	0.737	48.0	1.5E-2
	4	0.94	1.66	0.960	48.0	2.0E-2
	Average	0.84	1.41	0.760	46.0	1.6E-2
	Stdev.	0.09	0.19	0.138	2.3	2.4E-3
	COV (%)	11	13	18	5	15
31.8	1	0.58	1.36	0.567	56.0	1.0E-2
	2	0.53	1.38	0.477	56.0	8.5E-3
	3	0.82	1.35	0.724	56.0	1.3E-2
	4	0.76	1.41	0.764	56.0	1.4E-2
	Average	0.67	1.37	0.633	56.0	1.1E-2
	Stdev.	0.14	0.03	0.134	0.0	2.4E-3
	COV (%)	21	2	21	0	21
38.0	1	0.66	1.14	0.523	46.0	1.1E-2
	2	0.57	1.06	0.372	47.0	7.9E-3
	3	0.51	1.16	0.414	46.0	9.0E-3
	4	0.43	1.10	0.345	47.0	7.3E-3
	Average	0.54	1.12	0.414	46.5	8.9E-3
	Stdev.	0.10	0.05	0.078	0.6	1.8E-3
	COV (%)	18	4	19	1	20



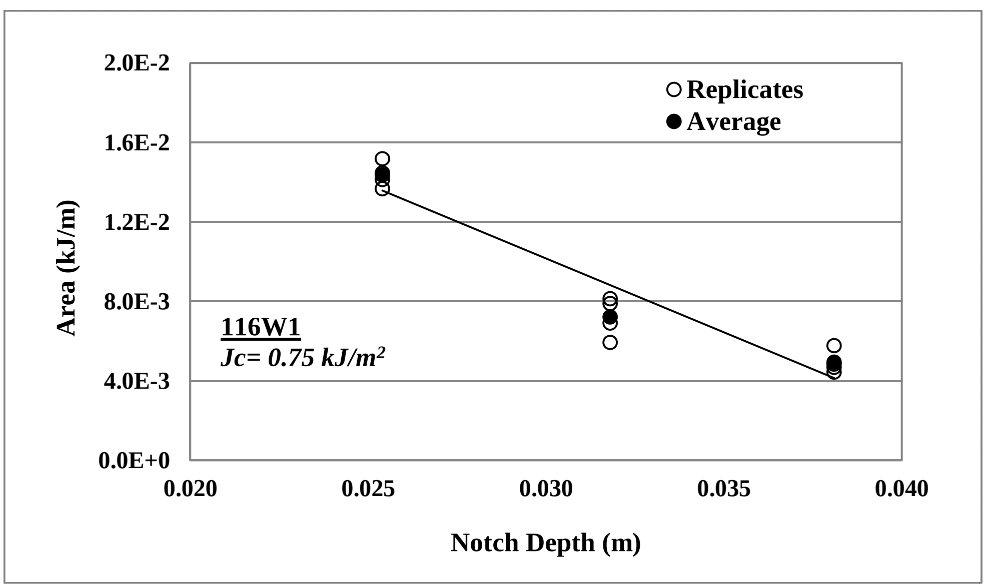
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.16	0.68	0.547	35.1	1.6E-2
	2	1.22	1.02	0.691	35.2	2.0E-2
	3	1.05	0.57	0.394	33.4	1.2E-2
	4	1.06	0.75	0.439	34.2	1.3E-2
	Average	1.12	0.76	0.518	34.5	1.5E-2
	Stdev.	0.08	0.19	0.132	0.8	3.5E-3
	COV (%)	7	25	26	2	23
31.8	1	1.02	0.70	0.363	39.8	9.1E-3
	2	0.88	1.21	0.463	37.6	1.2E-2
	3	0.86	0.65	0.341	40.9	8.3E-3
	4	1.10	0.90	0.628	41.3	1.5E-2
	Average	0.96	0.86	0.449	39.9	1.1E-2
	Stdev.	0.11	0.25	0.131	1.7	3.2E-3
	COV (%)	12	29	29	4	28
38.0	1	0.45	0.67	0.204	39.7	5.1E-3
	2	0.50	0.94	0.253	42.8	5.9E-3
	3	0.55	0.59	0.222	32.5	6.8E-3
	4	0.51	0.58	0.208	32.9	6.3E-3
	Average	0.50	0.69	0.222	37.0	6.1E-3
	Stdev.	0.04	0.17	0.022	5.1	7.2E-4
	COV (%)	9	24	10	14	12



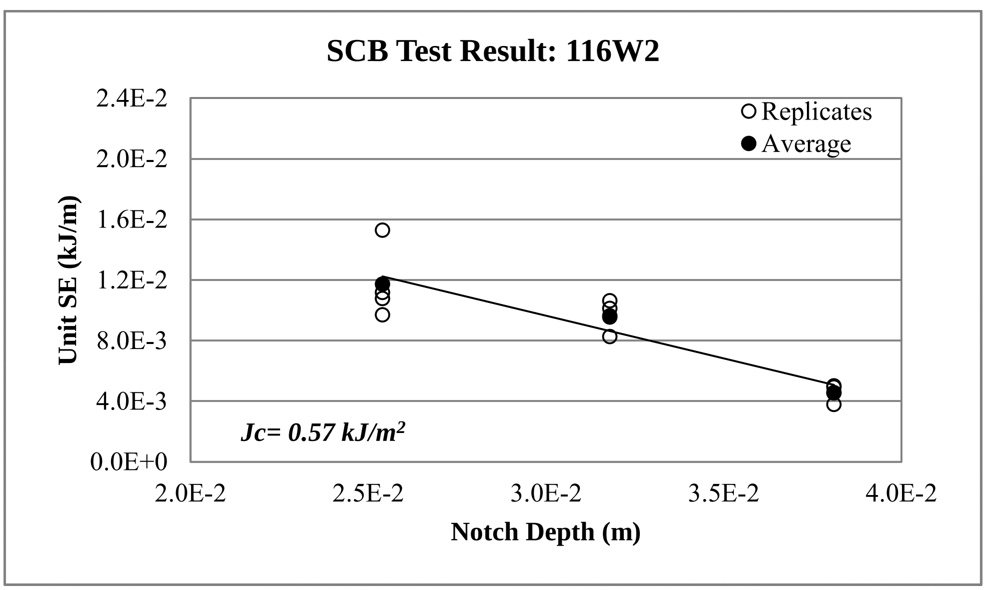
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.28	0.55	0.444	44.4	1.0E-2
	2	1.09	0.56	0.383	44.7	8.6E-3
	3	1.37	0.71	0.615	54.3	1.1E-2
	4	1.49	1.01	0.857	54.0	1.6E-2
	Average	1.31	0.71	0.575	49.4	1.1E-2
	Stdev.	0.17	0.22	0.212	5.5	3.2E-3
	COV (%)	13	31	37	11	28
31.8	1	0.99	0.68	0.448	44.1	1.0E-2
	2	1.03	0.76	0.486	44.1	1.1E-2
	3	0.95	0.46	0.254	45.9	5.5E-3
	4	1.13	0.74	0.498	46.1	1.1E-2
	Average	1.02	0.66	0.421	45.1	9.4E-3
	Stdev.	0.08	0.14	0.113	1.1	2.6E-3
	COV (%)	8	21	27	2	28
38.0	1	0.67	0.77	0.338	45.2	7.5E-3
	2	0.61	0.75	0.317	45.2	7.0E-3
	3	1.07	0.58	0.345	50.1	6.9E-3
	4	0.87	0.55	0.298	50.2	5.9E-3
	Average	0.80	0.66	0.324	47.7	6.8E-3
	Stdev.	0.21	0.11	0.021	2.9	6.5E-4
	COV (%)	26	17	7	6	10



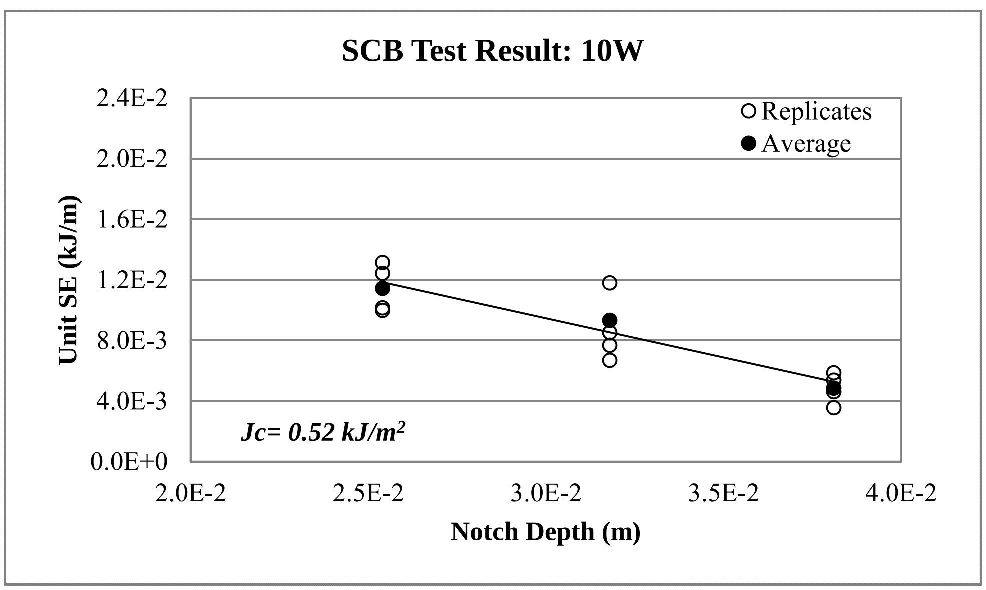
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.12	0.69	0.506	37.0	1.4E-2
	2	1.05	0.92	0.533	37.7	1.4E-2
	3	1.21	0.68	0.568	37.4	1.5E-2
	4	1.13	0.74	0.535	37.0	1.4E-2
	Average	1.13	0.76	0.535	37.3	1.4E-2
	Stdev.	0.07	0.11	0.025	0.3	6.3E-4
	COV (%)	6	14	5	1	4
31.8	1	0.70	0.56	0.260	32.9	7.9E-3
	2	0.59	0.68	0.268	33.0	8.1E-3
	3	0.68	0.47	0.216	36.4	5.9E-3
	4	0.65	0.58	0.253	36.6	6.9E-3
	Average	0.65	0.57	0.249	34.7	7.2E-3
	Stdev.	0.05	0.08	0.023	2.1	1.0E-3
	COV (%)	7	15	9	6	14
38.0	1	0.56	0.53	0.196	40.6	4.8E-3
	2	0.63	0.57	0.232	40.2	5.8E-3
	3	0.40	0.58	0.159	35.9	4.4E-3
	4	0.52	0.48	0.169	36.0	4.7E-3
	Average	0.53	0.54	0.189	38.2	4.9E-3
	Stdev.	0.09	0.05	0.033	2.6	5.9E-4
	COV (%)	18	8	17	7	12



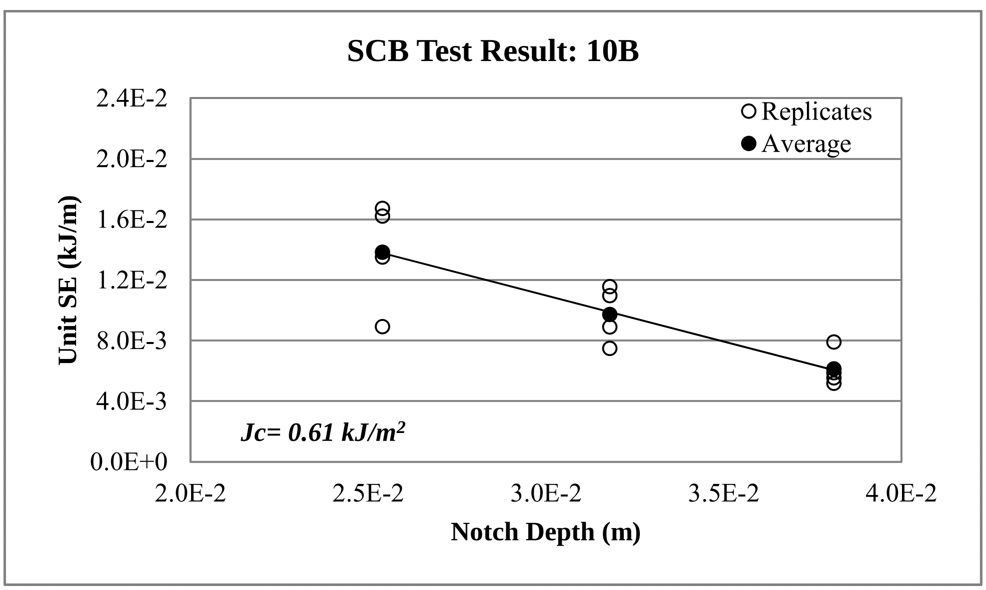
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.64	0.57	0.564	52.3	1.1E-2
	2	1.49	0.59	0.514	53.0	9.7E-3
	3	1.59	0.88	0.793	51.9	1.5E-2
	4	1.50	0.81	0.586	52.4	1.1E-2
	Average	1.56	0.71	0.614	52.4	1.2E-2
	Stdev.	0.07	0.16	0.123	0.5	2.4E-3
	COV (%)	5	22	20	1	21
31.8	1	1.16	0.90	0.550	51.8	1.1E-02
	2	0.91	0.79	0.430	52.0	8.3E-3
	3	1.05	0.72	0.450	47.1	9.6E-3
	4	0.93	0.79	0.480	47.4	1.0E-2
	Average	1.01	0.80	0.477	49.6	9.6E-3
	Stdev.	0.11	0.07	0.053	2.7	1.0E-3
	COV (%)	11	9	11	5	11
38.0	1	0.73	0.55	0.249	54.7	4.6E-3
	2	0.87	0.49	0.273	54.4	5.0E-3
	3	0.70	0.43	0.196	51.9	3.8E-3
	4	0.73	0.55	0.253	51.3	4.9E-3
	Average	0.76	0.51	0.243	53.1	4.6E-3
	Stdev.	0.08	0.06	0.033	1.7	5.6E-4
	COV (%)	10	11	13	3	12



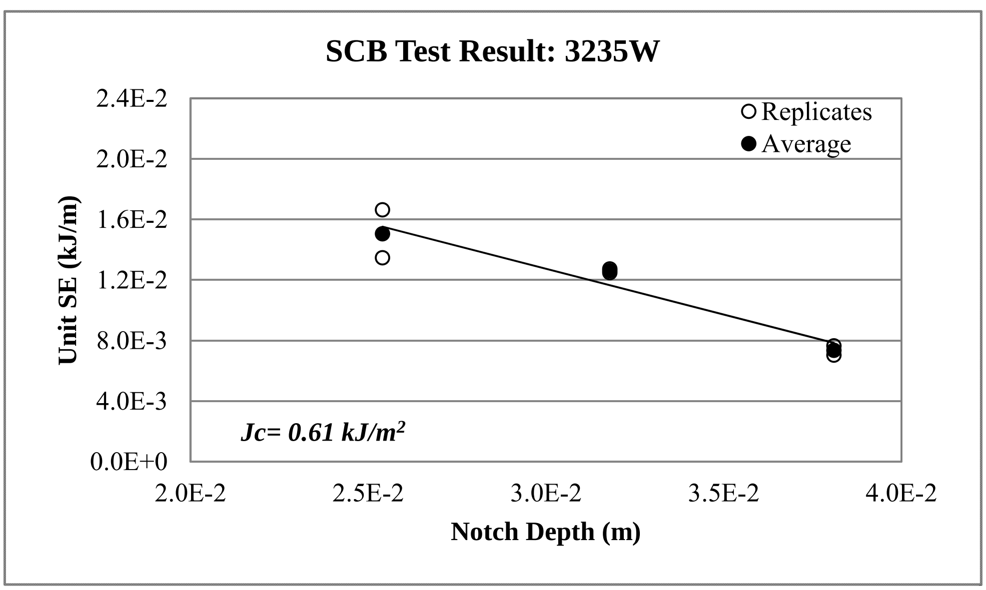
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.29	0.73	0.561	42.7	1.3E-2
	2	1.15	0.72	0.429	43.0	1.0E-2
	3	1.26	0.72	0.458	45.2	1.0E-2
	4	1.39	0.81	0.565	45.5	1.2E-2
	Average	1.27	0.74	0.503	44.1	1.1E-2
	Stdev.	0.10	0.04	0.070	1.5	1.6E-3
	COV (%)	8	6	14	3	14
31.8	1	1.24	0.46	0.338	50.6	6.7E-3
	2	1.19	0.76	0.388	50.6	7.7E-3
	3	1.13	0.75	0.426	49.9	8.5E-3
	4	1.07	0.93	0.602	51.1	1.2E-2
	Average	1.16	0.72	0.438	50.6	8.7E-3
	Stdev.	0.07	0.19	0.115	0.5	2.2E-3
	COV (%)	6	27	26	1	25
38.0	1	0.45	0.65	0.188	40.7	4.6E-3
	2	0.66	0.61	0.243	41.4	5.9E-3
	3	0.72	0.57	0.245	45.6	5.4E-3
	4	0.69	0.42	0.163	46.0	3.6E-3
	Average	0.63	0.56	0.210	43.4	4.9E-3
	Stdev.	0.12	0.10	0.041	2.8	1.0E-3
	COV (%)	20	18	19	6	21



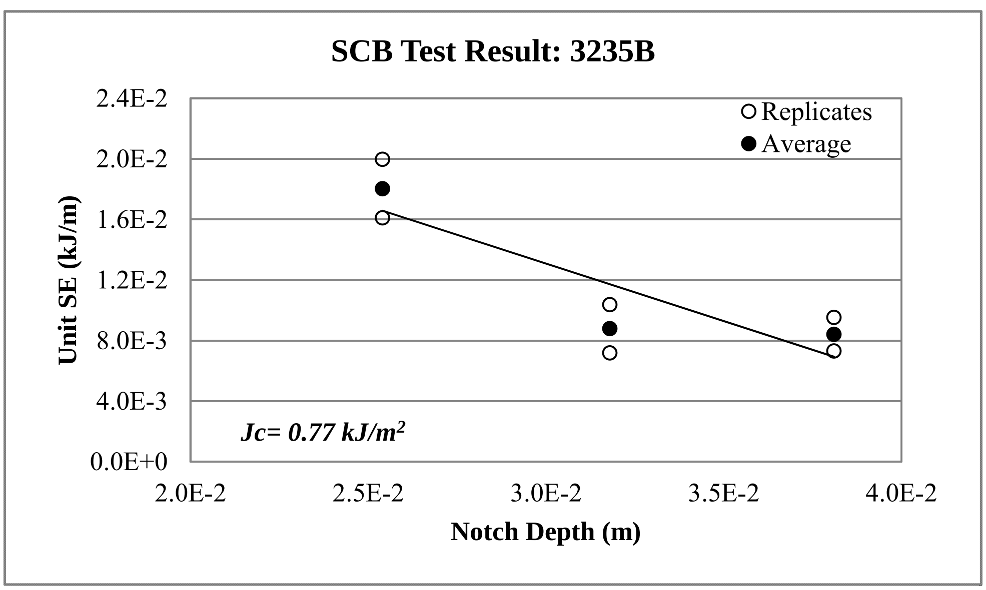
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.99	1.05	0.883	54.5	1.6E-2
	2	1.65	0.57	0.486	54.5	8.9E-3
	3	2.14	0.90	0.913	54.6	1.7E-2
	4	1.70	0.97	0.734	54.3	1.4E-2
	Average	1.87	0.87	0.754	54.5	1.4E-2
	Stdev.	0.23	0.21	0.195	0.1	3.6E-3
	COV (%)	13	24	26	0	26
31.8	1	1.22	0.98	0.609	52.7	1.2E-2
	2	1.51	0.73	0.585	53.4	1.1E-2
	3	1.44	0.76	0.489	54.9	8.9E-3
	4	1.39	0.56	0.410	54.9	7.5E-3
	Average	1.39	0.76	0.523	54.0	9.7E-3
	Stdev.	0.13	0.18	0.092	1.1	1.9E-3
	COV (%)	9	23	18	2	19
38.0	1	1.27	0.48	0.322	54.8	5.9E-3
	2	1.09	0.50	0.282	54.5	5.2E-3
	3	1.38	0.71	0.470	59.5	7.9E-3
	4	1.29	0.53	0.335	60.3	5.6E-3
	Average	1.26	0.55	0.352	57.3	6.1E-3
	Stdev.	0.12	0.11	0.082	3.1	1.2E-3
	COV (%)	10	19	23	5	20



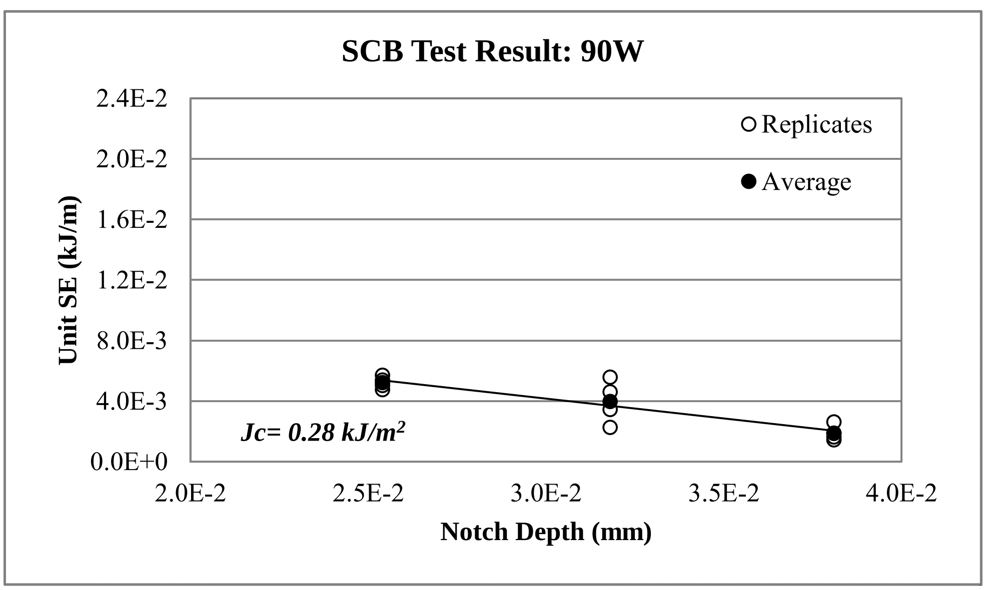
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	1.19	0.96	0.715	43.0	1.7E-2
	2	1.12	0.80	0.579	43.0	1.3E-2
	3					
	4					
	Average	1.15	0.88	0.647	43.0	1.5E-2
	Stdev.	0.05	0.12	0.096	0.0	2.2E-3
	COV (%)	4	13	15	0	15
31.8	1	0.72	1.35	0.512	41.0	1.2E-2
	2	0.80	1.00	0.522	41.0	1.3E-2
	3					
	4					
	Average	0.76	1.17	0.517	41.0	1.3E-2
	Stdev.	0.05	0.25	0.007	0.0	1.8E-4
	COV (%)	7	21	1	0	1
38.0	1	0.36	1.41	0.339	44.3	7.7E-3
	2	0.42	1.15	0.317	45.0	7.0E-3
	3					
	4					
	Average	0.39	1.28	0.328	44.7	7.4E-3
	Stdev.	0.04	0.19	0.016	0.5	4.3E-4
	COV (%)	11	15	5	1	6



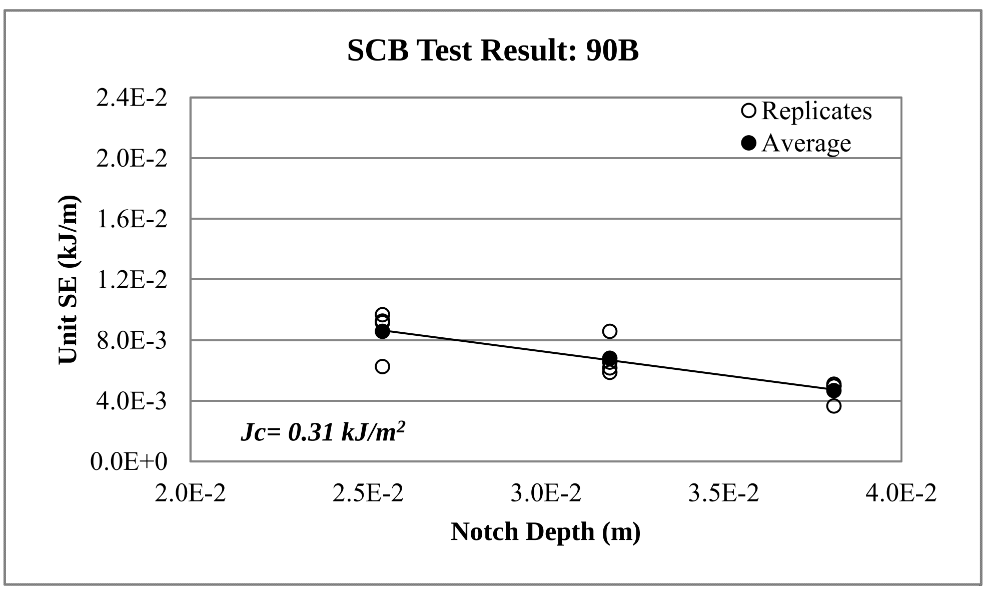
Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.96	1.19	0.701	43.5	1.6E-2
	2	1.24	1.22	0.884	44.3	2.0E-2
	3					
	4					
	Average	1.10	1.21	0.793	43.9	1.8E-2
	Stdev.	0.20	0.02	0.130	0.6	2.7E-3
	COV (%)	18	2	16	1	15
31.8	1	0.98	0.89	0.552	53.2	1.0E-2
	2	0.72	0.78	0.375	52.1	7.2E-3
	3					
	4					
	Average	0.85	0.84	0.463	52.7	8.8E-3
	Stdev.	0.18	0.08	0.125	0.8	2.3E-3
	COV (%)	21	9	27	1	26
38.0	1	0.68	1.22	0.529	55.5	9.5E-3
	2	0.64	0.96	0.409	56.0	7.3E-3
	3					
	4					
	Average	0.66	1.09	0.469	55.8	8.4E-3
	Stdev.	0.02	0.18	0.085	0.4	1.6E-3
	COV (%)	4	17	18	1	19



Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.40	0.70	0.195	41.0	4.8E-3
	2	0.43	0.84	0.222	41.0	5.4E-3
	3	0.53	0.58	0.190	37.8	5.0E-3
	4	0.57	0.77	0.216	37.8	5.7E-3
	Average	0.48	0.72	0.206	39.4	5.2E-3
	Stdev.	0.08	0.11	0.015	1.8	4.2E-4
	COV (%)	16	16	7	5	8
31.8	1	0.41	0.95	0.180	39.0	4.6E-3
	2	0.35	0.38	0.089	39.0	2.3E-3
	3	0.38	0.50	0.123	35.5	3.5E-3
	4	0.43	0.68	0.198	35.5	5.6E-3
	Average	0.39	0.63	0.147	37.3	4.0E-3
	Stdev.	0.03	0.25	0.051	2.0	1.4E-3
	COV (%)	9	39	34	5	36
38.0	1	0.18	0.51	0.059	31.7	1.9E-3
	2	0.21	0.57	0.084	31.7	2.6E-3
	3	0.19	0.41	0.052	31.5	1.6E-3
	4	0.17	0.41	0.046	31.5	1.5E-3
	Average	0.19	0.48	0.060	31.6	1.9E-3
	Stdev.	0.02	0.08	0.017	0.1	5.2E-4
	COV (%)	9	17	28	0	27



Notch Depth (mm)	Sample ID	Peak Load (Kn)	Peak Disp (mm)	SE (Kn-mm)	Thickness (mm)	Unit SE (kJ/m)
25.4	1	0.81	0.86	0.445	46.0	9.7E-3
	2	0.73	0.88	0.421	46.0	9.1E-3
	3	0.81	0.66	0.293	46.8	6.3E-3
	4	0.72	0.92	0.430	46.5	9.3E-3
	Average	0.77	0.83	0.397	46.3	8.6E-3
	Stdev.	0.05	0.12	0.070	0.4	1.6E-3
	COV (%)	6	14	18	1	18
31.8	1	0.63	0.64	0.275	44.5	6.2E-3
	2	0.76	0.58	0.265	45.0	5.9E-3
	3	0.59	0.69	0.282	43.0	6.6E-3
	4	0.71	0.76	0.378	44.0	8.6E-3
	Average	0.67	0.67	0.300	44.1	6.8E-3
	Stdev.	0.08	0.07	0.052	0.9	1.2E-3
	COV (%)	12	11	17	2	18
38.0	1	0.48	0.54	0.163	44.6	3.7E-3
	2	0.50	0.64	0.222	44.6	5.0E-3
	3	0.49	0.67	0.230	45.0	5.1E-3
	4	0.51	0.70	0.224	45.0	5.0E-3
	Average	0.50	0.64	0.210	44.8	4.7E-3
	Stdev.	0.01	0.07	0.031	0.2	6.8E-4
	COV (%)	3	11	15	1	15



B-3. IDT |*E**| Test Results

Table B.1
Indirect tension dynamic modulus (IDT |*E|) test results for I10Egan WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	EW 2-1	6.6	1977	1855	1731	1549	1354	1074
	EW 2-2	6.1	2129	2054	1982	1929	1770	1480
	Average		2053	1954	1856	1739	1562	1277
	Stdev		107	141	177	269	295	287
	CV (%)		5	7	10	15	19	22
10	EW 2-1	6.6	1027	893	737	617	433	291
	EW 2-2	6.1	1290	1197	1024	864	611	351
	Average		1158	1045	881	740	522	321
	Stdev		186	216	203	175	126	42
	CV (%)		16	21	23	24	24	13
30	EW 2-1	6.6	453	382	297	228	166	102
	EW 2-2	6.1	318	249	216	162	110	69
	Average		385	315	256	195	138	86
	Stdev		95	94	57	47	40	23
	CV (%)		25	30	22	24	29	27

Table B.2
Indirect tension dynamic modulus (IDT |*E|) test results for I10Egan BC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	EB 1-2	4.3	2362	2218	2010	1922	1721	1241
	EB 2-1	3.3	2687	2446	2353	2295	2031	1885
	EB 6-2	3.1	3123	2998	2827	2686	2505	2012
	Average		2724	2554	2397	2301	2086	1713
	Stdev		382	401	410	382	395	413
	CV (%)		14	16	17	17	19	24
10	EB 1-2	4.3	1169	1033	789	701	520	208
	EB 2-1	3.3	1475	1264	1064	1055	740	402
	EB 6-2	3.1	2090	1536	1220	1080	908	420
	Average		1578	1277	1024	945	723	343
	Stdev		469	251	218	212	194	117
	CV (%)		30	20	21	22	27	34
30	EB 1-2	4.3	248	214	150	115	79	44
	EB 2-1	3.3	338	286	198	160	108	52
	EB 6-2	3.1	419	307	205	181	132	81
	Average		335	269	185	152	106	59
	Stdev		85	49	30	34	26	20
	CV (%)		25	18	16	22	25	34

Table B.3
Indirect tension dynamic modulus (IDT |*E|) test results for I10Vinton WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	VW 1-6	2.8	2378	2420	2273	2160	2002	1473
	VW 2-2	9.1	2781	2551	2442	2229	1961	1586
	VW 6-1	6.4	1579	1545	1510	1450	1424	1258
	Average		2246	2172	2075	1947	1796	1439
	Stdev		612	547	497	431	322	166
	CV (%)		27	25	24	22	18	12
10	VW 1-6	2.8	1387	1289	1081	870	670	411
	VW 2-2	9.1	1388	1336	1078	854	650	303
	VW 6-1	6.4	1202	1165	1072	1004	916	509
	Average		1325	1263	1077	909	746	408
	Stdev		107	88	4	83	148	103
	CV (%)		8	7	0	9	20	25
30	VW 1-6	2.8	457	349	231	206	164	104
	VW 2-2	9.1	456	326	201	156	113	98
	VW 6-1	6.4	725	539	324	280	172	148
	Average		546	404	252	214	149	117
	Stdev		155	117	64	62	32	27
	CV (%)		28	29	25	29	22	24

Table B.4
Indirect tension dynamic modulus (IDT |*E|) test results for LA964 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	2_4	5.1	2495	2358	2154	2096	1983	
	5_4	4.8	4488	4227	3952	3809	3515	
	6_1	4.4	3675	3525	3378	3308	3127	
	Average		3553	3370	3161	3071	2875	
	Stdev		1002	944	918	880	797	
	CV (%)		28	28	29	29	28	
10	2_4	5.1	1691	1593	1362	1270	1077	
	5_4	4.8	2743	2616	2266	2158	1781	
	6_1	4.4	2710	2603	2312	2157	1938	
	Average		2381	2271	1980	1861	1599	
	Stdev		598	587	536	512	459	
	CV (%)		25	26	27	28	29	
30	2_4	5.1	800	746	559	466	318	
	5_4	4.8	1324	1102	855	748	486	
	6_1	4.4	1396	1295	982	814	573	
	Average		1173	1048	799	676	459	
	Stdev		325	279	217	185	129	
	CV (%)		28	27	27	27	28	

Table B.5
Indirect tension dynamic modulus (IDT |*E|) test results for LA964 BC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	3_3	3.8	2889	2776	2545	2481	2225	
	5_4	3.5	3760	3449	3125	3026	2776	
	6_5	3.4	4415	4342	4125	4011	3737	
	Average		3688	3522	3265	3173	2913	
	Stdev		765	785	799	775	765	
	CV (%)		21	22	24	24	26	
10	3_3	3.8	1817	1733	1471	1269	980	
	5_4	3.5	2368	2146	1695	1506	1120	
	6_5	3.4	2992	2766	2244	2079	1632	
	Average		2393	2215	1803	1618	1244	
	Stdev		588	520	398	416	343	
	CV (%)		25	23	22	26	28	
30	3_3	3.8	570	475	354	293	150	
	5_4	3.5	809	714	488	411	290	
	6_5	3.4	1211	870	569	533	292	
	Average		863	686	470	413	244	
	Stdev		324	199	109	120	81	
	CV (%)		38	29	23	29	33	

Table B.6
Indirect tension dynamic modulus (IDT |*E|) test results for LA3121H WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E3	5.1	2848	2490	2381	2283	2019	1607
	E4	5.9	2604	2490	2255	2137	1890	1496
	E5	3.9	2539	2426	2381	2083	1904	1547
	Average		2664	2469	2339	2167	1937	1550
	Stdev		163	37	73	103	71	55
	CV (%)		6	1	3	5	4	4
10	E3	5.1	1365	1251	970	857	615	330
	E4	5.9	1509	1380	1082	958	702	387
	E5	3.9	1558	1415	1104	972	693	369
	Average		1477	1349	1052	929	670	362
	Stdev		100	86	72	63	48	29
	CV (%)		7	6	7	7	7	8
30	E3	5.1	480	395	240	198	112	52
	E4	5.9	434	354	213	173	97	45
	E5	3.9	476	390	232	186	106	49
	Average		463	380	228	186	105	49
	Stdev		25	22	14	13	8	3
	CV (%)		5	6	6	7	8	7

Table B.7
Indirect tension dynamic modulus (IDT |E^*|) test results for LA3121W1 WC mixture

Temperature (°C)	Sample ID	Air Voids (%)	IDT |E^*| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E1	5.1	2648	2604	2509	2389	2105	1558
	E3	4.8	2562	2443	2239	2149	1949	1612
	E6	4.4	2403	2322	2135	2043	1832	1485
	Average		2538	2456	2294	2194	1962	1551
	Stdev		124	142	193	177	137	64
	CV (%)		5	6	8	8	7	4
10	E1	5.1	1574	1399	1035	892	598	284
	E3	4.8	1419	1278	983	858	609	313
	E6	4.4	1383	1246	964	848	608	335
	Average		1458	1308	994	866	605	311
	Stdev		101	81	37	23	6	26
	CV (%)		7	6	4	3	1	8
30	E1	5.1	494	406	234	183	115	60
	E3	4.8	495	417	262	214	134	66
	E6	4.4	473	389	240	189	112	54
	Average		487	404	245	196	121	60
	Stdev		13	14	15	16	12	6
	CV (%)		3	4	6	8	10	10

Table B.8
Indirect tension dynamic modulus (IDT |*E|) test results for LA3121W2 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E2	5.5	2421	2318	2106	1984	1745	1334
	E3	2.7	2718	2599	2301	2166	1867	1361
	E5	3.2	2773	2685	2428	2301	2067	1604
	Average		2637	2534	2278	2150	1893	1433
	Stdev		189	192	162	159	162	149
	CV (%)		7	8	7	7	9	10
10	E2	5.5	1214	1085	795	675	443	204
	E3	2.7	1585	1419	1047	897	599	279
	E5	3.2	1534	1371	1011	867	560	255
	Average		1444	1292	951	813	534	246
	Stdev		201	181	136	121	81	38
	CV (%)		14	14	14	15	15	16
30	E2	5.5	326	257	141	112	59	26
	E3	2.7	402	322	178	134	74	39
	E5	3.2	426	344	198	155	89	48
	Average		385	308	172	134	74	38
	Stdev		53	45	29	22	15	11
	CV (%)		14	15	17	16	20	29

Table B.9
Indirect tension dynamic modulus (IDT |*E|) test results for LA116H1 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E1	2.5	3266	3208	2976	2866	2598	2133
	E3	4.7	2806	2731	2544	2475	2277	1925
	E6	4.1	3086	3031	2906	2805	2580	2222
	Average		3052	2990	2809	2715	2485	2093
	Stdev		232	241	232	210	180	152
	CV (%)		8	8	8	8	7	7
10	E1	2.5	2099	1972	1582	1447	1084	614
	E3	4.7	2266	1959	1636	1572	1174	720
	E6	4.1	1947	1836	1576	1465	1194	788
	Average		2104	1922	1598	1495	1151	707
	Stdev		160	75	33	68	59	88
	CV (%)		8	4	2	5	5	12
30	E1	2.5	750	639	408	334	203	96
	E3	4.7	868	754	511	431	275	131
	E6	4.1	942	796	537	460	305	152
	Average		853	730	485	408	261	126
	Stdev		97	81	68	66	52	28
	CV (%)		11	11	14	16	20	22

Table B.10
Indirect tension dynamic modulus (IDT |*E|) test results for LA116H2 BC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E4	4.5	3115	2956	2751	2687	2536	2230
	E5	5.1	2806	2680	2520	2459	2325	2135
	E6	5.3	3291	3045	2872	2793	2638	2390
	Average		3071	2894	2714	2646	2500	2252
	Stdev		245	190	179	171	160	129
	CV (%)		8	7	7	6	6	6
10	E4	4.5	2113	2030	1738	1610	1304	866
	E5	5.1	2015	1989	1780	1593	1315	898
	E6	5.3	2108	2052	1797	1682	1402	971
	Average		2079	2024	1771	1628	1340	912
	Stdev		55	32	30	47	54	54
	CV (%)		3	2	2	3	4	6
30	E4	4.5	984	861	607	511	337	165
	E5	5.1	954	840	605	519	358	179
	E6	5.3	1026	907	663	570	391	198
	Average		988	869	625	533	362	181
	Stdev		36	35	33	32	27	17
	CV (%)		4	4	5	6	7	9

Table B.11
Indirect tension dynamic modulus (IDT |*E|) test results for LA116W1 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E4	4.7	3077	3017	2814	2733	2530	2122
	E5	6.3	2515	2507	2290	2195	1950	1772
	E6	6.8	2694	2646	2491	2424	2236	1916
	Average		2762	2723	2531	2451	2239	1937
	Stdev		287	263	264	270	290	176
	CV (%)		10	10	10	11	13	9
10	E4	4.7	2186	2079	1816	1675	1382	978
	E5	6.3	1850	1737	1481	1366	1088	818
	E6	6.8	2069	1930	1649	1519	1214	830
	Average		2035	1915	1649	1520	1228	875
	Stdev		171	171	168	155	147	89
	CV (%)		8	9	10	10	12	10
30	E4	4.7	1168	1001	694	623	380	186
	E5	6.3	896	753	521	444	286	148
	E6	6.8	955	826	567	471	298	150
	Average		1006	860	594	513	322	161
	Stdev		143	127	90	96	51	22
	CV (%)		14	15	15	19	16	13

Table B.12
Indirect tension dynamic modulus (IDT |*E|) test results for LA116W2 BC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E4	4.8	3022	2966	2779	2730	2539	2334
	E5	5	2831	2785	2617	2539	2345	2028
	E6	3.8	3231	3168	2976	2880	2675	2405
	Average		3028	2973	2791	2716	2520	2255
	Stdev		200	192	180	171	166	200
	CV (%)		7	6	6	6	7	9
10	E4	4.8	2323	2222	1942	1787	1452	990
	E5	5	2017	1830	1554	1434	1145	746
	E6	3.8	2496	2356	1975	1821	1458	953
	Average		2279	2136	1824	1681	1352	897
	Stdev		243	273	234	214	179	131
	CV (%)		11	13	13	13	13	15
30	E4	4.8	973	843	574	481	298	142
	E5	5	891	763	510	426	262	117
	E6	3.8	992	861	594	501	324	158
	Average		952	822	559	469	295	139
	Stdev		54	52	44	39	31	21
	CV (%)		6	6	8	8	11	15

Table B.13
Indirect tension dynamic modulus (IDT |*E|) test results for US171H WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E1	3.9	2443	2381	2158	2101	1873	1542
	E3	5.7	2391	2325	2148	2062	1846	1515
	E5	4.3	2380	2317	2157	2089	1894	1597
	Average		2405	2341	2154	2084	1871	1551
	Stdev		33	35	5	20	24	42
	CV (%)		1	1	0	1	1	3
10	E1	3.9	1072	960	721	626	425	210
	E3	5.7	925	823	606	520	349	177
	E5	4.3	1172	1058	815	720	513	288
	Average		1057	947	714	622	429	225
	Stdev		124	118	104	100	82	57
	CV (%)		12	13	15	16	19	25
30	E1	3.9	228	179	100	83	57	33
	E3	5.7	225	181	105	85	55	32
	E5	4.3	317	256	150	120	78	40
	Average		257	206	118	96	63	35
	Stdev		53	44	28	21	13	4
	CV (%)		20	21	24	22	20	11

Table B.14
Indirect tension dynamic modulus (IDT |*E|) test results for US171W1 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E1	3.1	2784	2683	2495	2410	2191	1862
	E2	3.7	2636	2572	2391	2313	2119	1792
	E5	2.9	2909	2844	2654	2577	2366	2002
	Average		2776	2700	2513	2433	2225	1885
	Stdev		136	137	132	133	127	107
	CV (%)		5	5	5	5	6	6
10	E1	3.1	1510	1385	1074	949	684	372
	E2	3.7	1506	1395	1116	989	728	417
	E5	2.9	1547	1431	1131	1006	735	407
	Average		1521	1404	1107	981	716	399
	Stdev		23	24	29	29	28	23
	CV (%)		1	2	3	3	4	6
30	E1	3.1	510	427	255	203	115	53
	E2	3.7	597	502	313	252	154	70
	E5	2.9	435	361	208	164	106	55
	Average		514	430	259	206	125	59
	Stdev		81	71	52	44	25	9
	CV (%)		16	16	20	21	20	16

Table B.15
Indirect tension dynamic modulus (IDT |*E|) test results for US171W2 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E2	5.2	2731	2636	2403	2298	2020	1647
	E3	5.7	2294	2229	2043	1969	1758	1449
	E5	5.5	2532	2455	2255	2170	1938	1586
	Average		2519	2440	2234	2145	1906	1561
	Stdev		219	204	181	166	134	101
	CV (%)		9	8	8	8	7	6
10	E2	5.2	1076	959	692	593	390	184
	E3	5.7	887	780	559	478	313	153
	E5	5.5	900	811	602	516	348	169
	Average		954	850	618	529	350	168
	Stdev		105	96	68	59	38	16
	CV (%)		11	11	11	11	11	9
30	E2	5.2	272	214	116	89	54	30
	E3	5.7	255	204	115	90	53	24
	E5	5.5	325	261	149	113	71	34
	Average		284	226	127	97	59	29
	Stdev		37	30	19	14	10	5
	CV (%)		13	13	15	14	17	18

Table B.16
Indirect tension dynamic modulus (IDT |*E|) test results for PF LA10 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	6	6.3	2788	2537	2354	2275	2102	1779
	12	5.6	2637	2525	2372	2305	2082	1761
	14	5.7	2789	2582	2404	2317	2151	1840
	Average		2738	2548	2376	2299	2111	1793
	Stdev		87	30	25	21	35	42
	CV (%)		3	1	1	1	2	2
10	6	6.3	1634	1498	1194	1073	802	459
	12	5.6	1652	1583	1295	1183	909	543
	14	5.7	1702	1549	1303	1184	903	530
	Average		1663	1544	1264	1146	872	511
	Stdev		35	43	61	64	60	45
	CV (%)		2	3	5	6	7	9
30	6	6.3	601	500	315	246	150	73
	12	5.6	668	549	352	266	171	70
	14	5.7	639	518	327	287	163	77
	Average		636	522	331	267	161	73
	Stdev		34	25	19	21	11	3
	CV (%)		5	5	6	8	7	4

Table B.17
Indirect tension dynamic modulus (IDT |*E|) test results for PF LA10 BC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	6	5.8	2680	2327	2171	2097	1932	1618
	9	4.6	2698	2539	2159	2085	1936	1659
	12	4.1	2512	2446	2340	2279	2105	1871
	Average		2630	2437	2223	2154	1991	1716
	Stdev		102	106	101	109	99	136
	CV (%)		4	4	5	5	5	8
10	6	5.8	1873	1506	1332	1222	970	630
	9	4.6	1765	1702	1343	1242	1001	652
	12	4.1	1732	1620	1461	1354	1108	749
	Average		1790	1609	1378	1272	1026	677
	Stdev		74	98	72	71	72	63
	CV (%)		4	6	5	6	7	9
30	6	5.8	718	620	417	349	218	103
	9	4.6	749	632	432	429	237	115
	12	4.1	833	702	492	364	274	140
	Average		767	651	447	381	243	119
	Stdev		60	44	40	42	28	19
	CV (%)		8	7	9	11	12	16

Table B.18
Indirect tension dynamic modulus (IDT |*E|) test results for PF LA3235 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	W43M	7.1	2249	2216	1921	1853	1684	1375
	W54R	4.6	2982	2621	2388	2329	2157	1836
	W55W	3.1	2659	2467	2353	2290	2114	1818
	Average		2630	2435	2221	2157	1985	1676
	Stdev		367	204	260	264	262	261
	CV (%)		14	8	12	12	13	16
10	W43M	7.1	1434	1218	949	836	593	298
	W54R	4.6	1628	1443	1140	1020	745	400
	W55W	3.1	1714	1509	1229	1107	803	417
	Average		1592	1390	1106	988	714	372
	Stdev		143	153	143	138	109	64
	CV (%)		9	11	13	14	15	17
30	W43M	7.1	468	383	225	171	102	45
	W54R	4.6	548	445	265	204	119	54
	W55W	3.1	576	472	275	211	124	56
	Average		531	434	255	195	115	52
	Stdev		56	46	27	21	12	6
	CV (%)		11	11	11	11	10	12

Table B.19
Indirect tension dynamic modulus (IDT |*E|) test results for PF LA3235 BC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	B14Q	4.1	2637	2538	2367	2272	2043	1696
	B21A	4.3	2667	2562	2372	2290	2094	1726
	B23K	4.2	3100	2832	2630	2572	2374	2089
	Average		2801	2644	2457	2378	2170	1837
	Stdev		259	163	150	168	178	219
	CV (%)		9	6	6	7	8	12
10	B14Q	4.1	1674	1493	1144	1001	697	343
	B21A	4.3	1486	1354	1054	925	646	321
	B23K	4.2	1540	1462	1146	1005	708	348
	Average		1567	1436	1114	977	683	337
	Stdev		96	73	53	45	33	14
	CV (%)		6	5	5	5	5	4
30	B14Q	4.1	576	469	274	213	130	57
	B21A	4.3	491	390	223	171	99	42
	B23K	4.2	594	482	278	215	125	57
	Average		554	447	258	200	118	52
	Stdev		55	50	31	25	17	9
	CV (%)		10	11	12	13	14	17

Table B.20
Indirect tension dynamic modulus (IDT |*E|) test results for PF US90 WC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E2	6.9	2184	2086	1892	1810	1593	1248
	E3	5.8	2140	2112	1935	1854	1648	1310
	E5	6.3	2105	2043	1881	1808	1612	1284
	Average		2143	2080	1903	1824	1618	1281
	Stdev		40	35	28	26	28	31
	CV (%)		2	2	1	1	2	2
10	E2	6.9	794	704	505	430	271	124
	E3	5.8	924	826	605	523	342	159
	E5	6.3	960	863	641	552	365	172
	Average		893	798	584	501	326	152
	Stdev		87	83	71	64	49	25
	CV (%)		10	10	12	13	15	16
30	E2	6.9	204	161	88	72	51	31
	E3	5.8	202	156	87	69	70	48
	E5	6.3	242	194	108	89	61	39
	Average		216	170	94	77	61	39
	Stdev		23	21	12	11	10	8
	CV (%)		11	12	13	14	16	21

Table B.21
Indirect tension dynamic modulus (IDT |*E|) test results for PF US90 BC mixture**

Temperature (°C)	Sample ID	Air Voids (%)	IDT |*E**| (ksi) values at different frequencies					
			10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	0.01 Hz
-10	E2	4.3	2534	2474	2301	2214	2003	1620
	E3	4.4	2876	2811	2626	2534	2300	1889
	E5	4.7	2605	2538	2371	2288	2036	1755
	Average		2672	2608	2433	2345	2113	1755
	Stdev		181	179	171	168	163	134
	CV (%)		7	7	7	7	8	8
10	E2	4.3	1520	1404	1100	972	688	342
	E3	4.4	1598	1460	1129	993	704	361
	E5	4.7	1387	1258	961	836	575	289
	Average		1502	1374	1063	933	656	331
	Stdev		107	104	90	85	70	38
	CV (%)		7	8	8	9	11	11
30	E2	4.3	375	297	164	128	76	33
	E3	4.4	486	386	217	166	101	52
	E5	4.7	398	322	183	144	86	36
	Average		420	335	188	146	88	41
	Stdev		59	46	27	19	13	10
	CV (%)		14	14	15	13	15	26

APPENDIX C

Reduced Specimen SCB Test Comparison

It is desirable to minimize the number of cores taken from the pavement after construction. For the SCB test, six cores are typically required. A new method was approached to reduce the number of cores required for one SCB testing.

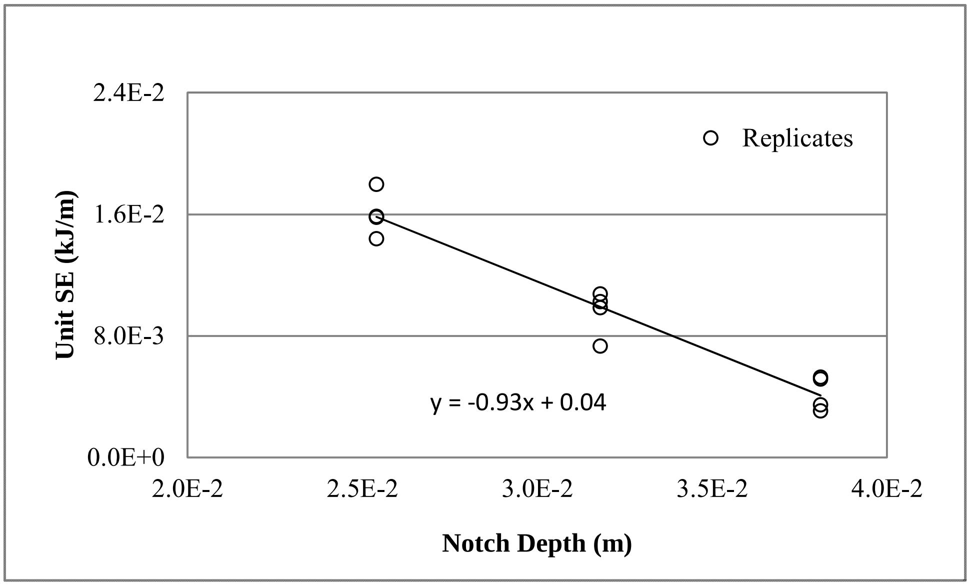


Figure C.1
Current method SCB Jc calculation

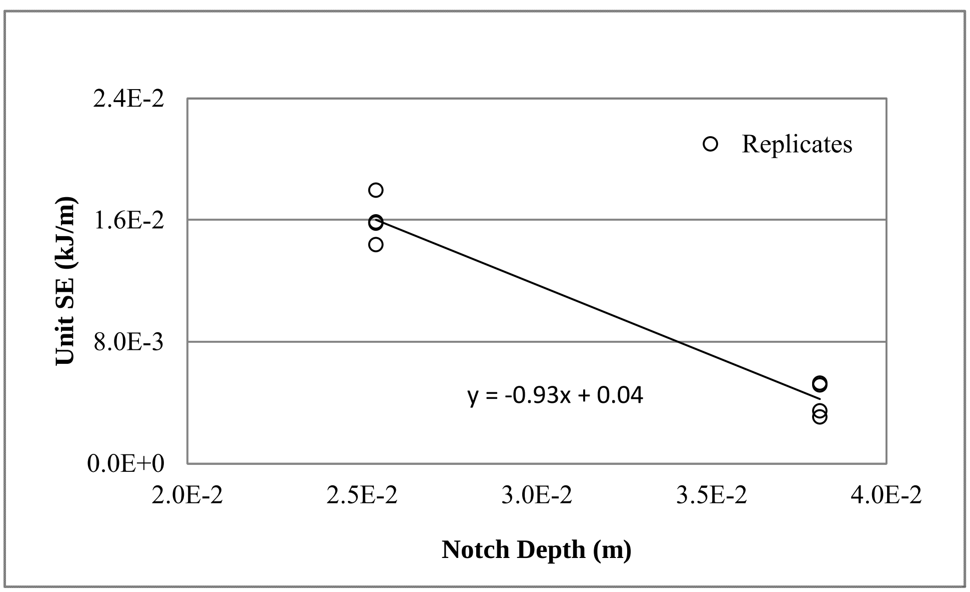


Figure C2
Proposed new method SCB Jc calculation

As shown in Figure C.1, three notch depths were taken into consideration for the measurement of critical strain energy release rate (Jc). Three notch depths were considered to verify the linearity between the strain energies recorded at individual notch depths. This criterion was found to be validated with most of the mixtures considered in this study. So in the new methodology (Method II), only two notch depths were considered in Jc calculations, which were 25.4 mm and 38.1 mm (Figure C.2). By adopting this methodology, one-third of the work can be reduced during the sample fabrication and also testing process.

Table C.1
SCB Test results with two notch depths

Project	Mix ID	Layer	SCB Jc, kJ/m^2		% Difference
			Method I[1]	Method II[2]	
I10 Egan	I10EW	WC	0.40	0.40	0.0%
	I10EB	BC	0.88	0.88	0.5%
I10 Vinton	I10VW	WC	0.93	0.93	0.0%
LA 964	964W	WC	0.30	0.30	0.8%
	964B	BC	0.43	0.43	0.4%
LA 3121	3121H1	WC	0.66	0.66	0.3%
	3121W1	WC	0.91	0.90	0.1%
	3121W2	WC	0.60	0.60	0.2%
LA 116	116H1	WC	0.52	0.52	0.2%
	116W1	WC	0.75	0.75	0.3%
	116H2	BC	0.34	0.34	0.2%
	116W2	BC	0.57	0.57	0.2%
US 171	171H1	WC	0.52	0.52	0.2%
	171W1	WC	0.73	0.73	0.0%
	171W2	WC	0.60	0.60	0.4%
LA 3235	3235W	WC	0.61	0.61	0.0%
	3235B	BC	0.77	0.76	1.3%
US 90	90W	WC	0.26	0.26	0.1%
	90B	BC	0.31	0.31	0.1%
LA 10	10W	WC	0.52	0.52	0.2%
	10B	BC	0.82	0.82	0.1%

- [1] three notches (25.4, 31.8, 38.1 -mm); [2] two notches (25.4, 38.1 -mm)

Table C.1 summarizes the SCB Jc values obtained from two methods. It is evident from the table that no considerable percentage difference (%) was observed between the results obtained from the two methods indicating the robustness of the approach. This validates that only two notch depths can be used to determine the critical strain energy release rate of asphalt specimens. With this method, instead of 6 cores (12 semi-circular specimens) for typical SCB testing, only 4 (8 semi-circular specimens) cores are required, which yields four semicircular specimens for two notch depths. This new approach for SCB test was utilized to propose a detailed sampling and testing plan.

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