Report No. UT-17.01

INTERMEDIATE TEMPERATURE CRACKING IN HMA: PHASE I SEMI-CIRCULAR BENDING (SCB) PRACTICALITY EVALUATION

Prepared For:

Utah Department of Transportation
Research Division

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RESEARCH

Keeping Utah Moving

Utah Department of Transportation - Research Division
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16. Abstract

The Utah Department of Transportation has implemented a program to test the rutting and moisture sensitivity of Dense Grade Asphalt. Under this program, asphalt mixes have become much harder and dryer in an effort to minimize rutting potential. The result of this program is the creation of mixes which are susceptible to cracking at intermediate and low temperatures. A test is being sought to help describe asphalt mix behavior in the temperature range above freezing but below softening. Louisiana State University has proposed a test to analyze the crack propagation energy in an asphalt mix using the semi-circular bending configuration. In this study, UDOT is evaluating this test procedure by setting up two test systems, creating a spreadsheet for data analysis and comparing the results of tests run on samples created in a single lab but performed in separate labs. The samples were created from a virgin mix design with increasing binder content but constant voids. Test results from one of the labs ranked the samples with increasing fracture propagation energy as binder content increased. Tests from the other lab provided an unexpected ranking with a scattering of results. Further evaluation is required to identify the causes of this anomaly.

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UNIT CONVERSION FACTORS

Preferably, present all measurements in the report in inch-pound or U.S. Customary system units. For non-conforming units, give data conversion units in parentheses throughout the report, or include applicable unit conversions here.

(Example) Units used in this report and not conforming to the UDOT standard unit of measurement (U.S. Customary system) are given below with their U.S. Customary equivalents:

- 1 meter (m) = 3.28 feet (ft)
- 1 kilometer (km) = 0.62 mile (mi.)
- Etc.

(Alternatively, the following conversion factors table may be included. Enlarge to fit.)

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

AASHTO	American Association of State Highway Transportation Officials
ASTM	ASTM International
AMPT	Asphalt Mixture Performance Tester
FHWA	Federal Highway Administration
G_{mm}	Maximum Theoretical Specific Gravity
HMA	Hot Mix Asphalt
HWTD	Hamburg Wheel Tracking Device
LSU	Louisiana State University
SCB	Semi-circular Bending
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

The Utah Department of Transportation has implemented a program to test the rutting and moisture sensitivity of Dense Grade Asphalt. Under this program, asphalt mixes have become much harder and dryer. The result of this program is to create mixes which are susceptible to cracking at intermediate and low temperatures.

A test is being sought to help describe asphalt mix behavior in the temperature range above freezing but below softening. Louisiana State University has proposed a test to analyze the crack propagation energy in an asphalt mix using the semi-circular bending configuration. In this study, UDOT is evaluating this test procedure by setting up two test systems, creating a spreadsheet for data analysis and comparing the results of tests run on samples created in a single lab but performed in separate labs.

The samples were created from a virgin mix design with increasing binder content but constant voids. Test results from one of the labs ranked the samples with increasing fracture propagation energy as binder content increased. Tests from the other lab provided an unexpected ranking with a scattering of results. Further evaluation is required to identify the causes of this anomaly.

1.0 INTRODUCTION

1.1 Problem Statement

For the past fifteen years, the Utah Department of Transportation (UDOT) has embraced the idea of mix performance specification. The idea comes about due to the final chapter of the Asphalt Institute publication SP-2. (Asphalt Institute, *SP-2* (1996)[2]) This chapter describes a level 3 Superpave mix design as being subjected to *mixture* tests targeting rutting, stripping, intermediate temperature fatigue and low temperature cracking.
Unfortunately, the tests proposed were not practical and required equipment of such great expense as to require use of regional laboratory centers using pooled fund financing. These centers were unprepared to handle the volume of testing required in a State's projects in any semblance of a timely manner. The entire system was abandoned and Utah embarked on a program to develop a performance testing system that met its needs.

The first of the tests embraced by the UDOT was the Hamburg Wheel Tracking Device (HWTD). This test addresses the dual issues of rutting and stripping. Much work was put into the test procedure such that reasonable repeatability was achieved. The test was implemented as a requirement for all mix designs in the 2012 Standard Specification. It is believed that implementation of this standard has yielded some very good results but has apparently produced a troubling side effect.

The focus on a single aspect of Hot Mix Asphalt (HMA) appears to have significantly unbalanced pavement performance. Utah sees little rutting in pavements built under the 2012 Standard Specification but top down (and thermal?) cracking has become a persistent feature. This appears to be a result of hardened and more brittle mixes. A specification solution to the unbalanced mix is being sought.

Fatigue cracking at intermediate temperature was looked at in the Superpave program as a beam flexure problem. The cyclic, four-point-bending-test was proposed to develop an understanding of this phenomenon. (SHRP report A-404, Tayebali, A. et. al. (1994)[5]). This test was built around the theory that the number of cycles to failure was a function of the reciprocal values of the Young's modulus and the strain. One of the main hypotheses in the study was that the problem could be expressed using linear fracture mechanics. This assumption means that all of the fracture properties are observed by a reduction of the initial stiffness modulus. A result of this assumption is that the stress-strain relationships fall within the linear region which is limited to around 50 micro-strain in HMA mixes. The studies promptly pushed the strains into the realm of 500 to 600 micro-strain. The conclusion of these studies, using linear fracture mechanics, was that if the modulus is high, the strain is small and the material survives a long time. This is a classic linear fracture conclusion and is fine for fatigue in relatively thick pavements where strains never exceed the linear region. UDOT attempted to follow the advice of FHWA by building two high modulus pavements on I-80 and I-84 during the 1998 and 1999 construction seasons. These pavements were built over stabilized bases and were much thinner than conventional design procedures would require. By 2003, both pavements had failed and repaving had to be scheduled. As a lead state in Superpave adoption and as an advocate of the concepts promoted by this technology, UDOT had proven that these ideas could be pushed too far. Something was missing with the model.

HMA is a visco-elastic material whose behavior is non-linear. These pavements are considered "flexible" and this property has been used to great advantage. A distinct exploitation of this characteristic is the construction of continuous, unbroken pavement. A seamless pavement is a smooth, quiet pavement. Brittle behavior is the antithesis of seamless, continuous pavements. Based on the UDOT experiences, brittle behavior can be shown to be correlated to current high-modulus UDOT HMA mixes.

A new strain tolerance concept is now being explored in the non-linear region of asphalt concrete. Strain tolerance is the ability of a material to strain a great deal without losing its ability to carry load. A material exhibiting this property is considered "tough". (King, G. et al (1999)[3]) It appears that toughness is a desirable quality in flexible pavements. Toughness is determined by understanding how much energy it takes to fracture a material. It is also determined by measuring how much energy is required to propagate a crack once the fracture begins. A tough material will continue to require energy to propagate a crack. A brittle material will fracture all at once. Since a monotonic test is used for this determination, the test can take as little as 4 hours as opposed to the cyclic test which could occupy 4 months of lab time.

To understand the crack propagation energy, some researchers have elected to plot the post peak side of the stress-strain curve and have proposed an ASTM test procedure using a semi-circular beam (SCB) configuration. Representatives from Louisiana State University (Mohammad, L. et al (2012)[5]) have proposed that the critical fracture energy Jc measured at incremental chord lengths is a more repeatable way to look at this fracture propagation energy. Using the SCB configuration, Dr. Mohammad proposes that the slope of the best fit, linear regression for J_c plotted against variable notch depths (height minus chord length) represents the energy required to propagate a crack. The steeper the absolute value of the slope, the tougher the material. He proposes that a test run at intermediate temperature (77°F) and 0.5mm/min should have a slope of at least |-0.60| to be tough enough to resist both top down and bottom up cracking.

LSU has asserted that the concept of toughness is directly related to intermediate temperature crack performance in pavements. (Mohammad. L., (2012)[5])

A copy of his test procedure, which has been approved by ASTM (D 8044-16), is included in Appendix 1.

1.2 Objectives

The objective of this research is to get two labs set up to do the LSU version of the SCB test and to run some tests. This involves taking two of the unused UDOT Asphalt Mix Performance Testers (AMPT) and setting them up in separate laboratories. Test heads, saws, cutting templates, incubators and software must be obtained or created. Once the testing apparatus has been set up, a number of samples are to be tested to see whether the test can:

1. Properly rank the material, and

2. whether the test can be repeated.

1.3 Scope

- Install an Asphalt Mixture Testing Machine in the UDOT Central Lab and also in a separate lab, including all support features to operate the machine.

- Identify, obtain or create the necessary fixtures and accessories to run the LSU SCB test. These fixtures and accessories include the sample fabrication tools, test fixtures and temperature control device.

- Identify or create tools to analyze the data outputs from the test equipment so as to identify the slope of the linear regression.

- Determine whether the test can identify increasing binder content as a factor in increasing J_c slope.

1.4 Outline of Report

1. Introduction: The introduction describes UDOT's history with mix testing and the common model of the day. It further describes a new idea and test procedure. The scope of the project is described.
2. Research Methods: Once the equipment is set up, a data analysis software is produced to work the machine outputs and calculate the result as described in the test procedure. A study is then run to validate the test.
3. Data Collection: Data is collected in the form of a .csv file and converted to an excel spreadsheet. Calculations are then performed on the data by the spreadsheet.
4. Data Evaluation: Results are graphed and evaluated.
5. Conclusions: Conclusions are drawn from the evaluations.
6. Recommendations and Implementation: Recommendations are made as to how to proceed.
7. Appendices: Proposed testing standard developed by LSU and submitted to ASTM.

2.0 RESEARCH METHODS

2.1 Overview

Setting up the AMPT for obtaining fracture energy results is the first goal of this research. This process involved setting up a suitable environment, installing the equipment, software and loading fixtures in each of two labs, one at the UDOT Central Materials Laboratory and one at the CME Laboratory.

The LSU method describes the analysis procedure but does not provide a tool to do the analysis. A spreadsheet was written in Microsoft Excel for this purpose.

Producing specimens which meet a narrow repeatability standard is necessary for meaningful results. Fixtures were developed to accurately cut and configure the samples.

Samples were initially produced and initially in a single laboratory environments to determine whether the test was capable of differentiating between binder contents. Samples were then produced in one lab and run both labs to determine whether the test could be run on a second machine with repeatable results.

2.2 Background/Methodology Equipment

UDOT purchased five, first generation Simple Performance Testers (SPT) from IPC Global in 2003 to support the implementation of the AASHTO Mechanistic and Empirical Design Guide. It was later determined that the “Simple” performance test was not so simple and that a level one design, as envisioned by the MEPDG, was impractical in the Design-Bid-Build project delivery system used by UDOT. The SPTs were renamed the Asphalt Mixture Performance Tester (AMPT) by the FHWA, and the five UDOT units were mothballed in 2008 having seen little service. The Department was looking for a use for these highly sophisticated machines, including their controlled temperature support capabilities. LSU announced the development of a fracture toughness test which appeared to fit a department need and was thought to be a perfect match for the unused SPT equipment since the test was developed on an

SPT of the same generation. The LSU researchers also evaluated a Humboldt Load-Master frame but decided to use the AMPT due to their availability.

2.2.1 Equipment Installation

The first generation AMPT is a servo hydraulic load frame with an environmental chamber which can maintain temperature to within ±0.2^{o}C. Although the LSU form of the Semi-circular Bending test can be run on a screw type load frame, the dynamic controller on the AMPT provides a constant velocity by monitoring the stroke displacement and providing three degrees of rate management. Specific software is needed for this control, which was written and provided to UDOT by IPC global as test UTS041. The SPT outputs to a .csv file which can be read by any software including Microsoft Excel.

These devices were installed along with an incubator and compressed air in both the UDOT Central Materials and CME labs.

Figure 2-1 Installed AMPT

2.2.2 Loading Head

LSU developed a loading head for use in the IPC Global SPT. For this investigation, it was determined that obtaining a loading head from LSU's supplier would provide greater repeatability than attempting to develop a device independently. The machine measures displacement through the stroke of the load piston. Since the load cell in in this line, any strain in the load cell is recorded as energy storage.

Figure 2-2 LSU Loading Head

2.3 LSU Crack Propagation Model

The LSU model for crack propagation begins with the assertion that the energy to move a crack at any point along the developing crack path is the energy contained under the stress-strain curve at the strain achieved at that load. (Mohammad, L. et al (2012)[5])

LSU has chosen to increment the notch depth to measure the energy required to initiate the crack at the incremental geometry. This allows tracking the pre-peak side of the stress-strain curve rather than the less predictable post-peak side.

Thus:

$$J_c = -\frac{1}{b}\int \frac{dU}{da}$$

Where:

J_c is the critical strain energy release rate required to initiate a crack in the sample

b is the width of the specimen

a is the notch depth

U is the strain energy to failure.

Three notch depths are used to develop a crack propagation curve. A shallower curve means that there is little difference in critical energy as related to sample geometry. A steeper curve indicates a higher degree of geometry dependence. Thus a shallow curve indicates a brittle material and a steep curve indicates a tough material.

Based on field observations, LSU has set a standard curve slope of -0.6 to indicate an acceptably tough asphalt mix for high traffic roads and -0.5 for low traffic roads. (Mohammad, L. et al (2012)[5])

2.3.1 Analysis Tool

Although LSU provides the method in its proposed standard, it provides no analysis tool. The .csv file for each specimen can contain 3,000 or more data points. A test consists of four sets of three notch depths or 12 specimens. All of these .csv files must be gathered, sorted and analyzed. A computer program is necessary to analyze this amount of data and provide consistent results.

Since a .csv file can be interpreted by Microsoft Excel and spreadsheets can be used to do integration, a spreadsheet seemed like a reasonably simple choice for an analysis tool.

When running the SPT test procedure, it was noted that there was quite a bit of noise in the data. Not only did the stress measurement bounce a great deal, but the displacement measurement moved forward and backward as related to time. Thus a best fit line must be generated to smooth the data for integration. A fourth order polynomial was determined to produce the best fit when the data was followed to a value between 1,000 and 2,000 points past the peak.

The vector function *Linest* was used to generate the coefficients of the best fit polynomial after which these coefficients were used to plot the Y (load) coordinate for each X (displacement) increment. The trapezoidal rule was then used to integrate the curve between X_o and the value of X, where Y is at max. This sum represents the energy required to initiate a crack at the specific notch depth. This process is performed four times for each of three notch depths. A linear best line fit is run on the three notch depths and the slope of that best fit line is obtained. This is performed for each of the four replicates and an average slope is calculated.

A macro was written to load the data files and properly import the relevant data for reduction and processing. Tools were developed at each step to validate data quality and processing validity. A copy of this spreadsheet is available for use by contacting the author.

2.4 Sample Preparation

A sample of asphalt concrete for the LSU version of the SCB test is made from a 150 mm diameter Superpave Gyratory puck. The pucks are compacted to a target air void (6%) plus or minus 0.5%. This is an important feature of the sample because no energy is required for a crack to pass through a void. Higher void content therefore leads to lower fracture propagation energy and more brittle mixes. Since a binder sweep is being performed, a new maximum theoretical specific gravity (G_{mm}) must be determined for each binder content. This assures that as binder is added and the bulk specific gravity falls, the appropriate weight of mix can be compacted to the 117 mm height and the voids can be held constant.

Although the mix design is 100 gyrations, the addition of binder over or under the design may change the volumetrics at N_{des}. Since void content appears to be the critical value in cracking, compaction was controlled by height rather than gyrations.

The 117 mm tall puck is cut in half with a 3 mm thick blade about the diameter so that the result is two 57 mm tall specimens. Each specimen is then cut in half again along the diameter to create four half rounds. Three pucks are made so that a total of 12 samples result. These samples are grouped into four groups of three and a notch of differing depth is cut into the flat face of each of the three semicircles in each group. Notches are cut 25.4, 31.8 and 38.1 mm deep and 3 mm wide. (Mohammad, L. et al (2012)[5])

Since binders undergo both steric and physical hardening and this may or may not affect the test outcome, all samples were compacted, the bulk gravity measured and then cut on day one. The samples were incubated to the test temperature overnight and tested in the morning of day 2. This procedure removes time hardening as a possible variable as the change in these binder effects are greatly slowed after 8 hours. (Anderson, D.A. et al. (1994)[1])

2.4.1 Cutting

Templates were developed to assure sample consistency. Figures 2.3 to 2.5 show the templates and saw.

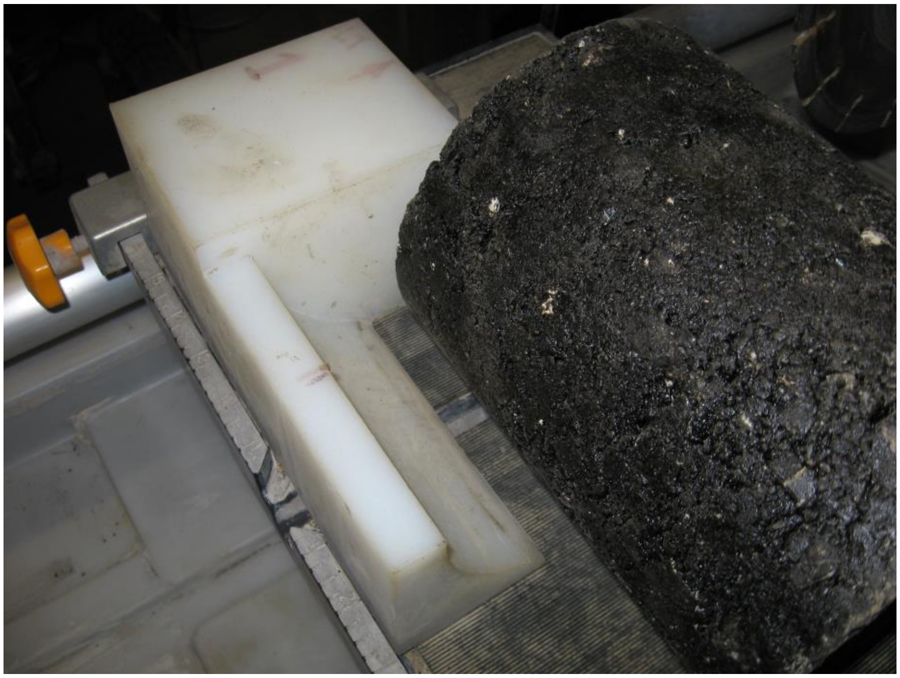

Figure 2-3 Diameter Cutting

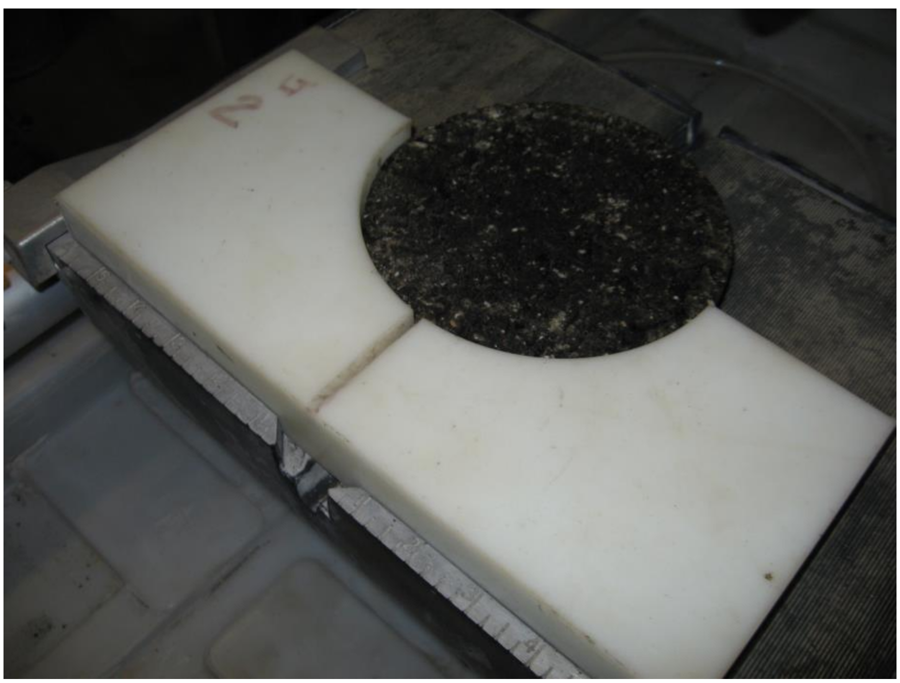

Figure 2-4 Quarter Cut

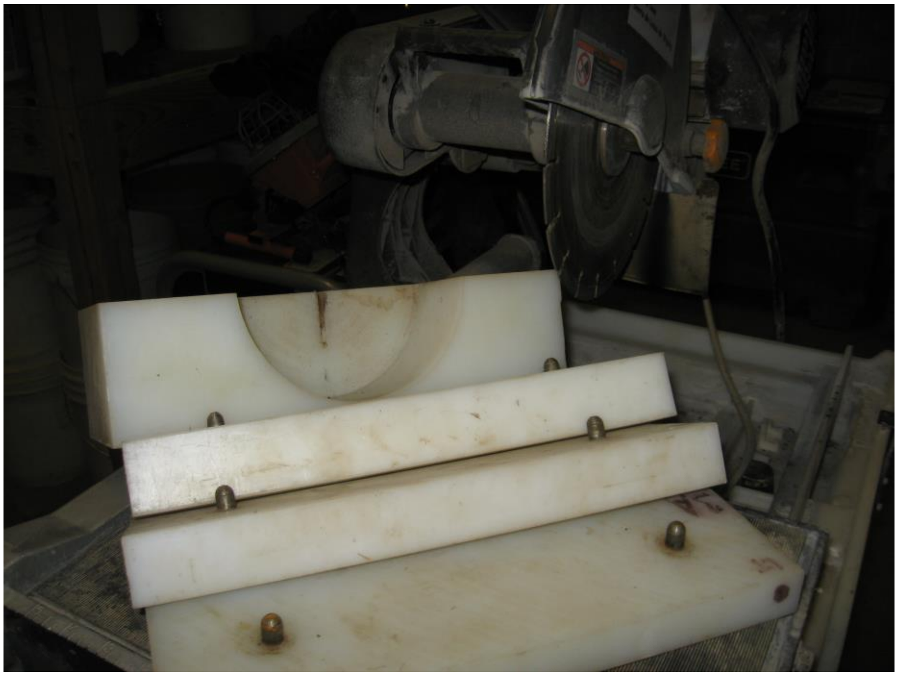

Figure 2-5 Notch Cut with Saw

2.5 Experimental Procedure

As discussed in the scope, the purpose of this experiment is to investigate two issues. The first is to demonstrate that the assertion that if additional binder is added to the asphalt concrete mix, the mix becomes tougher. The second is to demonstrate the repeatability of the test procedure and apparatus between labs.

2.5.1 Binder Sweep

A 100 gyration, ¾” N_{max}, hard limestone mix design was developed by a local contractor for the purpose of this research and was used in all testing. The mix is treated with 1% hydrated lime and uses a local PG 64-28 styrene butadiene modified asphalt. This is a typical Utah paving mix without Recycled Asphalt Pavement (RAP). Mixing temperature is 321 ^{o}F and Compaction temperature is 309 ^{o}F. The mix design calls for 4.6% binder based on total mix weight. The binder sweep includes 4.1%, 4.6% and 5.1% binder. The maximum specific gravity (Rice) of the mix is determined for each binder content, and the mix is compacted to 6% air void ±0.5%. As previously noted, the mix was prepared, aged, compacted, bulk specific gravity determined and cut on the first day. Samples were incubated at 25^{o}C overnight. Testing was performed on the second day.

2.5.2 Inter-lab Repeatability

The goal of this work was to minimize as much of the variability as possible, other than location and equipment. All samples were prepared in the UDOT lab. The calibrated equipment and test heads were set up to be as closely similar as possible. Only incubation and testing were performed in both labs. The testing environment and laboratory technician were also different.

2.6 Summary

There are two issues that are to be determined in this study. First, can the test properly differentiate between varied binder contents in a mix? Second, can the test results be repeated between test equipment and technicians sufficient to be worth further efforts at implementation? The included experiment was set up to isolate and address these issues.

3.0 DATA COLLECTION

3.1 Overview

Data is collected in the form of a .csv file by the AMPT machine. This raw data consists of the vertical displacement record and the force record. Also recorded are temperature and confinement pressure. Specimen information including date, time, test label, binder content, width, notch depth and void content are also collected. This raw data is processed by a Microsoft Excel spreadsheet where J_c is calculated.

3.2 Data Collection Item 1

A summary of the results which are relevant to the analysis are listed in table 3.1.

All samples are built from Staker Parsons, Beck Street Limestone and Calumet, PG 64-28 binder								
The maximum nominal aggregate is 3/4 inch								
The number of gyrations are those required to reach the specified height rather than Ndes								
Test #	Binder Content	Average Void Content	Range of Void Content	Average Jc (kJ/m2)	Coefficent of Jc Variation	Maximum Theroetical Specific Gravity	Testing Laboratory	
1.1	4.1	6.30	6.2 to 6.4	0.39	11.8%	2.530	UDOT	
1.2	4.6	6.35	6.1 to 6.5	0.45	35.9%	2.511	UDOT	
1.3	5.1	6.10	5.7 to 6.3	0.59	57.9%	2.492	UDOT	
1.4	4.1	5.70	5.5 to 5.9	0.72	32.7%	2.530	CME	
1.5	4.6	5.85	5.8 to 5.9	0.53	52.7%	2.511	CME	
1.6	5.1	6.45	6.4 to 6.5	0.91	41.8%	2.492	CME	
2.1	4.1	6.60	6.4 to 6.8	0.34	24.8%	2.530	UDOT	
2.2	4.6	6.50	6.3 to 6.7	0.48	9.0%	2.511	UDOT	
2.3	5.1	6.15	5.9 to 6.3	0.51	71.4%	2.492	UDOT	
2.4	4.1	5.65	5.6 to 5.7	0.41	48.2%	2.530	CME	
2.5	4.6	5.91	5.8 to 6.1	0.47	37.9%	2.511	CME	
2.6	5.1	6.52	6.4 to 6.6	0.68	23.30%	2.492	CME	

Table 3-1 Test Results

3.3 Summary

Data relevant to the project was collected, filtered and displayed in the order of testing. Critical values such as void content J_c and measures of variation were tabulated along with G_{mm} and testing laboratory.

4.0 DATA EVALUATION

4.1 Overview

The small amount of data produced does not yield well to statistical evaluation. The researchers preferred to graph and sort the data to reveal relationships.

4.2 Graphed Data

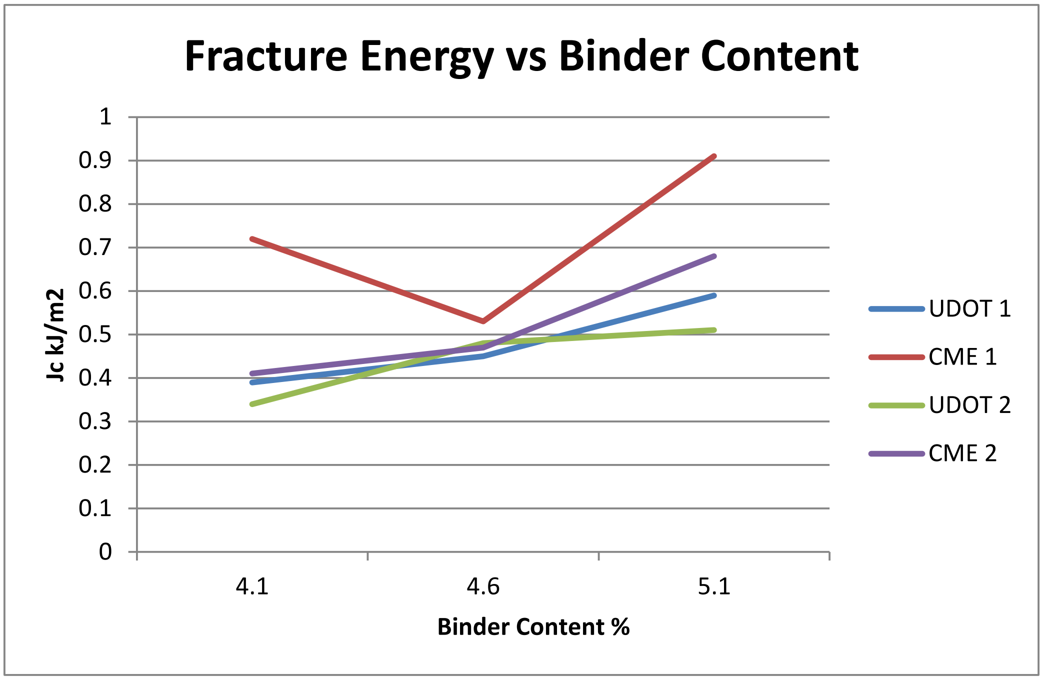

Figure 4-1 Fracture Energy vs Binder Content

From this figure, there is clearly an outlier coming from the first CME laboratory results. The researchers cannot determine why this outlier occurred but when it was noticed, the equipment was re-calibrated. The second test in CME's lab is much more consistent with the two tests run in UDOT's lab. The purple, green and blue tests all show an increasing J_c value with increasing binder content. There is some degree of repeatability with better grouping around the design binder content and reduced precision with increased binder.

4.3 Tabulated Data Sorted by Binder Content

Binder Content	Average Jc (kJ/m2)	Coefficent of Jc Variation	Testing Laboratory	Compared to UDOT
4.1	0.39	11.8%	UDOT	
4.1	0.34	24.8%	UDOT	
4.1	0.72	32.7%	CME	up
4.1	0.41	48.2%	CME	up
4.6	0.45	35.9%	UDOT	
4.6	0.48	9.0%	UDOT	
4.6	0.53	52.7%	CME	up
4.6	0.47	37.9%	CME	dn
5.1	0.59	57.9%	UDOT	
5.1	0.51	71.4%	UDOT	
5.1	0.91	41.8%	CME	up
5.1	0.68	23.30%	CME	up

Table 4-1 Data Sorted by Binder Content

From this tabulation, there appear to be two outliers. The 4.6 binder content from CME is also high of the associated values. It is apparent there is some unidentified problem associated with this particular test result. The second test run by CME is much more in line with UDOT's lab however the trend is for CME's lab to be consistently higher than UDOT's results. There appears to be a relationship between the coefficient of variation and the binder content and the J_c value. The CV is no higher for either lab.

4.4 Summary

By visual evaluation and sorting the test data, an anomaly was discovered. Steps were taken to standardize the equipment and the subsequent test results were normalized. There is a clear trend showing increasing J_c with increasing binder. There is also an appearance of increasing variability with deviation from mix design. CME's lab tended to produce higher J_c results than UDOT's lab.

5.0 CONCLUSIONS

5.1 Summary

UDOT is seeking a test which would provide an indication of fracture resistance in the field. LSU's research has linked fracture toughness to fracture resistance and has set a threshold value of 0.6 as a specification limit. (Mohammad, L.et al.(2012)[5]) The contractor's mix design at 4.6% binder and 6% void produced fracture energy well below the LSU threshold. This is expected for a 100 gyration mix with a Hamburg Wheel Tracker requirement of less than 10mm rut in 20k passes. This mix would be expected to be cracking susceptible and local experience would substantiate this expectation. The higher binder content mix meeting the LSU SCB thresholds appears to be a much more balanced mix indicating that the LSU variation of the SCB test would seem to meet the Department's need, with some improvement regarding procedure repeatability.

5.2 Findings

The researchers were able to set up two surplus SPT machines and were able to prepare samples in a repeatable manner. After calibration, the machines produced reasonably similar results.

In reviewing the results, a clear outlier was found in the data. Steps were taken to discover and correct the anomaly. There is a clear trend in the data indicating increasing fracture energy with increasing binder content.

If this SCB test is used for mix design evaluation, better correlation between laboratories will be needed. At 5.1% binder, the CME lab shows a J_c value of 0.68. The UDOT lab shows values of 0.51 and 0.59. CME would have passed the mix with a threshold at 0.60 while UDOT would have failed it. The spread around the 0.60 value is far too great for specification purposes.

5.3 Limitations and Challenges

This research was very preliminary. It shows the promise of the test procedure and threshold values. It is difficult to draw specific conclusions about the test but some degree of single lab and inter-lab repeatability was demonstrated.

6.0 RECOMMENDATIONS AND IMPLEMENTATION

6.1 Recommendations

Sufficient data was produced to provide an indication of an effective test and some degree of repeatability. The equipment has been set up and the evaluation tools developed. It will now be necessary to run a statistically valid factorial test to identify the causes of variation so as to produce a reliable and repeatable procedure.

The test is not yet ready for use in a specification. Although a threshold has been established for the state of Louisiana, such a threshold may not apply in Utah.

6.2 Implementation Plan

The next step in test validation is to develop a statistically valid factorial program to isolate the causes of variability. This plan should address the following, at a minimum.

1. Equipment Calibration
2. Breaking Head Configuration
3. Lubricant and Slip Plane Materials
4. Temperature Stabilization
5. Sample Loading and Placement Variability
6. Sample Preparation Variability, including notch depth and location variation, and end effects of uncut puck edges
7. Curing Time Variability

Following the establishment of a statistically defendable procedure and identification of controllable sources of variability, a local threshold will need to be established based on a combination of test results and field performance. The UDOT Materials Library may be an excellent source of information for this particular stage of implementation.

REFERENCES

Anderson, D.A. et al. (1994) SHRP-A-367, "Binder Characterization and Evaluation Volume 1"

Asphalt Institute, "SP-2", PP 89-101 (1997) ASIN: B019PJJU52

King, G., King, H., Pavlovich, R. D., Epps, A. L., & Kandhal, P. (1999). Additives in asphalt. *Journal of the Association of Asphalt Paving Technologists*, *68*, 32-69.

Mohammad, L. et al (2015) "Draft Standard Method of Test for Evaluation of Asphalt Mixture Crack Propagation using the Semi-Circular Bend Test (SCB)"

Mohammad, L. et al (2012) "The Flexural Strength of Asphalt Mixtures Using the Semi-Circular Bending (SCB) Test" 7^{th} Rilem International Conference on Cracking in Pavements PP 1-10

Tayebali, A., et.al. (1994), SHRP A-404 "Fatigue Response of Asphalt-Aggregate Mixes"

<u>**APPENDIX A: Test Procedure**</u>

LSU has allowed for copying the draft SCB test procedure here.

6.2.1.1Method of Test for Evaluation of Asphalt Mixture Crack Propagation Using the Semi-Circular Bend Test (SCB)

1. SCOPE

1.1. This test method covers procedures for the preparation, testing, and measurement of fracture failure of semi-circular asphalt mixtures of specimens loaded monotonically.

1.2. This standard may involve hazardous material, operations, and equipment. This standard does not purport to address all safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2. REFERENCED DOCUMENTS

2.1. AASHTO STANDARDS

- R 30, Mixture Conditioning of Hot Mix Asphalt (HMA)
- T 67, Load Verification of Testing Machines
- T 166, Bulk Specific Gravity of Compacted Hot Mix Asphalt Using Saturated Surface-Dry Specimens
- T 168, Sampling Bituminous Paving Mixtures
- T 209, Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA)
- T 269, Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures
- T 312, Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor

3. SUMMARY OF TEST METHOD

3.1. A semi-circular specimen is loaded monotonically until fracture failure. The load and deformation are continuously recorded and the critical strain energy rate, J_c, is determined.

4. SIGNIFICANCE AND USE

4.1. The critical strain energy rate is used to compare the fracture properties of asphalt mixtures with different binder types.

4.2. This fundamental engineering property can be used as a performance indicator of fracture resistance based on fracture mechanics, the critical strain energy release rate, also known as Jc value.

5. APPARATUS

5.1. Load Test System- A load test system consisting of a testing machine, environmental chamber, and data acquisition system. The test system shall meet the minimum requirements specified below.

5.2. Testing Machine- The testing machine should be a closed loop system capable of applying a 4.5kN load monotonically under a constant cross-head deformation rate of 0.5 mm/min in a three point bend load configuration.

5.3. Environmental Chamber- A chamber for controlling the test specimen at the desired temperature is required. The environmental chamber shall be capable of controlling the temperature of the specimen at 25°C to an accuracy of +/- 1ºC.

5.4. Measurement System- The system shall include a data acquisition system comprising analog to digital conversion and/or digital input for storage and analysis on a computer.

The system shall be capable of measuring and recording the time history of the applied load for the time duration required by this test method. The system shall be capable of measuring the load and resulting deformations with a resolution of 0.5 percent.

5.4.1. Load- The load shall be measured with an electronic load cell having adequate capacity for the anticipated load requirements. The load cell shall be calibrated in accordance with AASHTO T 67.

5.4.2. Axial Deformations- Axial deformations shall be measured with linear variable differential transformers (LVDT).

5.4.3. Temperature- Temperature shall be measured with Resistance Temperature Detectors (RTD) accurate to within +/- 1ºC

5.5. Gyratory Compactor- A gyratory compactor and associated equipment for preparing laboratory specimens in accordance with AASHTO T 312 shall be used.

5.6. Saw- The saw shall be capable of producing three different notch sizes ranging from 0 – 50 mm. The width of the saw blade shall be 3.0mm.

5.7. Loading Frame- The loading frame shall consist of a loading rod and two sample support rods. The schematic of the test apparatus is shown in Figure x (need permission from ATM). The diameters of the loading and supports rods shall be 25.4 mm and the anvil span shall be 127.0 mm.

6. TEST SPECIMENS

6.1. Semi- circular bend testing may be performed on field cores or laboratory prepared test specimens.

6.2. Specimen Size- The test specimen shall be 150 mm diameter and 57 mm thick.

6.2.1. The semi-circular shaped specimens are prepared by slicing the 150 mm by 57 mm specimen along its central axis into two equal semi-circular samples.

6.2.2. Field cores can also be used if pavement is at least 57 mm.

6.3. Notching- A vertical notch is introduced along the symmetrical axis of each semicircular specimen. The three nominal notch sizes are 25.4 mm, 31.8 mm, and 38.1 mm. The notch depth tolerance is ± 1.0 mm. The width of the notch shall be 3.0 ± 0.5mm

6.4. Prepare four test specimens at the target air void content ±0.5%.

6.5. Aging- Laboratory-prepared mixtures shall be temperature-conditioned in accordance with the oven conditioning procedure outlined in AASHTO PP2. Field mixtures need not be aged prior to testing.

6.6. Air Void Content- Prepare four test specimens at the target air void content ±0.5%.

6.7. Replicates- Four specimen should be tested at each at each notch depth (25.4-, 31.8-, and 38.1-mm).

7. PROCEDURE

7.1. Place the specimen on the bottom support, ensuring the support is centered and level (as shown in Figure 1), in the environmental chamber and allow it to stabilize to 25ºC. A dummy specimen with a temperature sensor mounted to its center can be monitored to determine when the specimen reaches 25ºC. In the absence of a dummy specimen, a minimum of 0.5 hours from room temperature is the required temperature equilibrium time.

7.2. After temperature equilibrium is reached, apply a preload of 10 lb to specimen to ensure the sample is seated properly. After ensuring the sample is level, release the load.

7.3. Begin to apply load to specimen in displacement control at a rate of 0.5 mm/min ensuring that time, force, and displacement are being collected and recorded. During the test have the load versus displacement plot visible, paying close attention to the peak load. Test may be terminated 120 seconds after peak load is reached.

8. CALCULATIONS

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

(Equation D.1)

where:

J_c = Critical fracture energy

b = sample thickness

a = notch depth

U = strain energy to failure.

8.1.1. Strain energy to failure, U is the area under the loading portion of the load vs. deflection curves, up to the maximum load measured for each notch depth (shown in Figure 2).

8.2. The specimens are randomly clustered into 4 groups of three (one specimen at each notch depth within the grouping) before testing. Each cluster of three notch depths may be analyzed individually. The three values of U (one at each notch depth) are plotted versus their respective notch depths. The data is then modeled with a linear regression line (shown in Figure 3). The slope of the linear regression line represents the strain energy release rate.

8.3. The critical value of J-integral (J_c) then computed by dividing the slope of the linear regression line (dU/da) by the specimen thickness, b.

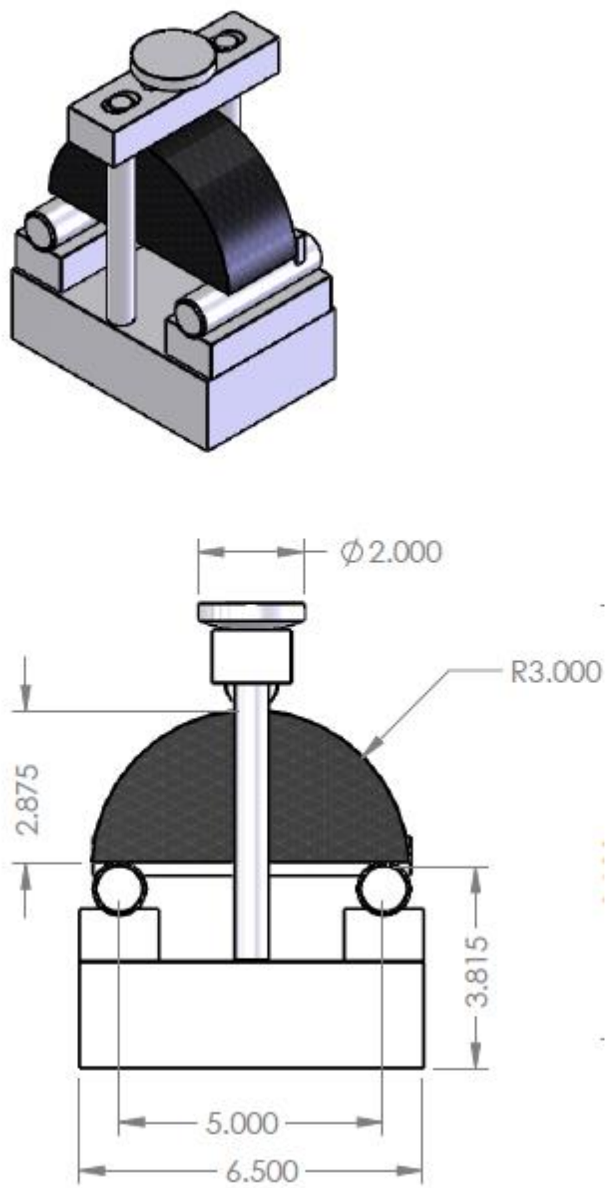

Figure D-1: Schematic of the loading apparatus

Figure D-2: Loading Position

Figure D-3:

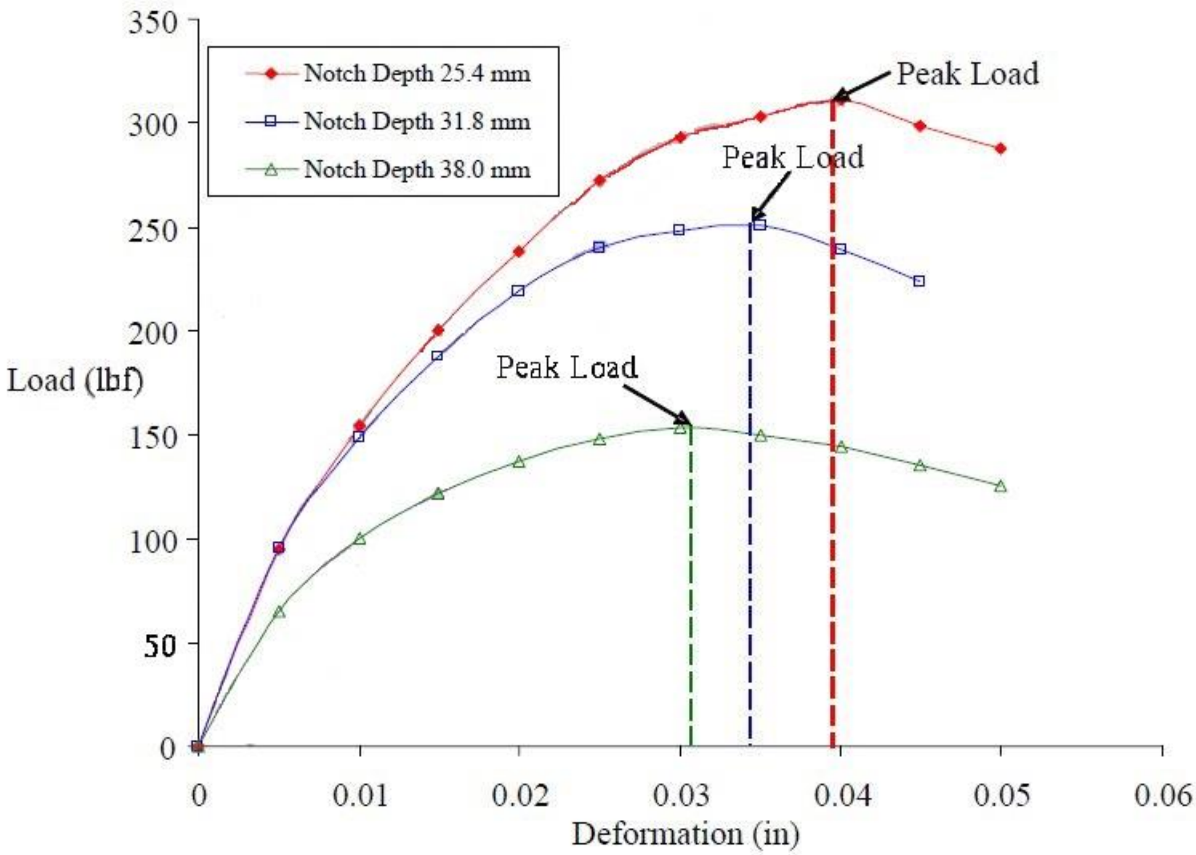

Figure D-4: Deformation versus Load

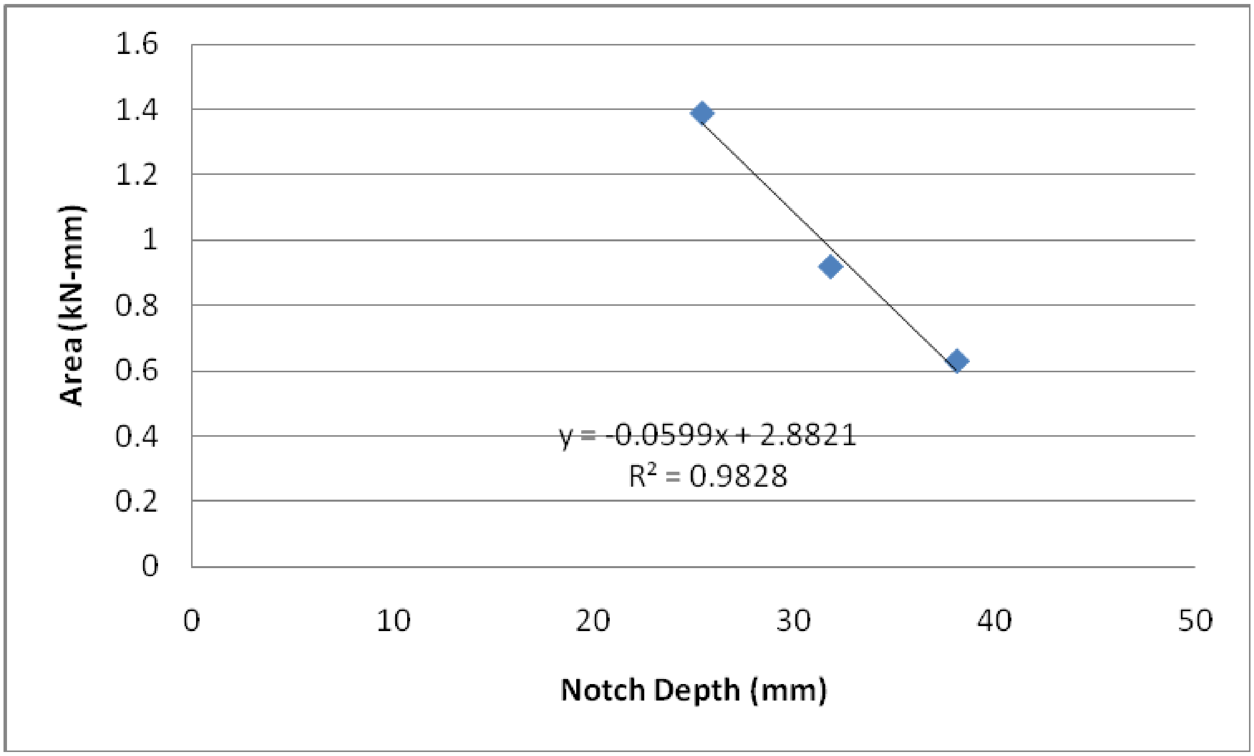

Figure D-5: Notch Depth versus Area

9. REPORT

9.1. *The report shall include the following parameters*:

9.1.1 Asphalt Mixture Type;

9.1.2 Test Temperature, °C;

9.1.3 Specimen Air Voids, %;

9.1.4 Jc per Notch Depth, kJ/m2;

9.1.5 Coefficient of Determination, R2;

9.1.6 Mean Jc Value, kJ/m2;

9.1.7 Standard Deviation of J_c;

9.1.8 Coefficient of Variation, %.