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Cold In-Place Recycling Using Solventless Emulsion – Phase IV (Emulsion Qualification and Long-Term Field Performance)

Prepared For:

Utah Department of Transportation
Research Division

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RESEARCH
UDOT Keeping Utah Moving
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DISCLAIMER

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16. Abstract

This report looks into how a successful Cold In-Place solventless emulsion behaves and how the emulsion break test developed in Phase III of this project demonstrates that behavior. Modifications to the test have been made to improve the consistency of the test. A modified laboratory procedure is proposed. The report also considers the factors contributing to successful field performance. Six CIR projects done over the last eight years were cored. These samples were subjected to Density, Stability and Fracture Energy determination. Results from these tests were compared to a Performance Index designed to normalize age, overlay condition and CIR condition. It was determined that, while poor performing projects exhibited similar stability to high performing projects, the poor performers exhibited low density and low fracture energy compared to the good performers.

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UNIT CONVERSION FACTORS

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 Highway and Transportation Officials
CIR	Cold In-Place Recycled Asphalt Pavement
FHWA	Federal Highway Administration
LSU	Louisiana State University
RAP	Milled Asphalt Pavement reduced to 1.5” sized particles
SCB	Semi-Circular Bending Test (Louisiana State University Method)
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

This report looks into how a successful Cold In-Place solventless emulsion behaves and how the emulsion break test developed in Phase III of this project demonstrates that behavior. Modifications to the test have been made to improve the consistency of the test. A modified laboratory procedure is proposed.

The report also considers the factors contributing to successful field performance. Six Cold In-Place Recycling (CIR) projects done over the last eight years were cored. These samples were subjected to Density, Stability and Fracture Energy determination.

Results from these tests are compared to a Performance Index designed to normalize age, overlay condition and CIR condition. It is determined that poor performing projects exhibit similar stability to high performing projects, however the poor performers show low density and low fracture energy.

1.0 INTRODUCTION

1.1 Problem Statement

A. Background

UDOT is in the latter stages of updating their laboratory design and field testing protocols and controls for both Cold In-Place Recycling (CIR) procedures for pavement rehabilitation. Part of the update of this practice includes the development of new end-result performance procedures that can be used in the lab and field to get good materials information in a timely manner to aid in the evaluation of the construction processes and determine proper opening times to traffic. To develop these procedures, field and lab data has been collected from projects and used to obtain a better understanding of how the materials react and perform during the construction and placement processes.

The use of CIR to reclaim and rehabilitate pavements has been shown to significantly reduce costs (25% TO 33%) compared to that of using virgin materials. The current versions of these tools utilize a solventless emulsion that provides for significantly shorter curing times and earlier opening to traffic. UDOT has fully adopted these pavement rehabilitation practices, however the current procedures used to design, control and evaluate the construction of these materials are time consuming and expensive, and have not been able to prevent some pavement failures due to inadequate timeliness and applicability of test results.

The ultimate performance of the CIR material is defined by the type and amount of emulsion added to the milled material. The design of the material must balance the need of more emulsion to achieve strength and reduce raveling with the need for less emulsion to prevent rutting. Historically, efforts have been focused on identifying the proper sampling practice and test procedure to define the proper performance of CIR so that specifications would not have to be prescriptive. Recent efforts have identified that, while the use of high-level performance testing is not practiced, the use of simple performance tests related to unbound materials is applicable.

Previous phases of this research have focused on:

1) Developing a field and lab testing protocol to produce consistent data for evaluation.

2) Field evaluation of mixes during the initial curing stages of the mix after compaction.

3) Refinement and evaluation of field testing procedures.

4) Development of a draft mix design process.

These were done with the ultimate goal of the research to qualify CIR binders and mixes with laboratory tests that will reasonably predict both the short-term construction behavior of the mix and the longer-term performance behavior of the mix.

Information gained from Phases I through III has resulted in two over-reaching conclusions:

The CIR material is significantly friable in the early stages (first 7 days or longer) and sampling and testing of the CIR material, both in the lab and the field, is highly variable. The primary exception is the LSU procedure for using the Semi-Circular Bending Beam (SCB) due to the relatively simple sample configuration and fracture energy analysis.

Field practices used to control voids during placement of the material are primarily dependent upon RAP temperature sensitivity and field-moisture/emulsion-content. neither of which are properly accounted for in the current design process.

A cone penetration procedure for qualifying the emulsion based on break characteristics for use in Solventless CIR was also developed such that an understanding of the drivers leading to emulsion break are better understood. The temperature, moisture and particle size requirements may now be included in coordination with project mix design and project control.

The cone penetration test uses a 1000 lb. press along with a 200 lb. load cell to push a 20 mm diameter 60° cone into a sample of emulsion mortar. The mortar is allowed to cure for incremental periods of time in a dry atmosphere at a constant temperature. A constant rate of penetration is used over a set distance. The resultant load is recorded and graphed. A delay in increasing viscosity for around two hours is expected with a subsequent increase in viscosity to around 50% of initial penetration force in around 3 hours.

Procedures for using this test are published in Appendix B of this study.

Figure 1-1 Cone Penetration, Emulsion Mortar test

These findings and conclusions were used in developing a mix design procedure that also addresses the RAP temperature sensitivity and moisture content sensitivity within the material. The procedure results in a mix that includes the maximum binder possible without compromising rutting stability. The design approach treats the CIR material as an unbound material during the placement and initial compaction stages, similar to an untreated base course. The mix design and field control procedures are therefore similar.

B. Current Research Plan

While overall mix properties are critical to the short-term construction and long-term performance, one of the primary critical components of the mix design is the evaluation and qualification of emulsions to be used in the CIR process. Emulsions that are designed to properly demulsify and cure in a pattern conducive to both field workability and to early opening to traffic are the basis for the modern CIR process. Elimination of emulsions that are likely not capable of meeting constructability and short-term opening to traffic needs of the project is critical to eliminating the previous costly failures that have led to limitations in the use of CIR in the state of Utah. While a prototype test has been developed, a variety of unknowns remain.

- What is the effect of particle distribution in the mortar?

- What is the effect of initial consolidation efforts (vibration, tapping, static load compaction, or dropping)?
- Does varying water content above optimum affect the outcome?
- Does an increase or decrease in the amount of emulsion applied to the system have an effect on break and cure reactions?
- Does the presence of lime play a role in emulsion break and cure reactions?

The establishment of the mix design process will allow for the evaluation of the presence of lime in the CIR mix. Currently, the use of lime introduces 1.5% solids and 4.5% moisture into a mix, thereby reducing the amount of room for additional emulsion. The presence of lime is based on the history of using quicklime slurry to generate heat to drive off moisture, combined with recent engineering judgments that the lime will provide moisture damage protection. Current emulsions are designed differently and both the heat generation and moisture damage concerns need to be evaluated and justified.

Lastly, the construction of CIR has historically included the presence of a noticeably higher void content (10% to 15% total voids) in the field than traditional hot mix applications (5% to 8% total voids). CIR, in multiple forms, has been widely used throughout the western states for many years. Discussions with industry indicate that the CIR mixes traditionally have 10% to 15% in-place voids and have still performed well. There is some concern, however that the high void content may lead to premature fatigue failure or other distresses. A performance evaluation of a group of older projects and the collection of some field conditions/properties of the CIR mixes is necessary to verify if the high void concern is valid.

C. Phase IV Objectives

a. Determine the field characteristics contributing to a successful project and those contributing to an unsuccessful one.
b. Demonstrate the repeatability of the cone penetration – emulsion mortar test developed in Phase III of this study.
c. Understand the effect of lime on the Solventless emulsion, demulsification process.

1.2 Phase IV Scope

a. Obtain samples of both successful and unsuccessful CIR projects. Evaluate the projects in the laboratory to find indicators of success or failure. Use Marshall Stability, Fracture Energy and Density as the basis for the analysis.
b. Determine the repeatability of the demulsification test developed in Phase III of this study. Use an emulsion of demonstrated success and determine the factors contributing to variability.
c. Determine the pH (lime) sensitivity of a successful solventless emulsion.

1.3 Outline of Report

- Introduction
- Research Methods
- Data Collection
- Data Evaluation and Analysis
- Conclusions
- Recommendations and Implementation
- Appendix A: LSU procedure for determining critical fracture energy using the SCB apparatus.
- Appendix B: UDOT procedure for qualifying solventless emulsions using cone penetration

2.0 RESEARCH METHODS

2.1 Overview

Two distinct issues are investigated. The first, what field characteristics contribute to CIR failure? The second, what issues were missed when the emulsion qualification proof of concept was done?

To determine why CIR pavements succeed or fail, six pavements from the UDOT inventory were cored and tested. The selected pavements have been built over the past 8 years and have all been capped with a hot asphalt overlay. To standardize pavement condition, a performance index designed to normalize age, overlay condition and CIR condition was developed. Common performance indicators such as density and stability along with a relatively new indicator, critical cracking energy, were used to understand long term performance.

A new test was proposed for qualifying emulsions for use in cold asphalt recycling. The proof of concept was published in Phase III of this study. Several questions remained such as what are the chemical drivers in cure imitation? What influence does particle size have? How does moisture effect demulsification. These questions are answered by varying each of the parameters and evaluating differences or similarities in results. Comparisons are done graphically.

2.2 Performance Index

The CIR pavements evaluated in this study were built at various times over the past nine years. Their surface conditions vary as do the condition of the CIR layers. To create an equalization of these factors, a Performance Index was developed. The age and condition factors were assigned a weight and the pavements were ranked. Age was given a weight of 40%, Surface condition 20% and CIR condition 40%. The age was ranked by years where the surface and CIR conditions were given a value between 1 and 10 with 1 being poor and 10 being excellent. The pavements were thereby ranked from 1 to 10 with 1 being poor and 10 being excellent. Since no pavement is 10 years of age, a rank of 10 is not possible.

2.3 Density

Density of asphalt concrete is generally stated as a percent of some maximum density. Historically, this has been a Marshall Density, which is somewhat like Maximum Laboratory (Proctor) Density in unbound materials. In the current Superpave paradigm, density is stated as a percentage of the Theoretical Maximum Density (G_{mm}). For the purposes of this study, G_{mm} will be used.

2.3.1 Theoretical Maximum Specific Gravity (G_{mm}) AASHTO T-209

G_{mm} is based on the amount of water displaced by the aggregates, lime and binder in a measured weight of asphalt concrete mix. G_{mm} allows for the direct association between weight of mix and volume of mix without air voids (Asphalt Institute, SP2). Emulsion based mixes set with the breaking and curing of the emulsion, and not by cooling as with hot mix. This factor requires that the sample be cured for a period of time to allow the emulsion to set and prevent re-emulsification. The procedure used in this study was to cure the mix at 100°F until no more than 0.1% of the total mass was lost in a 10 minute curing interval. When cores were taken from the field, they were tested for Marshall Stability and then broken down so that the G_{mm} could be obtained.

G_{mm} is measured by taking a measured weight of asphalt concrete mix, breaking it up into particles approximating the largest aggregates in the mix, then placing it in water and vacuuming with agitation so as to remove any trapped air. The weight of the sample is then measured while submerged in water.

The difference in the weight dry and the weight submerged is the amount of water displaced by the mix. Since the unit weight of water is known, the volume of the mix is now known. .(Archimedes) When SI units are used, the weight in grams and the volume in cubic centimeters is one to one and the specific gravity is the relationship of the weight of one gram of mix to one cc (gram) of water.

2.3.2 Density of compacted mix G_{mb} AASHTO T-166

Bulk density of the mix G_{mb} (Asphalt Institute, SP2) is determined by weighing a compacted sample of mix dry. The sample is then weighed while submersed in water. The difference in weights is the displaced water. (Archimedes) When SI units are used, the weight in grams and the volume in cubic centimeters is one to one and the specific gravity is the relationship of the weight of one gram of mix to one cc (gram) of water.

2.3.3 Percentage of G_{mm}

Compacted samples cored from the field are compared to G_{mm} as follows:

$$\%Compaction = \frac{Gmb}{Gmm} x100 \quad (2.2.1)$$

2.4 Marshall Stability AASHTO T-245

AASHTO T 245 is a method of determining the rut susceptibility in a Hot Mix Asphalt. Both saturated and unsaturated flow (distance to maximum load) and stability (maximum load) are determined. The test was originally set up to use the 4 inch Marshall pill, but has been modified to accept the 6 inch SGC puck. Marshall Stability is determined by:

$$St = \frac{2 * P}{3.14 * D * t} \qquad (2.3.1)$$

Where:

S_t = tensile strength (psi)

P = maximum load (lb)

D = specimen diameter (in)

t = specimen thickness (in)

A Marshall Stability machine is shown in Figure

Figure 2.1: Marshall Stability Machine

2.4.1 Thickness

Since AASHTO T-245 does not prescribe thickness for a 6 inch diameter sample and since all samples taken from the road were 6 inch cores, the sample thickness was established by the thinnest Cold Recycled layer in the pavements studied. This thickness turned out to be 2⅝ inches (67 mm).

2.4.2 Temperature

Consistent temperature in Stability tests is important. All samples were brought to 80°F using an incubator.

2.4.3 Speed

Marshall Stability is run at a load travel rate of 2 inches per minute.

2.4.4 Replicates

Limited coring was performed. However, two specimens from each core site were tested. Only unsaturated stability was determined.

2.5 Semi-Circular Bending (LSU Procedure)

Concern has been expressed among asphalt pavement owners that although rutting has been minimized by the implementation of tests such as Marshall Stability, Hveem Stability, Hamburg Rut testing, etc., current asphalt pavements appear to be exhibiting excessive cracking behavior. This appears to be a direct result of concentrating on mix stiffness and ignoring crack resistance. Current pavement layer modeling relies on mix stiffness and composition to predict reduced cracking. Additionally, common performance tests, such as the 4 point bending test for fatigue life, demonstrate that the higher the modulus within the linear region (50 microstrain), the greater the number of cycles to crack initiation. Although the opposite is actually practiced, this model precludes building thinner asphalt layers because increasing stiffness in asphalt naturally leads to increased brittle behavior, which is exacerbated by thinner pavements. Only by resisting strain can the material remain intact. These properties further lead to top down cracking due to thermal stresses near the pavement surface.

The SHRP SuperPave project was created as a means to mitigate rutting and therefore was predisposed to creating a stiffer mix. The SuperPave system recommended the 4 point bending test as a cracking performance indicator in level 3 mix designs (Asphalt Institute SP3). As an early adopter of SuperPave, UDOT engineers embraced the idea of high modulus asphalt pavements and built two sections of Interstate pavement to demonstrate the concept. Sections of I-80 in Echo Canyon and I-84 near Morgan were built to demonstrate “non-rutting”, “thin-layer” technology. Both pavements failed by fatigue cracking within 5 years of installation. It became clear that something was missing in the “high modulus” concept.

It has been suggested that understanding the energy required to propagate a crack through a material might lead to materials which are tough and strain resistant. It has also been suggested that a balance between anti-rutting and strain resistant properties might be a better solution than relying strictly on stiffness. A number of attempts to look at crack propagation in asphalt concrete have been made over the past 20 years. One such method is the semi-circular bending test (SCB). A number of variations on this test configuration have been tried including one which was demonstrated in Phase III of this study. That method, where the energy required to propagate a fracture was determined by measuring the post-peak stress/strain curve, was unsuccessful.

A new variation on the SCB was developed at Louisiana State University by Dr. Louay Mohammad and his students. This procedure measures the energy required to start a crack using an incremented ligament. The incremental energies are then compared to produce the energy required to propagate the crack. When the energy required to fracture the sample is plotted against the ligament length, a best fit line and slope are produced. The shallower the slope, the less the fracture energy is dependent on geometry and the more brittle the material behaves. The steeper the slope, the more the fracture energy is dependent on geometry, and the tougher the material behavior is. A draft of this procedure is included in Appendix A. A threshold value of the critical energy Jc, was selected by Dr. Mohammad to be -0.60 for the production of balanced asphalt mixes.

2.5.1 Replicates

One sample taken from five cores obtained from each of the test sections was tested to determine Jc.

2.5.2 Test conditions

Tests were run in accordance with the LSU draft procedure at 80°F in the AMPT using fixtures and IPC Global software developed for the machine. Analysis was run using an Excel spreadsheet designed for the IPC Global outputs and written according to the LSU procedure.

2.6 Coring Plan

CIR Project Coring Summary

Project	Date placed	Core #	HMA Summary	CIR Summary	Notes
Monticello	2008	MO1	3" HMA High void content	3.5" CIR typical voids	Chip seal on all cores. Core MO1 to MO6 had approximately 1" of underlying asphalt. Cores 7, 8 which were taken closer to the travel lane had around 4" of underlying asphalt.
		MO2	3.25 HMA some voids	3" CIR Typical voids	
		MO3	3.25" HMA High voids bottom	3.25 " CIR typical voids	
		MO4	3.25 HMA High voids bottom	3.25" CIR typical voids	
		MO5	3" HMA High voids bottom	3" CIR Typical voids	
		MO6	3" HMA some voids	3" CIR higher voids	
		MO7	3" HMA some voids	3" CIR typical voids	
		MO8	3" HMA some voids	3" CIR separated, deteriorated	
SR 32 Peoa	2011	P1	3.25" HMA High voids	4.25" CIR typical voids	The botom layer of existing asphalt in Peoa was 4" thick and very deteriorated. The cores separated between the CIR and bottom layer of asphalt.
		P2	3.5 HMA high voids	3" CIR typical voids	
		P3	3" HMA some voids	3" CIR separated, deteriorated	
		P4	3.5 HMA typical voids	4" CIR typical voids	
SR 32 Marion	2011	M1	3.75 HMA some voids	4.25 CIR some voids	The HMA at Marion had extrememly high voids. M4 was separated from asphalt below with a whitish residue on bottom (lime?) M2 had a crack or long joint below
		M2	3" HMA very high voids	3" CIR typical voids	
		M3	3" HMA some voids	3" CIR typical voids	
		M4	3" HMA some voids	3" CIR typical voids	
I-84 West	2012	I1	3" HMA typical voids	3" CIR high voids deteriorated	The I-84 West CIR appeared crumbly and not well bound compared to other projects. Underlying material was not remvoed with the CIR as the cores separated easily.
		I2	3.25 HMA some voids	3" CIR some voids	
		I3	3" HMA typical voids	3" CIR some voids	
		I4	2.75" HMA some voids	3" CIR some voids	
I-84 East	2012	E1	3"HMA typical voids	3" CIR some voids	The I-84 East CIR appeared crumbly and not well bound compared to other projects. Underlying material was not remoed with the CIR as the cores separated easily.
		E2	2.75" HMA typical voids	3" CIR some voids	
		E3	2.75 HMA typical voids	3" CIR some voids	
		E4	3.25 HMA typical voids	2.75" CIR some voids	
US 40 Strawberry	2011	S1	3" HMA very high voids at bottom	3.5" CIR typical voids	Cores taken from EB lane. Core S1 was from outside wheelpath near long. Crack. Cores 2 and 3 were from a transverse crack. Core 4 was from 4' into lane in line with a transverse crack. All cores were in poor condition with high voids in all layers. Total
MP 44 EB lane		S2	3.25" HMA cracked	3.5" CIR cracked, high voids	
N40, 13', 43.1"		S3	3" HMA	3.25 CIR all layers cracked	
W111, 07', 04.0"		S4	3.25 HMA high voids	3.5 CIR high voids	
US 40 Strawberry	2011	T1	3.25 HMA typical voids	3.25" CIR deteriorated while coring	Cores taken from WB outside lane in an area with transverse and longitudinal cracks. T4 was at long. crack. T3 was at long. Line in pavement. Cores were in generally poor condition with very high voids in the HMA and CIR. Average total depth 14".
MP 48.8		T2	3.25 HMA typical	3" CIR Typical voids	
N 40, 11', 13.4"		T3	3.5 HMA high voids at bottom	3.25" CIR some voids	
W 111, 03', 57.0"		T4	3.5 HMA very high voids	3.5 CIR high voids	
US 40 Current Creek	2009	C1	3.25' HMA Well compacted	2.75 CIR some voids	Cores taken from WB outside lane. C1 taken from center of lane in line with trans. Crack. C2 taken from wheel path next to C1. C3 taken 100' W of C1 from outside wheel path, cracked below CIR. C4 center of lane similar to C3. Total depth 13"
MP 56.8		C2	3.25" HMA voids at bottom	2.75" CIR some voids	
N 40, 11', 47.9"		C3	3.25 HMA well compacted	2.75 CIR well compacted	
W 110, 55', 40.2"		C4	3.5 HMA well compacted	2.5" CIR some voids	
US 40 Current Creek	2009	D1	3.25 HMA well compacted	3 CIR some voids	Taken from WB outside climbing lane. D1 from inside wheel path, D2 center of lane, D3 outside wheel path and D4 at shoulder.
MP 57.8		D2	3.25 HMA well compacted	3 CIR some voids	
N 40, 12', 59.5"		D3	3.25 HMA well compacted	3.25 CIR well compacted	
W 110, 54', 41.3"		D4	3.25 HMA well compacted	3 CIR well compacted	

Table 2-1 Coring Plan

2.7 Cone Penetration - UDOT Emulsion Test

CIR emulsion has a unique set of challenges related to curing time. The RAP mix, along with any additives, including emulsion, must exit the mixing pugmill and be deposited in a windrow where it rests until it is picked up and placed in a paver. The mix is then distributed into a 2½ to 3½ inch thick mat for compaction. This operation may take place across a temperature range of 80°F or more throughout the day, and in near rain or arid conditions. The emulsion must not break for at least 30 minutes after application on the RAP, but must reach release-to-traffic strength within 4 hours to meet current UDOT expectations. This seems an impossible task, however, CIR emulsions have been developed which meet these requirements over wide temperature conditions with lows beginning in the 40°F to 50°F range, and highs up to 120°F, both with low to moderate humidity. Adjustments can be made in the emulsion plant to adjust to field conditions. The challenge has been to differentiate emulsions which can meet these challenges from those which can't.

UDOT identified a test in Phase III of this study. The cone penetration test showed great promise in controlling the major factors in the demulsification of Cold In-place Asphalt Recycling Emulsions, thereby providing a method of differentiating between emulsions which were and were not suitable.

The Phase III study considered a number of factors including Sample Size, Aggregate Size, Moisture in the Sample, Moisture in the curing chamber, Load Cell precision, Head configuration, Cup configuration, Vibration/Consolidation, Temperature, Test Head Speed and Time.

Several factors were yet to be studied:

1. How does the presence of lime affect the emulsion break?
2. Does water content above the minimum required to control emulsion break affect set time?
3. Does the quality of the base RAP material affect the outcome?
4. What is the effect of particle distribution in the mortar?
5. What is the effect of initial consolidation (vibration, tapping, pressing, dropping). The question of tapping, pressing or dropping the sample to achieve compaction arose later in the Phase III testing process. Vibration alone did not always produce consistent sample consolidation.

Figure 2.5.1 shows the testing head and Figure 2.5.2 shows a test sample.

Figure 2.5.1 Cone Penetration Test Head

Figure 2-1Cone Penetration Test Sample

2.7.1 Test matrix

Gradation Variants						
	Fine		Medium		Coarse	
Screen	% retain	% pass	% retain	% pass	% retain	% pass
30	20	80	35	70	40	60
50	20	60	25	45	30	30
100	20	40	10	35	10	20
200	20	20	10	15	10	10
-200	20		15		10	

Table 2-2 Experimental Gradations

Table 2-2 defines the gradations used in the tests. A single RAP source is used throughout the testing. Test readings are taken at 10, 20, 30, 45, 60, 120, 180 and 300 minutes.

All test materials are stored and cured at 100°F. This curing temperature was chosen to be at the middle of a potential construction grading system. The proposed grade ranges would be 70°F to 90°F, 90°F to 110°F and 110°F to 130°F. Testing is done at room temperature.

The test protocol published in phase III of this study was used for all testing.

. Table 2-3 is the test matrix to determine whether 1.5% lime content changes the pH from the no lime condition.

Factoral Plan pH			
Gradation	Fine	Medium	Coarse
Lime	FL	ML	CL
No Lime	FNL	MNL	CNL
Determine pH			

Table 2-3 Plan for Determination of pH variation

The question is whether RAP is acidic and if so, does the fineness of the RAP create a change in acidity? Is any of this changed by the lime?

The test was done with an Oakton Eco PH2 calibrated at two points with pH 4 and 10 buffers. Testing was done after 24 hours saturation at 25°C. Liquid was distilled water, pH 7.0

Table 2-4 lays out the experimental plan for determining whether an engineered emulsion responds to increased or decreased water content.

Effect of Water above and below Optimum				
Factoral Plan				
Single Solventless Emulsion				
Single RAP Source				
Lime = 1.5% Coarse Aggregate				
Gradation	Fine	Medium	Coarse	
H20, Opt ± %	-3	-3	-3	
	0	0	0	
	+3	+3	+3	
Does greater or lesser water effect break/cure time				

Table 2-4 Plan for Determining the Effect of Water on Emulsion Reactivity

The question of "how accurate optimum moisture determination needs to be" goes to the consistency of the test. Optimum moisture has been determined by the appearance of "liquefaction". Liquefaction is the point where sufficient water is present in the particle distribution to fill all of the voids and begin to push the particles apart. It is apparent when vibration causes the peaks in the surface of the particle sample to soften and a water-sheen to develop.

The results will also give insight into field behavior.

Table 2-5 is the plan for determining how closely optimum emulsion must be determined.

Effect of Emulsion				
Factoral Plan				
Single Solventless Emulsion				
Single RAP Source				
Lime = 1.5% Coarse Aggregate				
Moisture at Optimum				
Gradation	Fine	Medium	Coarse	
	-3	-3	-3	
Emuls, Opt ± %	0	0	0	
	+3	+3	+3	
Does greater or lesser Emulsion effect break/cure time				

Table 2-5 Plan to determine the Effect of Varied Emulsion

Optimum emulsion has been determined by adding sufficient emulsion to obtain a "creamy" appearance. Do changes in the 3% of dry weight make a difference in test outcome? Insight into field behavior may be a result of this experiment.

2.8 Summary

Two subjects have been addressed and work plans have been developed for them. The first was a plan to core six UDOT CIR projects of different ages. These cores were then used to determine how performance metrics for high, medium and low temperature related to the field performance of the mix. To do this, a performance index has been proposed.

The second plan was to use a test developed in Phase III of this study to qualify an emulsion for use in CIR at intermediate temperature. Variables such as water content, emulsion content, particle size and pH were studied.

3.0 DATA COLLECTION

3.1 Overview

This study contains two parts.

The first is to determine if there are measurable characteristics with thresholds which would lead to a successful CIR project. Measurements were taken on six UDOT pavements varying in age from two to seven years.

The second is to determine what factors cause variability in the emulsion qualification project. In this type of testing, it is important to hold all but one factor equal. Varying one parameter allows for a simple comparison and allows one optimum condition for each variable. Four variables were thus evaluated and an optimum procedure was developed.

3.2 Data Collection for the Density, Marshall Stability, SCB and Performance Index

For the portion of the study concerned with the performance of existing CIR pavements, cores were collected from selected CIR sites in accordance with the plan identified in Table 2-1. The cores were documented and then subjected to Marshall Stability, SCB and Density testing. Each location was evaluated for pavement surface condition and CIR layer condition. The procedures are enumerated below.

3.2.1 Core Collection

Cores were collected from two locations in each of 6 projects completed over the prior 8 year period. Photos of typical cores and pavement conditions are presented below in figures 3-1 to 3-5. Note that the Peoa and Marion pavements were combined as they were basically two phases of the same project. Each core is divided into the surfacing cap on the left, the CIR layer in the center and the underlying pavement (if any) on the right. Each core was separated along the layer interface with a wet asphalt saw.

Figure 3-1 SR-491 Monticello Pavement Surface and Typical Core

Figure 3-2 US-40 Currant Creek Pavement and Typical Core

Figure 3-3 SR-32 Peoa-Marion Pavement and Typical Core

Figure 3-4 I-84 Henefer Pavement and Typical Core

Figure 3-5 US-40 Strawberry Pavement and Typical Core

3.2.2 Marshall Stability

Two cores were randomly selected from each sample location and subjected to Marshall Stability testing, AASHTO T-245. These cores were further trimmed to 2⅝ inches tall and tested in a Humboldt Loadmaster. Test speed was the standard 2 inches per minute and the specimens were held at 78°F for 3 hours prior to testing. Figures 3-6 and 3-7 show the equipment and procedure. Figure 3-8 shows test result plots. A comparison to HMA is included. Tabulated results can be found in Table 3-1

Figure 3-6 Humboldt Load Master

Figure 3-7 Marshall Stability Test

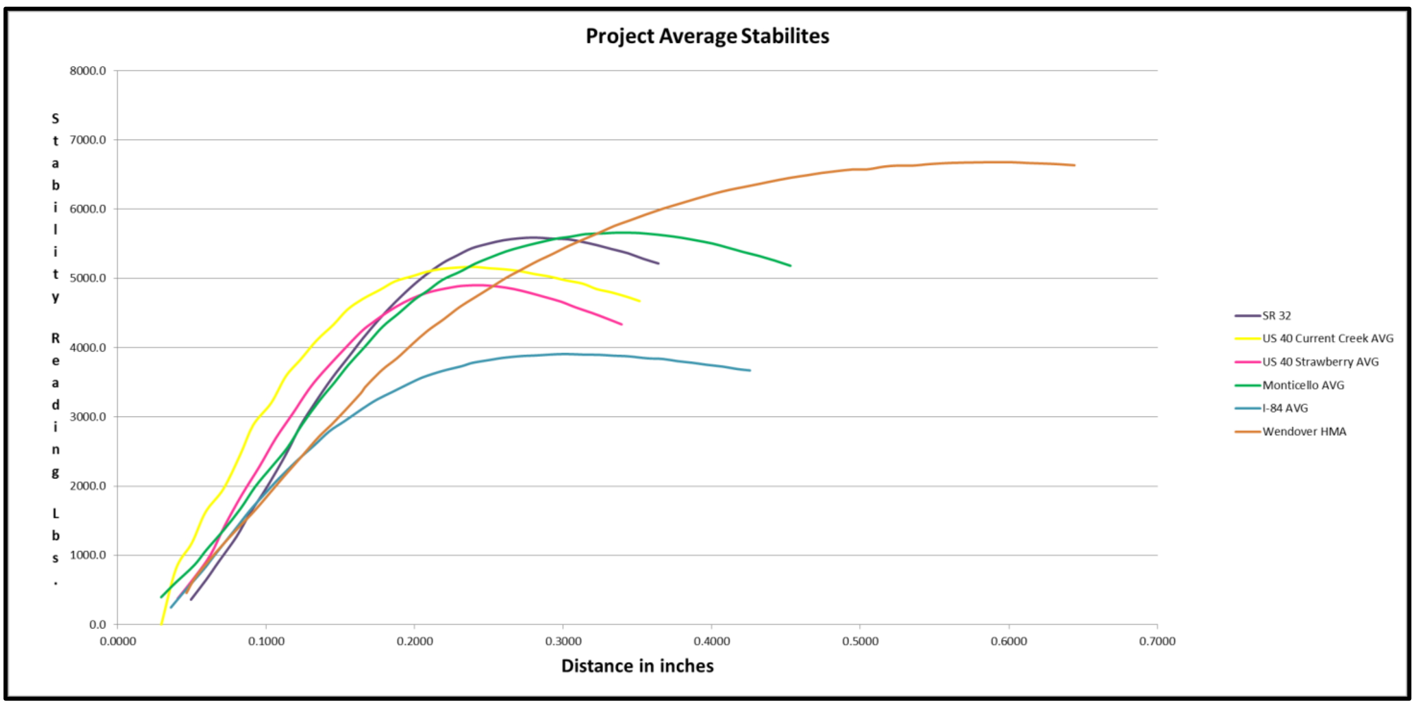

Figure 3-8 Marshall Stability Average Values

<u>3.2.3 Density</u>

Prior to stability testing, all samples were tested for Bulk Specific Gravity of the Mix. Tabulated results can be found in Table 3-1.

After completion of the stability tests, the broken pucks were heated to soften the asphalt and then were broken down and their Maximum Theoretical Specific Gravities were determined according to AASHTO T-209

3.2.4 SCB

Three of the cores remaining after stability testing were used to create two sets of three SCB samples for each coring location. This procedure deviates from the LSU procedure where 6 cores would have been required to produce 4 sets of three. This procedure produces somewhat greater uncertainty but was considered preferable to putting more holes in the pavement. The results of this testing can be found in Table 3-1. A measurement above 0.50 is considered acceptable by LSU for high load/volume roads where 0.60 is the minimum threshold for low load/volume facilities. Where the table contains readings of 0.00, testing was not possible due to the friability of the samples.

3.2.5 Performance Index

Looking at figures 3-1 through 3-5, a significant difference is observed in the condition of the pavement surface as well as the condition of the CIR layer. Some of the surfaces are in very good condition while being older and some are quite poor while being newer. Since comparing old pavements to new is problematic, an index was developed to normalize the pavement and CIR condition, which is described in detail below. Although this index is somewhat subjective, it serves to give insight into a diverse set of observations.

Three issues were considered in the index. First, the age of the pavement was tabulated. The oldest pavement was 8 years old; the newest was placed 2 years prior to coring. This factor was given a weight of 0.40. Second, the condition of the surface layer was judged against a scale of 1 to 10, with 1 being a failed surface and 10 being a perfect pavement. This factor was weighted 0.20. The remaining 0.40 weight comes from the condition of the CIR layer, which was also evaluated against a scale of 1 to 10. Again, 1 was a completely disintegrated layer and 10 had no flaws. Table 3-1 contains the results.

Performance Test Results							
Site	Density	Stability Avg.	SCB	Age Years	Surface Condition	CIR Condition	Performance Index
Peoa	89.5	5859.5	0.00	3	8	6	5
Marion	89.9	5546.5	0.56	3	9	8	6
I-84 W	89.0	3659.5	0.33	2	9	4	4
I-84 E	89.4	4172.0	0.33	2	9	4	4
Monticello E	93.6	5234.5	0.73	7	9	10	9
Monticello W	93.4	6272.5	0.73	7	9	10	9
Strawberry E	87.2	5845.5	0.00	3	3	2	2
Strawberry W	87.5	4027.0	0.00	3	5	2	3
Currant Creek E	91.7	5268.5	0.82	6	8	8	7
Currant Cr. W	94.4	5097.0	0.82	6	6	7	6

Table 3-1 Performance Test Results

3.3 Data Collection for Cone Penetration

The following data was collected in the laboratory to demonstrate bases for the procedural requirements implemented to reduce test variability. These requirements are included in Appendix B.

3.3.1 Cone Penetration, Acidity

Table 3.2 gives the results of the pH tests. Neutral is 7.0. Below 7.0 is acidic. Above 7.0 is Basic.

Lime Results pH			
Gradation	Fine	Medium	Coarse
Lime	12.5	12.4	12.5
No Lime	8.2	8.3	8.3

Table 3-2 pH Results

3.3.2 Cone Penetr+ation, Moisture Variable

		Minus 3%					Plus 0%					Plus 3%		
Medium Gradation														
Batch time:	11:43:00 AM	Sample		011215A	Batch time:	11:17:00 AM	Sample		011315A	Batch time:	10:39:00 AM	Sample		012715A
Sample #	Time to test	Time of test		Max Load	Sample #	Time to test	Time of test		Max Load	Sample #	Time to test	Time of test		Max Load
1	10	11:53:00 AM		7.08	1	10	11:27:00 AM		4.66	1	10	10:49:00 AM		19.95
2	20	12:03:00 PM		7.78	2	20	11:37:00 AM		8.18	2	20	10:59:00 AM		14.88
3	30	12:13:00 PM		7.87	3	30	11:47:00 AM		6.65	3	30	11:09:00 AM		15.3
4	45	12:28:00 PM		5.61	4	45	12:02:00 PM		5.67	4	45	11:24:00 AM		15.01
5	60	12:43:00 PM		5.79	5	60	12:17:00 PM		5.08	5	60	11:39:00 AM		12.97
6	120	1:43:00 PM		5.4	6	120	1:17:00 PM		4.74	6	120	12:39:00 PM		9.48
7	180	2:43:00 PM		5.55	7	180	2:17:00 PM		5.76	7	180	1:39:00 PM		10.67
8	240	3:43:00 PM		4.69	8	240	3:17:00 PM		5.11	8	240	2:39:00 PM		12.42
9	360	5:43:00 PM		7.03	9	360	5:17:00 PM		6.95	9	360	4:39:00 PM		10.63
10				9.14	10				8.07	10				

Fine Gradation														
Batch time:	11:17:00 AM	Sample	012815A		Batch time:	10:44:00 AM	Sample	012915A		Batch time:	10:50:00 AM	Sample	013015A	
Sample #	Time to test	Time of test	MAX Load open	Max Load Closed	Sample #	Time to test	Time of test	MAX Load open	Max Load Closed	Sample #	Time to test	Time of test	MAX Load open	Max Load Closed
1	15	11:32:00 AM		11.34	1	15	10:59:00 AM		9.58	1	15	11:05:00 AM		9.56
2	30	11:47:00 AM		7.32	2	30	11:14:00 AM		8.69	2	30	11:20:00 AM		7.92
3	45	12:02:00 PM		6.9	3	45	11:29:00 AM		6.82	3	45	11:35:00 AM		6.69
4	60	12:17:00 PM		6.67	4	60	11:44:00 AM		6.57	4	60	11:50:00 AM		6.47
6	180	2:17:00 PM		5.94	6	180	1:44:00 PM		5.95	6	180	1:50:00 PM		6.39
8	300	4:17:00 PM		8.34	8	300	3:44:00 PM		6.83	8	300	3:50:00 PM		6.53
10	30	11:47:00 AM	9.39		10	30	11:14:00 AM	7.08		10	30	11:20:00 AM	7.89	
5	60	12:17:00 PM	7.02		5	60	11:44:00 AM	8.6		5	60	11:50:00 AM	10.15	
7	180	2:17:00 PM	10.77		7	180	1:44:00 PM	8.6		7	180	1:50:00 PM	9.66	
9	300	4:17:00 PM	24.56		9	300	3:44:00 PM	12.14		9	300	3:50:00 PM	10.32	

Coarse Gradation														
Batch time:	9:55:00 AM	Sample	020215A		Batch time:	8:57:00 AM	Sample	020415A		Batch time:	10:12:00 AM	Sample	020515A	
Sample #	Time to test	Time of test	MAX Load open	Max Load Closed	Sample #	Time to test	Time of test	MAX Load open	Max Load Closed	Sample #	Time to test	Time of test	MAX Load open	Max Load Closed
1	15	10:10:00 AM		13.91	1	15	9:12:00 AM		18.42	1	15	10:27:00 AM		7.6
2	30	10:25:00 AM		10.03	2	30	9:27:00 AM		12.82	2	30	10:42:00 AM		7.54
3	45	10:40:00 AM		11.05	3	45	9:42:00 AM		9.9	3	45	10:57:00 AM		7.21
4	60	10:55:00 AM		9.43	4	60	9:57:00 AM		9.18	4	60	11:12:00 AM		6.74
6	180	12:55:00 PM		9.18	6	180	11:57:00 AM		10	6	180	1:12:00 PM		7.13
8	300	2:55:00 PM		8.28	8	300	1:57:00 PM		10.76	8	300	3:12:00 PM		7.6
10	30	10:25:00 AM			10	0	8:57:00 AM			10	30	10:42:00 AM	8.81	
5	60	10:55:00 AM	10.35		5	60	9:57:00 AM	14.37		5	60	11:12:00 AM	8.43	
7	180	12:55:00 PM	15.08		7	180	11:57:00 AM	12.39		7	180	1:12:00 PM	16.37	
9	300	2:55:00 PM	16.12		9	300	1:57:00 PM	17.85		9	300	3:12:00 PM	22.27	

Table 3-3 Moisture Variance - Results

3.3.3 Cone Penetration - Emulsion Content Variable

		Plus 0%					Minus 3%					Plus 3%		
Medium Gradation														
Batch time:	10:27:00 AM	**Sample**	**020615A**		**Batch time:**	9:32:00 AM	**020915A**			**Batch time:**	10:18:00 AM	**Sample**	**021115A**	
Sample #	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**	**Sample #**	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**	**Sample #**	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**
1	15	10:42:00 AM		18.58	1	15	9:47:00 AM		10.89	1	15	10:33:00 AM		17.81
2	30	10:57:00 AM		11.94	2	30	10:02:00 AM		9.1	2	30	10:48:00 AM		9.4
3	45	11:12:00 AM		9.02	3	45	10:17:00 AM		10.37	3	45	11:03:00 AM		8.52
4	60	11:27:00 AM		8.87	4	60	10:32:00 AM		7.96	4	60	11:18:00 AM		8.26
6	180	1:27:00 PM		9.79	6	180	12:32:00 PM		8.25	6	180	1:18:00 PM		7.48
8	300	3:27:00 PM		9.15	8	300	2:32:00 PM		7.82	8	300	3:18:00 PM		8.36
10	30	10:57:00 AM	13.38		10	30	10:02:00 AM	10.93		10	30	10:48:00 AM	9.59	
5	60	11:27:00 AM	13.32		5	60	10:32:00 AM	9.42		5	60	11:18:00 AM	13.71	
7	180	1:27:00 PM	16.23		7	180	12:32:00 PM	11.79		7	180	1:18:00 PM	14.61	
9	300	3:27:00 PM	33.85		9	300	2:32:00 PM	16.03		9	300	3:18:00 PM	28.99	
Fine Gradation														
Batch time:	9:46:00 AM	**Sample**	030915A		**Batch time:**	9:53:00 AM	**Sample**	**031015A**		**Batch time:**		**Sample**		
Sample #	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**	**Sample #**	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**	**Sample #**	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**
1	15	10:01:00 AM		11.89	1	15	10:08:00 AM		12.73	1	15	12:15:00 AM		
3	60	10:46:00 AM		8.54	3	60	10:53:00 AM		9.17	2	30	12:30:00 AM		
5	1440	9:46:00 AM		13.87	5	1440	9:53:00 AM			3	45	12:45:00 AM		
		9:46:00 AM					9:53:00 AM			4	60	1:00:00 AM		
2	30	10:16:00 AM	13.5		2	30	10:23:00 AM	10.53		6	180	3:00:00 AM		
4	60	10:46:00 AM	14.64		4	60	10:53:00 AM	10.05		8	300	5:00:00 AM		
6	180	12:46:00 PM	13.07		6	180	12:53:00 PM	16.16		10	30	12:30:00 AM		
7	300	2:46:00 PM	28.52		7	300	2:53:00 PM	25.01		5	60	1:00:00 AM		
8	1440	9:46:00 AM	44.31		8	1440	9:53:00 AM	29.33		7	180	3:00:00 AM		
9	2880	9:46:00 AM	61.6		9	2880	9:53:00 AM	48.67		9	300	5:00:00 AM		
						4320		51.16						
Coarse Gradation														
Batch time:	11:30:00 AM	**Sample**	**021215A**		**Batch time:**	10:02:00 AM	**Sample**	**021715A**		**Batch time:**	11:25:00 AM	**Sample**	**021815A**	
Sample #	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**	**Sample #**	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**	**Sample #**	**Time to test**	**Time of test**	**MAX Load open**	**Max Load Closed**
1	15	11:45:00 AM		13.14	1	15	10:17:00 AM		16.42	1	15	11:40:00 AM		15.35
3	60	12:30:00 PM		9.27	3	60	11:02:00 AM		8.97	3	60	12:25:00 PM		9.81
5	180	2:30:00 PM		8.12	5	180	1:02:00 PM		9.31	5	1440	11:25:00 AM		14.95
8	1700	3:50:00 PM		10.15	7	1440	10:02:00 AM		11.17			11:25:00 AM		
2	60	12:30:00 PM	12.74		9	30	10:32:00 AM	15.8		9	15	11:40:00 AM	16.02	
4	180	2:30:00 PM	20.5		2	60	11:02:00 AM	18.42		2	30	11:55:00 AM	16.56	
6	300	4:30:00 PM	24.91		4	180	1:02:00 PM	16.94		4	60	12:25:00 PM	20.92	
7	1700	3:50:00 PM	45.54		6	300	3:02:00 PM	18.66		6	180	2:25:00 PM	25.04	
		11:30:00 AM			8	1440	10:02:00 AM	37.61		7	300	4:25:00 PM	54.25	
		11:30:00 AM					10:02:00 AM			8	1440	11:25:00 AM	73.12	

Table 3-4 Emulsion Variance - Results

3.4 Summary

Data was successfully collected from both the laboratory and the field. The data was presented for field performance in the form of photographs, collection sites and measurements. Data for the emulsion qualification is tabulated so that time, test conditions and results are available.

4.0 DATA EVALUATION

4.1 Overview

Data evaluation under these circumstances is more an observation than a mathematical contrivance. Each data set was graphed in such a way as to illustrate what was observed in the field and in the lab. These pictorial representations were evaluated and the relationships described.

4.2 Correlation between Density, Marshall Stability, SCB and Performance Index

The available data comes from projects of diverse age, location and condition. A performance index was created to normalize pavement condition with respect to age, upper surface condition and CIR condition. Where any possibility of correlation was noticed, linear regression was used as a measure of the correlation.

4.2.1 Density vs Marshall Stability

Figure 4-1 plots Density vs Marshall Stability

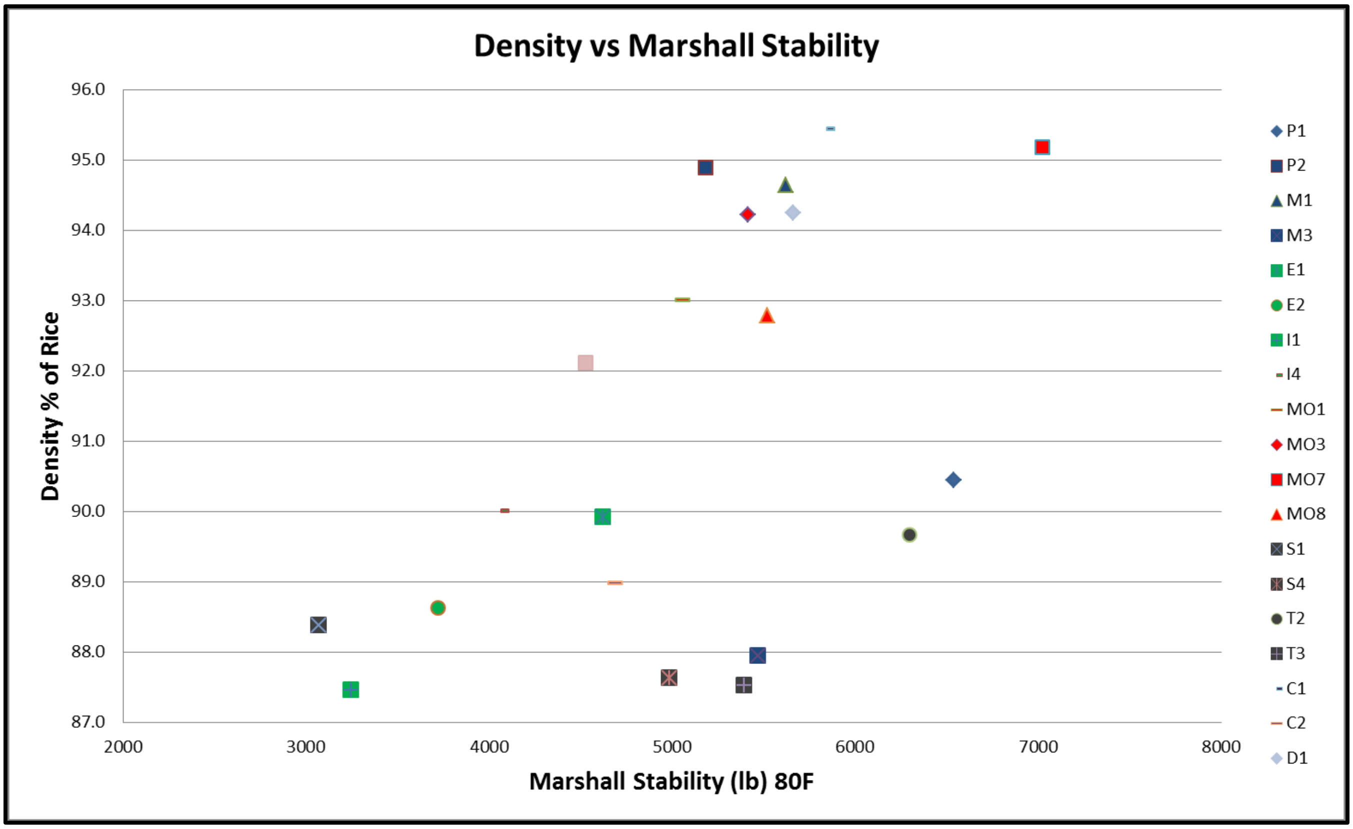

Figure 4-1 Density vs Marshall Stability

This plot demonstrates no correlation between a dense sample and a stable sample nor does it demonstrate a relationship between an unstable sample and low density. No relationship can be shown between anti rutting and any particular density target.

The failure of this plot to demonstrate any correlation leads us to create a performance index allowing us to make comparisons between measured properties and performance rather than trying to correlate unrelated measured properties.

4.2.2 Density vs Performance Index

Figure 4-2 shows a marked relationship between density and performance index. The Currant Creek samples are an anomaly but a clear trend is present in all other data.

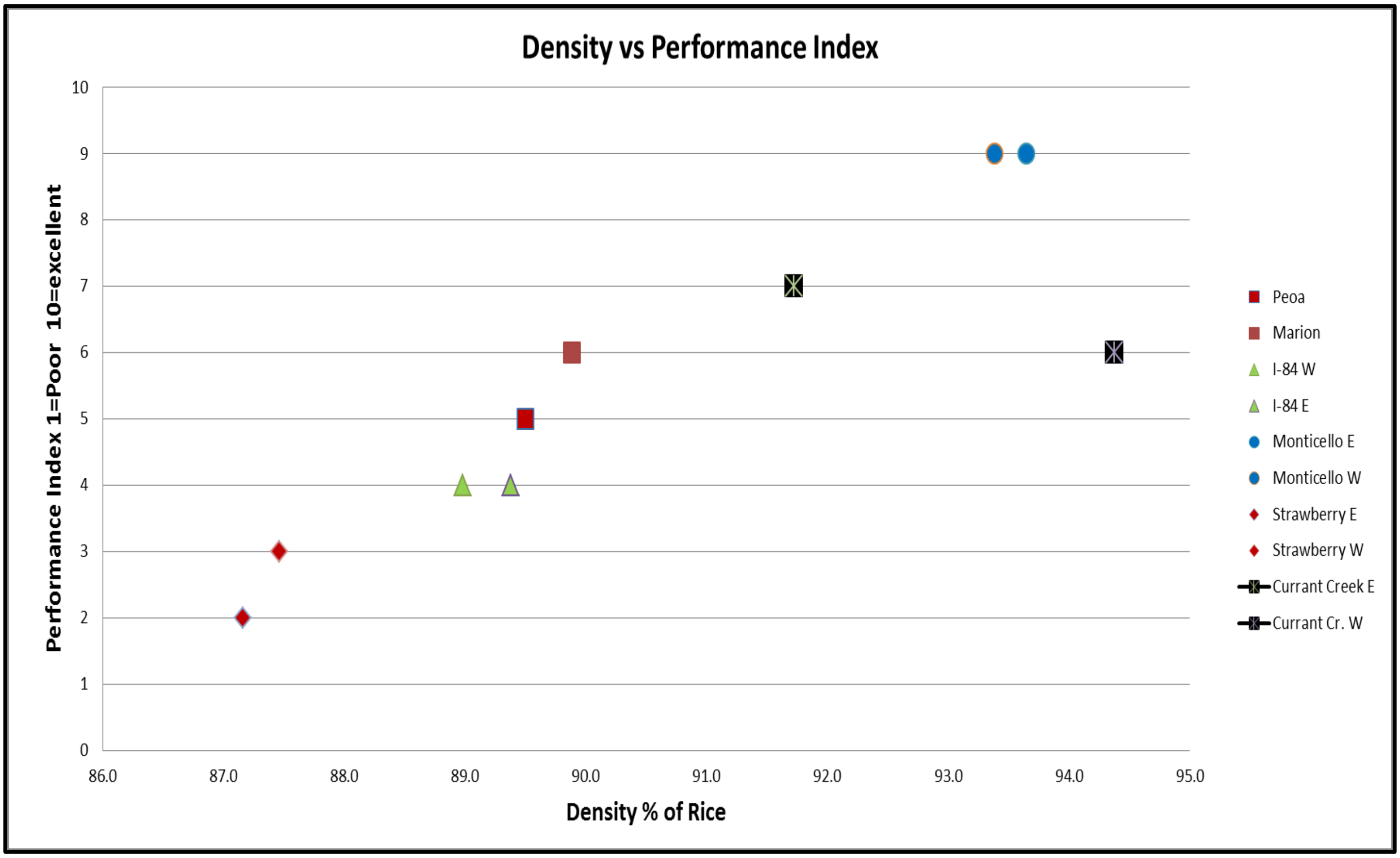

Figure 4-2 Density vs Performance Index

4.2.3 Marshall Stability vs Performance Index

Figure 4-3 shows Stability vs Performance Index. Since no correlation exists, it is clear that the Marshall anti-rutting performance has little to do with long term performance.

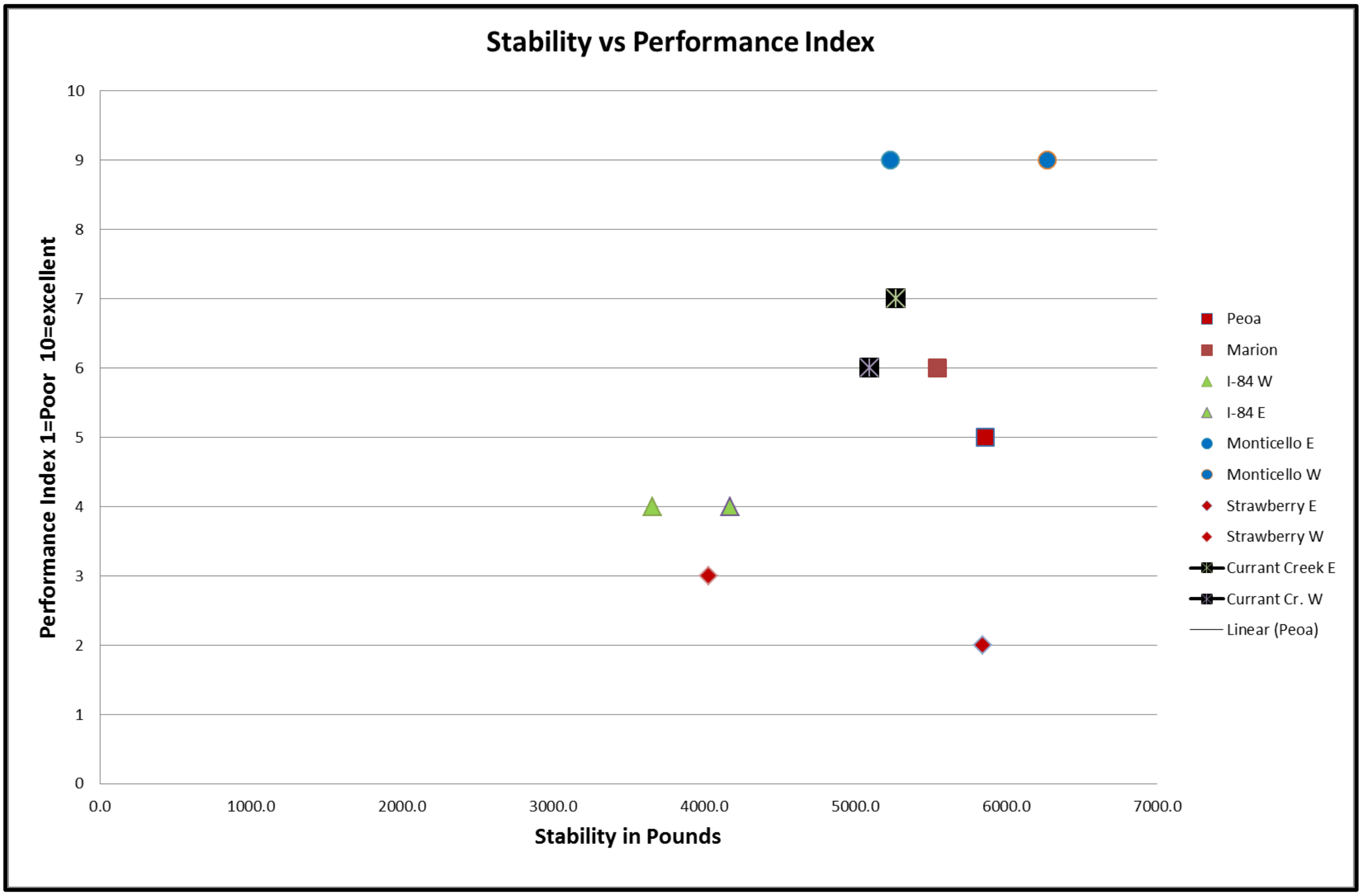

Figure 4-3 Marshall Stability vs Performance Index

4.2.4 SCB vs Performance Index

Figure 4-4 plots SCB results against the developed Performance Index. A clear relationship is observed demonstrating that the proposed threshold value 0.50 results in moderate or better performance.

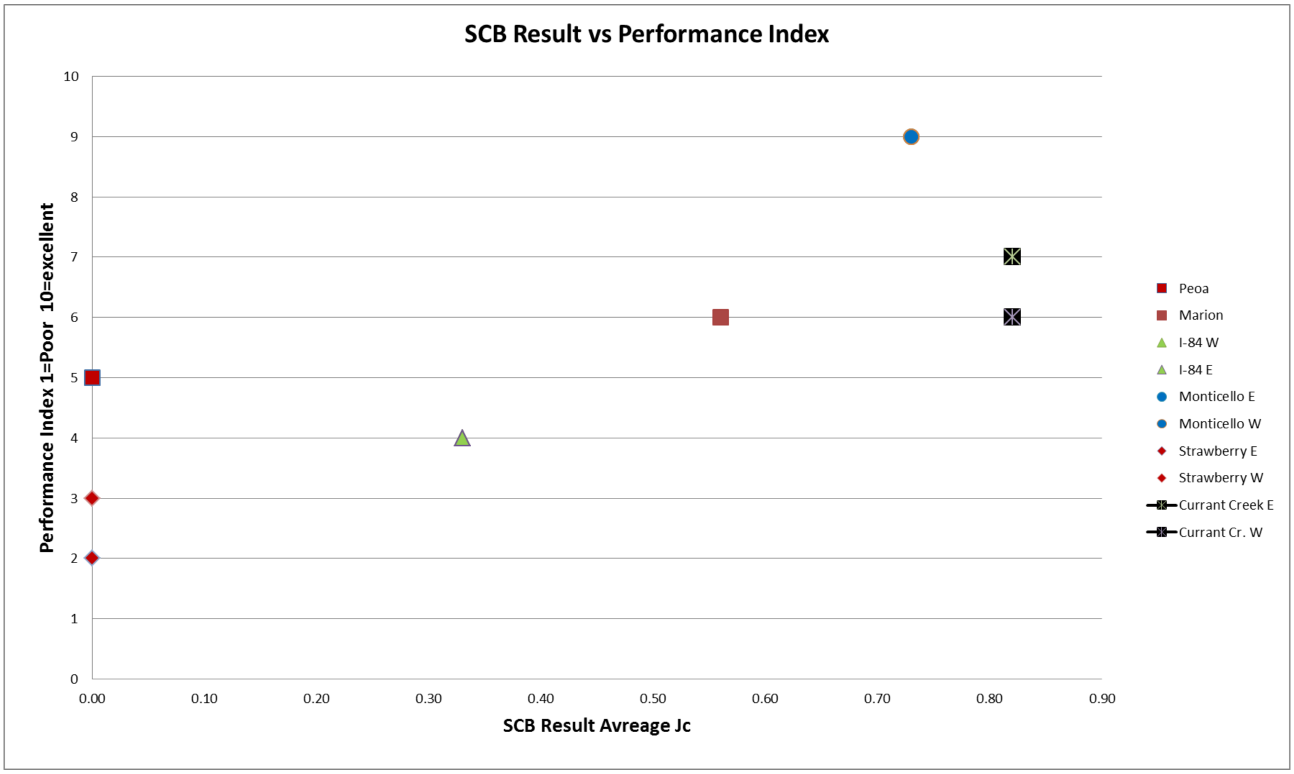

Figure 4-4 SCB vs Performance Index

4.2.5 Density vs SCB

Figure 4-5 plots Density vs SCB. As you might expect, a fairly strong relationship exists between density and fracture energy. Long term performance is dependent on obtaining a dense mix. This relationship has been observed in many other variations of Asphalt Concrete. In this case, it appears that fracture energies of 0.60 require 92% densities, based on a linear best fit. The proper relationship at higher densities needs to be better defined.

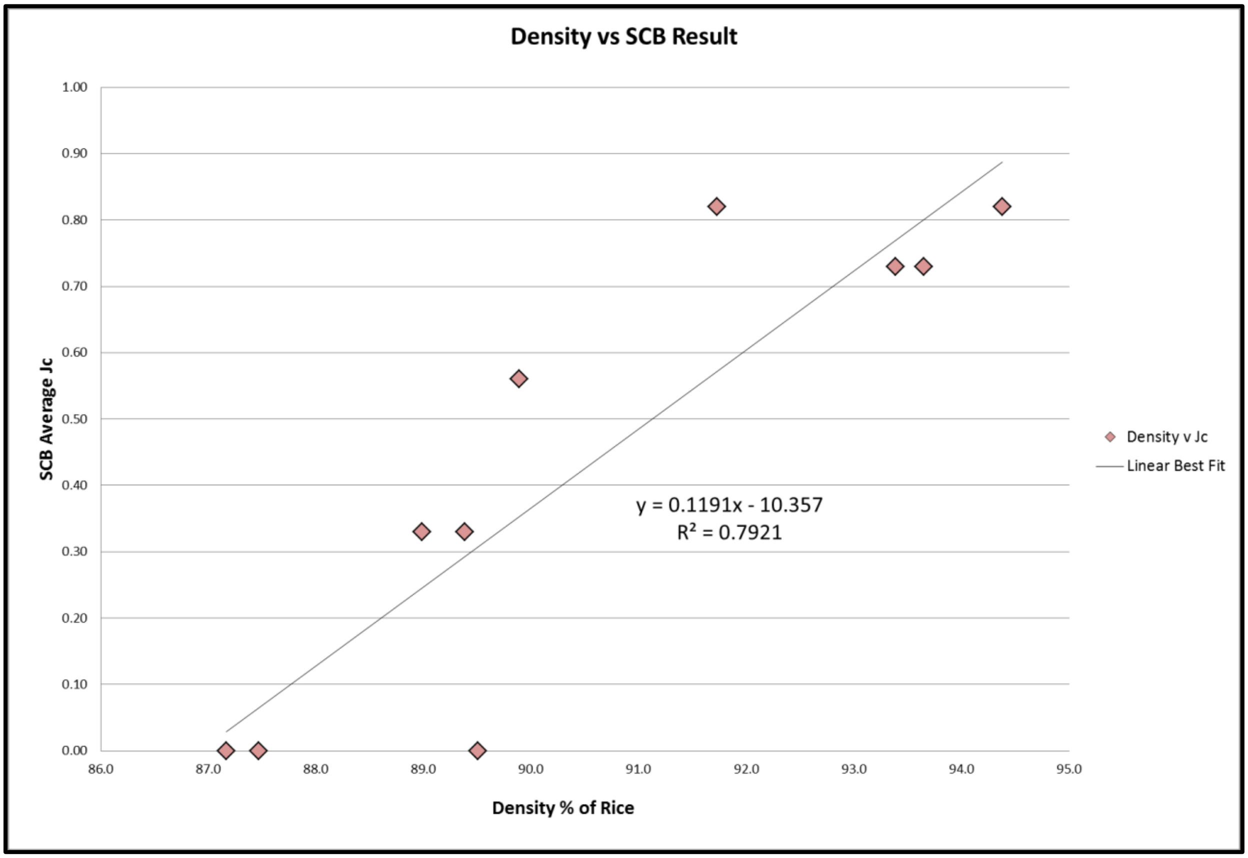

Figure 4-5 Density vs SCB

4.3 Cone Penetration

Data for these variables was graphed and relationships noted.

4.3.1 Cone Penetration Acidity

Test results show that RAP alone is slightly basic and that particle size does not change the pH. The test results also show that the addition of lime creates a strongly basic environment and strongly masks any other chemistry in the sample. This indicates that so long as lime is used, RAP sources with equal gradations may be used interchangeably without impacting pH.

4.3.2 Cone Penetration, Moisture Variable

4.3.2.1 Medium Gradation

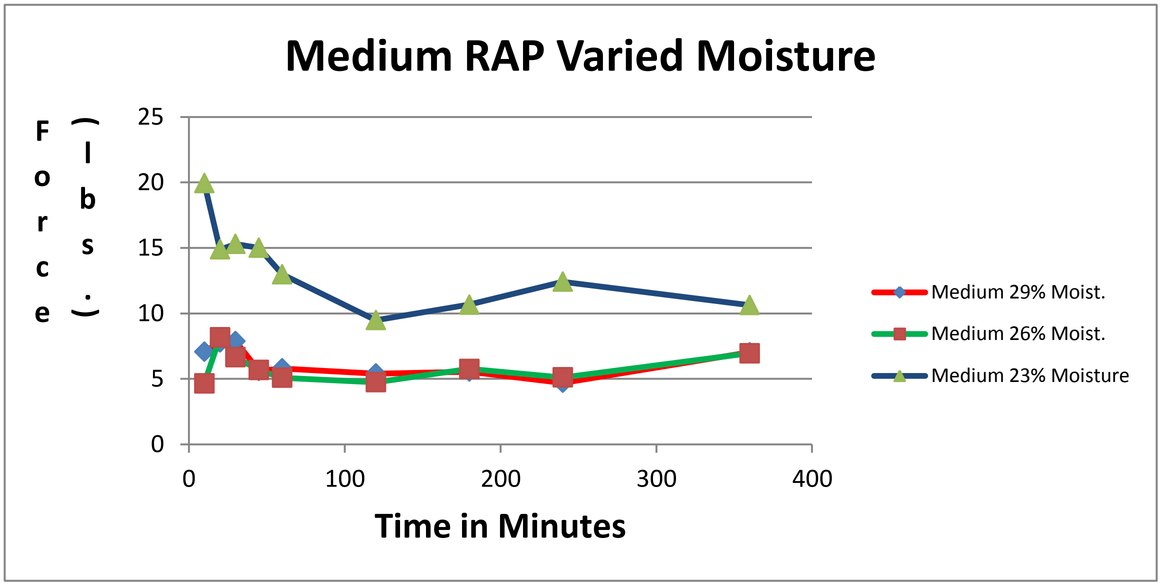

Figure 4-6 Cone Penetration Medium Gradation - Varied Moisture Results

These results show that water below optimum caused the emulsion to break quicker, to the point where it was actually breaking in the bowl during mixing. Water in excess of optimum slowed the break characteristics. The high force reading with a falloff over the next 150 minutes is indicative of water being released into the system. These samples were capped (constant moisture) so that no evaporation could take place. Note that there is no viscosity increase from the emulsion over the 360 minutes of curing.

4.3.2.2 Fine Gradation

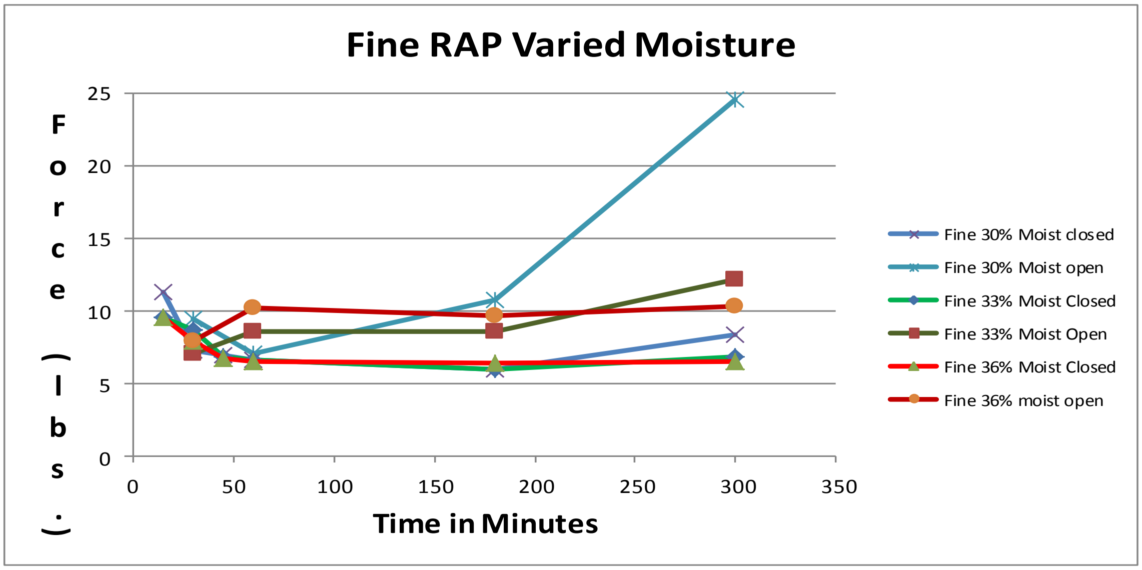

Figure 4-7 Cone Penetration Fine Gradation – Varied Moisture Results

These results show a difference between capped (constant moisture) and uncapped samples. Uncapped samples show greater 60 minute viscosity and higher viscosity throughout. The slightly drier sample shows much higher long term viscosity gain, indicating the sensitivity of the break characteristics to moisture content.

4.3.2.3 Coarse Gradation

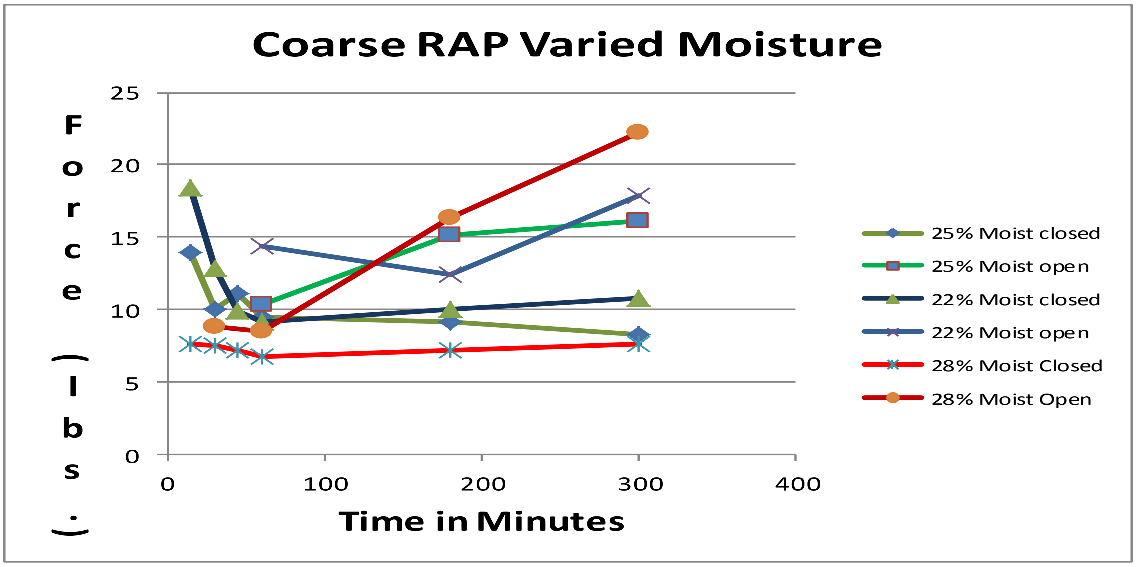

Figure 4-8 Cone Penetration Coarse Gradation – Varied Moisture Results

These results show a difference between capped (constant moisture) and uncapped samples. Uncapped samples show greater 100 minute viscosity and higher viscosity throughout. It was observed that the 22% moisture samples broke in the bowl during mixing, leading to high initial force, and then released moisture causing the viscosity to drop. The 25% moisture samples also show an increased viscosity at 10 minutes with a falloff and then gain in viscosity over the next 45 minutes. The 28% moisture samples were decidedly low in initial viscosity but the uncovered sample demonstrated rapid viscosity increase over the 300 minute period.

4.3.3 Cone Penetration Emulsion Content Variable

4.3.3.1 Fine Gradation

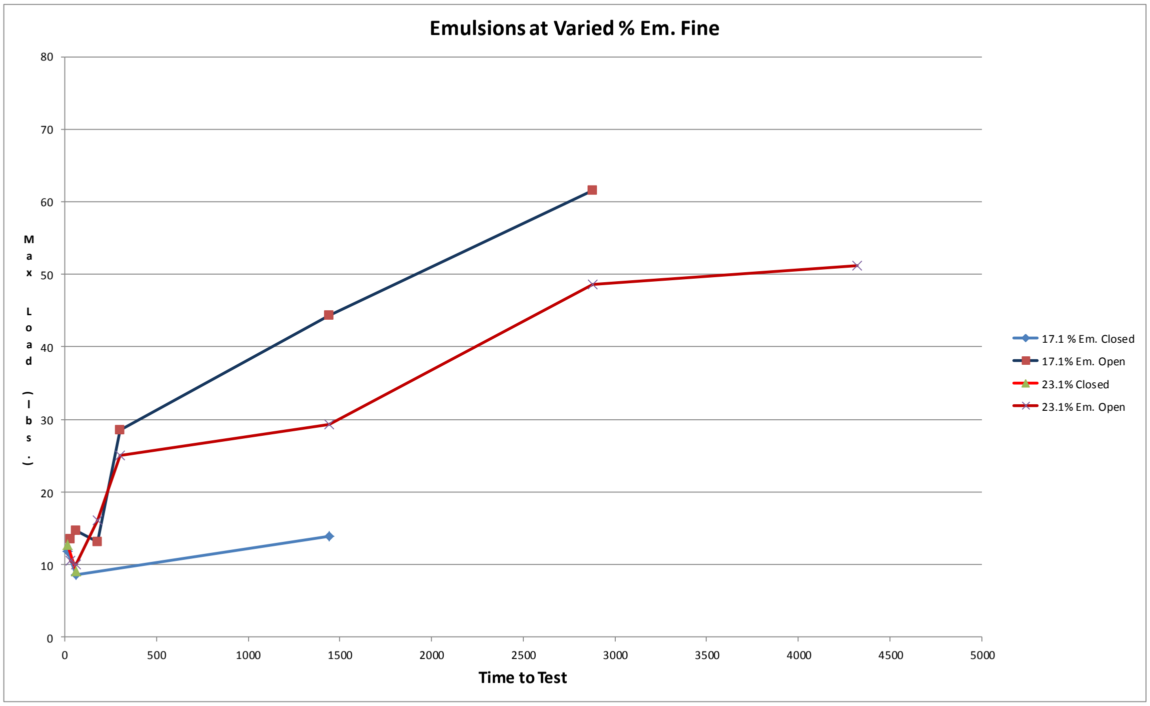

Figure 4-9 Varied Emulsion Content – Fine Gradation

Note that all three emulsion contents begin very near 12 pounds. The behavior in the first hour is strikingly different for closed vs open samples. This result further illustrates the requirement for evaporation in the emulsion curing process. Also observed is the lagging of the higher emulsion content. Both open samples exhibit a delay in viscosity gain over the first 100 minutes and then increase rapidly over the next 100 minutes. A mature cure seems to take 3000 minutes to develop.

4.3.3.2 Medium Gradation

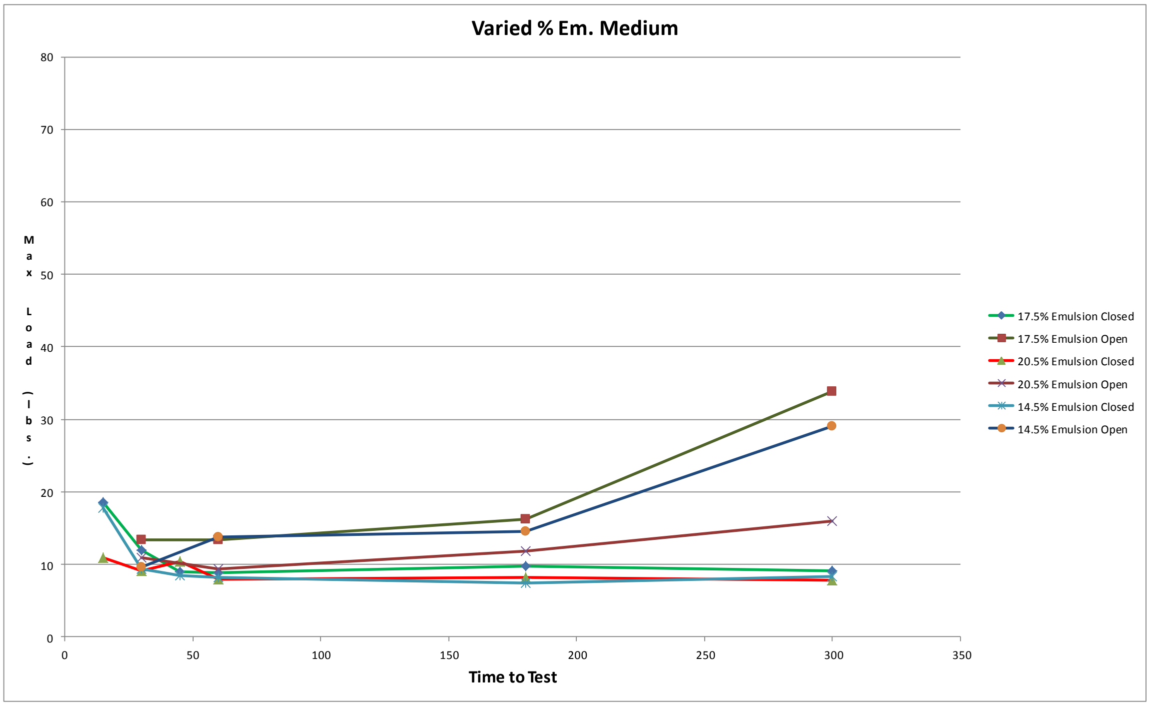

Figure 4-10 Varied Emulsion Content – Medium Gradation

This data set includes both covered and uncovered samples. As with other observations, the covered samples do not cure. Given that lime is present at 1.5% of the total RAP and the fine RAP is set to be 25% of the total RAP, then the lime is 4.6% of the fine RAP if it is assumed that all of the lime is present in the fines. At this level of lime, the pH is 12. Clearly the cationic emulsion is not responding to this highly basic environment. The emulsion is responding to evaporation. The 10.5% and the 14.5 % emulsion content samples perform similarly with the 20.5% lagging the other two. The extra moisture seems to affect this gradation out to 300 minutes. This emulsion is performing as expected, with a delay in cure onset for 3 hours.

4.3.3.3 Coarse Gradation

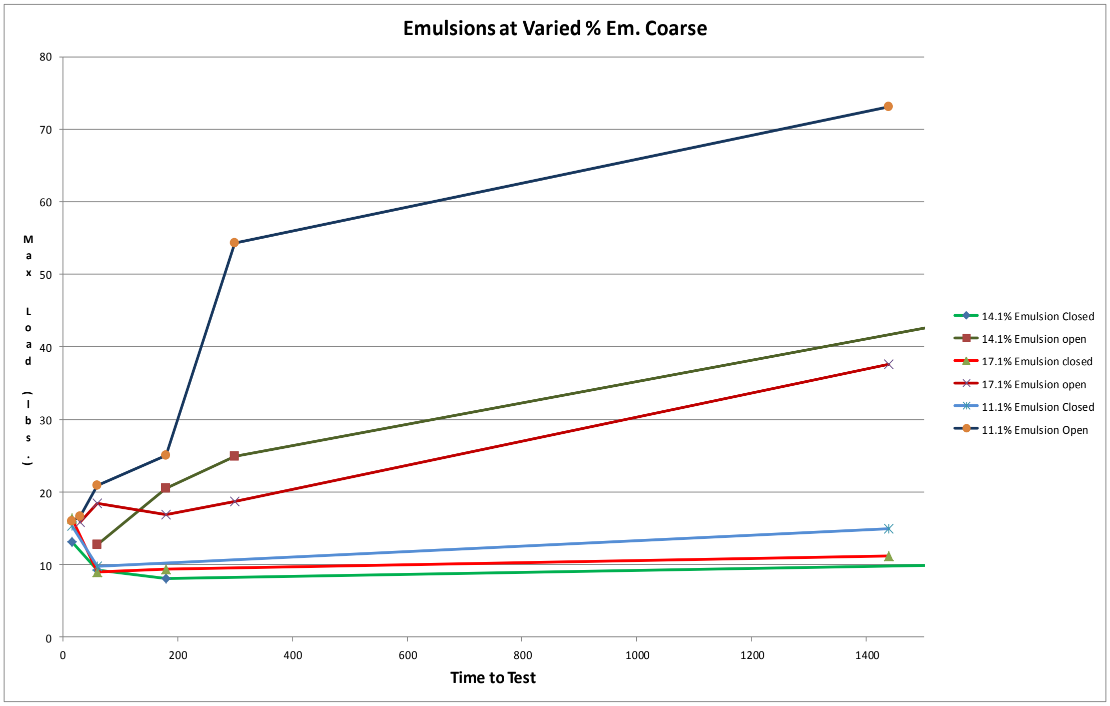

Figure 4-11 Varied Emulsion Content – Coarse Gradation

Again it can be seen that the emulsion responds to evaporation. All tests begin near 14 lb. with the uncovered samples increasing viscosity over time. Here, in the case of the coarse gradation, the emulsion content makes a great deal of difference in the outcome. The results are distinctly ordered with increasing emulsion resulting in lower viscosity. Neither the 11.1% nor the 14.1% emulsion content was dormant for the desired 120 minutes. Both had more than doubled in viscosity at the 180 minute test time. The 17.1% sample demonstrates some dormancy and then a steady gain in viscosity from 180 minutes to the end of the test.

Since the test results demonstrate that the emulsion is not reacting to the high pH setting nor is it curing in a high moisture environment, particle size is the only other variable.

4.3.3.4 Gradation Variable

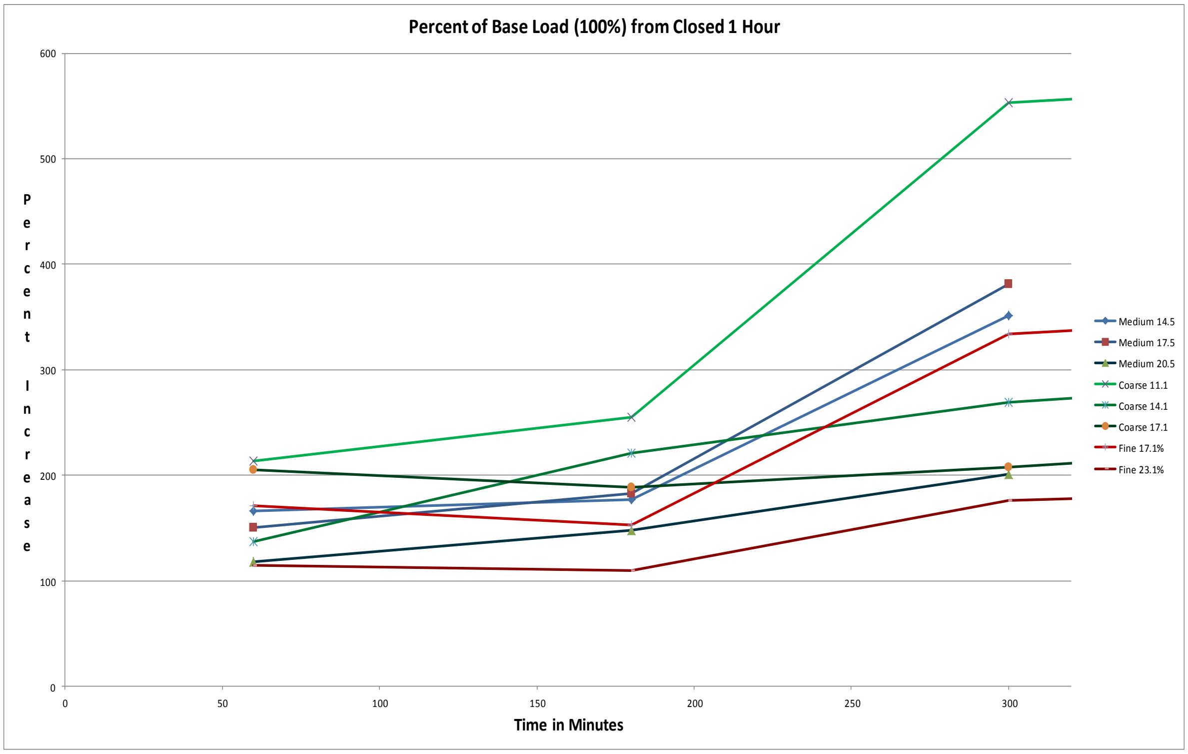

Figure 4-12 Percent of Base Load (100%) over Time

If the red (fine gradation) lines are considered, emulsion content has a great deal of effect on both beginning and ultimate viscosity. This result would lead to instability in the test. The green (coarse gradation) is equally erratic. Two of the blue lines (medium gradation) are similar indicating reduced sensitivity to under moistening and a better choice for use as a test gradation. The third blue sample (high emulsion content) exhibits a lag in both initial and cured viscosity indicating too much moisture in the system.

From these results, the emulsion is sensitive to both moisture content and particle size.

4.4 Summary

Results from both areas of investigation are presented.

1. Field performance was investigated using density, stability and fracture energy. Correlations between a field performance index and these three factors were made. A clear relationship between density and performance was observed while no relationship between stability and performance could be established. Since fracture energy is known to be significantly affected by density, a relationship to performance naturally follows.

2. Three areas related to the cone penetration test for emulsion suitability were investigated. Moisture and particle size were found to be drivers in the break and curing of the emulsion. Chemistry (pH) was found to be not significant.

5.0 CONCLUSIONS

5.1 Summary

Two issues were considered in this study. The first, why do some CIR projects perform well and some do not? The second, what issues were missed when the emulsion qualification test was proposed?

For the CIR project performance, one observation stands out above all others. Density yields performance. All of the failed projects had densities below 91% of the theoretical maximum density of the mix. The critical cracking energy threshold is not reached until density is above 92%. None of the pavements failed because they were too soft and rutted. All failures were due to cracking.

The cationic emulsions used in CIR do not react to strong base environments. They can lay dormant in a sealed container of RAP mix for weeks or months. They do respond strongly to loss of moisture. The faster the water content falls below a threshold, the faster they demulsify. This feature is particle size dependent because smaller particles hold water longer. More water and more emulsion leads to slower reaction and longer dormancy. Lower temperatures and higher humidities also lead to slower increases in viscosity.

5.2 Summary of Findings

The findings for each of the categories are enumerated below.

5.2.1 Density vs Marshall Stability

No correlation exists.

5.2.2 Density vs Performance Index

The best performing pavements have densities above 91%.

5.2.3 Marshall Stability vs Performance Index

No correlation exists.

5.2.4 SCB vs Performance Index

It is known that as density decreases, fracture energy decreases. An expectation that high fracture energy would correlate to a high performance index seems logical. Testing validates this logic.

5.2.5 SCB vs Density

A good correlation, R^2 value of 0.72, is observed. Critical cracking energy above the 0.6 threshold is obtained at densities above 92% of theoretical maximum.

5.2.6 pH

The pH of RAP is not acidic as expected. In fact it is slightly basic. Adding lime to the fine fraction of RAP in accordance with common usage drives the pH to 12.

5.2.7 Moisture content variable

Finer gradations hold more moisture than coarse gradations. Finer gradations are more sensitive to early emulsion demulsification than are coarse gradations. Moisture levels slightly (1%) above the onset of liquefaction prevent early break in coarse gradations but not always in fine gradations.

5.2.8 Emulsion content variable

Lower emulsion contents promote faster break and faster curing. The effect of changing emulsion content expresses itself to a greater degree in coarse and fine gradations. Medium gradations are more stable.

5.3 Limitations and Challenges

In the issues surrounding reliable pavement performance, the root cause of CIR layer failure was identified. Looking at the temperature sensitivity results from Phase III of this study, achieving the final density of the mix is a moving target. In the past, CIR processors have argued that what comes out of the machine is what you get. Compaction is then based on maximum achievable density from a rolling pattern. This paradigm cannot stand. Methods must be found to insert sufficient mortar to fill the void spaces between the large particles. Since this is a temperature sensitive issue, rapid feedback must be provided to the processor so adjustments can be made to the mix components and optimum ingredients can be fed to the mix.

Although the proposed cone penetration test appears to be a stable test for qualifying cold recycling emulsions, the test has yet to be applied to a variety of emulsions, nor have any acceptance thresholds been set. It also seems that since particle size and distribution are critical to test stability, any variance in the specific gravity of the RAP could change the outcome of the test. Using a standard mortar gradation and material may be necessary for test stability. A standard sand or other medium may be required.

6.0 RECOMMENDATIONS AND IMPLEMENTATION

6.1 Recommendations

In the case of each of the subjects, a recommended procedure has been written for adoption into the Materials Manual of Instruction. In the case of field performance, the concepts and tests should be worked into a design procedure.

In the case of emulsion qualification, all CIR emulsion candidates should be tested. Standard Slow, Quick and Medium set emulsions should also be tested for comparison.

6.2 Implementation Plan

A CIR specification and manual of instruction are being written. It will contain mix design procedures and requirements as well as field control procedures. A number of test projects are planned in the coming year. The procedures and practices developed in this study will be applied and adjusted as field conditions dictate.

REFERENCES

Wu, Zhong; Mohammad, L; et al. (2005). “Fracture Resistance Characterization of Superpave Mixtures Using the Semi-Circular Bending Test”, Journal of ASTM International, March 2005, Volume 2, Number 3.

VanFrank et al. (2015). “Cold In-Place Recycle. Phase III, Mix Design” Research Report No. UT-15.08, Utah Department of Transportation.

APPENDIX A: Semi Circular Bending Test, LSU Method

Note: This method is used by permission of its author, Dr. Louay Mohammad at Louisiana State University. This method references AASHTO T 67, a discontinued method of test. Please refer to ASTM E 4 for equivalent standard.

Method 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

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

where:

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.

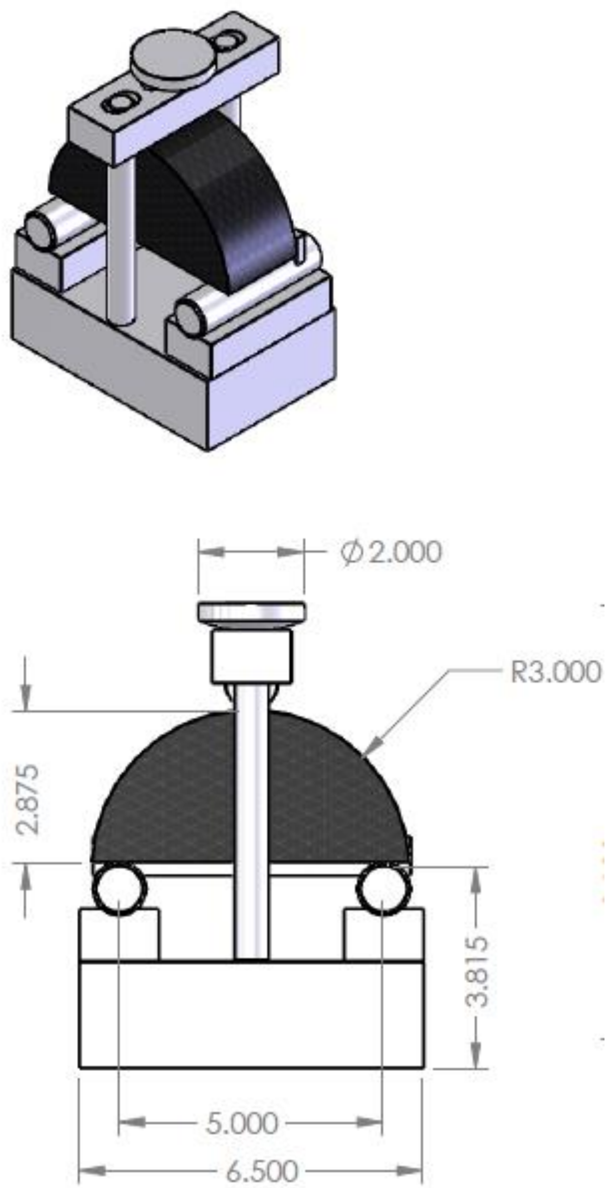

Figure 1: Schematic of the loading apparatus

Figure 1: Loading Position

Figure 2:

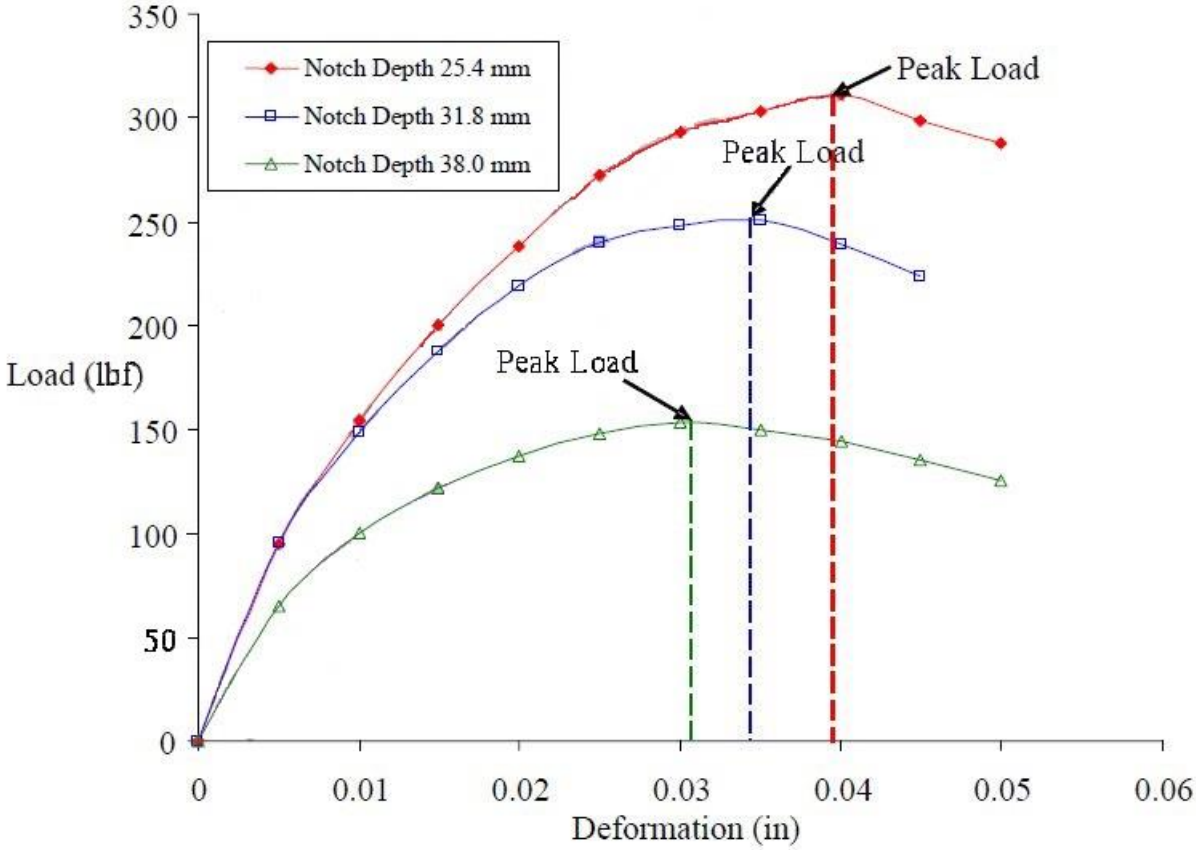

Figure 2: Deformation versus Load

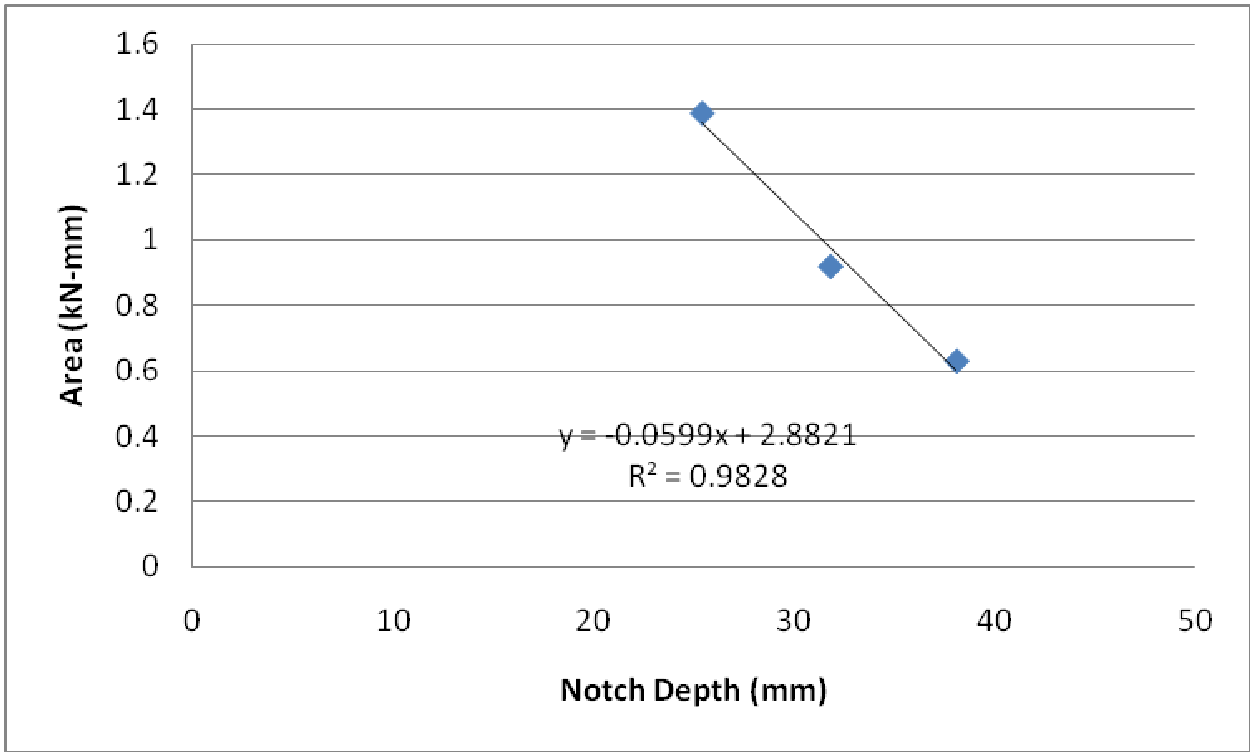

Figure 3: Notch Depth versus Area

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,%.

APPENDIX B: Emulsion Qualifying Test

This is the revised test procedure for qualifying solventless emulsion for use in cold asphalt recycling. It was previously presented in Phase III of this study. Minor revisions have been made based on this more current research.

Utah Test 965-xK Qualifying Engineered Solventless Cold Recycling Emulsions (ESCRE)

Purpose: This test is to determine the rate of demulsibility of an ESCRE in the presence of water, RAP fines, Hydrated Lime, Constant temperature and vibration. The test will determine viscosity change in the mortar fraction of a RAP mixture over time.

Apparatus: The test requires a vertical press with an adjustable speed control allowing for 0.5 ± 0.05 inches per minute and a load cell with a span of no greater than 200 pounds. A reporting accuracy of 0.1 pound must be provided. The press must have position control with accuracy within 0.01 inch. The data recording device must be capable of recording at a minimum of 50 points per second and must report these points in a form which may be graphed. Use a test head which is 0.79 in. in diameter and 0.68 in. tall with a 60 degree cone coming to an acute tip. The surface of the cone will be finished with 1000 grit sandpaper with all finish marks being concentric to the axis. Control temperature with an incubator with temperature control to within 1°F. of the target in the range of 60 to 150°F. Vibrate the sample on a vibratory table producing 60 hz. at an amplitude of 0.125 inches.

Figure 1: Test Head

A cup to contain the sample must be correctly sized to reduce interaction between the test head and the sidewalls. A cup at least 2 inches in diameter and 1.75 inches deep is required.

Figure 2: Sample Cup

Sample Preparation: Select a test temperature. Samples may be qualified at 80, 100, 120 or 140°F depending on the temperature that processing is expected. Bring all parts of the test sample to test temperature in the incubator. Include mixing tools and sample containers. For the sample cup shown, obtain 600 grams of minus #16 RAP from the proposed project. Obtain 20g lime and at least 100g potable water. 56.7g of emulsion will be added after wetting the 560g of RAP. Use the following RAP gradation. Assume that this weight is 25% of the total weight of the RAP. Apply lime at the rate of 1% of the total RAP weight.

		Medium Mortar Mix			Sand Recipie at 18% Water
Target weight aggregates	560				
Size	**Weight**	**Cumulative**	**Percent passing**	**Cumulative Percent**	**Ind Percent Ret.**
#16	0.0	0.0	100.0	0.0	0.0
#30	151.2	151.2	73.0	27.0	27.0
#50	126.0	277.2	50.5	49.5	22.5
#100	50.4	327.6	41.5	58.5	9.0
#200	100.8	428.4	23.5	76.5	18.0
minus #200	76.2	504.6	9.9	90.1	13.6
			0.0		
Lime	**18.2**	522.7			
Total Dry Wt.	**522.7**				
Weight of H2O	**94.1**	18.0%	H2O % of Full Agg Mix	4.66%	
Weight of Emulsion	**56.7**	10.9%	Emuls. % of Full Agg Mix	2.81%	
Total Sample Weight	**673.5**		Lime % of Full Agg Mix	0.90%	
		% Lime	% minus #16	Total Agg Mix Weight	% Lime in minus #16
Weight of Lime	18.2	1.00%	25.0%	2,018.2	90.0%
Number of sample cups	8				
Weight of Sample Cup (g)	80				
Minimum Total Sample Wt.	640	**Enough Wt.**			

Thoroughly mix the RAP and lime with 80g of water. This recipe can be adjusted to accommodate larger sample cups. Vibrate the mix on the vibration table for 15 seconds and watch for liquefaction. Increase water content in 10g increments. Mix and vibrate at each increment. Watch for liquefaction. Add 5 g water after the peaks on the mortar surface collapse and a water sheen appears on the surface. Add 56.7g emulsion and mix until evenly distributed in the mortar. Consistency should be like a milkshake and should self-level. Spoon the mortar into the sample cups so that each cup contains 80 ± 5g. Drop each sample cup three times from a height of 6 ± 2 inches onto a table to consolidate the mortar. Vibrate each sample for 15 ± 3 seconds on the vibratory table to level the surface. Return the samples to the incubator. Increase these weights proportional to the chosen sample container. A standard asphalt testing tin takes 100g of mortar.

Test Procedure: Tests will be run at 15 and 30 minutes, 1, 2, 3, 4, 6 and 24 hours. Uncover the sample and place in the test apparatus within one minute of the target time up to one hour and within 5 minutes of the target time after one hour. Gently remove any water from the surface of the sample with a towel. Do not disturb the surface of the mortar. Bring the tip of the test head into contact with the surface of the mortar without penetration. This is the beginning displacement. Press the cone into the mortar at the rate of 0.5 in/min to a depth of ¾ inch. Remove the test head from the sample. Clean the head with acetone.

Reporting:

Emulsion Mfgr.

Emulsion Label

Test Technician and Lab

Manufacturer of press and controls system

Date of sample preparation

Time at beginning of each test

Test Temperature

Maximum force required to penetrate ¾ inch into the sample at each test time

Graph of maximum force vs time

Graph of % change in force vs time