IMPLEMENTATION OF LOW TEMPERATURE TESTS FOR ASPHALT MIXTURES TO IMPROVE THE LONGEVITY OF ROAD SURFACES

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Disclaimer

ABSTRACT

Field samples were obtained from cores taken from multiple roads around the Salt Lake Valley in Utah and prepared for BBR testing. The response of field cores showed that even though the same binder grade used in the region was the same, the resulting mixtures have significant differences in creep moduli and m-values. This indicates that binder testing alone might not be enough to control the material's creep modulus.

The combination of BBR test results and field surveys indicate that both creep modulus and m-value play a significant role in low-temperature performance of asphalt pavements. Pavements with high creep moduli and low m-values are more susceptible to low-temperature thermal distress. From field observations, the field performance of each section was known; by plotting the test results of the field samples on a Black Space Diagram, it can be observed that a thermal stress failure envelope might exist. These results will allow the development of asphalt mixtures that have resistance to both low and high temperature distresses. However, more research will be necessary to further define this specification.

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EXECUTIVE SUMMARY

Thermal cracking due to stress at low temperature is a major factor in roadway degradation. The purpose of this study was to measure low temperature response of asphalt from field cores, assess the practicality of using the Bending Beam Rheometer (BBR) to test field mixtures, compare test results to observed field performance, determine whether a specification value can be obtained to evaluate low-temperature performance of the pavement, and determine if samples constructed in the laboratory using the same mix design are representative of field samples.

In this study, the BBR was used to test multiple asphalt mixtures including field samples and samples prepared in the laboratory. Field samples were obtained from cores which were taken from multiple roads around the Salt Lake Valley in Utah and prepared for BBR testing. Laboratory samples were constructed for all sections with available materials.

The response of field cores and subsequent viscoelastic analysis showed that even though the same binder grade is used in the region, the resulting mixtures have significant differences in creep moduli and slope (m-value). This indicates that binder testing alone might not be enough to control the material’s properties as they relate to thermal distresses.

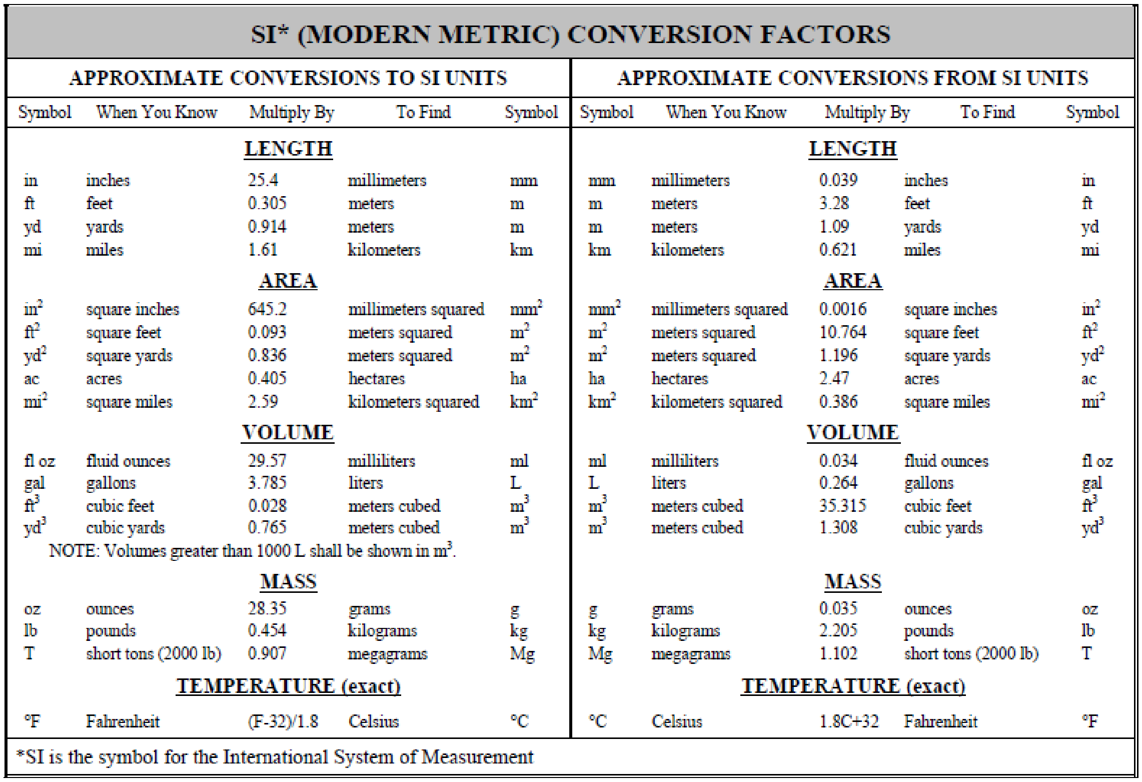
The results showed that using the BBR to test field mixtures is practical; the process is simple. Coring, cutting, and testing at one temperature could all be completed for a single core within one work day.

The combination of BBR test results and field surveys indicated that both creep modulus and m-value play a significant role in low-temperature performance of asphalt pavements. Pavements with high creep moduli and low m-values were more susceptible to low-temperature thermal distress. From field observations, the field performance of each section was known; by plotting the test results of the field samples on a Black Space Diagram it was observed that a thermal stress failure envelope might exist. These indicate that conceptually, by controlling the m-value, mixtures with high modulus could be developed that can resist rutting without thermal cracking. However, more research will be necessary to further define this specification.

For roads with original materials available, lab samples were created and tested in the same manner as field samples. Results show that lab samples are not always representative of field construction samples. Although the same mix design and sample preparation protocol were used, the results vary widely. In order to improve the use of samples constructed in the laboratory, it is recommended that mix from the construction site be sampled and stored in a sealed can to later be compacted and tested in the laboratory. These results should then be compared to field sample results of the same mix to determine the source of variation in results.

It is recommended that all sections that displayed a creep modulus/m-value relationship near the possible thermal stress failure envelope continue to be monitored for thermal distress. It is also recommended that future research focuses on taking field cores of thick layered pavements with known mix designs that show thermal distress to verify the conclusion, which states that pavements with a combination of high creep moduli and low m-values are more prone to thermal distress.

CONVERSION FACTORS



SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

1. INTRODUCTION

Thermal cracking due to stress at low temperature is a major factor in roadway degradation. Many studies have found that in areas which routinely experience freezing temperatures, thermal cracking is the principal form of deterioration of asphalt pavements [1]. In this study, the Bending Beam Rheometer (BBR) was used to test multiple asphalt mixtures, including field samples and samples prepared in the laboratory. Field samples were obtained from cores that were taken from different roads around the Salt Lake Valley in Utah and prepared for BBR testing. Laboratory samples were constructed for all sections with available materials. Each laboratory sample was made by following Utah Department of Transportation (UDOT) mix designs for the designated section. Both field samples and laboratory samples were tested in the same manner and their results were analyzed and compared to each other. All the mixtures were made using binders that had the same low-temperature grade of -28 ºC, as appropriate for the region. The resulting BBR data were then compared to low-temperature field performance. This was completed through a series of visual surveys of the sections. Each section was surveyed on three separate occasions.

Testing asphalt mixtures using the BBR has many advantages, including the fact that a minimal amount of material is needed and the equipment is presently operated in many material testing labs to test the stiffness of asphalt binders, so there is an existing familiarity with the procedure.

Testing was completed for seven field sections as well as six laboratory mixes to evaluate both the test method, in terms of practicality and precision and, to determine reliability of laboratory samples as a representative of field performance, and the possibility of using a single point measurements such as creep modulus or m-value at 60 seconds or for a quality check of the in-place material. This report details the testing methods employed in the study, resulting data, field surveys, laboratory comparisons, and conclusions formed from the results of each.

2. BACKGROUND

Thermal cracking of asphalt concrete is the resulting distress from exposure to low-temperature conditions. Like most materials, asphalt concrete contracts when exposed to low temperatures. This contraction is countered by the frictional force of the underlying layers inducing thermal stresses on the pavement. As temperatures decrease, contraction of the pavement subsequently increases and results in an increase in thermal stress experienced by the pavement. Once the stress reaches the strength of the material, a crack will develop. Different materials will accumulate stresses at a different rate depending on their properties, specifically their relaxation modulus. Thus, relaxation modulus is considered the most important material property used to predict thermal cracking.

2.1 Testing Modes

Determination of the relaxation modulus of asphalt mixtures is done through mechanical testing. Testing of any material is done in one of two ways: stress controlled or strain controlled. In a stress controlled test, the stress function is known while the corresponding response of strain is measured. For the case of time-dependent materials, such as asphalt concrete, the stress is known and the strain is time dependent. A specific example of a stress controlled test is the creep test. In a creep test, a constant load is applied resulting in a constant stress (σ_c) and the time-dependent strain (ε_t) is measured. The ratio of these two values is called the creep compliance, D(t), of the material as shown in Equation 1.

$$\mathrm{D(t)} = \frac{\varepsilon(\mathrm{t})}{\sigma_c} \tag{1}$$

Strain controlled tests, also known as relaxation tests, are just the opposite. They involve applying a known strain while the response of stress is measured. Again, for asphalt concrete and other time dependent materials, the strain is known while the responding stress is time dependent. A specific example of a strain controlled test is the relaxation test in which a material is subject to an instantaneous strain (ε_c). The strain is held constant while the decreasing stress (σ_t) is measured. The ratio between these two values is referred to as the relaxation modulus, E(t), shown in Equation 2.

$$\mathrm{E(t)} = \frac{\sigma(\mathrm{t})}{\varepsilon_c} \tag{2}$$

Creep compliance and relaxation modulus are representations of the same viscoelastic behavior. However, they are not reciprocals of each other due to the fact that in creep compliance there is constant stress while strain is time dependent, but the opposite is true for relaxation modulus [2]. Although they are not reciprocals of each other, if one is known the other one can be determined by transforming the time relationship to a different domain through the use of the LaPlace Transform. The LaPlace Transform is discussed in detail in Section 2.3.3 Data Analysis.

2.2 Test Procedures

Currently, there are multiple tests that can be conducted to determine low-temperature performance of asphalt mixtures. Three of the most common are the Temperature Specimen Restraint Specimen Test (TSRST), the Superpave Indirect Tensile Test (IDT), and the Bending Beam Rheometer (BBR).

2.2.1 Thermal Stress Restraint Specimen Test

The TSRST is a strain and temperature controlled test used to determine if an asphalt pavement is susceptible to low-temperature thermal cracking by simulating a thermal event that may be experienced in the field. In this test, the temperature is lowered at a constant rate while the sample is restrained. This restraint keeps the sample from contracting, which results in tensile stress. Load cells and LVDTs are used to take measurements throughout the test, allowing for both the load and the temperature to adjust simultaneously while determining tensile strength [3 and 4].

2.2.2. Superpave Indirect Tensile Test

The IDT is a stress controlled test that can be used to determine creep compliance and indirect tensile strengths of asphalt mixtures. The IDT is normally conducted at low temperatures for thermal cracking predictions. In this test, a cylindrical specimen undergoes a compressive creep load on its radius. Over the loading period, the deformation is measured and the creep compliance is calculated [5].

2.2.3. Bending Beam Rheometer

Like the IDT, the BBR is a stress controlled test. AASHTO T313/ASTM D6648 describes the BBR, pictured in Figure 2.1, as being used to perform tests on beams of asphalt binder after being conditioned at the desired test temperature [6 and 7]. The test produces the creep stiffness and the stress relaxation capacity by way of applying the elastic solution to a simply supported beam. These values have been used to calculate thermal stresses [8]. Using the BBR to test asphalt mixtures in place of binder was proposed by Marasteanu et al. [9, 10, and 11]. The compliance curves resulting from their tests showed good correlation with curves generated by the IDT. This research was further advanced by Ho and Romero [12 and 13], who determined that BBR testing of small amounts of material can produce behavioral results that are representative of the entire mixture.

Figure 2.1 Cannon Bending Beam Rheometer

Both the TSRST and the IDT can be used for the prediction of low-temperature thermal cracking of asphalt pavements, but they both require more material and are a more comples testing process than the BBR. Because of this, BBR testing is considered more practical and was chosen to be used in this study. A more detailed description of the BBR testing procedure can be found in the BBR Testing section under the subheading Testing Procedure.

2.3 BBR Testing and Data Interpretation

2.3.1 Sample Fabrication

The BBR test requires minimal amounts of material. Because of this, it is possible to directly test field cores as well as gyratory prepared samples that are constructed in the laboratory. Sample preparation is detailed in the following section.

2.3.2 Testing Procedure

BBR testing has been used to determine properties of asphalt mixes at low temperatures [1, 6, 7, 8, 9, 10, 11, 12, and 13]. However, an actual limit, which would indicate whether or not a mixture would experience cracking and can potentially be used to develop a performance-based specification, has not been determined. Furthermore, there are still questions regarding the practicality of using this method on field cores.

The BBR test requires each core or gyratory sample to be cut into beams that measure 12.7mm x 6.35mm x 127 mm (width x thickness x length). Cores often consist of more than one layer of asphalt concrete, as shown in Figure 2.2.

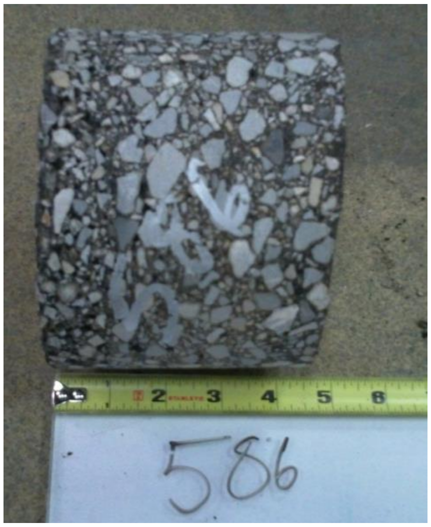


Figure 2.2 Field core displaying multiple layers of asphalt concrete

The uppermost, or most recent, layer of each core is removed from the rest of the layers and further prepared for testing. The top layer can be removed by the use of a lapidary saw. In some cases, a chip seal may be present. This layer is too thin to test using the BBR, so it should be removed from the uppermost layer of asphalt concrete. The remaining puck is then cut into rectangular blocks in order to maximize the number of beams each core could produce. This is shown in Figure 2.3. Blocks can be cut by using a small tile saw. The blocks were then cut into beams with the correct dimensions previously described.

Figure 2.3 Example of block being removed from circular puck

It is important to keep track of the original location of each beam with respect to the roadways surface. In order to do this, for this study, each beam was labeled with a letter depending on the layer it came from as shown in Figure 2.4 (with A being the top, closest to the road's surface, and D being the bottom, farthest from the surface). Each beam was labeled by core, layer, and section number, (i.e., 596-C3) as needed per core.

The fact that each beam was only 6.35 mm thick allowed us to obtain a sufficient number of samples from each core, even if the top layer of interest was relatively thin. This is an advantage of using the BBR.

To ensure that each beam had consistent dimensions as specified by Romero et al. [13] a template was used. This template, pictured in Figure 2.5, confirms that each beam's width and thickness are within the acceptable range of ± 0.25 mm. Acceptable beams would fit within each of the slots, but would not be able to pass beyond the shelf. The larger slot measures width while the smaller slot measures thickness.

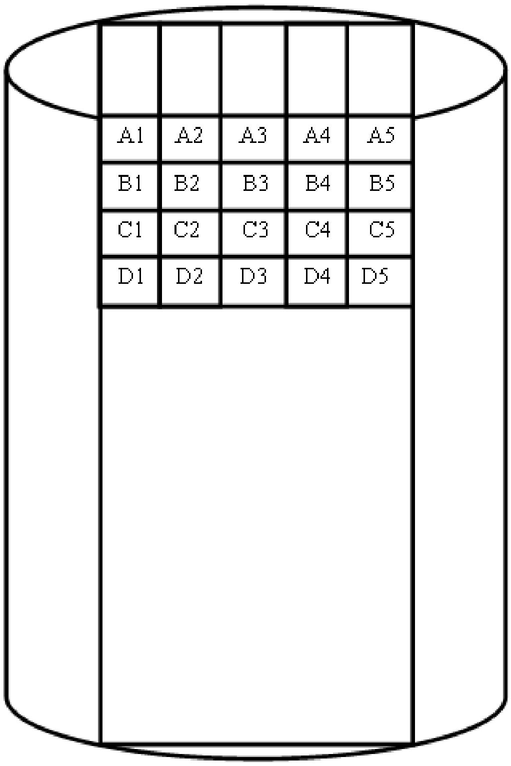


Figure 2.4 Schematic showing how each beam was labeled

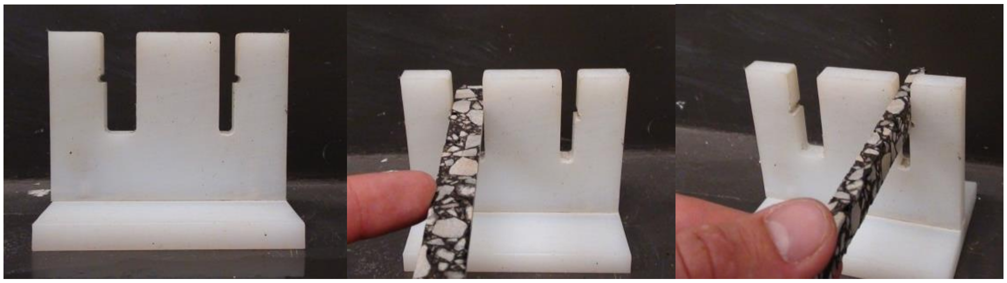


Figure 2.5 Template used to ensure proper beam dimensions

Next, the exact dimensions of each beam are measured. The measurements included total length, thickness at one-third of the total length from each end, width one-third of the total length from each end, and mass. Once the samples were cut to proper dimensions, they were stored together on a flat tray at room temperature for less than one week. This ensures any excess water from the cutting process evaporates and prevents deformation.

Beams were tested at three temperatures: low binder grade +10°C, low binder grade +16°C, and low binder grade +4°C. Mixtures in this study have low-temperature binder grades of -28°C so BBR testing took place at temperatures of -12°C, -18°C, and -24°C. Before each testing session, the BBR was calibrated for both temperature and force/deflection as recommended by the manufacturer. Prior to testing, each sample soaks in the temperature-controlled bath for 60 minutes to ensure that the entire beam is brought to test temperature. Testing of each sample requires approximately eight minutes. Every 10 minutes, a beam can be added to the bath. After an hour, the first beam placed in the bath is ready to test. Every 10 minutes, the beam that has been in the bath for one hour is ready to be tested, the previously tested sample is removed, and a new beam is placed in the bath to begin soaking. This allows for a quick and effective way to test materials. All testing procedures follow AASHTO T313 *Standard Test Method for Determining the Flexural Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)* [6] with minor modifications as described next.

The initial load (35 mN, milliNewton, ± 10 mN) applied by the BBR is the same as described in AASHTO T313. The testing protocol of the BBR manufacturer states that the BBR can apply up to a 450-gram force without further change in the air bearing system. Previous research has determined that the 450 grams of applied loading for the BBR test can produce significant deflections of asphalt mixture beams at the recommended test temperatures of PG +10°C [13 and 14]. This led to the applied load of 450 grams (4413 mN ± 50 mN) being selected for the BBR tests in this research. Each test produces a series of data that includes force and deflection as a function of time. These values are then used to calculate creep modulus and the m-value (slope). Figure 2.6 shows the BBR with a beam in testing position.

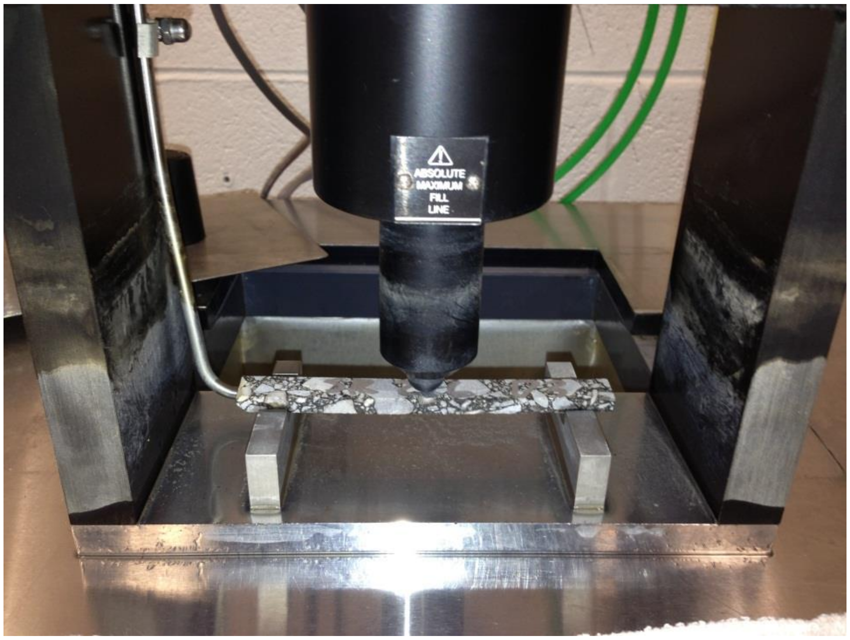


Figure 2.6 Sample beam in the BBR testing position (pictured out of bath for clarity)

2.3.3 Data Analysis

The BBR automatically records the load and the deformation of the beam. Knowing the beam dimensions and using beam elastic solutions along with elastic-viscoelastic correspondence principle, the compliance as a function of time of the material is determined. Following this determination for each mixture, the data are averaged to obtain the compliance of the mixture as a whole. The compliance is plotted against time to create the individual creep compliance curve for each mixture at all three test temperatures as shown in Figure 2.7.

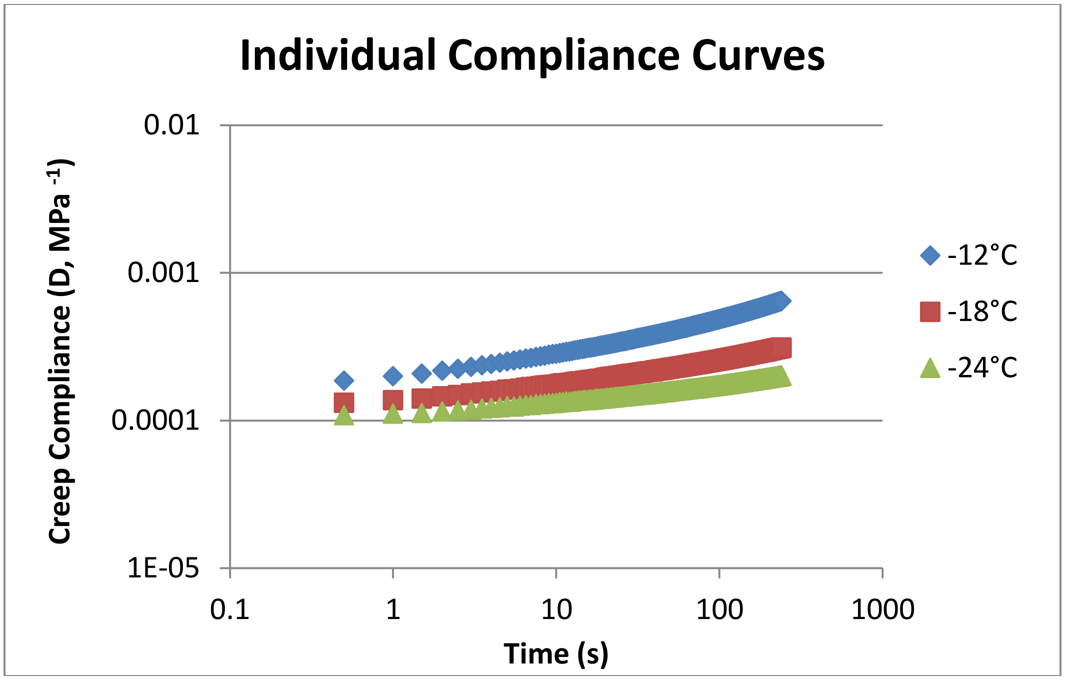


Figure 2.7 Individual compliance curves of three test temperatures

In order to generate a master creep compliance curve, it is necessary to use shift factors. The concept of Time-Temperature Superposition Principle (TTSP) can be implemented as has been used in other studies [1, 2, 12, 13, 14, 15, 16, and 17]. The master compliance curve of each test sample is based on the TTSP. This provides an extended time domain for compliance curves on a log of compliance versus a log of reduced time scale. The master compliance curves look similar to the example shown in Figure 2.8.

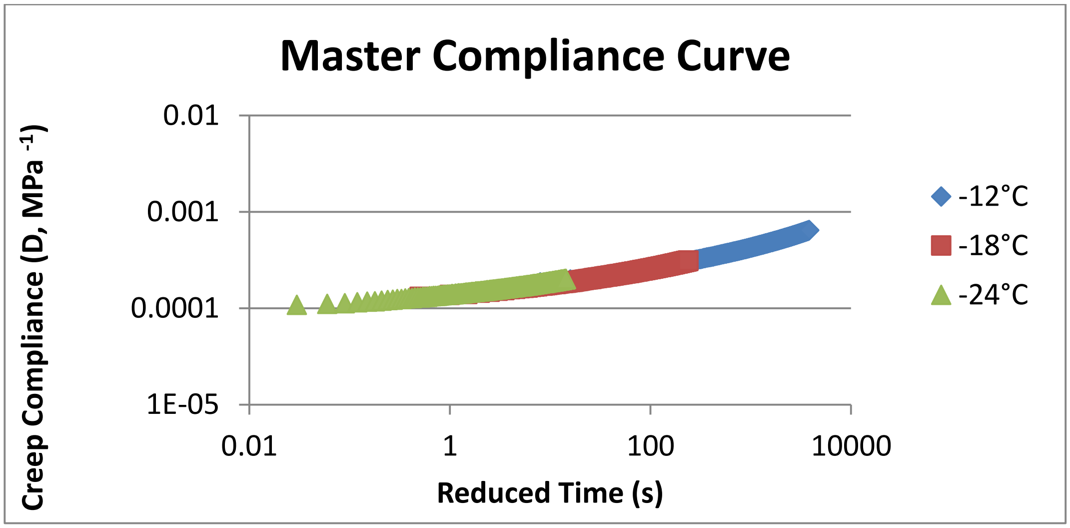


Figure 2.8 Master Compliance Curve showing shifted data of all three test temperatures

Using a reference temperature, -18°C in this example, the shift factors for -12°C and -24°C are manually manipulated to shift their respective individual compliance curves until the master compliance curve fit together as a uniform set of data. This ensures the shape of the data remains unchanged [16]. Knowing the shift factors, the reduced time can be calculated in terms of real time, t, and temperature shift factor, a_T, as shown in Equation 3:

$$\xi = t \cdot a_T \tag{3}$$

where ξ = reduced time,

a_T = shift factor, and

t= time

Shift factors are then plotted in log scale with respect to temperature as can be seen in Figure 2.9. The exponential best fit line is then generated and later used in the determination of cracking temperature.

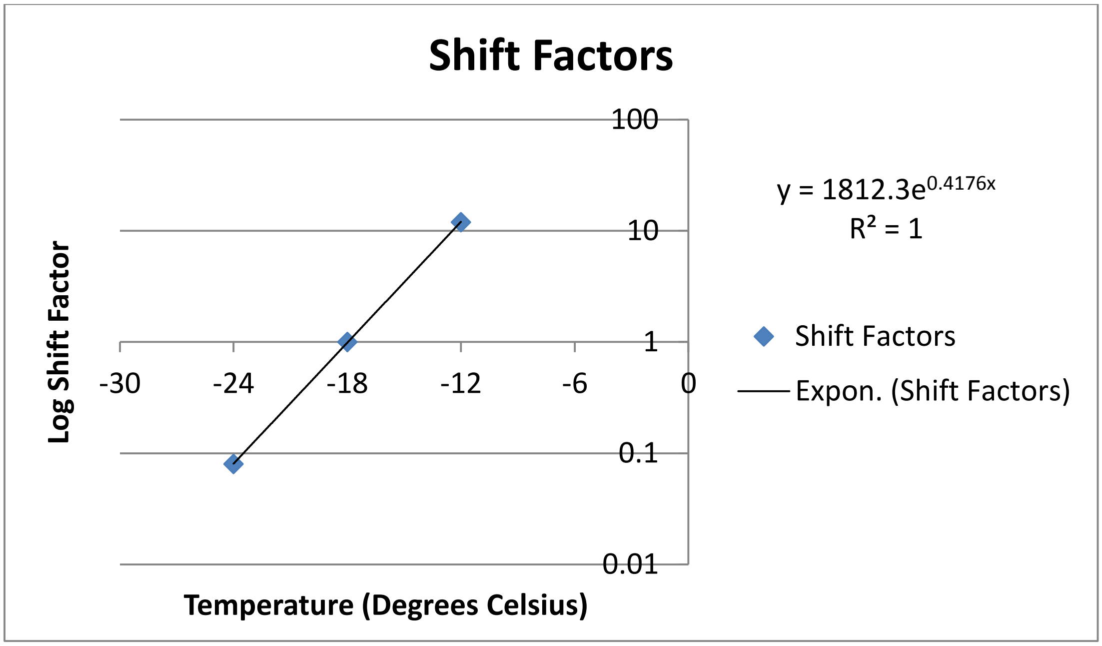


Figure 2.9 Shift factors vs. Temperature and exponential fit line

The pre-smoothing technique is used to generate a continuous fitted curve in place of the overlapping compliance curves. Pre-smoothing required minimizing the sum of squared errors between the raw data and fitted compliance values by implementation of nonlinear regression methods [10, 16, and 17]. The expression used for minimizing the errors is shown as Equation 4:

$$\text{Minimize} \quad \sum \left| D_p(\xi) - D(\xi) \right|^2 \tag{4}$$

where $D_p(\xi)$ = fitted power law response at reduced time, ξ
$D(\xi)$ = raw experimental data at reduced time, ξ

Power law parameters D_o, D_1, and n are found and used to create the fitted creep compliance curve. Figure 2.10 shows an example of a fitted creep compliance curve in relation to the master compliance curve used to create it. The power law function is as follows:

$$D(t) = D_0 + D_1 \cdot t^n \tag{5}$$

where $D(t)$ = creep compliance at reduced time, t, and D_0, D_1, and n = power function parameters.

The Linear Viscoelastic Theory (LVE) can be used to predict the behavior of asphalt concrete mixtures [2, 11, 12, 17, and 18]. The relationship between relaxation modulus and creep compliance can be used to determine thermal stress [12 and 19].

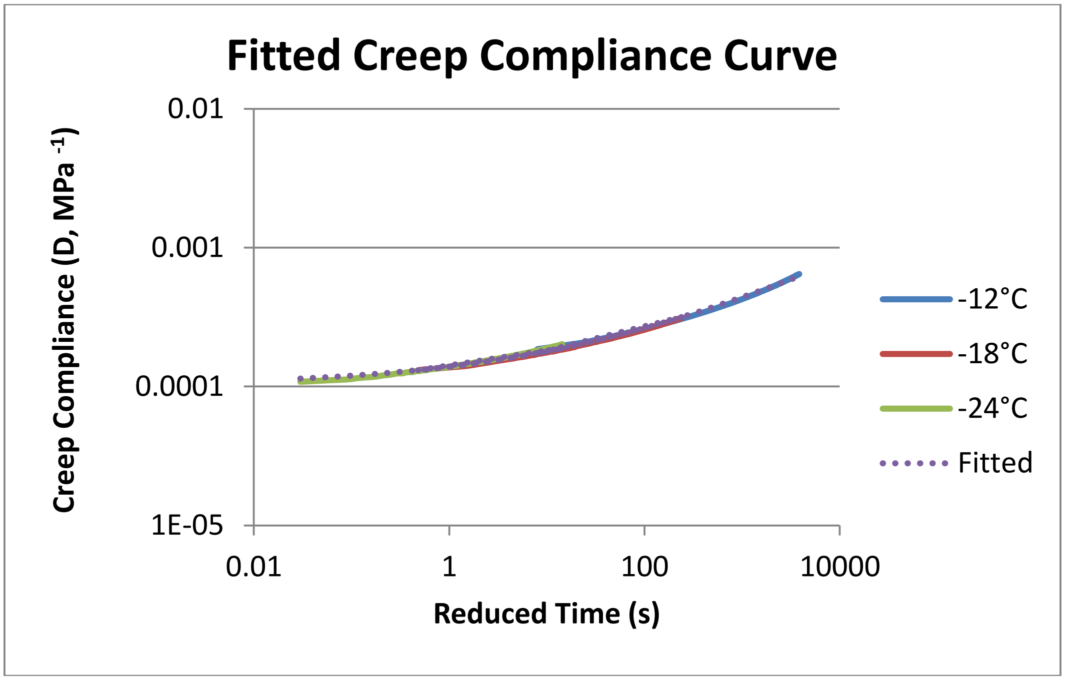


Figure 2.10 Fitted creep compliance curve overlapping experimental data

The relaxation modulus, $E(t)$, is needed to find the thermal stresses of each core at varying temperatures. In the creep compliance function, $D(t)$, strain is a function of time while stress is not, and the opposite is true in the relaxation modulus function. Therefore, the relaxation modulus function can be found only by transforming the creep compliance into a different domain. $E(t)$ is determined by taking the Laplace transform of the power law function. The relaxation modulus relates to creep compliance by the Equation 6 [20 and 21]:

$$\hat{D}(s)\hat{E}(s) = \frac{1}{s^2} \tag{6}$$

where $\hat{D}(s)$ and $\hat{E}(s)$ are the Laplace transforms of creep compliance, $D(t)$ and relaxation modulus, $E(t)$, respectively.

By taking the Laplace Transform of the power law function (Equation 5), and substituting into Equation 6 we obtain Equation 7:

$$\hat{E}(s) = \frac{1}{\hat{D}(s)s^2} = \frac{1}{sD_0 + D_1\Gamma(n+1)s^{1-n}} \tag{7}$$

where Γ is defined as a gamma function.

To solve for $E(t)$, Equation 7 needs to be inverted. An approximate method for inverting Equation 7 was presented by Schapery [20] and, as cited by Ho [12], can be used to determine the relation between $E(t)$ and power law parameters. This is shown in Equation 8.

$$E(t) = \frac{1}{D_0 + D_1\Gamma(n+1)(1.786t)^n} \tag{8}$$

Another method, the "direct method" proposed by Christensen, is also applicable [2]. These two methods have been compared and showed a good correlation to one another [12]. Thus, the approximate method was validated and can be applied to compute the relaxation modulus.

$$E(t) = \frac{1}{D_0 + D_1\Gamma(n+1)(1.73t)^n} \tag{9}$$

The temperature at which thermal cracking will occur is predicted by using the calculated relaxation modulus of each sample. The thermal stresses are predicted by the following equation:

$$\sigma(T) = \int_0^T E(T-T')\frac{\partial\varepsilon(T)}{\partial T'}dT' \tag{10}$$

where *E(T-T')* is the relaxation modulus that has been previously determined.
T' refers to the parameter of integration.
E(T) is the strain at temperature T.
E(T) = α (coefficient of thermal contraction) multiplied by dT/dt (temperature increment).

The values of α (1.7x10-4 mm/mm/°C) and dT/dt (1°C per hour) were used as recommended by Bouldin et al. [22].

The application of these equations determines the thermal stresses of each mixture. Predicted cracking temperature can then be determined by the temperature at which the thermal stress reaches the strength [13]. Figure 2.11 shows an example of a thermal stress curve with predicted cracking temperature included.

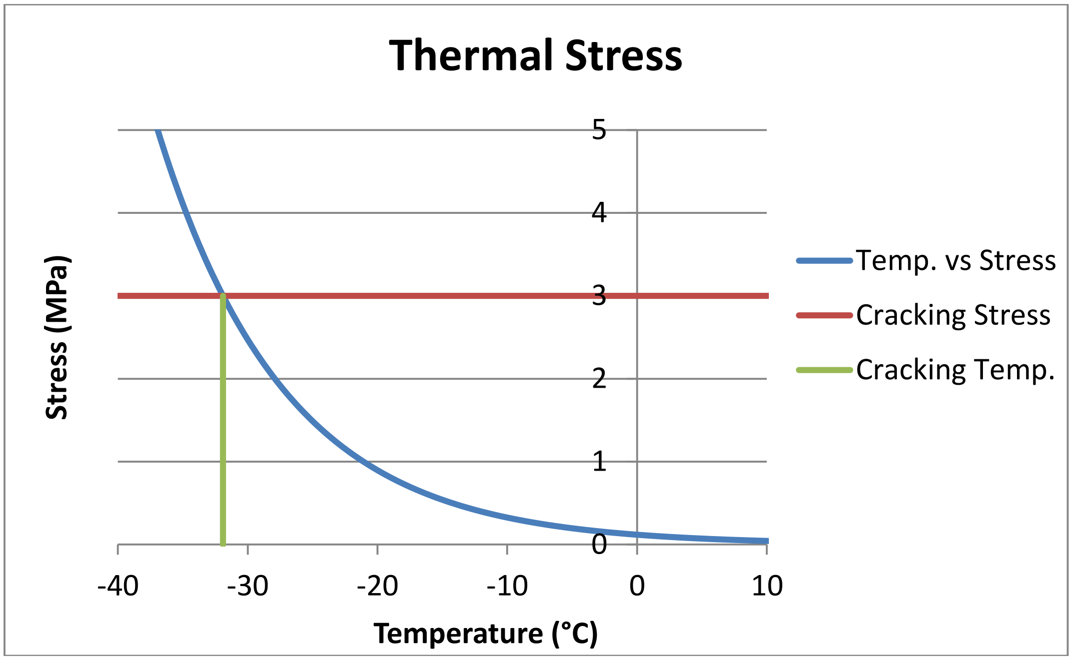


Figure 2.11 Thermal stress graph indicating predicted cracking temperature

3. RESEARCH APPROACH

3.1 Objectives

The objectives of this work are:

- Measure the low-temperature response of asphalt mixtures obtained from field cores using the BBR
- Assess the practicality of using the BBR to test field mixtures
- Compare the test results of field cores to observed field performance
- Determine whether a specification value can be obtained to evaluate low-temperature performance of the pavement with the understanding that this value should be as simple as possible.
- Determine if samples constructed in the laboratory using the same mix design are representative of field samples

For the BBR to be practical for field performance testing, we must eliminate the rigorous calculations and, instead, focus on the implications of accessible test outputs to identify and develop performance-based specifications. Two outputs readily available from the BBR test are the creep stiffness and m-value at 60 seconds; thus, while significantly more data were collected, this research concentrated on those parameters at that specific time.

3.2 Creep Modulus and m-value

The standard BBR currently used in binder laboratories reports the creep stiffness and m-value at 60 seconds. The term creep stiffness is simply the ratio of force to displacement and is related to the modulus and the geometry of the beam (EI). Because the geometry of the beams tested by the BBR is known, the creep modulus is also known. The m-value is the slope of the stiffness curve generated during the BBR test and is indicative of the material's ability to relax. A high m-value is associated with high relaxation abilities while a low m-value has lower relaxation abilities [23].

Original testing indicated that using longer loading times, such as two hours, to evaluate limiting stiffness and m-value was best. However, this amount of time was considered to be too long, so the TTSP was implemented to decrease the testing time. With the reduced testing time, binder specifications were developed for both creep stiffness and m-value. The maximum allowable creep stiffness at 60 seconds for a binder is 300 MPa, while the minimum allowable m-value for a binder is 0.300 [23]. Although these are the specifications set in place, for binder and mixtures will react differently, it is important to remember that both values play a role in low-temperature performance. The familiarity with such parameters (S and m-value) for asphalt binders makes them attractive to use in asphalt mixtures, too.

3.3 Methods to Predict Thermal Cracking

Limiting thermal cracking can be done one of two ways: limit the creep modulus of the material or increase the relaxation modulus of the material. Creep modulus and relaxation modulus of the material are key factors that influence thermal cracking. Therefore, theoretically, a limiting value should be able to be determined to develop a specification or prediction of performance.

Deme and Young evaluated results from a test road in St. Anne, Canada, in the 1980s [24]. Their study shows that pavements with high stiffness moduli (creep moduli) demonstrated severe thermal distress during the first winter while mixtures which incorporated softer, less susceptible-asphalts resisted cracking for more than eight years. They suggested that if the stiffness of the mixture at 180 seconds is greater than 1,500,000 psi, then thermal cracking is to be expected. This conclusion coincides with results obtained at Penn State during the Strategic Highway Research Program [4 and 25] and was the focus of this research.

4. FIELD SAMPLES

4.1 Site Selection

Field cores were taken from seven state roads around the Salt Lake Valley, each of which were constructed based upon UDOT design specifications. The selection of the sections was based upon the following criteria:

- All were constructed within the past three years
- Had thick pavement layers to ensure any visible distress was not reflective of the underlying layers
- All were built using the same low-temperature binder grade (-28°C)
- Had the same materials available to recreate laboratory samples
- Had the ability to obtain cores

In order to obtain cores, the road or lane must be closed following UDOT safety protocols. Without express permission from UDOT, this cannot be done, thus certain roadways were not available for use in this study. Roads were selected and cored without prior distress surveys being conducted in order to eliminate any bias. The locations of these cores can be seen in Figure 4.1. Anywhere from two to four cores were taken from each section. The cores were taken in close proximity to one another; because of this we can assume that cores taken from the same road are of the same mixture and should have very similar properties. The cores were numbered in order and grouped according to the road from which they were taken. For example, cores 590 and 591 both were taken from SR 266. All core numbers and the roads they came from can be seen in Table 4.1.

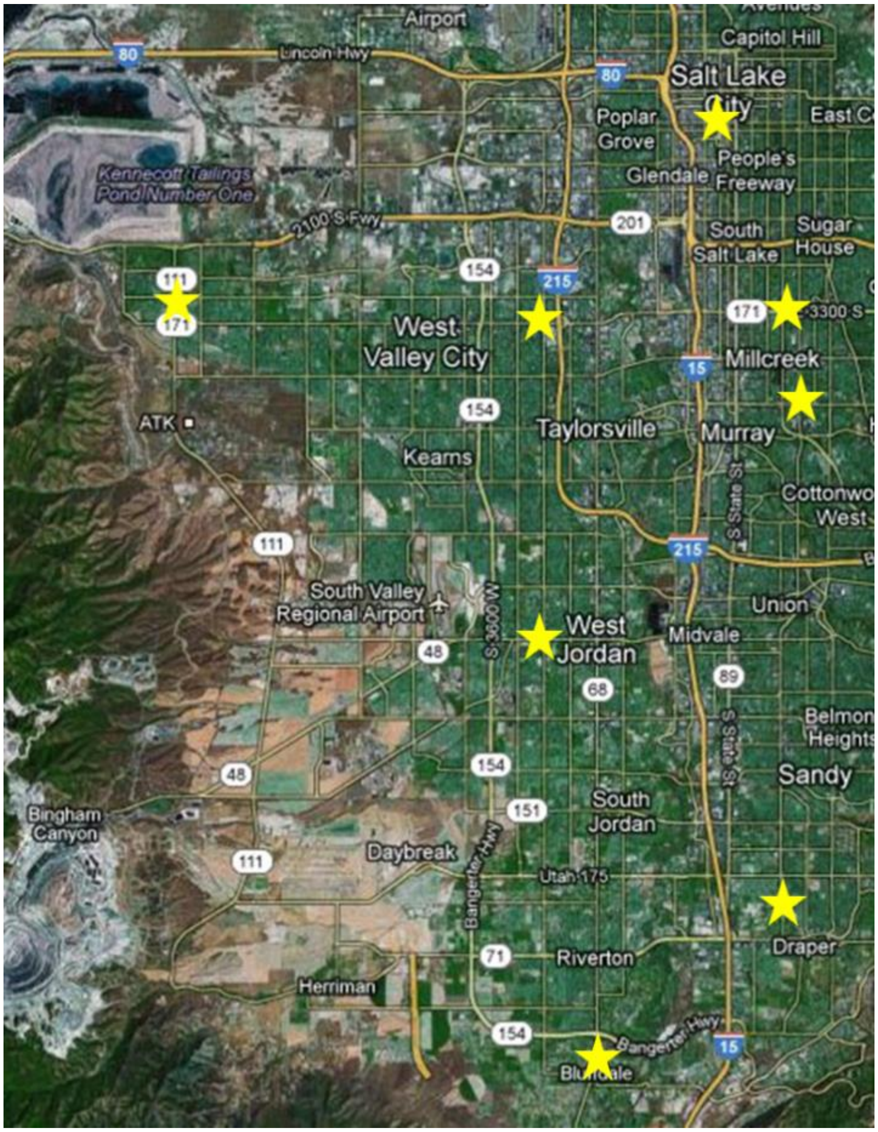


Figure 4.1 Map of the Salt Lake Valley with stars indicating core locations

4.2 Mix Design Information

All road surfaces evaluated were designed based on UDOT specifications [26]. They were all Superpave, densely graded mixtures designed based on an N-design of 100 gyrations. The VMA was in the range of 13%-14% and the air voids were between 2.5%-3.7%. The low-temperature binder grade of all sections was -28°C as shown in Table 4.1.

Table 4.1 Summary of Field Sample Results

Project	Core ID	Binder Grade	Creep Modulus @ 60s -18 ºC (MPa)	Coefficient of Variation Creep Modulus (%)	m-Value @ 60s -18ºC	Beams Tested
SR 171	576	PG64-28	2 938	8.5	0.233	8
	577	PG64-28	2 715	10.9	0.211	4
	578	PG64-28	2 626	15.1	0.280	8
	579	PG64-28	2 550	12.2	0.285	6
SR 111	580	PG64-28	9 081	15.7	0.103	10
	581	PG64-28	11 386	10.9	0.124	10
SR 269	586	PG64-28	5 726	15.4	0.159	5
	587	PG64-28	5 186	15.5	0.179	10
SR 266	590	PG64-28	6 523	6.0	0.084	4
	591	PG64-28	7 388	12.7	0.130	4
SR 71	592	PG64-28	9 533	10.2	0.126	13
	593	PG64-28	8 931	13.8	0.127	11
SR 68	594	PG64-28	4 284	7.1	0.185	5
	595	PG64-28	4 547	10.4	0.181	7
SR 48	596	PG64-28	10 437	13.3	0.160	12
	597	PG64-28	10 774	14.1	0.151	16

4.3 Quality Control of Data

A quality check of the data was conducted for each core by using the creep modulus at 60 seconds during each test. The coefficient of variation (CV) was determined by dividing the standard deviation by the mean. Previous work has shown that a CV of 15% or less is reasonable when testing asphalt mixtures [12, 13, 14, and 15]. These works also show that when conducting analysis of many beams, such as 50 or more, the results are similar to results from far less beams as long as the CV is 15% or less. In cases where the CV was greater than 15%, a trimmed mean method was used. The trimmed mean method is particularly useful for this study because it removes the samples with results lying farthest from the mean in both the positive and negative direction. This allows for the data to take the form of a normal distribution, as any group of samples from the same mixture should be.

Once the variability of the test was verified, the compliance of each sample beam was used to calculate the average compliance of each core at the selected temperature. The point of evaluation was selected to be 60 seconds. It is important to have the point of evaluation be at least 10 seconds after the initial load to allow for stabilized readings. After this, the time which is taken for the point of evaluation is irrelevant as long as it is consistent throughout each test. The point of evaluation was taken at 60 seconds for two reasons: 60 seconds is the default output for the BBR testing program and it is also the same for the BBR binder testing protocol AASHTO T313/ASTM D6648 [6 and 7].

4.4 Field Sample Test Results

4.4.1 Variability

As can be seen in Table 4.1, the coefficient of variation for each core was 15% or less. The difference in creep stiffness between cores was less than 10% for all but one section as shown in Figure 4.2.

During preparation, precautions were taken to ensure that the layer each beam came from was documented. This allowed for evaluation of the stiffness at different depths within each core. No correlations were observed between the depth of the sample and stiffness.

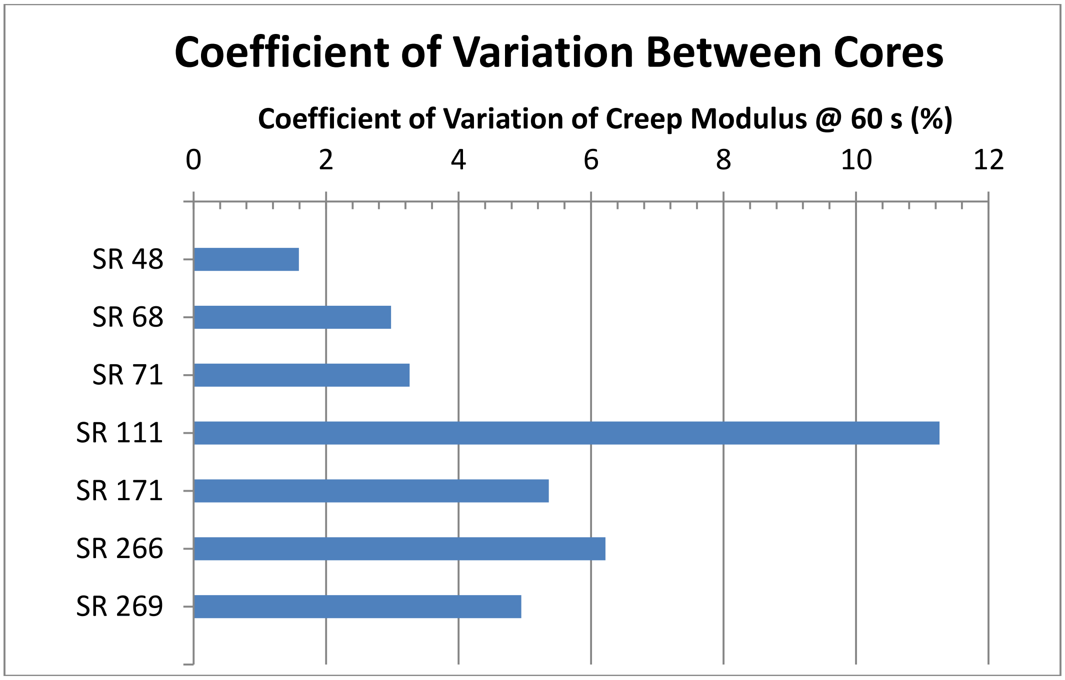


Figure 4.2 Comparison of variation between cores from each section

4.4.2 Creep Modulus and m-value

As can be seen in Table 4.1, the values of the creep modulus varied widely even though all asphalt binders used had the same low-temperature grade. For example, SR 171 had an average creep modulus of 2,700 MPa while SR 48 had an average creep modulus of 10,600 MPa despite the fact that both of these sections used PG64-28 binder. The m-values for these two sections were 0.252 and 0.156, respectively.

This indicates that both binder and mixture properties influence performance characteristics of pavements. Other research has shown similar results and has tried to bridge the gap by modeling the different components [27]. BBR testing allows for direct measurement of mixture properties.

As previously mentioned, the results had a wide range of creep moduli and m-values. However, two roads stood out: SR 111 and SR 48 both had relatively high creep modulus when compared with the other roads. Material with a high modulus has been shown to be prone to thermal cracking, as discussed previously [24]. A very simple explanation is a drop in temperature causes thermal strain ($\varepsilon = \alpha\Delta T$) and stress is $\sigma = \varepsilon E$. Because of this, it was predicted that these two roads had the highest potential to show low-temperature thermal distress.

5. FIELD SURVEYS

In order to make a direct comparison of data to field performance it was necessary to evaluate the roads from which the cores came from. The location of the core removal was found in every road to ensure the accuracy of the survey. Each road was surveyed and photographed to document signs of thermal cracking and degradation or the lack thereof. Surveys were conducted on three separate occasions:

1. June 13, 2012
2. January 9, 2013
3. January 23, 2013

The surveys that took place on June 13, 2012, resulted in no visual thermal distresses on any of the sections in question. Surveys on January 9, 2013, also showed no thermal distresses. In the days following January 9, 2013, the Salt Lake Valley experienced a stretch of extremely cold weather, as shown in Figure 5.1.

In the days following these extremely low temperatures, it was determined that one more round of visual surveys would be necessary. On January 23, 2013, each section was surveyed once more. As predicted, SR 111 showed signs of thermal distress in the form of thermal cracking. This can be seen in Figure 5.2. SR 48 and all other roads did not display thermal distresses of any kind.

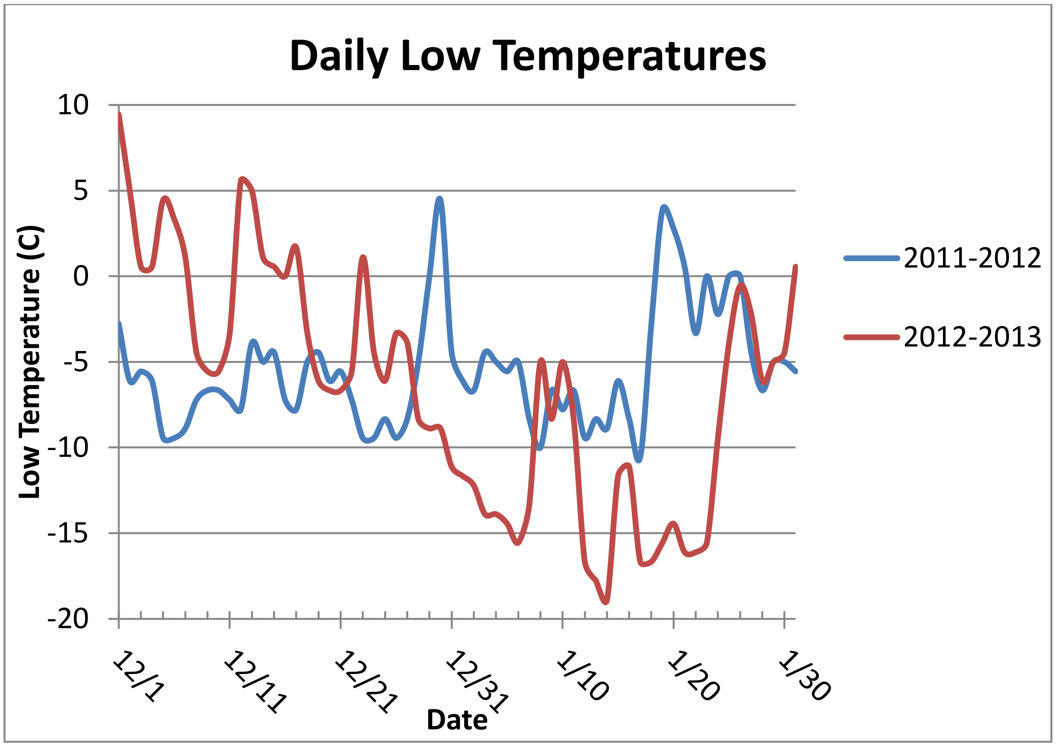


Figure 5.1 Daily low temperatures for Salt Lake City [28]

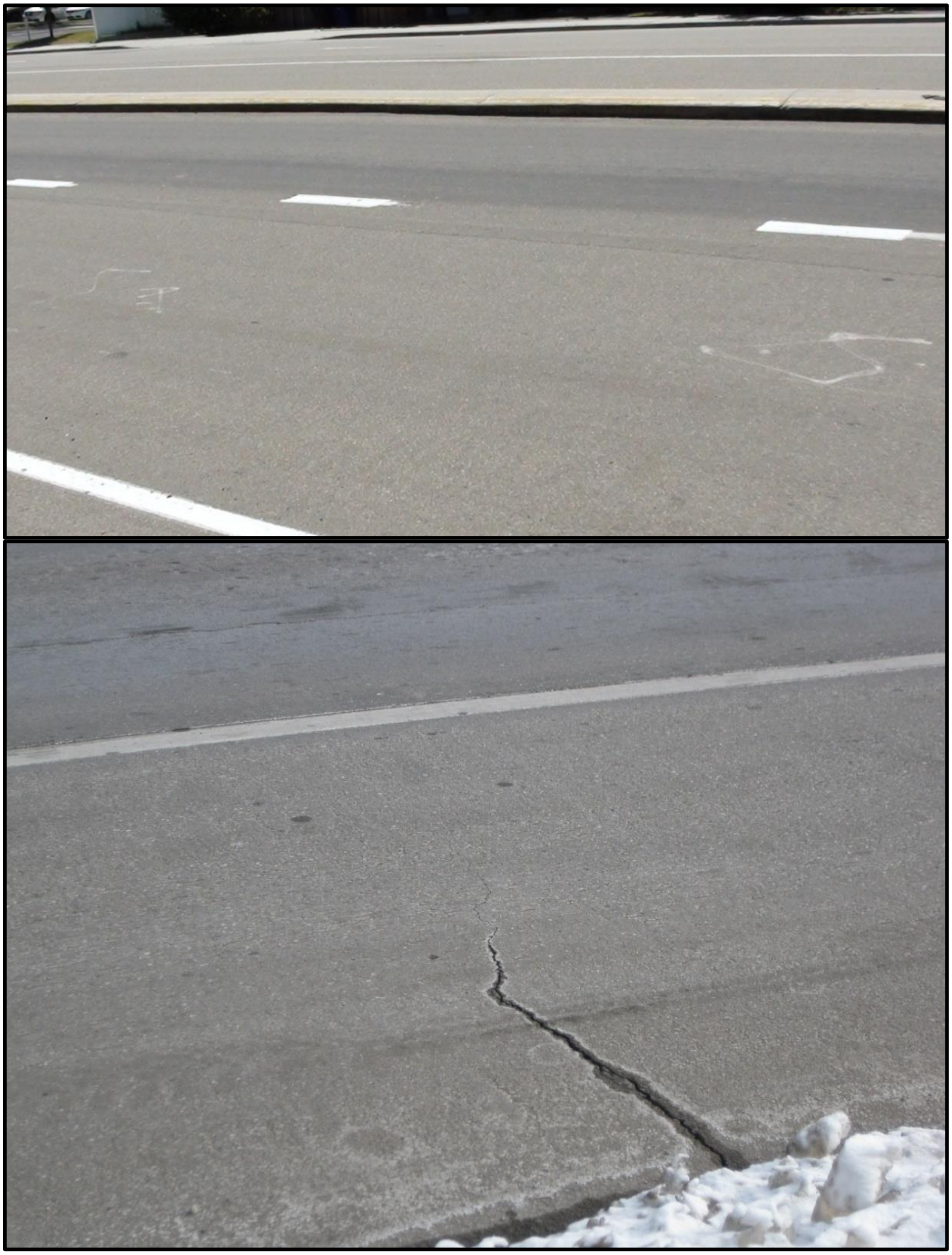


Figure 5.2 SR 111 on June 13, 2012, no visible thermal distress (Top) and January 23, 2013, showing a thermal crack (Bottom)

Although both SR 111 and SR 48 have high creep moduli, SR 111 has a significantly lower m-value, or a lesser ability to relax. This observation leads to the idea that energy, absorption and loss, must be considered when evaluating asphalt concrete mixtures.

5.1 Black Space

As discussed on the previous section, both the creep modulus and the m-value are needed to predict low-temperature cracking. The m-value is related to the energy dissipated. In a viscoelastic material, such as asphalt concrete, phase angle is the time delay of a material's reaction to an applied load during a sinusoidal type test. Mathematically, the phase angle is approximately equal to the derivative of the logarithm of stiffness, much like the m-value [29].

Rheological plots, which relate a dynamic modulus such as shear modulus (G*) and phase angle (δ), are known as Black Space diagrams. These diagrams are typically created from results of Dynamic Shear Rheometer testing, but since at low temperatures asphalt mixtures have very low phase angles it is reasonable to substitute stiffness and m-value from BBR results for G* and δ, respectively, in the Black Space diagram [30]. It has also been suggested that the use of Black Space diagrams be restricted to samples of the same geometry. This is also consistent for the application of testing of asphalt concrete beams with the BBR [31].

Asphalt concrete mixtures are viscoelastic materials; because of this, it is important to evaluate not only the structural reaction which takes the form of stress, but also the energy component of the reaction. When a viscoelastic material is loaded, the work done by the external load is either stored as potential energy by the material or lost through heat, flow, etc. At low temperatures, the flow of the material, asphalt concrete, is limited. When the material's rate of relaxation fails to keep up with the rate of deformation, the energy balance is maintained by the creation of a new surface in the form of a crack. Black Space diagrams allow for evaluation of the relationship of creep modulus and m-value when assessing BBR test results of asphalt mixtures. Although Black Space diagrams typically create a master curve from multiple data points, a variation of this method could compare multiple mixtures by way of a single point of evaluation. In the case of BBR testing, it is logical to choose 60 seconds since it is the default output of the test. Figure 5.3 shows the Black Space diagram of the field samples.

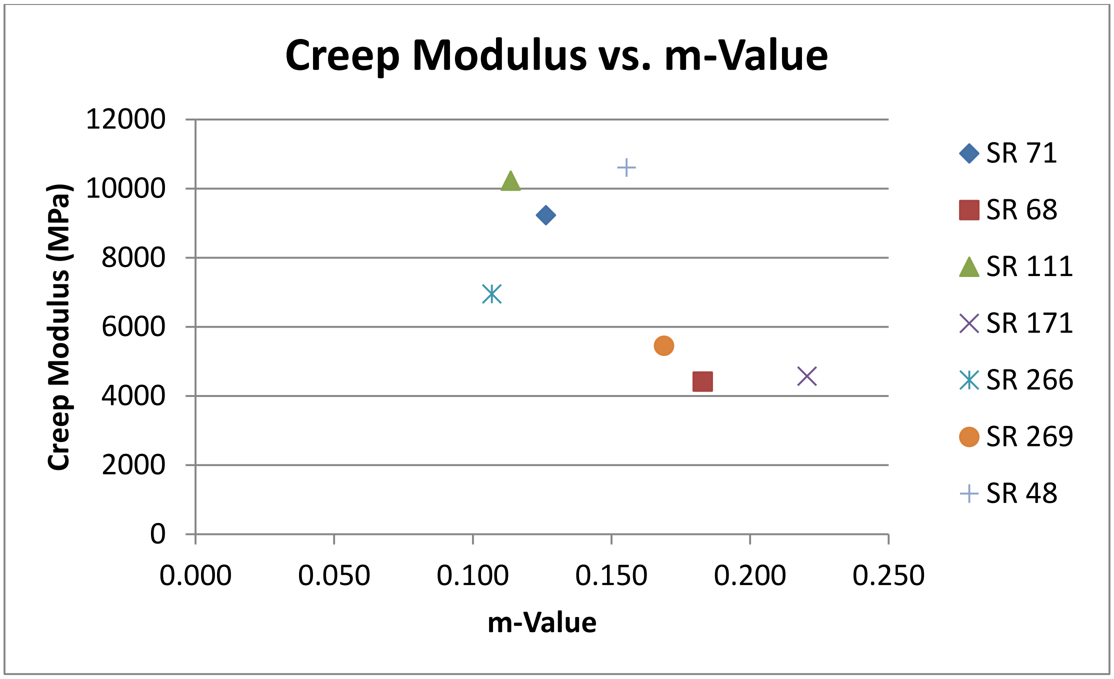


Figure 5.3 Black Space diagram of field samples

6. LABORATORY SAMPLES

It was clear that the next step in the study would be to reproduce laboratory samples of each section for which the correct materials were available. This is important at the mix design phase as results will help determine if laboratory samples are representative of how the mixture performs in the field. If the test results from the laboratory samples correlate with the test results of the field cores, then, theoretically, samples could be created and tested to determine the low-temperature performance of the mix prior to construction to avoid costly failures.

The samples were constructed following the original mix designs and by using the same raw materials, even going so far as to collect aggregates and RAP from the same pits and using binder of the same year from the same plant. Once the laboratory samples were created, they were tested and analyzed following the same protocol as previously described.

6.1 Creep Modulus and m-value

A summary of laboratory sample test results can be seen in Table 6.1. Laboratory sample results displayed a wide range of creep moduli and m-values. All samples also had a satisfactory coefficient of variation.

Table 6.1 Summary of Lab Results

Project	Binder Grade	Creep Modulus @ 60s, -18ºC (MPa)	Coefficient of Variation of Creep Modulus (%)	m-Value @ 60s, -18 ºC
SR 68	PG64-28	14 842	12.7	0.156
SR 71	PG64-28	8 367	15.5	0.162
SR 111	PG64-28	9 578	12.2	0.161
SR 171	PG64-28	11 403	15.4	0.150
SR 266	PG64-28	14 900	15.4	0.141
SR 269	PG64-28	13 141	15.7	0.132

7. COMPARISON OF LAB AND FIELD RESULTS

The test results of laboratory samples and field samples were compared. Figure 7.1 shows the comparison of creep moduli for each available section. Figure 7.2 shows the comparison of m-values for the same sections. A line of equality is present in both figures. It can be seen that, except for two sections, the creep modulus for laboratory samples is considerably greater than that of the field samples of the same mix design. They also do not show a linear correlation as would be expected. It is also apparent that the m-value for laboratory samples and field samples do not demonstrate any correlation with each other.

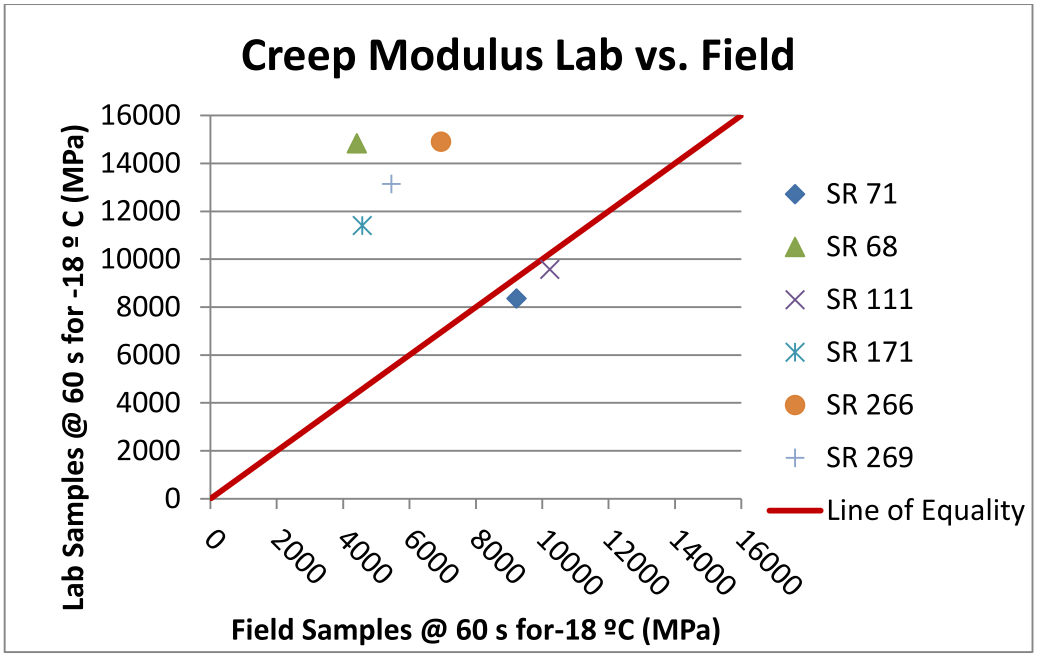


Figure 7.1 Comparison of laboratory and field sample creep moduli

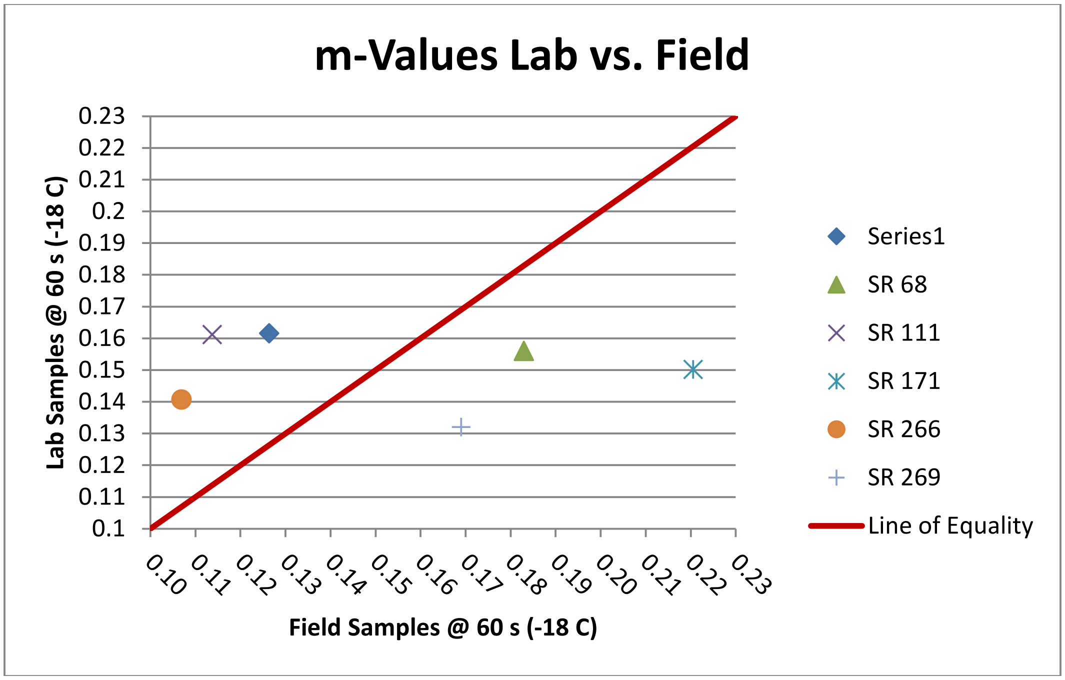


Figure 7.2 Comparison between laboratory and field sample m-values

Possible explanations for the reasons the laboratory sample results do not match that of the field samples include variation regarding RAP and aggregate sources and mixing methods. Although care was taken to obtain RAP and aggregates from the same source as the original mixture, it is possible, and likely in the case of RAP, that the material obtained is not identical to the material used in the original mix. It is possible that the source of the RAP used to create the laboratory samples has aged differently, resulting in different absorption and in different binder grades than the RAP used in the field mix. If this is true, then the response of the laboratory mix will be different than that of the field mix even though both mixes had similar RAP content. Another possible source of variation comes from mixing methods. In the lab, it is possible to precisely control the lending and mixing procedure. Such control is much more difficult to achieve in the construction process with such large batches. Any deviation in the mixing procedure could produce varied results.

Given the difficulties in reproducing field properties in the lab, it became clear that more research is needed to achieve satisfactory results. Such research was outside the scope of this project so no further analysis was performed.

8. CONCLUSIONS

The purpose of this study was to:

1. measure low-temperature response of asphalt from field cores
2. assess the practicality of using the BBR to test field mixtures
3. compare test results to observed field performance
4. determine whether a specification value can be obtained to determine low-temperature performance of the pavement
5. determine if laboratory prepared samples are representative of field samples of the same mix design

The response of field cores and subsequent viscoelastic analysis showed that even though the same binder grade is used in the region, the resulting asphalt mixtures have significant differences in creep moduli and m-values. This leads to the conclusion that binder testing alone might not be enough to control the material's creep modulus. Mixture testing in thus necessary to properly characterize asphalt mixtures and predict performance.

The results show that using the BBR to test field mixtures was found to be practical; the process is simple. A core can be taken from the project in question; the uppermost layer can be removed even if it is only one to two inches thick. The layer in question can be cut into small beams, which can then be measured and tested within a short period of time. Although not done in this study, it has been shown that coring, cutting, and testing at one temperature could all be completed for a single core within one work day.

The first two rounds of field surveys showed that no cracking was present on the seven sections evaluated. After the Salt Lake Valley experienced of period of extremely low temperatures, another survey was conducted. One of the two sections with relative high modulus, SR 111, showed signs of thermal distress; the other section, SR 48, did not. The difference between those two sections was the m-value. SR-48 had a higher m-value thus had a better ability to relax thermal induced stressed.

It is theorized that a specification used to predict low-temperature performance will need to include the creep modulus and the relaxation ability of the material, which are represented through the creep stiffness and the m-value output of the BBR test. When evaluating the Black Space diagram, the relationship between creep moduli and m-values, it can be seen that a possible thermal stress failure envelope could be developed. An example of this possible envelope is depicted as a red line in Figure 8.1. It is clear that there are two distinct groups in the relationship: one group is near the envelope while the others are distant. SRs 48, 71, 111, and 266 are all near the possible envelope. Although only SR 111 has shown thermal stress to date, it is likely that the other three sections near the envelope are more "at risk" to thermal distress and would be expected to crack prior to the sections that are further away from the envelope.

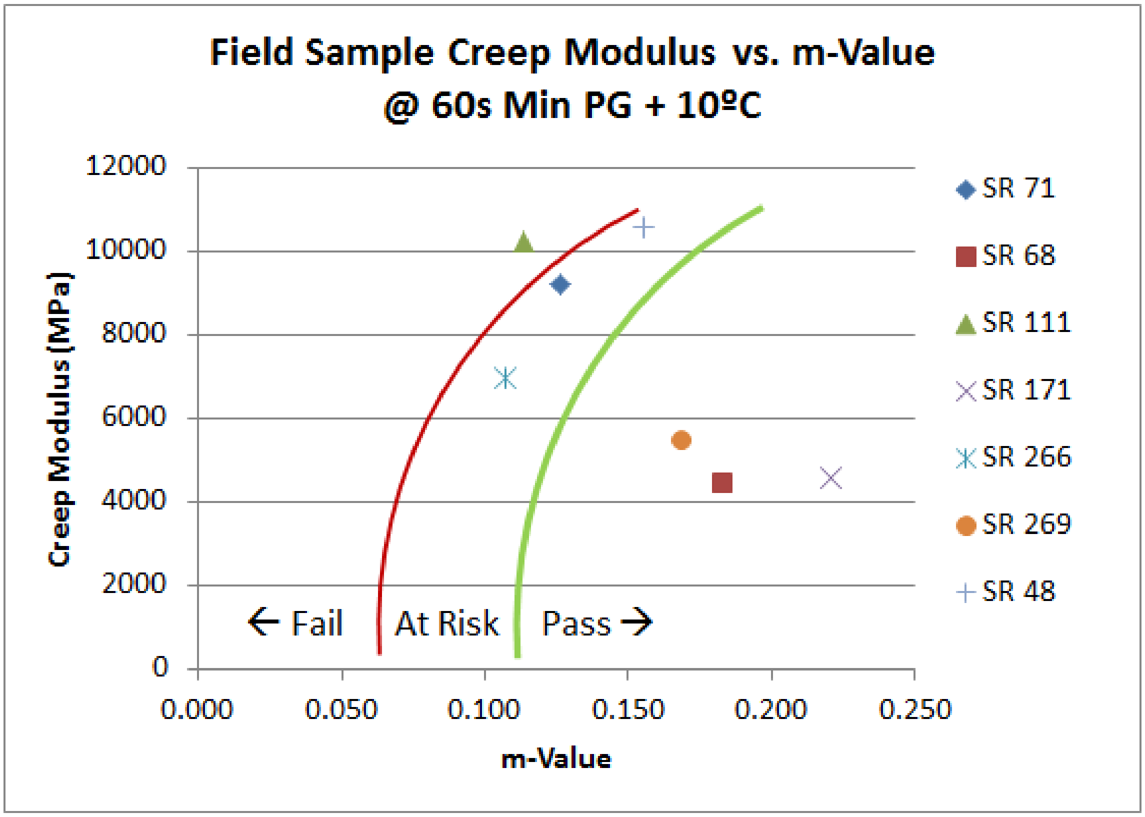


Figure 8.1 Black Space diagram with the possible thermal stress failure envelope

Based on the proposed failure envelope, it is theorized that a mixture with high modulus can be used in pavement construction as long as it has a high m-value. Knowing that a high modulus mix with a high m-value can successfully perform at low temperatures can be beneficial, in that they can also resist permanent deformation. These results thus help optimize mixtures for both high and low temperature conditions.

Finally, although every attempt was made to reproduce field mixture properties in the lab, it became evident that the same material sources would result in different mechanical properties. Thus, lab mixtures are not considered representative of field mixes for this project. The reasons for these differences are not clear and should be further investigated.

While surveying the roads within this project, adjacent roads were also observed. These roads theoretically experience identical thermal conditions as well as similar traffic conditions. Nearly all adjacent roads showed thermal distress as well as other distresses not present on the roads evaluated as part of this project. Although information regarding the age and design of these adjacent roads is not available, it is clear that the UDOT constructed roads are performing at a much higher level. This indicates that the construction quality and/or maintenance for non-state road projects is lower than that of state projects and suggests that, as a minimum, UDOT construction and maintenance standards should be implemented in all projects.

9. RECOMMENDATIONS

It is recommended that all sections that displayed a creep modulus/m-value relationship near the possible thermal stress failure envelope continue to be monitored for thermal distress.

Further research should focus on taking field cores of thick layered pavements with known mix designs that show thermal distress to verify the conclusion which states that pavements with a combination of high creep moduli and low m-values are more prone to thermal distress. Analysis of more mixtures that are prone to thermal stress will allow for a more accurate definition of the proposed thermal stress failure envelope. Field testing of pavements that do not show thermal distress will also be beneficial in defining the thermal stress failure envelope. Sources of these pavements should not be limited to state roads; they should also include city, county, and federal sections.

It is clear that more research is needed in order to reproduce the response of field samples with lab samples and thus predict performance. It is recommend that for future new construction or full-depth reconstruction projects, a sample of field mix be stored in a sealed can in order to prevent aging. This will allow for the mix to be compacted in the lab and tested. Results from these tests would help indicate whether the relationship between lab and field samples is strictly influenced by material variance or construction differences.

Finally, data should be collected as part of every new project and shared with producers to determine the range of low temperature properties of the material currently being produced as well as the ability of the asphalt mixture producers to meet future specification requirements.

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