MOUNTAIN-PLAINS CONSORTIUM

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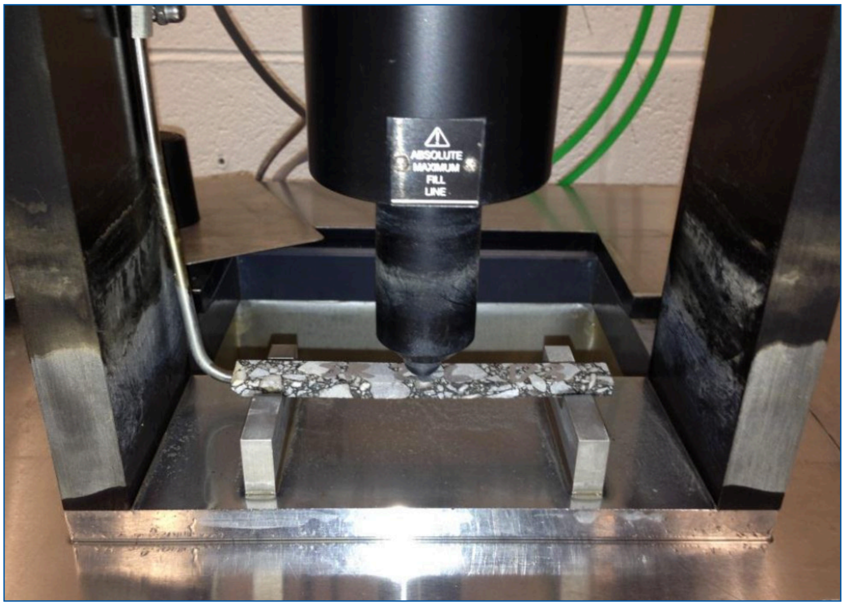
FIELD PERFORMANCE OF ASPHALT PAVEMENTS AT LOW AND INTERMEDIATE TEMPERATURES



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16. Abstract

Asphalt mixtures were collected from seven field projects and distributed to different laboratories to determine their potential for cracking. Samples were prepared in the lab for testing at two conditions: low, in-service temperatures using the bending beam rheometer device based on AASHTO TP-125 and intermediate temperature using the Illinois Flexibility Index tests based on AASHTO TP-126.

All mixtures are suitable for a low temperature of -22 ºC, but only three of the mixtures are suitable for a low temperature of -34 ºC. At an intermediate temperature of 25 °C, two mixtures had a low flexibility index value and are predicted to show premature cracking.

Evaluation was also done regarding the change in properties from the aging that occurs between mixing and laydown. In three mixtures, the changes were of sufficient magnitude to make a detrimental difference in the performance predictions. Comparisons between different laboratories were conducted to evaluate the tests variability.

This work indicates that while the tests can differentiate between different mixtures, work still need to be done to reduce their variability. A follow-up study is recommended to document the field performance of the mixtures and compare it to the laboratory predictions.

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Field Performance of Asphalt Pavements at Low and Intermediate Temperatures

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Disclaimer

ABSTRACT

Asphalt mixtures were collected from seven field projects and distributed to different laboratories to determine their potential for cracking. Samples were prepared in the lab for testing at two conditions: low, in-service temperatures using the bending beam rheometer device based on AASHTO TP-125 and intermediate temperature using the Illinois Flexibility Index tests based on AASHTO TP-126.

All mixtures are suitable for a low temperature of -22 ºC, but only three of the mixtures are suitable for a low temperature of -34 ºC. At an intermediate temperature of 25 °C, two mixtures had a low flexibility index value and are predicted to show premature cracking.

Evaluation was also done regarding the change in properties from the aging that occurs between mixing and laydown. In three mixtures, the changes were of sufficient magnitude to make a detrimental difference in the performance predictions. Comparisons between different laboratories were conducted to evaluate the tests variability.

This work indicates that while the tests can differentiate between different mixtures, work still need to be done to reduce their variability. A follow-up study is recommended to document the field performance of the mixtures and compare it to the laboratory predictions.

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EXECUTIVE SUMMARY

The work presented in this document is part of a continuous effort to develop mechanical tests that can relate to the expected performance of asphalt mixtures once placed in the field. In support of such effort, asphalt mixtures were collected from seven different locations across the state of Utah. The mixtures had different components and were designed using different procedures (Superpave and Marshall). Once locations of material production were identified, staff were sent to collect enough samples for testing. The asphalt mixtures were collected at two locations: at the plant and at laydown in the field. At the plant, material was obtained from the conveyor slat as it came from the mixer; while at laydown, the material was collected from the windrow dump. For all cases, the material was placed in five-gallon metal buckets and sealed while still hot. The temperature of the material at sampling was recorded and then transported to a central location where it was distributed to the three different testing labs.

The asphalt mixtures were compacted in the laboratory where samples were prepared for testing at two conditions: low, in-service temperature using the bending beam rheometer based on AASHTO TP-125 and intermediate temperature using the Illinois Flexibility Index tests based on AASHTO TP-126.

Results indicate that all mixtures are suitable for an environment corresponding to a PG XX-22. At a lower temperature environment corresponding to a PG XX-28, four out of the seven mixtures are suitable; and at an even lower temperature corresponding to a PG XX-34, only three of the mixtures were found to be suitable. At an intermediate temperature of 25 °C, two mixtures had a low flexibility index value and are predicted to crack.

Evaluation was also done regarding the change in properties from the aging that occurs between mixing and laydown. In three of the mixtures, the changes were of sufficient magnitude to make a detrimental difference in the performance predictions.

Finally, comparisons between different laboratories were conducted, and it was concluded that enough differences still exist between the results to require further research.

The conclusions of this work indicate that while the tests can differentiate between different mixtures, work still need to be done to reduce the variability. It was recommended that a follow-up study be conducted to document the short-term performance of the mixtures in the field and compare laboratory predictions to field observations.

1. INTRODUCTION

1.1 General

Within its current practice, state transportation agencies are using aggressive rutting and stripping testing to qualify asphalt mixes for use in highway construction. This practice was in response to the typical distresses found in pavements from the late 1980s and early 1990s. In most states, this has generally resolved rutting issues, but has led to a detrimental effect on cracking and raveling behavior in the pavements. This one-dimensional approach has been recognized as a challenge to be addressed within the mix design process. Highway agencies have been seeking practical tests to provide a performance balance and increase mix durability. Asphalt mixes now contain Recycled Asphalt Pavement (RAP) and less asphalt binder — both virgin and total — in an attempt to resist rutting and save on materials. Furthermore, with the high cost of asphalt binder and the increase in available substitutes and modifiers, asphalt binder testing alone is no longer adequate to predict pavement performance. Therefore, mix performance testing at all temperatures is becoming increasingly important. Building a mix to avoid rutting and cracking requires a balance of priorities because these behaviors are often in direct conflict with each other. However, in the absence of practical tests, mix design and acceptance programs currently favor rutting resistance, leaving a clear imbalance and skewed performance. As the practice continues, these effects are becoming more pronounced. Should current practices continue without adjustment for durability performance, constructed pavements will continue to exhibit early age cracking (both thermal and fatigue) and the performance of the pavements will be significantly affected, leading to a significant loss of investment by highway agencies.

A new test to evaluate low temperature performance of asphalt mixtures was developed with previous funding assistance from the MPC. This test uses the existing Bending Beam Rheometer (BBR) to test asphalt mixes. Test protocols were created for both cores, and laboratory compacted samples and the relation to pavement performance was determined. This test was voted as an AASHTO provisional specification (TP-125) and could soon be adopted as a requirement for asphalt mix design. In a parallel effort, the Semi-Circular Bending/Fracture Energy test (SCB) was determined as a feasible test for intermediate temperature performance and was also voted as an AASHTO provisional specification (TP-126). By using these two tests (BBR and SCB), mixes can be evaluated for cracking potential in regard to RAP content, asphalt binder content, binder modification, etc., resulting in a complete performance-related specification.

However, adoption of any pavement performance specification requires an understanding of ALL aspects of mixture design, including questions, such as: How will the new requirement affect the binder content? How will the new requirement affect the durability of asphalt pavements? How will the requirement affect current rutting tests (i.e., Hamburg Wheel Tracking results)? How do these tests complement each other?

This research attempts to answer these questions by evaluating selected asphalt mixtures for low-temperature cracking and intermediate temperature fracture energy to ensure that the addition of a low-temperature test will not affect the high temperature performance or the durability of pavements. This work will allow for better optimization of mixes and reduction of poor performance potential of highway assets.

1.2 Research Objectives

The overall objective of this work is to determine the applicability of the Bending Beam Rheometer on asphalt mixtures and the semi-circular bend test, as described in AASHTO TP125 and 126, respectively, to predict short-term low- and intermediate-temperature field performance.

Specifically, this work evaluated asphalt mixtures collected from paving projects across the state of Utah and researched their difference in term of predicted performance. The following steps were followed:

1. Collect material from different projects across the state of Utah.
2. Test the materials in the laboratory to determine the range of low temperature properties.
3. Test the materials in the laboratory to determine the range of intermediate temperature properties.
4. Determine how changes in mixture characteristics and aging between production and delivery to the paver affect the test results.
5. Establish relations between the different tests and their ability to predict field performance.

1.3 Scope

This study consisted of the evaluation of asphalt mixture properties at two different temperature ranges (low and intermediate) using two different tests. One test — the BBR — addresses the cold temperature properties while the other — the SCB, — addresses the intermediate temperature properties of asphalt mixtures. Data was produced by preparing samples appropriate for each method and testing them based on established protocols or controlled testing variations.

The materials used in this study were obtained from asphalt mixture plants situated across the state of Utah intended for actual road construction. While every effort was made to use consistent materials, it was recognized that there were small differences in composition from the one location to another and from one sample unit to the next.

2. LITERATURE REVIEW

2.1 Overview

Asphalt mixtures are complex composite materials that, once placed in the field, are meant to withstand severe temperature extremes. To develop a more mechanics-based approach to evaluate potential asphalt mixture performance, two tests setups were proposed, the Bending Beam Rheometer to evaluate low temperature (thermal) cracking and the Semi-Circular Bend (SCB) to evaluate intermediate temperature (fatigue) cracking. The development of these two tests is discussed here.

2.2 Low Temperature Testing and Evaluation

As a simple, fast, relatively inexpensive, and repeatable method of testing, low-temperature properties of asphalt mixtures, researchers proposed the use of small beam specimens (12.7 mm width x 6.35 mm thickness x 127 mm length) made from asphalt concrete and tested on the Bending Beam Rheometer (BBR) (1, 2). It was shown that this testing configuration could be used to evaluate low-temperature properties comparable to other mixtures tests, such as the Indirect Tensile Test (IDT). These tests do not necessarily result in the same numerical value for creep modulus but, the comparison between the two of them are highly correlated (3). Moreover, it has been demonstrated that both "creep modulus or stiffness" and "stress relaxation capacity or m-value" (slope of the logarithm of modulus vs. the logarithm of time curve) play a significant role in low-temperature performance of asphalt pavements. Asphalt concrete mixtures with high creep moduli and low m-values at their environmental design temperature (i.e., performance grade) are more susceptible to low-temperature thermal distress (4). Success in these studies led to the formation of a provisional test standard for determining low-temperature properties of asphalt mixtures i.e., AASHTO TP125-16.

2.3 Intermediate Temperature Testing and Evaluation

To evaluate intermediate-temperature performance (i.e., fatigue cracking) in asphalt materials, many tests have been developed including indirect tension test (IDT), dissipated creep strain energy test (DCSE), four-point beam fatigue test (FBT), single-edge notched beam (SEB), disk-shaped compact tension (DCT), Texas overlay tester (OT) and semi-circular bending test (SCB).

Most tests that use fracture energy to rank fracture toughness were developed by researchers in the field of rock or ice mechanics. These tests are specified for cored-based specimens with modifications to the Chevron bend specimen and short rod specimen (5). In this manner, the SCB test was originally developed to determine crack resistance and crack growth rate in rocks.

During the 1990s, the SCB test was proposed for bituminous mixtures. It was believed that this configuration was easier in comparison to other methods that were expensive and complex for regular use (6). The SCB test gained some popularity for property characterization, such as crack resistance, by determining fracture toughness of asphalt mixtures in the early 2000s. The popularity of the test is due to simplicity in terms of specimen preparation using the Superpave Gyratory Compactor (SGC) or coring from the field (7, 8, 9). Many researchers used SCB to study fracture properties of asphalt specimens at low temperature to differentiate cracking resistance (8, 9, 10, 11). Standard protocols to unify different methods of SCB test at low temperatures, such as EN12697-44: 2010 (12) and AASHTO TP105-2013 (13), were established. Recently, many researchers have studied the intermediate temperature fracture resistance of various asphalt mixtures using the same SCB test configuration (14 – 21) leading to the development of parameters, such as the Flexibility Index (FI).

The goal of the SCB development was to eliminate mixtures that have a tendency for premature failure through a cracking-related mechanism. In this manner, the asphalt mixtures would be tested in the laboratory prior to production. The ones characterized as improper by the fracture resistance properties would be eliminated. While this is an extension of the low-temperature testing, it is believed that the fracture resistance at intermediate temperature would result in better fatigue performance of the pavement in the field. Standard protocols have been developed for different methods, such as ASTM D8044-2016 (22), known as the Louisiana method of SCB test, and AASHTO TP124-2016 (23), known as the Illinois flexibility index (I-FIT). These standards specify test procedures such as loading rate, specimen geometry and support conditions to obtain a value for fracture resistance.

Geometry and the loading configuration of SCB test, based on the standards, ensures that the tensile fracture (mode I) is dominant. Energy dissipation in SCB test is primarily governed by fracture mechanisms of crack initiation and crack propagation. To investigate the fracture mechanism in SCB, Arabani and Ferdowsi studied SCB tests and compared them to a suite of conventional tests, such as indirect tensile strength test (ITS). It was observed that the SCB specimens fail with less distortion and a clear and anticipated crack path while the ITS test exhibits multiple modes of failure including wedging (14).

Promising configuration of SCB test and convenient fabrication of specimen from gyratory pucks encouraged Mull et al. to investigate the applicability of the SCB specimens by Jc characterization. Traditionally, J-integral values have been implemented by researchers as a tool to investigate fatigue crack growth of different materials. In a fatigue crack propagation study on asphalt mixture SCB specimens, Mull et al. investigated the energy release rate Jc from the fatigue hysteresis loops as a comparative tool. It was observed that compliance of the specimen increases with increased crack length (16).

Mohammad et al. investigated the sensitivity of J-integral values with varied notch depths and different asphalt mixtures to the indirect tensile stress and strain test results. Their study asserted that the concept of toughness (fracture toughness) is directly related to intermediate temperature crack performance (fracture resistance) in pavements. The Louisiana State University Model (LSU) assumes that the energy (toughness) to move a crack at any point along the developing crack path is the energy under the stress-strain curve to the point that crack propagation commences. They observed that J-integral values from the semi-circular fracture test were sensitive to the change in asphalt binder type. It was found that the SCB measured Jc values demonstrated a good correlation with field cracking performance data (18, 19).

Al-Qadi et al. developed another test method that has been implemented to calculate fracture energy. This test is known as the Illinois Flexibility Index Test (I-FIT). They found that the results have consistent and repeatable trends corresponding to changes in AC mixture design properties (20).

Nsengiyumva et al. investigated an experimental-statistical approach on SCB testing variables (i.e., the minimum recommended number of specimens, thickness, notch length, loading rate, and testing temperature) to evaluate fracture behavior of AC mixtures at intermediate service temperature conditions. Based on the test-analysis outcomes, it was concluded that the temperature of 21˚C, the loading rates of 0.1 to 0.5 mm/min, 5 mm length of the notch, thicknesses of 40 to 60 mm and a minimum of five to six samples are the statistical minimum to sufficiently represent fracture behavior of asphalt samples (21).

Many departments of transportation (DOT), including Utah DOT, have been trying to address balanced asphalt mixtures to reduce premature failures and improve pavement performance by implementing the SCB standards. In this manner, VanFrank et al. evaluated the SCB test based on the Louisiana protocols and concluded that the standards provided trends that were consistent with the expected behavior. However, the sample preparation — especially the different notch lengths — and the data analysis based on ASTM D8044-2016 were deemed too difficult for routine testing (23). Romero and VanFrank evaluated more samples to determine if FI as proposed by Illinois could detect changes in mixture components. This study explored the effects of increased or reduced binder content, increased RAP content, and increased laboratory aging on the same materials (2). The conclusions were that the FI can differentiate between different mixtures composition, such as binder content, RAP content, and aging. Based on this work, FI was selected as a viable candidate to evaluate the intermediate temperature performance of asphalt mixtures in Utah.

2.4 Summary

Based on the literature review, it is evident that the BBR and SCB can be successfully used to evaluate the cracking performance of asphalt mixtures. The parameters obtained from BBR testing, namely creep modulus and relaxation capacity (m-value), have been shown to relate to field performance, high modulus and low m-value and would result in poor performing mixtures. The parameter obtained from SCB testing, namely Flexibility Index, has been shown to follow the expected trends that might result in poor performance. Both tests combined elements of mechanics-based analysis, with some practicality, to allow for adoption as routine tests.

3. MATERIAL COLLECTION AND SAMPLE PREPARATION

3.1 Overview

The objective of this work was to obtain a representative sampling of the material produced in the state of Utah and then measure their low- and intermediate- temperature properties using the proposed tests. Knowledge of the range of properties, and eventually the performance of the materials once place in the field, will allow for the development of a specification limit capable of reducing the risk of early failure from cracking.

3.2 Material Selection

The state of Utah has a diverse climate and geology, as such, it is expected that mixtures with different properties are produced across the state. Therefore, the plan for material selection consisted of identifying projects across the state where mixtures were being placed during spring and summer 2018 and where access was available within the available resources. To understand how different asphalt mixtures respond to the proposed testing, the range of mixtures was not limited to mixtures used by UDOT and, as such, mixtures with higher RAP content that normally would not be placed on UDOT roads were collected. Also, mixtures designed using both Marshall and Superpave methods were selected.

3.3 Material Collection Process

Once the locations of materials production were identified, staff were sent to collect enough samples for testing. Material was collected at two locations: at the plant and at the field at laydown. At the plant, material was obtained from the conveyor slat as it came from the mixer; while at laydown, the material was collected from the windrow dump. For all cases, the material was placed in five-gallon metal buckets and sealed while still hot. The temperature of the material at sampling was recorded. The material was then transported to a central location where it was distributed to the three testing labs.

3.4 Material Properties

The material collected as part of this study had the properties listed in Table 3.1 based on the mixture design information provided by the producers. The name of the producers, or the exact location where the mixtures were obtained and placed, is not provided in this report to respect any proprietary business information.

Table 3.1 Description of Materials Collected

Mix ID	Design Method	Aggregate NMAS	RAP Content	Total Binder by Mass	Virgin Binder by Mass/ Vol	Virgin Binder	Intended Climate
UT-01	50-Blow Marshall[1]	12.5 mm	30%	5.4%	3.8%/ 9.0%	PG 64-22	Hot
UT-02	75-Blow Marshall[1]	19 mm	30%	4.9%	3.4%/ 9.6%	PG 58-34	Medium
UT-03	75-NDES Superpave[2]	12.5 mm	25%	5.3%	4.0%/ 9.6%	PG 64-34	Cold
UT-04	75-NDES Superpave[2]	12.5 mm	15%	5.3%	4.6%/ 10.9%	PG 64-34	Medium
UT-05	50-Blow Marshall[1]	12.5 mm	30%	6.3%	4.4%/ 10.1%	PG 58-28	Cold
UT-06	75-NDES Superpave[2]	12.5 mm	25%	4.8%	3.7%/ 11.2%	PG 58-28	Cold
UT-07	75 NDES Superpave[2]	12.5 mm	10%	5.3%	4.9%/ 11.1%	PG 64-28	Medium

[1] Based on APWA specifications
[2] Based on UDOT 2741 specifications
All information provided by the supplier and not verified by research team

3.5 Sample Preparation

The material was collected and brought to a central location. From this location, buckets were distributed to three different laboratories: University of Utah, a private consultant, and UDOT Central Materials Lab. These labs will be referred to in this report as Labs A, Lab B, and Lab C, respectively.

Given that the amount of materials was limited, Lab B performed extensive volumetric testing on each mixture to determine the maximum theoretical specific gravity, Gmm, of each mixture. Knowing the Gmm was necessary so the right amount of material could be added to the Superpave gyratory compactor and achieve the target air voids. However, even with all the volumetric testing at one lab, the process still required a trial-and-error process until the right quantities were determined. Small variations in material made it sometimes difficult for the other labs to achieve the exact target air voids during compaction of their first gyratory cylinder; most materials required a second compaction. Lab A utilized the first compacted cylinder to evaluate the effect of air voids and other “out of spec” variables; Lab B only reported testing results of the final compaction while Lab C only reported one specimen. Once ready, the samples were cut for SCB testing in each of the three labs. All three labs found that producing consistent cuts was difficult and many of the samples did not meet the production standards defined by the test procedure. These inconsistencies may have introduced some level of variability to the test values; however, all the results were used when analyzing results. Lab A also tested the material in the BBR for low temperature performance; Lab C did a limited number BBR testing to verify test results.

4. EVALUATION OF FIELD-PRODUCED MATERIAL USING THE BBR TEST

4.1 Overview

As previously described, asphalt mixtures from seven different projects were tested for low temperature properties using the procedures described in AASHTO TP125. All BBR testing was done at Lab A with limited tested done at Lab C. The details of the seven mixtures were presented in Table 3.1.

4.2 Sample Preparation and Testing

Once the materials were received in the lab, the collected mixture was cataloged and the material available was weighted. Based on the information provided by the producer and volumetric results measured at Lab B, enough material was weighted, so a 110-mm high gyratory cylinder could be compacted to 4 ± 1 % air voids. This range of air voids was used since previous studies have indicated that results from the BBR are not particularly sensitive to air voids within that range. For each mixture, a gyratory cylinder was compacted and allowed to cool; it was cut into small beams based on the procedures described in AASHTO TP125-16. Over 20 samples were obtained from each cylinder out of which the best 12, in terms of consistent dimensions, were selected for testing.

The small beams were conditioned following the protocols described in previous studies (1, 2). Each beam was tested at three temperatures in order of coldest to warmest. Previous studies have demonstrated that repeated testing of the same beam is acceptable and does not affect the results (24). The test temperatures were -24 ºC, -18 ºC, and -12 ºC to represent the low temperature performance grade environments seen in Utah (PG XX-34, PG XX-28, and PG XX-22) and not necessarily the binder performance grade used in the mix. This was done, so the mix could be evaluated for a given environment and in recognition of the fact that the "true" binder grade of the mix once binder, aging, aggregates, and RAP interact is not known.

4.3 Results

Each mixture was loaded in creep for 180 seconds at each temperature. In practice, this provides the complete time- and temperature-dependent creep modulus of the material. However, given that the specification only requires data at 60 seconds, the data was summarized for that specific time. For each test, the creep modulus (referred to as modulus in this document for simplicity) and the relaxation capacity, or m-value (slope of the log-modulus log-time curve at the given time), were determined. The values for the 12 samples tested for each mix were averaged and the standard deviation was determined. These results are presented in Table 4.1 and Table 4.2.

As can be seen in the tables, the results are fairly consistent with a coefficient of variation below 25% in all cases and, in most, even below 15%. The data shows the expected trend of decreasing modulus and increasing m-value as the temperature increases. In four out of the seven sections (UT-02, UT-03, UT-06, and UT-07), there is an increase in modulus and a decrease in m-value between the material collected at plant and the material collected in the field, indicating that short-term aging occurred. In two sections (UT-01 and UT-05), there is not a clear indication of aging as the results are within the margin of error. Of concern are the results for UT-04, which shows an unexpected trend of decrease in modulus and increase in m-value between plant and field collection. Since this was unexpected, tests were run in Lab C at -24 ºC. The results from Lab C also show a decrease in modulus (11,569 MPa versus 10,520 MPa) and an increase in m-value (0.118 versus 0.141) for the same sampling locations, thus confirming the results of the test. It is unclear if these results are indeed a representation of some actual physical behavior, some outlying result, or a labeling mistake.

Table 4.1 BBR Results for Projects 01 through 04

	Testing Temperature, °C	**-24**		**-18**		**-12**	
	Sampling Location	**Plant**	**Field**	**Plant**	**Field**	**Plant**	**Field**
	Sample Size (n)	12	12	12	12	12	12
UT-01	**Ave. Modulus at 60s (MPa)**	**18 192**	**17 362**	**14 442**	**14 583**	**11 460**	**11 505**
	Standard Deviation, s	2089.57	4070.27	1532.95	1673.77	1353.08	1862.70
	Coefficient of Variation	0.11	0.23	0.11	0.11	0.12	0.16
	Average m-value at 60s	**0.089**	**0.098**	**0.123**	**0.110**	**0.166**	**0.147**
	Standard Deviation, s	0.0080	0.0165	0.0080	0.0125	0.0087	0.0141
	Coefficient of Variation	0.09	0.17	0.07	0.11	0.05	0.10
UT-02	**Ave. Modulus at 60s (MPa)**	**16 692**	**17 808**	**14 075**	**14 958**	**10 562**	**11 437**
	Standard Deviation, s	2042.93	3766.71	2230.42	2731.11	1213.21	1819.95
	Coefficient of Variation	0.12	0.21	0.16	0.18	0.11	0.16
	Average m-value at 60s	**0.087**	**0.106**	**0.118**	**0.118**	**0.158**	**0.152**
	Standard Deviation, s	0.0088	0.0143	0.0130	0.0121	0.0097	0.0138
	Coefficient of Variation	0.10	0.13	0.11	0.10	0.06	0.09
UT-03	**Ave. Modulus at 60s (MPa)**	**14 033**	**15 133**	**9 339**	**9 743**	**6 253**	**6 648**
	Standard Deviation, s	1867.59	1181.94	1431.96	2546.22	1297.29	1669.68
	Coefficient of Variation	0.13	0.08	0.15	0.26	0.21	0.25
	Average m-value at 60s	**0.126**	**0.121**	**0.170**	**0.169**	**0.241**	**0.242**
	Standard Deviation, s	0.0127	0.0128	0.0102	0.0163	0.0220	0.0155
	Coefficient of Variation	0.10	0.11	0.06	0.10	0.09	0.06
UT-04	**Ave. Modulus at 60s (MPa)**	**13 308**	**10 715**	**10 228**	**7 855**	**6 264**	**4 189**
	Standard Deviation, s	1302.07	2385.37	764.09	1437.04	763.13	725.95
	Coefficient of Variation	0.10	0.22	0.07	0.18	0.12	0.17
	Average m-value at 60s	**0.130**	**0.162**	**0.188**	**0.220**	**0.259**	**0.298**
	Standard Deviation, s	0.0130	0.0188	0.0080	0.0233	0.0106	0.0328
	Coefficient of Variation	0.10	0.12	0.04	0.11	0.04	0.11

Table 4.2 BBR Results for Projects 05 through 07

	Testing Temperature, °C	**-24**		**-18**		**-12**	
	Sampling Location	**Plant**	**Field**	**Plant**	**Field**	**Plant**	**Field**
	Sample Size (n)	12	12	12	12	12	12
UT-05	**Ave. Modulus at 60s (MPa)**	**20 083**	**19 917**	**17 167**	**15 408**	**12 408**	**11 921**
	Standard Deviation, s	2251.80	1444.63	3235.41	1981.02	1171.21	1580.20
	Coefficient of Variation	0.11	0.07	0.19	0.13	0.09	0.13
	Average m-value at 60s	**0.100**	**0.099**	**0.125**	**0.126**	**0.166**	**0.178**
	Standard Deviation, s	0.0130	0.0086	0.0141	0.0150	0.0128	0.0114
	Coefficient of Variation	0.13	0.09	0.11	0.12	0.08	0.06
UT-06	**Ave. Modulus at 60s (MPa)**	**14 507**	**20 808**	**12 101**	**16 225**	**8 043**	**13 125**
	Standard Deviation, s	3614.04	3749.05	2608.50	2414.02	1789.09	2012.74
	Coefficient of Variation	0.25	0.18	0.22	0.15	0.22	0.15
	Average m-value at 60s	**0.105**	**0.094**	**0.141**	**0.114**	**0.178**	**0.161**
	Standard Deviation, s	0.0113	0.0120	0.0129	0.0080	0.0189	0.0120
	Coefficient of Variation	0.11	0.13	0.09	0.07	0.11	0.07
UT-07	**Ave. Modulus at 60s (MPa)**	**12 479**	**14 683**	**9 836**	**11 686**	**6 061**	**7 335**
	Standard Deviation, s	3188.65	1888.64	2285.15	2284.05	1159.33	1405.58
	Coefficient of Variation	0.26	0.13	0.23	0.20	0.19	0.19
	Average m-value at 60s	**0.138**	**0.122**	**0.189**	**0.167**	**0.248**	**0.243**
	Standard Deviation, s	0.0170	0.0119	0.0260	0.0140	0.0281	0.0200
	Coefficient of Variation	0.12	0.10	0.14	0.08	0.11	0.08

Previous research (4) has recommended values below 12,000 MPa for modulus and m-values above 0.12 as a criterion for low- temperature performance. Based on the modulus limit alone, none of the mixtures tested are appropriate for a PG XX-34 environment, two (UT-03 and UT-07) are appropriate for a PG XX-28 environment and nearly all of them are adequate for a PG XX-22 environment. Using only the m-value as a criterion, UT-03, UT-04, and UT-07 might be appropriate for the PG XX-34 environment, and all, except UT-02, might be appropriate for the PG XX-28 environment; all mixtures have m-values above 0.12 at PG XX-22. However, performance is not based on one single value; research has shown that high modulus might have acceptable performance as long as the m-value is high.

4.4 Multi-Laboratory Comparison

To evaluate the between-labs variability of the tests, limited testing on the same material was performed at Lab C. Previous comparisons between the two labs have shown that a difference of less than 10% would be expected (24). The results, shown in Table 4.3, show a significant difference in the results obtained at the two labs.

Table 4.3 BBR Results at Lab A and Lab C

Section	Sampling Location	Test Temp, ºC	Creep Modulus, MPa Lab A	Lab C	Diff	m-value Lab A	Lab C	Diff
UT-01	Plant	-12	11 460	7 959	31%	0.166	0.149	10%
	Field		11 505	8 257	28%	0.147	0.108	26%
UT-02	Plant	-18	14 075	8 137	42%	0.118	0.128	-9%
	Field		14 958	8 358	44%	0.118	0.125	-6%
UT-03	Plant	-24	14 033	10 473	25%	0.126	0.120	5%
	Field		15 133	14 769	2%	0.121	0.149	-23%
UT-04	Plant	-24	13 308	11 569	13%	0.130	0.118	10%
	Field		10 715	10 520	2%	0.162	0.141	13%
UT-05	Plant	-18	17 167	9 705	43%	0.125	0.136	-8%
	Field		15 408	10 013	35%	0.126	0.115	9%
UT-06	Plant	-18	12 101	9 503	21%	0.141	0.136	4%
	Field		16 225	9 635	41%	0.114	0.122	-7%
UT-07	Plant	-18	9 836	6 371	35%	0.189	0.176	7%
	Field		11 686	9 398	20%	0.167	0.136	19%
				Average	27%		Average	3%
				Max	44%		Max	26%

On average, a difference of 27% in the creep modulus was measured; yet on the same data, the average difference in the m-value was only 3% with only three3 out of 14 tests having an absolute difference greater than 15%. Given that, in the past, multiple comparisons have been done between Lab A and Lab C that resulted in values closer to each other, and, that it is unlikely that the modulus would be different when the m-value is not, an investigation of the procedures followed by both laboratories was done. This consisted in staff from both labs visiting and discussing the procedures that were followed during specimen fabrication and testing. No specific cause was found, but it is known that small changes in air voids do not have a significant effect in the results. It is also known that steric hardening, does not play a role after a few hours; therefore, an error in measurement was suspected.

The first observation from Table 4.3 is the fact that the difference does not appear to be random. There is a bias in the data where Lab C results are always lower by an average of approximately 4,000 MPa when compared to Lab A. As previously mentioned, given that the m-value does not show such bias, an error in either load or deflection measurement is suspected. If a value of 4,000 MPa is added to Lab C's data, then the difference in the modulus between both labs decreases to an average of 3% with only three out of 14 sections showing a difference greater than 17%.

A comparison of the results both before and after the correction was applied is shown in Figure 4.1. The corrected values show better agreement between the two labs.

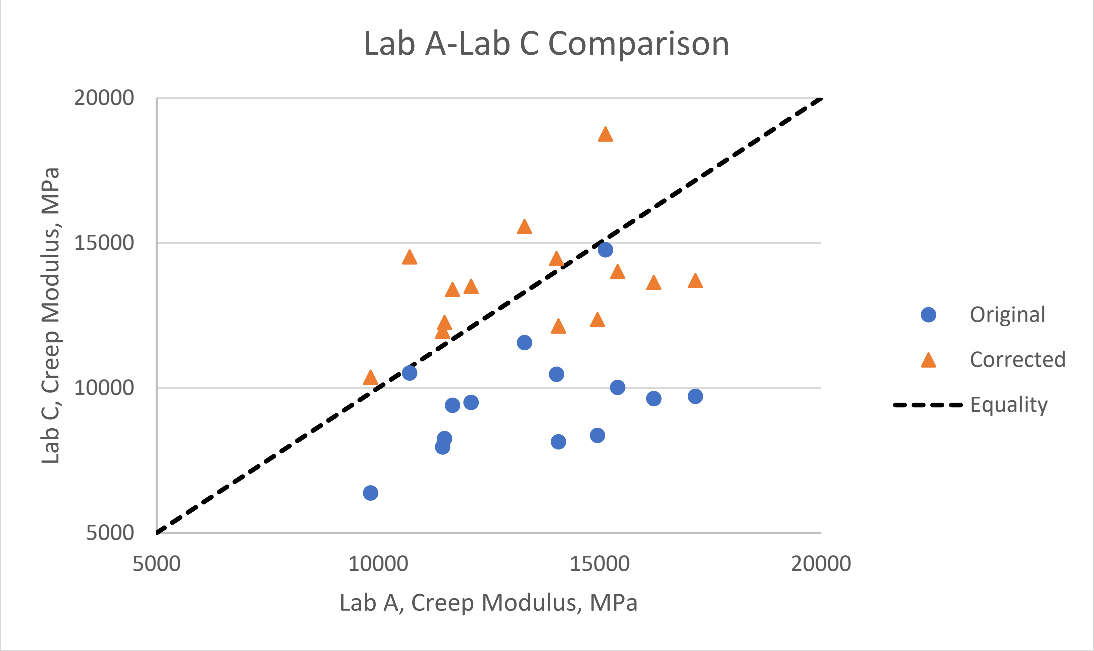

Figure 4.1 Comparison of Creep Modulus Between Lab A and Lab C

To verify that testing in both labs provides the same results once any errors were corrected, 10 new beams from a single mixture (different from the ones already evaluated) were tested at both labs. The results are shown on Table 4.4.

Table 4.4 Results from Lab A and Lab C on a new Material

Lab A		**Lab C**		**Difference (A-C)**	
Modulus MPa	m-value	Modulus MPa	m-value	Modulus	m-value
8 974	0.156	9 191	0.159	-2.4%	-1.7%

As shown in Table 4.4, a difference of less than 3% between both labs is observed for the modulus and the m-value. This is consistent with previous work.

4.5 Summary

The results from low-temperature testing of asphalt mixtures collected from seven field projects were shown in this chapter. While most mixtures have a modulus that might be considered too high for low temperature cracking, the combination of modulus and m-value might allow them to adequately perform. The expected performance is presented on Table 4.5.

Table 4.5 Predicted Performance at Different Environments

	Low Temperature Environment		
Mixture	**PG XX-34**	**PG XX-28**	**PG XX-22**
UT-01*	Fail	Fail	Pass
UT-02*	Fail	Pass	Pass
UT-03	Pass	Pass	Pass
UT-04	Pass	Pass	Pass
UT-05*	Fail	Fail	Pass
UT-06	Fail	Fail	Pass
UT-07	Pass	Pass	Pass

* Mixtures with 30% RAP

Comparison of the mixtures properties after short-term aging indicates the test is capable of quantifying the changes observed in the field that are mixture specific. In one case (UT-05), even after 17 hours of storage, the modulus and m-value did not change significantly; but, in another case (UT-06), 1.5 hours was enough to significantly change the properties between plant and laydown. This difference in the amount of aging measured for different mixtures is consistent with previous reports that showed certain combination of virgin binder and RAP to be more susceptible to aging.

Based on the results from BBR testing, it is apparent that the low-temperature properties of the mixes are dependent on the interaction between the asphalt binder type, grade, and amount; the type and amount of RAP; the aging environment and time; and, possibly, the aggregate type and gradation. This, in itself, shows the value of the BBR for asphalt mixtures testing since it evaluates the properties when all components are combined, thus allowing for a direct performance prediction.

The results also indicate that, as long as the equipment is properly calibrated and procedures closely followed, the results are repeatable between labs.

5. EVALUATION OF FIELD PRODUCED MATERIALS USING THE FLEXIBILITY INDEX TEST

5.1 Description

As was previously described, representative materials from across the state of Utah, based on both UDOT and non-UDOT projects, were collected from seven different projects. The material was distributed to three different labs where each of the labs compacted, cut, and tested the samples based on the procedures described in AASHTO TP124-16. Unfortunately, due to variations in field collected materials, not all samples obtained were within the limits (in terms of air voids or cutting geometry) specified in the AASHTO specifications. Given the limited availability of materials, all samples were tested and all the data is reported.

5.2 Results

Testing of the material was done following the procedures described in AASHTO TP124-16. Each of the three participant labs prepared two gyratory compacted cylinders for each mixture. Given that four semi-circular samples can be obtained from one gyratory-produced cylinder, the two compacted cylinders resulted in eight samples for each mixture at the two conditions (plant and field laydown).

Table 5.1 shows the average FI of each gyratory sample (i.e., puck) tested (average of four tests), the coefficient of variation (standard deviation divided by the mean) of all the samples tested, and the mean of the results for each mixture at each of the testing labs.

As can be seen in Table 5.1, it is not unusual to have a significant difference in FI between the first gyratory puck and the second gyratory puck. Most previous work indicate that more than one gyratory puck should be compacted, and testing should be done on as many individual SCB samples as possible to obtain a reliable mean. These data support such statements. The data also shows that the coefficient of variation of all results is often greater than 20% and there are differences in the results obtained between all three labs greater than the expected variability. Mixtures from UT-06 and UT-07 show particularly large differences between labs. Also, for the plant mixes, with the exception of UT-02, the results from Lab A and Lab C are closer to each other than to Lab B. In five out the seven mixtures obtained at the plant and in six out the seven mixtures obtained at laydown, Lab B had more material and compacted compact more samples that were within the target air voids and dimensions. It is possible that the bias seen on Lab B values is actually the results of more control of the samples tested.

Table 5.1 Results of FI from Different Labs

		Lab A		Lab B		Lab C	
		Plant	**Field**	**Plant**	**Field**	**Plant**	**Field**
UT-01	Puck 1	6.7	4.6	9.6	7.4	5.8	6.9
	Puck 2	5.1	7.2	4.6	8.2	-	-
	Coeff Var[1]	**31%**	**39%**	**38%**	**17%**	**14%**	**26%**
	Average	**5.9**	**5.9**	**7.1**	**7.8**	**5.8**	**6.9**
UT-02	Puck 1	5.5	3.7	3.9	3.6	3.1	2.1
	Puck 2	4.3	3.0	4.0	3.4	3.4	-
	Coeff Var	**29%**	**24%**	**24%**	**16%**	**25%**	**38%**
	Average	**4.9**	**3.4**	**4.0**	**3.5**	**3.3**	**2.1**
UT-03	Puck 1	12.0	8.7	11.7	8.9	7.0	9.3
	Puck 2	4.6	-	7.7	12.8	-	-
	Puck 3	-	-	-	13.5	-	-
	Coeff Var	**20%**	**27%**	**32%**	**30%**	**24%**	**29%**
	Average	**8.3**	**8.7**	**9.7**	**11.7**	**7.0**	**9.3**
UT-04	Puck 1	15.3	10.0	8.7	10.6	13.4	9.5
	Puck 2	8.4	7.4	9.5	9.5	-	-
	Coeff Var	**38%**	**27%**	**20%**	**27%**	**32%**	**40%**
	Average	**11.8**	**8.7**	**9.1**	**10.1**	**13.4**	**9.5**
UT-05	Puck 1	3.8	4.5	11.3	5.2	6.8	4.8
	Puck 2	7.8	9.4	11.8	4.8	8.8	-
	Coeff Var	**39%**	**40%**	**19%**	**19%**	**13%**	**24%**
	Average	**5.8**	**7.0**	**11.6**	**5.0**	**7.8**	**4.8**
UT-06	Puck 1	2.9	3.3	7.8	6.0	2.9	2.1
	Puck 2	3.2	4.1	3.4	6.5	3.2	2.4
	Coeff Var	**23%**	**18%**	**47%**	**30%**	**20%**	**20%**
	Average	**3.0**	**3.7**	**5.6**	**6.2**	**3.0**	**2.3**
UT-07	Puck 1	14.3	10.1	18.8	18.8	8.4	8.4
	Puck 2	9.0	15.8	22.5	17.8	-	-
	Coeff Var	**28%**	**29%**	**22%**	**24%**	**29%**	**28%**
	Average	**11.6**	**12.9**	**20.6**	**18.3**	**8.4**	**8.4**

[1] Coefficient of Variation (standard deviation divided by the mean of all samples tested)

To improve the variability of the results, the highest value from each gyratory sample (puck) is eliminated and the resultant six samples are averaged for Labs A and B. This was not done for Lab C to ensure that at least six data points were used to obtain a reliable average. The results are shown on Table 5.2.

Table 5.2 FI Results without the Highest Value

		Lab A		**Lab B**	
		Plant	**Field**	**Plant**	**Field**
UT-01	Average	5.3	5.1	7.0	7.5
	Coeff Var	31%	40%	39%	19%
UT-02	Average	4.4	3.1	3.6	3.2
	Coeff Var	26%	23%	14%	11%
UT-03	Average	11	-*	9	10
	Coeff Var	20%	-*	33%	26%
UT-04	Average	10.8	7.9	8.4	9.1
	Coeff Var	33%	22%	17%	25%
UT-05	Average	5.5	5.7	10.5	6.5
	Coeff Var	38%	39%	14%	17%
UT-06	Average	4.1	3.6	5.1	5.3
	Coeff Var	17%	18%	49%	13%
UT-07	Average	11.0	12.2	18.7	16.3
	Coeff Var	29%	33%	6%	14%

As the data in Table 5.2 shows, even after removing the highest value, there is significant variability in the results. It is hypothesized that most of the variability comes from one of the individual measurements used to calculate the flexibility index. To verify such claim, the variability of the individual parameters used to calculate the Flexibility Index (FI), namely Fracture Energy and slope, were determined for the data in Lab A. These results are summarized in Table 5.3.

As can be seen in Table 5.3, the coefficient of variation of the fracture energy is, on average, less than 12% and, in eight out of 14 mixtures, less than 10%. In contrasts, the coefficient of variation of the slope is, on average, 26% and in only two out of 14 mixtures the value is less than 15%. The flexibility index, on average, has a coefficient of variation of 30% which is higher than expected for a within-lab specification. More research is needed to determine if an alternative parameter can result in lower test variability while still capturing the desired flexibility of the material.

Table 5.3 Coefficient of Variation for Different Parameters in Lab A

		Coefficient of Variation[1], %		
		Fracture Energy	**Slope**	**Flexibility Index**
UT-01	**Plant**	8.5	28.0	31.1
	Field	19.9	22.4	38.6
UT-02	**Plant**	13.1	21.7	29.0
	Field	15.0	15.3	23.8
UT-03	**Plant**	11.1	19.0	19.9
	Field	16.6	13.8	27.0
UT-04	**Plant**	9.0	41.5	37.7
	Field	7.2	27.1	26.8
UT-05	**Plant**	6.0	42.2	38.7
	Field	9.1	43.8	39.7
UT-06	**Plant**	8.4	18.8	22.6
	Field	12.0	11.5	17.5
UT-07	**Plant**	13.3	19.3	27.8
	Field	9.7	34.2	28.7

Even though the data shows that there are variability issues and differences between testing labs that must be resolved, there is consistency when it comes to identifying mixtures that might result in poor performance. The results from all labs show that plant mixtures from projects UT-02 and UT-06 are likely to have poor intermediate temperature performance since both have the lowest FI values (below 5). In the same manner, all labs show that plant mixtures from projects UT-03, UT-04, and UT-07 have FI values above 7 and, thus, better intermediate temperature performance would be expected. For the other two sections (UT-01, and UT-05), the results are inconclusive since some labs had FI values below 6 and some have FI values above 6. These results are shown graphically in Figure 5.1.

5.2.1 Comparison to Low Temperature Results

A comparison between the performance predictions at low temperature (Table 4.5 for PG XX-34) and the predictions at intermediate temperature (FI <6) result in some commonalities. Both tests agree that material from sections UT-03, UT-04, and UT-07 would not be expected to crack while materials from sections UT-01, UT-02, and UT-06 might not have good cracking performance. There is no agreement with material from UT-05 given the difference in FI obtained between labs.

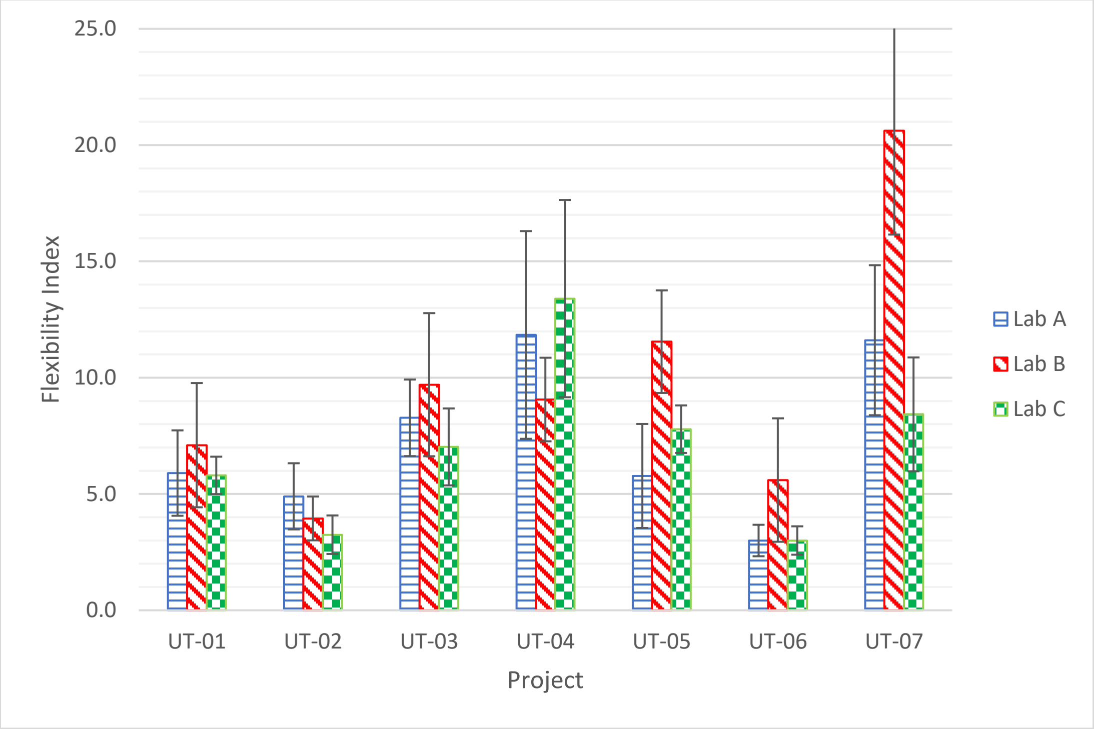

Figure 5.1 Average Flexibility Index of Plant Mixtures at all Three labs
Error bars represent ± one standard deviation

5.3 Effect of Short-term Aging

The material was collected at two locations, at the plant and at laydown; due to storage and transportation to the site, the material collected at laydown (i.e., field material) is the same material collected at the plant but in a short-term aged condition. The change in FI due to short-term again can be evaluated by comparing the test results.

Before analysis of the short-term aging of mixtures is discussed, and, given the variability of the test results, it is important to understand what values can be considered as a significant difference. Assuming a FI threshold value of 6 and a variability of 20%, a change in FI of 1.2 can be considered to be not significant. Using this as reference, the data indicates that in mixtures from sections UT-01, UT-02, and UT-06 there is no significant aging (i.e., the difference in FI between the plant and laydown is less than 1.2). Mixtures from sections UT-01 and UT-02 also showed no significant short-term aging in the low-temperature results; however, the mixture from section UT-06 shows significant aging at low temperatures, but no change in FI.

For mixtures from sections UT-04 and UT-05, there is a decrease in FI in two out of the three labs. Recall that the effect of aging on mixtures from these two sections was not detected in the BBR tests. In fact, the aging results from sections UT-04 and UT-05 were an anomaly in regard to aging. The mixture from UT-05 was stored in a silo for 17 hours, so some aging is expected but only detected in the FI value. The FI from mixtures obtained in projects UT-03 and UT-07 show significant changes but contradictory FI results from different labs regarding aging. At low temperatures, mixtures from UT-03 show no significant aging while mixtures from UT-07 show significant aging. Based on mixed results, no conclusions are reached for these two sections. These results are shown graphically in Figure 5.2.

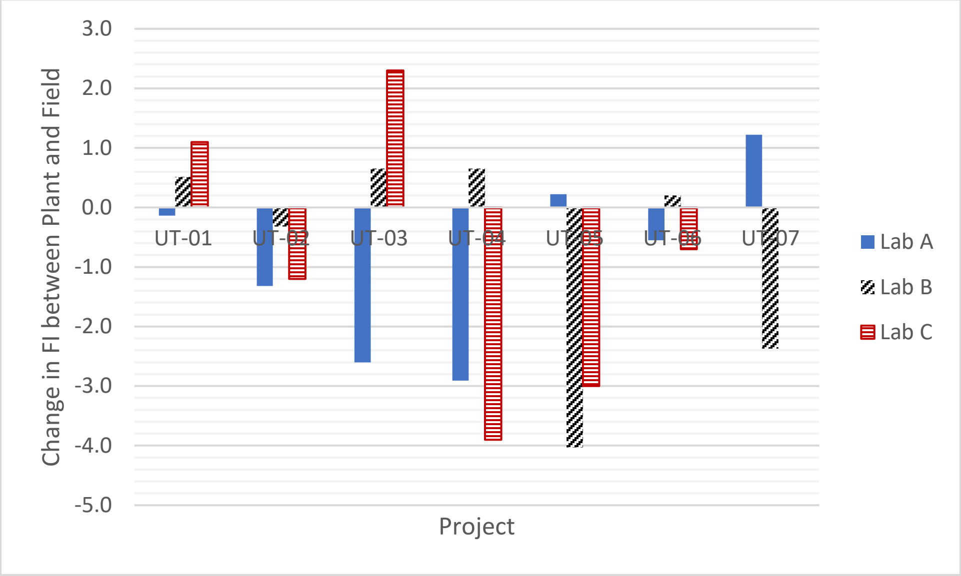

Figure 5.2 Change in FI between Plant and Laydown

5.4 Summary

The results presented in this section indicate that more work must be done to control the variability of the Flexibility Index, both in terms within-lab variability and differences between labs. Even after a trimmed, mean approach was used, where the highest value was eliminated, the coefficient of variation was larger than what is desired in a specification test. It is believed that issues, such as control of the air voids after cutting and tolerances for sample preparation (e.g., notch depth) can play a role in the variability of the results.

Notwithstanding the variability observed in the flexibility index, comparisons of the results obtained at the different labs, indicate that the test can consistently predict the extreme expected performers from the different mixtures collected. Based on the literature, an FI limit between 6 and 10 would separate mixtures based on their expected performance; application of this limit would result in three mixtures being eliminated. Furthermore, the predictions are consistent with the results obtained using the BBR.

Regarding the aging that occurred between the plant and laydown, the results indicate that the effects were mixture-specific and not always consistent with the results at low temperatures. For example, mixtures from sections UT-01 and UT-02 showed no aging in both tests, while section UT-06 show aging in the BBR results but no change in FI; mixtures from sections UT-04 and UT-05 showed clear indications of aging (i.e., a decrease in FI) but were considered an anomaly in the BBR results.

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Seven asphalt mixtures were collected at different plants from the slats and at laydown from the windrow. The mixtures were considered representative of the material produced in the state of Utah. They were compacted in three different labs and tested at low and intermediate temperatures using the bending beam rheometer (AASHTO TP125-16) and the semi-circular bend test configuration (AASHTO TP124-16). The creep modulus and relaxation capacity were determined at low temperatures and the flexibility index was measured at intermediate temperatures. Both tests provided insight as to the potential performance of the mixtures.

6.1.1 Low-temperature Cracking

The study of field-produced mixtures indicates that three out of the seven mixtures tested — UT-03, UT-04, and UT-07 — are expected to have good performance even at the lowest temperature environment of PG XX-34. While all of these mixtures had a creep modulus above 12 000 MPa at the test temperature of -24 ºC, their m-value was above 0.12 indicating good relaxation capacity. The range in the RAP content of these specific mixtures varied from a low of 10% (UT-07) to as much as 25% (UT-03), indicating that RAP content alone is not an indicator of expected performance. This supports the notion that the low temperature performance of the mixture does not depend on a single design parameter (i.e., RAP content, binder grade, etc.) but rather on how all components of the mix combine into a system. All seven mixtures collected are expected to have good low temperature performance at the warmer environment of PG XX-22.

In four out of the seven sections tested (UT-02, UT-03, UT-06, and UT-07), there was an increase in modulus and a decrease in m-value between the material collected at the plant and the material collected in the field, indicating that short-term aging occurred. In two of the sections tested (UT-01 and UT-05), there was no clear indication of aging as the results are within the margin of error.

The within-lab repeatability of the BBR results was usually below 10%. Results for the between-lab repeatability comparison seemed to show a bias in the modulus measurement for one of the labs. No specific cause for this bias was identified, but further repeated testing confirmed the results from previous studies in which the differences between labs was less than 10%.

6.1.2 Intermediate-temperature Cracking

The Flexibility Index of the mixtures tested ranged from a low value of 3.9 to a high value of 13.6 for plant-produced, unaged material. Mixtures with the lowest virgin binder content resulted in the lowest FI. Short-term aging resulted in a relatively small decrease in FI for three of the mixtures tested while in the remaining four, short-term aging resulted in a decrease in FI of 25 to 30 percent.

Given the large variability observed in the results, it is not believed that the Flexibility Index parameter can be used to accurately rank the expected performance of different mixtures. In other words, an asphalt mixture with an FI of 11, such as UT-04, might not necessarily have better performance than another mixture with an FI of 8, such as UT-05. It is possible, however, that once a threshold is established, the test can be used to identify mixtures that are susceptible to early fatigue cracking, a pass-fail type test. For example, if a threshold of 6, as suggested by other states, is found adequate, then UT-02 and UT-06 should not be placed on the road. Actual field performance is needed before a determination can be made.

Finally, it was observed that sample preparation requires significant effort in terms of materials, compaction, and cutting. More research is needed to determine how the sample preparation affected the large variability observed in the test.

6.2 Conclusions

After extensive testing of asphalt mixtures collected from seven different pavement sites across the state of Utah, the following conclusions were reached.

1. The low temperature limits proposed as part of previous study will allow to evaluate the expected performance of asphalt mixtures at specific, low-temperature environments. While most of the mixtures produced have a relatively high creep modulus at the intended environment (creep modulus >12,000 MPa), their relatively high relaxation capacity (m-value >0.12) should result in good performance. These predictions are based on the mixture as a system and are not based on individual parameters, such as neat asphalt binder grade or RAP content.
2. Aging that occurs between the plant and laydown is mixture-specific and is not always consistent with the results at different temperatures. Based on low-temperature testing, the current practice of loose mix aging for two to four hours is adequate to simulate the changes observed in the field.
3. Variability in the within-lab and between-lab results at intermediate temperature (FI) continues to be a problem. While sample preparation was a challenge and might have contributed to some of the observed variability, the actual source of the high variability remains unknown.
4. Notwithstanding the large coefficient of variation in the data, the test can predict the extreme expected performers out of the different mixtures collected. Asphalt mixtures sampled at the plant can be expected to have a FI between 3.0 and 20.0. The material sampled at laydown can be expected to have a FI between 2.1 and 18.3. Based on the literature, an FI limit between 6 and 10 would separate mixtures based on their expected performance; application of this limit would result in three out of the seven mixtures being eliminated. These predictions are consistent with the results obtained using the BBR.

6.3 Recommendations

Based on the work described in this report, the following recommendations are made.

It is recommended that AASHTO TP125-16: Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Mixtures Using the Bending Beam Rheometer (BBR) be adopted as a method to control the performance of asphalt mixtures at low temperatures.

It is recommended that more research is done, regarding methods, to reduce the variability of the intermediate temperature test before it is adopted. This includes determination of alternate, more robust, test parameters outside those that are used to calculate the flexibility index, evaluation of the effect of sample preparation (compaction and cutting) on the results, alternate geometries, such as testing in the indirect tensile mode where no sample cutting is required, and different loading rates.

It is recommended that field performance data be collected on the seven sections evaluated as part of this study. Knowing the actual performance would assist in selecting appropriate loading rates or any other parameter for the test. Knowing the actual field performance will allow development of a threshold that can eventually be used as a specification limit.

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