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Evaluation of Low-Temperature Cracking (LTC) Performance Testing Methods to Assess Nebraska Asphalt Mixtures

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16. Abstract

Current advancements in asphalt mixture design in the United States are increasingly shifting toward performance-based specifications, particularly through implementation of the Balanced Mix Design (BMD) framework. However, most existing BMD protocols primarily emphasize rutting and mid-temperature cracking resistance, often overlooking low-temperature cracking (LTC), which is a critical distress mode in cold-climate regions. This study aims to investigate LTC performance-based methodologies for the asphalt mix design to support the development of a Nebraska BMD framework. With that, selection of appropriate LTC performance tests that can be sensitive to Nebraska recycled mixture's variables was the main goal developed in this phase of study. To this end, well-established mixture-level LTC tests were sought, including Semi-Circular Bending (SCB) test, Indirect Tensile (IDT) Creep/Strength Test, and Bending Beam Rheometer (BBR) for mixtures, and performance parameters from different mixtures were compared. Dynamic modulus (DM) test was also conducted to verify potential differences in mixture's stiffness at sub-zero temperature. Additionally, commonly used binder level tests (DSR and BBR) and IDEAL-CT tests were performed to complete the binder and mixture performance characterization, respectively. Three Nebraska recycled mixtures subjected to short- and long-term aging protocols were selected in this initial phase of the study, being two SPR mixtures (SPR1 and SPR2) and one SLX. Binder-level results highlighted the limitations of binder testing in differentiating the LTC performance of the studied recycled mixtures. At the mixture level, lab-produced SPR mixtures exhibited different LTC performance trends. SCB fracture energy and IDT creep compliance were the only index parameters that consistently captured these differences. Plant-produced SPR and SLX mixtures confirmed the sensitivity of selected performance-based index parameters to differentiate the mixture's LTC resistance. Finally, these laboratory-derived indicators were compared against observed field thermal cracking performance to assess the predictive accuracy and applicability of the laboratory test methods at a field-production scale. Findings from this report must be extended for a broad range of mixtures and site locations.

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Chapter 1 Introduction

Significant efforts are ongoing in the U.S. to implement performance-based specifications to verify the susceptibility of asphalt mixtures to critical distress during the mix design stage with goals of improving pavement durability [1-3]. In this view, several state Departments of Transportation (DOTs) have conducted research projects to determine suitable test methods and performance indicators to be implemented in Balanced Mix Design (BMD) protocols, taking into account local climate and traffic conditions [4-6]. Even though different types of distress can be considered in BMD protocols, primary focus has been placed on rutting and mid-temperature cracking assessment [7-11]. Research outcomes from proposed BMD approaches are practically efficient and implementable, but most of them do not assess low temperature cracking (LTC) resistance of asphalt mixtures, which is considered one of the main concerns in cold climate states. Based on the NCHRP 20-07(406) report, only a few states in the mid-U.S. regions adopted thermal cracking tests in their mix design specifications [4, 5].

LTC is a critical pavement distress in cold climate regions and in areas where daily temperature fluctuations are significant. Over half of the United States experiences extreme daily temperature ranges of 20–25 °F during the winter months [12]. Such thermal variations cause pavement layers to contract, inducing tensile stresses that can exceed the tensile strength of the asphalt mixtures, ultimately leading to the initiation and propagation of LTC [13]. These cracks compromise the structural integrity of the pavement by creating direct pathways for water infiltration. In particular, snowmelt and precipitation events combined with traffic-imposed pore pressure can force moisture deep into the pavement layers through these cracks. This moisture infiltration accelerates moisture-induced damage mechanisms such as stripping and freeze-thaw cycles, thereby weakening the asphalt-aggregate bond and reducing the overall service life of the pavement [14]. Moreover, highway agencies have increased the sustainability goals by promoting the use of reclaimed asphalt pavement (RAP) in asphalt mixtures [15]. However, the use of RAP further worsens the LTC as RAP tends to stiffen the mixture and reduce its flexibility, thereby increasing susceptibility to thermal cracking [16, 17]. Therefore, the assessment of LTC in RAP-recycled mixtures is essential for ensuring long-term performance.

The conventional approach to evaluating LTC has relied on binder-level testing, such as the bending beam rheometer (BBR) test, measuring binder stiffness and relaxation properties at low temperatures [13, 18, 19]. However, research studies have demonstrated that binder-level tests are insufficient for predicting the in-service behavior of asphalt mixtures, especially in recent applications of different and alternative paving materials in asphalt mixtures [20, 21]. Mixture-level testing is necessary to capture the complex interactions between binder, aggregate, and air voids, which collectively influence cracking resistance. This led to the development and adoption of advanced laboratory test methods that assess the LTC performance of asphalt mixtures at low temperatures, such as the thermal stress restrained specimen test (TSRST), indirect tensile (IDT) strength test, disk-shaped compact tension (DCT) test, semi-circular bending (SCB) test, and mixture-level BBR test [22-24]. TSRST measures the temperature at which restrained specimen cracks under controlled cooling, providing a direct indicator of LTC susceptibility due to temperature variation [25]. The BBR and IDT tests offer insights into the mixture's stiffness and strength at low temperatures which can be correlated to other test parameters [26]. The DCT and SCB tests can minimize the effects of other damage mechanisms, and isolate the response of the mixtures to cracking, bringing insights on the material’s fracture energy and crack evolution at low temperatures [27, 28]. As can be seen, each test method presents specific indicators of LTC resistance and a multi-test assessment approach with different types of LTC test methods can provide a comprehensive evaluation of LTC resistance [29].

Another essential component to better determine suitable and reliable test methods to be implemented in BMD approaches is the field performance evaluation, which plays a critical role in validating laboratory results and benchmarking mixture performance under real-world traffic and environmental conditions [30, 31]. However, most field performance and benchmarking studies have primarily concentrated on rutting and intermediate-temperature fatigue cracking, with limited attention to LTC [31, 32]. As a result, critical insights into how asphalt mixtures respond to cold climate remain uncertain in BMD protocols. Only a few studies have attempted to incorporate LTC into field performance evaluation by correlating laboratory test results from DCT and SCB tests with observed field cracking behavior [9, 11, 33]. These efforts represent a significant step forward; however, they are limited by several factors, most notably, the low percentage use of RAP materials.

Recent Nebraska BMD research reports [8, 31] presented a comprehensive analysis of performance indicators of several plant-produced RAP mixtures in the laboratory and included field monitoring for validation. These studies primarily focused on rutting and mid-temperature cracking performance. However, LTC has not been adequately investigated, despite Nebraska being a cold-climate region where thermal cracking has been seen as a critical distress mode. This gap highlights the need for more detailed evaluation of both mid- and LTC resistance in cold regions. It also underscores the importance of expanding field validation efforts within the BMD framework to explicitly address LTC performance, particularly for high-RAP mixtures. Addressing these gaps is essential for developing more reliable and climate-resilient mix design criteria that ensure pavement durability across different environmental conditions with focuses on regions vulnerable to extreme cold and thermal distress.

1.1 Research Objectives and Scope

The major objective of this phase 1 study is to identify a suitable cold-temperature cracking performance test(s) to be included in the Nebraska BMD method. More specifically:

- Conduct LTC tests on the different binders and mixtures collected from Nebraska field projects to verify the sensitivity and reproducibility of suggested tests from literature.
- Compare results from the two scales (binder & mixture) of material testing with results obtained from samples collected from NDOT paving projects approved by NDOT TAC members.
- Establish preliminary pass/fail thresholds based on the obtained results and comparison with literature for future QC and acceptance purposes.

1.2 Methodology

To achieve the research objectives, this study was conducted in two sequential stages, beginning with the evaluation of two Superpave Recycled (SPR) mixtures—previously characterized on NDOT BMD Reports Phase 1 and Phase 2 [8, 31]—with distinct thermal cracking response from the field according to the PMS data collected during BMD phases 1 and 2. Due to limited resources of plant-produced mixtures, the two SPR mixtures were reproduced in controlled laboratory conditions using virgin materials collected from same source used by the original projects. Thus, laboratory-produced (LP) mixtures underwent a comprehensive suite of characterizations—starting from gradation analysis, analysis of mix design volumetric parameters, and mid-temperature cracking resistance (IDEAL-CT)—to compare results with plant-produced results. Subsequently, those mixtures were subjected to monotonic low-temperature cracking (LTC) tests (BBR, SCB, and IDT), and dynamic modulus (DM) testing. Based on the findings and performance trends identified in Stage 1, the second stage shifted focus to plant-produced (PP) SPR and SLX mixtures, utilizing the test methods identified as most effective in the laboratory phase to examine performance in representation of field construction. To simulate different aging conditions present in the field, all mixtures were evaluated at both STA and LTA conditions. Additionally, binder-level testing was conducted to evaluate the limitations of binder-level characterization in representing RAP-containing mixtures. The results were applied to statistical analysis, including ANOVA and Tukey's HSD, to identify meaningful relationships and performance trends among the various LTC assessment parameters. Finally, these laboratory-derived indicators were compared against observed field thermal cracking performance to assess the accuracy and applicability of the laboratory test methods to a field-production scale. The entire methodology and testing process are shown in Figure 1.1.

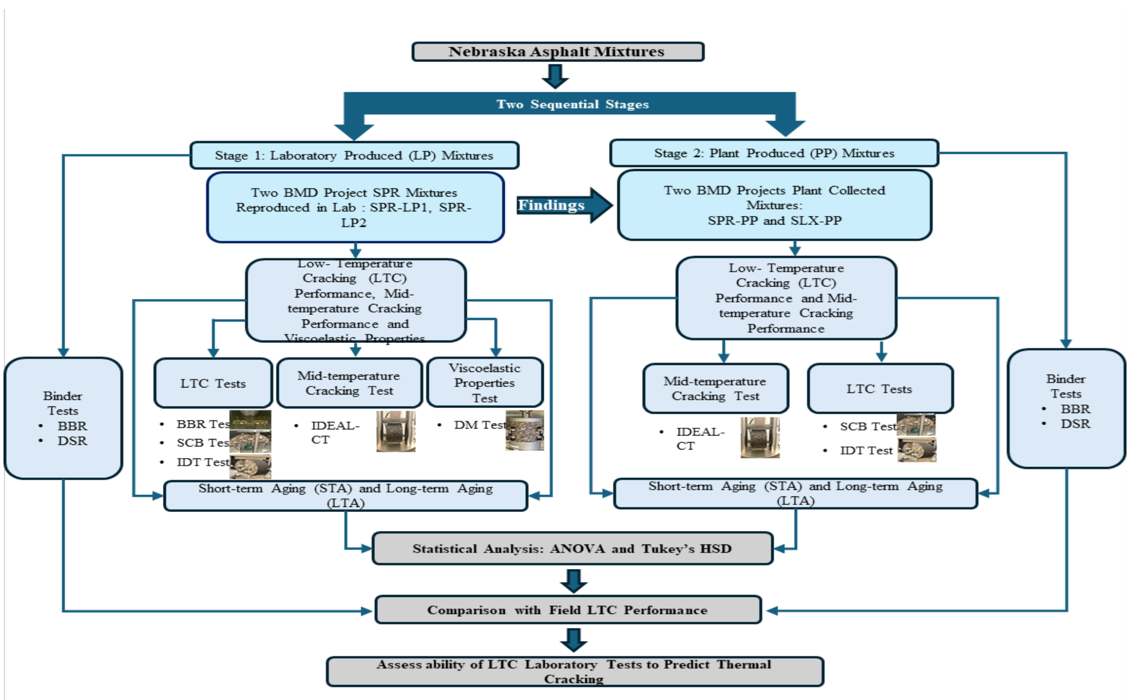


Figure 1.1 Methodology for the research study.

1.3 Organization of the Report

This report is organized into seven chapters. Chapter 1 introduces the study and outlines the research objectives and scope. Chapter 2 presents a comprehensive literature review of LTC test methods adopted for BMD, along with factors influencing LTC resistance. Chapter 3 describes the materials used, test methods followed, and specimen fabrication procedures. Chapter 4 presents and discusses the experimental results obtained from laboratory-produced BMD mixtures of similar types, with emphasis on observed differences in field performance. Based on the findings from Chapter 4, Chapter 5 applies the test methods that most effectively characterize LTC resistance in laboratory-produced mixtures to plant-produced mixtures. Chapter 6 presents field-based thermal cracking or LTC performance of pavement sections constructed using the evaluated mixtures. Finally, Chapter 7 summarizes the major findings of the study and provides recommendations for future research.

Chapter 2 Background

Asphaltic concrete composed primarily of mineral aggregates and asphalt binder are complex materials widely used in road infrastructure. These materials exhibit highly heterogeneous and multiscale behavior, with their structure and performance influenced across various length scales and temperature—from the full pavement system to the asphalt concrete layer to the asphalt binder [34]. Different tests methods are conducted to understand performance at different levels and temperatures. Additionally, key volumetric parameters such as air void content, binder content, and aggregate gradation significantly influence the LTC behavior, all of which are critical in low temperature cracking performance [10, 33]. In recent years, there has been growing interest in incorporating sustainable and eco-friendly alternatives such as RAP alongside waste plastics and recycling agents to reduce environmental impact and material costs [16, 17, 35, 36]. However, the addition of recycled materials further increases the variability and complexity of asphalt systems. On the other hand, BMD primarily emphasizes mid-temperature cracking resistance and high-temperature rutting performance, leaving a gap in the evaluation of low-temperature cracking behavior. Therefore, there is a pressing need for a comprehensive evaluation of recycled asphalt mixtures within BMD frameworks to assess their low-temperature performance, making pavements more durable and sustainable.

2.1 Low-temperature Cracking Test for Asphaltic Materials

LTC is one of the major forms of distress observed in asphalt pavements during winter seasons. It occurs due to thermal contraction and the associated tensile stress that leads to the formation of cracks, which eventually degrades the pavement performance. Various test methods have been developed to evaluate the susceptibility of asphalt mixtures to LTC, as presented in Figure 2.1. LTC performance testing can be generalized into binder- and mixture-level testing. Further discussion on LTC tests is presented in the upcoming sections.

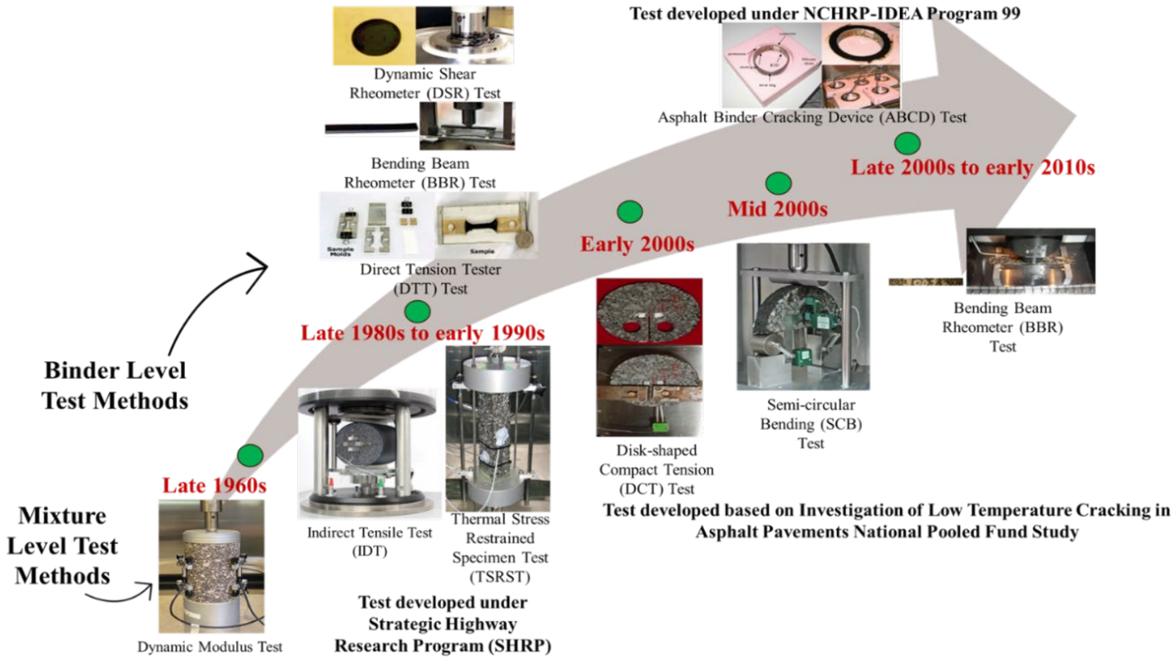


Figure 2.1 LTC test methods.

2.1.1 Binder Level Testing for LTC

To evaluate LTC resistance of asphalt mixtures, most of the studies and DOT laboratories focus on asphalt binder rheological characterization to identify potential discrepancies on the LTC performance of asphalt mixture as well as pavement performance. Considering that a typical asphalt mixture consists of asphalt binder and mineral aggregates, researchers often focus on evaluating binder behavior at subzero temperatures because the binder is more susceptible to low temperature-induced stresses than the aggregates. Properties like tensile strength and stress-relaxation capability of the asphalt binder have therefore been identified as critical for increasing the risk of thermal cracking in asphalt pavements [37, 38]. To date, the Bending Beam Rheometer (BBR) and Direct Tension Test (DTT) are two of the most commonly used tests that could provide information on low low-temperature performance of asphaltic binder.

The BBR test is a widely utilized test for evaluating the LTC resistance of asphalt binders [13, 19, 39]. It measures the stiffness of binders under bending deformation at low temperatures and provides information on their creep stiffness and relaxation properties, indicating the binder's ability to resist thermal cracking. In this test method, a binder beam is loaded in a three-point loading setup at the low-temperature Performance Grade (PG) temperature plus 10°C and given a creep load for 240 seconds and displacement is measured with respect to time. With that, creep stiffness (S-value) and relaxation properties (m-value) are obtained as shown in Figure 2.2.

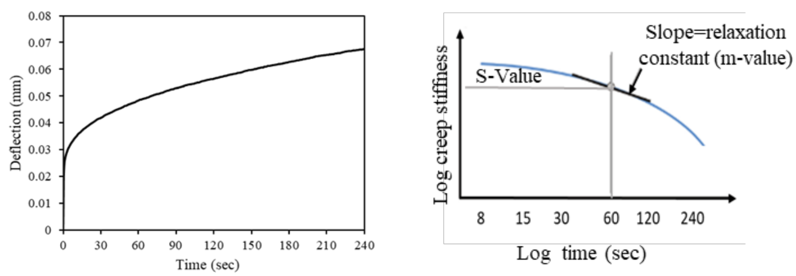


Figure 2.2 BBR test output (left) and common test parameters (right).

Moreover, in recent years, ΔTc has been widely used as an indicator of binder embrittlement and susceptibility to low-temperature cracking. The ΔTc parameter extends beyond stiffness and relaxation properties by capturing the governing failure mechanism at low temperature, whether cracking is primarily stiffness-controlled or relaxation-controlled. ΔTc is defined as the difference between the critical low-temperature grade determined from the BBR stiffness criterion (S = 300 MPa) and the critical low-temperature grade determined from the m-value criterion (m = 0.300) [40]. In general, a negative ΔTc shows asphalt binder susceptibility to embrittlement. Furthermore, the BBR test is widely used in the Superpave Binder Specification, helping select binders for regions with cold climates where LTC is a concern.

Because the BBR test possesses properties like accuracy, repeatability, and the ability to assess binder properties, it has been widely utilized for quality control and binder modification studies. However, there are a few obstacles in using this test, given the fact that the entire performance characterization is based on the binder properties, which do not represent the global behavior of asphalt mixtures. This test method does not capture the general complexity of the pavement accounting for asphalt and aggregates with air voids [23].

In addition to the BBR test, the DSR test is also used to evaluate the rheological properties of asphalt binders, specifically their viscoelastic response under shear stress (AASHTO T 315). It measures the binder's viscoelastic properties, such as dynamic shear modulus (G*) and phase angle (δ), which provides information on how the binder resists deformation behavior under different temperatures and loading conditions. Asphalt binders are viscoelastic materials that exhibit both elastic and viscous responses under shear loading, resulting in a phase lag (δ) between stress and strain as shown in Figure 2.3.

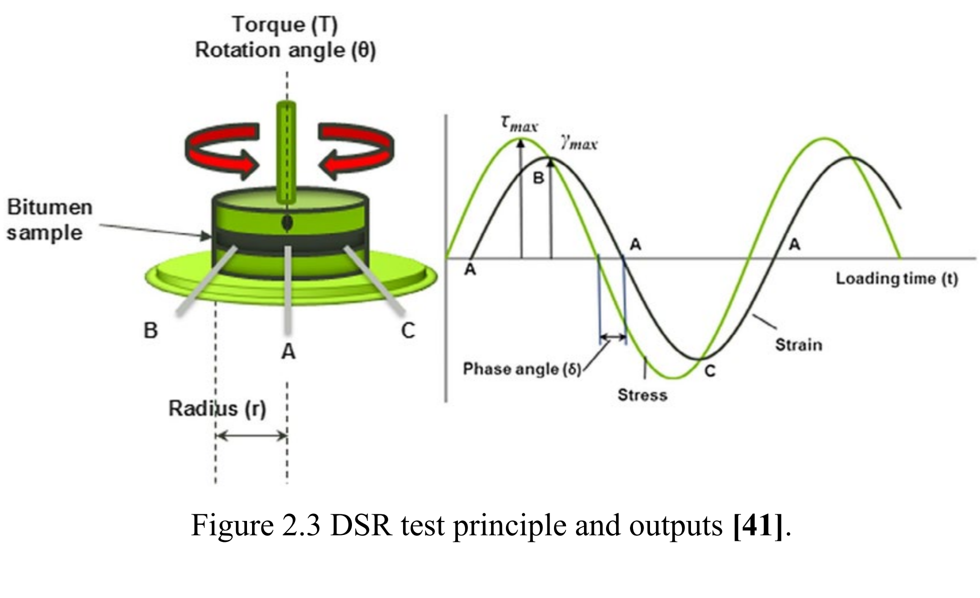


Figure 2.3 DSR test principle and outputs **[41]**.

The binder viscoelastic parameter, complex shear modulus (G*), is directly related to the stiffness of the asphalt binder under oscillatory shear loading. It represents the total resistance of the material to deformation, combining both elastic (recoverable) and viscous (non-recoverable) components. Higher G* values indicate a stiffer binder with greater resistance to deformation, which is typically associated with improved rutting resistance at high service temperatures. However, excessively high stiffness may reduce the binder's ability to relax stresses, potentially increasing susceptibility to cracking at intermediate and low temperatures.

It is noted that DSR results are primarily used for evaluating high- and mid-temperature performance (e.g., rutting resistance and intermediate-temperature fatigue cracking). Recently, DSR test had been suggested for assessing LTC, too [42, 43]. A higher shear modulus (G*) indicates a stiffer, more brittle binder, which is more prone to cracking under thermal contraction during cold conditions. A lower phase angle indicates a more elastic response (greater ability to recover deformation), while a higher phase angle reflects more viscous behavior (greater energy dissipation). In the context of low-temperature performance, binders with lower stiffness (lower G*) and a higher capacity for stress relaxation are generally preferred to minimize thermal cracking. Although δ is more commonly interpreted at intermediate and high temperatures (e.g., rutting and fatigue), it still provides insight at lower temperatures: a binder with an appropriate balance of viscoelasticity (i.e., not overly elastic/brittle) can better dissipate thermal stresses.

In addition to BBR and DSR tests, the Direct Tension Test (DTT) and the Asphalt Binder Cracking Device (ABCD) test are also used to evaluate the LTC resistance of asphalt materials. The DTT performed under AASHTO T 314 involves applying uniaxial tensile load to a specimen of asphalt binder or mixture at low temperatures to determine the material's ability to withstand LTC under tension. This test measures parameters such as failure stress (σ_f) and failure strain (ε_f). In addition, the ABCD test directly measures the LTC potential of asphalt binders under field-representative conditions. The test induces thermal tensile stress by restraining the thermal contraction of the binder until failure occurs. This test method is conducted following the AASHTO T 387 standard and has the capacity to measure the critical cracking temperature or fracture temperature (T_f) alongside fracture stress (σ_f) of asphalt binder at low temperatures. Results reported in the literature indicate that binders with lower T_f exhibit better resistance to low-temperature cracking than those with higher T_f [44]. In addition, polymer-modified binders generally show improved LTC resistance, as they tend to exhibit lower T_f and enhanced flexibility compared with unmodified binders [44, 45].

It has been observed that binder-level testing provides the necessary information on low-temperature pavement cracking to some extent. However, the demerits show that LTC results from binder-level testing is not fully represented since binder testing does not account for the interactions between binder and aggregates or the effect of air voids in the mixture [28]. Furthermore, relying solely on binder characterization tests would not be enough to determine different LTC responses observed from mixtures produced with the same binder type and source. For that reason, mixture-level testing has been developed, and many test standards are designed to assess the LTC resistance of asphalt mixtures. These tests provide a more comprehensive understanding of how asphalt mixtures perform under low-temperature conditions, incorporating factors such as aggregate gradation, binder content, air void distribution, and other material properties that influence cracking behavior.

2.1.2 Mixture Level Testing for LTC

Different test methods have been developed to assess the LTC of asphalt mixtures, as mixture-level testing can potentially capture the effects of mixture heterogeneities and microstructure changes. Different mixture level testing, as presented in Figure 2.4, are briefly described in the next paragraphs.

The Dynamic Modulus (|E*|) test, like the DSR testing for asphalt binder, serves as an indirect method for evaluating the LTC resistance of asphalt mixtures. This test has been one of the most established and widely used procedures to assess the viscoelastic properties of asphalt mixtures under varying temperatures and loading conditions performed based on the AASHTO T 342 standard. The dynamic modulus (|E*|) and phase angle (δ) are key parameters measured during the test, which can correlate with the mixture's low-temperature performance. |E*| represents the mixture's overall stiffness, and δ provides insight into the material's viscous and elastic behavior. The mechanical response of asphalt mixtures is highly dependent on temperature. As temperature decreases, the dynamic modulus (|E*|) increases substantially, indicating a shift toward more elastic and brittle material behavior (Figure 2.4). Concurrently, the phase angle (δ), which represents the lag between applied stress and resulting strain decreases, reflecting a reduction in viscous energy dissipation and an increase in stress retention. This evolution in material behavior is critical for evaluating the susceptibility to LTC. Elevated |E*| values and reduced phase angles at low temperatures suggest that the mixture lacks sufficient stress relaxation capacity, thereby increasing the likelihood of thermally induced cracking.

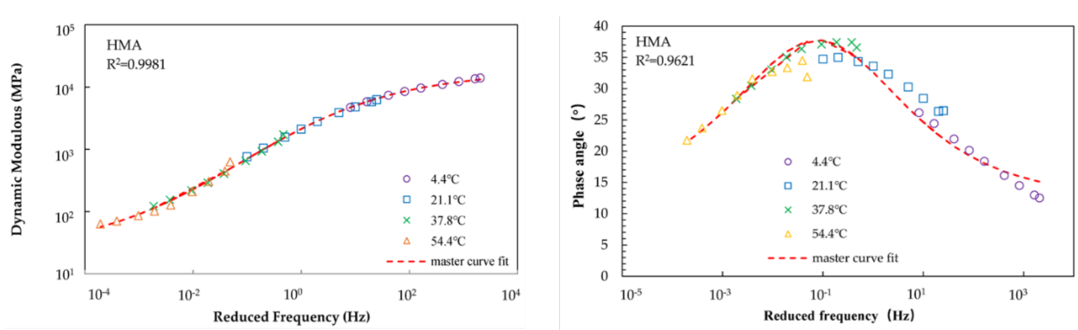


Figure 2.4 Dynamic modulus and phase angle relationship with temperature [46].

The Thermal Stress Restrained Specimen Test (TSRST), developed in the early 1990s as part of the Strategic Highway Research Program, is used for evaluating the LTC susceptibility of asphalt concrete following the AASHTO TP 10 standard. A beam specimen trimmed from slab specimens is used in this test. The test specimen measures 250 × 50 × 50 mm and is glued to the loading plates to simulate restrained conditions during testing. The TSRST simulates thermal cracking by restraining an asphalt concrete specimen, which will be cooled constantly at a rate of 10°C per hour. As the temperature drops, thermal stress builds due to the specimen's inability to contract, and the test continues until a fracture occurs in the specimen. The resulting stress-temperature curve provides information on fracture temperature (T_f) and failure stress (σ_f). Several studies have employed TSRST to assess LTC susceptibility in asphalt mixtures, focusing on the effects of binder modification, aggregate gradation, and aging conditions [47-49]. It was found that polymer-modified binders with higher elastomeric content exhibit improved resistance to thermal cracking, as evidenced by lower fracture temperatures. In contrast, aged mixtures tend to exhibit decreased fracture temperatures, indicating greater susceptibility to LTC. Additionally, finer aggregate gradations have been found to increase vulnerability to LTC, as they result in higher stress concentrations and lower failure temperatures. Although several studies highlight the effectiveness of TSRST in evaluating asphalt mixture performance at low temperatures, the complexity of specimen preparation and testing limits its practicality for routine QA/QC applications.

The Indirect Tension Test (IDT) is commonly used to evaluate the creep compliance and tensile strength of asphalt concrete mixtures which provide information on the viscoelastic properties and low-temperature performance of asphalt mixtures [50]. The IDT Creep Test measures the time-dependent strain response of the material under constant stress by applying a static load to a cylindrical specimen. This non-destructive test is performed at multiple temperatures and allows the calculation of creep compliance (D_t) utilizing the deformation measured at each temperature. On the other hand, the IDT Strength Test is destructive and measures the maximum tensile stress a specimen can withstand before failure. The specimen is loaded until failure occurs, and tensile strength (S) is calculated based on the maximum load. The test method follows the AASHTO T 322 standard.

Another important LTC test method is the Disk-Shaped Compact Tension (DCT). This test is conducted following the AASHTO T 321 standard and involves loading a circular specimen with a single-edge notch in tension under a constant crack mouth opening displacement (CMOD) rate of 0.017 mm/second at sub-zero temperatures. The loading is applied until the specimen fractures. The main outcome from this test is the fracture energy (G_f) of asphalt concrete mixtures. Higher fracture energy values indicate better resistance to LTC. However, this test is performed at a single loading rate, which is one of its limitations. Only fracture energy is considered the criteria for understanding the LTC in this test method.

The Semicircular Bend (SCB) test, as specified by the AASHTO TP 105 standard, is a fracture mechanics-based method used to evaluate the LTC resistance of asphalt mixtures. Conducted at specified low temperatures based on the low-end PG of the asphalt binder, the test measures key parameters such as fracture energy (G_f), peak load (Pmax), and fracture toughness (K_{IC}) to assess the asphalt mixture's ability to resist thermal stresses and crack propagation. These parameters are derived from the load versus displacement curve.

Additionally, in recent days, to capture the mixture level performance and further simplify the test methods developed, the BBR test was adapted for asphalt concrete mixtures following the AASHTO TP 125 protocol. Under this test method, the LTC susceptibility of the asphalt mixture is evaluated using the earlier developed parameters such as creep stiffness (S-value) and relaxation properties (m-value). The test involves applying a constant load to a small beam specimen at low temperatures to assess resistance to thermal cracking. Specimens are cut from gyratory-compacted samples or field cores and conditioned in a BBR bath before a load is applied to the beam. Deflection over time is measured which is further utilized to calculate the creep modulus and m-value to assess LTC performance. The BBR mixture level test offers a representative evaluation of asphalt mixtures, with both binder and aggregates, rather than the binder level testing, which could represent the actual behavior of asphalt mixtures. Additionally, this test method allows multiple specimens from a single sample, ensuring comprehensive testing.

More importantly, all these test methods provide different test parameters that can be correlated with the LTC resistance of the asphalt mixtures. Table 2.1 summarizes the important test parameters derived from each test method and the test temperature information. In some cases, higher values of these parameters are desired, while in some cases, lower values are desired. The arrow in the parenthesis shows such relationships of each of the parameters towards the LTC resistance. Additionally, each test method runs on a single cycle, in most cases governed by the low-temperature PG, while some test temperatures are gradually decreased until the fracture occurs.

Table 2.1 LTC test parameters and test temperatures.

Testing Level	Test Methods	Test Parameters			Test Temperature
Binder	BBR	Flexural Creep Stiffness (S) (↓)	Relaxation Constant (m) (↑)	Delta T_c (ΔT_c) (↑)	Low-temperature PG
	DSR	Phase angle (δ) (↑)	Complex modulus (G*) (↓)		Mid- and high-temperature
	DTT	Failure Stress (σ_f) (↑)	Failure Strain (ε_f) (↑)		Performed at the temperature range of 6°C to -36°C until the sample fails.
	ABCD	Fracture Stress (σ_f) (↑)	Fracture Temperature (T_f) (↑)		Temperature drop at a initial rate of 40°C/ h until binder reaches -20°C, then 10°C/ h until the sample fails.
Mixture	BBR	Flexural Creep Stiffness (S) (↓)	Relaxation Constant (m) (↑)		Low-temperature PG.
	IDT	Creep Compliance (D_t) (↑)	Tensile Strength (S) (↑)		Low-temperature PG.
	DCT	Fracture Energy (G_f) (↑)			Low-temperature PG.
	TSRST	Fracture Stress (σ_f) (↑)	Fracture Temperature (T_f) (↑)	Transition Temperature (T_c) (↑)	Drop in temperature at a rate of 10°C/ h until failure.
	SCB	Fracture Energy (G_f) (↑)	Stiffness (S) (↓)	Toughness (K_{IC}) (↑)	Low-temperature PG.
	DM	Phase angle (δ) (↑)	Dynamic Modulus (E*) (↓)		Indirect measurement. In general, performed at a range of -10°C to 54°C.

As observed, there are two main scales to evaluate asphalt mixture LTC resistance: binder-level and mixture-level tests. Binder-level tests, like BBR and DSR, provide information on the stiffness and viscoelastic properties of binders at low temperatures. While these tests are useful for understanding binder performance, they do not fully reflect the behavior of asphalt mixtures and their heterogeneity. Mixture-level tests, such as the TSRST, IDT, DCT, SCB, and BBR, assess the overall mixture's resistance to LTC, potentially capturing the effects of aggregates and binder interaction. These mixture-level tests offer advantages such as improved field correlation and the ability to simulate real-world conditions [23].

2.2 Implementation of LTC Tests Towards Asphalt Mixture Performance Evaluation

Considering the above test methods, many studies have already utilized performance-based test parameters to assess the LTC resistance of asphalt mixtures. One of the key concerns is the impact of RAP on the mixture’s LTC resistance. As the use of RAP on roadway construction has significantly increased in recent years, incorporating higher amounts of RAP into asphalt mixtures can negatively impact the pavement's functional performance, particularly leading to premature cracking [15]. Increasing RAP content provides a detrimental effect on the LTC of asphalt pavements. Numerous studies have highlighted that RAP can degrade the ability of asphalt mixtures to resist cracking at low temperatures [16, 51-54].

Babagoli et al. [53] examined the LTC resistance of asphalt mixtures containing RAP dosages of 15% and 50%, in two aging conditions (STA and LTA), as well as four different grades of asphalt binder. The study found that incorporating RAP lowered the fracture energy, as determined by the SCB test performed at -18 and -24 °C and applying a crack mouth opening displacement rate of 0.0005 mm/s. Furthermore, LTA conditions decreased the mixture’s LTC resistance. The study also indicated that softer binders offered better resistance to LTC compared to stiffer ones due to their increased relaxation value, i.e., m-value, and decreased stiffness value.

Similarly, Moon et al. [55] evaluated the LTC resistance of RAP mixtures using the mixture-level BBR test. The study evaluated the RAP dosages of 15%, 25%, and 30% and found that RAP content reduced LTC resistance due to the stiffer nature of the mixtures. It was found that incorporating up to 15% RAP does not significantly degrade LTC resistance compared to a control (0% RAP) mixture, although minor increases in stiffness and decreases in capacity of relaxation were observed. Higher RAP contents (25–30%) notably increased stiffness and thermal stress while reducing m-values, making the asphalt mixture more susceptible to LTC.

In another study by Behnia et al. [56], DCT test was used to assess the fracture energy of mixtures with RAP at 10%, 20%, and 50%. The results showed a slight drop in fracture energy at 10% RAP compared to the virgin mixture. However, fracture energy decreased by nearly 50% when 20% RAP is applied. No further significant decline in fracture energy was observed at higher RAP content. This reduction in fracture energy with increased RAP content can be attributed to the higher stiffness of the mixture at lower temperatures, where the stiffening effect of reduced temperature eventually outweighs the inherent stiffness contributed by the aged binder in the RAP. These findings highlight the negative impact of RAP on LTC resistance, and multiple studies have consistently demonstrated similar trends across different RAP dosages and testing methods.

In addition to RAP content, other mixture properties such as asphalt content, air voids, types of asphalt binders, fine aggregate content, etc. play a crucial role in understanding the LTC resistance of asphalt mixtures. Over the years, numerous studies have explored the influence of these variables on the LTC behavior of asphalt mixtures. For instance, the effect of air voids is particularly significant in determining how cracks propagate under low-temperature conditions. Increasing the air void content in asphalt mixtures can negatively impact its LTC resistance, as air voids provide a pathway for crack initiation and propagation [57, 58]. This is because cracks are more likely to develop and expand within voids under thermal stress. Conversely, mixtures with lower air void content, which require more compaction effort, tend to be more resistant to LTC. A denser mix with fewer air voids is less prone to cracking failures at low temperatures, as the material is more cohesive and less susceptible to thermal stress. A study by Budzinski et al. [59] focused on the effect of air voids on LTC resistance using the TSRST. The results showed that asphalt mixtures with lower air voids could withstand higher thermal stresses before fracturing, highlighting the fact that air voids dominate the low-temperature performance of asphalt mixtures. This finding underscores the importance of optimizing mixture properties to enhance low-temperature cracking (LTC) resistance and to better replicate real-world conditions in which pavements are subjected to varying thermal stresses.

Regarding the impact of asphalt content and binder type, research has consistently shown that the binder grade is a more significant factor influencing the LTC resistance of asphalt mixtures than the asphalt content itself [60]. Studies have investigated the effects of different binder grades, particularly focusing on the low-temperature PG of the binder. It was found that binders with lower low-temperature PG values, which typically correspond to lower glass transition temperatures (Tg), exhibited higher LTC resistance. A lower Tg delays the transition of the binder to its glassy state, meaning that the binder remains more flexible at lower temperatures [61]. However, as the temperature decreases further and the binder transitions to a glassy state, it becomes more brittle, reducing its ability to relax stresses. This increased brittleness contributes to a higher susceptibility to cracking in asphalt pavements under low-temperature conditions.

In contrast, increasing the binder content does not significantly alter the LTC resistance of the asphalt mixture, as highlighted in a 2007 study by Braham et al. [62]. Analyzing twenty-eight asphalt mixtures from across the northern U.S., it was found that changes in binder percentage had a minimal impact on fracture energy, as measured by the DCT test at low temperatures. The research also emphasized that variations in binder content tend to have a more pronounced effect at higher temperatures. Binders can dissipate substantial energy at typical intermediate and high pavement temperatures, improving the performance of the mixture. However, the excess binder may create a brittle matrix at very low temperatures, increasing cracking rather than improving resistance. Thus, it would be misleading to assume that a higher binder content would automatically improve LTC resistance, as it might be at intermediate temperatures.

In addition to the binder content and binder performance grade, aggregate gradation plays a significant role in the LTC resistance of asphalt mixtures. Although the effect of aggregate gradation on LTC is often underexplored, several studies have suggested that a higher fine aggregate content in the mixture may increase susceptibility to LTC [63]. This occurs because finer aggregates require more binders to adequately coat them, leaving less binder available for the coarse aggregates. As a result, the mixture may experience a binder deficiency in the coarse aggregate phase, which reduces the binder-aggregate overall adhesion and makes the asphalt mixture more prone to cracking under low-temperature conditions. Beyond gradation, the source of the aggregate itself can also influence the LTC resistance of asphalt mixtures. A study comparing two commonly used aggregate types in the U.S. found that asphalt mixtures produced with granite aggregates exhibited better LTC resistance than those using limestone aggregates according to fracture energy results obtained from SCB and DCT [64]. According to the authors, this difference is likely due to the distinct physical properties of the aggregates, such as their shape, texture, and stiffness, which affect the mixture's ability to resist thermal stress and crack formation at low temperatures.

Moreover, a few studies have also investigated the effects of recycling agents (rejuvenators) to reduce thermal stresses in RAP-recycled mixtures [17, 65-67]. Recycling agents can help restore the properties of aged binders in RAP, improving their low-temperature performance, as they are designed to restore the rheological properties of aged asphalt binders by improving the asphaltene to maltene ratio, reducing asphaltene cluster size, and increasing molecular mobility [68]. This eventually reduces the stiffness and embrittlement of the recycled binder and improves its LTC resistance with enhancement in relaxation properties. Considering this phenomenon, Kaseer et al. [68] have shown that adding recycling agents can significantly increase the fracture energy of recycled asphalt mixtures, an indicator of improved resistance to LTC. The fracture energy increase can be over 50% with the optimal recycling agent dosage.

Another important method for reducing thermal stress and associated LTC in asphalt pavement structures, which has been widely explored, is using fibers. Park et al. [21] showed that using steel fibers in asphalt concrete helped enhance the LTC resistance of asphalt mixtures, as measured by fracture energy. Moreover, the positive impacts on mechanical performance were only gained when proper dosages, length, and diameter of fibers were utilized. Similar results on the use of fibers for reducing thermal stress in pavements were also reported by other researchers using diverse types of fibers such as aramid and polyacrylonitrile [69-71]. However, in most of these studies, cost and economic analysis were not performed to justify the use of fibers in the mixtures. It is uncertain whether fibers could provide economical solutions considering the LTC enhancement of asphalt pavements. Hence, some researchers are currently exploring the use of waste plastics as fibers or additives to reduce thermal stress and enhance the LTC resistance of asphalt mixtures [72-74]. In this scenario, Kakar et al. compared the performance of polyethylene-modified asphalt mixtures with polymer-modified binders. They found that the fracture energy increased with the use of waste plastics, as measured by the SCB test performed at 0°C [36]. In other studies, the efficacy of waste plastics in delaying microcrack formation at low temperatures is clearly described [75-77].

Despite significant advancements in understanding the impact of RAP on LTC resistance, several research gaps remain. A critical challenge is optimizing RAP content to balance sustainability and pavement performance, as higher RAP percentages often degrade LTC resistance. Further research is needed to examine the influence of key mixture design variables—such as air void content, asphalt binder type, and aggregate gradation—on LTC resistance. Understanding how these factors interact with RAP mixtures under different aging conditions is essential to fully grasp the role of long-term aging in LTC susceptibility.

2.3 Implementation of LTC Test in BMD

A recent survey by the Federal Highway Administration (FHWA) on the implementation of BMD revealed that LTC is a critical form of distress. Nearly all states across north of U.S. identified LTC as a primary pavement concern, as illustrated in Figure 2.5 [78]. Nonetheless, only few states are focusing on exploring and implementing LTC test methods on their balanced mix design framework [78]. North Dakota, Minnesota, Utah, and Wisconsin are actively exploring different approaches to evaluate LTC resistance of locally produced asphalt mixtures as shown by Figure 2.6.

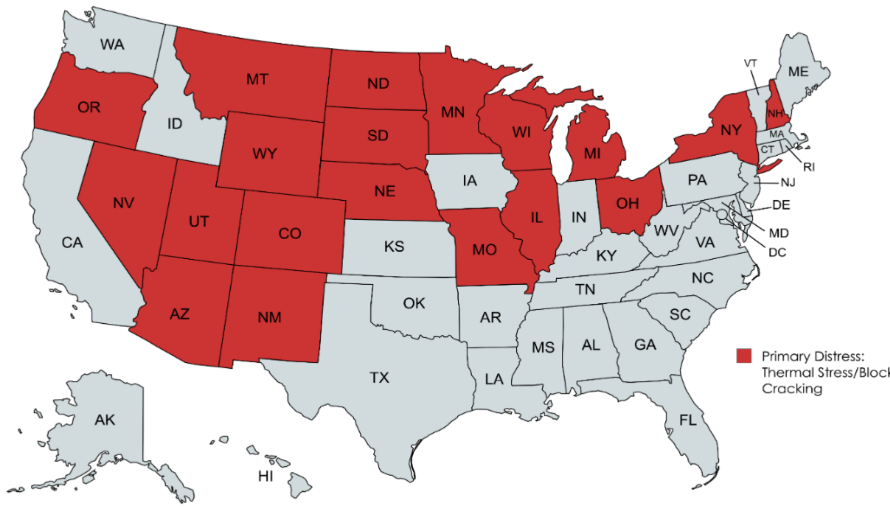


Figure 2.5 States identifying LTC or thermal cracking as a primary distress (compiled from the survey reports on implementation of BMD by FHWA *[78]*).

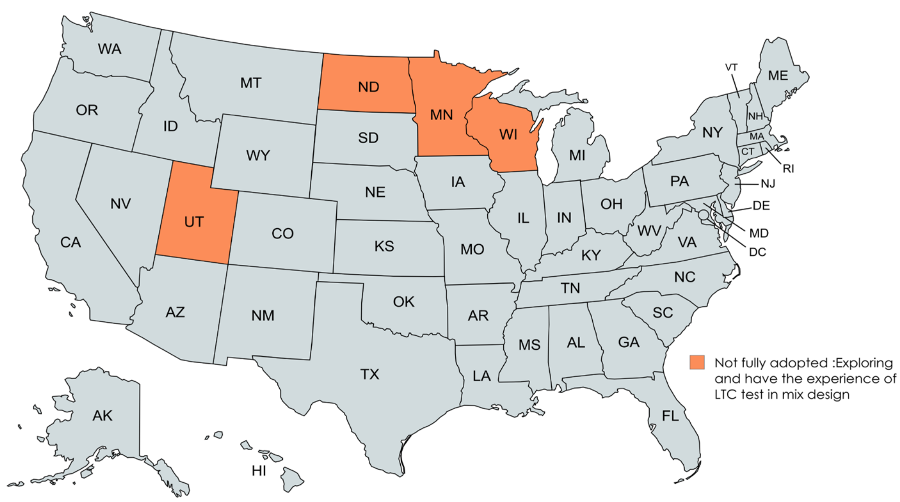


Figure 2.6 U.S. States actively focusing on implementing LTC test methods in their mix design.

North Dakota, Minnesota, and Wisconsin have focused on the use of DCT test as a mixture-level method to characterize LTC performance [79] [80]. In contrast, Utah is investigating the use of mixture-level BBR testing as a potential alternative for assessing LTC resistance [81]. Recent efforts across these states have emphasized evaluating the sensitivity of these test methods to high-RAP mixtures and varying volumetric properties, reflecting an ongoing pursuit to integrate reliable low-temperature performance metrics within balanced mix design frameworks.

Minnesota has implemented the Disk-Shaped Compact Tension (DCT) test as a primary method for evaluating fracture energy and resistance to thermal cracking, with minimum thresholds based on traffic demand: > 690 J/m² for high traffic levels (> 30 million ESALs), > 460 J/m² for moderate traffic (10–30 million ESALs), and > 400 J/m² for low traffic (< 10 million ESALs) [10]. Minnesota has also evaluated the Semi-Circular Bending (SCB) test for LTC assessment, demonstrating a reasonable correlation with field transverse cracking. A minimum fracture energy of > 350 J/m² was recommended when aging is not considered, based on short-term aged mixtures and their relationship to field performance. When aging-related field effects were incorporated, the recommended threshold was increased to > 400 J/m² to better reflect long-term performance. The underlying concept is to require mixtures with higher fracture energy to compensate for long-term field transverse cracking and ensure adequate durability throughout the pavement service life.

Similarly, several Midwestern states, including Iowa and Missouri, use DCT fracture energy thresholds adjusted by traffic level (ESALs), underscoring regional consistency in fracture-based performance specifications for cold-climate pavements.

Utah DOT evaluated mixture performance in their report *Balanced Asphalt Concrete Mix Performance in Utah – Phase V[81]*, where mixture-level Bending Beam Rheometer (BBR) testing was used to assess low-temperature performance. The study showed that mixture-based BBR parameters can effectively identify pavement sections most susceptible to thermal cracking.

For mixtures containing up to 30% RAP, recommended criteria include an S-value < 12,000 MPa and an m-value > 0.12, which proved effective in screening mixtures likely to exhibit poor performance under low-temperature conditions.

Despite these advances, important limitations remain. Fracture energy thresholds and mixture-based BBR criteria are often region-specific. In addition, the relationship between laboratory performance indices and long-term field cracking remains limited across diverse mixture types and environmental conditions. Consequently, further research is needed to refine the performance thresholds while accounting for state-specific climatic conditions, material characteristics, and mixture applications to ensure reliable and durable pavement performance.

Chapter 3 Material, Mixtures, Test Methods and Test Specimen Fabrication

This chapter describes the pavement locations included in this study, the raw materials used (binders, aggregates, and RAP), the binder and mixture blends evaluated, and the sample preparation procedures and experimental test methods adopted.

3.1 Site Location

This study investigates the LTC resistance of asphalt mixtures produced in Nebraska, using pavement sections selected from recently completed BMD research projects [Ref1, Ref 2]. The projects were chosen based on observed differences in field performance, particularly thermal cracking, and variations in laboratory performance, with emphasis on mid-temperature cracking behavior. Thus, three pavement sections located in different regions of Nebraska were included in this study, along with the corresponding materials used in their construction, being two projects with Nebraska SPR mixtures and one project with a Nebraska SLX mixture. Figure 3.1 illustrates the locations of these sections and identifies the type of mixtures evaluated at each site, including lab-produced (LP) mixtures, plant-produced (PP) mixtures, or both. The pavement section in Tekamah, designated as SPR2-LP, was evaluated using only LP mixtures. In contrast, the Ong Spur section, referred to as SPR1-LP and SPR1-PP, included both LP and PP mixtures. The third pavement section, located in Grand Island, utilizes only PP mixtures and is designated as SLX-PP. Additional details regarding the mixture types and material characteristics are provided in the following sections.

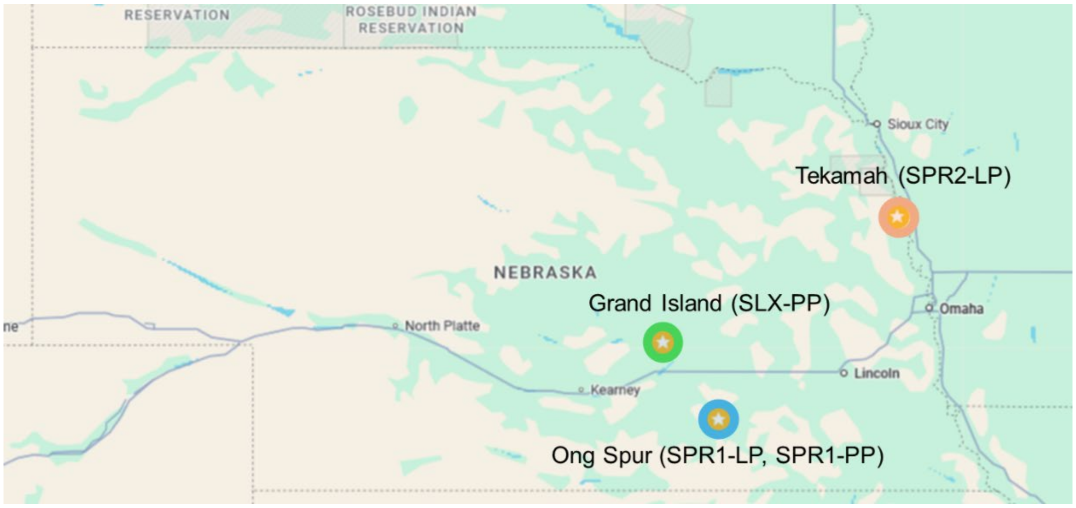


Figure 3.1 Pavement sections considered in this study.

3.2 Materials

In the first stage of this study, mixtures SPR1 and SPR2 were intentionally selected as they presented similar gradation curves, RAP content, and binder type. However, they had different CT indices and field performances. Due to limitations on plant-produced materials, similar raw materials used to produce those two mixtures during project implementation were collected to re-produce them in the laboratory. The lab-produced mix design parameters were cross-checked with NDOT SPR limits as well as with the Cracking Tolerance Index (CT_{index}) obtained from the plant produced mixtures in the time of field construction.

Then, to verify the combined effect of gradation and RAP content, and considering the use of plant produced mixtures, plant-produced SPR and SLX were used in the second stage of this research.

3.2.1 Recycled Asphalt Pavement (RAP)

Field-collected RAP was used to produce SPR1-LP and SPR2-LP. The sample was obtained from a local asphalt plant stockpile near Lincoln, Nebraska. One ton of RAP was collected and transported to the storage area in the Infrastructure Materials & Pavement Research (IMPAR) Lab at the University of Nebraska-Lincoln (UNL). To prevent exposure to moisture and further aging, the material was stored in a covered bag at room temperature.

It is important to highlight that, since the field projects were constructed two years ago, the RAP source used for the lab-produced mixtures in this study differed from that used for the original plant-produced samples in the field projects. Some slight differences were observed in the RAP gradation, but the final blends were overall similar to the original gradation curves. However, other variables, such as RAP aging level, can still play a role and affect the final reproducibility of the sample, leading to different mixture performance.

3.2.2 Aggregates

Limestone and gravel (2A, 3ACR, and 47B types) virgin aggregates with a nominal maximum aggregate size (NMAS) of 12.5 mm were used in this study for SPR-LP mixtures. 55% of virgin aggregates were combined with 45% of RAP to obtain the final aggregate blend used for the studied high-RAP mixtures. Figure 3.2 shows the gradation of the lab-produced SPR1-PP and SPR2-PP mixtures. The final blend fell between the minimum and maximum control points set by the Nebraska Department of Transportation (NDOT) [82].

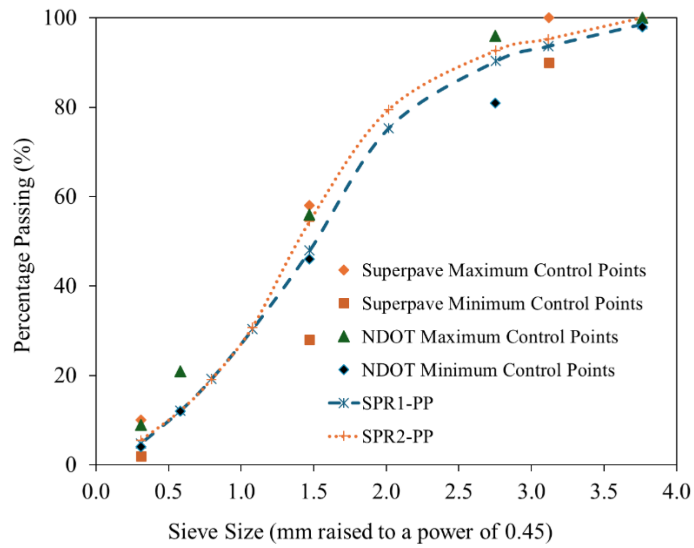


Figure 3.2 Aggregate gradation for LP mixtures

The aggregate gradation curves for the plant-produced mixtures (SPR-PP and SLX-PP), along with the minimum and maximum control points, are shown in Figure 3.3. It should be noted that the SLX-PP mixture incorporated 35% RAP and SPR1-PP incorporated 45 % RAP.

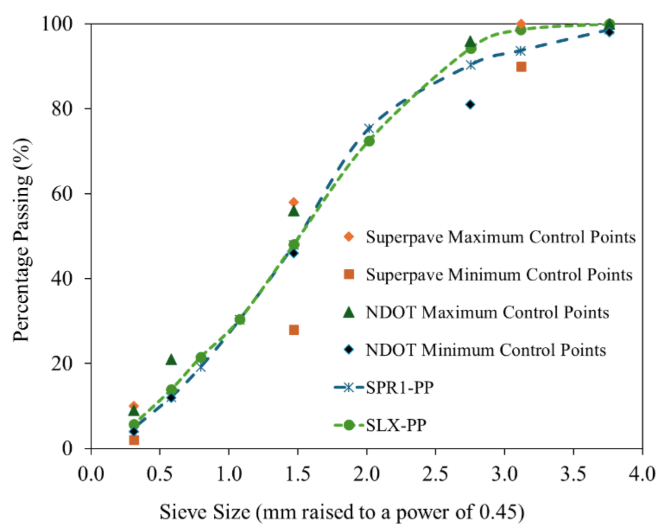


Figure 3.3 Aggregate gradation for PP mixtures.

In addition, the proportions of different aggregate types—limestone and gravel—in both laboratory-produced and plant-produced mixtures are summarized in Table 3.1. Among the laboratory-produced mixtures, SPR1-LP contained a higher proportion of gravel, whereas SPR2-LP had a higher limestone content. For the plant-produced mixtures, SPR-PP and SLX-PP exhibited similar gravel content; however, SLX-PP had a higher percentage of limestone compared to SPR-PP. Similarly, absorption tests performed on these aggregates based on ASTM C127 showed that limestone had an absorption of 1.39%, while gravel had an absorption of 0.60%.

Table 3.1 Proportion of aggregate types for each mixture.

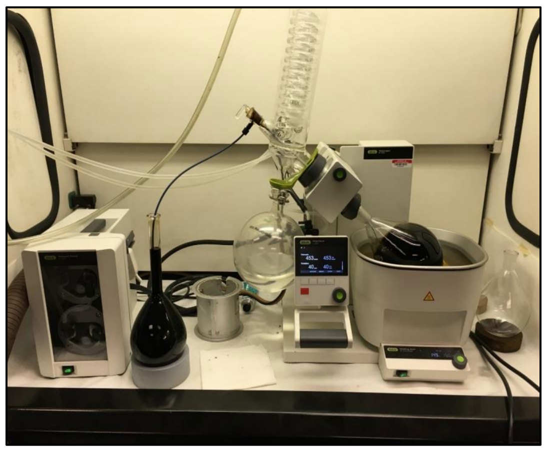
Mixture Types	**Aggregates (%)**		
	Limestone	**Gravel**	**RAP**
SPR1-LP	48	7	45
SPR2-LP	10	45	45
SPR-PP	10	45	45
SLX-PP	20	45	35

3.2.3 Asphalt Binders

A PG 58H-34 binder from Flint Hills was selected as a virgin binder (VB) for this study to keep the same source and PG grade as used in the field projects. For the binder-level tests, one binder was produced in the laboratory by mixing the VB with RAP extracted binder, named RAB hereafter. The RAB was obtained using a three-step procedure based on the ASTM D 2172 [83], ASTM D1856 [84], and ASTM D 5404 [85] standards for centrifuge extraction, microcentrifugation, and rotavapor recovery processes, respectively, and they are illustrated in Figure 3.4.

(a)

(b)



(c)

Figure 3.4 Binder extraction process from RAP a) Centrifuge extraction, b) Microcentrifuge extraction, and c) Rotavapor recovery.

After the extraction process, a blend of 45% of the RAB and 55% of the VB (PG 58H-34) were prepared and named SPR binder, assuming 100% of binder availability from RAP. It is important to mention that the blends were produced using a high-shear mixture, maintaining the shear rate of 2000 rpm and the temperature of 150 °C for one hour during the blending process. In addition to that, utilizing the same binder recovery procedure discussed above, binders from plant produced mixtures were also extracted and further tested at the binder level and named

SPR1-PP and SLX-PP considering the two mixture types used in this study. The binders used in this study are presented in Table 3.2.

Table 3.2 Binder ID and composition.

Binder ID	Binder Composition
VB	PG 58H-34
SPR-LP	55% PG 58H-34+ 45% RAB
SPR1-PP	Extracted Binder from SPR1-PP
SLX-PP	Extracted Binder from SLX-PP

3.2.4 Asphalt Mixtures

The SPR mixture was produced by mixing 45% RAP with 55% virgin materials in the laboratory. The high-RAP mixtures were designed to meet the NDOT criteria for SPR mixtures [82] and accounting for the same mix design as described for Nebraska Balanced Mix Design (BMD) project. The RAP binder content was determined at 5.01%. Therefore, an additional base binder PG 58H-34 was added to obtain the overall high-RAP mixture binder content as required by the mixture types. These mixtures were named SPR1-LP and SPR2-LP. The design-specific details of the two SPR mixtures produced in the lab based on the NDOT guidelines are presented in Table 3.3.

Table 3.3 Volumetric parameters for SPR1-LP and SPR2-LP.

Property	NDOT Requirement	SPR1-LP	SPR2-LP
Binder Content (%)	>5 %	5.50	5.35
Dust to Binder Ratio	0.7-1.70	0.77	1.01
Air Voids (%)	3 ± 1%	2.25	2.29
Voids in Mineral Aggregate (%)	N/A	12.6	12.1
Voids Filled with Asphalt (%)	N/A	82.1	81.1

In addition to the two LP mixtures, two PP mixtures were evaluated for LTC resistance in this study. These PP mixtures were selected to correspond with one of the LP mixtures and to represent a commonly used mixture in Nebraska, SLX. Accordingly, the PP mixtures were designated as SPR1-PP and SLX-PP. Both mixtures had a binder content of 5.5 %. In total, four mixtures were investigated to evaluate the LTC resistance of high-RAP mixtures: SPR1-LP, SPR2-LP, SPR1-PP, and SLX-PP.

All mixtures were subjected to STA and LTA conditions. The STA was performed by heating the loose mixture at 135 °C for four hours, in accordance with the AASHTO R 30 standard. For LTA, mixtures were conditioned following the procedure outlined in the National Cooperative Highway Research Program (NCHRP) Report 09-54 [86]. The mixture was conditioned at 95 °C for three days and then used to prepare the specimen for cracking tests. This simulates the long-term cracking performance of the asphalt mixture after eight years of field aging under 20 mm below the pavement surface, considering the climatic conditions in Nebraska (Figure 3.5).

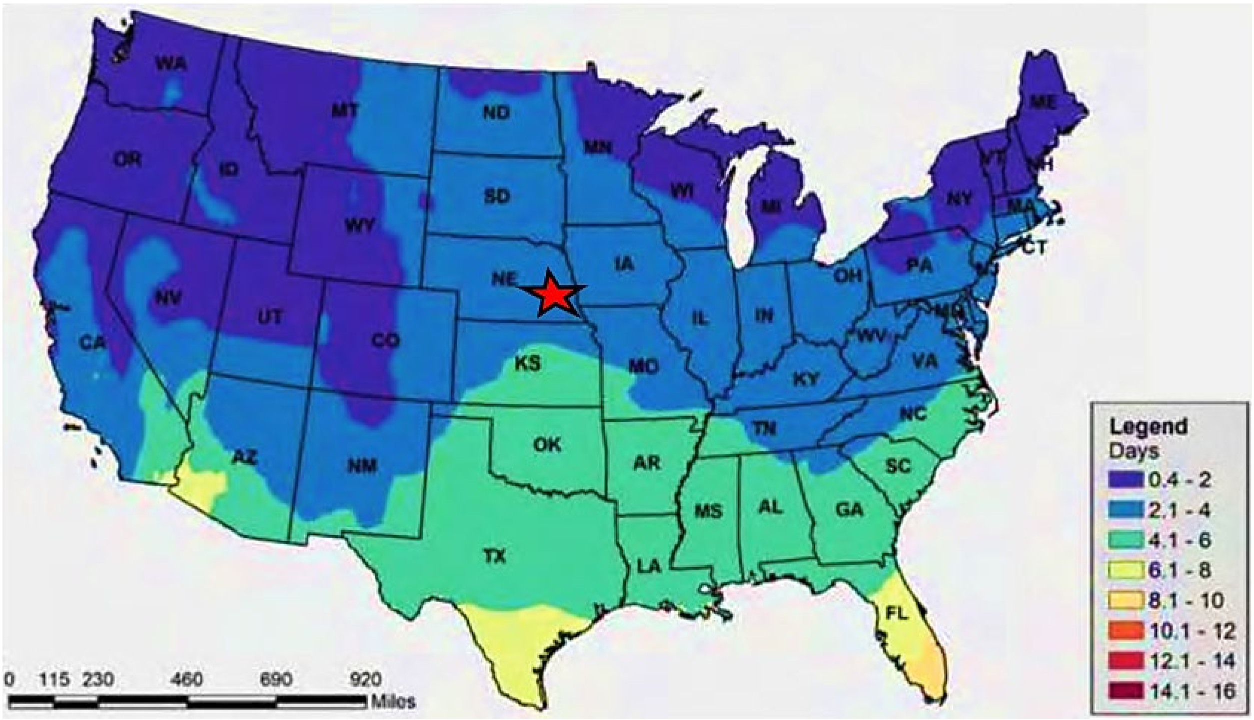


Figure 3.5 Long-term aging duration to simulate years under 20mm depth [86].

3.3 Specimen Fabrication and Test Methods

3.3.1 Fabrication of Binder Test Specimen and Test Methods

Binder specimens were prepared to characterize the continuous performance grade (PG) of the studied binders. Binder testing was conducted using DSR and BBR specimens under different aging conditions, according to the AASHTO T 315 [87] and AASHTO T 313 [88] standards, respectively. Initially, tests were performed on the virgin PG 58H-34 binder and on blends of virgin and RAB. These binder samples were subjected to two aging conditions: STA and LTA. The STA condition, which represents aging associated with asphalt mixture production and placement in the field, was simulated using the rolling thin-film oven (RTFO) test in accordance with the ASTM D2872 standard [89]. High-temperature rutting performance of the binders was evaluated under the STA condition.

Evaluation of low-temperature cracking behavior required binders to be in the LTA condition. Accordingly, long-term aging was performed using a pressure aging vessel (PAV) following the ASTM D6521 standard [90]. Standardized LTA (RTFO followed by one PAV cycle) was applied to the virgin and blended binders. For binders extracted from plant-produced mixtures, a similar procedure was followed; however, only PAV aging was applied prior to low-temperature cracking evaluation using BBR, as the plant-produced mixture had already undergone STA at the plant. The PAV aging was conducted at 100 °C under a pressure of 2.1 MPa. After aging, the required binder specimens were fabricated for the respective rheological tests described earlier.

3.3.1.1 Fabrication of Asphalt Concrete Specimen and Test Methods

This study primarily investigates the low-temperature cracking (LTC) resistance of laboratory-produced and plant-produced asphalt mixtures using multiple test methods. In addition, to examine the relationship between mid-temperature cracking behavior and LTC resistance, a mid-temperature cracking test was performed on the laboratory-produced mixtures. The LTC resistance of RAP-recycled mixtures was evaluated using three monotonic test methods: BBR, SCB and IDT tests. Key performance parameters obtained from these tests—including relaxation constant and stiffness from BBR, fracture energy and stiffness from SCB, and creep compliance and tensile strength from IDT—were analyzed and correlated with fundamental viscoelastic properties, namely dynamic modulus and phase angle, measured through dynamic modulus (DM) testing. Furthermore, the IDEAL-CT test was conducted to assess mid-temperature cracking resistance, providing a more comprehensive evaluation of cracking performance and enabling potential correlations with LTC-related parameters. Multiple specimens were fabricated for each test, and the specimen preparation and test procedures are described in the following sections.

3.3.1.2 Low Temperature Semi-circular Bending Test (SCB)

SCB testing was performed following the AASHTO TP 105 standard [91]. SCB specimens were obtained from cylindrical samples produced using the Superpave gyratory compactor (SGC), with dimensions of 150 mm in diameter and 110 mm in height, targeting an air void content of 7 ± 0.5%. Following compaction, the samples were cut and notched to produce SCB specimens with a 25 mm thickness and a 15 mm deep notch. The SCB test was conducted at a low temperature of -24 °C based on the low temperature PG of the binder. Prior to testing, each specimen was conditioned for two hours at -24 °C. The crack mouth opening displacement (CMOD) gauge was attached to the loading rate, as instructed in the AASHTO TP 105 standard (Figure 3.6a). The testing sequence began with the application of a small contact load of 0.3 ± 0.02 kN at a rate of 0.05 mm/s, followed by a seating load applied at a constant displacement rate of 0.005 mm/s until the load reached 0.6 ± 0.02 kN. The loading rate was then reduced to 0.001 mm/s until the force reached 1 kN. At this stage, the control mode was switched from force-controlled to CMOD-controlled, with a reduced displacement rate of 0.0005 mm/s, continuing until the test concluded—either when the load dropped below 0.5 kN or when the CMOD gauge reached its limit. For each asphalt mixture type, three SCB specimens were tested. The average results and standard deviations were reported to assess variability. Throughout the test, force and displacement data were recorded over time (Figure 3.6b), and the resulting load-displacement curves were analyzed to derive key parameters related to low-temperature cracking (LTC) resistance. These included fracture energy and stiffness of the mixture. Equation 1 was used to calculate the fracture energy, while stiffness represents the pre-peak slope of the load-displacement plot.

$$\text{Fracture Energy, } G_f = \frac{W_f}{(r-a).t} \qquad \textbf{Equation 1}$$

Where W_f = work of fracture (J), r = specimen radius (mm), t = specimen thickness (mm), a = notch length (mm).

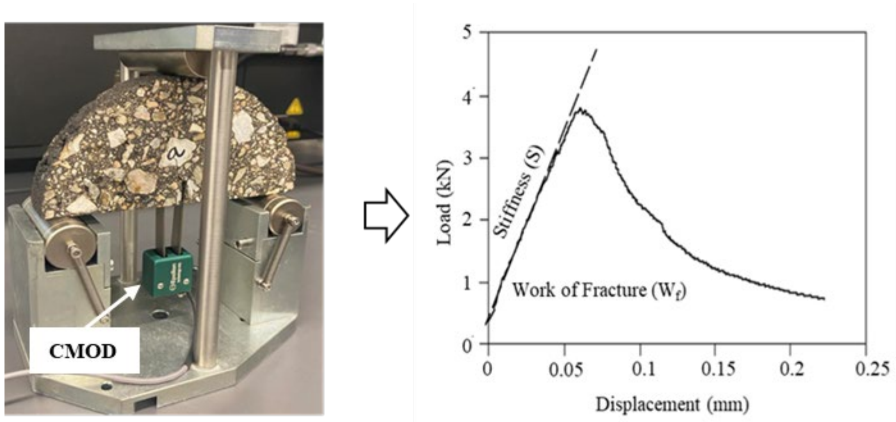


Figure 3.6 SCB a) test specimen with CMOD attachment and b) test output.

3.3.1.3 Bending Beam Rheometer Test (BBR)

Mixture-level BBR testing was performed following the AASHTO TP 125 standard [92]. Two key parameters were evaluated: creep stiffness (S) and the m-value, which represent the material's stiffness and stress relaxation capability, respectively. In this study, SGC compacted asphalt specimens with dimensions of 150 mm in diameter and 110 mm in height, and target air voids of 7 ± 0.5%, were prepared. These compacted samples were then cut into beam specimens measuring 120 ± 5 mm in length, 12.7 ± 0.25 mm in width, and 6.35 ± 0.25 mm in height. The testing was conducted at -24 °C, which is 10 °C above the binder's low-temperature PG, in accordance with the AASHTO TP 125 recommendations. Prior to testing, specimens were conditioned in the BBR bath for one hour to ensure thermal equilibrium (Figure 3.7a). During the test, a constant load of 2350 ± 50 mN was applied to each beam, and deflection at the center of the specimen was recorded at time intervals from 0 to 240 seconds (Figure 3.7b). The corresponding stiffness and m-values were computed at specific time points—8, 15, 30, 60, 120, and 240 seconds—to assess the viscoelastic response of the mixture. For each mixture type, six specimens were tested, and the average values, along with their standard deviations, of stiffness and m-value at 60 seconds were reported for comparative analysis.

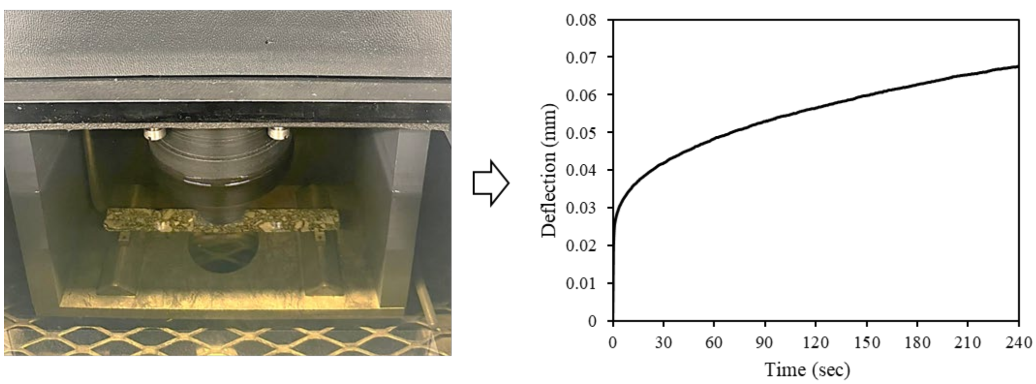


Figure 3.7 BBR test a) setup and b) output.

3.3.1.4 Indirect (IDT) Creep Compliance and Strength Test

The IDT creep and strength test was performed based on the AASHTO T 322 standard [93]. Initially, gyratory compacted samples of 170 mm in height and 150 mm in diameter with air voids of 7% ± 0.5 were fabricated and eventually trimmed to a height of 38 mm for preparing three circular disc-shaped test specimens. These specimens were provided with two pairs of linear variable displacement transducers (LVDTs) on each side of the samples. Two LVDTs measured the vertical deflection on either side of the specimen, while two LVDTs were used to measure horizontal displacement simultaneously. With the attachment of LVDTs, as shown in

Figure 3.8, specimens were conditioned at the test temperature for three hours before testing. Moreover, three temperatures were selected for testing, considering the binder grade used. In this study, corresponding to the use of PG 58H-34 grade of asphalt binder, testing was performed at -10, -20, and -30 °C. At each temperature, with the application of a creep load for a duration of 1000 seconds, horizontal and vertical deformations were recorded and further utilized to obtain the creep compliance, D(t), of the asphalt mixtures based on the method stated in the AASHTO T 322 standard.

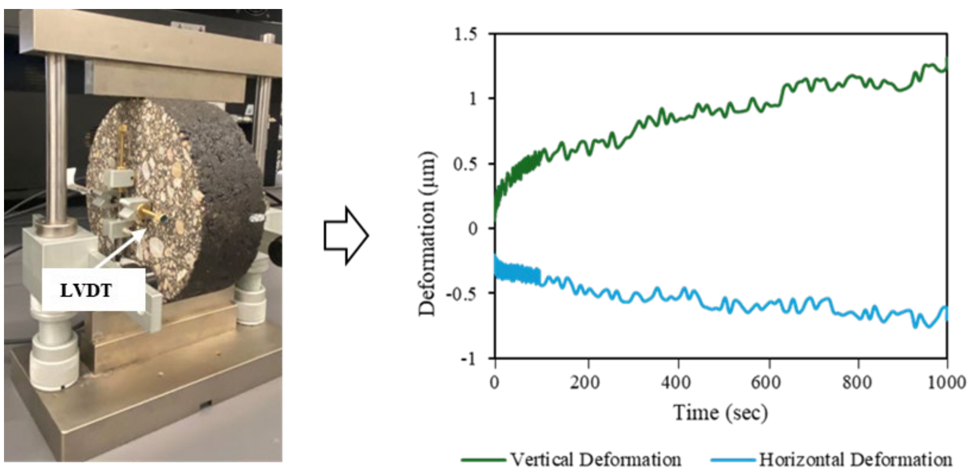


Figure 3.8 IDT Creep and Strength test specimen and test output.

Additionally, the tensile strength test was also performed after the completion of the creep test, using a sample load of 12.5 mm/min until failure. The strength test was conducted at the middle creep and compliance test temperature, which was -20 °C in this case. Then, the IDT strength was calculated using the following equation.

$$S_{t,n} = \frac{2\ x\ P_{f,n}}{\pi\, x\ b_n\ x\ D_n} \qquad \textbf{Equation 2}$$

Where for each specimen n, $S_{t,n}$ is the IDT strength of the specimen (MPa), $P_{t,n}$ is the maximum loading value of the specimen (N), D_n is the diameter of the specimen (mm), and b_n is the height of the specimen (mm).

3.3.1.5 Dynamic Modulus (DM) Test

The DM test was carried out in accordance with the AASHTO T 378 standard [94] to characterize the viscoelastic behavior of asphalt mixtures under various temperature and loading conditions. Two key parameters measured during the test were the dynamic modulus (E*) and the phase angle (δ). As the temperature decreases, the mixture's dynamic modulus increases significantly, indicating a transition toward stiffer, more elastic, and potentially brittle behavior. Simultaneously, as the phase angle decreases, it indicates diminished viscous energy dissipation and increased stress retention. These changes in mechanical response are crucial indicators of a mixture's vulnerability to thermal cracking. For this study, SGC specimens were initially compacted to dimensions of 170 mm in height and 150 mm in diameter at air voids of 7% ± 0.5. The compacted samples were then trimmed and cored to produce standard test specimens with dimensions of 100 mm in diameter and 150 mm in height. Two replicates for each of the mixture were used for the test and the DM test was performed at temperatures of 4°C, 21°C, and 40°C, and at loading frequencies ranging from 0.01 to 25 Hz, allowing for a comprehensive evaluation of the temperature- and frequency- dependent mechanical properties of the asphalt mixtures. Figure 3.9a illustrates the DM test setup, where three linear variable differential transformers (LVDTs) are affixed to the specimen surface to measure deformation during loading. The time–temperature superposition principle (TTSP) was applied to construct the master curve at the selected reference temperature of 21 °C, as shown in Figure 3.9b. Additionally, to assess the evolution of |E*| and δ under colder conditions, master curves were constructed at −24 °C corresponding to 10 °C above the low-temperature PG of the binder.

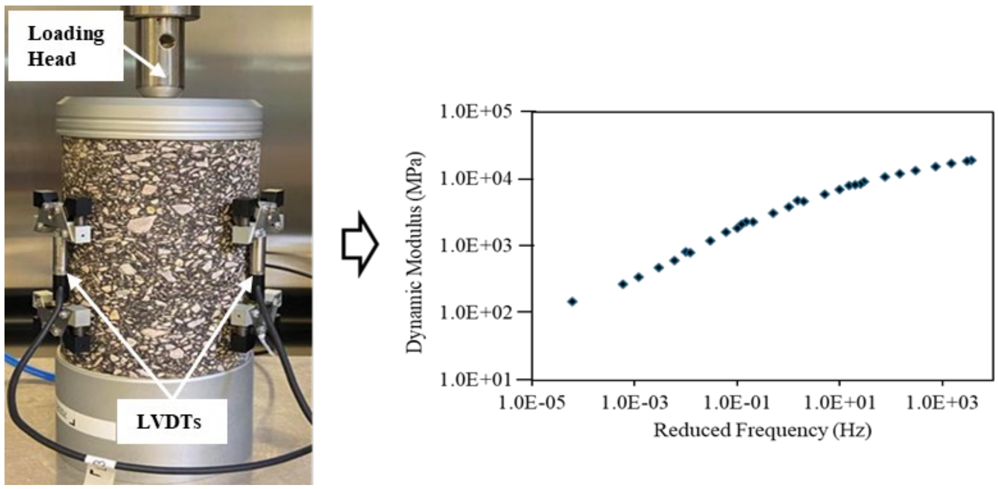


Figure 3.9 Dynamic modulus test a) setup and b) DM master curve at reference temperature

3.3.1.6 Indirect Tensile Cracking Test (IDEAL-CT)

In addition to LTC tests, the IDEAL-CT test was also conducted to verify the mid-temperature cracking resistance of lab-produced samples and cross-check with plant produced samples used in the field. The IDEAL-CT test was conducted to evaluate the cracking resistance of asphalt mixtures at 25 °C in accordance with the ASTM D8225 standard [95]. Specimens compacted using an SGC measuring 150 mm in diameter and 62 mm in thickness with air voids of 7% ± 0.5 were tested using a mechanical loading system. A constant displacement rate of 50 mm/min was applied until failure, and load-displacement curves (as shown in Figure 3.10) were obtained. The load-displacement curve was analyzed to calculate the Cracking Tolerance Index ($\mathrm{CT_{index}}$) of the mixtures. Equation 3 presents the CTindex:

$$CT_{index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \qquad \textbf{Equation 3}$$

Where G_f is the fracture energy, calculated as the area under the load–displacement curve divided by the cross-sectional area of the specimen, $|m_{75}|$ represents the absolute slope of the curve at the point where the load drops to 75% of the peak value after the peak, l_{75} is the corresponding displacement at the 75% load level and D and t refer to the specimen's diameter and thickness, respectively, in millimeters.

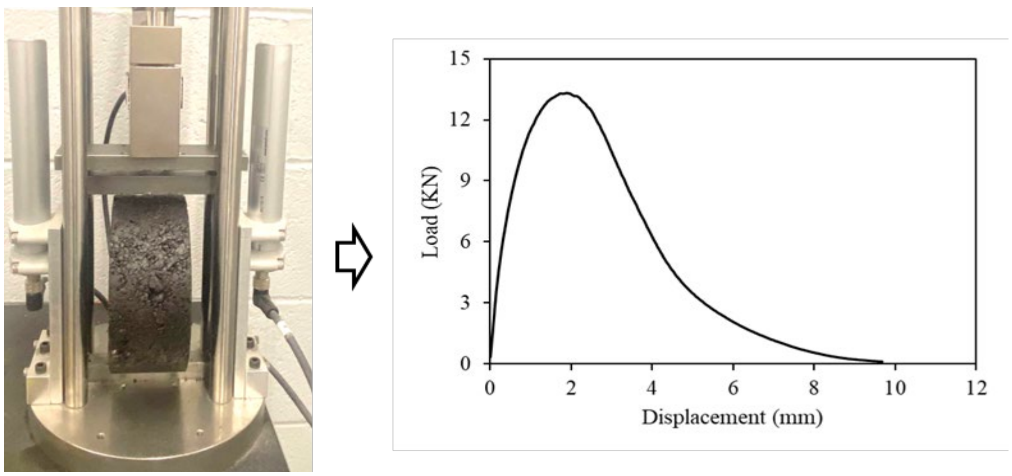


Figure 3.10 IDEAL-CT Test a) setup and b) output.

3.3.2 Statistical Analysis

This study employed multiple test methods to evaluate the mid- and low-temperature cracking performance of recycled asphalt mixtures. Given the variety of performance parameters and the two mixture types under investigation, it was essential to assess the statistical significance of the results. Initially, an analysis of variance (ANOVA) was conducted at a 95% confidence level. When the resulting p-value was found to be less than the α-level (0.05), the null hypothesis was rejected, indicating that at least one mixture exhibited a statistically significant difference in performance. Following the ANOVA, Tukey's Honest Significant Difference (HSD) test was used to further examine pairwise comparisons and to group the mixtures based on their performance. The mixtures were categorized into statistically distinct groups, labeled Group A and Group B, based on the results of the Tukey HSD analysis confirming the presence of significant differences between them. Mixtures assigned to the same group are statistically indistinguishable, indicating that any observed differences in their mean values are not significant at the chosen confidence level.

Chapter 4 LTC Evaluation for Lab-Produced Mixtures

This chapter primarily outlines the laboratory tests conducted in this study and presents their results. Initially, the conventional procedure for characterizing asphalt binders through rheological testing using DSR and BBR was performed at the binder level. Subsequently, mixture-level testing was conducted using a range of LTC test methods alongside mid-temperature cracking tests and viscoelastic performance evaluations. All tests were performed under STA and LTA conditions, and the resulting parameters were statistically analyzed.

4.1 Binder level performance evaluation

At the binder level, the high-temperature and low-temperature performance grades (PG) were evaluated for both the virgin binder and the blended binder extracted from the SPR mixture. The blended binder represents the effective binder condition resulting from binder interaction within the mixture; however, as discussed earlier, this analysis assumes 100% blending between the virgin binder and the RAP binder. Table 4.1 summarizes the continuous high- and low-temperature performance grades of the evaluated binders, alongside stiffness and m-value at binder low-temperature PG plus 10°C. In addition, the ΔTc parameter is reported, which represents the difference between the critical low-temperature grade, determined from the BBR stiffness criterion (S = 300 MPa) and the m-value criterion (m = 0.300). This parameter is commonly used as an indicator of binder embrittlement and cracking susceptibility at low temperatures.

Table 4.1 Binder performance evaluation corresponding to LP mixtures.

Samples	**High-temperature PG (°C)**	**Low-temperature PG (°C)**	**Stiffness (MPa) at -24°C**	**m-value at -24°C**	**ΔTc (°C)**
VB	63.30	-36.20	187	0.361	+3.20
SPR-LP	72.80	-29.82	358	0.238	-0.95

Based on the PG results, the VB exhibited both a lower high-temperature PG and a lower low-temperature grade compared to the SPR-LP binder, indicating that VB behaves as a relatively softer and more flexible binder. In contrast, the SPR-LP binder showed higher high- and low-temperature PG grades, which can be attributed to the incorporation of approximately 45% reclaimed asphalt binder (RAB). The presence of aged RAB increased overall binder stiffness and shifted the low-temperature grade by one increment toward a warmer temperature, consistent with the influence of a stiffer and more oxidized binder fraction.

Stiffness and m-value measurements at −24 °C exhibited similar trends. SPR-LP showed substantially higher stiffness (358 MPa) than VB (187 MPa), indicating a stiffer and more brittle binder system at low temperatures. Increased stiffness reduces the binder's ability to accommodate thermal contraction, promoting stress buildup and elevating the risk of thermal cracking. The m-value results further highlight the effect of RAB incorporation. VB exhibited a higher m-value (0.361), reflecting superior stress relaxation capability. In contrast, SPR-LP showed a lower m-value (0.238), indicating a reduced ability to dissipate thermally induced stresses over time. The aged RAB fraction restricts molecular mobility within the binder matrix, limiting viscoelastic relaxation under low-temperature loading [18, 38].

Further insight was obtained from the ΔTc analysis, which revealed distinct low-temperature behavioral trends between the two binders. The virgin PG 58H-34 binder exhibited stiffness-dominated behavior ($\Delta Tc > 0$), whereas the addition of 45% RAP binder led to a transition toward relaxation-dominated behavior ($\Delta Tc < 0$) in the blended system. This shift is primarily attributed to the highly oxidized nature of the RAP binder, which significantly impairs stress relaxation capacity, as evidenced by the accelerated reduction in m-value with decreasing temperature. As a result, the low-temperature cracking susceptibility of the RAP-modified binder is governed predominantly by diminished relaxation capability rather than excessive stiffness alone. Moreover, both binders fall within the threshold failure limit of $\Delta Tc = -5$ °C, suggesting that their use is acceptable based on the ΔTc criterion [40].

In general, the binder-level analysis demonstrates that the incorporation of RAB into the virgin binder adversely affects low-temperature cracking resistance. However, despite the use of two distinct mixture types, because both mixtures had the same binder type and RAP source and percentage, the analysis of the binder-level yielded similar low-temperature cracking resistance, highlighting a fundamental limitation of binder-scale testing for assessing the low-temperature cracking performance of RAP mixtures, especially if only the VB is used for QA/QC. We should highlight that differences in RAP quality can impact the binder testing results. If the field projects used different RAP sources, differences in RAP quality could affect the overall LTC resistance as evidenced by the data captured in the binder level tests. However, in this initial stage, since the same RAP source was used for both SPR1-LP and SPR2-LP, the potential difference cannot be captured. Consequently, these findings emphasize the need for complementary mixture-level investigations to more accurately capture the mechanisms governing low-temperature cracking in RAP-containing asphalt mixtures.

4.2 Mechanical Performance Testing and Characterization of Asphalt Concrete

4.2.1 Mid-Temperature Cracking Performance of Asphalt Mixtures

Figure 4.1 presents the CT_{Index} results for the mixtures studied. As observed, the LP mixtures exhibit a consistent trend with their PP counterparts in terms of cracking resistance; however, the CT_{index} values for the LP mixtures are comparatively lower. This reduction may be attributed to differences in aging level associated with RAP in lab-produced mixtures. Despite the lower values, the preservation of the trend across both production methods supports the validity of using the LP mixtures for comparative LTC evaluations in this study as same mix designs were followed in both cases. As illustrated in Figure 4.1, SPR1 in both plant and lab-produced mixtures exhibited significantly higher cracking resistance than SPR2, as indicated by its elevated CT_{index} value. This improved performance can likely be attributed to the higher binder content in SPR1 (5.5%) compared to SPR2 (5.35%), which enhances energy dissipation and provides greater flexibility under loading conditions [96]. The CT_{index} for SPR2 exhibited an approximate reduction of 44% compared to SPR1 in the LP mixtures, while the PP mixtures showed a similar reduction of 41% between SPR1 and SPR2.

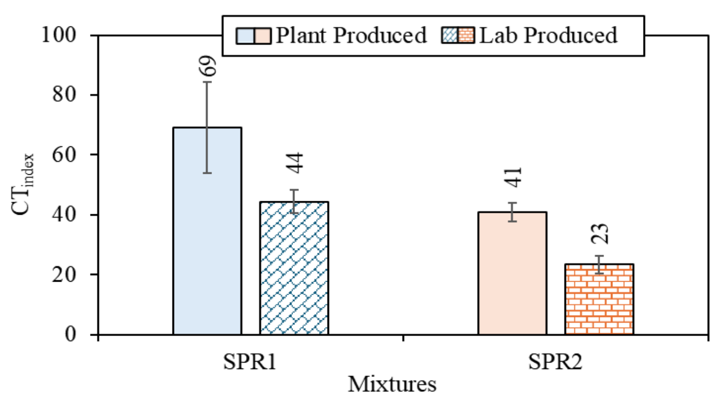


Figure 4.1 CTindex for LP and PP mixtures

Statistical analysis using Tukey's HSD confirmed that the differences were significant in both plant and lab-produced mixtures, with SPR1 and SPR2 falling into separate statistical groups (A and B), indicating distinct performance categories. Additionally, based on statistical analysis, SPR1-PP and SPR1-LP were also statistically similar and shared a common group despite a big difference in the CT_{index}.

4.2.2 Low-temperature Cracking Performance Evaluation

4.2.2.1 SCB Results

The fracture energy and stiffness of mixtures SPR1-LP and SPR2-LP at −24 °C, as determined from the SCB test, are shown in Figure 4.2. The two mixtures exhibited distinct trends in LTC performance based on SCB-derived parameters. SPR2-LP consistently demonstrated higher fracture energy and lower stiffness compared to SPR1-LP. Fracture energy serves as a key indicator of LTC resistance, with higher values implying a greater capacity to absorb and dissipate energy before crack propagation [97, 98]. In this context, the higher fracture energy of SPR2-LP suggests improved resistance to thermal cracking relative to SPR1-LP. Notably, SPR1-LP exhibited 33% lower fracture energy than SPR2-LP, indicating greater susceptibility to LTC. This observation is further supported by Figure 4.2b, where SPR2-LP, with 25% lower stiffness than SPR1-LP, exhibits better resistance to LTC due to its greater flexibility in accommodating thermally induced stresses. This finding is particularly noteworthy because SPR2-LP, which showed inferior performance under mid-temperature cracking conditions, outperformed SPR1-LP in terms of fracture energy at low temperatures.

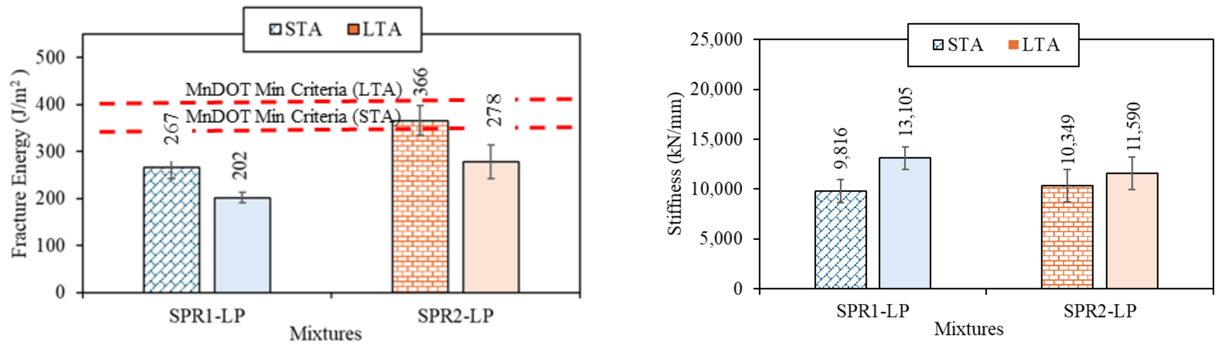


Figure 4.2 SCB Test Results a) Fracture Energy and b) Stiffness.

Tukey's HSD test confirmed that the differences in fracture energy between the two mixtures were statistically significant, grouping them into distinct categories (Group A for SPR2-LP and Group B for SPR1-LP). This indicates that the difference between their mean values exceeded the critical threshold at the 95% confidence level. The observed differences in LTC performance between the two mixtures can also be attributed to differences in aggregate type. The SPR1-LP mixture contains predominantly gravel, whereas the SPR2-LP mixture is dominated by limestone. This variation may influence binder–aggregate adhesion characteristics and, consequently, fracture performance. In contrast, stiffness values measured at −24 °C showed no statistically significant difference between the two mixtures, as both were assigned to the same statistical group (Group A) in the Tukey HSD analysis.

The mixtures were also evaluated after LTA, and a similar trend to STA was observed. SPR2-LP maintained higher fracture energy than SPR1-LP, and both mixtures exhibited a comparable reduction in fracture energy after LTA (approximately 30%). Despite this similar percentage reduction, SPR2-LP retained a higher absolute fracture energy after LTA, indicating superior LTC performance even under advanced aging conditions. More importantly, fracture energy of both the mixtures was in different groups (A and B) highlighting the sensitivity of the

SCB test in characterizing the LTC resistance of mixtures under LTA conditions in terms of fracture energy. With respect to stiffness, both mixtures exhibited comparable values after LTA, consistent with the trend observed under STA. This consistency across aging conditions indicates that the stiffness parameter derived from SCB is relatively insensitive to the effects of aging, at least in distinguishing between the two mixtures. In other words, while fracture energy clearly captured differences in cracking resistance and aging susceptibility, stiffness did not reflect these distinctions.

A possible explanation lies in the nature of the stiffness measured in the SCB test. The reported stiffness corresponds to the pre-peak response, representing the initial elastic behavior of the specimen before crack initiation and propagation. At −24 °C, the material response is already dominated by low-temperature-induced stiffening, which significantly increases mixture rigidity. Under such conditions, additional stiffening due to aging may be less distinguishable, as both mixtures are already in a highly stiffened state due to thermal effects. Moreover, LTC occurs once the material begins to accumulate damage, and the initial stiffness captured in the pre-peak load does not account for this behavior. Consequently, low-temperature stiffening may overshadow aging-induced changes in stiffness, limiting this parameter's ability to differentiate mixture performance. This explains why stiffness remained statistically similar between mixtures and across aging levels, whereas fracture energy—being more sensitive to crack initiation and propagation—provided clearer insight into LTC resistance and aging effects.

Additionally, the fracture energy results were also compared with the preliminary Minnesota threshold under STA conditions [10]. Only the SPR2-LP mixture exceeded the 350 J/m^2 threshold. Minnesota has further suggested increasing the threshold to 400 J/m^2 to account for aging; under this criterion, none of the mixtures met the requirement under either STA or

LTA conditions. However, threshold limits for BMD should be established with caution, as they must reflect site-specific factors such as climate, traffic, and local materials. Therefore, this study does not recommend adopting preliminary threshold values at this stage.

BBR Results

Figure 4.3 presents the mixture-level BBR results in terms of (a) creep stiffness and (b) m-value for SPR1-LP and SPR2-LP under STA and LTA conditions. Despite differences observed in SCB fracture energy, both mixtures exhibited comparable creep stiffness and m-values in the BBR test, suggesting similar LTC performance from a mixture-level viscoelastic perspective. Under STA, the stiffness values of SPR1-LP and SPR2-LP were relatively close, and although LTA increased stiffness for both mixtures, the relative ranking between them remained unchanged. A similar trend was observed for the m-value, where both mixtures demonstrated comparable stress relaxation capability.

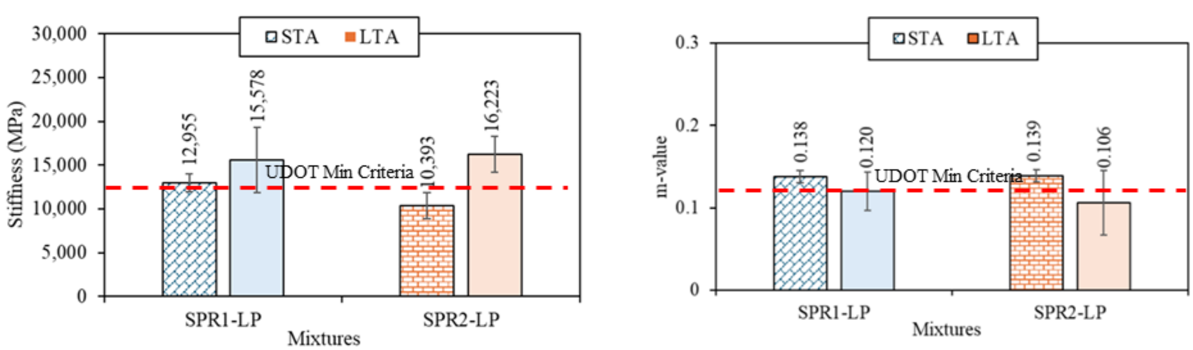


Figure 4.3 BBR Test Results a) Stiffness and b) m-value.

Tukey's HSD analysis grouped both mixtures into the same statistical category (Group A) for stiffness and m-value, confirming that the numerical differences were not statistically significant at the 95% confidence level. Because this is a mixture-level BBR test, the measured response reflects the combined effect of binder, aggregates, and internal structure. However, the test is still conducted under loads and within a linear viscoelastic regime. As a result, the loading condition does not activate microcracking, aggregate interlock degradation, or fracture processes that are critical to thermal cracking resistance [10]. This explains why the mixture-level BBR parameters were unable to distinguish between SPR1-LP and SPR2-LP, whereas the SCB test—operating under fracture-controlled conditions—identified significant differences in fracture energy. In other words, the mixture-level BBR captures time-dependent viscoelastic relaxation of the composite system, but it does not sufficiently mobilize damage mechanisms governing crack initiation and propagation. Therefore, mixtures that differ in fracture resistance may still appear similar when evaluated only through stiffness and m-value.

Moreover, when compared with the proposed Utah criteria (S-value < 12,000 MPa and m-value > 0.12) [81] which were developed based on BBR testing of plant-produced mixtures (minimum aging), field-collected mixtures at laydown (STA), and 3-year field cores (LTA), it was observed that only the SPR2-LP mixture under STA conditions satisfied the specified criteria. However, at LTA conditions, none of the mixtures met the specified thresholds. Once again, threshold limits for BMD should be established with caution, as they must reflect site-specific factors such as climate, traffic, and local materials. Therefore, this study does not recommend adopting preliminary threshold values at this stage.

Additionally, the variability (standard deviation) was noticeably higher for LTA specimens compared to STA. This increased scatter is attributed to fabrication challenges. After long-term aging, the mixtures became more brittle, and minor chipping occurred during cutting and trimming of the small BBR beams resulting in not being smooth as presented in Figure 4.4. This probably influences deflection measurements and increases data variability.

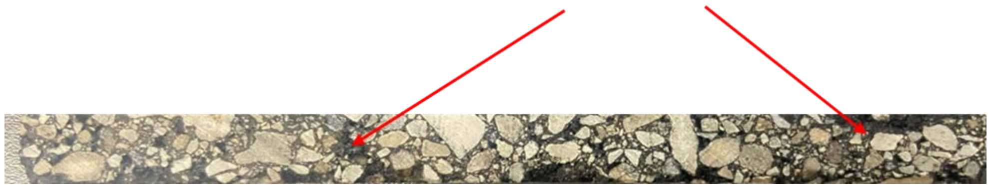


Figure 4.4 Chipping in BBR sample under LTA condition.

In summary, the mixture-level BBR results indicate comparable performance between SPR1-LP and SPR2-LP but an inability to statistically differentiate the mixtures. Given the small load applied, the material does not enter a damage state, highlighting the limitations of relying solely on stiffness- and relaxation-based BBR parameters to evaluate mixture-level LTC resistance. This is especially true for RAP-containing systems, where fracture behavior plays a governing role and underscores the sensitivity of LTC tests to specimen type and underlying test mechanisms.

IDT Creep Compliance and Strength Test Results

Figure 4.5a presents the mixture-level IDT creep compliance results (expressed in 10^{-6} MPa^{-1}) for SPR1-LP and SPR2-LP under STA and LTA conditions at −20 °C using a 10 kN constant load applied for 1000 seconds. Under STA conditions, SPR2-LP exhibited substantially higher creep compliance (4.34×10^{-6} MPa^{-1}) compared to SPR1-LP (1.31×10^{-6} MPa^{-1}). This nearly threefold increase indicates that SPR2-LP has a significantly greater ability to undergo viscoelastic deformation and relax thermal stresses at low temperatures. In contrast, the lower compliance of SPR1-LP reflects a stiffer and more brittle response, increasing its susceptibility to thermally induced cracking. After LTA, creep compliance decreased for both mixtures, reflecting the stiffening effect of long-term oxidative aging. However, the relative trend remained consistent: SPR2-LP (1.25×10^{-6} MPa^{-1}) maintained higher compliance than SPR1-LP

(0.93 × 10^{-6} MPa^{-1}). Although aging reduced the overall relaxation capacity, SPR2-LP continued to demonstrate superior low-temperature viscoelastic performance. This consistency across aging levels reinforces the observation from SCB fracture energy results that SPR2-LP possesses improved LTC resistance despite showing inferior mid-temperature cracking performance.

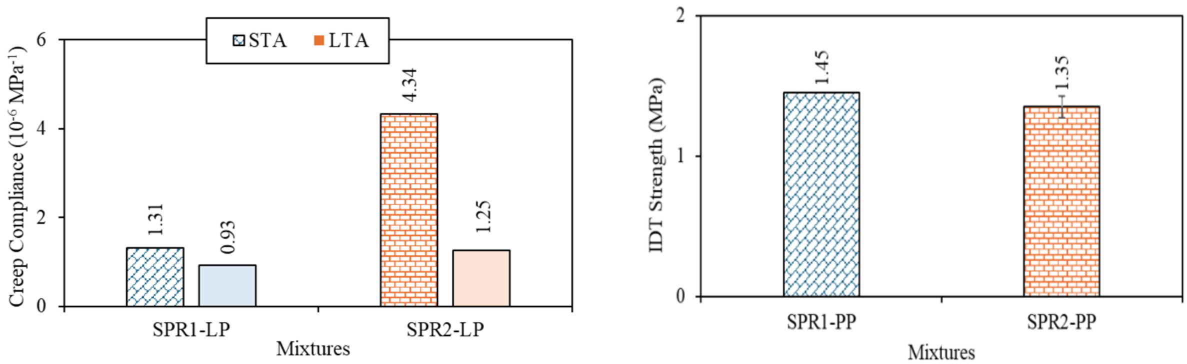


Figure 4.5 IDT Test Results a) Creep compliance and b) Tensile strength.

Figure 4.5b presents the IDT tensile strength results at −20 °C. Under STA conditions, both mixtures exhibited similar tensile strength values (approximately 1.45 MPa for SPR1-LP and 1.35 MPa for SPR2-LP), indicating minimal distinction in their resistance when evaluated purely through peak strength. Due to the test-equipment load limitations, tests were unable to be conducted under LTA.

The similarity in tensile strength, combined with the clear separation observed in creep compliance, suggests that strength-based parameters alone may not adequately capture differences in LTC resistance. Tensile strength reflects the peak load-carrying capacity at failure, whereas creep compliance reflects the material’s ability to relax stresses prior to fracture. In cold climates, thermal contraction produces gradual stress buildup within the pavement structure, making the mixture’s ability to relax stresses more critical than its peak tensile strength. Under these conditions, low temperatures significantly increase mixture stiffness, limit stress dissipation and increase the potential for crack initiation if adequate stress relaxation capacity is not present. While tensile strength showed little distinction between SPR1-LP and SPR2-LP, creep compliance consistently identified SPR2-LP as having superior relaxation capacity under both STA and LTA conditions. These findings further emphasize that performance trends observed at mid-temperatures do not necessarily persist at low temperatures and highlight the necessity of incorporating dedicated LTC evaluation metrics particularly those sensitive to viscoelastic stress relaxation for comprehensive assessment of recycled mixtures in cold regions.

4.2.3 Viscoelastic Properties Evaluation

4.2.3.1 Dynamic Modulus Test Results

Figure 4.6 presents the |E*| and δ master curves for the SPR1-LP and SPR2-LP mixtures under STA and LTA conditions at −24 °C. At this temperature, the |E*| master curves show no distinct differences in stiffness between the two mixtures. Likewise, the δ master curves exhibit minimal variation between SPR1-LP and SPR2-LP across the entire frequency spectrum under both aging conditions.

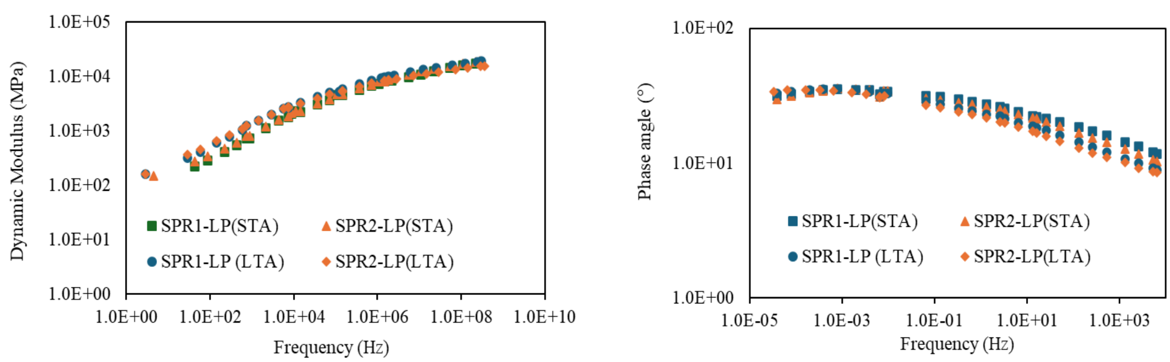


Figure 4.6 DM Test Results: a) Dynamic Modulus Master Curve, and b) Phase Angle Master Curve at -24°C.

Because |E*| represents overall mixture stiffness and δ reflects the balance between elastic and viscous response, the nearly identical trends indicate that the mixtures possess comparable linear viscoelastic behavior and similar energy dissipation characteristics. These similarities highlight an important limitation of the dynamic modulus test when used to evaluate LTC performance. The test is performed under small-strain, linear viscoelastic conditions and therefore does not adequately replicate thermal stress development, microcrack initiation, and fracture propagation that occur in the field under cold climates. Consequently, despite similar viscoelastic properties, the actual resistance of SPR1-LP and SPR2-LP to thermal contraction and fracture may differ substantially which is the behavior that is not captured by |E*| and δ alone. Results under LTA exhibited similar trends; although both mixtures showed a general shift toward increased stiffness and slightly reduced phase angle compared with STA, neither parameter effectively distinguished mixture performance with respect to LTC susceptibility.

4.3 Summary of LTC Test Methods for LP Mixtures

It was observed that the two SPR recycled mixtures evaluated in this study exhibited different performance trends with respect to mid-temperature cracking and LTC. Notably, the relative ranking of mixture performance reversed when assessed under LTC conditions. However, consistent statistical significance between the mixtures was not captured by many of the test methods. At low temperatures, previously observed differences diminished, and most parameters (including SCB stiffness, BBR stiffness and m-value, IDT strength parameters, and dynamic modulus results) did not show statistically significant distinctions between the mixtures. In contrast, a limited number of parameters, particularly SCB fracture energy and IDT creep compliance, were able to distinguish the mixtures with statistical significance. This finding highlights the sensitivity of fracture- and relaxation-based parameters to cracking susceptibility and underscores the limitations of stiffness-based metrics alone in differentiating mixture performance under low-temperature conditions.

Chapter 5 LTC Evaluation of Plant-Produced Mixtures

This chapter further explores laboratory tests with the potential to characterize the LTC resistance of LP mixtures towards PP recycled mixtures used in Nebraska—SPR and SLX. Two tests, SCB and IDT creep and strength, which demonstrated sensitivity to LTC characterization, were selected for further evaluation. Rheological testing using DSR and BBR was first performed to investigate LTC performance at the binder level, followed by mixture-level mid-temperature cracking evaluation using IDEAL-CT. Finally, the selected LTC tests were conducted to determine whether the resulting parameters could statistically distinguish the PP mixtures.

5.1 Binder level performance evaluation

At the binder level, the high-temperature and low-temperature continuous performance grades were evaluated for the extracted binder from both SPR-PP and SPR-SLX mixtures. The extraction procedure is outlined in Section 3.2.3. Test were run on the extracted binder to evaluate the continuous high- and low-temperature performance grades. The blended binder represents the conditions of the binder extracted from the mixture. Table 5-1 summarizes the continuous high- and low-temperature performance grades of the evaluated binders. In addition, the ΔT_c parameter is reported, which represents the difference between the critical low-temperature grade determined from the BBR stiffness criterion (S = 300 MPa) and that determined from the m-value criterion (m = 0.300), and is commonly used as an indicator of binder embrittlement and cracking susceptibility.

Table 5.1 Binder performance evaluation corresponding to PP mixtures.

Samples	High-temperature PG (°C)	Low-temperature PG (°C)	Stiffness (MPa) at -24°C	m-value at -24°C	ΔTc (°C)
SPR-PP	73.70	-27.01	443	0.271	-2.80
SLX-PP	74.10	-32.15	337	0.301	+1.62

Both SPR-PP (45% RAP) and SLX-PP (35% RAP) exhibit comparable high-temperature PG values. In contrast, a clear divergence is observed in low-temperature performance. The continuous low-temperature grade decreases from –32.15°C for SLX-PP to –27.01°C for SPR-PP. This trend is further corroborated by BBR results at –24°C, where SPR-PP exhibits substantially higher stiffness (443 MPa) and a lower m-value (0.271) compared to SLX-PP (337 MPa and 0.301), reflecting a stiffer and more brittle binder at higher RAP levels.

Beyond the reduction in low-temperature grade, the ΔTc values highlight a fundamental shift in the governing failure mechanism if ΔTc value greater and less than 0°C is accounted for. The SLX-PP binder (ΔTc = +1.62°C) is stiffness-controlled, indicating that failure is primarily governed by excessive stiffness while maintaining sufficient stress relaxation capacity. In contrast, the SPR-PP binder (ΔTc = –2.80°C) is relaxation-controlled, suggesting a diminished ability to dissipate thermal stresses. As a result, the SPR-PP is expected to be considerably more susceptible to LTC, as it combines elevated stiffness with inadequate stress relaxation and limits its ability to accommodate thermally induced strains. These findings establish a critical connection to subsequent sections, where mixture-level testing and field performance evaluations indicate that SPR-PP and SLX-PP exhibit distinct low-temperature performance characteristics. SLX-PP consistently demonstrates superior resistance to LTC compared to SPR-PP.

5.2 Mechanical Performance Testing and Characterization of Asphalt Concrete

5.2.1 Mid-Temperature Cracking Performance of Asphalt Mixtures

The mid-temperature cracking resistance of the plant-produced mixtures was evaluated using the IDEAL-CT test at 25 °C and presented in Figure 5.1, where SLX-PP exhibited a substantially higher CT_{index} compared to SPR-PP. This pronounced difference indicates that SLX-PP has a significantly greater resistance to crack initiation and propagation under monotonic tensile loading at intermediate temperatures. The superior CT_{index} of SLX-PP can be attributed to its mixture design characteristics, particularly the lower RAP content (35%) and smaller NMAS (9.5 mm). Reduced RAP content results in a less brittle effective binder and enhances ductility at intermediate temperatures, which directly improves the mixture's ability to tolerate cracking without rapid damage accumulation [29]. Additionally, the finer aggregate structure associated with the smaller NMAS promotes improved stress distribution and crack bridging, both of which are known to positively influence IDEAL-CT performance.

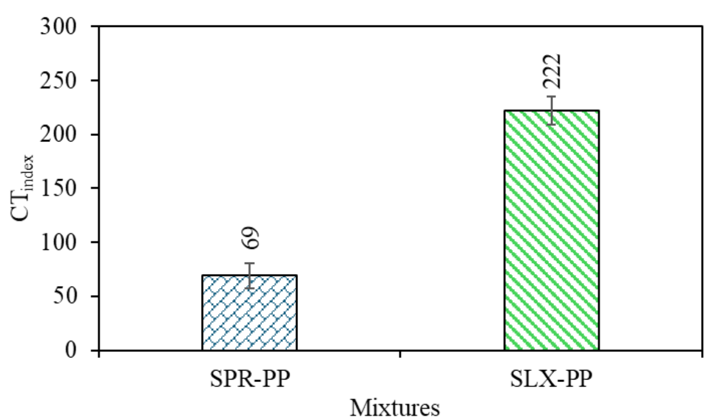


Figure 5.1 CT_{index} for SPR-PP and SLX-PP mixtures.

Notably, the IDEAL-CT results show a much stronger difference between mixtures highlighting the sensitivity of the CT-Index to mixture ductility and cracking tolerance at intermediate temperatures. Furthermore, IDEAL-CT results demonstrate that SLX-PP provides markedly improved mid-temperature cracking resistance compared to SPR-PP, reinforcing the influence of RAP content, aggregate gradation, and mineral composition on cracking performance. Despite those differences, there is a need to verify if that difference would remain under low temperature conditions.

5.2.2 Low-temperature Cracking Performance Evaluation

SCB Results

The SCB fracture energy and stiffness of mixtures SPR-PP and SLX-PP at −24 °C are shown in Figure 5.2. Under STA conditions, SLX-PP exhibited a fracture energy of approximately 410 J/m² compared to about 265 J/m² for SPR1-PP. After LTA, fracture energy decreased for both mixtures, with SLX-PP at approximately 322 J/m² and SPR-PP at about 209 J/m². Although aging reduced fracture energy by roughly 20–25%, the relative ranking remained unchanged, and SLX-PP consistently maintained a substantially higher energy absorption capacity as measured through the fracture energy parameter.

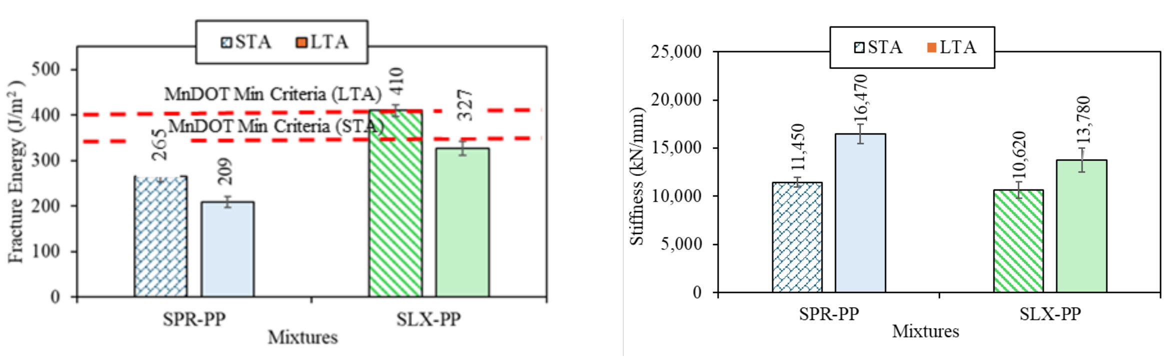


Figure 5.2 SCB Test Results a) Fracture Energy and b) Stiffness.

The superior fracture performance of SLX-PP can be attributed primarily to its lower RAP content (35%) compared to SPR-PP (45%). The higher RAP fraction in SPR-PP likely increased the effective binder stiffness and brittleness, limiting its ability to undergo deformation prior to crack propagation. While increased RAP content generally enhances mixture stiffness, it often reduces ductility and post-peak energy dissipation capacity at low temperatures, thereby lowering fracture energy. Aggregate characteristics further contributed to the observed differences. SLX-PP has a smaller NMAS (9.5 mm) compared to 12.5 mm for SPR-PP, promoting a more uniform aggregate skeleton and most probably improved stress distribution during crack initiation [99]. Additionally, SLX-PP contains a higher limestone fraction (20%) than SPR-PP (10%), which may enhance binder–aggregate adhesion and increase crack path tortuosity. These factors collectively improve resistance to crack propagation, resulting in higher fracture energy. Moreover, considering Tukey's HSD analysis, it was observed that each of the mixture SPR-PP and SLX-PP were in different groups in both STA and LTA conditions. This further shows that fracture energy parameter from SCB test was able to discriminate between these two mixtures.

Fracture energy results for PP mixtures were also compared with the Minnesota threshold under STA conditions, as indicated by the red line in Figure 5.2a [10]. The SLX-PP mixture exceeded the 350 J/m^2 STA threshold and surpassed 400 J/m^2, indicating improved LTC resistance under long-term conditions. This finding aligns with the SLX mix design, which has demonstrated superior field performance in Nebraska. In contrast, the SPR-PP mixture exhibited fracture energy values below the established threshold. However, as noted earlier, adopting a specific threshold was not the primary objective of this study; additional long-term performance field data across a broader range of mixtures are needed before such criteria can be used for mixture selection or specification.

In the case of stiffness derived from the SCB test for PP mixtures, they did not show statistically significant differences between the mixtures. Under STA conditions, both mixtures were classified within the same statistical group (Group A), while after LTA both shared Group B. Although stiffness did not distinguish between the mixtures, both exhibited a statistically significant increase after aging (SPR1-PP: ~11,450 to ~16,470 N/mm; SLX-PP: ~10,620 to ~13,780 N/mm), reflecting oxidative hardening. This increase in stiffness corresponded with reduced fracture resistance, as the mixture with higher stiffness (SPR1-PP) consistently exhibited lower fracture energy. This highlights an important mechanistic distinction: stiffness represents the pre-peak elastic response, whereas fracture energy captures the total energy required for crack initiation and propagation. At low temperatures, increased stiffness often indicates reduced ductility and a more brittle response, limiting displacement capacity and reducing the energy dissipated during fracture. Consequently, excessive stiffening, whether due to higher RAP content or aging, can promote brittle cracking and reduce low-temperature performance. The results indicate that the reduced RAP content, smaller NMAS, and higher limestone fraction in SLX-PP collectively enhanced its low-temperature fracture resistance under both STA and LTA conditions, whereas SPR1-PP did not demonstrate comparable LTC resistance.

5.2.2.1 IDT Creep Compliance and Strength Test Results

The IDT Creep Compliance and Strength of mixtures SPR-PP and SLX-PP at −24 °C are shown in Figure 5.3. Under STA conditions, SLX-PP exhibited a creep compliance of approximately 2.57×10^{-6} MPa^{-1}, which is substantially higher than that of SPR-PP (1.50×10^{-6} MPa^{-1}). After LTA, compliance decreased for both mixtures due to oxidative hardening;

however, SLX-PP (1.15×10^{-6} MPa^{-1}) remained more compliant than SPR-PP (1.10×10^{-6} MPa^{-1}). Although the gap narrowed after aging, the ranking between mixtures remained consistent. The substantially higher compliance of SLX-PP under STA indicates a more favorable viscoelastic response allowing greater strain development under constant stress and reducing internal stress accumulation during thermal contraction. This behavior is critical in cold climates, where gradual temperature drops induce restrained contraction stresses rather than instantaneous loading. The lower compliance observed for SPR-PP is consistent with its higher RAP content (45%), which increases the effective binder stiffness through the contribution of aged binder. The stiffer binder phase restricts molecular mobility and limits viscous flow, thereby reducing time-dependent strain development [100]. As a result, stress relaxation capacity diminishes, promoting brittle response and increasing cracking susceptibility.

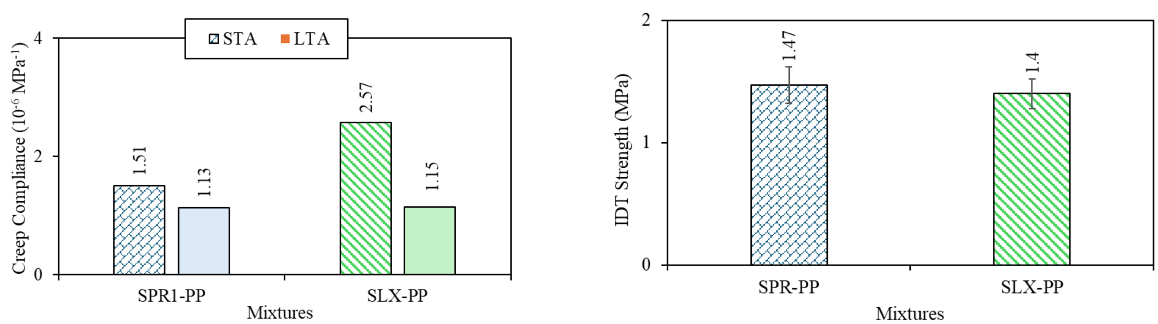


Figure 5.3 IDT Test Results a) Creep compliance and b) Tensile strength.

The smaller NMAS (9.5 mm) and lower RAP content (35%) of SLX-PP likely contributed to a more uniform aggregate skeleton and a less constrained mastic phase, enabling greater deformation compatibility between binder and aggregates. These factors collectively explain the higher fracture of energy previously observed for SLX-PP at −24 °C, demonstrating consistency between viscoelastic deformation capacity and fracture resistance. The reduction in compliance after LTA for both mixtures reflects aging-induced stiffening of the binder matrix, which decreases viscous dissipation and increases elastic dominance at low temperatures. However, even after aging, SLX-PP maintained comparable or slightly higher compliance, suggesting that low RAP content and smaller NMAS size had been influential in enhancing LTC of SLX-PP mixture.

In contrast to creep compliance, as shown in Figure 5.3, the IDT strength results show minimal differentiation between the mixtures. SPR-PP exhibited a tensile strength of approximately 1.47 MPa, while SLX-PP measured approximately 1.40 MPa and were placed in a same statistical grouping. The small difference is indicative of tensile strength that reflects the maximum stress at failure but does not capture pre-failure stress relaxation or post-peak energy dissipation behavior. Consequently, mixtures with similar peak strengths can exhibit substantially different cracking performance if their deformation and relaxation characteristics differ [29]. This explains why SPR-PP and SLX-PP showed comparable strength values despite clear differences in creep compliance and fracture energy.

Chapter 6 Field Performance Testing and Relationship with Laboratory Test Results

This chapter presents the field performance evaluation of the pavement sections constructed with the mixtures used for LTC assessment in this study. In particular, observed thermal cracking in the field is related to the results of the various LTC tests conducted in the laboratory.

6.1 Thermal Cracking Assessment

Thermal cracking performance of the three mixtures (SPR1, SPR2, and SLX) was evaluated based on the number of transverse thermal cracks (per mile) measured at six months, two years, and three years after construction, as presented in Figure 6.1. The results reveal distinct temporal cracking trends among the mixtures, reflecting the combined influence of mixture design and site-specific environmental conditions. At six months, thermal cracking was negligible across all mixtures. Both SPR1 and SLX exhibited no cracking, while SPR2 showed only a minimal level (0.129 cracks per mile), indicating comparable early-age thermal performance among the sections. Similarly, after two years, no significant differences were observed: SPR1 and SLX continued to exhibit no thermal cracking, whereas SPR2 showed a slight increase from 0.129 to 0.31 cracks per mile. These observations suggest that thermal cracking was not a critical distress mechanism during the early service life of these pavement sections under Nebraska conditions

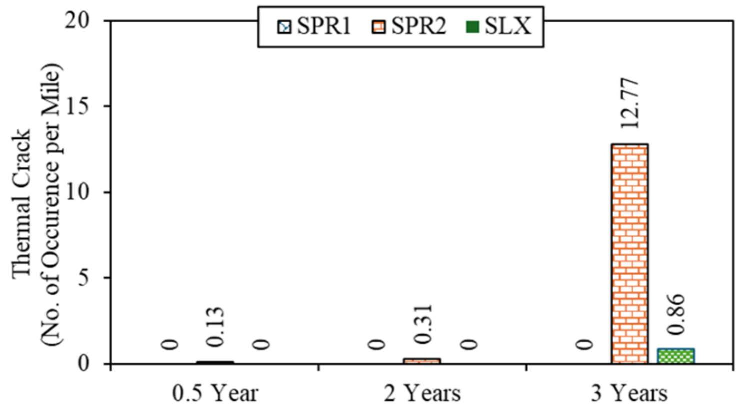


Figure 6.1 Thermal cracks on pavement sections.

However, by the third year, SPR2 exhibited a substantial increase in thermal cracking, rising sharply from 0.31 to 12.77 cracks per mile, while SPR1 and SLX continued to show minimum to no observable cracking. The minimum cracking in SLX is consistent with its superior laboratory-based cracking resistance. In contrast, the field performances of SPR1 and SPR2 highlight a deviation from laboratory expectations. Although SPR1 did not exhibit particularly strong cracking resistance in laboratory evaluations, it performed satisfactorily in the field. Conversely, SPR2, which showed comparatively better laboratory performance, experienced significant cracking in the field, indicating that laboratory metrics alone may not adequately account for long-term environmental effects such as freeze–thaw (F-T) cycles. This divergence highlighted the importance of incorporating field observations, condition measurements, and environmental variables when interpreting laboratory results for low-temperature cracking performance

6.2 Linkage between Laboratory Cracking Tests Parameter and Field Thermal Cracking Performance

As discussed in the previous section, a contradiction was observed between laboratory predictions and field performance. Based on unconditioned fracture energy results, the SPR2 mixture exhibited higher fracture energy than SPR1, indicating superior resistance to LTC. However, field observations did not support this trend. While both mixtures showed comparable levels of thermal cracking during the first two years of service, the SPR2 mixture developed a significantly higher number of cracks after three years. This discrepancy suggests that an important environmental variable (i.e., freeze-thaw cycles) influencing long-term performance was not captured in the initial laboratory evaluation. Therefore, to further understand such discrepancies, two laboratory produced mixtures (SPR1 and SPR2) were investigated.

In this study, F-T action was identified as a critical missing mechanism, given its strong coupling with moisture damage and thermal stresses in the field. To incorporate this effect, conditioning was first performed following AASHTO T 283 for 10 F–T cycles. While this approach provided initial insight into LTC induced by moisture damage, the limited number of cycles was insufficient to simulate long-term environmental damage. Therefore, an extended and accelerated conditioning protocol was adopted using ASTM C666 to subject specimens to 90 F–T cycles, enabling a more realistic representation of cumulative damage.

For the sample conditioned in accordance with AASHTO T 283 initially, the specimens were saturated to a moisture level of 70–80%. After achieving the desired saturation level, they were wrapped in thin plastic film, placed in airtight zip-lock bags containing 10 mL of water, and stored in a freezer at –24 °C for 18 hours to complete one freezing cycle. For thawing, the specimens were transferred to a water bath maintained at 60 °C for six hours. The F-T procedure was repeated for 10 full cycles. For the ASTM C 666 method, saturation to a moisture level of

70-80% was performed before putting in the environmental conditioning chamber; however, in this method, freezing was performed at -18 °C, and thawing was performed at 4.4 °C and the F-T cycles were run for 90 cycles in a conditioning chamber. Based on the standard, one F-T cycle in this process was conducted in a period of two to five hours. The conditioned samples from both methods were eventually fractured using SCB test methods. The SCB results considering the effects of F-T cycles coupled with the LTC test is presented in Figure 6.2.

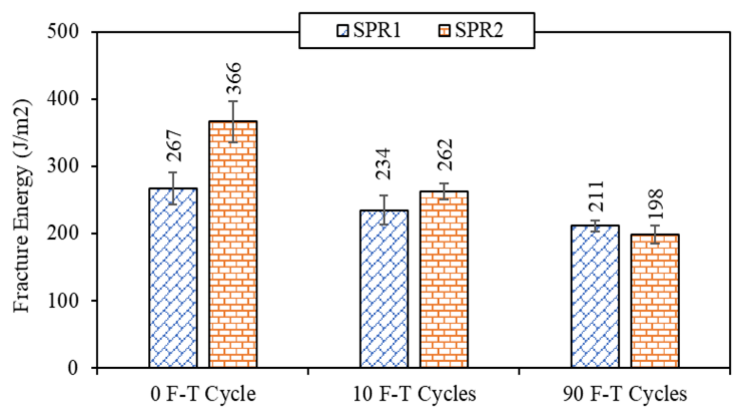


Figure 6.2 SCB fracture energy under different F-T cycles.

As shown in Figure 6.2, the fracture energy results under different conditioning levels reveal a clear evolution in material behavior. Under unconditioned conditions (0 F–T cycles), SPR2 demonstrated significantly higher fracture energy compared to SPR1. This trend persisted after 10 F–T cycles, although both mixtures experienced a reduction in fracture energy due to the onset of environmental damage. With extended conditioning (90 F-T cycles), the distinction between the mixtures became more pronounced in terms of degradation behavior. SPR2 exhibited a substantial reduction in fracture energy (approximately 46% relative to its initial value), whereas SPR1 showed a comparatively smaller reduction (~24%), indicating greater resistance to F-T induced damage. This trend suggests that SPR1 possesses improved durability under prolonged environmental conditions. Similar reductions in mixture's LTC performance with increasing numbers of F-T cycles have been reported in previous studies [101, 102]. Moreover, higher F-T conditioning levels are considered more representative of the long-term environmental exposure experienced by pavement structures in the field, thereby providing a more realistic assessment of material performance.

Furthermore, Tukey's HSD analysis performed at each conditioning level indicated that while SPR2 was statistically different from SPR1 under unconditioned conditions with different group A and B, this distinction diminished after the introduction of F-T cycles. At both 10 and 90 F–T cycles, no statistically significant difference was observed between the mixtures. This convergence suggests that although SPR2 initially possessed superior fracture resistance, it was more susceptible to environmental degradation, ultimately leading to comparable performance with SPR1 under prolonged conditioning.

Moreover, the normalized fracture energy measured as ratio of fracture energy after F-T cycles to unconditioned samples or 0 cycles conditions further highlights this divergence (Figure 6.3), with SPR2 decreasing to approximately 0.55 of its original value, while SPR1 remained about 0.78. These results indicate that although SPR2 possesses higher initial fracture resistance, it undergoes significantly greater degradation under repeated F-T exposure. The observed behavior is influenced by aggregate absorption characteristics and environmental conditioning. Limestone aggregates, used in SPR2, typically provide better initial adhesion with asphalt binder, contributing to higher fracture energy, however, it is also to be noted that the limestone aggregate used in SPR2 exhibited higher absorption compared to the gravel aggregate in SPR1, indicating a greater capacity for moisture retention. Previous studies have shown that moisture retained within aggregates can freeze and expand during F-T cycles leading to internal microcracking and weakening of the aggregate binder interface [103, 104]. Therefore, the higher absorption of the limestone aggregate may have contributed to increased damage accumulation and a greater reduction in fracture resistance. In contrast, the lower absorption of the gravel aggregate likely limited internal moisture-related damage under F-T conditioning.

Also, if the comparison is made based on the widely known measure of tensile strength ratio (TSR) from IDT test, under 90 F-T cycles, the performance of SPR1-LP is near to the threshold signifying the lesser degradation. However, it should be noted that this discussion is introduced solely for comparison purposes as this research uses fracture energy.

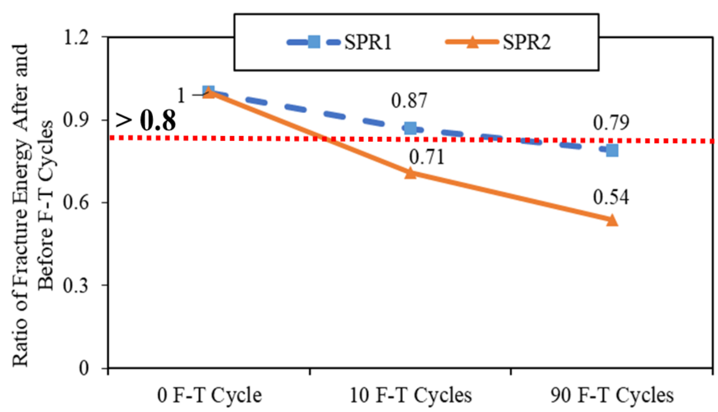


Figure 6.3 Ratio of fracture energy after and before F-T cycles.
Note: *The red dashed line at 0.8 or 80% represented threshold criteria for IDT TSR value and is shown here for comparison purposes only.*

These laboratory findings under conditioning align closely with field observations. The mixture that exhibited the greatest reduction in fracture energy under extended F–T cycles (SPR2) correspond to the mixture with increased thermal cracking after three years in service. This agreement indicates that field performance is governed not by the initial fracture resistance, but by the rate of damage accumulation under environmental exposure. The result reflects a fundamental limitation of conventional testing, which evaluates materials in a damage-free state. In contrast, field pavements experience progressive deterioration due to coupled environmental effects. When these effects are incorporated through F-T conditioning, the laboratory results begin to capture the same trends observed in the field.

Furthermore, the results demonstrate that low-temperature cracking performance is controlled by two mechanisms: (1) initial fracture resistance, and (2) durability under environmental conditioning. While SPR2 performs better in terms of initial resistance, its higher degradation rate leads to inferior long-term performance. Therefore, initial fracture energy alone is insufficient to predict field cracking behavior and incorporating durability-based parameters—such as retained fracture energy or degradation rates are essential for improving laboratory-to-field correlation. This result highlights the importance of integrating environmental conditioning into low-temperature cracking evaluation frameworks. The incorporation of F-T damage provides a more realistic assessment of mixture performance and enables identification of materials that may perform well initially but deteriorate rapidly in the field. For future implementation, long-term pavement condition monitoring is highly recommended to further validate laboratory findings under real service conditions. Continuous tracking of thermal cracking progression across different pavement sections will enable improved comparison between mixtures with varying material characteristics and environmental exposure histories. Ultimately, this integration would support more reliable mixture selection by accounting for both initial resistance and long-term durability under environmental loading.

Chapter 7 Conclusions and Future Work

This research focused on evaluating the LTC resistance of high-RAP asphalt mixtures produced in Nebraska within the BMD framework. The findings emphasize the critical need to integrate dedicated LTC test methods into the BMD protocol, particularly for mixtures intended for use in cold climate regions where thermal stress-induced cracking poses a significant performance concern. Based on the comprehensive experimental program, the following key conclusions were drawn:

- Mixtures that demonstrated statistically significant differences in mid-temperature cracking resistance did not exhibit corresponding differences in LTC performance, highlighting a disconnect between these two failure modes.
- Binder-level testing only cannot distinguish differences in LTC among mixtures, especially when similar binder types and RAP sources are used.
- For LP mixtures, stiffness and m-value from BBR, SCB stiffness, and IDT tensile strength were unable to meaningfully differentiate LTC performance under both STA and LTA conditions. These findings suggest that while useful for general characterization, these metrics may be insufficient to capture subtle yet critical differences in low-temperature behavior.
- Fracture energy (SCB) and creep compliance (IDT creep) provided differences in two recycled mixture LTC performance, indicating superior sensitivity to differences in recycled mixture behavior under thermal stress at both STA and LTA conditions.
- $|E^*|$ and δ master curves at −24 °C derived from DM testing showed minimal differences between the LP mixtures, failing to distinguish low-temperature performance under different aging conditions.

- For PP mixtures, SCB- and IDT-related parameters effectively distinguish between SPR and SLX mixtures and follow similar LTC performance trends to those observed in the extracted binder testing. Higher fracture energy was observed in SLX mixtures (lower RAP content and smaller NMAS), whereas lower fracture energy was associated with mixtures containing higher RAP content and larger NMAS. This trend was consistent across both aging levels, highlighting the sensitivity of these parameters for assessing the LTC resistance of PP mixtures.
- Initial comparisons between field thermal cracking and laboratory performance indicators, specifically SCB fracture energy and IDT creep compliance, did not establish a direct correlation with observed field behavior.
- The inclusion of F–T conditioning, under varying cycles, revealed clearer distinctions in mixture performance that aligned more closely with field observations. However, it is important to recognize that the available field cracking data represents only the first three years of pavement performance. As such, these findings should be considered preliminary, and longer-term field monitoring is necessary before drawing definitive conclusions regarding mixture behavior and performance relationships.

7.1 Recommendations

Overall, this study underscores the critical importance of integrating LTC evaluation methods within the BMD framework for mixtures intended for cold-climate regions where thermal stress–induced damage is prevalent. The primary focus of this phase was to identify and assess LTC test methods capable of effectively characterizing the low-temperature performance of RAP recycled mixtures and establishing meaningful relationships with observed field performance under both STA and LTA conditions. Future research must build upon this work by evaluating mixtures with varying RAP contents, incorporating environmental conditioning and assessing a broad range of PP mixtures across Nebraska to capture regional material and climatic variability. Developing robust correlations with field performance data will provide a more comprehensive understanding of LTC behavior and support the development of performance-based specifications that ensure the long-term durability of recycled asphalt mixtures in cold regions.

References

1. Meroni, F., et al., *Application of Balanced Mix Design Methodology to Optimize Surface Mixes with High-RAP Content.* Materials (Basel), 2020. **13**(24).

2. Hatailah, H.A. and E. Kassem, *Balanced mix design for high RAP asphalt mixtures prepared with recycling agents.* Road Materials and Pavement Design, 2024: p. 1-27.

3. Hanz, A., E. Dukatz, and G. Reinke, *Use of performance-based testing for high RAP mix design and production monitoring.* Road Materials and Pavement Design, 2016. **18**(sup1): p. 284-310.

4. Coleri, E., Sreedhar, S. and Obaid, I.A, *Development of a balanced mix design method in Oregon* 2020, Oregon. Dept. of Transportation.

5. Hajj, E.Y., Aschenbrener, T.B. and Nener-Plante, D., *Case Studies on the Implementation of Balanced Mix Design and Performance Tests for Asphalt Mixtures: Illinois Department of Transportation (IDOT)*. 2021, UNR Pavement Engineering & Science Program.

6. West, R.Y., F.; Rodezno, C.; Taylor, A., *Balanced Mixture Design Implementation Support*. 2021, Wisconsin Department of Transportation.

7. Diefenderfer, S.D. and B.F. Bowers, *Initial Approach to Performance (Balanced) Mix Design: The Virginia Experience.* Transportation Research Record: Journal of the Transportation Research Board, 2019. **2673**(2): p. 335-345.

8. Yazdipanah, F., Khedmati, M. and Haghshenas, H.F., *Nebraska Balanced Mix Design–Phase I*. 2023, Nebraska Department of Transportation.

9. Newcomb, D.E., et al., *Test Methods to Quantify Cracking Resistance of Asphalt Binders and Mixtures*. 2021, Minnesota Department of Transportation.

10. Marasteanu, M., Buttlar, W., Bahia, H. and Williams, C., *Investigation of Low Temperature Cracking in Asphalt Pavements, National Pooled-Fund Study Phase II*. 2012, Minnesota Department of Transportation.

11. Newcomb, D.E., *Balanced Design of Asphalt Mixtures*. 2018, Minnesota Department of Transportation.

12. Kimble, C.A. *Extreme Temperature Ranges*.

13. Behnia, B., W. Buttlar, and H. Reis, *Evaluation of Low-Temperature Cracking Performance of Asphalt Pavements Using Acoustic Emission: A Review.* Applied Sciences, 2018. **8**(2).

14. Dave, E.V., Braham, A.F., Buttlar, W.G., Paulino, G.H. and Zofka, A. *Integration of laboratory testing, field performance data, and numerical simulations for the study of*

low-temperature cracking. in *6th RILEM International Conference on Cracking in Pavements* 2008.

15. Brett A. Williams, J.R.W., & Joseph Shacat, *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2021*. 2022, National Asphalt Pavement Association.

16. Li, M., et al., *Low-temperature performance improvement strategies for high RAP content recycled asphalt mixtures: Focus on RAP gradation variability and mixing process.* Fuel, 2025. **387**.

17. Bastola, N.R., et al., *Investigating the Field Performance of High- Recycled Asphalt Pavement Mixtures with Bio-oil Recycling Agent.* Transportation Research Record: Journal of the Transportation Research Board, 2024.

18. Ahmed, M., M. Khedmati, and H.F. Haghshenas, *Using Crude Vegetable-Based Oils and Antioxidants to Improve the Performance of Asphalt Binders.* Transportation Research Record: Journal of the Transportation Research Board, 2023.

19. Nsengiyumva, G., et al., *Mechanical-Chemical Characterization of the Effects of Type, Dosage, and Treatment Methods of Rejuvenators in Aged Bituminous Materials.* Transportation Research Record: Journal of the Transportation Research Board, 2020. **2674**(3): p. 126-138.

20. Hesp, S., Terlouw, T., & Vonk, W. *Low temperature performance of SBS-modified asphalt mixes*. in *Asphalt Paving Technology*. 2000.

21. Lu, X., Isacsson, U. L. F., & Ekblad, J., *Influence of polymer modification on low temperature behaviour of bituminous binders and mixtures.* Materials and Structures, 2003. **36**: p. 652-656.

22. Gražulytė, J., et al., *Methods and criteria for evaluation of asphalt mixture resistance to low temperature cracking.* The Baltic Journal of Road and Bridge Engineering, 2017. **12**(2): p. 135-144.

23. Salehi Ashani, S., et al., *Investigation of low-temperature cracking resistance of asphalt mixtures by conducting Disc-Shaped Compact Tension (DC(T)) and Semi-Circular Bend (SCB) tests.* Construction and Building Materials, 2022. **359**.

24. Board, T.R., *Glossary of Terms for Balanced Design of Asphalt Mixtures.* 2022(E-C280).

25. Prasad, A.N., N. Saboo, and A. Pani, *Material and mix design aspects of hot recycled asphalt mixes: A review.* Environ Sci Pollut Res Int, 2023. **30**(50): p. 108411-108447.

26. Moon, K.H., M.O. Marasteanu, and M. Turos, *Comparison of Thermal Stresses Calculated from Asphalt Binder and Asphalt Mixture Creep Tests.* Journal of Materials in Civil Engineering, 2013. **25**(8): p. 1059-1067.

27. Li, X.J. and M.O. Marasteanu, *Using Semi Circular Bending Test to Evaluate Low Temperature Fracture Resistance for Asphalt Concrete.* Experimental Mechanics, 2009. **50**(7): p. 867-876.

28. Johanneck, L., Geib, J., Deusen, D. V., Garrity, J., Hanson, C., Dave, E., *DCT Low Temperature Fracture Testing Pilot Projec*. 2015, Minnesota Department of Transportation.

29. Bastola, N.R. and J.E.S.L. Teixeira, *Low-temperature cracking assessment of high-RAP mixtures modified with waste plastics and vegetable oil using multi-test performance-based parameters.* Construction and Building Materials, 2025. **485**.

30. Shaikh, S. and A. Gupta, *Laboratory-to-field correlation and validation of performance specifications for bituminous mixtures.* Construction and Building Materials, 2025. **464**.

31. Yazdipanah, F., Khedmati, M., Teixeira, J. and Haghshenas, H.F, *Nebraska Balanced Mix Design–Phase II*. 2025, Nebraska. Department of Transportation.

32. Chitnis, V., M. Sukhija, and E. Coleri, *Benchmarking the performance of asphalt mixtures for the implementation of Balanced Mix Design (BMD) in Oregon.* International Journal of Pavement Engineering, 2025. **26**(1).

33. Mihai Marasteanu, A.Z., Mugur Turos, Xinjun Li, Raul Velasquez, Xue Li, William Buttlar, Glaucio Paulino, Andrew Braham, Eshan Dave, Joshua Ojo, Hussain Bahia, Christopher Williams, Jason Bausano, Andrea Kvasnak, Allen Gallistel, Jim McGraw, *Investigation of Low Temperature Cracking in Asphalt Pavements*, M.D.o. Transportation, Editor. 2007.

34. Wang, W. and L. Wang, *Review on Design, Characterization, and Prediction of Performance for Asphalt Materials and Asphalt Pavement Using Multi-Scale Numerical Simulation.* Materials (Basel), 2024. **17**(4).

35. Kaseer, F., et al., *Stiffness Characterization of Asphalt Mixtures with High Recycled Material Content and Recycling Agents.* Transportation Research Record: Journal of the Transportation Research Board, 2017. **2633**(1): p. 58-68.

36. Rafiq Kakar, M., et al., *High and low temperature performance of polyethylene waste plastic modified low noise asphalt mixtures.* Construction and Building Materials, 2022. **348**.

37. Zeiada, W., et al., *An efficient and robust method for evaluating the low-temperature performance of asphalt binder based on DSR testing.* Construction and Building Materials, 2024. **448**.

38. Guo, M., X. Yao, and X. Du, *Low temperature cracking behavior of asphalt binders and mixtures: A review.* Journal of Road Engineering, 2023. **3**(4): p. 350-369.

39. Muhammad Ahmed, M.K., Hamzeh Haghshenas Fatmehsari, *Using Crude Vegetable-Based Oils and Antioxidants to Improve the Performance of Asphalt Binders.* Transportation Research Record: Journal of the Transportation Research Board, 2023.

40. FHWA, *Delta Tc Binder Specification Parameter*. 2021.

41. Mukandila, E.M., W.J.v.d.M. Steyn, and T.I. Milne, *Modelling of cohesion and adhesion damage of seal based on dynamic shear rheometer testing.* International Journal of Pavement Engineering, 2016. **19**(9): p. 786-797.

42. Lu, X. and U. Isacsson, *Effect of Binder Rheology on the Low-Temperature Cracking of Asphalt Mixtures.* Road Materials and Pavement Design, 2011. **2**(1): p. 29-47.

43. Kim, S.R.K.Y.R., *Investigation of DSR Test Methods to Determine Binder Low Temperature Properties*. 2018.

44. Kovach, S.K.Z.D.W.J., *Low-Temperature Thermal Cracking of Asphalt Binder by Asphalt Binder Cracking Device.* Transportation Research Record: Journal of the Transportation Research Board, 2006.

45. Issa, M.A., et al., *Influence of softening agents on low and intermediate temperature cracking properties of highly polymer modified asphalt binders.* Construction and Building Materials, 2025. **490**.

46. Zhang, W., et al., *Comparison of Relaxation Modulus Converted from Frequency- and Time-Dependent Viscoelastic Functions through Numerical Methods.* Applied Sciences, 2018. **8**(12).

47. D. Jung, T.S.V., *Thermal Stress Restrained Specimen Test To Evaluate Low-Temperature Cracking of Asphalt-Aggregate Mixtures.* Transportation Research Record, 1993.

48. H. Ma, C.Z., D. Feng, L. Sun, *Influence of Fine Aggregate Content on Low-Temperature Cracking of Asphalt Pavements.* Journal of Testing and Evaluation, 2017.

49. B.B. Teltayeva, C.O.R., G.G. Izmailovaa, E.D. Amirbayeva, A.O. Elshibayeva, *Evaluating the effect of asphalt binder modification on the low-temperature cracking resistance of hot mix asphalt.* Case Studies in Construction Materials, 2019.

50. Gu, F., et al., *Development of a new cracking index for asphalt mixtures using indirect tensile creep and strength test.* Construction and Building Materials, 2019. **225**: p. 465-475.

51. Mensching, D.J., et al., *Low-temperature properties of plant-produced RAP mixtures in the Northeast.* Road Materials and Pavement Design, 2014. **15**(sup1): p. 1-27.

52. Xiao, F., et al., *Low Temperature Performance Characteristics of Reclaimed Asphalt Pavement (RAP) Mortars with Virgin and Aged Soft Binders.* Applied Sciences, 2017. **7**(3).

53. Babagoli, R., N. Norouzi, and A. Ameli, *Laboratory investigation of the influence of aging and compaction effort on low temperature performance of asphalt mixture containing different percentage of RAP.* Construction and Building Materials, 2021. **298**.

54. Singh, D. and S. Girimath, *Influence of RAP sources and proportions on fracture and low temperature cracking performance of polymer modified binder.* Construction and Building Materials, 2016. **120**: p. 10-18.

55. Moon, K.H., et al., *Low temperature rheological properties of asphalt mixtures containing different recycled asphalt materials.* International Journal of Pavement Research and Technology, 2017. **10**(1): p. 84-97.

56. Behnia, B., Dave, E., Ahmed, S., Buttlar, W., Reis, H., *Investigation of Effects of the Recycled Asphalt Pavement (RAP) Amounts on Low Temperature Cracking Performance of Asphalt Mixtures using Acoustic Emissions (AE).* Transportation Research Record, 2011.

57. Ren, J. and L. Sun, *Characterizing air void effect on fracture of asphalt concrete at low-temperature using discrete element method.* Engineering Fracture Mechanics, 2017. **170**: p. 23-43.

58. Aliha, M.R.M., et al., *Effect of temperature and air void on mixed mode fracture toughness of modified asphalt mixtures.* Construction and Building Materials, 2015. **95**: p. 545-555.

59. Budziński, B., et al., *Influence of bitumen grade and air voids on low-temperature cracking of asphalt.* Case Studies in Construction Materials, 2023. **19**.

60. Du, J. and Z. Fu, *Enhancement Effect of Aggregates on the Low-Temperature Cracking Resistance of Asphalt Mixtures.* Materials (Basel), 2024. **17**(12).

61. Apostolidis, P., et al., *Glass transitions in bituminous binders.* Materials and Structures, 2021. **54**(3).

62. Braham, A.F., W.G. Buttlar, and M.O. Marasteanu, *Effect of Binder Type, Aggregate, and Mixture Composition on Fracture Energy of Hot-Mix Asphalt in Cold Climates.* Transportation Research Record: Journal of the Transportation Research Board, 2007. **2001**(1): p. 102-109.

63. Ma, H., et al., *Influence of Fine Aggregate Content on Low-Temperature Cracking of Asphalt Pavements.* Journal of Testing and Evaluation, 2017. **45**(3): p. 835-842.

64. Li, X., et al., *Effect of Factors Affecting Fracture Energy of Asphalt Concrete at Low Temperature.* Road Materials and Pavement Design, 2011. **9**(sup1): p. 397-416.

65. Bastola, N.R., et al., *Effects of the simultaneous use of post-industrial polypropylene waste plastic and soybean oil recycling additive on the performance of high-RAP recycled mixtures.* Construction and Building Materials, 2024. **424**.

66. Haghshenas, H.F., et al., *Research on High-RAP Asphalt Mixtures with Rejuvenators - Phase II*. 2020.

67. Martin, A.E., et al., *Evaluating the Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios*. 2020, Texas A&M Transportation Institute.

68. Kaseer, F.M.S., *The effects of recycling agents on asphalt mixtures with high recycled materials content*. 2019, Texas A&M University.

69. Behzad Behnia, P.A., Noah LaRussa-Trott *Investigating Low-Temperature Cracking Behavior of Fiber-Reinforced Asphalt Concrete Materials.* International Journal of Pavement Research and Technology, 2023.

70. Chiara Riccardi, I.I., Di Wang, Pedro Lastra-Gonz´alez, Augusto Cannone Falchetto, Daniel Castro-Fresno, *Low temperature performances of fiber-reinforced asphalt mixtures for surface, binder, and base layers.* Cold Regions Science and Technology, 2023.

71. Qian, S., et al., *Fiber reinforcing effect on asphalt binder under low temperature.* Construction and Building Materials, 2014. **61**: p. 120-124.

72. Wu, S. and L. Montalvo, *Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review.* Journal of Cleaner Production, 2021. **280**.

73. Bennert, T., et al., *Assessment of Plastic Waste Modification to Asphalt Materials Using the Wet Process.* Transportation Research Record: Journal of the Transportation Research Board, 2024.

74. Sadeghi, P., A. Goli, and M. Asadi, *Fracture Resistance of RAP Containing Recycled Polyethylene and Different Rejuvenators at Low and Medium Temperatures Using a Nonstandard SCB Test.* Journal of Materials in Civil Engineering, 2024. **36**(6).

75. Liang, M., et al., *Phase behavior and hot storage characteristics of asphalt modified with various polyethylene: Experimental and numerical characterizations.* Construction and Building Materials, 2019. **203**: p. 608-620.

76. Du, Z., et al., *Low temperature performance characteristics of polyethylene modified asphalts – A review.* Construction and Building Materials, 2020. **264**.

77. Ge, D., et al., *Modification mechanism of asphalt binder with waste tire rubber and recycled polyethylene.* Construction and Building Materials, 2016. **126**: p. 66-76.

78. (FHWA), F.H.A. *Asphalt Mixture Design and Balanced Mix Design*. Peer Exchange on Balance Mix Deisgn 2023 [cited 2024; Available from: https://www.fhwa.dot.gov/pavement/asphalt/amdbmd/.

79. Michael Vrtis, C.R., Randy West, Joseph Podolsky, Jacob Calvert and Dave Van Deusen, *MnROAD Cracking Group Experiment: Validation of Low-Temperature Cracking Tests for Balanced Mix Design*. 2023.

80. Yin, R.W.C.R.F.L.F., *Development of a Framework for Balanced Mix Design* in *Project NCHRP 20-07/Task 406*. 2018.

81. Romero, P., *Balanced asphalt concrete mix performance in utah phase v: Field evaluation for intermediate and low temperature cracking*. 2021.

82. NDOT, *Superpave Asphaltic Concrete*. 2016, Nebraska Department of Transportation.

83. ASTM, *ASTM D2172-Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures*. 2018.

84. D1856, A., *Standard Test Method for Recovery of Asphalt from Solution by Abson Method*. 2021.

85. ASTM, *ASTM D5404-Standard Practice for Recovery of Asphalt Binder from Solution Using the Rotary Evaporator*. 2021.

86. Kim, Y.R., et al., *Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction: Phase III Results*. 2021.

87. AASHTO, *AASHTO T 315-24: Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*. 2024.

88. AASHTO, *AASHTO T 313 Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*. 2022.

89. ASTM, *ASTM D2872-Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)*. 2022.

90. ASTM, *ASTM D6521-Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)*. 2022.

91. *AASHTO TP 105 Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)* 2020, American Association of State Highway and Transportation Officials.

92. *AASHTO TP 125 Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Mixtures Using the Bending Beam Rheometer (BBR)* 2016, American Association of State Highway and Transportation Officials.

93. *AASHTO T 322 Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device* 2007, American Association of State Highway and Transportation Officials.

94. *AASHTO T 378 Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)* 2017, American Association of State Highway and Transportation Officials.

95. *ASTM D8225 Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*. 2019, American Society for Testing and Materials.

96. Saha Chowdhury, P., S.L.A. Noojilla, and M.A. Reddy, *Evaluation of fatigue characteristics of asphalt mixtures using Cracking Tolerance index (CTIndex).* Construction and Building Materials, 2022. **342**.

97. Song, W., et al., *Fracture investigation of asphalt mixtures containing reclaimed asphalt pavement using an equivalent energy approach.* Engineering Fracture Mechanics, 2021. **253**.

98. Zhang, J., et al., *Evaluating Crack Resistance of Asphalt Mixture Based on Essential Fracture Energy and Fracture Toughness.* International Journal of Geomechanics, 2019. **19**(4).

99. Zhang, Y., L. Sun, and H. Cheng, *Effects of nominal maximum aggregate size and compaction effort on the mechanical properties of hot-mix asphalt (HMA).* Construction and Building Materials, 2022. **324**.

100. Wang, Y., et al., *Viscoelastic constitutive models of asphalt binder in a wide stress range.* Measurement, 2026. **258**.

101. Ho, C.-H., et al., *Material Testing Apparatus and Procedures for Evaluating Freeze-Thaw Resistance of Asphalt Concrete Mixtures.* Advances in Civil Engineering Materials, 2017. **6**(1): p. 429-443.

102. Ho, C.-H. and C.P. Martin Linares, *Representation Functions to Predict Relaxation Modulus of Asphalt Mixtures Subject to the Action of Freeze-Thaw Cycles.* Journal of Transportation Engineering, Part B: Pavements, 2018. **144**(2).

103. Yan, Y., W. Li, and L. Wang, *Effect of recycled aggregate and freeze-thaw cycles on fatigue performance of asphalt concrete.* Frontiers in Materials, 2025. **12**.

104. Xu, H., W. Guo, and Y. Tan, *Internal structure evolution of asphalt mixtures during freeze–thaw cycles.* Materials & Design, 2015. **86**: p. 436-446.