Critical Factors Affecting Asphalt Concrete Durability

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16. Abstract

This research evaluated changes to the composition of asphalt concrete mixtures that the Wisconsin Department of Transportation (WisDOT) should consider to improve the durability of flexible pavement constructed in Wisconsin. Based on a synthesis of current research, a laboratory experiment was conducted to quantify the effect of: (1) effective binder volume, (2) low temperature performance grade, (3) recycled binder content, and (4) polymer modification on the resistance of typical Wisconsin mixtures to aging and load associated cracking. For the types of mixtures normally used in Wisconsin, the laboratory experiment found mixture composition had little effect on aging; however, cracking resistance was significantly affected. The laboratory experiment produced a regression equation that was used to evaluate current WisDOT specification requirements. This evaluation concluded that recent specification changes made by WisDOT will improve the cracking resistance of asphalt concrete mixtures, with the greatest improvement occurring for overlays in the Southern Asphalt Zone. The regression equation was also used to recommend additional specification changes that WisDOT should consider.

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Executive Summary

Project Summary

This research evaluated changes to the composition of asphalt concrete mixtures that the Wisconsin Department of Transportation (WisDOT) should consider to improve the durability of flexible pavements constructed in Wisconsin. Based on a synthesis of current research, a laboratory experiment was conducted to quantify the effect of: (1) effective binder volume, (2) low temperature performance grade, (3) recycled binder content, and (4) polymer modification on the resistance of typical Wisconsin mixtures to aging and load associated cracking. For the types of mixtures normally used in Wisconsin, the laboratory experiment found mixture composition had little effect on aging; however, cracking resistance was significantly affected. The laboratory experiment produced a regression equation that was used to evaluate current WisDOT specification requirements. This evaluation concluded that recent specification changes made by WisDOT will improve the cracking resistance of asphalt concrete mixtures, with the greatest improvement occurring for overlays in the Southern Asphalt Zone. The regression equation was also used to recommend additional specification changes that WisDOT should consider.

Background

For asphalt concrete mixtures, durability refers to the ability of the mixture to resist deterioration as it ages. Raveling and surface initiated cracking are the primary distresses associated with durability issues. Traditionally, durability has been addressed in asphalt mixture design and construction through a combination of the following:

1. Asphalt binder specifications that limit changes in binder properties under simulated aging.
2. Aggregate specifications that limit the amount of clay and other deleterious materials and guard against breakdown of aggregates during production and under traffic and environmental effects during the service life of the pavement.

3. Limits on volumetric properties to provide a sufficient volume of asphalt binder in the mixture to properly coat the aggregates and to minimize aging during production and the service life of the mixture.
4. Testing and requirements to ensure that the mixture is not sensitive to moisture.
5. In-place compaction requirements to minimize permeability which minimizes water infiltration and slows the rate of age hardening in the mixture.

Although these requirements have been largely successful, highway agencies question whether the durability of asphalt concrete surface mixtures can be improved either through changes to mixture composition or the use of performance related mixture testing. Considering the potential cost savings that WisDOT can realize by increasing the average service life of surface courses, this research project aimed at evaluating WisDOT's mixture criteria relative to best practices associated with durability has the potential to provide a substantial benefit to WisDOT.

Process

This project included three major components: (1) a synthesis of current research associated with improving the durability of asphalt concrete mixtures; (2) a laboratory prepared mixtures experiment designed to evaluate, using Wisconsin materials, the promising methods for improving asphalt mixture durability that were identified by the synthesis of current research; and (3) a plant mixture verification experiment to confirm the findings of the laboratory prepared mixtures experiment. Based on the synthesis of current research the promising methods for improving asphalt mixture durability through mixture composition that are applicable to the fine graded surface course mixtures commonly used in Wisconsin are:

- Increase the effective binder content for all mixtures.
- Increase the effective binder content in proportion to the amount of recycled binder.
- Use a softer grade of binder in recycled mixtures.
- Use polymer modified binder in all surface course mixtures.
- Use polymer modified binder in recycled mixtures.
- Use balanced mixture design.

The laboratory prepared mixtures experiment investigated the effects of: (1) effective binder volume, (2) recycled binder content, (3) virgin binder low temperature grade, and (4) polymer modification on simulated long-term aging and resistance to cracking as measured by a semi-circular bend test at intermediate temperatures. This experiment produced regression models that were used to evaluate WisDOT specification requirements. The evaluation was based on improving the resistance of mixtures to aging and load associated cracking.

The plant mixture verification experiment was used to verify the flexibility index regression model that was developed during the laboratory prepared mixtures experiment. Cracking resistance improves with increasing flexibility index. The plant mixture verification experiment showed excellent agreement between rankings of cracking resistance based on the regression model compared to rankings from testing to measure the flexibility index for the plant mixtures.

Findings and Conclusions

With respect to resistance to aging, the laboratory study concluded that for mixtures normally produced in Wisconsin, changes in mixture composition had little effect on the aging characteristics of asphalt concrete mixtures. With respect to resistance to cracking, the laboratory study concluded that cracking resistance was significantly affected by:

- **Aging.** Cracking resistance decreases significantly with aging.
- **Volume of Effective Binder.** Increasing the effective volume of binder in the mixture improves the cracking resistance of the mixture.
- **Amount and Type of Recycled Binder.** The cracking resistance of asphalt concrete mixtures decreases with increasing amounts of recycled binder. The effect is greater for recycled asphalt shingles (RAS) compared to reclaimed asphalt pavement (RAP).
- **Low Temperature Grade of the Virgin Binder.** Mixtures produced with softer virgin binder have improved resistance to cracking.
- **Polymer Modification.** Mixtures produced with polymer modified binders have higher resistance to cracking.

The regression models developed from the laboratory experiment were used to evaluate recent specification changes made by WisDOT. This evaluation concluded that the recent specification changes will improve the cracking resistance of asphalt concrete mixtures, with the greatest improvement occurring for overlays in the Southern Asphalt Zone.

Recommendations

The primary recommendation from this research project is that WisDOT should consider using the regression models developed from the laboratory experiment to further modify asphalt concrete mixture specifications to improve the cracking resistance of asphalt concrete mixtures used in Wisconsin. Examples of how the regression model can be used for specification improvement were provided.

This research also showed that 9.5 mm mixtures with higher design volume of effective binder have greater resistance to cracking compared to 12.5 mm mixtures. WisDOT should consider expanding the use of 9.5 mm mixtures in surface course mixtures.

Acknowledgement

The author acknowledges the contributions made by the Project Oversight Committee to the success of the project including:

- Reviewing and improving the experimental design.
- Identifying materials to be used in the laboratory studies and coordinating collection of the necessary samples.
- Reviewing and improving this report.

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

This report documents the work completed in Wisconsin Highway Research Program (WHRP) Project 0092-14-06, *Critical Factors Affecting Asphalt Concrete Durability*. The objective of this project was to develop recommended revisions to Wisconsin Department of Transportation (WisDOT) specifications and guidance documents to improve the durability of asphalt concrete mixtures. The project focused on changes to the composition of asphalt mixtures that WisDOT should consider to improve durability. The recommendations contained in this report are based on promising findings from completed research addressing asphalt concrete durability and the results of a laboratory study formulated specifically to evaluate the effectiveness of these promising findings for Wisconsin materials and environmental conditions. WHRP Project 0092-14-06 included six tasks that are briefly described below.

Task 1: Synthesis of Current Research. Task 1 included a review of the findings and recommendations from completed and ongoing research addressing the durability of asphalt concrete mixtures. The review addressed the factors affecting durability, the methods used to evaluate durability, and the implementation of specific methods aimed at improving durability.

Task 2: Work Plan Development. In Task 2, a laboratory experiment was designed to evaluate the effectiveness of promising findings from Task 1 using Wisconsin materials and environmental conditions. This experiment included evaluating the resistance to cracking and simulated aging using laboratory prepared mixtures. The work plan was modified during the course of the project to include verification of the findings from the laboratory prepared mixtures experiment using several plant mixtures.

Task 3: Interim Presentation and Project Memorandum. Task 3 included the preparation of the Interim Report documenting the results of Tasks 1 and 2 and a meeting with the Project Oversight Committee (POC). The Interim Report was submitted on April 23, 2014. The Interim Report Presentation to the POC was made on July 1, 2014. The POC approved the work described in Chapter 3 and agreed to assist with identifying appropriate aggregates, mixture designs, and binders for the laboratory experiment; and appropriate plant mixtures for the verification experiment.

Task 4: Execution of Work Plan and Analysis of Results. Task 4 included the execution and analysis of the experiments designed in Task 2 and approved by the POC in Task 3. Work on the laboratory prepared mixtures experiment started in October, 2014 and the testing and data analysis were completed in January, 2015. Work on the plant mixture verification experiment started in February, 2015 and the testing and data analysis was completed in March, 2015.

Task 5: Project Deliverables. Task 5 consisted of the preparation and submission of the Draft Final Report and Close Out Presentation, documenting all significant work completed during the project. The Draft Final Report was submitted April 25, 2016. Close Out Presentation materials were submitted on July 11, 2016.

Task 6: Final Report and Project Closeout Activities. Task 6 was the final project task. It included presenting the Close Out Presentation to the POC and revising the Draft Final Report based on comments received from WisDOT. The Close Out Presentation was made on July 11, 2016. The Final Report was submitted on September 1, 2016.

Chapter 2 of this report presents the findings from the synthesis of current research. It includes: (1) factors affecting asphalt mixture durability, (2) approaches that have been used to evaluate asphalt mixture durability, and (3) recent recommended specification changes to improve asphalt mixture durability.

Chapter 3 presents the two experimental plans that were developed. The first was a laboratory prepared mixtures study to evaluate promising methods for improving asphalt mixture durability. This experiment included the evaluation of the effect of five factors and their interaction on the cracking resistance of asphalt mixtures. The factors included in the experiment were: (1) asphalt binder volume, (2) recycled binder content and stiffness, (3) virgin binder grade, (4) virgin binder modification, and (5) simulated laboratory aging. The cracking resistance was evaluated using various parameters from semi-circular bend tests conducted at 15 °C. The second experiment was a verification experiment aimed at verifying the results from the laboratory prepared mixtures experiment using plant mixtures. Sixteen plant mixtures representing 9 combinations that were not tested in the laboratory prepared experiment and 5 combinations that were tested in the laboratory prepared mixtures experiment were included in the verification experiment.

Chapter 4 presents the analysis of the results of the two experiments. The laboratory prepared mixtures experiment produced two regression models quantifying the effects of: (1) asphalt binder volume, (2) recycled binder content and stiffness, (3) virgin binder grade, (4) virgin binder modification, and (5) simulated laboratory aging on the flexibility index from semi-circular bend tests conducted at 15 °C. The measured data from the plant mixtures were compared to estimates made using the regression models.

Chapter 5 presents an analysis of various specification scenarios using the regression models developed in this project. These analyses were used to recommend specification revisions for consideration by WisDOT. Finally, Chapter 6 presents conclusions and recommendations resulting from the research conducted in WHRP Project 0092-14-06.

Chapter 2 Synthesis of Current Research

2.1 Definition of Durability

Asphalt mixture durability is defined as the ability of compacted asphalt concrete to maintain its structural integrity throughout its expected service life when exposed to the damaging effects of the environment and traffic loading (*1*). Asphalt mixture durability is one of several factors affecting pavement durability, which is defined as the ability of a pavement to retain a satisfactory level of performance over its expected service life without major maintenance (*1*). To be durable, a flexible pavement must be:

1. **Structurally adequate.** The pavement layers must be sufficiently thick to carry the intended traffic loading and protect the supporting subgrade soil.
2. **Properly drained.** This includes adequate cross slope to drain water from the surface of the pavement as well as adequate slide slopes, ditches, or inlets to move water away from the pavement and minimize water infiltration into the pavement structure.
3. **Properly constructed.** Good construction practices must be used for all pavement layers. This includes proper grading and compaction of the subgrade, proper thickness and compaction control for all layers and proper bond between asphalt layers. For surface layers minimizing segregation, including temperature segregation, and proper joint construction are important aspects of quality construction needed for a durable flexible pavement.
4. **Built with durable materials.** The materials used in the pavement must be able to withstand the effects of aging, traffic, and the environment. Base and subbase materials should not be susceptible to moisture or frost. Asphalt concrete surfaces must resist the effects of aging and moisture, as well as the forces applied by traffic and environmental loading.

The fourth item above was the primary subject of this research. Raveling and surface initiated cracking are the primary distresses associated with asphalt mixture durability issues.

Traditionally, durability has been addressed in asphalt mixture design and construction through a combination of the following:

1. Asphalt binder specifications that limit changes in binder properties under simulated aging. Examples include retained penetration, minimum ductility, and maximum viscosity after Thin Film Oven conditioning in the penetration and viscosity grading systems; and the maximum intermediate stiffness after Rolling Thin Film Oven (RTFO) test and Pressure Aging Vessel (PAV) conditioning in the performance grading system.
2. Aggregate specifications that limit the amount of clay and other deleterious materials and guard against breakdown of aggregates during production and under traffic and environmental effects during the service life of the pavement.
3. Limits on volumetric properties to provide a sufficient volume of asphalt binder in the mixture to properly coat the aggregates and to minimize aging during production and the service life of the mixture.
4. Testing and requirements to ensure that the mixture is not sensitive to moisture.
5. In-place compaction requirements to minimize permeability which minimizes water infiltration and slows the rate of age hardening in the mixture.

Although these requirements have been largely successful, highway agencies question whether the durability of asphalt concrete surface mixtures can be improved either through changes to mixture composition or the use of performance related mixture testing. Of particular interest are mixtures with moderate to high percentages of recycled asphalt material, either reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS).

2.2 Factors Affecting Asphalt Mixture Durability

Table 1 summarizes a number of factors that affect the durability of an asphalt mixture in a flexible pavement. Although this research was limited to the effect of the mixture composition category on durability, the other categories are discussed briefly to provide more complete coverage of the topic.

Table 1. Factors Affecting Asphalt Mixture Durability.

General Category	Specific Factors
Environment	Temperature Moisture
Drainage	Surface Subsurface
Construction	Weather Conditions Segregation Compaction Joints Layer Bond
Mixture Composition	Aggregate Properties Binder Properties Gradation Volumetric Properties

2.2.1 Environment

Environmental conditions at the project location have a major effect on asphalt concrete durability. Temperature is a primary consideration when designing flexible pavements and asphalt concrete mixtures. Temperature affects the structural stiffness, rutting resistance, and cracking resistance of asphalt concrete mixtures. The performance grading system for asphalt binders was developed to select binders that, for properly designed and constructed asphalt concrete mixtures, will provide acceptable rutting and cracking performance over the range of temperatures at a project location (*2*). Although much research has been done in an effort to improve the performance grading system, it has not changed substantially since its introduction over 20 years ago. The possible exception is the use of the Multiple Stress Creep Recovery test for high temperature grading, which appears to provide a more accurate assessment of rutting potential of a wide range of polymer modified binders (*3*).

Temperature also has an important effect on the aging of asphalt binders and asphalt concrete mixtures during the service life of the pavement. The detrimental effects of binder aging on the durability of asphalt concrete mixtures has been long recognized (*4*); therefore, specifications for asphalt binders include limits on the change in properties after simulated aging. The performance grading system uses tests before and after RTFO test conditioning to evaluate stiffening during plant aging, and a maximum stiffness limit after PAV conditioning to limit stiffening due to in-service aging. Since asphalt binder aging is an oxidation reaction, it is significantly affected by the pavement temperature. Aging rates increase as pavement temperatures increase. The performance grading system accounts for this effect by varying the temperature of the PAV conditioning from 90 °C in cool climates to 110 °C for desert climates (*2*). Short-term and long-term oven conditioning procedures have also been developed for asphalt concrete mixtures to simulate the binder aging that occurs during production and during the service life of the pavement (*5*). Short-term conditioning is routinely used during mixture design; however, because mixture performance testing is not routinely performed, the long-term conditioning procedure has primarily been used in research projects.

Moisture is the second environmental factor affecting asphalt concrete durability. There are three ways that moisture may damage asphalt concrete mixtures: (1) loss of cohesion within the asphalt binder or mastic; (2) loss of adhesion between the asphalt binder and the aggregate, and (3) aggregate degradation particularly when freezing occurs in the mixture (*6*). A number of tests have been developed to identify asphalt mixtures that may be susceptible to moisture damage and nearly every highway agency includes a moisture sensitivity test in their mixture design process. The most common moisture sensitivity tests used in practice today are: (1) the Modified Lottman Test (AASHTO T283), and (2) the Hamburg Wheel Tracking Test (AASHTO T324).

2.2.2 Drainage

The importance that proper drainage plays in the durability of asphalt concrete mixtures and flexible pavements cannot be overstated. As discussed above, moisture damage may occur in asphalt concrete mixtures if moisture is permitted to enter through interconnected voids and becomes trapped in the mixture. Additionally, aggregate bases and subgrade soils in flexible pavements loose strength and stiffness with increasing moisture content. Water can enter a flexible pavement structure from all directions. It can enter from the surface if the asphalt concrete wearing surface is permeable or has cracks and joints. It can enter from the sides and from below depending on the depth of ditches and the location of the water table. Therefore, proper drainage is needed to remove water from the surface and to keep water from infiltrating into the base and foundation layers of the pavement.

2.2.3 Construction

The way a pavement is constructed has a major effect on the durability of asphalt concrete mixtures. Construction related issues usually result in localized defects and distresses while deficiencies associated with mixture composition are usually more widespread. Construction issues are not always in the complete control of the paving contractor. Decisions made during design and project delivery can significantly affect how the pavement is constructed. Examples include: (1) selection of mixtures and layer thickness that do not provide sufficient lift thickness to obtain adequate compaction, (2) insufficient depth of milling to remove surface initiated cracking, (3) inadequate treatment of areas exhibiting fatigue failure, and (4) bidding schedules that result in late season paving.

The weather during construction can affect the durability of asphalt concrete mixtures. The rate of cooling of asphalt concrete, and therefore the time available for compaction, is affected by temperature, moisture, and wind. Temperature and moisture also affect the bond between lifts. Although warm mix asphalt permits compaction at lower temperatures, the underlying layer must be heated sufficiently by the layer being placed to ensure adequate bond between layers which is critical to the structural integrity of the pavement.

Segregation is a common construction problem that significantly affects asphalt mixture durability. Segregation is defined as localized areas of either coarse or fine aggregates in the finished mat. Areas of the pavement with excessive coarse aggregate have lower binder content, higher air void content, and greater permeability compared to non-segregated areas. These areas are prone to durability distresses including raveling, accelerated aging, and damage from moisture infiltration (*7*).

Another form of segregation is thermal segregation. Thermal segregation is the presence of large temperature differentials in the asphalt layer at the time of compaction (*8*). The primary cause of these temperature differentials is differences in temperature between material near the middle and the outsides of the bed of haul trucks. The cooler parts of the mat are more difficult to compact resulting in areas with higher air void content, and greater permeability compared to the hotter parts of the mat. These areas are prone to the same durability distresses described above for aggregate segregation.

Many asphalt technologists will agree that the degree of compaction of an asphalt concrete mixture, measured by the volume of air voids, is probably the most important factor affecting the performance of the mixture. For dense graded mixtures it is generally agreed that the air void content of the pavement should be no higher than 8 percent and should never fall below 3 percent during the service life of the pavement (*9*). High in-place air voids allow air and water to penetrate into the asphalt mixture resulting in more rapid aging and potential for moisture damage. Asphalt concrete mixtures with low air voids are prone to rutting and shoving. One rule of thumb based on field performance data that is often cited for dense graded mixtures is that pavement life is reduced about 10 percent of each 1 percent increase in in-place air voids above 7 percent (*10*). Many researchers have studied the effects of compaction on the properties of asphalt concrete mixtures. The general consensus of these studies is increased compaction or decreased air voids had the following effects (*11*):

- Reduced oxidative aging of the binder,
- Decreased permeability,
- Increased strength,
- Increased resistance to moisture damage,
- Increased mixture stiffness,
- Increased resistance to rutting except at very low air void contents where instability may occur, and
- Increased resistance to fatigue cracking

Often the performance of the longitudinal joints governs the service life of the asphalt concrete wearing surface (*12*). All joints in asphalt concrete are locations of potential weakness where the mixture is likely to be less compacted, more permeable, and possibly segregated. Therefore, the number of both transverse and longitudinal joints should be minimized. Transverse joints are easily minimized through proper planning and scheduling; however, it is difficult to eliminate longitudinal joints on most projects. It is possible to eliminate some longitudinal joints in new construction by paving in echelon or using wide pavers; however, most projects are paved under traffic one lane at a time and include one or more longitudinal joints. The Asphalt Institute and the Federal Highway Administration (FHWA) recently developed a best practices guide for constructing and specifying longitudinal joints (*12*). This document and associated training materials confirm that durable longitudinal joints can be constructed in a number of ways. Best practices are provided for: (1) specifications and associated testing, (2) project planning, (3) mixture selection, (4) laydown operations, (5) compaction operations, and (6) use of joint adhesives or overbanding with asphalt binder.

Layer bond is an element of pavement construction that has received considerable attention in recent years (*13,14*). A major assumption in the design of flexible pavements is that there is full bond between asphalt concrete layers. If full bond is not achieved during construction, the pavement may fail prematurely as a result of slippage of the wearing surface or cracking because tensile strains in the as-constructed pavement are much higher than considered in design. Therefore, it is imperative that the assumption of full bond be followed through during construction. This can be done through the proper application of tack coats at each layer interface (*14*). In addition to providing bond between layers, uniform tack coat application will resist the infiltration of water between pavement layers.

2.2.4 Mixture Composition

Mixture composition, which was the subject of this project, also has a major effect on the durability of asphalt concrete mixtures. Much research has been performed on how the properties of asphalt concrete mixtures are affected by their composition. The sections that follow summarize the major findings of this research and discuss recent research aimed primarily at mixtures with moderate to high recycled binder contents.

2.2.4.1 Aggregate Properties

The properties of the aggregates used in asphalt concrete that are generally associated with asphalt mixture durability are (*15*):

- Toughness and abrasion resistance as measured by AASHTO T96, *Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles*

Machine. For an asphalt mixture to be durable, the aggregates must be resistant to degradation during production and under traffic loading.

- Durability and soundness as measured by AASHTO T104, *Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate*. For an asphalt mixture to be durable, the aggregates must be sound to resist disintegration due to weathering, particularly freezing and thawing.
- Plastic fines as measured by the Sand Equivalent, AASHTO T 176, *Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test*, or the Plasticity Index, AASHTO T90, *Determining the Plastic Limit and Plasticity Index of Soils*. Clay particles are undesirable in asphalt concrete mixtures because they weaken the bond between the asphalt binder and the aggregate resulting in the potential for moisture damage.

Although relationships between these aggregate properties and asphalt mixture durability are not available, (*15*) it is generally accepted that current specification limits provide suitable aggregates for durable asphalt concrete mixtures (*9*).

2.2.4.2 Binder Properties

As discussed earlier, selecting an appropriate binder for the environmental conditions at the project location is critical to ensuring that an asphalt mixture will be durable. Much of the published research related to asphalt durability addresses the aging characteristics of the asphalt binder, and the development of laboratory tests to simulate the aging that occurs during construction and during the service life of the pavement (*16*). The performance grading system, which is used by all states in the United States for neat asphalt binders (*17*), includes intermediate and low temperature tests and criteria on binder that has been conditioned in the RTFO test to simulate construction aging and the PAV to simulate long-term, in-service aging. The widespread use of the performance grading system over the last 20 years demonstrates the reasonableness of binder selection using this system.

The economic and environmental benefits associated with recycling have resulted in an increase in the use of recycled materials in asphalt mixtures. Most mixtures produced today contain either RAP or RAS. Research completed in National Cooperative Highway Research Program (NCHRP) Project 9-12 recommended using linear blending charts to select an appropriate grade of virgin binder for mixtures with recycled binder such that the blend of the recycled and virgin binder meets performance grading criteria at the project location (*18*). Based on the properties of binders from a limited number of RAP sources tested in NCHRP Project 9-12, the following guidance was provided for selecting virgin binders based on the expected RAP content of the mixture:

- If the RAP content is less than 15 percent, no change in binder grade
- If the RAP content is between 15 and 25 percent, select a virgin binder that is one grade softer.
- If the RAP content is greater than 25 percent, use a blending chart analysis to select an appropriate grade of virgin binder.

These recommendations assumed that the binder content of the RAP was approximately equal to that in the mixture, so the recycled binder ratio, defined as the proportion of recycled binder in the mixture (*19*), was approximately equal to the RAP content. These recommendations were incorporated into AASHTO M323, *Superpave Volumetric Mix Design*. Several state highway agencies, including WisDOT, allow greater than 15 percent recycled binder without changing the virgin binder grade and treat recycled binder from RAP and RAS the same even though RAS binders are much stiffer than RAP binders and change the grade of the blend of virgin and recycled binders approximately twice as quickly as RAP binders (*20*). Recycled binder ratios as high as 0.25 to 0.35 are permitted before changing the grade of the virgin binder (*20*).

Several researchers have used various engineering property and performance tests to evaluate the effect of recycled binders on asphalt mixtures (*19*). The properties that have been measured include: volumetric properties, dynamic modulus, indirect tensile strength, rutting resistance, fatigue cracking resistance, reflective cracking resistance, fracture energy, low temperature compliance and strength, and moisture sensitivity. There is general agreement among the various studies that stiffness and rutting resistance increase with increasing recycled binder ratio. For this project on asphalt concrete durability the findings associated with resistance to moisture damage and cracking are of the greatest interest. Table 2 summarizes the findings of several studies that included an evaluation of the effect of recycled binder on moisture sensitivity as measured by the Modified Lottman test and the Hamburg Wheel Track test. Based on these findings, it appears that recycled binders do not have an adverse effect on the moisture sensitivity of most asphalt mixtures. Table 3 summarizes the findings of several studies that included an evaluation of the effect of recycled binder on the load associated cracking resistance using a variety of tests. Based on these findings, recycled binder appears to have an adverse effect on the load associated cracking resistance of most asphalt mixtures. Table 4 summarizes the findings of several studies that included an evaluation of the effect of recycled binder on thermal cracking resistance of using a variety of tests. The resistance to thermal cracking generally decreased for mixtures with greater than about 25 percent RAP. The findings summarized in Tables 2 through 4 support limiting recycled binder ratios when no modifications to the mixture are made to improve cracking resistance.

Table 2. Effect of RAP Binder on Mixture Resistance to Moisture Damage.

Study	Mix Type	RAP content	Test Method	
			Tensile Strength Ratio	Hamburg
Stroup-Gardner & Wagner (*21*)	Lab	0, 15-40	Improves	
Mogawer et. al (*22*)	Plant	0 – 40		No difference
Zhao et. al (*23*)	Plant WMA	0, 30, 40, 50	Improves	Improves
	Plant HMA	0, 30	Improves	Improves
Hajj et. al (*24*)	Plant & Lab	0, 15, 30	No difference	
West, et. al (*19*)	Lab	0, 25, 40, 55	Mix dependent	

Table 3. Effect of RAP Binder on Mixture Resistance to Load Associated Cracking.

Study	Mix Type	RAP Content	Test				
			Flexural Fatigue	Energy Ratio	Overlay Tester	Cyclic Direct Tension	Indirect Tension Fracture Energy
McDaniel, et. al (*18*)	Lab	0, 10, 20, 40	Decreases				
Shu, et. al (*25*)	Lab	0, 10, 20, 30	Decreases	Decreases			
Hajj, et. al (*26*)	Lab	0, 15, 30	Decreases				
Mogawer et. al (*22*)	Plant	0 – 40			Decreases		
Zhao et al. (*23*)	Lab WMA	0, 30, 40, 50	Increases	Increases			
	Lab HMA	0, 30	Decreases	Increases			
West, et. al. (*19*)	Lab	0, 25, 40, 55					Decreases
Lee & Gibson (*27*)	Lab	0, 20, 40				Decreases	

Table 4. Effect of RAP Binder on Mixture Resistance to Low Temperature Cracking.

Study	Mix Type	RAP Content	Low Temperature Cracking			
			Disc Shaped Compact Tension	Semi-Circular Bend	Indirect Tension	Thermal Stress Restrained Specimen Test
Li et. al (*28*)	Lab	0, 20,40		Lower fracture energy for 40 %		
McDaniel, et. al (*29*)	Plant	0, 15, 25, and 40			Lower cracking temperature for 40 %	
Hajj et. al (*24*)	Plant & Lab	0, 15, 50				Higher fracture temperature for 50 %
Behnia et al. (*30*)	Lab	0, 30	Lower fracture energy for 30 %			
West, et. al. (*19*)	Lab	0, 25, 40, 55		Mixture and temperature dependent		

The use of polymer modified binders has grown significantly since the implementation of the performance grading system for asphalt binders. The specifications for nearly all state highway agencies in the United States include one or more binder grades that require polymer modification (*17*). Polymer modified binders were first specified to improve rutting resistance on heavily trafficked pavements. A study comparing the performance of overlays constructed with polymer modified binder with comparable overlays constructed with neat binder concluded that the use of polymer modified binders reduced all forms of distress, increasing the life of flexible pavements by 2 to 10 years (*31*). Some states make extensive use of polymer modified binders. For example, the Nevada Department of Transportation specifies polymer modified binder for all surface course mixtures (*26*). In a laboratory study of the fatigue resistance of Nevada mixtures, the Western Regional Superpave Center found the fatigue resistance of mixtures made with both neat and polymer modified binder decreases with increasing RAP content; however, the fatigue resistance of polymer modified binder mixtures with up to 30 percent RAP was significantly greater than that of virgin neat binder mixtures (*26*). This finding indicates that it may be possible to use polymer modification to counteract the detrimental effect of recycled binder on the cracking resistance of asphalt mixtures.

2.2.4.3 Gradation

The nominal maximum aggregate size and gradation of an asphalt mixture affect its durability in three ways. First, smaller nominal maximum aggregate size mixtures are designed and constructed with a higher effective volume of binder (VBE). As will be discussed in greater detail in the next section, mixtures with higher VBE have greater resistance to cracking which is often used as a measure of mixture durability. Second, for the same density, smaller nominal maximum aggregate size mixtures, and finer mixtures have lower permeability (*32, 33, 34, 35, 36*). Moisture infiltration and binder age hardening are less in mixtures with lower permeability. WHRP project 0092-06-02 found the permeability of Wisconsin pavements to be very low (*37*). The fine gradation of most Wisconsin 12.5 mm surface mixtures likely contributed to this finding. Finally, evidence is beginning to appear in the literature where mixtures with smaller nominal maximum aggregate size have improved fatigue resistance compared to mixtures with larger nominal maximum size mixtures (*19*, *38*). The improved fracture resistance for small nominal maximum size mixtures is likely due to the higher VBE and smaller flaw size (air voids) in these mixtures.

2.2.4.4 Volumetric Properties

The NCHRP recently completed three research studies evaluating the effect of mixture volumetric properties on the performance of asphalt mixtures (*35, 39*). These studies concluded that when quality aggregates and an appropriate binder are used, the in-place air void content and the VBE in the asphalt concrete mixture are the two volumetric properties that most affect both the durability and fatigue cracking resistance of asphalt concrete mixtures. In-place air voids are primarily controlled by construction, and the durability and fatigue life of asphalt concrete mixtures increases with decreasing in-place air void content. As discussed earlier, asphalt concrete mixtures with lower in-place air void contents are less permeability to both air and water, reducing binder age hardening and the potential for moisture damage. Asphalt concrete mixtures with lower in-place air voids also have greater strength and are more resistant to fatigue damage.

VBE is the primary mixture design factor affecting both durability and fatigue cracking resistance. Durability and fatigue resistance improve with increasing VBE. VBE is equal to the voids in the mineral aggregate (VMA) minus the air void content. The minimum VBE in current mix design procedures is controlled by the minimum VMA and the design air voids. Table 5 summarizes the design minimum VBE for different mixtures from AASHTO M323 and M325. For dense graded mixtures, the minimum design VBE increases with decreasing nominal maximum aggregate size; therefore, smaller nominal maximum aggregate size mixture should have improved durability and resistance to load associated cracking. Stone matrix asphalt (SMA) mixtures, which are considered to be extremely durable and crack resistant have the highest minimum design VBE.

Table 5. Summary of AASHTO M323 and AASHTO M325 Design Minimum VBE.

Mixture Nominal Maximum Aggregate Size, mm	Minimum Design VMA, vol %	Design Air Voids, vol %	Minimum Design VBE, vol %
37.5	11	4	7
25.0	12	4	8
19.0	13	4	9
12.5	14	4	10
9.5	15	4	11
4.75	16	4	12
All SMA	17	4	13

2.3 Methods to Improve Durability

Researchers have recommended and several state highway agencies have tried various approaches to improve the durability of asphalt mixtures and flexible pavements. Some of these were in response to local conditions and some were the result of perceived deficiencies in mixtures designed in accordance with AASHTO M323 (*40*). The sections that follow discuss several of these approaches.

2.3.1 Polymer Modification

It is common practice to specify polymer modified binders in mixtures subjected to high traffic volumes primarily to improve rutting resistance. Some state highway agencies, however, specify polymer modified binders for all surface course mixtures to improve durability. The Nevada Department of Transportation was one of the first states to adopt this philosophy. The extreme range in daily and seasonal temperatures in Nevada was the justification to use polymer modified binder (*26*). The Louisiana Department of Transportation and Development is another agency that specifies polymer modified binders in all surface course mixtures.

2.3.2 Increasing Effective Binder Content

Several methods have been recommended and used to increase the effective binder content of asphalt mixtures. The mix design manual developed in NCHRP Project 9-33 recommends that agencies should consider increasing the design VMA by 1.0 percent "*to obtain mixtures with increased asphalt binder content, which can improve field compaction, fatigue resistance, and general durability*"(*39*). Increasing the design VMA by 1.0 percent while keeping the design air void content at 4.0 percent will increase the VBE of the mixture by 1.0 percent. The NCHRP 9-33 mix design manual cautions that the increased design VMA may have an adverse effect on rutting resistance and the mixtures should be tested to ensure that they maintain adequate rutting resistance. For the same nominal maximum aggregate size, the design VMA for airfield mixtures designed in accordance with the P-401 specification is 1.0 percent higher than the design VMA in AASHTO M323 (*41*). Durability is an extremely important consideration for airfield mixture design to minimize the potential for foreign object damage due to surface raveling. A survey of the life of airfield pavements conducted by the Federal Aviation Administration showed the average pavement condition index for airfield runway and taxiways remained in the good range through 20 years of service (*42*). Several state highway agencies have increased design VMA to increase the effective binder content of mixtures (*40*).

Another way to increase the design VBE is to decrease the design air void content. Several state highway agencies have decreased the design air void content from 4.0 percent to 3.5 percent (*40*). This increases the design VBE by 0.5 percent.

A number of state highway agencies have decreased the design gyration levels in an attempt to increase effective binder contents (*40*). For the same aggregates and gradation, the optimum binder content will increase with decreasing design gyration level. However, decreasing the design gyrations may not always produce mixtures with higher VBE. If a producer is able to change gradation or the source of some of the aggregates in the mixture, it may be possible to remain near the minimum design VBE at the lower gyration level.

Another approach that has been used to increase VBE is to use smaller nominal maximum aggregate size mixtures or to use SMA mixtures. Some states that initially used 12.5 mm nominal maximum aggregate size mixtures for surface courses early during the implementation of AASHTO M323 have changed to 9.5 mm nominal maximum aggregate size mixtures (*40*) . This increases the design VBE of the surface course by 1.0 percent. Another option that was adopted by the Maryland State Highway Administration (MSHA) is to use SMA mixtures whenever high durability is required. This approach combines the beneficial effects of high VBE and polymer modification. The MSHA believes the benefits obtained from the additional pavement life exceeds the higher initial cost of the SMA mixtures (*43*).

2.3.3 Use of Softer Binders in Recycled Mixtures

A number of state highway agencies specify the use of softer binder in mixtures when the recycled binder ratio exceeds 0.25. Although pavement performance data verifying the effectiveness of this approach is not available, it has been evaluated using various performance tests in several research studies (*22, 30, 44, 45*). Using the Texas Overlay Tester, Mogawer, et. al (*22*) found the use of a softer binder was not effective in improving the resistance of mixtures with recycled binder to reflection cracking. Behnia, et. al (*30*), on the other hand, found that the use of a softer binder was effective at increasing low temperature fracture energy of mixtures.

Two studies compared the effectiveness of: (1) using a softer binder to (2) increasing the binder content for improving the cracking resistance of mixtures with recycled binder. Willis, et. al (*44*) evaluated laboratory produced mixtures with 10, 25, and 50 percent RAP. The recycled mixtures were produced at the design binder content with PG 67-22 and PG 58-28 binders. Recycled mixtures with PG 67-22 binder were also produced with 0.25 and 0.50 percent additional binder. The energy ratio and Texas Overlay tests were used to evaluate the cracking resistance of the mixtures. Both using a softer binder and increasing the binder content improved the cracking resistance as measured by the energy ratio analysis for the 10 and 50 percent RAP mixtures. Both methods also increased the cycles to failure in the Texas Overlay test, but because of the high variability of this test, the improvements were not statistically significant. Bennert, et. al (*45*) summarized the results of various cracking tests that were conducted on plant mixtures to evaluate the effectiveness of using a soft binder in RAP mixtures and increasing the binder content of RAP mixtures by limiting the RAP binder contribution. When using a softer binder in RAP mixtures, the conclusions were test dependent. The softer binder improved the low temperature cracking resistance of mixtures with 20, 30, and 40 percent RAP when measured with the Thermal Stress Restrained Specimen Test, but not when measured with the low temperature indirect tensile creep and strength tests. The softer binder also improved the fatigue cracking resistance of the same mixtures as measured by the flexural fatigue test, but not the reflective cracking resistance as measured by the Texas Overlay test. For a 20 percent RAP mixture, increasing the binder content by limiting the RAP binder contribution to 75 and 50 percent of the RAP binder content improved both the fatigue cracking resistance as measured by flexural fatigue test and the reflective cracking resistance as measured by the Texas Overlay test. The increase in binder content was 0.3 percent when 75 percent RAP binder contribution was assumed and 0.5 percent when 50 percent RAP binder contribution was assumed. These increases are approximately equal to increases in VBE of 0.50 to 1.0 percent.

2.3.4 Warm Mix Asphalt

One of the benefits that is often cited for warm mix asphalt (WMA) is improved asphalt mixture durability as a result of reduced aging of the binder during plant production (*46*). Research completed to date has not documented that WMA mixtures have improved durability; however, research documenting the long-term performance of WMA is currently underway (*47*). In the previously described laboratory study of the cracking resistance of RAP mixtures, Willis, et. al (*44*) found that producing RAP mixtures as WMA improved the cracking resistance as measured by the energy ratio test. Producing RAP mixtures as WMA also improved the cycles to failure in the Texas Overlay test, but because of the high variability of this test, the improvements were not statistically significant. Based on this testing, producing RAP mixtures as WMA was considered a viable alternative to using a softer binder or increasing the effective binder content for improving the cracking resistance of RAP mixtures.

2.3.5 Balanced Mixture Design

Recently three state highway agencies have reported on research to develop and implement the concept of balanced mixture design (*45, 48, 49, 50*). This approach uses performance tests for rutting resistance and load associated cracking resistance to select volumetric and binder properties that will provide adequate resistance to both rutting and load associated cracking. The balanced mix design concept was initially developed by researchers at the Texas Transportation Institute using the Hamburg Wheel Track test to evaluate rutting resistance and the Texas Overlay test to evaluate cracking resistance (*48*). The Louisiana Transportation Research Center developed a similar approach using the Hamburg Wheel Track test to evaluate rutting resistance and the Semi-Circular Bend test to evaluate cracking resistance (*49*). The New Jersey Department of Transportation has implemented performance testing in the design and production of some asphalt concrete mixtures in an effort to improve the cracking resistance of asphalt mixtures (*45, 50*). New Jersey's approach uses the Asphalt Pavement Analyzer to evaluate rutting resistance and the Texas Overlay test to evaluate cracking resistance. The tests are used during mixture design and for mixture acceptance. (*45, 50*). In a recent evaluation of field sections using the balanced mix design approach, the Texas Transportation Research Institute researchers concluded that it is necessary to vary the criteria in the Texas balanced mix design approach depending on the climate at the project location (*51*).

2.3.6 Matching Design and Field Compaction

In a project for the Indiana Department of Transportation, researchers at Purdue University investigated whether asphalt mixture durability can be improved by making mixtures more compactable without sacrificing rutting resistance (*52*). The philosophy behind this research is that mixtures should be designed in the laboratory using an air void content that is achievable during construction. The recommended target for both laboratory design and field compaction is 5 percent air voids. Currently mixtures designed in accordance with AASHTO M323 are designed for 4 percent air voids. Typical in-place compaction specifications result in these mixtures being constructed at an average of 7 percent in-place air voids. As discussed earlier, reducing in-place air voids reduces aging and the potential for moisture damage. The design procedure that was developed uses a design gyration level of 50, a design air void content of 5.0 percent, and the same design VBE that is currently included in AASHTO M323. Dynamic modulus and flow number testing on mixtures produced using this design procedure and compacted to 5.0 percent air voids showed improved stiffness and rutting resistance compared to mixtures designed in accordance with AASHTO M323 using a design gyration level of 100 and compacted to 7.0 percent air voids. In a field project, a mixture designed using the procedure was successfully placed and compacted to the target 5.0 percent air voids. The field performance of the project is being monitored.

2.4 Models for Assessing Mixture Performance

A number of empirical models have been develop that relate mixture composition to engineering properties. Some of these models have been successfully used in previous WHRP projects (37, *53, 54*). Brief descriptions of these models and their application are presented below.

2.4.1 Hirsch Model for Asphalt Concrete Mixture Modulus

The dynamic modulus of asphalt concrete is an important engineering property for pavement structural design. It is the primary input in the AASHTOWare Pavement ME Design software. It is also an important input in various asphalt concrete fatigue equations. The Hirsch Model (*55*), presented in Equation 1, directly considers three of the factors affecting mixture durability: (1) effective volume of binder, (2) air void content, and (3) binder stiffness. As discussed in the next section, the dynamic modulus from the Hirsch Model is also needed for fatigue analysis.

$$|E^*| = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+G_b\left(\frac{VFA\ xVMA}{10{,}000}\right)\right]+\frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000}+\frac{VMA}{G_b(VFA)}\right]} \quad (1)$$

Where:

$$P_c=\frac{\left(20+\frac{G_b(VFA)}{VMA}\right)^{0.58}}{650+\left(\frac{G_b(VFA)}{VMA}\right)^{0.58}}$$

$|E^*|$ = mixture dynamic modulus, psi

VMA = Voids in mineral aggregates, %

VFA = Voids filled with asphalt, %

G_b = binder shear modulus, psi

2.4.2 Asphalt Institute Fatigue Equation

Several fatigue relationships have been developed by various researchers. Equation 2 presents the Asphalt Institute fatigue equation, which is the basis for the fatigue transfer function in AASHTOWare Pavement ME Design software (*56*). When combined with the Hirsch Model for estimating dynamic modulus, the Asphalt Institute fatigue equation can be used to evaluate the effect of effective volume of binder, (2) air void content, and (3) binder stiffness on the relative fatigue life of mixtures.

$$N_f = 18.4 * 0.00432 C \varepsilon_t^{-3.291} |E^*|^{-0.854} \quad (2)$$

Where:

$|E^*|$ = mixture dynamic modulus, psi

ε_t = applied tensile strain

$C = 10^{\left(\frac{VBE}{V_a + VBE} - 0.69\right)}$

VBE = effective volume of binder

V_a = air voids

18.4 = field adjustment factor

2.4.3 Resistivity Rutting Model

Some of the methods that have been suggested for improving asphalt mixture durability may have an adverse effect on rutting resistance. The resistivity rutting model developed in NCHRP Project 9-25 and improved in work completed as part of the Asphalt Research Consortium can be used to evaluate relative rutting resistance. Equation 3 presents the current version of the resistivity rutting model (*38*). The resistivity rutting model includes binder effects using the non-recoverable compliance as well as a number of important compositional factors that likely affect mixture durability including: VMA, design air voids, in-place air voids, and aggregate surface area.

$$TR = 1.31 \times 10^{-4} N_{des}^{1.578} \left(\mathrm{P} K_a K_s\right)^{1.238} \left(\frac{V_{QC}}{V_{IP}}\right)^{1.09} \tag{3}$$

Where:

TR = million ESALs to a maximum rut depth of 12 mm (95 % confidence level)

P = resistivity, s/nm

$= \frac{S_a^2 G_a^2}{4.9 J_{nr,3.2} VMA^3}$

$J_{nr,\,3.2}$ = the non-recoverable compliance at 1 second loading and 3.2 kPa stress (1/Pa)

K_a = age hardening ratio, determined from the modified Mirza-Witczak global aging system

$\cong 0.62 \times (t/2)^{0.37}$, where t is total design life in months

K_s = speed correction

= (v/70), where v is the average traffic speed in km/hr

S_a = specific surface of aggregate in mixture, m^2/kg

≅ the sum of the percent passing the 75, 150 and 300 micron sieves, divided by 5.0

≅ 2.05 + (0.623 × percent passing the 75 micron sieve)

G_a = the bulk specific gravity of the aggregate blend

VMA = voids in the mineral aggregate for the mixture, volume %, as determined during QC testing

N_{des} = design gyrations

V_{QC} = air void content, volume %, determined during QC testing at design gyrations

V_{IP} = air void content, volume %, in-place

2.4.4 WHRP Project 0092-10-07 Low Temperature Creep Compliance and Strength Models

The relative effect of various specification changes on thermal cracking can be estimated using the Excel application LTSTRESS.xls (*57*). LTSTRESS was developed at the Northeast Center of Excellence for Pavement Technology to perform a simplified thermo-viscoelastic analysis. This analysis is similar to the thermal fracture model in the AASHTOWare Pavement ME Design software. It provides an estimate of the expected thermal cracking temperature. It does not consider thermal fatigue or crack propagation, and is strictly only accurate for single-event thermal cracking as occurs during extreme low temperature events. Compliance data for the LTSTRESS analysis can be obtained using Equation 4 that was developed in WHRP Project 0092-10-07 for Wisconsin mixtures having a RAP binder ratio of 0.25 (*58*). The strength at 10 °C, is also needed for the LTSTESS analysis. In WHRP Project 00920-10-07, the average strength of all mixtures tested at 10 °C was 430 psi with a standard deviation of 30 psi (*58*).

$$D(t) = 3.729 \times 10^{-7} + 10^{-9.3552 - 0.0645 \times PG_{Low}} \left[\frac{t}{10^{0.0655(T+4)}} \right]^{0.4705} \quad (4)$$

Where:

$D(t)$ = creep compliance, 1/psi

T = temperature, °F

PG_{Low} = low temperature continuous grade of the binder in the mixture, °C

t = time, sec

2.4.5 Asphalt Research Consortium Permeability Equation

As discussed earlier, permeability is an important factor affecting the durability of asphalt concrete pavements. The permeability model developed in NCHRP Project 9-25 and improved in work completed as part of the Asphalt Research Consortium can be used to evaluate relative permeability. Equation 5 presents the permeability model (*38*). Completed WHRP research has shown that the fine 12.5 mm mixtures commonly used as surface courses in Wisconsin have very low permeability at currently specified in-place compaction levels (*36, 37)*. Since WisDOT specifications and AASHTO M323 provide great latitude in selecting gradation, Equation 5 can be used to evaluate whether both coarse and fine gradations provide sufficiently low permeability at current WisDOT in-place density requirements.

$$\mathrm{Log}(\kappa) = 0.471 + 0.222\,\mathrm{VTM} + 1.64\log(\mathrm{D}_{50}) - 1.22\log(\mathrm{NMAS}) \tag{5}$$

Where:

κ = permeability, cm/s × 10^{-5}

VTM = air void content, %

D_{50} = median aggregate particle size, mm

$NMAS$ = nominal maximum aggregate size, mm

2.5 Mixture Tests for Assessing Durability

There is no standard test for evaluating the durability of dense graded asphalt concrete mixtures. The following sections describe tests that were considered for use in WHRP Project 0092-14-06.

2.5.1 Cantabro Abrasion Test

The Cantabro abrasion test is used in the design of open graded mixtures to assess durability (*59*). In this test, compacted specimens are placed in the Los Angeles Abrasion machine and subjected 300 revolutions at room temperature without the charge of steel balls. The specimen mass loss expressed as a percentage of the original specimen mass is used as a measure of the resistance of open graded mixtures to aggregate loss. A recent evaluation of the Cantabro test using dense graded asphalt concrete, showed the Cantabro test to be sensitive to: (1) VBE, (2) air voids, (3) binder grade, (4) RAP content, and (5) laboratory conditioning (*60*). Although the test appears sensitive to changes in composition, no relationship to field performance has been developed.

2.5.2 ASTM D7196

ASTM D7196, *Standard Test Method for Raveling Test of Cold Mixed Emulsified Asphalt Samples*, is used in the design of cold in-place recycling (CIR) to evaluate resistance to raveling.

In this test, a laboratory prepared specimen is mounted on a Hobart mixer and subjected to abrasion by a free floating rubber hose for 15 minutes. The specimen is weighed before and after the abrasion testing. The maximum raveling loss permitted in most CIR specifications is 2 percent. The test has not been used with asphalt concrete because the cohesion of asphalt concrete mixtures is much higher than CIR mixtures.

2.5.3 Mixture Stiffness

Changes in mixture stiffness after oven conditioning that simulates long-term in-service aging was used in two studies to evaluate the effect of mixture volumetric properties on durability (*35, 61*). Both of these studies used the long-term oven conditioning of compacted specimens of 120 hours at 85 °C as specified in AASHTO R30. Based on the limited research completed during the Strategic Highway Research Program, it appears that this level of conditioning equates to approximately 6 to 9 years of in-service aging (*62*). A current NCHRP project, NCHRP Project 9-54, Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction, is evaluating whether an improved procedure can be developed and calibrated (*63*). Modulus measurements were made with the field shear device in NCHRP Project 9-25 (*35*). The NCAT study used resilient modulus measurements in accordance with ASTM D4123 (*61*). Dynamic modulus measurements in accordance AASHTO TP79 could also be used to evaluate changes in mixture stiffness.

2.5.4 Cracking Tests

Resistance to load associated cracking has long been considered a measure of the durability of asphalt concrete mixtures. Until recently, the only test available to evaluate load associated cracking resistance was the flexural fatigue test, AASHTO T321. In this test, a beam specimen is subjected to repeated loading in a four-point bending geometry. Failure is usually defined as the point at which the stiffness of the beam is reduced to 50 percent of its initial value. Loading is usually performed in a constant strain mode, but may also be performed using a constant applied load. Because flexural fatigue testing is time consuming, requires special specimen fabrication equipment, and yields high variability, it is not routinely performed.

Recently several cracking tests have been developed that are simpler to perform than the flexural fatigue test. These include: (1) uniaxial fatigue testing, (2) fracture energy tests, and (3) the Texas Overlay test.

Uniaxial fatigue testing is similar to flexural fatigue, but is more fundamental in nature (*64*). A cylindrical specimen is loaded sinusoidally until failure occurs; loading may be stress controlled or strain controlled. Analysis is typically done using continuum damage principles, based upon the rate of damage to the specimen, as measured by the reduction in modulus. This test is not as time consuming as the flexural fatigue test, but is still relatively difficult to perform and analyze.

A number of fracture energy tests have been developed by various researchers and used as measures of fracture resistance. The general concept of relating fracture energy to engineering performance has been widely used in the selection of materials for many diverse applications (*65*).

The disc-shaped compact tension (DCT) test and semi-circular bend (SCB) test have been recommended for evaluating the thermal cracking resistance of asphalt mixtures (*66*). In the DC(T), a roughly disk-shaped specimen with a notch in one side is sawed from a gyratory specimen or core. The specimen is loaded in tension; the load is applied through two holes on either side of the notch. A crack opening displacement gage is placed across the notch in order to measure the crack opening and control the crack opening displacement rate. The fracture energy is computed as the area under the load versus crack mouth opening displacement curve. This test procedure appears to work well, providing relatively repeatable measurements of fracture toughness, but specimen preparation and load control is more complicated than some other fracture energy tests. The SCB test uses a semi-circular specimen sawn from either a gyratory specimen or a core. A notch is sawn through the center of the specimen starting at the flat edge of the specimen. In the version of this test used to measure resistance to low temperature cracking, a crack opening displacement gage is placed across the notch to measure the crack opening and to control the crack opening displacement. The fracture energy is computed as the area under the load versus crack mouth opening displacement curve. Like the DC(T), this version of the SCB test appears to work well, providing relatively repeatable measurements of fracture toughness, but the test requires closed loop load control, which complicates the testing.

A version of the SCB test has been developed by researchers at the Louisiana Transportation Research Center to measure the resistance of asphalt mixtures to cracking at intermediate temperatures, 25 °C (*67*). This version of the test differs from the version used for low temperature cracking in two important ways. First, the mixture cracking resistance is evaluated using the critical strain energy release rate; resistance to cracking increases with increasing critical strain energy release rate. The critical strain energy release rate is the rate of change in strain energy to failure with notch depth. Thus, this version of the test requires testing specimens using a least two different notch depths. Second, the specimen is loaded at a constant vertical displacement and the strain energy to failure is calculated as the area under the load versus vertical displacement curve. This greatly simplifies the load control, making it possible to perform the test on simple compression machines.

Researchers at the University of Illinois have recommended a parameter from an intermediate temperature SCB test called the Flexibility Index (FI) as a indicator of the cracking resistance of an asphalt mixture (*68*). The FI is equal to the fracture energy from the SCB divided by the post peak slope of the SCB load versus vertical displacement curve. The University of Illinois research showed the post peak slope is related to the brittleness of the mixture. The post peak slope decreases as the mixture becomes more brittle. Measured values for the FI for laboratory prepared mixtures ranged from 16 for a virgin mixture with polymer modified binder to 2 for mixtures with high recycled binder ratios from RAP and RAS. The FI also showed reasonable correlation to cracking from test sections at the FHWA's Pavement Testing Facility.

The Fénix test is a fracture energy test that can be conducted at intermediate and low temperatures (*69*). The test uses the same notched specimen as the SCB test except the flat portion of the specimen is glued to loading platens that are pulled apart at a constant displacement rate. The fracture energy is computed as the area under load displacement curve. In addition to the fracture energy, a stiffness index is calculated as 50 percent of the maximum load divided by the displacement at 50 percent of the maximum load.

Researchers at the University of Florida have proposed the energy ratio analysis for characterizing the resistance of an asphalt concrete mixture to top down cracking (*70*). This testing requires three indirect tensile (IDT) tests at 10 °C: (1) resilient modulus, (2) creep, and (3) strength, to calculate the energy ratio. Higher values of energy ratio have been correlated to greater resistance to top-down cracking.

A potentially useful variation of the IDT strength test is the IDT fracture energy test (*71*). In this procedure, an IDT specimen is loaded to failure at a constant rate of deformation. Load and horizontal strain are measured to failure and used to calculate total energy absorbed by the specimen prior to failure. IDT fracture energy is probably a better indicator of low temperature performance and possibly fatigue resistance than IDT strength because it is a function both of stress and strain at failure. Limited research has related the results of this test to field performance. A simplified version of the test has been proposed in which fracture energy is determined from vertical deformation and applied load, without the need for strain measurements.

The Texas Overlay Test (OT) was developed to evaluate the resistance of asphalt concrete mixtures to reflective cracking (*72*). In this test a 6-inch long, 1-1/2 in thick, by 3 in wide specimen is sawed from either a gyratory specimen or core and is glued to two platens. The platens are moved using a repeated triangular wave form that opens the platens to a maximum width of 0.025 inches, to simulate horizontal movements of cracks beneath an overlay. The results of this test have been correlated to field performance of pavements in Texas.

2.6 Summary

Asphalt mixture durability is defined as the ability of compacted asphalt concrete to maintain its structural integrity throughout its expected service life when exposed to the damaging effects of the environment and traffic loading (*1*). Asphalt mixture durability is affected by a number of factors associated with: (1) the environment, (2) drainage conditions, (3) construction, and (4) mixture composition. WHRP Project 0092-14-06 focused on mixture composition. For mixtures produced with sound, durable aggregates, the compositional factors affecting durability include:

1. **Binder Properties.** This includes the intermediate stiffness after PAV conditioning to simulate long-term aging, the amount and stiffness of recycled binder, and whether the binder is polymer modified.
2. **Gradation.** The gradation affects the permeability of the mixture to air and water. Permeability affects the rate of aging and the potential for moisture damage.
3. **Air Void Content.** The in-place air void content affects the strength, stiffness, and permeability of the mixture and is primarily controlled by compaction specifications.
4. **Volume of Effective Binder.** The volume of effective binder controls the thickness of the asphalt coating the aggregate. More effective binder slows the rate of aging and improves the resistance of mixtures to cracking.

Several methods for improving durability were identified by this synthesis of current practice. These include:

1. **Increase in-place compaction.** The general consensus of a number of studies is lower in-place air voids improve all performance related properties of asphalt concrete mixtures. Perhaps the most important compaction consideration at this time is reducing air voids in the vicinity of longitudinal joints. Often the performance of the longitudinal joints governs the service life of the asphalt concrete wearing surface (*12*). A variation on the concept of improved compaction is the approach of matching design and in-place air voids that is being evaluated in Indiana (*52*). The philosophy behind this research is that mixtures should be designed in the laboratory using an air void content that is achievable during construction. The recommended target for both laboratory design and field compaction is 5.0 percent air voids, which represents a substantial improvement in in-place compaction.

2. **Polymer Modification.** Polymer modification has been shown to reduced all forms of pavement distress, increasing the life of flexible pavements by 2 to 10 years (*31*). The Nevada Department of Transportation and the Louisiana Department of Transportation and Development specify polymer modified binders for all surface course mixtures.
3. **Increase Effective Binder Content.** The mix design manual developed in NCHRP Project 9-33 recommends increasing the design VMA by 1.0 percent to produce mixtures with improved durability (*39*). Increasing the design VMA by 1.0 percent while keeping the design air voids at 4.0 percent increases the VBE of the mixture by 1.0 percent. Two other ways to increase the effective binder content that have been proposed and used are: (1) decreasing design air voids, and (2) decreasing design gyration level (*40*).
4. **Use Smaller Nominal Maximum Aggregate Size Mixtures.** Smaller nominal maximum aggregate size mixtures have higher effective binder content. Changing from 12.5 mm to 9.5 mm surface mixtures will increase the design VBE by 1.0 percent. Smaller nominal maximum aggregate size mixtures also have lower permeability for the same in-place air void content.
5. **Use a Softer Binder in Mixtures with Recycled Binder.** Many highway agencies specify the use of a softer binder in mixtures when the recycled binder ratio exceeds 0.25. There are conflicting results in the published literature on the effectiveness of using a softer binder to improve the load associated cracking resistance of mixtures with recycled binder.
6. **Use Warm Mix Asphalt.** One of the benefits that is often cited for WMA is improved asphalt mixture durability as a result of reduced aging of the binder during plant production. Research completed to date has not documented that WMA mixtures have improved durability. In one laboratory study, the effect of WMA on the cracking resistance of mixtures with recycled binder was similar to using a softer grade of binder (*44*).
7. **Balanced Mix Design.** The Texas Department of Transportation, the Louisiana Department of Transportation and Development and the New Jersey Department of Transportation have reported on research to develop and implement the

concept of balanced mixture design (*48, 49, 50*). This approach uses performance tests for rutting resistance and load associated cracking resistance to select volumetric and binder properties that will provide adequate resistance to both rutting and load associated cracking.

The effect of some changes to WisDOT specifications that may be recommended as a result this research can be evaluated using empirical models that relate mixture composition to engineering properties. Models are available for (1) modulus, (2) rutting resistance, (3) fatigue cracking resistance, (4) permeability, and (5) low temperature compliance and strength.

There is no test for directly evaluating the durability of dense graded asphalt concrete mixtures. The Cantabro abrasion test is used to evaluate the durability of open graded mixtures and a raveling test is included in many cold in-place recycling specifications. Relationships between these empirical tests and the durability of dense graded asphalt concrete are not available.

The effect of mixture properties on durability has been evaluated in the past by measuring changes in mixture stiffness after oven conditioning that simulates long-term, in-service aging. The long-term, compacted specimen conditioning procedure in AASHTO R35 is the only standardized procedure available for simulating long-term in service aging, although NCHRP Project 9-54 may produce an improved procedure in the near future. Mixture stiffness, rather than cracking resistance, has been used in the past because until recently the only available test for cracking resistance was the flexural fatigue test, which is very time consuming and has highly variable results. Recently fracture energy tests have been developed and related to cracking resistance. The intermediate temperature SCB test developed at the Louisiana Transportation Research Center and the Illinois Modified SCB test appear well suited for the laboratory studies in this project.

Chapter 3 Laboratory Experiments

This chapter presents the design of the laboratory experiments that were conducted in WHRP Project 0092-14-06. The objective of the laboratory experiments was to evaluate the effectiveness of the promising methods to improve durability identified in the synthesis of current practice presented in Chapter 2. Two experiments were conducted. The first was an experiment using laboratory prepared mixtures that was designed to develop relationships between promising factors affecting asphalt mixture durability and cracking resistance as measured by SCB testing at intermediate temperatures. The second experiment was a verification experiment using plant mixtures that was designed to compare estimates of cracking resistance obtained from the regression equations developed from the laboratory prepared mixtures experiment with values measured from intermediate temperature SCB testing. The sections that follow describe the design of the two experiments and the materials and test methods used in the experiments.

3.1 Experimental Factors

3.1.1 Basis for Selection

Since the focus of WHRP Project 0092-14-06, as stated in the Request for Proposals, was on changes to the composition of asphalt mixtures that WisDOT should consider to improve durability, the laboratory experiments were designed to investigate the effect of mixture composition on the durability of dense graded asphalt concrete. There is no standard test for measuring the durability of dense graded asphalt concrete; therefore, the resistance to simulated long-term aging and cracking at intermediate temperatures were used as measures of durability.

Based on the review of current practice presented in Chapter 2, the promising methods for improving mixture durability through mixture composition that are applicable to the fine graded surface course mixtures commonly used in Wisconsin are:

1. **Increase effective binder content for all mixtures.** As discussed in Chapter 2, this can be accomplished in a number of ways including: increase design VMA, decrease design

air voids, decrease design gyration level, and use smaller nominal maximum size mixtures.

2. **Increase the effective binder content in proportion to the amount of recycled binder.** This addresses the question of whether all of the recycled binder in a mixture is effective. Increasing the effective binder content in mixtures with recycled binder is equivalent to placing a limit on the contribution of the recycled binder. Laboratory data from two studies show that this approach improves the cracking resistance of mixtures with recycled binder (*44,45*).
3. **Use a softer grade of binder in recycled mixtures.** Many highway agencies have adopted this approach for mixtures having a recycled binder ratio greater than 0.25. There are conflicting results in the published literature on the effectiveness of using a softer binder to improve the load associated cracking resistance of mixtures with recycled binder.
4. **Use polymer modified binder in all surface course mixtures.** Polymer modification has been shown to reduce all forms of pavement distress, increasing the life of flexible pavements by 2 to 10 years (*31*). At least two state highway agencies specify polymer modified binders for all surface course mixtures.
5. **Use polymer modified binder in recycled mixtures.** In a laboratory study of the fatigue resistance of Nevada mixtures, the Western Regional Superpave Center found the fatigue resistance of mixtures with polymer modified binder with up to 30 percent RAP was significantly greater than that of virgin mixtures with neat binder (*26*).
6. **Use balanced mixture design.** Rather than specify requirements for mixture composition that may be different for virgin compared to recycled mixtures, this approach provides the producer the flexibility to design mixtures to meet specific requirements for resistance to rutting and cracking. For this approach to be effective, mixture designers need information concerning the effect that changes in composition have on the resistance to rutting and cracking. Relatively simple empirical relationships, such as the resistivity rutting model, are available for rutting resistance. The laboratory experiments from this project were designed to develop relationships for load associated cracking resistance that could be used by mixture designers should the balance design approach be recommended.

The methods for improving durability that were identified in the review of current practice presented in Chapter 2 that were not addressed by the laboratory study are:

1. **Increase in-place compaction requirements.** There is substantial published literature related to the effect of in-place density on the performance related properties of asphalt concrete mixtures (*11*). For many highway agencies, improved joint compaction is an important consideration at this time (*12*). In-place compaction was not considered in the experimental design based on the focus of WHRP Project 0092-14-06, which was the effect of changes in mixture composition on the durability of asphalt concrete mixtures. The effort in Indiana to improve field compaction by matching design air voids and field air voids (*52*) was not included because the goal of this approach is improved field compaction.
2. **Use smaller nominal maximum aggregate size to reduce permeability.** One of the benefits of using smaller nominal maximum size mixtures is reduced permeability for the same in-place air void content. The proposed experiment did not evaluate the effect of gradation on permeability for two reasons. First, completed WHRP research has shown that the fine graded surface course mixtures commonly used in Wisconsin have low permeability at current in-place compaction levels (*36, 37*). Second, the effects of gradation on permeability can be evaluated using the Asphalt Research Consortium permeability equation (*38*).
3. **Use warm mix asphalt.** The use of WMA is a variation on the use of a softer grade of binder. The lower production temperatures associated with WMA reduce plant aging, resulting in softer binders at the time of construction. The reduction in binder stiffness depends on the temperature of the WMA, but is typically less than a one performance grade change (*73*). Most agencies require one grade softer binder for mixtures with a recycled binder ratio exceeding 0.25.

To evaluate the selected promising methods for improving durability, the laboratory experiments included the following factors: (1) effective binder volume, (2) recycled binder content, (3) virgin binder low temperature grade, and (4) polymer modification. As will be discussed in greater detail in the experimental design for the laboratory prepared mixtures experiment, each of these factors was evaluated at three levels to address possible non-linear effects, and the interaction between factors. It is important to evaluate interactions to determine if mixtures with recycled binders should be treated differently than virgin mixtures in specifications. For example should recycled mixtures have higher effective binder volume, or polymer modification in addition to a softer grade of binder? The factors that were included in the experiment and their levels are discussed in greater detail below.

3.1.2 Effective Binder Volume

The effective binder volume was evaluated at three levels. These three levels were obtained by using 19.0, 12.5, and 9.5 mm mixtures in the experiment. This provided an approximately 2 percent range in the effective binder volume of the mixtures. All of the mixtures used in the study were mixtures that have been accepted by WisDOT.

3.1.3 Recycled Binder Content

The recycled binder content was evaluated at three levels: (1) none, (2) approximately 20 to 25 percent RAP by weight of aggregate, and (3) approximately 3 to 5 percent RAS plus 20 to 25 percent RAP by weight of aggregate. It appears that many of the higher recycled binder ratio mixtures are being produced with the combination of RAP and RAS.

3.1.4 Virgin Binder Low Temperature Grade

The virgin binder low temperature grade was evaluated at three levels: (1) PG 64-22, (2) PG 58-28, and (3) PG 52-34. Although recent WisDOT specification changes eliminated the use of PG 64-22 binders, it was important to include this level in the experimental design to provide a 2 grade range in the low temperature properties of the virgin binder.

3.1.5 Polymer Modification

Three levels of polymer modification were included in the experiment based on AASHTO M332: (1) Standard Grade “S”, (2) High Grade “H”, and (3) Very High Grade “V”. The “H” and “V” grades were made with polymer modification.

3.2 Laboratory Prepared Mixtures Experiment

3.2.1 Experimental Design

An experiment to assess the effect of (1) effective binder volume, (2) recycled binder content, (3) virgin binder low temperature grade, and (4) polymer modification on the aging of an asphalt binder in a mixture and the resistance of the mixture to intermediate temperature cracking is a classical response surface experiment (*74*). The objective in a response surface experiment is to define the shape of the response surface in a well defined region. The response surface can then be used to determine the combination of factors that produce an optimal response over the region of interest. In the case of this study, that is the combinations of the four factors listed above that (1) minimize binder aging and (2) provide acceptable resistance to cracking.

Since response surface experiments are often used in process improvement, efficient designs that allow for interaction and non-linear effects have been developed (*74*). The Box-Behnken design allows a general quadratic model given by Equation 6 to be fit using data obtained from 27 combinations of the four factors (*74*). A full factorial experiment for 4 factors at 3 levels requires testing 81 (3^4) combinations.

$$\begin{aligned} \hat{y} &= b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 \\ &+ b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_2x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 \\ &+ b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{44}x_4^2 \end{aligned} \qquad (6)$$

Where:

$\hat{y}$ = predicted response

x_i = value of response i

b_{ij} = model coefficients

Table 6 presents the Box-Behnken design for the laboratory prepared mixtures experiment. This design is best visualized considering two factors at a time as shown in Figure 1. The 27 combinations in the Box-Behnken design include one run at the four mid-points of the sides for the six two factor combinations (VBE-Recycle, VBE-Low Grade, VBE-Modification, Recycle-Low Grade, Recycle-Modification, Low Grade-Modification) plus three runs at the center point to estimate testing error. Each run represents tests on mixtures made with the specific combination shown in Table 6. The runs were randomized to minimize systematic errors.

Table 6. Box Behnken Design.

Run	VBE	Recycle	Low Grade	Modification	Space
1	19.0	Virgin	-28	H	VBE – Recycle
2	9.5	Virgin	-28	H	
3	19.0	RAP+RAS	-28	H	
4	9.5	RAP+RAS	-28	H	
5	12.5	RAP	-22	S	Low Grade – Modification
6	12.5	RAP	-34	S	
7	12.5	RAP	-22	V	
8	12.5	RAP	-34	V	
9	12.5	RAP	-28	H	Center
10	19.0	RAP	-28	S	VBE – Modification
11	9.5	RAP	-28	S	
12	19.0	RAP	-28	V	
13	9.5	RAP	-28	V	
14	12.5	Virgin	-22	H	Recycle - Low Grade
15	12.5	RAP+RAS	-22	H	
16	12.5	Virgin	-34	H	
17	12.5	RAP+RAS	-34	H	
18	12.5	RAP	-28	H	Center
19	12.5	Virgin	-28	S	Recycle – Modification
20	12.5	RAP+RAS	-28	S	
21	12.5	Virgin	-28	V	
22	12.5	RAP+RAS	-28	V	
23	19.0	RAP	-22	H	VBE – Low Grade
24	9.5	RAP	-22	H	
25	19.0	RAP	-34	H	
26	9.5	RAP	-34	H	
27	12.5	RAP	-28	H	Center

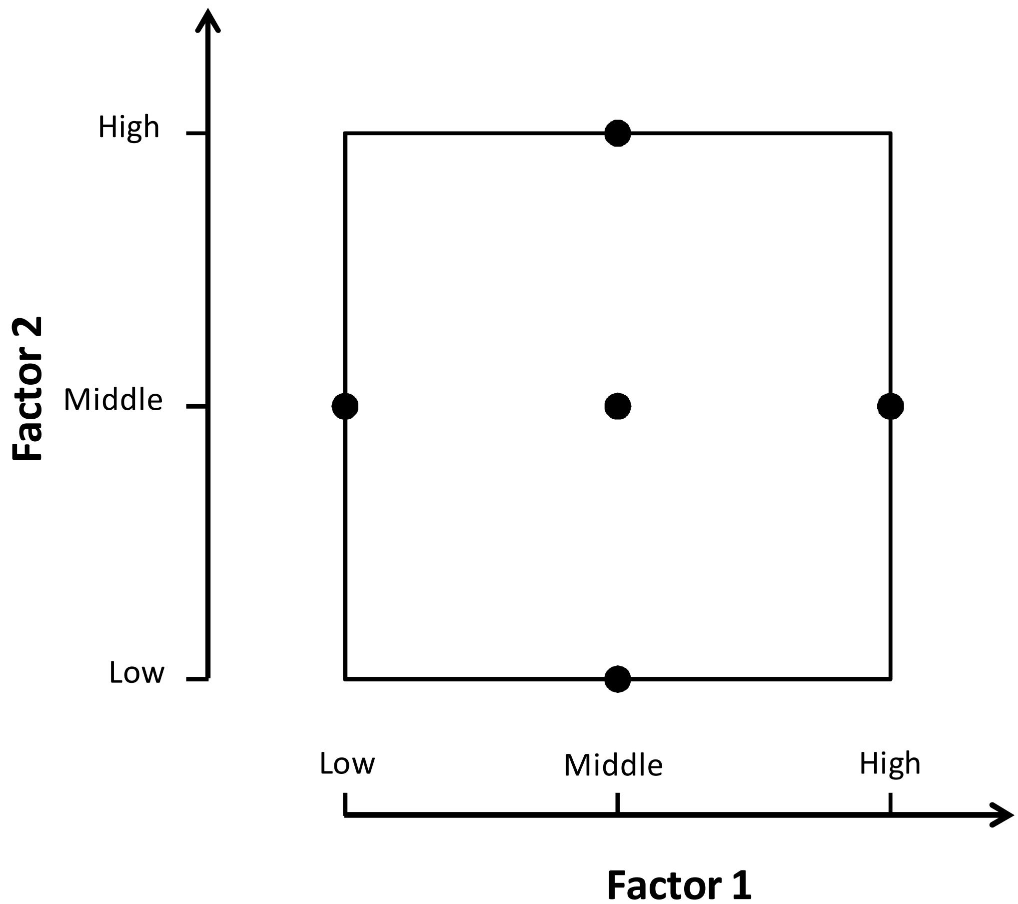


Figure 1. Box Behnken Design for Two of the Four Factors.

Response surfaces can be developed for the various tests discussed later in this chapter by fitting Equation 6 to the measured data. Linear regression can be used after appropriate transformation of the variables (*75*). The response surfaces can then be used to assess the relative effects of the factors to develop guidance for specification changes that will minimize binder aging and provide acceptable resistance to cracking.

3.2.2 Responses and Test Procedures

Binder age hardening and mixture resistance to intermediate temperature cracking after short- and long-term oven conditioning were the responses measured to evaluate asphalt concrete mixture durability. Asphalt concrete durability will be improved if age hardening is minimized, and the cracking resistance exceeds an acceptable level.

The intermediate SCB test developed at the Louisiana Transportation Research Center (*67*) was initially selected to be used in the project. The advantages of this test include: (1) it has been related to field cracking, (2) test specimens can be prepared from gyratory specimens or cores with minimal effort, (3) the test does not require closed loop control or specimen mounted transducers, (4) a measure of stiffness can be obtained from the load displacement curve, and (5) the strain energy to failure has a low coefficient of variation. Figure 2 presents a schematic of this test.

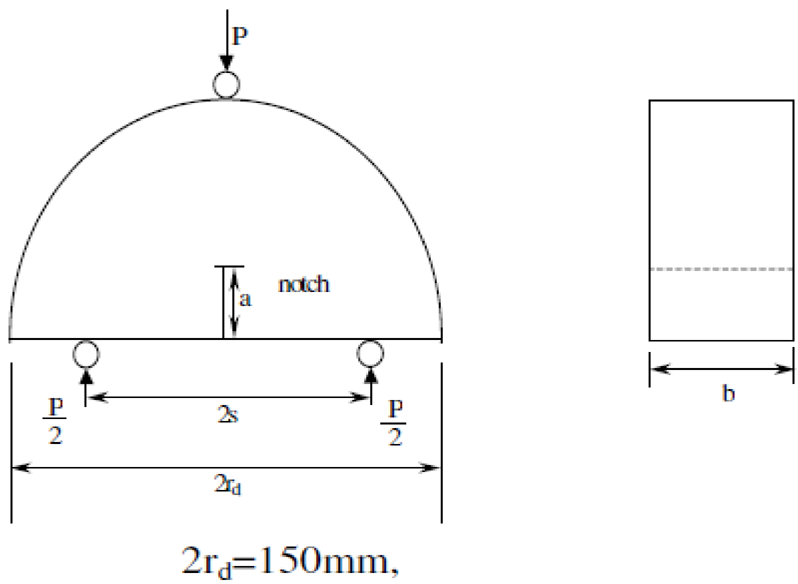


Figure 2. Schematic of Intermediate Temperature SCB Test. (From Reference 67).

In the intermediate SCB test, load displacement curves are obtained by loading specimens with different notch depths at an intermediate temperature with a ram displacement rate of 0.5 mm/min. The strain energy to failure is calculated as the area under the load displacement curve, shown in Figure 3, up to the peak load. The critical strain energy release rate, J_c, is then calculated from the slope of a plot of the strain energy to failure divided by the thickness of the specimen as a function of notch depth. The minimum J_c recommended in the balanced mix design procedure developed at the Louisiana Transportation Research Center is 0.60 kJ/m^2 (*49*).

The slope of the load displacement curve for the smaller notch depth at 50 percent of the peak value was used to define a stiffness index. An aging ratio was then calculated as the ratio of the stiffness index after long-term oven conditioning divided by the stiffness index after short-term oven conditioning. This aging ratio is a measure of the age hardening that occurs in the mixture.

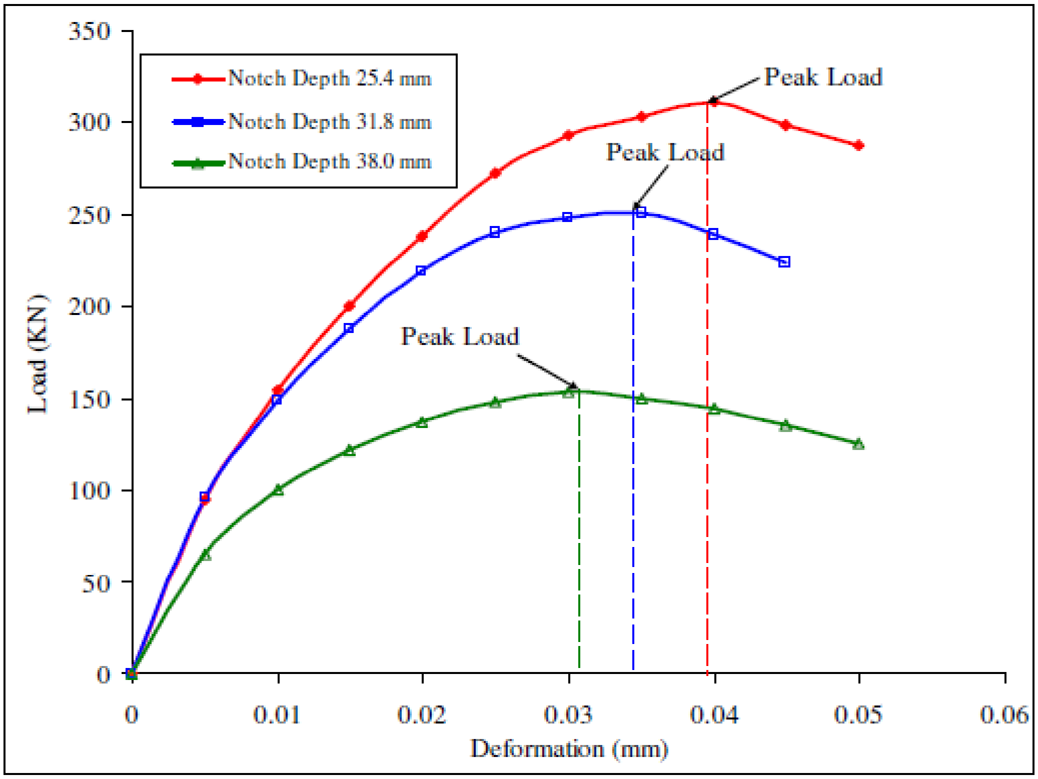


Figure 3. Typical Load Displacement Curves for SCB Intermediate Temperature SCB Test (From Reference 67).

Based on SCB testing conducted in the Wisconsin pilot high recycle projects, the SCB test temperature was reduced from the 25 °C recommended by the Louisiana Transportation Research Center to 15 °C. This produced J_c values ranging from 0.17 to 1.03 kJ/m^2 which were in reasonable agreement with those reported by the Louisiana Transportation Research Center. However, when comparing results for short-term conditioning to those for long-term conditioning it was observed that long-term conditioning often produced higher J_c values implying improved cracking resistance with aging.

The SCB data were also used to calculate a flexibility index (FI) as recommended by the University of Illinois research (*68*). The FI is equal to the fracture energy divided by the slope of the post peak load-displacement curve at the inflection point. This is shown in Figure 4. Using time-temperature superposition, the loading conditions of 15 °C, 0.5 mm/min are approximately equivalent to 8.5 mm/min at 25 °C, which is somewhat slower than the 50 mm/min used in the University of Illinois research. Therefore, FI values presented in this study should not be compared directly with those from the University of Illinois research. The measured FI values ranged from 2 to 15 for short-term conditioned specimens and 1 to 10 for long-term conditioned specimens. Considering the wide range in FI values and the rational trend of reduced cracking resistance with long-term conditioning, the FI was the response selected for final analysis.

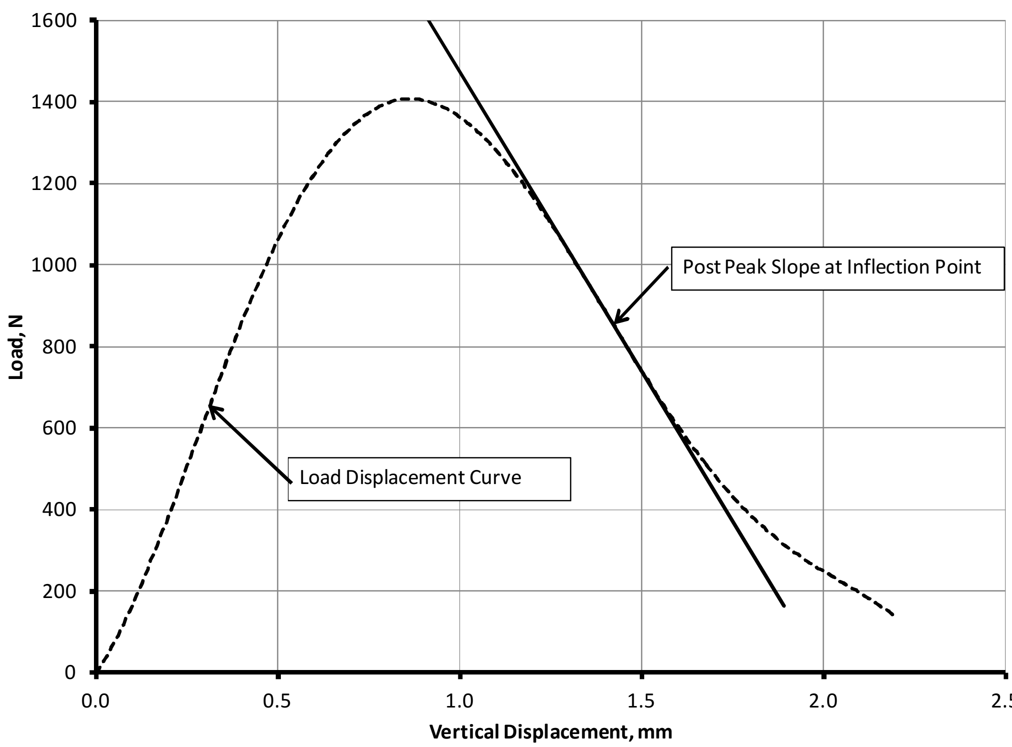


Figure 4. Load-Displacement Curve and Slope Used in Calculating the Flexibility Index.

Finally, after SCB testing, the binder in the specimens was extracted and recovered to measure properties of the binder that have been related to cracking and aging. These properties include: (1) the intermediate and low temperature continuous grade temperature, (2) the parameter ΔT_c which is the difference in the temperature where bending beam rheometer (BBR) stiffness is 300 MPa and the temperature where the BBR m-value is 0.300, and (3) the Glover-Rowe parameter. As a binder ages, ΔT_c becomes more negative with values more negative than -5.0 °C indicating that cracking is likely (*76*). The Glover-Rowe parameter is defined by Equation 7 and can be obtained from a master curve constructed from data at intermediate temperatures (*77*).

$$G - R = \frac{G^* (\cos\delta)^2}{\sin\delta} \tag{7}$$

Where:

G-R = Glover-Rowe parameter, kPa

G* = shear modulus, kPa at reduced frequency for 15 °C, 0.005 rad/s

δ = phase angle at reduced frequency for 15 °C, 0.005 rad/s

As a binder ages, the Glover-Rowe parameter becomes larger with recommended limits of 180 kPa and 600 kPa for the onset of damage, and significant cracking, respectively (*77*).

The testing that was conducted for each cell in Table 6 is shown in Figure 5. This testing required sufficient batches for 6 gyratory specimens and 2 maximum specific gravity specimens to be prepared and short-term conditioned for 4 hours at 135 °C. Three gyratory specimens were prepared from the short-term conditioned batches. The remaining batches were long-term conditioned for 120 hours at 85 °C. The long-term conditioning was performed on loose mixture rather than compacted specimens as specified in AASHTO R30 to minimize aging gradients in the specimens. Gyratory specimens for short-term and long-term conditioned mixtures were prepared to a target air void content of 7.0 ±0.5 percent based on the theoretical maximum specific gravity measured after appropriate conditioning. Triplicate SCB specimens with notch depths of 25 mm and 38 mm were prepared and tested at 15 °C using a loading rate of 0.5 mm/min. The data from these tests were used to calculate the critical strain energy release rate, the stiffness index from the 25 mm notch depth, and the flexibility index from the 25 mm notch depth. Finally, the binder from the test specimens was extracted and recovered in accordance with AASHTO R59, *Standard Specification for Recovery of Asphalt Binder from Solution by Abson Method.* The continuous high, intermediate, and low temperature grade of the recovered binder was determined in accordance with ASTM D7643, *Standard Practice for Determining the Continuous Grading Temperatures and Continuous Grades for PG Graded Asphalt Binders* without additional. The ΔT_c parameter was calculated from the continuous low temperature grade data. A master curve of the recovered binder was constructed using the Christensen-Anderson model (*78*) and frequency sweep data measured at 10, 22, and 34 °C in accordance with AASHTO T315, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*. The Glover-Rowe parameter was calculated from the master curve using Equation 7.

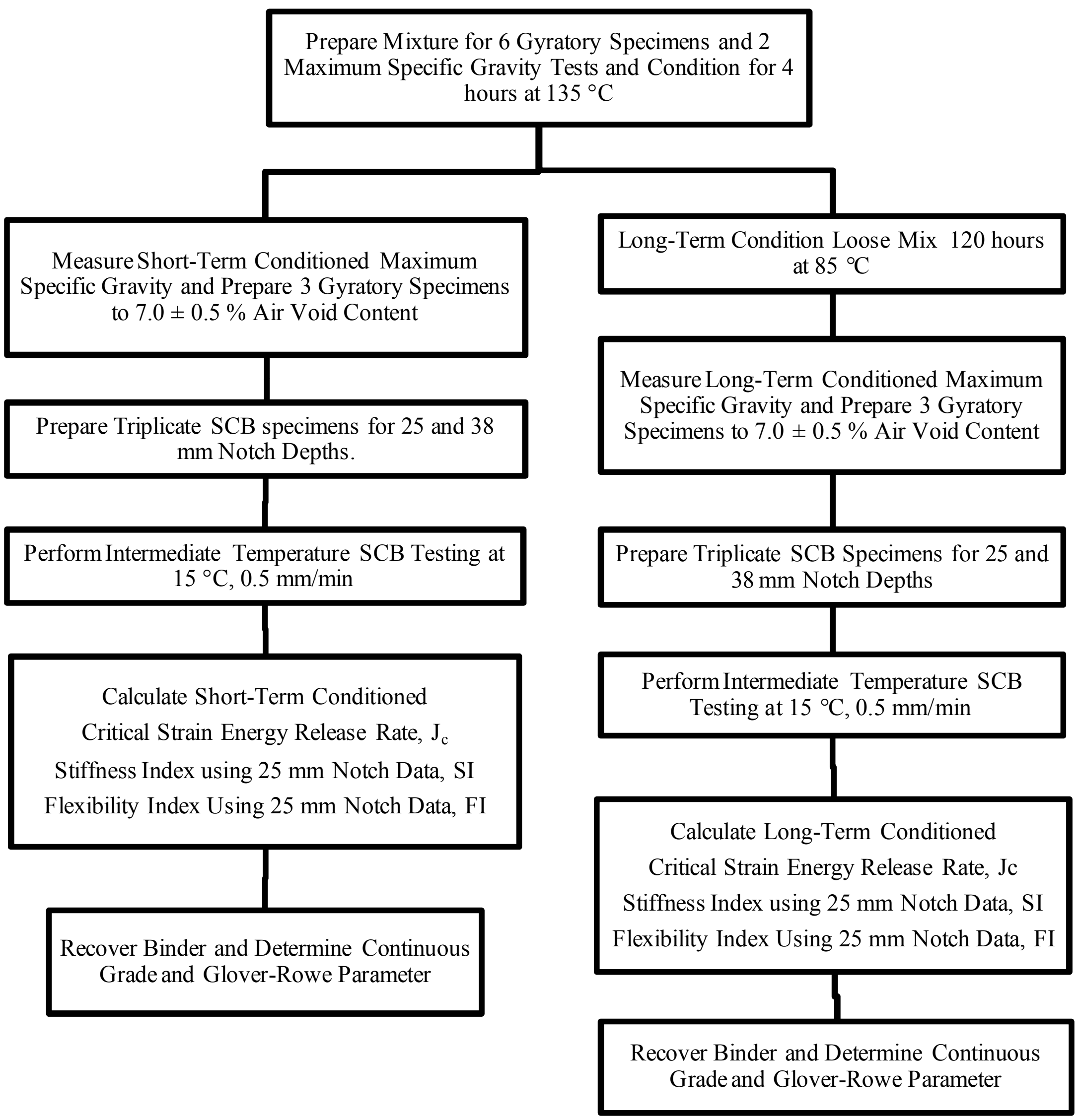


Figure 5. Flow Chart for Intermediate SCB Testing.

3.2.3 Materials

The laboratory prepared mixtures experiment used nine different binders, and nine different mixtures from Wisconsin. Table 7 lists the suppliers of the binders. The majority of the binders were supplied by Payne and Dolan and are commercially available in Wisconsin. The PG 64-22 H and PG 64-22 V grade binders were laboratory blends that were provided by Stark Asphalt. Table 8 lists the suppliers of the aggregates for the mixtures. All mixtures were designed as E-3 mixtures. Seven of the nine mixtures had approved mix designs. The exceptions were the 12.5 and 9.5 mm virgin mixtures. These mixtures were modifications of low RAP content mix designs provided by the suppliers.

Table 7. Binder Suppliers.

Binder	Supplier	Source
PG 64-22, Grade S	Payne and Dolan	Commercial
PG 64-22, Grade H	Stark Asphalt	Lab Blend
PG 64-22, Grade V	Stark Asphalt	Lab Blend
PG 58-28, Grade S	Payne and Dolan	Commercial
PG 58-28, Grade H	Payne and Dolan	Commercial
PG 58-28, Grade V	Payne and Dolan	Commercial
PG 52-34, Grade S	Payne and Dolan	Commercial
PG 58-34, Grade H	Payne and Dolan	Commercial
PG 58-34, Grade V	Payne and Dolan	Commercial

Table 8. Aggregate Suppliers.

Category	Nominal Maximum Aggregate Size	Supplier	Approved Mix Design
Virgin	19.0	Chippewa County	Yes
	12.5	Stark Asphalt	No
	9.5	Mathy, Rosenmeyer	No
RAP	19.0	Mathy, Hauser Street	Yes
	12.5	Mathy, Hauser Street	Yes
	9.5	Stark Asphalt	Yes
RAP+RAS	19.0	Payne and Dolan, Waukesha	Yes
	12.5	Mathy, Plant 22	Yes
	9.5	Payne and Dolan, Waukesha	Yes

Table 9 summarizes AASHTO M320 and AASHTO M332 grading properties for the binders. The binders provide a wide range of properties. The intermediate continuous grade varies from 10.5 to 23.8 °C. The low temperature continuous grade varies from -24.2 to -36.4 °C. The percent recovery, which is an indicator for the presence of elastomeric polymer modification varies from 0 to 86 percent. Based on AASHTO M332, V and E grade binders were supplied in lieu of the H and V grades shown in the experimental design. The binder supplied as PG 58-28 S has an intermediate stiffness greater than 5,000 kPa at 19 °C; therefore, it grades as PG 58-22 based on AASHTO M320 and PG 58-22 S based on AASHTO M332.

Table 10 summarizes compositional properties of the mixtures. All mixtures are fine graded mixtures meeting WisDOT E-3 requirements. The mixtures provide a range of VBE from 8.8 to 12.3 percent. For the mixtures with recycled asphalt material, the binder contents and recycled binder ratios reported in Table 10 are based on the binder content of the RAP and RAS that was supplied as determined by Method A of AAHTO T164, *Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot-Mix Asphalt (HMA)*. The binder contents of the recycled materials are somewhat different than reported by the suppliers in the mixture designs that were provided. The gradations reported in Table 10 are based on the gradation of the fine aggregates and recycled materials, as supplied. For preparing the mixture specimens, the coarse aggregates were sieved into individual sizes. The fine aggregates and recycled materials were not sieved, resulting in minor differences from the mixture designs provided by the suppliers. The aggregate bulk specific gravity used in calculating the VBE reported in Table 10 was obtained from the measured effective specific gravity of the test specimens adjusted by the difference between effective specific gravity and aggregate bulk specific gravity reported in the mixture designs provided by the suppliers.

Table 9. AASHTO M320 and AASHTO M332 Grading for the Laboratory Prepared Mixtures Experiment Binders.

Specification	Property	PG 52-34 S	PG 58-34 H	PG 58-34 V	PG 58-28 S	PG 58-28 H	PG 58-28 V	PG 64-22 S	PG 64-22 H	PG 64-22 V
AASHTO M320 Continuous Grading Data	Tank High, °C	54.2	62.9	68.7	58.2	68.5	74.4	66.1	77.6	80.6
	RTFO Test High, °C	55.8	65.6	69.4	59.7	69.9	75.1	67.1	78.4	82.2
	Intermediate, °C	11.9	13.1	10.5	20.2	19.1	15.8	23.7	22.8	21.9
	Stiffness Low, °C	-34.0	-36.4	-36.2	-29.8	-29.6	-32.0	-25.9	-24.2	-24.3
	m-value Low, °C	-35.6	-36.9	-36.7	-29.0	-28.9	-31.8	-25.6	-25.1	-25.3
	Grade	52-34	58-34	64-34	58-22*	64-28	70-28	64-22	76-22	76-22
AASHTO M332 Grading Data	$J_{nr3.2}$ at 58 °C, 1/kPa	6.42	0.57	0.24	3.64	0.57	0.07			
	J_{nrdiff} at 58 °C, %	10.1	28.7	9.2	10.3	25.3	5.6			
	Recovery at 58 °C, %	0.0	59.6	75.1	0.0	34.6	86.0			
	$J_{nr3.2}$ at 64 °C, 1/kPa							3.05	0.34	0.10
	J_{nrdiff} at 64 °C, %							10.0	23.2	6.9
	Recovery at 64 °C, %							0.3	49.4	79.1
	Grade	52-34 S	58-34 V	58-34 E	58-22 S*	58-28 V	58-28 E	64-22 S	64-22 E	64-22 E

* fails intermediate stiffness of 5000 kPa at 19 °C.

Table 10. Composition of the Mixtures for the Laboratory Prepared Mixtures Experiment.

Category	Nominal Maximum Aggregate Size, mm	Binder Content, wt %	VBE, vol. %	RAP recycled binder ratio	RAS recycled binder ratio	Dust/ Binder Ratio	Gradation, % passing Sieve Size in mm										
							25.0	19.0	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Virgin	19.0	4.8	9.9	0	0	1.12	100	98	87	78	57	45	32	24	12	7	4.8
	12.5	5.7	11.6	0	0	0.86	100	100	98	87	67	50	31	20	9	5	4.3
	9.5	6.3	11.7	0	0	1.03	100	100	100	100	71	53	42	32	18	9	5.3
RAP	19.0	4.9	8.8	0.255	0	1.26	100	100	89	82	64	48	36	26	16	9	4.8
	12.5	5.4	10.5	0.186	0	0.99	100	100	95	89	73	56	42	30	17	9	4.6
	9.5	6.1	12.0	0.246	0	1.10	100	100	100	96	81	65	48	34	16	8	5.7
RAP+RAS	19.0	5.1	9.2	0.208	0.162	1.26	100	98	89	79	60	49	41	33	17	7	5.0
	12.5	5.8	12.3	0.119	0.158	0.96	100	100	94	85	68	56	44	31	15	8	5.3
	9.5	5.7	11.7	0.121	0.180	1.00	100	100	100	98	74	53	38	26	13	7	5.1

Table 11 and Table 12 present the results of binder content and recovered binder properties measured for the recycled materials. Data for the RAP sources are presented in Table 11 and data for the RAS sources are presented in Table 12.

The binder properties for the RAP sources were determined using the procedures for developing a blending chart in the Appendix to AASHTO M323, *Standard Specification for Superpave Volumetric Design*. Following this procedure, the intermediate and low temperature continuous grade temperatures were measured on RTFO test residue without PAV conditioning. The recovered RAP binder properties are similar for the three sources and within the range of the RAP sources tested in WHRP Project 0092-10-06. The average continuous grade for the RAP tested in WHRP Project 0092-10-06 was PG 82.8 (26.9) – 21.8. The average in Table 11 for the four sources used in this project is PG 86.0 (26.2) -21.6.

Table 11. Properties of Recovered RAP Binders.

Property	**Stark Asphalt**	**Mathy Hauser St**	**Payne & Dolan Waukesha**	**Mathy Plant 22**
Experimental Design Mixture Number	1	5 and 6	3 and 4	7
Binder Content, %	4.78	4.78	4.42	4.16
As Recovered High, °C	84.1	87.6	88.9	91.1
RTFO Test High, °C	82.1	85.6	87.4	89.1
Intermediate, °C	25.5	27.1	26.3	25.8
Stiffness Low, °C	-25.1	-23.6	-24.6	-25.2
m-value Low, °C	-22.5	-19.7	-20.9	-23.3
ΔT_{c}, °C	-2.6	-3.9	-4.0	-1.9

The binder properties for the RAS sources were determined using the procedure developed in WHRP Project 0096-10-06. The RAS binder was first recovered in accordance with AASHTO R59, *Standard Practice for Recovery of Asphalt Binder From Solution by Abson Method.* A 30/70 blend of the recovered RAS binder in the PG 52-34 S was prepared and graded in accordance with AASHTO R29, *Standard Practice for Grading or Verifying the Performance Grade (PG) of an Asphalt Binder.* A linear blending chart was then used to determine the extrapolated RAS binder continuous grade. Please note that this approach does not provide the actual grade of the RAS because the properties of RAS blends become highly non-linear at RAS binder ratios exceeding about 0.50 (*20*). However, the RAS properties determined in this manner may be used to evaluate mixtures with RAS binder ratios of 0.30 or less, which is a reasonable limit for mixtures with RAS. The RAS materials supplied for this project are somewhat softer than the RAS sources tested in WHRP Project 0092-10-06. In WHRP Project 0092-10-06, the extrapolated high temperature continuous grade temperature ranged from 110.0 to 126.0 °C; the intermediate continuous grade temperature ranged from 29.3 to 33.6 °C; and the low temperature continuous grade temperature ranged from -4.5 to -10.1 °C. Using the average of the recovered binder data for the RAP and RAS sources in a linear blending chart with the PG 52-34 S binder, the RAS sources will change the intermediate temperature continuous grade temperature 1.3 times faster and the low temperature continuous grade temperature 1.6 times faster than the RAP sources.

Table 12. Properties of Recovered RAS Binders.

Property		**Payne & Dolan Waukesha**	**Mathy Plant 22**
Experimental Design Mixture Number		3 and 4	7
Binder Content, %		29.41	23.63
30/70 Blend of RAS and PG 52-34 S	As Recovered High, °C	70.4	71.6
	RTFO Test High, °C	73.3	72.6
	Intermediate, °C	17.6	17.1
	Stiffness Low, °C	-32.1	-32.7
	m-value Low, °C	-28.8	-30.7
	$\Delta T_{c,}$ °C	-3.3	-2.0
Extrapolated RAS	As Recovered High, °C	108.2	112.2
	RTFO Test High, °C	114.1	111.8
	Intermediate, °C	30.9	29.2
	Stiffness Low, °C	-27.7	-29.7
	m-value Low, °C	-12.9	-19.3
	$\Delta T_{c,}$ °C	-14.8	-10.4

3.3 Plant Mixture Verification Experiment

3.3.1 Experimental Design

The POC modified WHRP Project 0092-14-06 to add a verification experiment using plant mixtures. The objective of this experiment was to compare estimates of cracking resistance obtained from the regression equations developed from the laboratory prepared mixtures experiment with values measured from intermediate temperature SCB testing of plant mixtures. The verification experiment did not include a statistical design. Mixtures were sampled based on availability during the 2015 construction season. Table 13 shows: (1) the 81 cells considered in the experimental design of the laboratory prepared mixtures experiment, (2) the 25 cells that were tested in the laboratory prepared mixtures experiment , and (3) the 16 plant mixtures included in the verification study. The shaded cells identify the cells that were tested in the laboratory prepared mixtures experiment, and the "V" numbers identify the plant mixtures that were included in the verification experiment. The verification experiment included 8 cells not tested during the laboratory prepared mixtures experiment and 5 cells that were tested. The verification experiment also included replicate mixtures in two of the cells.

Table 13. Design Matrix Showing Laboratory Prepared Mixtures and Plant Mixture Verification Mixtures.

Recycle Content	NMAS, mm	PG 52 or 58-34			PG 58-28			PG 64-22		
		S	H	V	S	H	V	S	H	V
Virgin	19.0									
Virgin	12.5									
Virgin	9.5						V1			
RAP	19.0									
RAP	12.5	V2,V3			V4,V5	V6	V7	V8		
RAP	9.5	V9			V10			V11		
RAP+RAS	19.0			V12	V13					
RAP+RAS	12.5				V14					
RAP+RAS	9.5				V15			V16		

Notes:

1. Shaded cells were tested in the laboratory prepared mixtures experiment.
2. "V" numbered mixtures represent plant mixtures used in the field validation experiment.

3.3.2 Test Procedures

A reduced amount of testing was performed on the plant mixtures from the verification experiment. Since the FI was the response that was modeled from the laboratory prepared mixtures experiment, only the SCB tests at 15 °C, 0.5mm/min loading rate, and 25 mm notch depth were conducted. Replicate gyratory specimens were prepared to an air void content of 7.0 ±0.5 percent to produce 4 SCB specimens. The plant mix sample were reheated for 2 hours at 135 °C prior to compaction. The volumetric properties and binder properties used in the FI regression models developed from the laboratory prepared mixtures experiment were obtained from mixture design data submitted by the supplier.

3.3.3 Plant Mixtures

Table 14 summarizes the plant mixtures used in the verification study. This includes information on the supplier, the project where the mixture was used, and pertinent information from the job mix formula needed for estimating the FI of the plant mixture. These mixtures include six different virgin binder grades with low temperature grade from -22 to -34 and AASHTO M332 traffic levels of S, H, and V. They also include a range of design VBE from 9.7 to 12.6 percent. The RAP binder ratio ranges from 0 to 0.226 and the RAS binder ratio ranges from 0 to 0.121.

Table 14. Plant Mixtures Used in the Verification Study.

Mix	Supplier	Project ID	Virgin Binder Grade	Recycle Type	NMAS	Design VBE, Vol %	RAP Binder Ratio	RAS Binder Ratio
V1	Mathy	Eau Claire Drag Strip	PG 58-28 V	None	9.5	12.2	0.000	0.000
V2	Payne and Dolan	1595-09-60	PG 52-34 S	RAP	12.5	11.1	0.123	0.000
V3	Mathy	1197-18-75 & 76	PG 52-34 S	RAP	12.5	11.2	0.226	0.000
V4	Payne and Dolan	3-55-0090-26	PG 58-28 S	RAP	12.5	10.7	0.137	0.000
V5	Mathy	1166-08-72 / 82	PG 58-28 S	RAP	12.5	10.8	0.173	0.000
V6	Mathy	7090-05-65	PG 58-28 H	RAP	12.5	11.2	0.123	0.000
V7	Mathy	8010-01-75 & 78	PG 58-28 V	RAP	12.5	12.0	0.140	0.000
V8	Payne and Dolan	1300-13-70	PG 64-22 S	RAP	12.5	10.9	0.226	0.000
V9	Payne and Dolan	1595-09-60	PG 52-34 S	RAP	9.5	12.3	0.098	0.000
V10	Payne and Dolan	5300-04-79	PG 58-28 S	RAP	9.5	11.9	0.172	0.000
V11	Payne and Dolan	1300-13-70	PG 64-22 S	RAP	9.5	12.1	0.203	0.000
V12	Mathy	1166-12-74	PG 52-34 V	RAP + RAS	19	10.1	0.219	0.107
V13	Payne and Dolan	1090-19-72	PG 58-28 S	RAP + RAS	19	9.7	0.210	0.121
V14	Payne and Dolan	1300-13-70	PG 58-28 S	RAP + RAS	12.5	10.8	0.109	0.117
V15	Payne and Dolan	1300-13-70	PG 58-28 S	RAP + RAS	9.5	12.6	0.129	0.102
V16	Payne and Dolan	40029	PG 64-22 S	RAP + RAS	9.5	12.2	0.133	0.107

Chapter 4 Test Results and Analysis

4.1 Laboratory Prepared Mixtures Experiment

4.1.1 Test Results

The intermediate temperature SCB results are summarized in Table 15 for the tests on the short-term oven conditioned mixtures and Table 16 for the tests on the long-term oven conditioned mixtures. These tables include the following properties and parameters:

1. **Effective Volume of Binder, VBE.** The VBE was calculated using the aggregate bulk specific gravity values determined from the effective specific gravity of the prepared specimens using the difference between the aggregate bulk specific gravity and effective specific gravity reported in the mixture design submittals.
2. **Apparent Film Thickness, AFT in µm.** The AFT was calculated by dividing the effective volume of binder by the surface area of the aggregates. The surface area of the aggregates was calculated from the aggregate gradation using surface area factors (*9*).
3. **Air Void Content, VTM.** The reported air voids are the average for the 3 gyratory specimens used to prepare the SCB test specimens.
4. **Stiffness Index, SI.** The stiffness index is the average slope of the load-displacement curve for 25 mm notch depth specimens at 50 percent of the peak load. The stiffness index was calculated as the derivative of a polynomial fit to the load-displacement curve at 50 percent of the peak load. The average coefficient of variation for the SI was 6.9 percent.
5. **Critical Strain Energy Release Rate, J_c in kJ/m^2.** J_c was calculated as the average difference in fracture energy to the peak load between 25 and 38 mm notch depths divided by the difference in the notch depths in m. The three tests of the center point mixture provide a measure of the variability of J_c. The coefficient of variation averaged over the short-term and long-term conditioned tests was 26.4 percent.

Table 15. Intermediate SCB Results for Short-Term Conditioned Mixtures.

Run	NMAS, mm	Recycle	Mix #	Low PG Grade	Recovery, %	VBE, %	AFT, µm	VTM, %	SI, N/mm	J_c, kJ/m^2	FE_{peak}, kJ/m^2	FE_{total}, kJ/m^2	FI
1	19	Virgin	8	-28.9	34.6	9.9	8.3	6.9	500	0.58	0.27	0.76	6.75
2	9.5	Virgin	9	-28.9	34.6	11.7	8.3	6.9	585	0.49	0.26	0.66	10.63
3	19	RAP+RAS	3	-28.9	34.6	9.2	6.8	7.1	724	0.47	0.21	0.50	2.60
4	9.5	RAP+RAS	4	-28.9	34.6	11.7	9.4	7.0	807	0.63	0.28	0.71	3.96
5	12.5	RAP	6	-25.6	0	10.5	7.7	7.0	913	0.51	0.30	0.72	3.12
6	12.5	RAP	6	-34.0	0	10.5	7.7	7.1	383	0.17	0.22	0.49	5.63
7	12.5	RAP	6	-24.3	79.1	10.5	7.7	6.9	1141	0.62	0.39	0.95	3.44
8	12.5	RAP	6	-36.2	75.1	10.5	7.7	6.9	449	0.23	0.25	0.58	9.14
9	12.5	RAP	6	-28.9	34.6	10.5	7.7	7.0	819	0.52	0.33	0.76	4.01
10	19	RAP	5	-29.0	0	8.8	6.8	6.8	619	0.27	0.20	0.51	3.70
11	9.5	RAP	1	-29.0	0	12.0	8.1	7.2	626	0.33	0.68	0.86	7.67
12	19	RAP	5	-31.8	86.0	8.8	6.8	6.9	705	0.30	0.27	0.66	4.76
13	9.5	RAP	1	-31.8	86.0	12.0	8.1	7.0	720	0.80	0.44	1.07	9.93
14	12.5	Virgin	2	-24.2	49.4	11.6	11.0	6.9	823	0.90	0.40	0.95	6.83
15	12.5	RAP+RAS	7	-24.2	49.4	12.3	9.1	6.9	817	0.59	0.29	0.80	5.56
16	12.5	Virgin	2	-36.4	59.6	11.6	11.0	7.0	322	0.38	0.19	0.49	11.43
17	12.5	RAP+RAS	7	-36.4	59.6	12.3	9.1	6.9	385	0.44	0.22	0.53	9.98
18	12.5	RAP	6	-28.9	34.6	10.5	7.7	7.0	870	0.56	0.36	0.81	4.23
19	12.5	Virgin	2	-29.0	0	11.6	11.0	6.5	528	0.44	0.28	0.68	7.47
20	12.5	RAP+RAS	7	-29.0	0	12.3	9.1	6.9	568	0.33	0.25	0.65	7.42
21	12.5	Virgin	2	-31.8	86.0	11.6	11.0	6.8	602	0.93	0.45	1.04	14.86
22	12.5	RAP+RAS	7	-31.8	86.0	12.3	9.1	6.9	643	0.73	0.35	0.85	8.96
23	19	RAP	5	-24.2	49.4	8.8	6.8	7.0	970	0.51	0.28	0.68	2.42
24	9.5	RAP	1	-24.2	49.4	12.0	8.1	7.2	965	0.52	0.33	0.89	4.53
25	19	RAP	5	-36.4	59.6	8.8	6.8	7.0	522	0.49	0.22	0.53	5.61
26	9.5	RAP	1	-36.4	59.6	12.0	8.1	7.1	453	0.50	0.28	0.66	11.77
27	12.5	RAP	6	-28.9	34.6	10.5	7.7	7.0	882	0.88	0.39	0.87	4.46

Table 16. Intermediate SCB Results for Long-Term Conditioned Mixtures.

Run	NMAS, mm	Recycle	Mix #	Low PG Grade	Recovery, %	VBE, %	AFT, µm	VTM, %	SI, N/mm	J_c, kJ/m^2	FE_{peak}, kJ/m^2	FE_{total}, kJ/m^2	FI
1	19	Virgin	8	-28.9	34.6	9.9	8.3	6.4	717	0.61	0.28	0.72	3.42
2	9.5	Virgin	9	-28.9	34.6	11.1	8.3	7.0	743	0.39	0.24	0.59	5.76
3	19	RAP+RAS	3	-28.9	34.6	9.2	6.8	7.4	883	0.36	0.17	0.43	1.19
4	9.5	RAP+RAS	4	-28.9	34.6	11.7	9.4	7.0	912	0.32	0.19	0.45	1.25
5	12.5	RAP	6	-25.6	0	10.5	7.7	7.0	1066	0.38	0.26	0.61	1.45
6	12.5	RAP	6	-34.0	0	10.5	7.7	7.1	595	0.49	0.26	0.55	4.17
7	12.5	RAP	6	-24.3	79.1	10.5	7.7	6.9	1372	0.50	0.28	0.65	1.08
8	12.5	RAP	6	-36.2	75.1	10.5	7.7	6.9	658	0.58	0.29	0.66	4.63
9	12.5	RAP	6	-28.9	34.6	10.5	7.7	6.9	1117	0.42	0.28	0.67	1.78
10	19	RAP	5	-29.0	0	8.8	6.8	7.1	706	0.30	0.17	0.44	2.03
11	9.5	RAP	1	-29.0	0	12.0	8.1	7.4	747	0.51	0.30	0.69	4.12
12	19	RAP	5	-31.8	86.0	8.8	6.8	7.1	928	0.62	0.32	0.78	3.42
13	9.5	RAP	1	-31.8	86.0	12.0	8.1	6.9	958	0.81	0.49	1.16	6.98
14	12.5	Virgin	2	-24.2	49.4	11.6	11.0	6.8	1212	0.97	0.41	0.89	2.51
15	12.5	RAP+RAS	7	-24.2	49.4	12.3	9.1	7.0	897	0.51	0.23	0.57	2.12
16	12.5	Virgin	2	-36.4	59.6	11.6	11.0	6.9	425	0.30	0.20	0.50	7.54
17	12.5	RAP+RAS	7	-36.4	59.6	12.3	9.1	7.1	548	0.46	0.22	0.53	4.99
18	12.5	RAP	6	-28.9	34.6	10.5	7.7	6.8	1002	0.38	0.27	0.63	2.10
19	12.5	Virgin	2	-29.0	0	11.6	11.0	6.5	740	0.78	0.37	0.96	6.86
20	12.5	RAP+RAS	7	-29.0	0	12.3	9.1	7.0	704	0.26	0.18	0.46	2.31
21	12.5	Virgin	2	-31.8	86.0	11.6	11.0	7.0	828	1.03	0.44	1.12	9.62
22	12.5	RAP+RAS	7	-31.8	86.0	12.3	9.1	6.9	765	0.62	0.30	0.73	4.79
23	19	RAP	5	-24.2	49.4	8.8	6.8	7.1	1132	0.57	0.23	0.61	1.39
24	9.5	RAP	1	-24.2	49.4	12.0	8.1	6.9	1239	0.60	0.33	0.77	2.02
25	19	RAP	5	-36.4	59.6	8.8	6.8	7.1	652	0.44	0.21	0.52	3.40
26	9.5	RAP	1	-36.4	59.6	12.0	8.1	6.9	603	0.48	0.29	0.69	6.48
27	12.5	RAP	6	-28.9	34.6	10.5	7.7	6.0	938	0.57	0.30	0.65	2.12

6. **Fracture Energy to Peak, FE_{peak} in kJ/m^2.** The reported FE_{peak} is the fracture energy to the peak load for the 25 mm notch depth. The fracture energy was calculated by fitting the load-displacement curve with a polynomial and then integrating to the peak load. The average of coefficient of variation for the FE_{peak} was 13.4 percent.
7. **Total Fracture Energy FE_{total} in kJ/ m^2.** The reported FE_{total} is the fracture energy to 10 percent of the peak load for the 25 mm notch depth. The fracture energy was calculated by fitting the load-displacement curve with a polynomial and then integrating to a post peak load of 10 percent of the peak load. The average of coefficient of variation for the FE_{total} was 11.1 percent.
8. **Flexibility Index, FI.** FI was calculated using the 25 mm notch depth data as 10,000 times the FE_{total} divided by the post peak slope at the inflection point in N/mm. The post peak inflection and its slope were determined by fitting the load-displacement curve with a polynomial, taking the derivative to determine the slope and taking the second derivative to find the inflection point. The average of coefficient of variation for the FI was 18.3 percent.

The recovered binder properties are summarized in Table 17 for the tests on the short-term oven conditioned mixtures and Table 18 for the tests on the long-term oven conditioned mixtures. These tables include the following properties and parameters:

1. **Continuous Performance Grade Temperatures, T_{high}, T_{int}, T_{lowS}, T_{lowm}.** These are the temperatures where the recovered binder meets the AASHTO M320 criteria of 2.20 kPa for T_{high}; 5000 kPa for T_{int}, 300 MPa for T_{lowS}, and 0.300 for $T_{lowm.}$
2. **ΔT_C Parameter.** ΔT_C was calculated as T_{lowS} minus T_{lowm}. Values less than -5.0 °C indicate that cracking is likely (*76*). The effect of recycle content and conditioning on ΔT_C are clearly evident. Virgin mixtures had average ΔT_C of 1.67 after short-term conditioning reducing to 0.50 after long-term conditioning. Mixtures with RAP had average ΔT_C of 0.79 after short-term conditioning reducing to -0.31 after long-term conditioning. Finally, mixtures with RAP and RAS had average ΔT_C of -0.63 after short-term conditioning reducing to -2.60 after long-term conditioning.

3. **Glover-Rowe Parameter, G-R.** The G-R parameter was calculated using Equation 7. The Christensen-Anderson master curve equation *(78)* was fit to DSR frequency sweep data collected at 10, 22, and 34 °C over the frequency range of 0.1 to 100 rad/sec to determine the G* and δ values at 15 °C, 0.005 rad/sec for Equation 7. Recommended limits for the Glover-Rowe parameter are 180 kPa for the onset of damage, and 600 kPa for significant cracking (*77*). The Glover-Rowe parameter and ΔT_C are highly correlated as shown in Figure 6 using the of the average results for the virgin, RAP, and RAP+RAS mixtures.
4. **G* at 19 °C, 10 rad/sec.** This parameter was calculated from the master curve and used to compute aging indices.

Table 17. Recovered Binder Results for Short-Term Conditioned Mixtures.

Run	NMAS, mm	Recycle	Mix #	Low PG Grade	Recovery, %	T_{high}, °C	T_{int}, °C	T_{lowS}, °C	T_{lowm}, °C	ΔT_c, °C	G-R, kPa	G* @ 19 °C, 10 rad/sec, kPa
1	19	Virgin	8	-28.9	34.6	76.6	16.2	-31.4	-32.7	1.3	22.3	4439
2	9.5	Virgin	9	-28.9	34.6	74.9	15.8	-32.2	-33.0	0.8	21.9	4557
3	19	RAP+RAS	3	-28.9	34.6	86.2	21.0	-28.8	-27.0	-1.8	161.8	10126
4	9.5	RAP+RAS	4	-28.9	34.6	87.6	20.5	-29.2	-27.7	-1.5	162.1	9538
5	12.5	RAP	6	-25.6	0	75.6	22.3	-26.9	-27.9	1.0	54.4	10753
6	12.5	RAP	6	-34.0	0	64.7	14.2	-33.4	-36.8	3.4	2.5	2397
7	12.5	RAP	6	-24.3	79.1	79.2	22.5	-25.3	-26.4	1.1	70.4	11709
8	12.5	RAP	6	-36.2	75.1	70.9	11.6	-35.0	-36.0	1.0	4.5	2313
9	12.5	RAP	6	-28.9	34.6	77.2	19.0	-30.3	-30.9	0.6	21.9	5196
10	19	RAP	5	-29.0	0	70.7	18.1	-29.7	-29.8	0.1	21.8	6159
11	9.5	RAP	1	-29.0	0	69.2	17.1	-30.1	-30.3	0.2	15.3	5218
12	19	RAP	5	-31.8	86.0	81.0	17.0	-31.0	-30.5	-0.5	46.1	5929
13	9.5	RAP	1	-31.8	86.0	79.7	16.1	-31.7	-31.2	-0.5	25.3	4718
14	12.5	Virgin	2	-24.2	49.4	75.0	20.1	-26.0	-28.5	2.5	24.0	8357
15	12.5	RAP+RAS	7	-24.2	49.4	84.9	22.8	-26.5	-26.1	-0.4	168.8	12856
16	12.5	Virgin	2	-36.4	59.6	69.7	8.1	-37.4	-39.9	2.5	3.6	1301
17	12.5	RAP+RAS	7	-36.4	59.6	80.8	13.8	-34.4	-34.4	0.0	47.5	3871
18	12.5	RAP	6	-28.9	34.6	77.2	19.0	-30.3	-30.9	0.6	21.9	5196
19	12.5	Virgin	2	-29.0	0	65.3	14.8	-32.2	-33.5	1.3	6.4	3724
20	12.5	RAP+RAS	7	-29.0	0	75.9	18.2	-29.9	-30.2	0.3	57.3	6781
21	12.5	Virgin	2	-31.8	86.0	78.7	13.0	-34.6	-36.2	1.6	18.0	2847
22	12.5	RAP+RAS	7	-31.8	86.0	80.8	17.6	-32.3	-31.9	-0.4	97.5	6263
23	19	RAP	5	-24.2	49.4	78.2	23.0	-25.0	-25.9	0.9	115.5	15242
24	9.5	RAP	1	-24.2	49.4	78.8	23.2	-25.4	-26.1	0.7	83.6	13180
25	19	RAP	5	-36.4	59.6	73.1	13.7	-33.8	-35.1	1.3	12.3	3275
26	9.5	RAP	1	-36.4	59.6	72.0	14.4	-34.7	-35.7	1.3	14.5	2881
27	12.5	RAP	6	-28.9	34.6	77.2	19.0	-30.3	-30.9	0.6	21.9	5196

Table 18. Recovered Binder SCB Results for Long-Term Conditioned Mixtures.

Run	NMAS, mm	Recycle	Mix #	Low PG Grade	Recovery, %	T_{high}, °C	T_{int}, °C	T_{lowS}, °C	T_{lowm}, °C	ΔT_c, °C	G-R, kPa	G* @ 19 °C, 10 rad/sec, kPa
1	19	Virgin	8	-28.9	34.6	82.5	19.7	-29.1	-29.8	0.7	58.7	7093
2	9.5	Virgin	9	-28.9	34.6	82.5	18.7	-30.4	-30.5	0.1	71.8	8093
3	19	RAP+RAS	3	-28.9	34.6	90.6	23.0	-28.8	-25.1	-3.7	296.9	12738
4	9.5	RAP+RAS	4	-28.9	34.6	90.7	21.7	-29.0	-25.2	-3.8	263.2	11104
5	12.5	RAP	6	-25.6	0	79.4	23.5	-25.7	-24.8	-0.9	121.8	13560
6	12.5	RAP	6	-34.0	0	68.9	16.6	-32.7	-35.0	2.3	7.7	3645
7	12.5	RAP	6	-24.3	79.1	83.4	23.6	-25.8	-25.6	-0.2	139.1	13853
8	12.5	RAP	6	-36.2	75.1	75.5	14.8	-33.4	-34.2	0.8	12.3	3747
9	12.5	RAP	6	-28.9	34.6	82.4	23.3	-29.9	-28.9	-1.0	76.0	8711
10	19	RAP	5	-29.0	0	75.2	20.1	-28.1	-27.5	-0.6	48.4	9141
11	9.5	RAP	1	-29.0	0	73.8	19.5	-29.2	-28.9	-0.3	47.4	7591
12	19	RAP	5	-31.8	86.0	86.0	19.8	-29.2	-27.1	-2.1	116.3	9260
13	9.5	RAP	1	-31.8	86.0	83.7	17.9	-31.4	-31.7	0.3	50.4	6388
14	12.5	Virgin	2	-24.2	49.4	80.9	23.2	-24.4	-25.1	0.7	95.8	12902
15	12.5	RAP+RAS	7	-24.2	49.4	91.3	25.7	-25.0	-23.1	-1.9	430.3	17853
16	12.5	Virgin	2	-36.4	59.6	74.8	10.2	-37.2	-38.1	0.9	10.2	2098
17	12.5	RAP+RAS	7	-36.4	59.6	85.9	16.1	-33.8	-32.3	-1.5	99.6	5546
18	12.5	RAP	6	-28.9	34.6	82.4	23.3	-29.9	-28.9	-1.0	76.0	8711
19	12.5	Virgin	2	-29.0	0	70.5	18.2	-30.5	-30.2	-0.3	21.7	6064
20	12.5	RAP+RAS	7	-29.0	0	81.3	20.2	-30.0	-27.5	-2.5	161.5	9348
21	12.5	Virgin	2	-31.8	86.0	85.3	16.1	-32.2	-33.1	0.9	44.5	4851
22	12.5	RAP+RAS	7	-31.8	86.0	93.4	20.3	-30.6	-28.4	-2.2	241.5	9560
23	19	RAP	5	-24.2	49.4	84.3	26.2	-23.5	-23.1	-0.4	241.5	18738
24	9.5	RAP	1	-24.2	49.4	81.3	25.0	-25.1	-25.3	0.2	189.7	16488
25	19	RAP	5	-36.4	59.6	77.7	16.1	-32.8	-32.1	-0.7	34.1	4997
26	9.5	RAP	1	-36.4	59.6	77.3	14.5	-33.8	-33.7	-0.1	30.9	3967
27	12.5	RAP	6	-28.9	34.6	77.2	19.0	-30.3	-30.9	0.6	21.9	8711

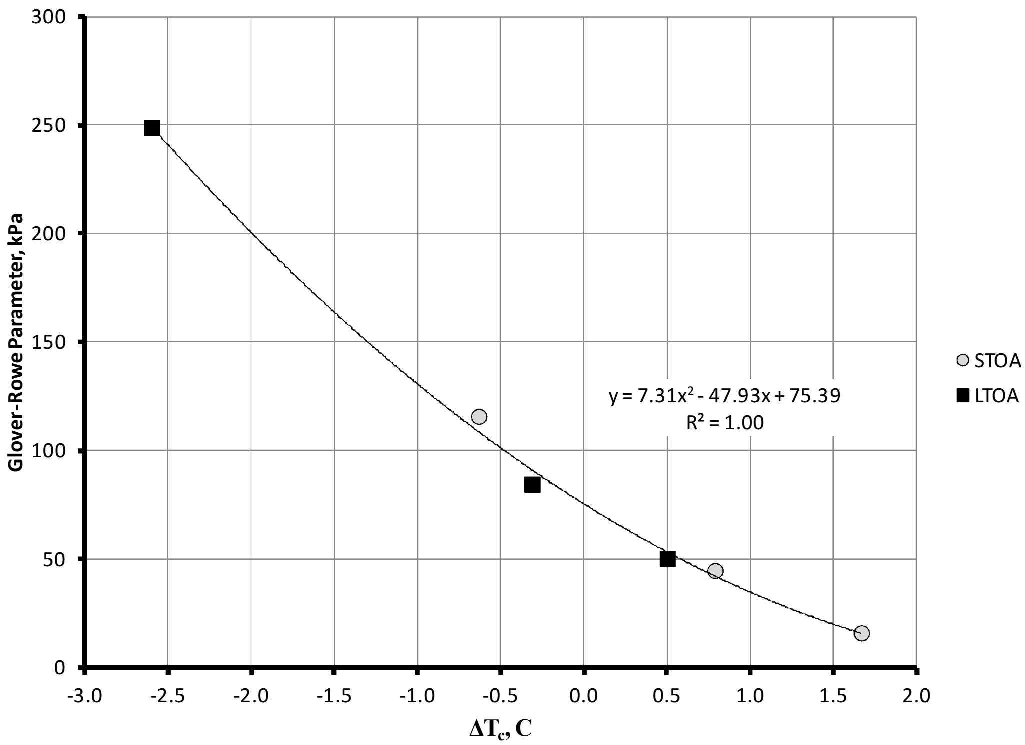


Figure 6. Comparison of Glover-Rowe and ΔT_c Parameters Using Average Recovered Binder Data.

The recovered binder data provided the opportunity to compare short-term oven mixture conditioning to RTFO test binder conditioning and long-term oven mixture conditioning to PAV binder conditioning. The experimental design included 6 virgin mixtures made with 5 different binders. Table 19 compares T_{high} from binders recovered from the short-term oven conditioned mixtures with T_{high} from RTFO test conditioning of the binder for the 6 virgin mixtures. This comparison shows that short-term oven conditioning for 4 hours at 135 °C is somewhat more severe than RTFO test conditioning. The paired t-test summarized in Table 19 shows that the difference in the high temperature grade temperature of 3.6 °C is statistically significant. Table 20 summarizes similar comparisons for T_{int} and T_{lowS} and T_{lowm} between PAV binder conditioning and long-term oven mixture conditioning. This table shows that PAV and long-term oven mixture conditioning produce similar intermediate and low temperature stiffnesses. However, the low temperature continuous grade temperature based on the m-value is on average 1 °C lower for long-term oven mixture conditioning compared to PAV binder conditioning.

Table 19. Comparison of T_{high} Between RTFO Test Binder and Short-Term Oven Mixture Conditioning.

Mix	Binder	T_{high}, °C		
		RTFO Test	STOA	STOA-RTFO Test
8	58-28 V	69.9	76.6	6.7
9	58-28 V	69.9	74.9	5.0
2	64-22 E	78.4	75.0	-3.4
2	58-34 V	65.6	69.7	4.1
2	58-28 S	59.7	65.3	5.6
2	58-28 E	75.1	78.7	3.6
Average Difference				3.60
Standard Deviation of Difference				3.60
Paired t				2.449
p-value				0.029
Statistically Significant ?				Yes

Table 20. Comparison of T_{int}, T_{lowS}, and T_{lowm} Between PAV Binder and Long-Term Oven Mixture Conditioning.

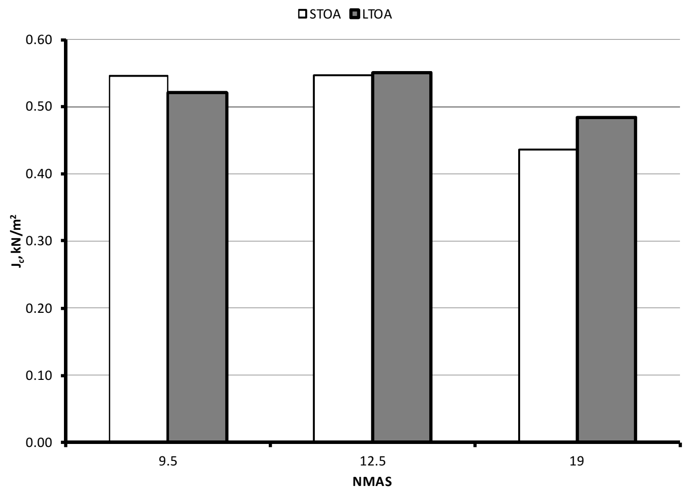
Mix	Binder	T_{int}, °C			T_{lowS}, °C			T_{lowm}, °C		
		PAV	LTOA	PAV-LTOA	PAV	LTOA	PAV-LTOA	PAV	LTOA	PAV-LTOA
8	58-28 V	19.1	19.7	-0.6	-29.6	-29.1	-0.5	-28.9	-29.8	0.9
9	58-28 V	19.1	18.7	0.4	-29.6	-30.4	0.8	-28.9	-30.5	1.6
2	64-22 E	22.8	23.2	-0.4	-24.2	-24.4	0.2	-25.1	-25.1	0.0
2	58-34 V	13.1	10.2	2.9	-36.4	-37.2	0.8	-36.9	-38.1	1.2
2	58-28 S	20.2	18.2	2.0	-29.8	-30.5	0.7	-29.0	-30.2	1.2
2	58-28 E	15.8	16.1	-0.3	-32.0	-32.2	0.2	-31.8	-33.1	1.3
Average Difference				0.67			0.37			1.03
Standard Deviation of Difference				1.45			0.51			0.55
Paired t				1.126			1.766			4.571
p-value				0.156			0.069			0.003
Statistically Significant ?				No			No			Yes

4.1.2 Preliminary Analysis

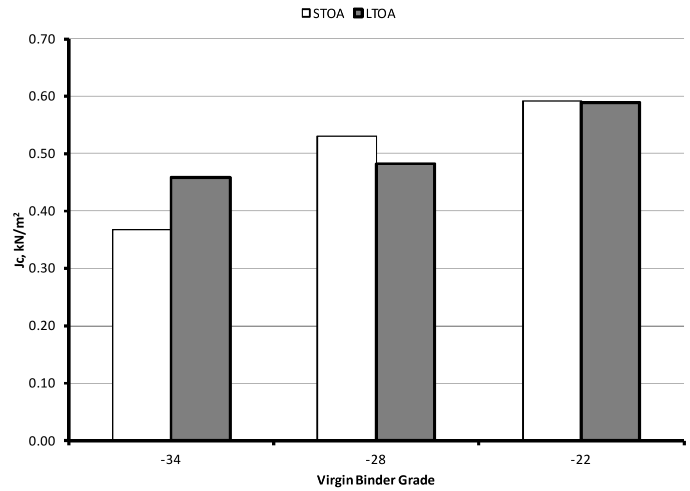
4.1.2.1 Intermediate SCB Parameters

The first analysis that was conducted was graphical analysis of the intermediate SCB and recovered binder test results to evaluate the rationality of the trends and identify possible relationships for more detailed statistical analysis. Recall, the primary experimental variables were: VBE varied by nominal maximum aggregate size, low temperature performance grade of the virgin binder, recycled binder content, and polymer content of the virgin binder varied by the AASHTO M332 traffic level. The average effect of the primary experimental variables are shown in Figure 7 for the critical strain energy release rate, J_c, and Figure 8 for the flexibility index, FI. These two intermediate temperature SCB parameters have been related to cracking resistance and show somewhat different effects as discussed below:

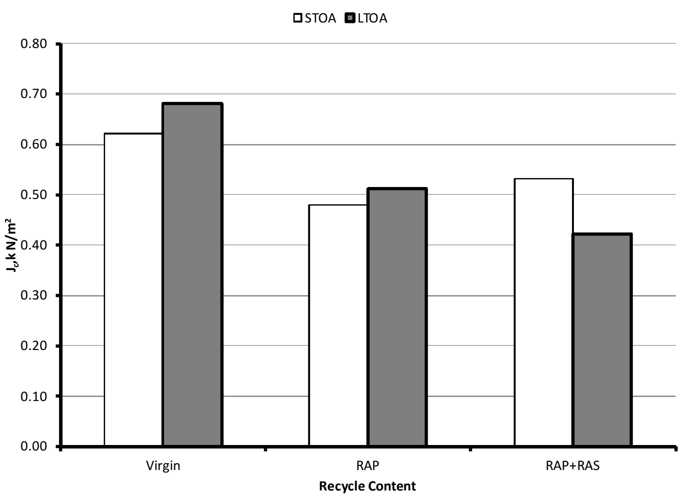
1. **Aging.** Figure 7 shows the critical strain energy release rate to be relatively insensitive to laboratory conditioning implying that the cracking resistance of asphalt mixtures does not change significantly on aging. On the other hand, Figure 8 shows the flexibility index to be quite sensitive to laboratory conditioning with values for long-term oven conditioned mixtures being approximately one-half of those for short-term conditioned mixtures. This implies a decrease in the resistance to cracking with aging which is in line with engineering intuition.
2. **VBE.** Both intermediate temperature SCB parameters show an increase in cracking resistance with decreasing nominal maximum aggregate size. In this experiment, nominal maximum aggregate size was the method by which the VBE of the mixture was changed. Comparing Figure 7a with Figure 8a, the flexibility index is more sensitive to changes in VBE as varied by nominal maximum aggregate size. As discussed in Chapter 2, much research has shown that increasing VBE significantly improves the cracking resistance of asphalt concrete mixtures.
3. **Low Temperature Performance Grade.** Figure 7 shows an increase in the critical strain energy release rate for mixtures using virgin binders with higher low temperature grades, while Figure 8 shows a decrease in the flexibility index for mixtures using virgin binders with higher low temperature grades. The trend for the flexibility index is in line with engineering intuition, particularly for mixtures with recycled binders. Seventy eight percent the mixtures included in the experiment had recycled binder. Current practice is to use softer binders to improve the cracking resistance of these mixtures.



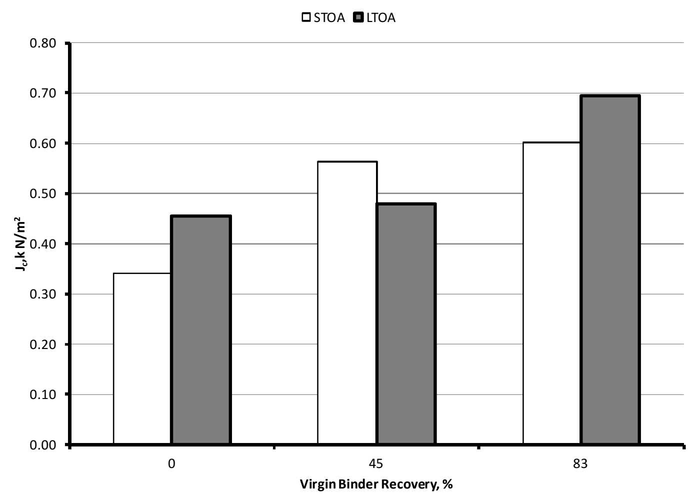
a. VBE.



b. Low Temperature Performance Grade.

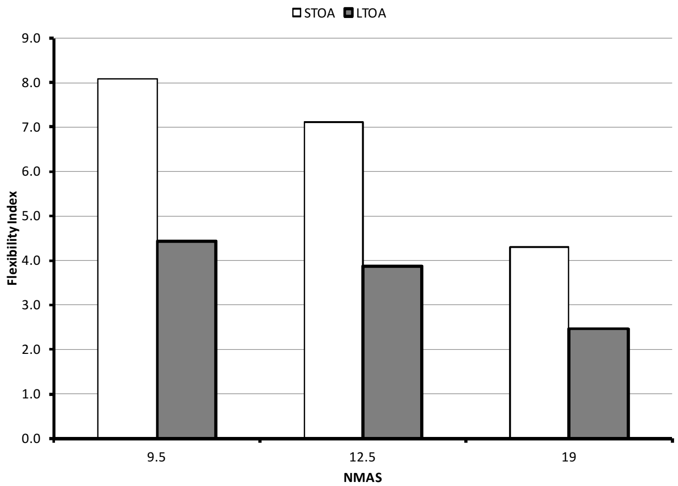


c. Recycled Binder Content.

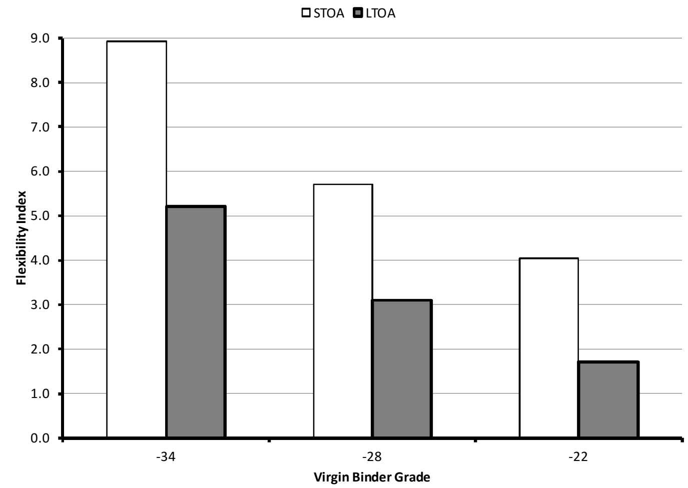


d. Polymer Modification.

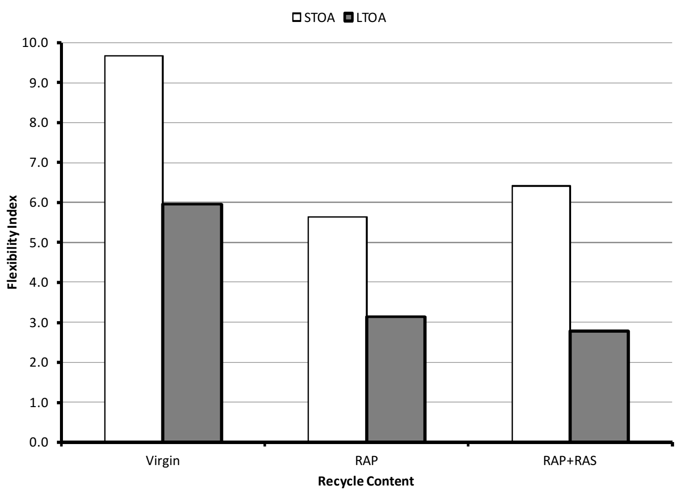
Figure 7. Effect of Primary Experimental Variables on Critical Strain Energy Release Rate, J_c,



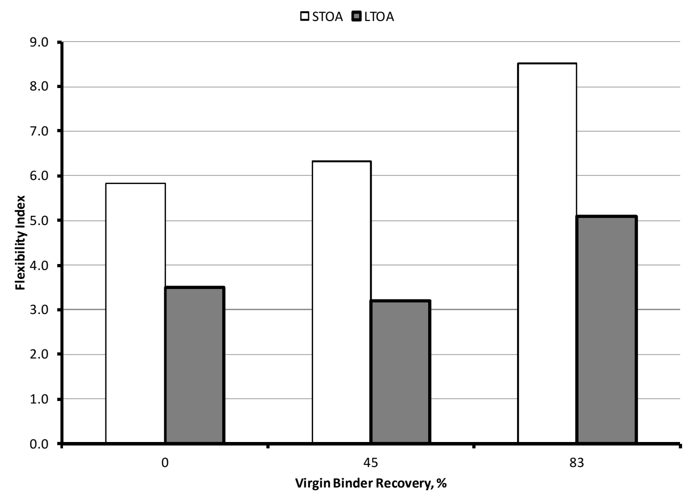
a. VBE.



b. Low Temperature Performance Grade.



c. Recycled Binder Content.



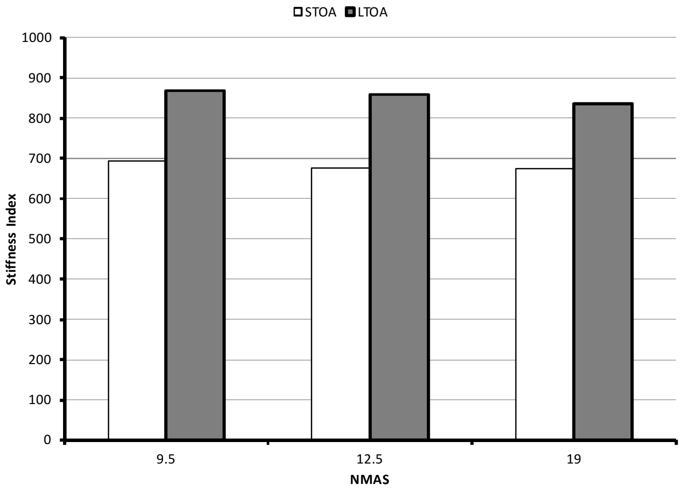
d. Polymer Modification.

Figure 8. Effect of Primary Experimental Variables on Flexibility Index, FI.

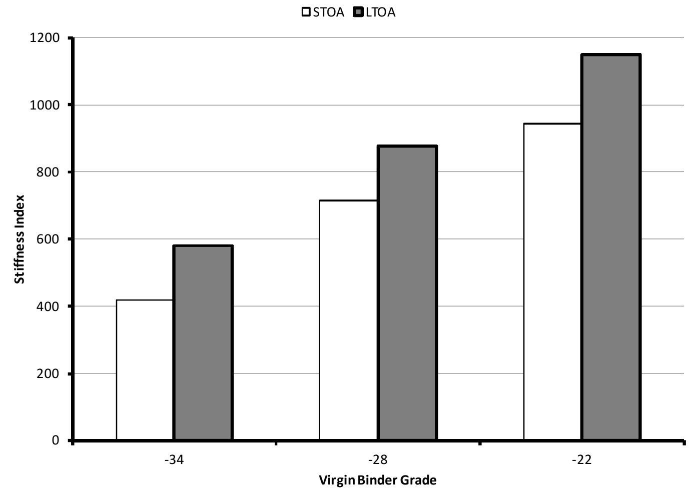
4. **Recycled Binder Content**. Both intermediate temperature SCB parameters show a decrease in cracking resistance for mixtures with higher amounts of recycled binder, which is in line with engineering intuition. Comparing Figure 7c with Figure 8c, it appears that the flexibility index is somewhat more sensitive than the critical strain energy release rate to the amount of recycled binder in the mixture.
5. **Polymer Modification.** Both intermediate SCB parameters show an improvement in cracking resistance with increased modification as measured by the percent recovery from AAHTO T350.

Figure 9 shows the effect of the primary experimental variables and laboratory conditioning on the stiffness index. This figure shows that the stiffness index is sensitive to laboratory conditioning, low temperature grade of the virgin binder, recycled binder content, and polymer modification, increasing with each of these factors. Figure 9a shows the stiffness index is relatively insensitive to the VBE of the mixture as varied by the nominal maximum aggregate size. The sensitivity of the stiffness index to the properties of the binder in the mixture is in agreement with other measures of mixture stiffness such as the dynamic modulus *(55)*.

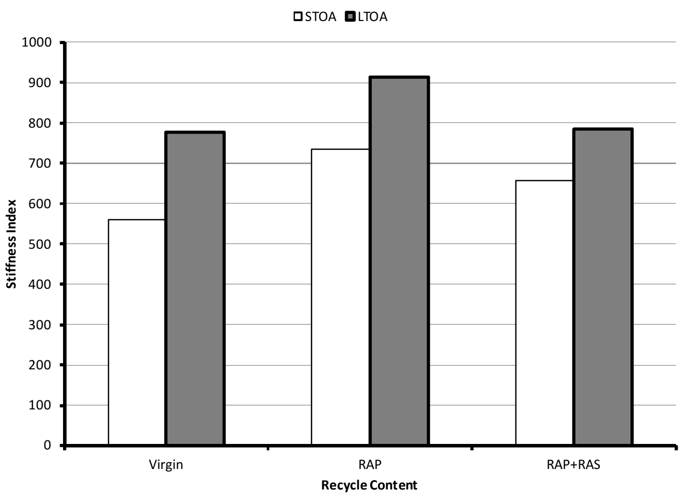
Finally, Figure 10 shows the relationship between the stiffness index and the flexibility index from the SCB testing. This figure shows that although the flexibility index generally decreases with increasing mixture stiffness, it is significantly affected by other variables that were included in the experiment. At a stiffness index of 700 N/mm, the flexibility index ranges from 2 to 10 which is approximately 60 percent of the overall range of the flexibility index data.



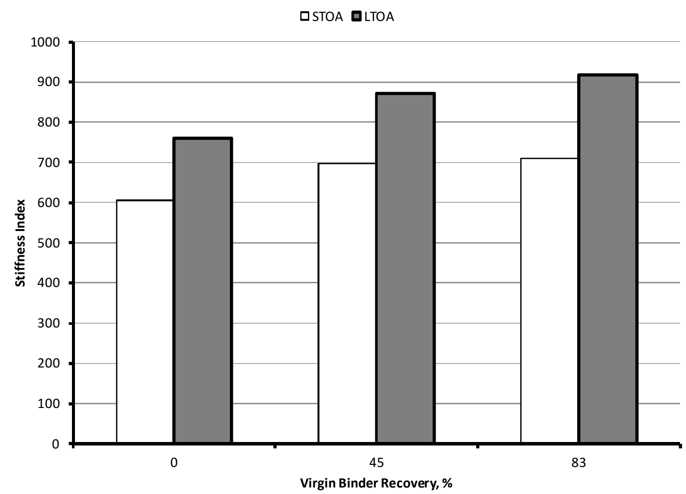
a. VBE.



b. Low Temperature Performance Grade.



c. Recycled Binder Content.



d. Polymer Modification.

Figure 9. Effect of Primary Experimental Variables on Stiffness Index, SI.

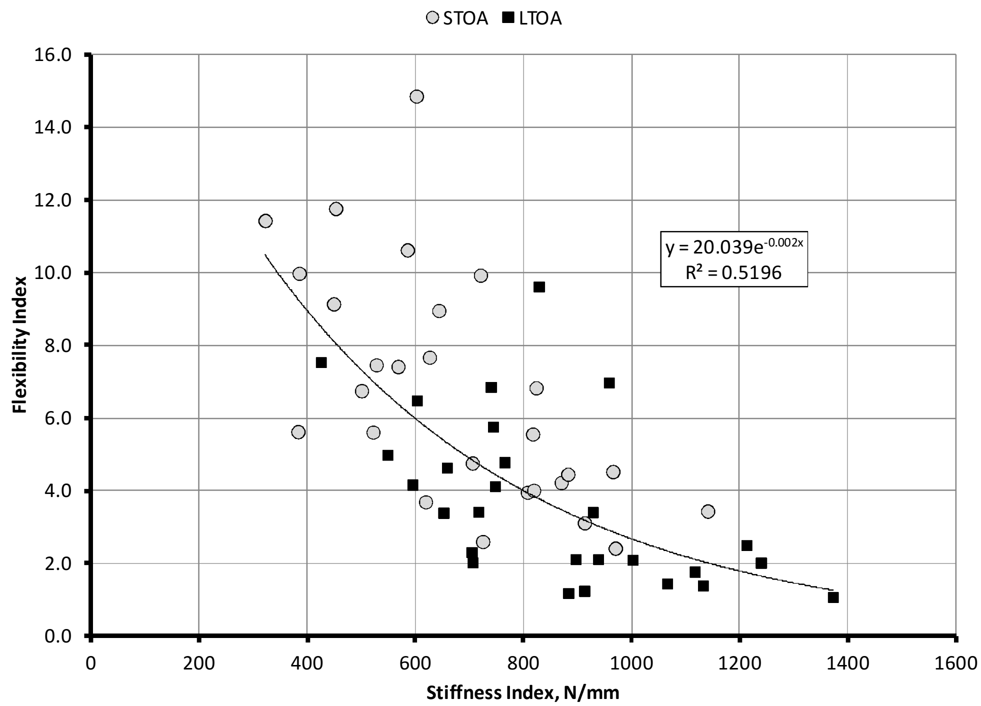


Figure 10. Relationship Between SCB Stiffness Index and SCB Flexibility Index.

4.1.2.2 Recovered Binder Properties

There were two reasons to include the recovered binder testing in the laboratory prepared mixtures experiment. The first, which is discussed in this section, was to evaluate possible relationships between the recovered binder properties and the cracking resistance as measured by the intermediate SCB test. The second, which is discussed in the next section, was to evaluate the effect of the primary experimental variables on changes in binder properties after long-term oven conditioning.

As expected, one of the best relationships was between the stiffness index measured in the intermediate SCB test and the intermediate temperature continuous grade temperature of the recovered binder. This relationship is shown in Figure 11 and reflects the well known fact that the stiffness of an asphalt concrete mixture is related to the stiffness of the binder in the mixture. There was also a similar relationship between the stiffness index and the low temperature grade as shown in Figure 12. Relationships between the SCB stiffness index and other binder parameters were poorer than shown in Figure 11 and Figure 12.

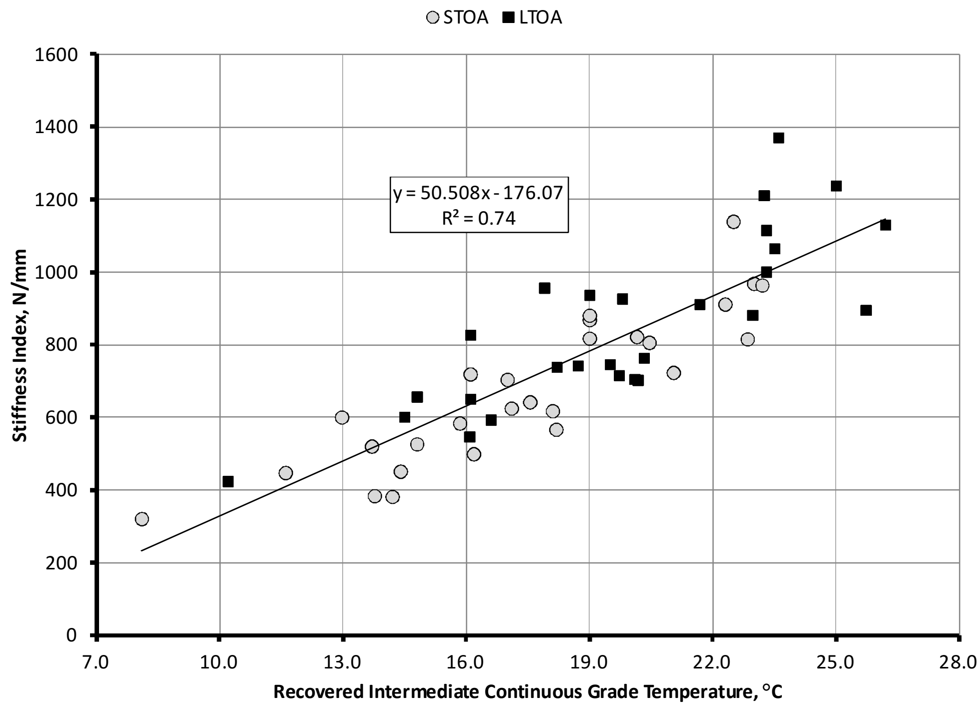


Figure 11. Relationship Between SCB Stiffness Index and Continuous Intermediate Temperature Grade of the Binder in the SCB Specimens.

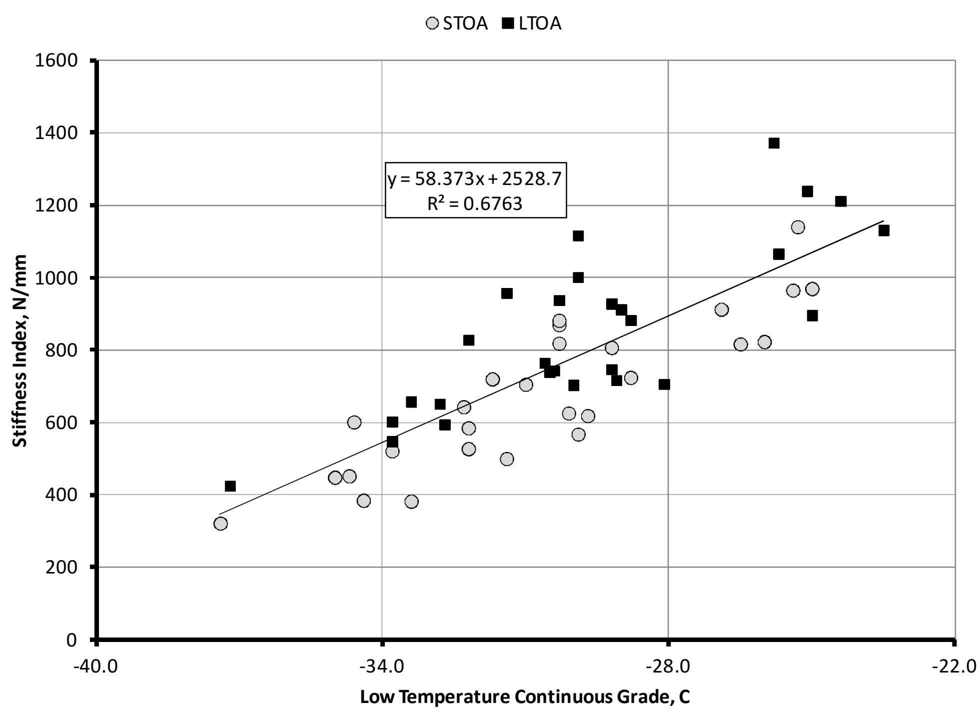


Figure 12. Relationship Between SCB Stiffness Index and Continuous Low Temperature Grade of the Binder in the SCB Specimens.

There was also a relationship between the flexibility index and the intermediate temperature continuous grade temperature as shown in Figure 13, although it is somewhat poorer than that shown in Figure 11 for the stiffness index. Relationships between flexibility index and other binder parameters including: (1) high temperature continuous grade, (2) low temperature continuous grade, (3) the Glover-Rowe parameter, and (4) the ΔT_c parameter were much poorer than Figure 13 for the intermediate temperature continuous grade. Figure 11 and Figure 13 confirm that binder stiffness is an important component of mixture response, but other factors included in the experiment are also important.

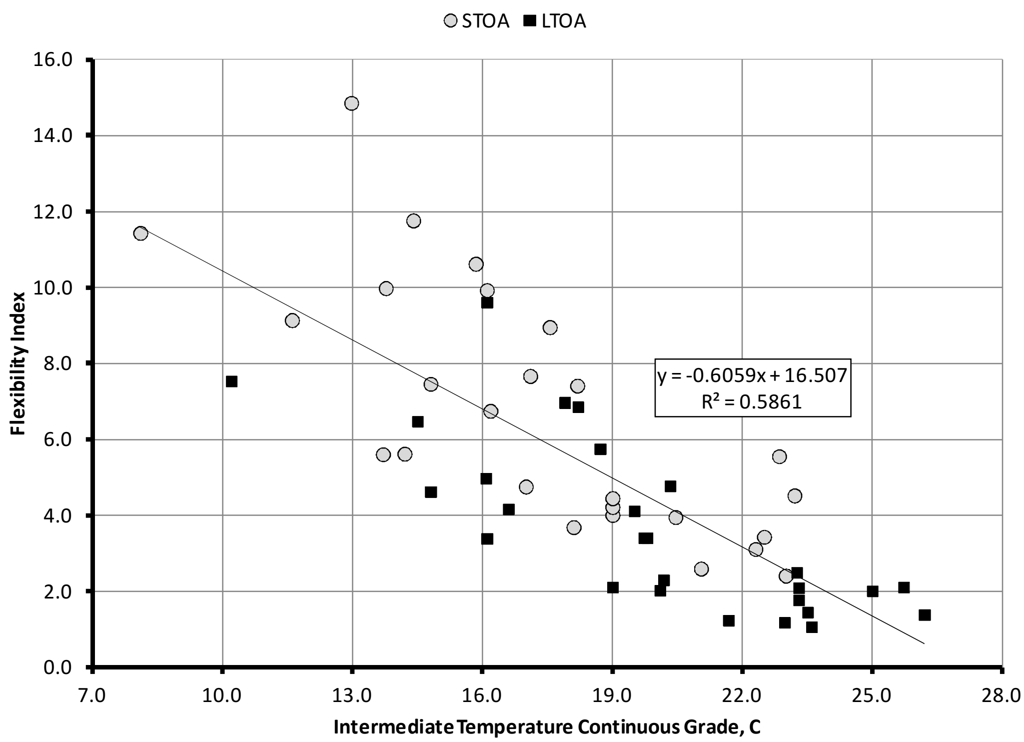


Figure 13. Relationship Between SCB Flexibility Index and Continuous Intermediate Temperature Grade of the Binder in the SCB Specimens.

There was no apparent relationships between the critical strain energy release rate and any of the recovered binder properties. Figure 14 shows an example. This figure shows the lack of any relationship between the intermediate temperature continuous grade temperature and the critical strain energy release rate from the intermediate SCB tests.

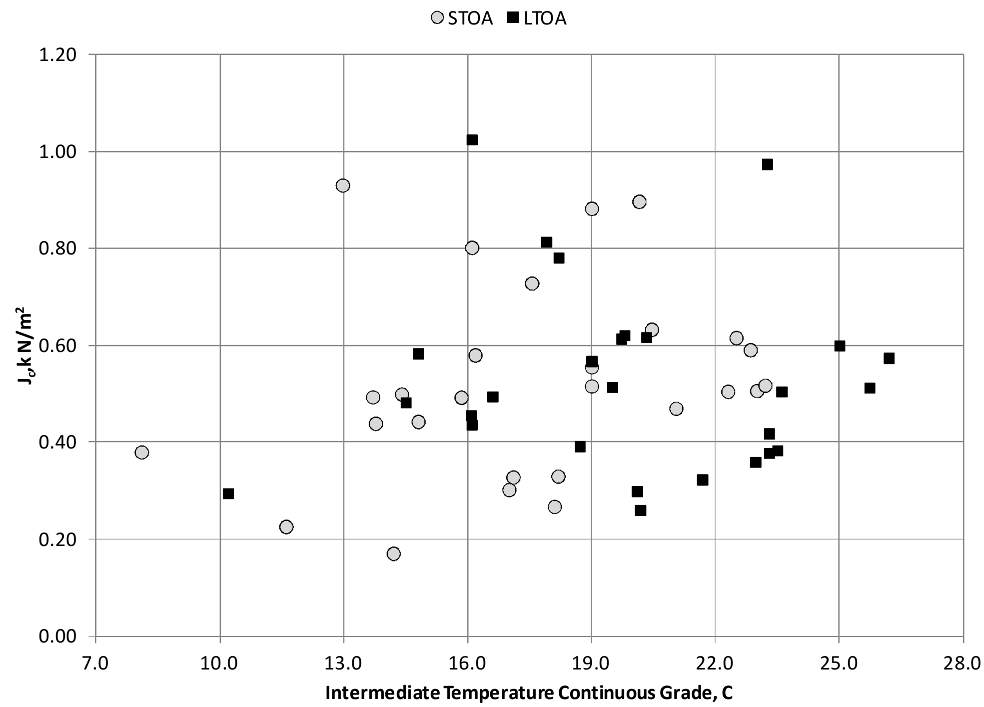
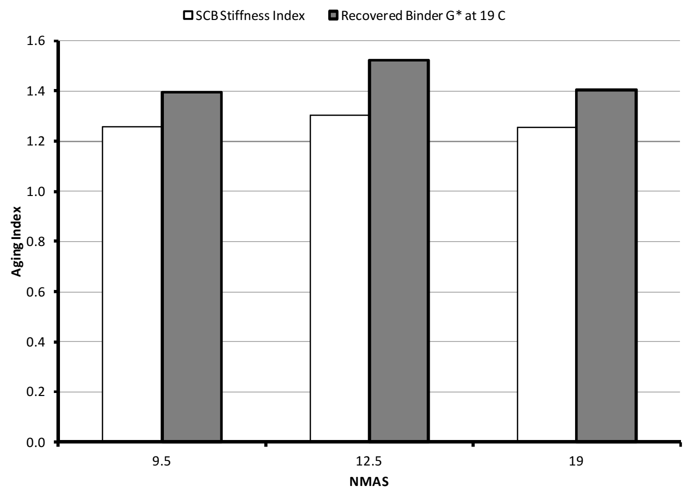


Figure 14. Relationship Between SCB Critical Strain Energy Release Rate and Continuous Intermediate Temperature Grade of the Binder in the SCB Specimens.

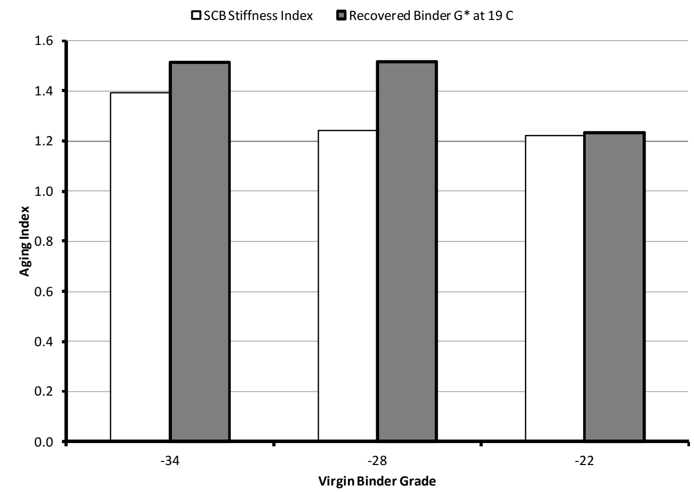
4.1.2.3 Aging

The preliminary analysis also included a graphical analysis of the effect of the primary experimental variables on aging as simulated by long-term oven conditioning. Aging indices, defined as a selected property measured after long-term oven conditioning divided by that property measured after short-term oven conditioning, were calculated for various properties.

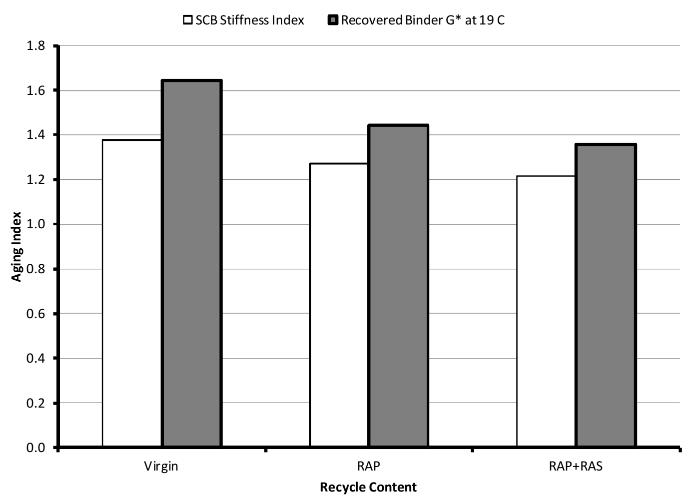
Figure 15 shows the effect of the primary experimental variables on aging indices derived from: (1) the SCB stiffness index, and (2) the recovered binder stiffness measured at 19 °C and 10 rad/sec. These two properties show similar effects. Mixture stiffening on long-term conditioning is relatively insensitive to the primary experimental variables. There does, however, appear to be a consistent trend in Figure 15c of lower aging indices with increasing recycle content for both the SCB and recovered binder data. The SCB stiffness index also shows a consistent trend in Figure 15b of lower aging indices with increasing low temperature grade. Both of these indicate that aging in stiffer mixtures is somewhat lower, which is in agreement with the Global Aging Model used in AASHTOWare Pavement ME *(79)*.



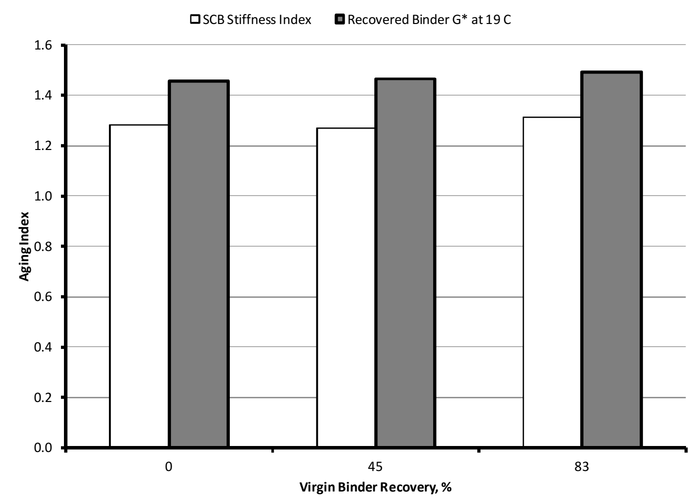
a. VBE.



b. Low Temperature Performance Grade.



c. Recycled Binder Content.



d. Polymer Modification.

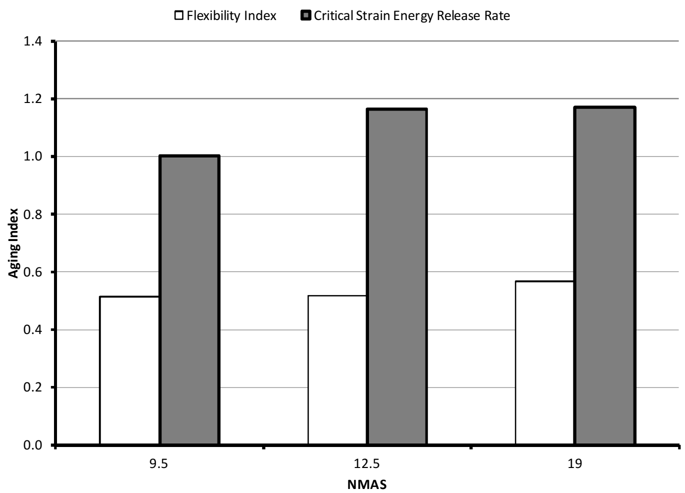
Figure 15. Effect of Primary Experimental Variables on Aging Indices From Mixture and Binder Stiffness Measurements.

Figure 16 shows the effect of the primary experimental variables on aging indices derived from: (1) the intermediate temperature SCB flexibility index, and (2) the intermediate temperature SCB critical strain energy release rate. Aging indices less than one indicate a decrease in cracking resistance after long-term conditioning while aging indices greater than one indicate an improvement in cracking resistance after long-term conditioning. As discussed earlier, the intermediate temperature SCB critical strain energy release rate often exhibits an irrational trend of improved cracking resistance with aging. The intermediate temperature SCB flexibility index on the other hand shows a consistent decrease in cracking resistance with aging. The ratio of the long-term aged flexibility index to the short-term aged flexibility index, however, is relatively insensitive to the primary experimental variables. Figure 16b indicates that the cracking resistance of mixtures produced with virgin binders having higher low temperature grades decreases somewhat more with aging than mixtures produces with softer virgin binders. Similarly, Figure 16c indicates that the cracking resistance of mixtures with higher recycle content decreases somewhat more than low recycle content and virgin mixtures. Considering the effects for the SCB stiffness in Figure 15 and the SCB flexibility index in Figure 16, it appears that more rapid stiffening of the binder in the mixture does not necessarily translate into more rapid reduction in the cracking resistance as measured by the intermediate flexibility index.

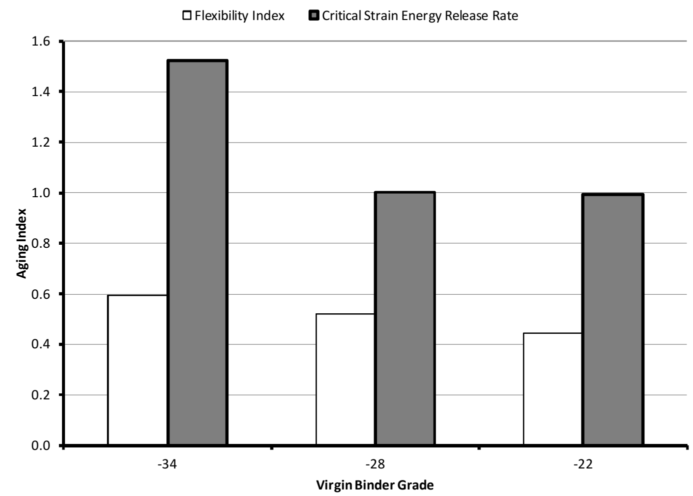
4.1.3 Final Analysis

4.1.3.1 Short-Term Conditioned Flexibility Index

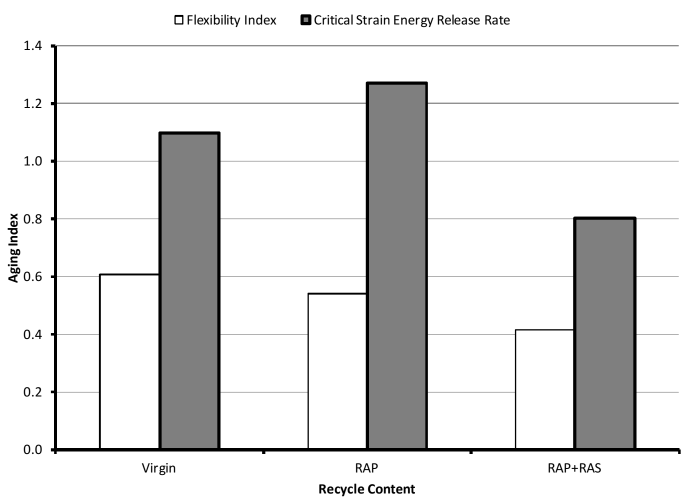
The intermediate temperature SCB flexibility index emerged from the preliminary analysis as the cracking response parameter for further analysis. Its selection was based on the sensitivity of the intermediate SCB cracking parameters to aging and the primary experimental variables, and the rationality of the trends. The final analysis of the data from the laboratory prepared mixtures experiment, therefore, focused on developing relationships between the flexibility index as a measure of cracking resistance and factors for asphalt mixtures that are easily specified and controlled. The final analysis was conducted using stepwise regression techniques with the regression function in Excel and relying heavily on the general trends shown in the preliminary graphical analysis.



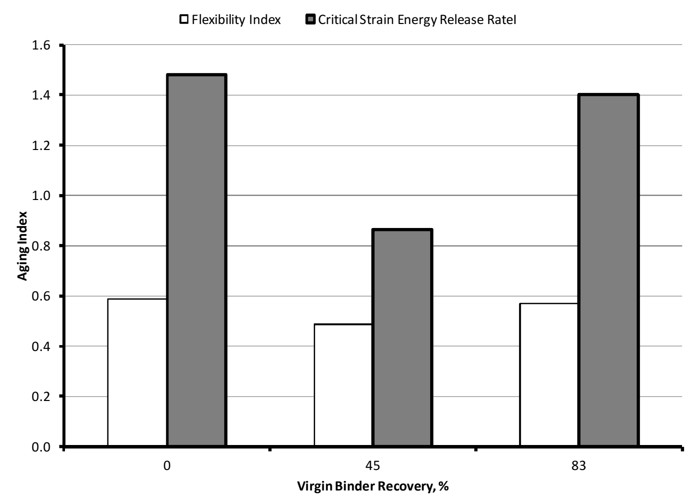
a. VBE.



b. Low Temperature Performance Grade.



c. Recycled Binder Content.



d. Polymer Modification.

Figure 16. Effect of Primary Experimental Variables on Aging Indices From SCB Parameters Related to Cracking Resistance.

Early work during the final analysis focused on estimating the flexibility index for short-term conditioned specimens by building on the relationship between the continuous intermediate temperature grade temperature of the recovered binder and the flexibility index shown earlier in Figure 13. Since the short-term conditioned, recovered intermediate grade temperature is not a specification or control property, relationships to estimate this from the low temperature grade of the virgin binder and the recycled binder content of the mixture were investigated. To properly account the fact that RAS binders change the intermediate grade temperature faster than RAP binders, an effective RAP binder ratio was used. The effective RAP binder ratio is given by Equation 8:

$$RBR_{EFF} = \frac{\%RAPBinder}{\%TotalBinder} + F \times \left(\frac{\%RASBinder}{\%TotalBinder} \right) \tag{8}$$

Where:

RBR_{EFF} = effective RAP binder ratio

%RAPBinder = % of total mix that is RAP binder

%RASBinder = % of total mix that is RAS binder

%TotalBinder = % of the total mix that is binder (virgin+recycled)

$$F = \frac{T_{c_{RAS}} - T_{c_{Virgin}}}{T_{c_{RAP}} - T_{c_{Virgin}}}$$

Where:

F = factor indicating how much faster RAS changes the intermediate temperature grade of a blended binder compared to RAP

$T_{c_{RAS}}$ = continuous intermediate grade temperature for RAS binder

$T_{c_{RAP}}$ = continuous intermediate grade temperature for RAP binder

$T_{c_{Virgin}}$ = continuous intermediate grade temperature for virgin binder

For the RAP and RAS used in this experiment, the factor F had an average value of 1.3. For the binders, RAP, and RAS used in this experiment, Equation 8 says that for the same amount of recycled binder, RAS binders will change the intermediate grade temperature 1.3 times faster than RAP binders. Table 21 summarizes the effective RAP binder ratio for the 9 different mixtures used in the laboratory prepared mixtures experiment.

Table 21. Effective RAP Binder Ratio (RBR_{EFF}) for Mixtures Used in the Laboratory Prepared Mixtures Experiment.

Mix	RAP Content, %	RAP Binder Content, %	RAS Content, %	RAS Binder Content, %	Virgin Binder Content, %	%RAPBinder, %	%RASBinder, %	%TotalBinder, %	RBR_{EFF}
1	31.4	4.78	0	0	4.60	1.50	0	6.10	24.6
2	0	0	0	0	5.70	0	0	5.70	0
3	24	4.42	2.8	29.41	3.20	1.06	0.82	5.08	41.4
4	15.7	4.42	3.5	29.41	4.00	0.69	1.03	5.72	35.0
5	26.2	4.78	0	0	3.65	1.25	0	4.90	25.5
6	21	4.78	0	0	4.40	1.00	0	5.40	18.6
7	16.7	4.16	3.9	23.63	4.20	0.69	0.92	5.82	32.1
8	0	0	0	0	4.80	0	0	4.80	0
9	0	0	0	0	6.30	0	0	6.30	0

Equation 9 is a regression equation for estimating the recovered short-term conditioned, continuous intermediate grade temperature from the continuous low grade temperature of the binder determined by AASHTO R29 and the effective RAP binder ratio.

$$T_{INT} = 39.693 + 0.8304 \times \left(T_{Virgin}\right)_{Low} + 13.004 \times RBR_{EFF} \quad (9)$$

Where:

T_{INT} = Estimate continuous intermediate grade temperature, °C

$(T_{Virgin})_{Low}$ = Continuous low temperature grade of the virgin binder, °C

RBR_{EFF} = Effective RAP binder ratio

The coefficient of multiple determination for this equation is 0.95 and the standard error of estimate is 0.87 °C. Figure 17 is a plot of the measured and estimated continuous intermediate grade temperatures. Considering the accuracy of extracted binder grading, it was concluded that the continuous low temperature grade of the virgin binder from standard grading tests and the effective RAP binder ratio could be used as surrogates for the intermediate grade temperature in subsequent analyses.

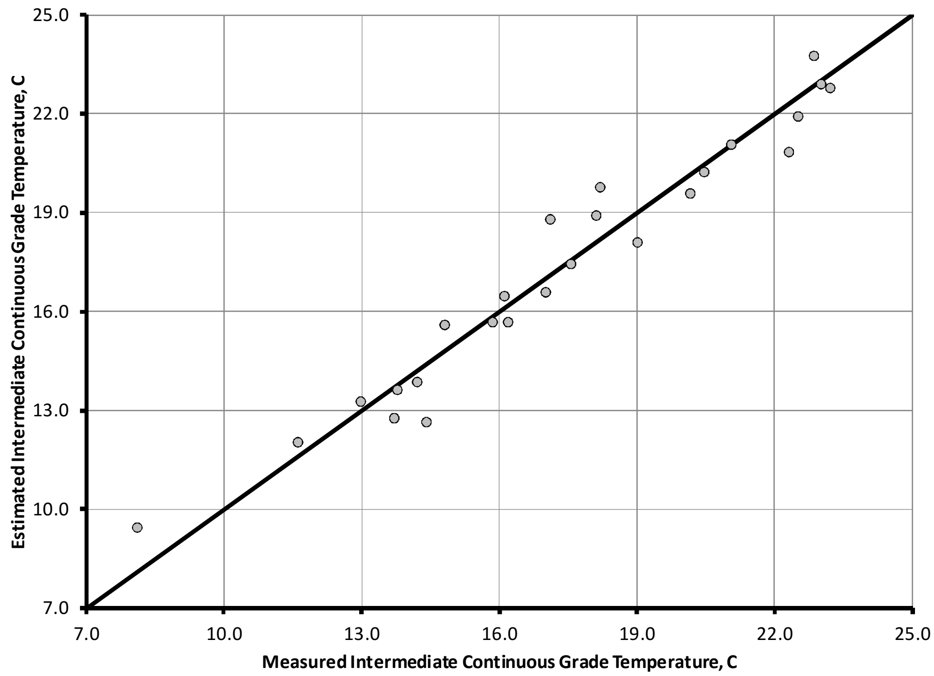


Figure 17. Estimated Versus Measured Continuous Intermediate Grade Temperature.

Linear regression was then used to develop an equation to estimate the short-term conditioned flexibility index from the variables included in the laboratory prepared mixtures experiment. Regression equations were developed for different combinations and nonlinear transformations of the variables used in the experiment. As discussed above, the low temperature grade of the virgin binder was quantified using the continuous low temperature grade of the binder determined from standard AASHTO R29 grading. The recycle content was quantified by the effective RAP binder ratio defined by Equation 8. The VBE of the mixture was used in the analysis rather than the nominal maximum aggregate size because the VBE of the 9.5 and 12.5 mm mixtures overlapped. Referring to Table 15, the VBE of the 9.5 mm mixtures ranged from 11.7 to 12.0 percent; the VBE of the 12.5 mm mixtures ranged from 10.5 to 12.3 percent; and the VBE of the 19.0 mm mixture ranged from 8.8 to 9.9 percent. Apparent film thickness, defined as the volume of effective binder divided by the surface area of the aggregate was also considered as a measure of the asphalt content effect. Using apparent film thickness, however, did not improve the accuracy of the regression equation. Finally, polymer content was quantified by the percent recovery from AASHTO M332 grading of the virgin binder. All of the predictor variables used in the regression analysis were properties that are normally included in specifications and can be controlled during production. The various regression equations were judged based on the following factors:

1. **Rationality of the Coefficients.** Since the primary objective of the regression equation was to evaluate the effect of various specification changes on the resistance of mixtures to cracking, it is imperative that the coefficients produce rational changes in the flexibility index over the range of mixtures evaluated. Using predictor variables that are correlated or including polynomial terms when not needed can result in irrational responses. The preliminary analysis did not reveal peaks or valleys in the flexibility index over the range of mixtures tested. The polymer content was the only variable that appeared to have a nonlinear effect, where the effect of this variable was much greater at high levels compared to intermediate levels.
2. **Significance of the Predictor Variables.** Again, the primary object of the regression equation was to evaluate the effect of specification changes; therefore, it is imperative that the predictor variables have a significant effect on the estimated flexibility index. The significance of the predictor variables was evaluated two ways. First was whether the regression coefficient is significantly different than zero. The p-value for the coefficient gives the probability that the coefficient is zero. In this analysis, the regression coefficient was considered significant if the p-value was less than 0.05. The second evaluation of the significance of the predictor variables was analysis of the standardized partial regression coefficients which are a measure of the relative importance of the predictor variables. The standardized partial regression coefficients and the partial regression coefficients are related by Equation 10 (*75*).

$$t_j = \frac{b_j \times S_j}{S_y} \tag{10}$$

Where:

t_j = standardized partial regression coefficient for predictor j

b_j = partial regression coefficient for predictor j

S_j = standard deviation of predictor j

S_y = standard deviation of the criterion variable.

3. **Goodness of Fit Statistics.** The goodness of fit statistics quantify how well the regression equation predicts the measured flexibility index. The two measures that were considered in this analysis were the coefficient of multiple determination, r^2, and the standard error or estimate. The r^2 is the percentage of the criterion variable variation that is explained by the regression equation. The standard error of estimate is the standard deviation of the residuals. The residuals are the difference between the measured values and those estimated by the regression equation. A good reference for evaluating the standard error of estimate for this analysis is the standard deviation of measured flexibility indices for the center point measurements (Runs 9, 18, and 27 in Table 15). The average of three measurements were reported in Table 19 for each run. The standard deviation of the flexibility index for the nine measurements at the center point for tests on short-term conditioned specimens was 0.88.
4. **Residuals.** The difference between the measured and estimated values were plotted against the estimated flexibility index and the predictor variables to confirm that the residuals were randomly distributed.

Equation 11 is the regression equation for estimating the flexibility index of short-term conditioned mixtures that was developed from the laboratory prepared mixtures experiment. This equation relates the flexibility index for short-term laboratory conditioned mixtures to parameters that can be specified and controlled: (1) effective volume of binder, (2) low temperature grade of the virgin binder, (3) effective RAP binder ratio, and (4) the percent recovery measured in the Multiple Stress Creep Recovery test.

$$FI_{STOA} = -18.759 + 1.368 \times VBE - 0.3905 \times \left(T_{Virgin}\right)_{Low} - 10.181 \times RBR_{EFF} + 3.100 \times \left(\frac{R\%}{100}\right)^2 \quad (11)$$

Where:

FI_{STOA} = short-term oven conditioned flexibility index

VBE = effective volume of binder, vol %

$(T_{Virgin})_{Low}$ = continuous low temperature grade of the virgin binder, °C

RBR_{EFF} = effective RAP binder ratio (see Equation 8)

R% = percent recovery from AASHTO M332

The r^2 for the equation is reasonable at 83 percent adjusted for the degrees of freedom. The standard error of estimate is 1.33 compared to a standard deviation of 0.88 for multiple measurements at the center point of the experiment. The analysis of the coefficients is shown in Table 22. The flexibility index rationally increases with: (1) increasing VBE, (2) decreasing virgin binder low temperature grade, (note the coefficient is negative and the low temperature grade is negative), (3) decreasing effective recycled binder ratio, and (4) increasing percent recovery. All of the coefficients are significant as shown by the very low p-values in Table 22. The standardized partial regression coefficients in Table 22 indicate the relative importance of the predictor variables. VBE and low temperature grade of the virgin binder are the most important having nearly equal standardized partial regression coefficients. These are followed by the effective RAP binder ratio and then the percent recovery.

Table 22. Analysis of the Regression Coefficients for Equation 11.

Variable	Partial Regression Coefficient	t- Statistic	p-value	Standardized Partial Regression Coefficient
Intercept	-18.759	-6.051	0.000004	0
VBE	1.368	6.325	0.000002	0.52
Virgin Binder Low PG	-0.3905	-5.773	0.000008	-0.49
Effective RAP Binder Ratio	-10.181	-4.736	0.000100	-0.39
% Recovery	3.100	2.893	0.008445	0.25

Figure 18 is a plot of the predicted versus measured flexibility index values and Figure 19 is a plot of the residuals versus the predicted values. These indicate the equation may underestimate for conditions yielding low flexibility index values. Low values of the flexibility index are not important in this research aimed at specification changes to improve cracking resistance. From Equation 11, the flexibility index for a 12.5 mm mixture with a VBE of 10.0, PG 58-28S binder and no RAP is 5.9 which is near the middle of range of flexibility index values in Figure 18. Figure 20 shows plots of the residuals versus each of the predictor variables. These residual plots show the residuals are reasonable randomly distributed and do not identify a particular predictor variable that is responsible for the underestimation of low flexibility index values.

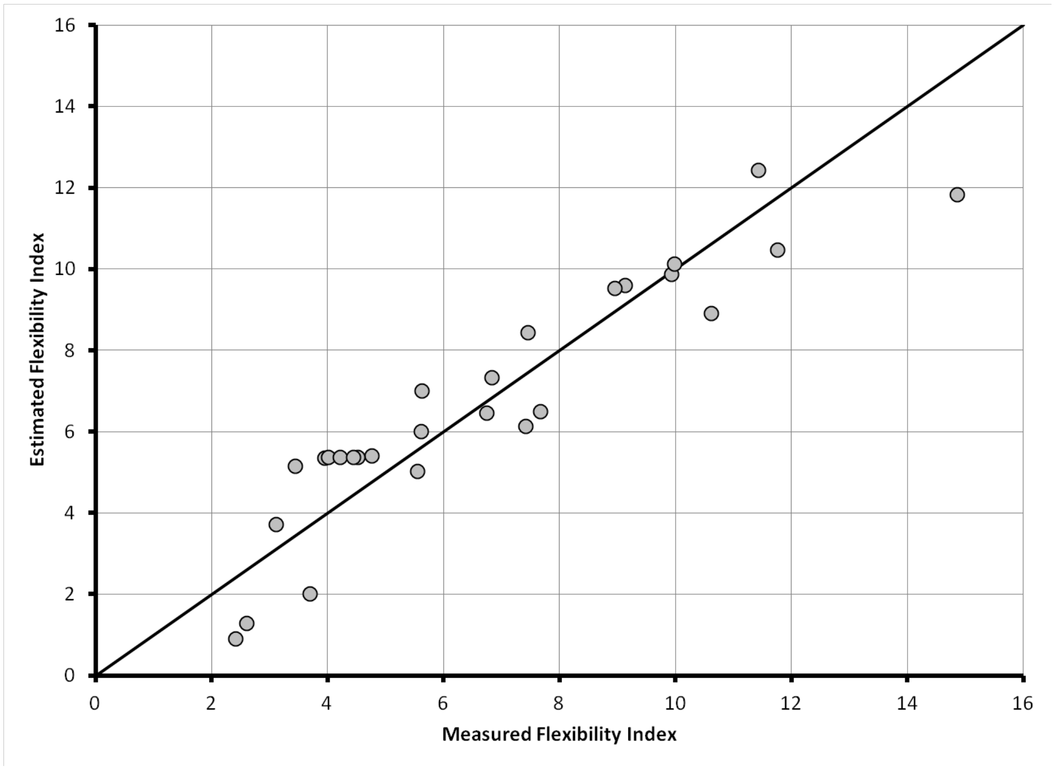


Figure 18. Estimated Versus Measured Short-Term Conditioned Flexibility Index.

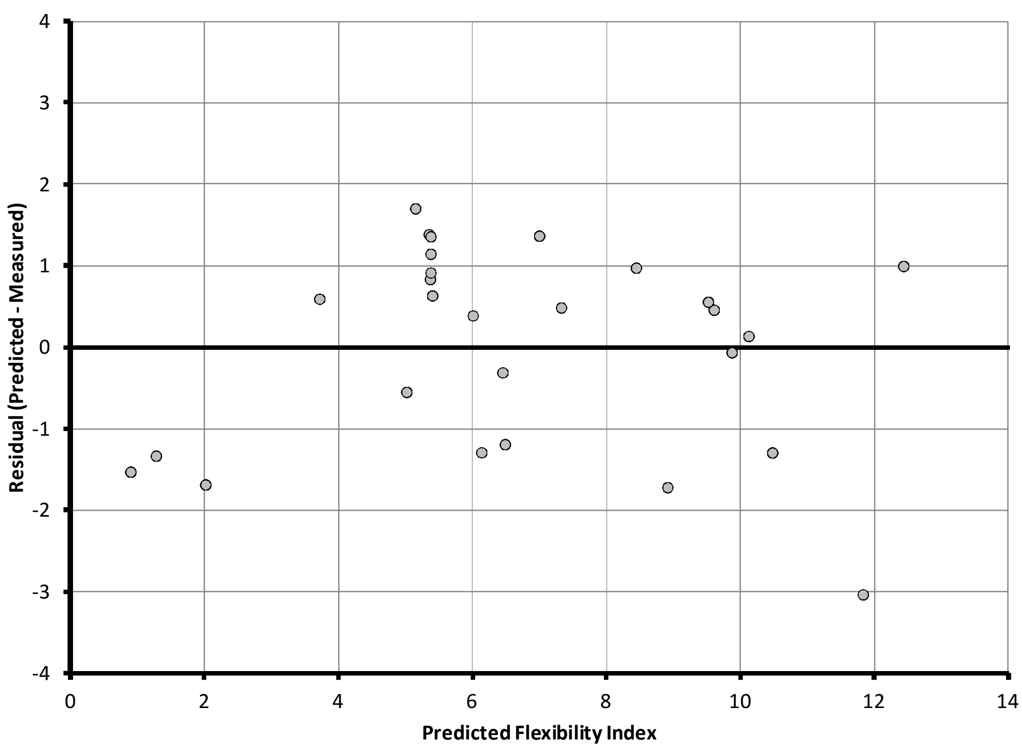
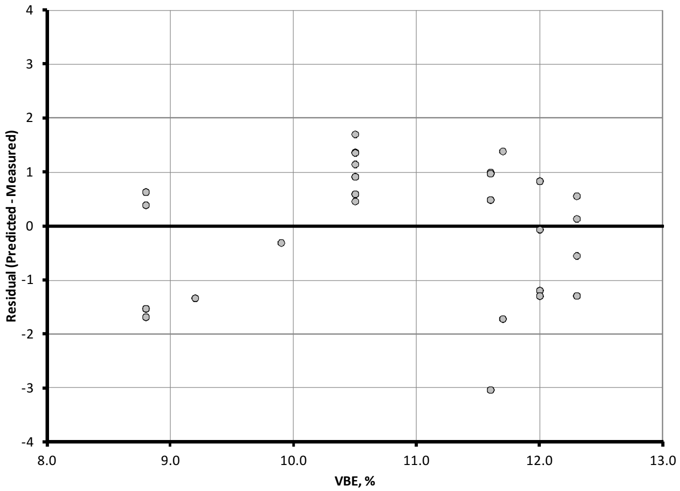
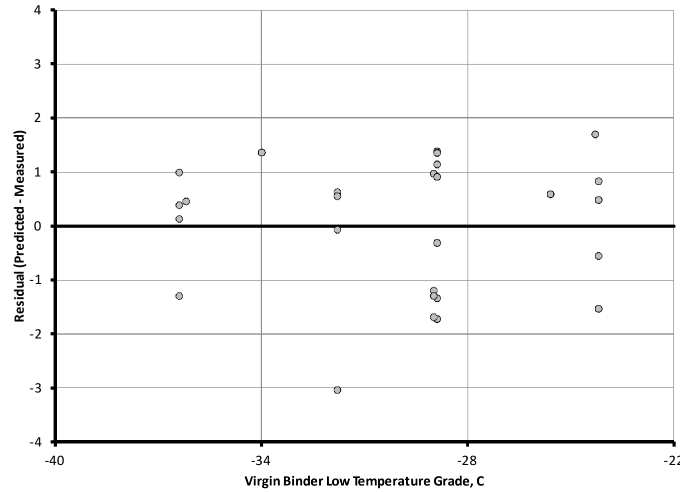


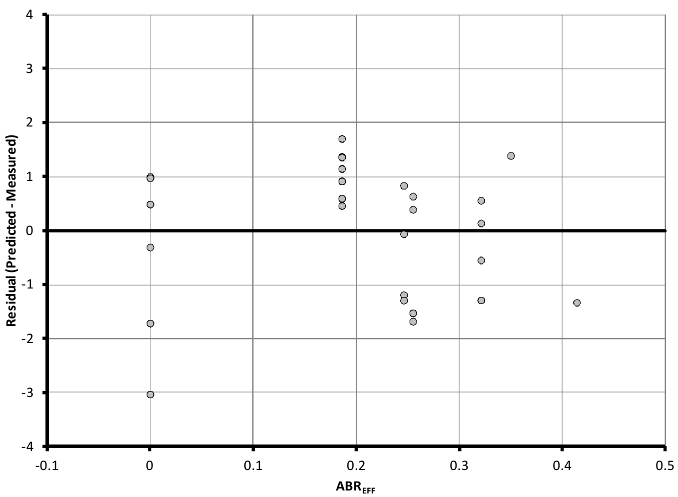
Figure 19. Plot of Residuals Versus Predicted Short-Term Conditioned Flexibility Index.



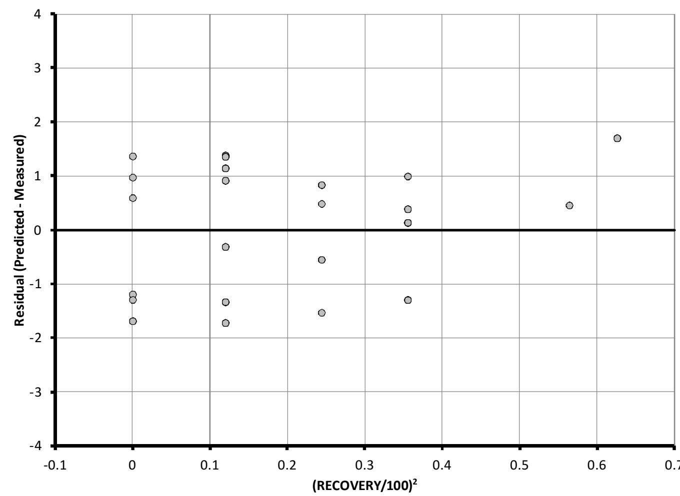
a. VBE.



b. $(T_{Virgin})_{Low}$.



c. ABR_{EFF}.



d. % Recovery.

Figure 20. Residual Plots for the Predictor Variables in Equation 11.

4.1.3.2 Long-Term Conditioned Flexibility Index

The preliminary analysis clearly showed that the flexibility index is sensitive to binder aging with flexibility index values for long-term conditioned mixtures being approximately half of that for short-term conditioned mixtures. It also appeared that the reduction caused by long-term conditioning was perhaps greater for mixtures made with stiffer binders and mixtures made with greater amounts of recycled binder.

Regression equations using various combination of the primary experimental variables as well as the short-term conditioned flexibility index were evaluated using the criteria discussed in the previous section. This evaluation found that the long-term conditioned flexibility is highly dependent on the short-term conditioned flexibility index. Equation 12 is the relationship for the long-term conditioned flexibility index that was developed from the laboratory prepared mixtures experiment.

$$FI_{LTOA} = 0.6550 \times FI_{STOA} - 0.7019 \tag{12}$$

Where:

FI_{LTOA} = long-term oven conditioned flexibility index

FI_{STOA} = short-term oven conditioned flexibility index

The explained variance for this equation is 84 percent and the standard error of estimate is 0.91 compared to a standard deviation of 0.37 for multiple measurements of the long-term conditioned flexibility index at the center point of the experiment. Figure 21 is a plot of the predicted versus measured long-term conditioned flexibility index values and Figure 22 is a plot of the residuals versus the predicted values. These figures show the equation provides an unbiased estimate over the range of the measured values.

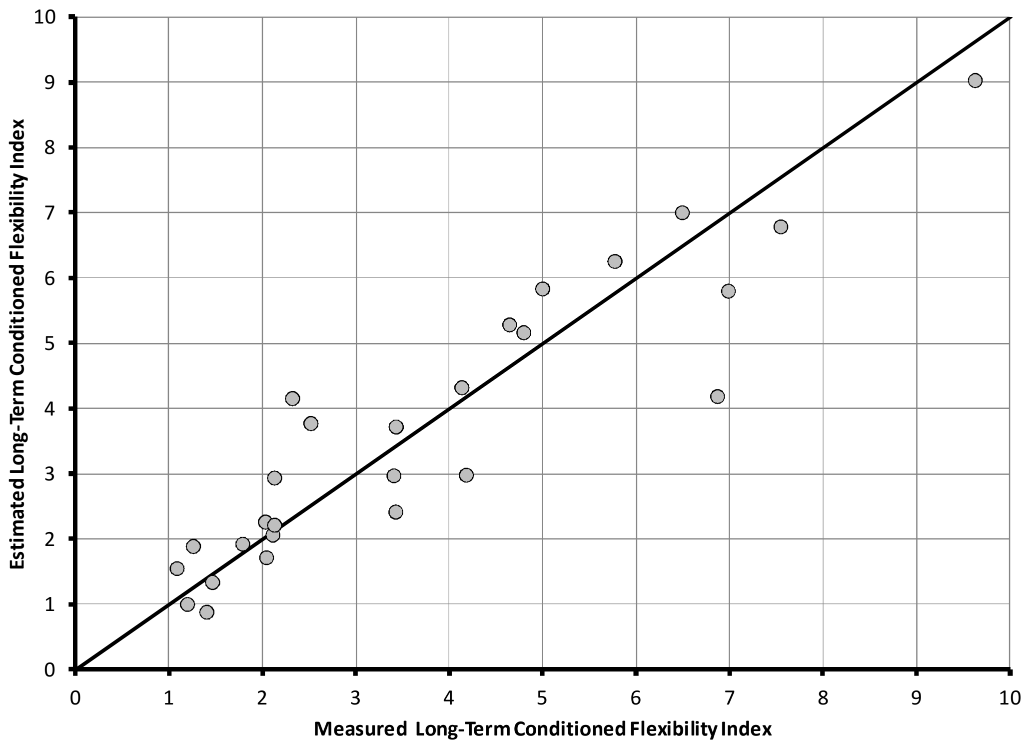


Figure 21. Estimated Versus Measured Long-Term Conditioned Flexibility Index.

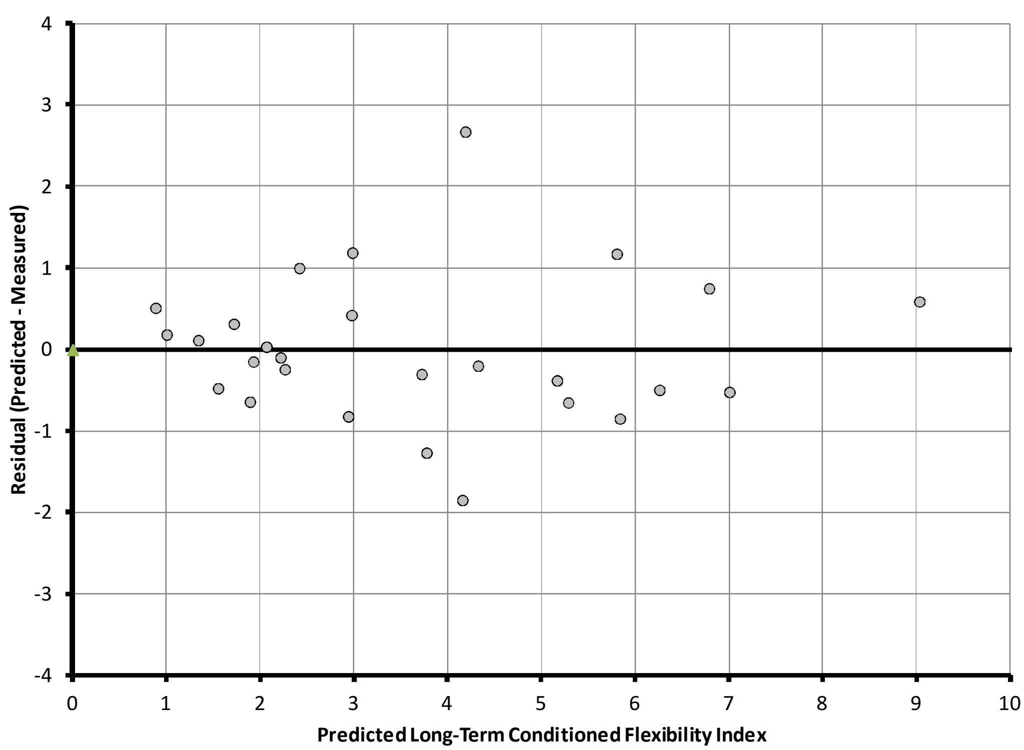


Figure 22. Plot of Residuals Versus Predicted Long-Term Conditioned Flexibility Index.

A few comments on Equation 12 are in order. First, for short-term conditioned flexibility index values less than 1.07, Equation 12 produces negative estimated values of the long-term conditioned flexibility index, which is not possible. As discussed in the previous section, low short-term conditioned flexibility index values are not important to this research to evaluate methods to improve cracking resistance. Second, the negative effects of increasing the effective RAP binder ratio and increasing the low temperature grade of the virgin binder that were evident in the preliminary analysis are captured through the effect of these variables on the short-term conditioned flexibility index. Increasing the effective RAP binder ratio and increasing the low temperature grade of the virgin binder both decrease the short-term conditioned flexibility index making the negative constant term in Equation 12 more important. This is illustrated in Table 23 which shows the effect of the constant term in Equation 12 on the ratio of the long-term to short-term conditioned flexibility index. As the short-term conditioned flexibility index decreases, the ratio of the long-term to short-term conditioned flexibility index also decreases. The important take away from this analysis is that methods that improve the short-term conditioned flexibility index will also improve the long-term conditioned flexibility index.

Table 23. Ratio of FI_{LTOA} to FI_{STOA} From Equation 12.

FI_{STOA}	FI_{LTOA}	FI_{LTOA}/FI_{STOA}
14.00	8.47	0.60
12.00	7.16	0.60
10.00	5.85	0.58
8.00	4.54	0.57
6.00	3.23	0.54
4.00	1.92	0.48
2.00	0.61	0.30

4.2 Plant Mixture Verification Experiment

4.2.1 Estimated Flexibility Index From Mix Design Submittals

The objective of plant mixture verification experiment was to compare estimates of cracking resistance obtained from the regression equations developed from the laboratory prepared mixtures experiment with values measured from intermediate temperature SCB testing of plant mixtures. Table 24 summarizes the calculation of estimated flexibility indices for the verification mixtures using Equation 11 based on data obtained from the mix design submittals. The estimated flexibility indices used the VBE from the mix design submittal, the specified low temperature performance grade from the mix design submittal, and for mixtures with RAS, the effective RAP binder ratio calculated using Equation 8 with the factor of 1.3 obtained from the laboratory mixtures experiment. The percent recovery used in estimating the flexibility index for H and V grades was estimated to be the same as that for the virgin binders tested in the laboratory mixtures experiment. The data in Table 24 are sorted from highest flexibility index to lowest flexibility index. The high flexibility index mixtures have high VBE, low effective RAP binder contents and were produced with binders with low temperature grades of -28 or -34. The low flexibility index mixtures use binders with low temperature grade of -22 or have low VBE, or high effective RAP binder contents.

4.2.2 Measured Flexibility Index

Table 25 summarizes measured flexibility indices for the verification mixtures. The measured flexibility indices are the average of four tests for each mixture conducted at 15 °C on plant mix that was reheated for 2 hours at 135 °C prior to compaction. The coefficient of variation for the tests on the plant mixtures ranged from 3 to 30 percent with an average of 15.1 percent. The data in Table 25 are also sorted from highest to lowest flexibility index.

4.2.3 Comparison of Estimated and Measured Flexibility Indices

From the comparison of estimated and measured indices shown in Figure 23, it is apparent that the values measured on the reheated plant mixtures are significantly higher compared to those estimated using the regression model developed from the laboratory prepared mixture experiment. This is likely the result of the difference in aging. Recall that the laboratory prepared mixtures experiment used conditioning of 4 hours at 135 °C, which typically results in greater aging compared to plant mixing (*73*). To minimize the aging effect, Figure 24 compares the ranking based on the estimated and measured flexibility indices. In this figure a rank of 1 is the best, and 16 is the worst. The rankings for most mixtures are in reasonable agreement except for the ones labeled in Figure 24. Mixtures V1 and V7 have ranks based on the measured data that are poorer than estimated while mixtures V4, and V11 have better ranks than estimated.

Table 24. Flexibility Indices for the Verification Mixtures From Mix Design Submittals.

Mixture	Supplier/Plant	Project ID	Binder Grade	Recycle Type	NMAS, mm	Design VBE, %	RAP Binder Ratio	RAS Binder Ratio	Equivalent RAP Binder Ratio	Estimated Recovery, %	Estimated FI
V1	Mathy	Eau Claire Drag Strip	PG 58-28 V	None	9.5	12.2	0.000	0.000	0.000	86	11.2
V9	Payne and Dolan	1595-09-60	PG 52-34 S	RAP	9.5	12.3	0.098	0.000	0.098	0	10.4
V7	Mathy	8010-01-75 & 78	PG 58-28 V	RAP	12.5	12.0	0.140	0.000	0.140	86	9.5
V2	Payne and Dolan	1595-09-60	PG 52-34 S	RAP	12.5	11.1	0.123	0.000	0.123	0	8.5
V3	Mathy	1197-18-75 & 76	PG 52-34 S	RAP	12.5	11.2	0.226	0.000	0.226	0	7.5
V15	Payne and Dolan	1300-13-70	PG 58-28 S	RAP and RAS	9.5	12.6	0.129	0.102	0.258	0	6.8
V10	Payne and Dolan	5300-04-79	PG 58-28 S	RAP	9.5	11.9	0.172	0.000	0.172	0	6.7
V6	Mathy	7090-05-65	PG 58-28 H	RAP	12.5	11.2	0.123	0.000	0.123	35	6.6
V12	Mathy	1166-12-74	PG 52-34 V	RAP and RAS	19	10.1	0.219	0.107	0.354	75	6.5
V4	Payne and Dolan	3-55-0090-26	PG 58-28 S	RAP	12.5	10.7	0.137	0.000	0.137	0	5.4
V5	Mathy	1166-08-72 / 82	PG 58-28 S	RAP	12.5	10.8	0.173	0.000	0.173	0	5.2
V14	Payne and Dolan	1300-13-70	PG 58-28 S	RAP and RAS	12.5	10.8	0.109	0.117	0.257	0	4.3
V11	Payne and Dolan	1300-13-70	PG 64-22 S	RAP	9.5	12.1	0.203	0.000	0.203	0	4.3
V16	Payne and Dolan	40029	PG 64-22 S	RAP and RAS	9.5	12.2	0.133	0.107	0.269	0	3.8
V8	Payne and Dolan	1300-13-70	PG 64-22 S	RAP	12.5	10.9	0.226	0.000	0.226	0	2.4
V13	Payne and Dolan	1090-19-72	PG 58-28 S	RAP and RAS	19	9.7	0.210	0.121	0.364	0	1.7

Table 25. Measured Flexibility Indices for the Verification Mixtures.

Mixture	Supplier/Plant	Project ID	Binder Grade	Recycle Type	NMAS, mm	Design VBE, %	Equivalent RAP Binder Ratio	Average FI	FI Coefficient of Variation, %
V9	Payne and Dolan	1595-09-60	PG 52-34 S	RAP	9.5	12.3	0.098	26.3	8.3
V3	Mathy	1197-18-75 & 76	PG 52-34 S	RAP	12.5	11.2	0.226	24.8	29.6
V2	Payne and Dolan	1595-09-60	PG 52-34 S	RAP	12.5	11.1	0.123	18.1	13.0
V4	Payne and Dolan	3-55-0090-26	PG 58-28 S	RAP	12.5	10.7	0.137	15.5	13.2
V15	Payne and Dolan	1300-13-70	PG 58-28 S	RAP and RAS	9.5	12.6	0.258	15.5	13.5
V6	Mathy	7090-05-65	PG 58-28 H	RAP	12.5	11.2	0.123	14.5	6.0
V1	Mathy	Eau Claire Drag Strip	PG 58-28 V	None	9.5	12.2	0.000	12.8	26.5
V10	Payne and Dolan	5300-04-79	PG 58-28 S	RAP	9.5	11.9	0.172	12.7	2.9
V11	Payne and Dolan	1300-13-70	PG 64-22 S	RAP	9.5	12.1	0.203	11.9	29.3
V5	Mathy	1166-08-72 / 82	PG 58-28 S	RAP	12.5	10.8	0.173	10.7	8.0
V14	Payne and Dolan	1300-13-70	PG 58-28 S	RAP and RAS	12.5	10.8	0.257	9.8	23.8
V7	Mathy	8010-01-75 & 78	PG 58-28 V	RAP	12.5	12.0	0.140	9.6	31.0
V12	Mathy	1166-12-74	PG 52-34 V	RAP and RAS	19	10.1	0.354	8.1	6.7
V8	Payne and Dolan	1300-13-70	PG 64-22 S	RAP	12.5	10.9	0.226	7.7	8.8
V13	Payne and Dolan	1090-19-72	PG 58-28 S	RAP and RAS	19	9.7	0.364	4.7	20.9
V16	Payne and Dolan	40029	PG 64-22 S	RAP and RAS	9.5	12.2	0.269	4.5	8.1

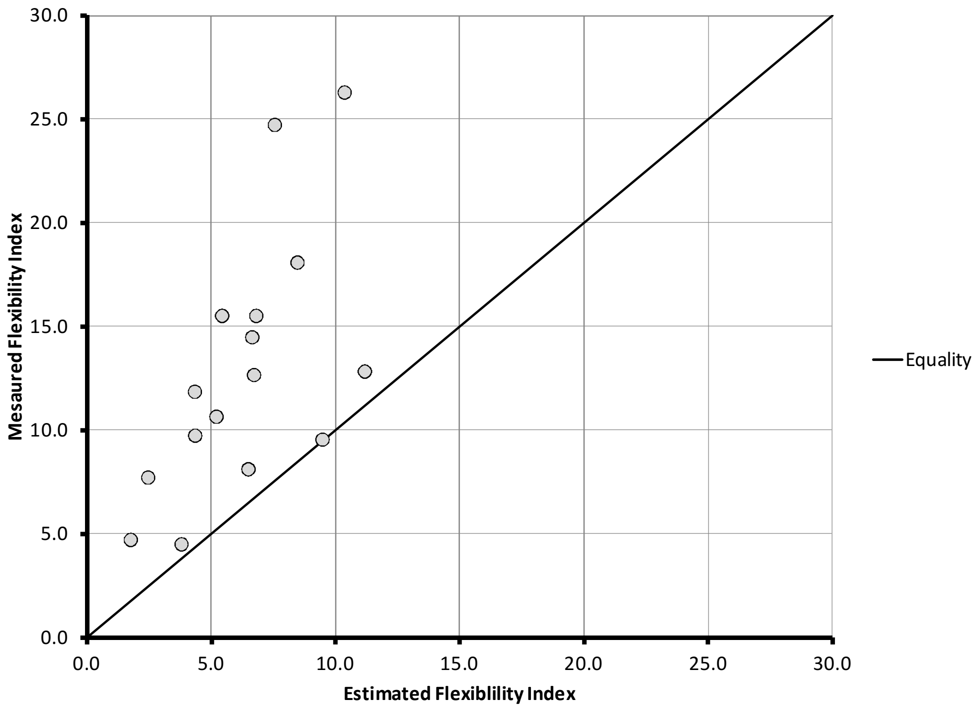


Figure 23. Comparison of Estimated and Measured Flexibility Indices for the Verification Mixtures.

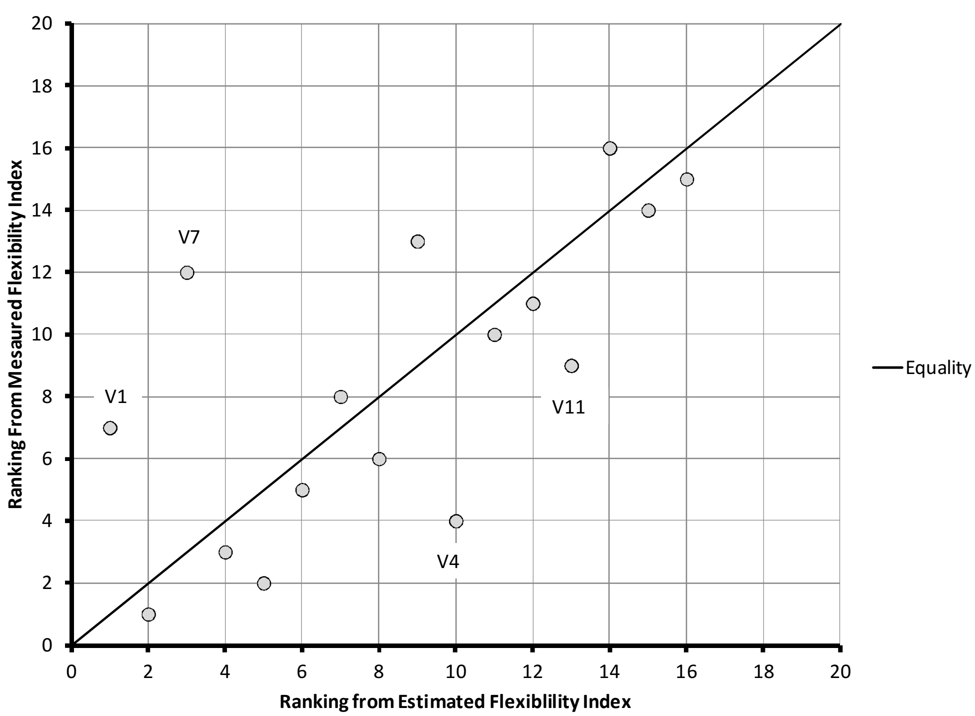


Figure 24. Comparison of Ranking Based on Estimated and Measured Flexibility Indices for the Verification Mixtures.

Additional analysis was performed to see if these discrepancies could be explained. First maximum specific gravity measurements made during the preparation of the plant mix SCB specimens were compared to those from the mix design. This comparison is summarized in Table 26. Using the multi-laboratory precision (acceptable range of two results, d2s) for AASHTO T209 of 0.019 as a guide, the asphalt content of the flexibility index specimens for mixtures V4, V7, V8, and V11 were measured using AASHTO T164 to determine if there were significant differences in the binder content of the plant mix samples compared to the mix design. Additionally, because mixture V1 did not contain any recycled binder, the binder was recovered and tested to verify that the low temperature grade and percent recovery of the virgin binder were in reasonable agreement with the data used to estimate the flexibility index. The results of this testing are summarized in Table 27 for the asphalt content and the resulting VBE, and Table 28 for the recovered binder properties. Note that the sample tested for V1 had very low recovery indicating that the binder in the samples tested was not modified with an elastomeric polymer. The binder was recovered in accordance with AASHTO R59 using reagent grade trichloroethylene. The data in Table 27 and Table 28 support that for the suspect mixtures there were differences in the volumetric and binder properties for the SCB samples compared to the properties in the mixture designs.

Table 26. Maximum Specific Gravity Comparison for Verification Mixtures.

Mixture	Tested Gmm	Mix Design Gmm	Gmm Difference
V1	2.464	2.468	0.004
V2	2.483	2.480	-0.003
V3	2.534	2.532	-0.002
V4	2.539	2.522	-0.017
V5	2.505	2.498	-0.007
V6	2.455	2.453	-0.002
V7	2.532	2.555	0.023
V8	2.534	2.510	-0.024
V9	2.466	2.460	-0.006
V10	2.450	2.453	0.003
V11	2.474	2.458	-0.016
V12	2.497	2.488	-0.009
V13	2.522	2.516	-0.006
V14	2.521	2.514	-0.007
V15	2.461	2.451	-0.010
V16	2.487	2.488	0.001

Table 27. Tested Binder Content and VBE of Suspect Verification Mixtures.

Mixture	Tested Binder Content, %	Mix Design Binder Content, %	Tested VBE, %	Mix Design VBE, %
V1	5.6	6.0	11.0	12.2
V4	5.5	5.1	11.6	10.7
V7	4.8	5.7	9.8	12.0
V8	5.9	5.3	11.9	10.9
V11	6.6	6.4	12.6	12.1

Table 28. Recovered Binder Properties for Verification Mix 1.

Property	Value
Continuous High, °C	65.5
Continuous Intermediate, °C	17.5
Continuous Low, °C	-30.6
ΔT_c, °C	1.1
Jnr, 1/kPa	1.45
% Recovery, %	2.8

Estimated flexibility indices were recalculated using the revised properties for the suspect mixtures. The results are summarized in Table 29, which like Table 24 and Table 25 are sorted from highest to lowest flexibility index. Figure 25 compares the rankings for the measured flexibility indices with the revised estimated values. The agreement in ranking is much better with no mixtures differing by more than 3 rank positions.

The verification experiment showed that the regression equation is capable of estimating the relative flexibility index for a wide range of Wisconsin mixtures. The verification experiment also showed that the flexibility index is sensitive to changes that may occur during production. The samples tested for mixtures V4 and V11 had higher binder content than the design and also had rankings based on the measured flexibility index that were significantly better than those based on the design volumetric properties. The sample tested for mixture V8 also had higher binder content than the design, but the improvement from the higher binder content had little effect on the ranking, because this mixture was produced with a very stiff binder, PG 64-22 S with a moderate effective RAP ratio. The sample tested for mixture V7 had lower binder content than the design and also had a ranking based on the measured flexibility index that was

Table 29. Revised Estimated Flexibility Indices for the Verification Mixtures.

Mixture	Supplier/Plant	Project ID	Binder Grade	Recycle Type	NMAS, mm	VBE, %	RAP Binder Ratio	RAS Binder Ratio	Equivalent RAP Binder Ratio	Recovery, %	Estimated FI
V9	Payne and Dolan	1595-09-60	PG 52-34 S	RAP	9.5	12.3	0.098	0.000	0.098	0	10.4
V2	Payne and Dolan	1595-09-60	PG 52-34 S	RAP	12.5	11.1	0.123	0.000	0.123	0	8.5
V3	Mathy	1197-18-75 & 76	PG 52-34 S	RAP	12.5	11.2	0.226	0.000	0.226	0	7.5
V1	Mathy	Eau Claire Drag Strip	PG 58-28 S	None	9.5	11.0	0.000	0.000	None	3	7.2
V15	Payne and Dolan	1595-09-60	PG 52-34 S	RAP and RAS	9.5	12.6	0.129	0.102	0.258	0	6.8
V10	Payne and Dolan	5300-04-79	PG 58-28 S	RAP	9.5	11.9	0.172	0.000	0.172	0	6.7
V4	Payne and Dolan	3-55-0090-26	PG 58-28 S	RAP	12.5	11.6	0.137	0.000	0.137	0	6.7
V6	Mathy	7090-05-65	PG 58-28 H	RAP	12.5	11.2	0.123	0.000	0.123	35	6.6
V7	Mathy	8010-01-75 & 78	PG 58-28 V	RAP	12.5	9.8	0.140	0.000	0.140	86	6.5
V12	Mathy	1166-12-74	PG 52-34 V	RAP and RAS	19	10.1	0.219	0.107	0.354	75	6.5
V5	Mathy	1166-08-72 / 82	PG 58-28 S	RAP	12.5	10.8	0.173	0.000	0.173	0	5.2
V11	Payne and Dolan	1300-13-70	PG 64-22 S	RAP	9.5	12.6	0.203	0.000	0.203	0	5.0
V14	Payne and Dolan	1300-13-70	PG 58-28 S	RAP and RAS	12.5	10.8	0.109	0.117	0.257	0	4.3
V8	Payne and Dolan	1300-13-70	PG 64-22 S	RAP	12.5	11.9	0.226	0.000	0.226	0	3.8
V16	Payne and Dolan	40029	PG 64-22 S	RAP and RAS	9.5	12.2	0.133	0.107	0.269	0	3.8
V13	Payne and Dolan	1090-19-72	PG 58-28 S	RAP and RAS	19	9.7	0.210	0.121	0.364	0	1.7

significantly poorer than that based on the design volumetric properties. Finally the sample tested for mixture V1 had lower binder content than the design and the binder did not have percent recovery consistent with the V grade binder as specified in the design. The ranking based on the measured flexibility index for this mixture was significantly poorer than that based on the design properties.

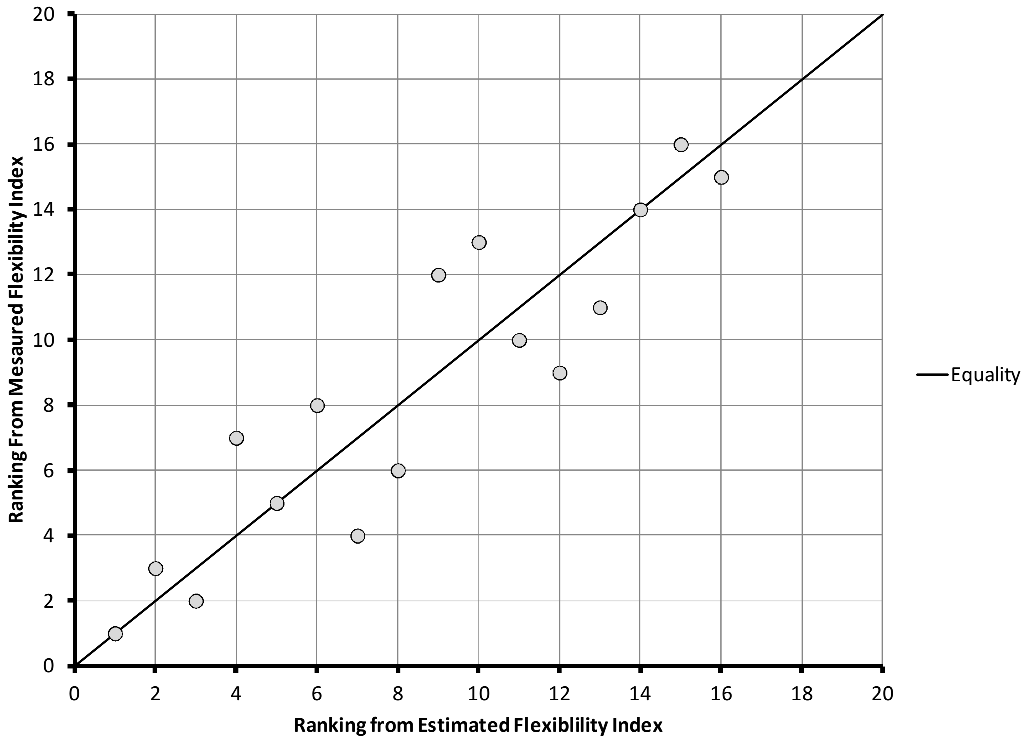


Figure 25. Comparison of Ranking Based on Recalculated Estimated and Measured Flexibility Indices for the Verification Mixtures.

Chapter 5 Evaluation of Specification Requirements

5.1 Introduction

The objective of this project was to provide recommended revisions to WisDOT specifications and guidance documents to improve the durability of asphalt concrete mixtures. The project focused on how mixture composition affects the aging and load associated cracking characteristics of asphalt concrete. Based on the synthesis of current research presented in Chapter 2, the promising methods for improving mixture durability through mixture composition that are applicable to the fine graded surface course mixtures commonly used in Wisconsin are:

- Increase effective binder content for all mixtures.
- Increase the effective binder content in proportion to the amount of recycled binder.
- Use a softer grade of binder in recycled mixtures.
- Use polymer modified binder in all surface course mixtures.
- Use polymer modified binder in recycled mixtures.
- Use balanced mixture design.

The laboratory experiments presented in Chapter 3 and Chapter 4 investigated the effects of: (1) effective binder volume, (2) recycled binder content, (3) virgin binder low temperature grade, and (4) polymer modification on simulated long-term aging and resistance to cracking as measured by a SCB test at intermediate temperatures. These experiments produced regression models that will be used in the analyses presented in this chapter to make specific recommendations for modifications to WisDOT specification requirements.

5.2 Improving Resistance to Aging

Within the scope of the mixtures tested and laboratory conditioning used for this project, the laboratory study found no major difference in the aging characteristics of the mixtures. Table 30 summarizes the scope of the mixtures included in the study. This scope covers the range of mixtures typically used in surface and lower layers in Wisconsin. This finding appears to contradict an earlier NCAT study that showed a significant reduction in aging with increased apparent film thickness (*61*); however the range of VBE considered in the NCAT study was from approximately 5 to 15 percent. Over the much narrower and realistic range of VBE included in this project, the 25 °C modulus ratio (ratio of long-term aged modulus to short-term aged modulus) in the NCAT study only varied from 1.33 to 1.17 which is similar in magnitude to the aging ratios for the stiffness index measured in this study. Additionally, the NCAT study did not account for the variability of the laboratory testing and only analyzed average data. The significant asphalt volume effect on aging reported in the NCAT study was the result of using mixtures with very low volumes of effective binder, well below those permitted by current Wisconsin specifications.

Table 30. Summary of the Scope of Mixtures Used in the Laboratory Experiments.

Property	Range			
Effective Volume of Binder, %	8.8 to 12.3			
Nominal Maximum Aggregate Size	9.5 to 19.0			
Gradation	Fine			
RAP Binder ratio	0 to 0.34			
RAP Continuous Grade, AASHTO M323 Appendix. °C	High	Intermediate	Low	ΔTc
	82.1 to 89.1	25.5 to 27.1	-19.7 to -23.3	-1.9 to -4.0
RAS Binder ratio	0 to 0.26			
Extrapolated RAS Continuous Grade, WHRP Project 0092-10-06 Procedure, °C	High	Intermediate	Low	ΔTc
	108.2 to 112.2	29.2 to 30.9	-12.9 to -19.3	-10.4 to -14.8
Effective RAP Binder ratio	0 to 0.41			
Virgin Binder Continuous Grade, °C	High	Intermediate	Low	ΔTc
	54.2 to 80.6	11.9 to 23.7	-36.4 to -24.2	1.6 to -0.7
Polymer Modification, AASHTO M332	S, V, and E			
% Recovery, AASHTO T350	0 to 86			

5.3 Improving Resistance to Load Associated Cracking

The laboratory experiments confirmed that the cracking resistance of Wisconsin mixtures is affected by the following properties that can be specified, and controlled through the quality control testing:

- **Volume of Effective Binder (VBE).** The cracking resistance of asphalt concrete mixtures improves with increasing VBE.

- **Low Temperature Grade of the Virgin Binder.** The cracking resistance of asphalt concrete mixtures improves as the low temperature grade of the binder decreases.
- **Recycle Content.** The cracking resistance of asphalt mixtures reduces as the recycle content of the mixture increases. The effect for RAS is greater than that for RAP, but the two can be combined by using an effective RAP binder ratio that accounts for the greater stiffening effect of RAS compared to RAP.
- **Polymer Content.** The cracking resistance of asphalt mixtures improves with increasing percent recovery as measured in AASHTO T350.

In this section, various options for improving the cracking resistance of mixtures were evaluated using the regression equation developed from the laboratory prepared mixtures experiment, Equation11. Since data relating the flexibility index to observed cracking was not available, the evaluations were made by comparing flexibility indices. The evaluations are divided into two sections: (1) recent WisDOT changes that have been made to improve pavement cracking performance, and (2) other changes that WisDOT should consider.

5.3.1 Evaluation of Recent WisDOT Specification Changes

Recently, WisDOT changed Chapter 14, Section 10 of the Facilities Development Manual to eliminate the use of PG 64-22 S binder in overlays and lower layer mixtures in the Southern Asphalt Zone. The effect of making this change is illustrated in Table 31, which compares flexibility indices calculated from Equation 11 for similar mixtures using PG 58-28 S and PG 64-22 S binders. The mixture used for the surface course comparison is a 12.5 mm mixture having VMA one percent above the AASHTO M323 design minimum of 14.0 which yields a VBE of 11 percent. The lower layer comparison uses a 19.0 mm mixture having VMA one percent above the AASHTO M323 design minimum of 13.0, which yields a VBE of 10 percent. The PG 58-28 S binder in these comparisons is assumed to have a low temperature continuous grade of -30 °C while the PG 64-22 S binder is assumed to have a low temperature continuous grade of -24 °C. The VMA and low temperature grade assumptions are reasonable considering how mixtures and binders are designed and produced.

Table 31 shows this specification change results in a substantial increase in the estimated flexibility index. Resistance to cracking increases with increasing flexibility. Although the University of Illinois research on the flexibility index has not yet quantified the cracking resistance in terms of pavement life *(68)*, the data in Table 31 can be used to make relative comparisons. For example, virgin PG 64-22 S mixtures have similar cracking resistance as PG 58-28 S mixtures with effective recycled binder ratios of 0.226. Assuming that the original decision to use PG 64-22 binder in overlays and lower layers in the Southern Asphalt Zone was made based on the performance of virgin mixtures, the recent revision to use PG 58-28 S binder in these mixtures appears to account for the amount of recycled binder that is now routinely used in Wisconsin asphalt mixtures. The average effective recycled binder ratio for the verification mixtures provided for this project that included recycled binder was 0.208.

Table 31. Effect on Cracking Resistance of Specifying PG 58-28 S Rather Than PG 64-22 S for Southern Asphalt Zone Mixtures.

Effective Recycled Binder Ratio	Estimated STOA Flexibility Index			
	12.5 mm PG 58-28 S	12.5 mm PG 64-22 S	19 mm PG 58-28 S	19 mm PG 64-22 S
0	8.0	5.7	6.6	4.3
0.1	7.0	4.6	5.6	3.3
0.2	6.0	3.6	4.6	2.3
0.3	5.0	2.6	3.6	1.2
0.4	3.9	1.6	2.6	0.2

A second recent modification to the WisDOT specifications was to increase the design VMA in Section 460 of the Standard Specification for 12.5 and 9.5 mm E-3 and E-0.3 mixtures by 0.5 percent. This change increases the VBE of these mixtures by 0.5 percent. Table 32 illustrates the effect on cracking resistance of making this change for the Southern Asphalt Zone while Table 33 shows the effect of this change for the Northern Asphalt Zone. These tables make reasonable assumptions about the mixtures: (1) VMA 1.0 percent above the respective design minimum, and low temperature continuous grade of the virgin binder grade 2 °C below the specified low temperature grade for PG 58-28 S, and 1 °C below the specified low temperature grade for PG 58-34 S. The 0.5 percent VMA increase improves the cracking resistance of the mixtures as measured by the flexibility index approximately 0.7. This is equivalent to a reduction of the recycled binder ratio of approximately 0.07 or decreasing the low temperature continuous grade of the binder by approximately 2 °C.

Table 32. Effect on Cracking Resistance of Specifying 0.5 Percent Increase in VMA for Southern Asphalt Zone Surface Mixtures.

Effective Recycled Binder Ratio	Estimated STOA Flexibility Index			
	12.5 mm VBE 11.0 PG 58-28 S	12.5 mm VBE 11.5 PG 58-28 S	9.5 mm VBE 12.0 PG 58-28 S	9.5 mm VBE12.5 PG 58-28 S
0	8.0	8.7	9.4	10.1
0.1	7.0	7.7	8.4	9.0
0.2	6.0	6.7	7.3	8.0
0.3	5.0	5.6	6.3	7.0
0.4	3.9	4.6	5.3	6.0

Table 33. Effect on Cracking Resistance of Specifying 0.5 Percent Increase in VMA for Northern Asphalt Zone Surface Mixtures.

Effective Recycled Binder Ratio	Estimated STOA Flexibility Index			
	12.5 mm VBE 11.0 PG 58-34 S	12.5 mm VBE 11.5 PG 58-34 S	9.5 mm VBE 12.0 PG 58-34 S	9.5 mm VBE12.5 PG 58-34 S
0	10.0	10.6	11.3	12.0
0.1	8.9	9.6	10.3	11.0
0.2	7.9	8.6	9.3	10.0
0.3	6.9	7.6	8.3	9.0
0.4	5.9	6.6	7.3	7.9

Tables 32 and 33 show that even larger improvements can be made by using the higher VMA 9.5 mm surface course mixture in lieu of the traditional 12.5 mm surface course with the lower VMA. In this case the improvement in the flexibility index is 2.0, which is equivalent to a reduction of the recycled binder ratio of approximately 0.21 or decreasing the low temperature continuous grade of the binder by approximately 5.4 °C, almost one grade level. Based on this study, using higher VMA 9.5 mm surface course mixtures may prove to be an effective tool for improving the cracking performance of mixtures in the Northern Asphalt Zone, where binders with low temperature grade below PG -34 are not readily available.

The combined effect of these two recent specification changes should be most evident for overlays in the Southern Asphalt Zone, where the low temperature binder grade has decreased 6 °C and the VBE has increased 0.5 percent. The effect of this combined change is illustrated in Table 34. Using the lower VBE, PG 64-22 S mixtures as the basis, a 12.5 mm mixture under current specifications with the same flexibility index can be made with an effective RAP binder ratio of almost 0.30. For a 9.5 mm mixture under current specifications, the effective RAP binder ratio increases to 0.428.

Table 34. Effect on Cracking Resistance of Specifying PG 58-28 S and Increasing VMA 0.5 Percent for Southern Asphalt Zone Overlay Surface Mixtures.

Effective Recycled Binder Ratio	Estimated STOA Flexibility Index		
	12.5 mm VBE 11 PG 64-22 S	12.5 mm VBE 11.5 PG 58-28 S	9.5 mm VBE 12.5 PG 58-28 S
0	5.7	8.7	10.1
0.1	4.6	7.7	9.0
0.2	3.6	6.7	8.0
0.3	2.6	5.6	7.0
0.4	1.6	4.6	6.0

5.3.2 Other Changes to Consider

The relative effects on the flexibility index of various mixture properties can be assessed by using Equation 11. One divided by each of the coefficients in Equation 11 gives the amount that each property needs to be changed to provide a unit increase in the flexibility index. To increase the flexibility index by 1 requires one of the following changes:

- Increase VBE by 0.73 percent
- Decrease the low temperature grade by 2.6 °C
- Decrease the effective RAP binder ratio by 0.10
- Increase the percent recovery by 57 percent

For surface mixes, the binder replacement section of Section 460 of the WisDOT Standard Specifications allows a recycled binder ratio of 0.25 when only RAP is used, 0.20 when only RAS is used, and 0.25 when a combination of RAP and RAS are used with the maximum RAS content being 5 percent of the aggregate. For a typical surface course mixture with 5.7 percent asphalt binder, the effective maximum RAP binder ratio as defined in this research is 0.25 for RAP only mixtures, and 0.26 for RAS only mixtures. When RAP and RAS are used in combination it can increase to 0.30 if the maximum amount of RAS, 5 percent by weight of aggregate, is used. Based on Equation 11, the flexibility index of surface mixtures with recycled binder under current WisDOT specifications can be as much as 3.0 lower compared to virgin mixtures using the same grade of binder. One method that has been proposed to improve the cracking resistance of mixtures with recycled binder *(45)*, and is supported by the findings of this research is to increase the VBE of the mixture for mixtures containing recycled binder. Based on the unit change in flexibility index analysis presented above, increasing the mixture VBE by 0.73 percent for each 0.10 increase in effective recycled binder ratio will produce mixtures with equivalent cracking resistance as measured by the flexibility index. This is summarized in Table 35 and Table 36 for 12.5 and 9.5 mm mixtures, respectively using the minimum design VBE from AASHTO M323 as the basis for the virgin mixtures. For an effective aggregate specific gravity of approximately 2.7, a 0.5 percent increase in design VBE is approximately equal to a 0.2 percent increase in asphalt content by weight of total mixture.

Table 35. Varying Design VBE with Recycled Binder Ratio for 12.5 mm Mixtures.

Design Effective Recycled Binder Ratio	Minimum Design VBE	Estimated STOA Flexibility Index	
		Southern Asphalt Zone PG 58-28 S	Northern Asphalt Zone PG 58-34 S
0.00	10.0	5.9	8.2
0.05	10.4	5.9	8.2
0.10	10.7	5.8	8.1
0.15	11.1	5.8	8.2
0.20	11.5	5.9	8.2
0.25	11.9	5.9	8.3
0.30	12.2	5.8	8.2

Table 36. Varying Design VBE with Recycled Binder Ratio for 9.5 mm Mixtures.

Design Effective Recycled Binder Ratio	Minimum Design VBE	Estimated STOA Flexibility Index	
		Southern Asphalt Zone PG 58-28 S	Northern Asphalt Zone PG 58-34 S
0.00	11.0	7.2	9.6
0.05	11.4	7.3	9.6
0.10	11.7	7.2	9.5
0.15	12.1	7.2	9.6
0.20	12.5	7.2	9.6
0.25	12.9	7.3	9.6
0.30	13.2	7.2	9.5

Four of the 13 surface course verification mixtures with recycled binder comply with VMA requirements in Table 35 and Table 36. Several of the verification mixtures with recycled binder, however, used softer low temperature grade binder or included polymer modification which also improve the flexibility index. Table 37 presents one way that the results of this research can be applied in a specification for 12.5 mm mixtures in the Southern Asphalt Zone to obtain mixtures with cracking resistance based on the flexibility index equivalent to that provided by virgin mixtures designed in accordance with AASHTO M323. Table 37 was constructed using Equation 11 and the following assumptions:

- Minimum VMA for 12.5 mm mixtures is 14.0 percent.
- Design air voids are 4.0 percent.
- PG 58-28 binders have a low temperature continuous grade of -30 °C.
- PG 58-34 binders have a low temperature continuous grade of -35 °C.
- Percent recovery for S grade binders is 0
- Percent recovery for H grade binders is 30 percent.
- Percent recovery for V grade binders is 55 percent.
- Percent recovery for E grade binders is 75 percent.

The assumed VMA and air voids are those currently specified in AASHTO M323. The assumed low temperature continuous grades are based on typical grading data. The percent recovery values are the minimum percent recovery requirements in the Combined State Binder Group

2016 Method of Acceptance for Asphalt Binder. (*80*). Table 37 gives the minimum design VBE for 12.5 mixtures for various recycled binder contents, and various grades of virgin binder. Cells with the minimum design VBE of 10.0 shown in bold, would have improved cracking resistance compared to a virgin 12.5 mm mixture and would not likely be supplied without an incentive. The maximum effective RAP binder ratio for the standard temperature grade of -28 is 0.20 based on thermal cracking considerations and the recommendations in from WHRP Project 0092-10-06, *Effect of Recovered Binders from Recycled Shingles and Increased RAP Percentages on Resultant Binder PG* (*20*). For effective RAP binder ratios above this level, the low temperature grade of the binder must be reduced one grade to reduce the potential for low temperature cracking. Based on the recommendations in WHRP Project 0092-10-06, the one grade reduction can accommodate an effective RAP binder ratio up to about 0.40 (*20*). The specification in Table 37 provides producers the flexibility to select the most economical combination of virgin binder grade, level of modification, and effective binder content to meet the specified cracking resistance.

Table 38 shows a similar specification for 12.5 mm mixtures in the Northern Asphalt Zone. Since a binder softer than -34 is not readily available and there is concern over effectiveness of softening agents (*81*), the specification for the Northern Asphalt Zone is somewhat more restrictive. It limits the effective RAP binder ratio to 0.20 based on low temperature cracking and includes only one low temperature grade of binder. Table 38 is based on Equation 1 and the same assumptions for mix and binder properties listed above.

Please note that Table 37 and Table 38 were developed based on the assumption that the cracking resistance of properly designed and constructed 12.5 mm virgin mixtures in Wisconsin is acceptable. If improved cracking resistance is desired, then the baseline VBE for virgin mixtures should be increased, for example by 1.0 percent as recommended in the new National Cooperative Highway Program Mix Design Manual (*39*). The relative changes in the minimum design VBE shown in Table 37 and Table 38 for increasing effective RAP binder ratio, decreasing low temperature grade, and increasing modification would be the same. Thus an effective method of improving the cracking resistance of mixtures in Wisconsin is to specify 9.5 mm mixtures using tables similar to Table 37 and Table 38 with all of the design VBE values increased by 1 percent. This approach is particularly useful in the Northern Asphalt Zone where a softer binder is not readily available.

Table 37. Example Minimum Design VBE Specification for 12.5 mm Mixtures in the Southern Asphalt Zone.

<table>
<tr><th rowspan="2">Effective RAP Binder Ratio</th><th colspan="8">Minimum Design VBE, vol %</th></tr>
<tr><th>58-28
S</th><th>58-28
H</th><th>58-28
V</th><th>58-38
E</th><th>58-34
S</th><th>58-34
H</th><th>58-34
V</th><th>58-34
E</th></tr>
<tr><td>0.00</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td></tr>
<tr><td>>0.00
≤0.05</td><td>10.4</td><td>10.2</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td></tr>
<tr><td>>0.05
≤0.10</td><td>10.7</td><td>10.5</td><td>10.1</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td></tr>
<tr><td>>0.10
≤0.15</td><td>11.1</td><td>10.9</td><td>10.4</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>10.0</td></tr>
<tr><td>>0.15
≤0.20</td><td>11.5</td><td>11.3</td><td>10.8</td><td>10.2</td><td>10.1</td><td>10.0</td><td>10.0</td><td>10.0</td></tr>
<tr><td>>0.20
≤0.25</td><td rowspan="4" colspan="4">Low Temperature Grade Controls</td><td>10.4</td><td>10.2</td><td>10.0</td><td>10.0</td></tr>
<tr><td>>0.25
≤0.30</td><td>10.8</td><td>10.6</td><td>10.1</td><td>10.0</td></tr>
<tr><td>>0.30
≤0.35</td><td>11.2</td><td>11.0</td><td>10.5</td><td>10.0</td></tr>
<tr><td>>0.35
≤0.40</td><td>11.5</td><td>11.3</td><td>10.9</td><td>10.3</td></tr>
</table>

Table 38. Example Minimum Design VBE Specification for 12.5 mm Mixtures in the Northern Asphalt Zone.

Effective RAP Binder Ratio	**Minimum Design VBE, vol %**			
	58-34 S	**58-34 H**	**58-34 V**	**58-34 E**
0.00	10.0	**10.0**	**10.0**	**10.0**
>0.00 to ≤0.05	10.4	10.2	**10.0**	**10.0**
>0.05 to ≤0.10	10.7	10.5	10.1	**10.0**
>0.10 to ≤0.15	11.1	10.9	10.4	**10.0**
>0.15 to ≤0.20	11.5	11.3	10.8	10.2

Chapter 6 Conclusions and Recommendations

6.1 Summary and Conclusions

WHRP Project 0092-14-06 included three major components: (1) a synthesis of current research associated with improving the durability of asphalt concrete mixtures; (2) a laboratory prepared mixtures experiment designed to evaluate, using Wisconsin materials, the promising methods for improving asphalt mixture durability that were identified by the synthesis of current research; and (3) a plant mixture verification experiment to confirm the findings of the laboratory prepared mixtures experiment. Based on the synthesis of current research presented in Chapter 2, the promising methods for improving asphalt mixture durability through mixture composition that are applicable to the fine graded surface course mixtures commonly used in Wisconsin are:

- Increase the effective binder content for all mixtures.
- Increase the effective binder content in proportion to the amount of recycled binder.
- Use a softer grade of binder in recycled mixtures.
- Use polymer modified binder in all surface course mixtures.
- Use polymer modified binder in recycled mixtures.
- Use balanced mixture design.

The laboratory prepared mixtures experiment presented in Chapter 3 and Chapter 4 investigated the effects of: (1) effective binder volume, (2) recycled binder content, (3) virgin binder low temperature grade, and (4) polymer modification on simulated long-term aging and resistance to cracking as measured by a semi-circular bend test at intermediate temperatures. This experiment produced regression models that were used in Chapter 5 to evaluate WisDOT specification requirements. The evaluation was based on improving the resistance of mixtures to aging and load associated cracking.

The plant mixture verification experiment was used to verify the flexibility index regression model that was developed during the laboratory prepared mixtures experiment. Based on research at the University of Illinois, cracking resistance improves with increasing flexibility index. The plant mixture verification experiment showed excellent agreement between rankings of cracking resistance based on the regression model compared to rankings based on SCB testing to measure the flexibility index for the plant mixtures.

The major conclusions drawn from research and analysis completed in WHRP Project 0092-14-06 are presented below:

6.1.1 Resistance to Aging

The laboratory prepared mixtures experiment included two levels of loose mix conditioning to simulate the effect of aging on the properties of asphalt mixtures: (1) short-term oven conditioning of 4 hours at 135 °C and (2) short-term oven conditioning followed by long-term oven conditioning of 120 hours at 85 °C. Binder and mixture stiffness increased significantly, and the resistance to cracking as measured by the flexibility index decreased significantly when the mixture was exposed to long-term conditioning compared to short-term conditioning. This confirmed that aging has a major effect on asphalt mixtures. However, neither the extent of stiffening nor the decrease in flexibility index were significantly affected by the composition of the mixture over the range of mixtures tested. This range included mixtures currently specified by WisDOT and included fine grained mixtures having:

- Nominal maximum aggregate sizes from 9.5 to 19.0 mm,
- VBE ranging from 8.8 to 12.3 percent,
- RAP binder ratio from 0 to 0.34,
- RAS binder ratio from 0 to 0.26,
- Effective RAP binder ratio from 0 to 0.41,
- Virgin binder low temperature grades from -34 to -22, and
- High temperature grades from PG 52 S to PG 64 E.

Based on average data, material property changes due to long-term conditioning were somewhat more when lower low temperature binder was used and somewhat less when recycled binder was used. However, the differences were not statistically significant.

6.1.2 Resistance to Cracking

Resistance to cracking was evaluated using the flexibility index developed by researchers at the University of Illinois (*68*). Testing conditions were different than those specified for the University of Illinois test to allow both the Illinois and Louisiana SCB criteria to be evaluated. For this project, the flexibility index was obtained from an SCB test at 15 °C using the Louisiana loading rate of 0.5 mm/min. The notch depth was 25 mm. Using time-temperature superposition, the loading rate used in this project is approximately equivalent to 8.5 mm/min at 25 °C, which is slower than the 50 mm/min specified for the University of Illinois test. The cracking resistance as measured by the flexibility index was significantly affected by:

1. **Aging.** The flexibility index for long-term conditioned mixtures ranged from 30 to 60 percent of that for short-term conditioned mixtures, with mixtures having higher flexibility indices retaining a higher percentage of their flexibility index after aging. Additionally, the plant mixtures tested in the verification experiment had higher flexibility index compared to the short-term conditioned mixtures used in the laboratory prepared mixture experiment. This indicates that laboratory short-term conditioning is more severe than plant aging. Lower flexibility indices imply lower resistance to cracking.
2. **VBE.** The flexibility index for short-term conditioned mixtures increases with increasing VBE, implying improved resistance to cracking for mixtures with higher effective volumetric binder contents.
3. **Amount and Type of Recycled Binder.** The flexibility index for short-term conditioned mixtures increases for binders with lower intermediate temperature continuous grade temperatures. The continuous intermediate grade temperature is affected by the low temperature grade of the virgin binder in the mixture and the amount and stiffness of any recycled binder in the mixture. As the amount of recycled binder increases, the flexibility index decreases implying poorer resistance to cracking. RAS binder which is much stiffer and affects the intermediate continuous grade more than RAP binder also has greater effect on flexibility index.
4. **Low Temperature Grade of the Virgin Binder.** As discussed above, the low temperature grade of the virgin binder affects the intermediate temperature continuous

grade of the binder in the mixture. As the low temperature grade of the virgin binder decreases, the flexibility index improves, implying improved resistance to cracking for softer low temperature grades.

5. **Polymer Modification.** The flexibility index increases for binders with higher percent recovery as measured in AASHTO T350 indicating an improvement in cracking resistance when polymer modified binders are used.

A regression equation for estimating the short-term flexibility index from specification properties was developed. The equation had an explained variance of 83 percent. The properties needed to use the equation are: (1) VBE, (2) recycled binder content, (3) low temperature grade of the virgin binder, and (4) the percent recovery for the virgin binder. There was a high degree of correlation between the short-term aged flexibility index and the long-term aged flexibility index. A second regression equation for estimating the long-term aged flexibility index from the short-term aged flexibility index was developed. This equation showed that mixtures with higher short-term flexibility indices retained a higher percentage of their flexibility index on aging. Thus, the short-term flexibility index could be used as an indicator of resistance to cracking.

The regression equation for the short-term flexibility index was used to evaluate current WisDOT specification criteria. This included an evaluation of recent changes made by WisDOT to improve asphalt concrete durability and other changes that WisDOT should consider. The recent changes that WisDOT made were: (1) eliminating the use of PG 64-22 S binder in overlays and lower layer mixtures in the Southern Asphalt Zone, and (2) increasing the design VMA for 12.5 and 9.5 mm E-3 and E-0.3 mixtures by 0.5 percent. The evaluation of these changes based on the research completed in this project concluded that both recent changes will improve the cracking resistance of WisDOT mixtures. The combined effect of the two recent specification changes will be most evident for overlays in the Southern Asphalt Zone.

6.2 Recommendations

6.2.1 Resistance Aging

The laboratory study concluded that for mixtures normally produced in Wisconsin, changes in mixture composition had little effect on the material property changes that occurred during simulated long-term aging. Therefore, no recommendations can be made to improve the aging characteristic of Wisconsin mixtures. This study used binders with normal aging characteristics and long-term conditioning of loose mix for 120 hours at 85 °C. WisDOT should monitor the aging characteristics of the binders supplied in Wisconsin and any additives intended to improve the low temperature properties of asphalt binders for use with mixtures incorporating recycled binders.

6.2.2 Resistance Cracking

The laboratory study used the flexibility index as a measure of cracking resistance and concluded that the flexibility index is affected by: (1) effective binder volume, (2) recycled binder content, (3) virgin binder low temperature grade, and (4) polymer modification. A regression equation was developed to estimate the effect of these specification properties on cracking resistance as measured by the flexibility index. WisDOT should consider using this regression equation to further modify their specifications for asphalt mixtures. The regression equation developed in this project can be used to specify mixtures with equivalent cracking resistance. Examples of how this can be done were provided in Chapter 5.

This research also showed that 9.5 mm mixtures with higher design VBE have higher flexibility indices compared to 12.5 mm mixtures implying improved resistance to cracking. WisDOT should consider expanding the use of 9.5 mm mixtures in surface course mixtures. The use of 9.5 mm mixtures will be an effective tool for the Northern Asphalt Zone where a binder with low temperature grade softer than -34 °C is not readily available.

6.2.3 Future Research

The research completed in this project showed the relative effects that changes in mixture composition have on simulated long-term aging, and cracking resistance as measured by the flexibility index from an SCB test. WisDOT should consider the future research listed below to verify the results from this project and further improve the durability of asphalt concrete mixtures.

1. The flexibility index developed at the University of Illinois appears to be a test that can likely be implemented in a balanced mixture design system. The test is: (1) sensitive to changes in mixture composition that affect cracking resistance, (2) relatively simple to perform, and (3) repeatable. Further improvement and standardization of the flexibility index test and analysis procedures are needed before the test can be recommended for routine use. Ruggedness testing for the flexibility index is included in the experiments proposed in NCHRP Project 9-57, *Experimental Design for Field Validation of Laboratory Tests to Assess Cracking Resistance of Asphalt Mixtures* (*82*). WisDOT should monitor the progress of this study.

2. Additional research is also needed to relate the flexibility index to pavement performance and develop criteria for cracking performance that can be used in specifications and asphalt mixture design. This work is being conducted by the University of Illinois (*68*). Validation of several cracking tests including SCB tests is included in the experiments proposed in NCHRP Project 9-57, *Experimental Design for Field Validation of Laboratory Tests to Assess Cracking Resistance of Asphalt Mixtures* (*82*). WisDOT should monitor the progress of these studies.

3. The development of relationships between properties that can be specified and controlled and performance related properties of asphalt mixtures similar to Equation 11 are critical to effective implementation of balanced mix design concepts. Such relationships provide agencies and producers the knowledge needed to specify, design, and control mixtures with improved cracking resistance. WisDOT should consider testing additional mixtures using the final flexibility index protocol or other appropriate test protocol should one emerge from the NCHRP cracking research to confirm the relationships developed in this study and perhaps expand them to a wider range of mixtures.

4. Research is ongoing in NCHRP 9-54, *Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction* (*63*), and other projects to define appropriate conditioning protocols for use with performance testing to simulate long-term aging. WisDOT should monitor these research projects and evaluate the findings from this study using representative mixtures should the ongoing research recommend a different long-term conditioning protocol.

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