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EVALUATION OF THE IMPACTS OF RE-REFINED ENGINE OIL BOTTOMS (ReOB) ON PERFORMANCE GRADED ASPHALT BINDERS AND ASPHALT MIXTURES

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Evaluation of PG-Graded Asphalts with Low Level of ReOB

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16. Abstract
This report provides findings of a laboratory study that assessed the performance grade (PG) of asphalt binder modified with re-refined engine oil bottoms (ReOB), and the performance of hot-mix asphalt (HMA) using these modified binders. The selected asphalt binder PG for this study was PG 58-28. Asphalt binder was blended with two ReOB products from two different manufacturers (CC-type and SK-type) at various percentages of ReOB (3%, 6%, and 9%). All asphalt binders (six different blends in addition to the control) were characterized using the SuperPave asphalt binder PG system. Even though the final PG of all blended asphalt binders was PG 58-28, a reduction in the stiffness of binder at intermediate and low temperatures was observed with increasing ReOB content. Some of the critical engineering properties of asphalt mixtures prepared with CC- and SK-type ReOB were evaluated. The mixtures' resistance to permanent deformation was evaluated using the Hamburg wheel track test (HWT). The HWT did not show any significant difference in permanent deformation of HMA with 9% ReOB compared with the control mix. The low- and intermediate-temperature cracking resistance was examined using the semi-circular bending beam (SCB) test at three aging levels: short-term, long-term, and extended long-term. Fracture energy and strength values obtained from the low-temperature SCB tests were comparable for all mixtures with increasing ReOB content. The SCB test results at 25°C (77°F) showed a consistent reduction in fracture energy and flexibility index (FI) with an increasing amount of ReOB at different levels of aging. Similar performance was observed for both CC- and SK-types of ReOB. The impact of ReOB in the mixes' fracture properties including fracture energy and FI was evident at intermediate temperatures.

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asphalt, engine oil, HMA, oil bottom, pavement, RAP, recycled, ReOB, RHVDO, RVTB, sustainable, WEO

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EXECUTIVE SUMMARY

Re-refined engine oil bottoms (ReOB) or waste engine oil (WEO) and other similar products are typically the heavy distillation bottoms (non-distillable fraction) remaining after the re-refining of used engine oil products. Modifying asphalt binders with re-refined products to obtain desired-grade asphalt binders has been in practice for over 20 years. The practice has been used in parts of Canada, California, and the midwestern United States. The Federal Highway Administration's (FHWA) Turner-Fairbank laboratories recently tested more than 1,000 asphalt samples from various parts of the United States and found that approximately 20% of the samples contained ReOB. The use of waste products has potential environmental and economic benefits because these materials might otherwise be discarded and can be obtained at relatively lower cost when only initial production costs are considered. However, some state departments of transportation have expressed concern about hot-mix asphalt (HMA) performance on the basis of recent published research suggesting that ReOB may have an adverse effect on pavement performance.

This report provides findings of a laboratory study that assessed the performance grade (PG) of an asphalt binder modified with various levels of ReOB, and the performance of asphalt mixtures using these modified binders. The selected asphalt binder PG for this study was PG 58-28. Asphalt binder was blended with two ReOB products (CC-type and SK-type) at various percentages of ReOB (3%, 6%, and 9%). The final PG of all blended asphalt binders was PG 58-28. All asphalt binders (six different blends in addition to the control) were characterized using the SuperPave asphalt binder PG system. Several tests at low, intermediate, and high temperatures were conducted on the studied binders, including the rotational viscosity (RV), the dynamic shear rheometer (DSR), and the bending beam rheometer (BBR). Tests were conducted at various aging levels including original binder, rolling thin film oven (RTFO), and pressure aging vessel (PAV). According to the results of the asphalt binder grading tests, even though the binder grade remained the same (PG 58-28), a reduction in the stiffness of binder at intermediate and low temperatures was observed with increasing ReOB content.

At the mixture level, permanent deformation, strength, and fracture characteristics of HMA prepared with CC-type and SK-type ReOBs were evaluated. The mixtures' resistance to permanent deformation was evaluated using the Hamburg wheel track test (HWT). The low- and intermediate-temperature cracking resistance was examined using the semi-circular bending beam (SCB) test including the IL-SCB test and flexibility index (FI) developed as part of ICT project R27-128 completed in December 2015. Asphalt mixtures were evaluated at 25°C (77°F) and –12°C (10.4°F) at three aging levels: short-term, long-term, and extended long-term.

The HWT did not show any significant difference in permanent deformation of mixes with 9% ReOB compared with the control mix. All mixes passed Illinois Department of Transportation (IDOT) standards (12.5 mm at 7,500 passes). The low-temperature SCB testing did not show any trend for fracture energy and peak load with increasing ReOB content with comparable fracture energy values for all mixes, regardless of ReOB presence. The SCB test results including fracture energy and FI at 25°C (77°F) showed a consistent reduction in fracture energy with an increasing amount of ReOB at different levels of aging. Similar performance was observed for both CC-type and SK-type of ReOB. The FI for short-term-aged specimens was in the range of 10 to 14, with no particular trend found between mixes.

With aging, the properties obtained from the intermediate-temperature SCB tests showed dramatic changes. Fracture energy dropped by approximately 15% at the end of 10 days of aging. The increase in peak load (in the range of 40% to 70%) and decrease in FI (in the range of 60% to 80%) at the end of 10 days of aging are valid signs of brittleness for all mixes. The changes in the fracture properties with aging are similar for mixtures containing either of the ReOB products at different concentrations.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Since the early 1990s and the adaptation and use of the SuperPave specification in North America, a large volume of research and experimentation has occurred regarding improvement of asphalt binders by increasing their performance grade (PG) span through the use of additives and process technologies. Much of this research has produced products with increased PG spans through the formation of a gel-type material at low or even reduced cost compared with virgin asphalt binder.

The use of acids, air blowing, waste engine oil residues, waxes, blending of incompatible asphalts, and numerous other approaches results in grades not readily accessible with normal distillation of regular crude oils. Use of economical modifiers and extenders for asphalt binder has become a topic of great interest because of the global economic oil climate and the need for increased environmental and economic sustainability. The use of waste products has potential environmental and economic benefits because these materials might otherwise be discarded and can be obtained at a relatively lower cost.

One such waste stream product is the vacuum tower bottoms remaining after the refining of used motor oil. Recycled and re-refined engine oil bottoms are commonly known as ReOB. With recycling efforts for used motor oil having become very successful in the 1990s, a large volume of ReOB became available, especially near the refineries. The question became, “Could something that originated from crude oil be reintroduced into asphalt binder, preserve its original properties, and provide positive physical properties?”

As stated by Johnson and Hesp (2014), “Waste engine oil residue [WEO, referred to as ReOB in this study] stands out as a modifier because it is a high volume by-product from the recycling of used oils without much value for further refining. As a consequence, the use of ReOB has become ubiquitous in Ontario, Canada and likely elsewhere.”

However, the effect of using ReOB on asphalt’s durability has received only limited attention. The limited number of papers or publications on that topic suggests that the practice of using ReOB in bituminous pavements does not appear to be widely known.

WEO and other similar products are generally known as re-refined heavy vacuum distillation oil (RHVDO) (D’Angelo et al. 2012, 2013) and re-refined vacuum tower bottoms (RVTBs) (Wielinski et al. 2014). This class of products is typically the heavy distillation bottoms (non-distillable fraction) remaining after the re-refining of used engine oil products.

Modifying with re-refined products to meet low-temperature properties and grade of asphalt binders has been in practice for over 20 years. The practice has been used in parts of Canada, California, and the midwestern United States. The Federal Highway Administration’s (FHWA) Turner-Fairbank laboratories recently tested more than 1,000 asphalt samples from various parts of the United States and found that approximately 20% of the samples contained ReOB. Some state departments of transportation have expressed concerns about hot-mix asphalt (HMA) performance, suggesting that ReOB might have an adverse effect on pavement performance. Publications have been primarily from three groups of authors: Johnson and Hesp (2014), D’Angelo et al. (2012, 2013), and Wielinski et al. on behalf of the Heritage Research Group (2014).

Johnson and Hesp (2014) focused their research on detecting the presence of ReOB (e.g., WEO, RVTB, RHDVO) through X-ray fluorescence (XRF) in asphalt binder, and the effect on asphalt binder quality and durability when modified with ReOBs. They attributed the poor performance of pavements in Ontario, Canada, to the presence and excessive amounts of ReOB as an asphalt binder modifier in those pavements. Visual surveys of numerous pavement projects were the basis for the connection between use of ReOB and poor pavement performance, in the form of premature and extensive cracking, when compared with projects in which ReOB was not detected in the asphalt binders.

The effect of WEOs on the quality and durability of asphalt binders was also evaluated by Johnson and Hesp (2014). This study included extended conditioning (aging) of ReOB-modified binders, to further investigate longer-term durability at high and low temperatures. Asphalt binders blended with 15% ReOB were evaluated in that study. In that study, it was suggested that the current Performance-Graded Asphalt Binder Specification (AASHTO M320) fails to account for excessive physical and chemical hardening and that where ReOB modification causes formation of gel-type binders as a result of asphalt high in asphaltenes, pavements constructed with those products are designed for early failure (Johnson and Hesp 2014). On the basis of a review of the currently published literature, it was noted that the study did not extend research into asphalt mixture performance testing.

In 2012, D’Angelo et al. published the results of a study that evaluated asphalt binders modified with ReOB at concentration levels ranging from 2% to 20%. D’Angelo et al. (2012) concluded that ReOB blends easily with typical asphalt binders; modification with ReOB reduces the high-, intermediate-, and low-temperature stiffness of the binder blends and is dependent on the sources of both the ReOB and the base asphalt; low-temperature strain tolerance of the binder blends is improved; and no negative effects on aging properties or adhesion properties of the asphalt binder ReOB blends were observed (D’Angelo et al. 2012). It was also noted that the study did not include extended conditioning, nor did it extend research in asphalt mixture performance testing.

In 2013, D’Angelo et al. published a second paper regarding ReOB-modified binders that consisted of a laboratory study of asphalt mixes blended with ReOB at various levels, ranging from 2% to 10%. Asphalt mixes evaluated consisted of an Illinois DOT N70 (70 gyration) and N90 (90 gyration) SuperPave mix. Each mix design was evaluated for rutting resistance, resistance to moisture damage, fatigue resistance, and low-temperature cracking. In that study, D’Angelo et al. (2012) concluded that the ReOB-blended mixes performed as well or better than the control mixes of similar binder stiffness in both of the high-temperature rutting performance tests (HWT and flow number). Tests for resistance to moisture-induced damage (AASHTO T283) indicated that binder blends up to 6% ReOB provided results equal to those of the various control binders and did not indicate any stripping potential. Beam fatigue testing (ASTM D7460) indicated that ReOB mixes provided equivalent or better fatigue response than the control mixes. Disk-shaped compact tension (DCT) testing (ASTM D7313) indicated that the ReOB mixes provided equal or greater crack resistance than the control mixes (D’Angelo et al. 2013). The study did not perform testing with long-term-aged mixtures.

In 2014, Heritage Research Group issued a paper titled “Chemical Analysis of Asphalt Blended with Re-refined Vacuum Tower Bottoms (RVTB) and Their Effect on HMA Mixture Performance” (Wielinski et al. 2014). In that study, the following conclusions were made regarding asphalt binder testing: (1) chemical analysis by XRF showed a higher presence of some inorganic compounds (metals) in the ReOB-modified binder than in the neat asphalt binder, with phosphorous and zinc being the two most prominent elements; (2) adding ReOB to asphalt binder did not produce a significant difference in carcinogens known as polycyclic aromatic compounds (PACs), indicating that blending with ReOB does not pose any additional environmental or health issues; (3) the molecular weight analysis indicated that ReOB might have caused accelerated aging as observed with the changes in molecular weight after aging of the ReOB blend, compared with the neat binder; (4) blending 9% RVTB with neat PG 64-22 produced an asphalt binder that meets PG 58-28 specification, and the PG 58-28 ReOB binder and neat PG 58-28 had comparable dynamic shear rheometer (DSR) results after rolling thin film oven (RTFO) and pressure aging vessel (PAV) aging, suggesting good fatigue properties.

The 2014 Heritage Research Group paper (Wielinski et al. 2014) also presented the results of asphalt mixture testing using neat PG 58-28 and PG 58-28 ReOB-blended binders. The results of that testing are summarized as follows: (1) The control asphalt mixture was successfully designed with 70 gyrations (N70) to meet IDOT's HMA requirements; (2) the ReOB binder mix was less susceptible to the loss of strength from water as evidenced by tensile strength ratio (TSR) test results, which showed better TSR values for the ReOB-blended binder. However, dry and wet tensile strength values were reduced with the modified asphalt mixture; (3) rutting resistance measured by HWT and flow number was nearly equal for both the neat and blended binder mixes and passed the Illinois rutting requirements; (4) stiffness of the asphalt mixes was found to be similar on the basis of dynamic modulus testing at low and intermediate temperatures; and (5) the results of artificially aged mix samples subjected to fatigue testing indicated that the ReOB mix had slightly improved resistance to fatigue (Wielinski et al. 2014).

1.2 RESEARCH OBJECTIVE

The current study was proposed to further evaluate the properties of asphalt binder modified with re-refined engine oil bottoms (ReOB) (e.g., WEO, RHVDO, and RVTB), or the non-distillation fraction of re-refined waste engine oils, and their effect on asphalt mixture benchmark performance tests. The objectives of this study are as follows:

- Evaluate the characteristics of PG asphalt binders modified with ReOB, and
- Evaluate the performance of asphalt mixtures utilizing ReOB-modified binders.

The neat and modified binders were evaluated initially through dynamic shear rheometer (DSR) testing (AASHTO T315) and bending beam rheometer (BBR) testing (AASHTO T313) in order to verify the target grade of PG 58-28 for the modified binder, which was used in the mixture-level tests. In addition, chemical characterization of the modified binders was performed in an accompanying study with a special focus on evaluating the impact of ReOBs on some of the chemical properties most representative of physical properties.

The performance of the modified binders in asphalt mixtures was evaluated through Hamburg wheel track (HWT) testing (AASHTO T324) and semi-circular bending (SCB) fracture testing (modified AASHTO TP105 and the recently proposed AASHTO test for intermediate-temperature fracture that resulted in a flexibility index used for characterization of overall damage resistance for asphalt mixtures). The effects of asphalt binder aging were evaluated on compacted mix samples using various laboratory aging procedures (short term, long term, and extended long term).

1.3 RESEARCH APPROACH

It was proposed to initially evaluate the PG of the neat binder (PG 58-28) and neat binder modified with 3%, 6%, and 9% ReOB, as shown on Table 1. Two different ReOB compounds were evaluated in this study, representing two separate sources of these products. At each ReOB blending percentage, the resultant binder grade was required to be PG 58-28 and was provided by Heritage Research Group. The neat PG 58-28 was also required to meet IDOT specification 1032.05 with no polyphosphoric acid (PPA) or other modifiers. True binder grading and multiple-stress creep recovery (MSCR) testing were performed by the North Central SuperPave Center for all asphalt binder samples used in the study.

This evaluation utilized an N70 design (70 gyrations) asphalt mixture. The asphalt mixture design was selected from established and previously evaluated IDOT-approved mix designs currently in use. The asphalt mixtures were prepared using neat binder, and ReOB-modified binders all with a target of PG 58-28, as indicated in Table 1. All of the mixture test specimens were prepared after short-term, 2 hr mix aging (STA) to simulate plant production and placement aging. One set of asphalt mixture samples was subjected to additional aging in accordance with the AASHTO R30 procedure to simulate long-term aging (LTA). The AASHTO R30 procedure consists of aging compacted test specimens at 85°C (185°F) for a period of 5 days prior to testing. Finally, a set of asphalt mixture samples was subjected to extended long-term aging (ELTA) by doubling the specified time for the long-term aging in the AASHTO R30 procedure to simulate extended long-term aging (i.e., longer than 10 years of service life). The performance of the STA specimens was evaluated using the HWT and SCB test methods. The SCB fracture tests were conducted at low and intermediate temperatures (e.g., –12°C [10.4°F] and 25°C [77°F]). The performance of the LTA and ELTA specimens was evaluated using the SCB test method conducted at 25°C (77°F) only. The test matrix also included determination of ash content based on ASTM D2939 and the Ontario Ministry of Transportation’s LS-227 for neat and modified binders.

The scope of the testing program and number of individual tests are presented in Table 1.

Table 1. Asphalt Mixture-Level Test Matrix[1,2,3]

Binder	STA–SCB	Wheel Track	LTA–SCB[2]	ELTA–SCB[2]	Ash Content
PG 58-28 (neat)	8 tests	2 tests	4 tests	4 tests	2 tests
PG 58-28 (using 3% ReOB)	8 tests	2 tests	4 tests	4 tests	2 tests
PG 58-28 (using 6% ReOB)	8 tests	2 tests	4 tests	4 tests	2 tests
PG 58-28 (using 9% ReOB)	8 tests	2 tests	4 tests	4 tests	2 tests

[1] The modified binder test matrix was completed for both ReOB compounds.

[2] SCB fracture tests were conducted only at 25°C (77°F) for LTA and ELTA specimens.

[3] Number of tests indicate proposed plans.

1.4 REPORT ORGANIZATION

The scope of the research study included laboratory testing for both asphalt binders and asphalt mixtures using the modified binders. The results from the industry survey are discussed first in this report followed by a description of the experimental program and presentation of the laboratory findings. Chapters are organized as follows:

Chapter 2 of this report presents a summary of the materials used in the study. The scope of the laboratory performance testing for the modified asphalt binder and the asphalt mixtures is also presented.

Chapter 3 includes laboratory testing results and analysis for asphalt binders and mixtures.

Chapter 4 summarizes the main findings of this study and presents a discussion and recommendation of potential applications.

CHAPTER 2: TESTING METHODOLOGY AND MATERIALS

An experimental program was developed to evaluate the PG of asphalt binder modified with ReOB, as well as the strength performance of asphalt mixtures using these modified binders. This chapter provides information on the aggregate and asphalt binder materials used in the project.

2.1 MATERIALS

The asphalt binder used in this study is PG 58-28. All binders were obtained from Heritage Research Group, where the neat binder was modified with varying additions of ReOB (3%, 6%, and 9%). Two ReOB materials were used in this study: SK-type and CC-type produced by two manufacturers. It is important to note that all binder final blends had a PG 58-28 grade. As ReOB increased from 0% to 9%, there was a corresponding reduction in asphalt flux (cutter stock) to maintain the same PG 58-28 grade. Aggregates were supplied and fractionated by Heritage Research Group. One type of asphalt mixture design was utilized for the seven different asphalt binder blends included in the study. The aggregate gradations of this mix are provided in Table 2. The aggregate blend had a combined aggregate specific gravity of 2.608. In addition to the IDOT-modified SuperPave mix design methods, the Bailey method was used to design the asphalt mixture. The asphalt mixture had an asphalt content of 6.1% for all binders assessed in this study. A summary of the mix design parameters is as follows:

- NMAS: 9.5 mm (3/8 in)
- Design Gyrations (N_d): 70
- Voids in Mineral Aggregates (VMA): 15.1% (for control) to 14.7% (for 9% CC-type ReOB)
- Voids Filled with Asphalt (VFA): 64.8% to 70.5%

Table 2. Aggregate Gradations and Mixture Design Parameters for the N70 Design

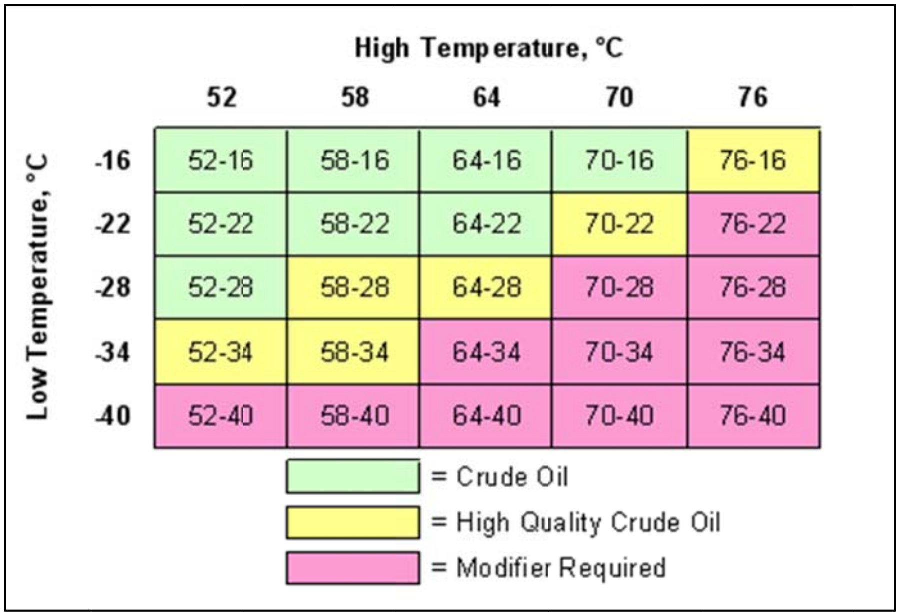
% Passing Sieve	Combined	CM16 (43.8%)	FM20 (25.7%)	FM01 (5.0%)	MF (0.5%)	Coarse RAP (1.6%)	Fine RAP (23.4%)
1" (25.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4" (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1/2" (12.5 mm)	100.0	100.0	100.0	100.0	100.0	87.4	100.0
3/8" (9.5 mm)	83.0	98.0	100.0	100.0	100.0	62.5	95.9
No. 4 (4.75 mm)	23.0	29.0	99.5	99.8	100.0	31.4	75.3
No. 8 (2.36 mm)	8.0	4.9	73.9	91.9	100.0	21.2	45.1
No. 16 (1.18 mm)	6.0	3.6	44.9	70.0	100.0	15.4	31.3
No. 30 (600 µm)	5.0	3.1	27.8	45.0	100.0	11.9	21.3
No. 50 (300 µm)	5.0	2.8	15.5	14.6	100.0	8.6	16.2
No. 100 (150 µm)	4.0	2.6	7.2	2.8	95.0	6.5	13.8
No. 200 (75 µm)	2.8	2.4	3.7	1.5	85	5.4	9.6
Bulk Spec Gravity	3.365	2.644	2.691	2.619	2.900	2.500	2.500
Apparent Spec Gravity	3.582	2.792	2.796	2.719	2.900	—	—-
Absorption (%)	1.80	2.00	1.40	1.40	1.00	1.00	1.00
Recycled Binder (%)						3.8%	5.7%

2.2 ASPHALT BINDER TESTS

This section describes the asphalt binder tests conducted in this study. All asphalt binders were graded using the American Association of State Highway and Transportation Officials (AASHTO) Performance-Graded Binder Specification (M320). In addition, the ash content was determined.

2.2.1 Asphalt Binder Performance Grading

The Strategic Highway Research Program (SHRP) produced the SuperPave binder specifications based on the idea that the asphalt binder's properties should be related to the conditions under which the asphalt binder will be used. The PG binders are tested and characterized to address asphalt pavement performance parameters such as rutting, fatigue cracking, and thermal cracking. The PG system uses a common suite of tests that considers aging and characterizes the temperatures and climatic conditions in which a specific binder should be used. Therefore, the SuperPave PG grading system provides a more precise relationship between the asphalt binder properties and the conditions of use. The rolling thin film oven (RTFO) and pressure aging vessel (PAV) are used to age the asphalt binder per the requirements of the conducted tests. The RTFO procedure is described in AASHTO T240, Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin Film Oven Test). The PAV procedure is described in ASTM D6521-13, Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV).The SuperPave PG grading uses the rotational viscometer (RV), the dynamic shear rheometer (DSR), the bending beam rheometer (BBR), and the direct tension tester (DTT) to grade the asphalt binder. The PG grading system uses two numbers to report the grade of the asphalt binder. The first is the average 7-day maximum pavement temperature (°C), while the second is the minimum pavement design temperature likely to be experienced (°C). It is important to note that these temperatures are pavement temperatures and not air temperatures. Figure 1 illustrates the predicted PG grades for different crude oil blends. Typically, PG binders that differ in the high- and low-temperature specification by 90°C or more require modification.



High Temperature, °C

Low Temperature, °C	52	58	64	70	76
-16	52-16	58-16	64-16	70-16	76-16
-22	52-22	58-22	64-22	70-22	76-22
-28	52-28	58-28	64-28	70-28	76-28
-34	52-34	58-34	64-34	70-34	76-34
-40	52-40	58-40	64-40	70-40	76-40

🟩 = Crude Oil
🟨 = High Quality Crude Oil
🟥 = Modifier Required

Figure 1. Predicted PG grades for different crude oil blends (accessed at www.pavementinteractive.org).

The standard summary table of the AASHTO M320 specification for the PG asphalt binder grading is presented in Appendix A. All of the SuperPave PG grading tests except the DTT were used to determine the grade of binders in this study. The top rows of that table are used to determine the desired PG grade based on the different conducted tests. Tests are run on the original binder to simulate no aging, after RTFO aging to simulate short-term aging, and after PAV aging to simulate long-term aging. However, it is important to note that this short- and long-term aging cannot be quantified to exact years of service in the field.

2.2.2 Ash Content (per ASTM D2939 and LS-227)

Section 10 of ASTM International’s D2939 and the Ontario Ministry of Transportation’s LS-227 were used to calculate the ash content of the studied asphalt binders with different percentages of ReOB. For this test, a porcelain crucible of 30 cm^3 capacity, a balance capable of weighing 50 g to within ± 0.01 g, and a muffle furnace capable of maintaining a temperature of 1100 ± 10°F were used. Prior to the test, the asphalt binder was stored in a desiccator at all times. The asphalt binder was thoroughly mixed. A 3 ± 0.5 g sample was weighed to the nearest 0.01 g in a previously ignited and tared crucible. The content was incinerated inside the muffle furnace at a temperature of 600°C (1110°F) to constant weight. This procedure was completed under a fume hood because the incineration produced black smoke. The mass of ash after ignition was recorded, and the ash content was calculated using the following equation:

$$\boldsymbol{A_r = A/S \times 100}$$

where

A_r is the ash content
A is the mass of ash after ignition (g)
S is the mass of sample (g)

2.3 ASPHALT MIXTURE TESTS

An experimental program was followed to evaluate the strength performance of asphalt mixtures with various percentages and materials of ReOB. The Hamburg wheel track (HWT) test was utilized to evaluate the mixtures’ resistance to permanent deformation, while the semi-circular bending beam (SCB) test was used to evaluate the low and intermediate-temperature cracking resistance at multiple aging levels.

2.3.1 Hamburg Wheel Track Test (Illinois Modified AASHTO T324)

The HWT was utilized to measure the rutting performance of the designed asphalt mixtures. The HWT is electrically powered and is designed to run a 203.2 mm (8.0 in) diameter, 47.0 mm (1.85 in) wide steel wheel over the tested specimen. The apparatus has two wheels to accommodate two testing specimens at a time. Each wheel has a load of 705 ± 4.5 N (158.0 ± 1.0 lb), and passes about 52 ± 2 passes per minute across the specimen at a speed of 0.305 m/s (1 ft/sec). Figures 2 and 3 show the HWT test specimen mold and apparatus. Samples were tested while being submerged in water bath that had a temperature of 50°C (122°F). The rutting performance was evaluated with the final rut depth caused by the movement of the wheels on the specimens after a specific number of passes. The HWT system records the displacement at 11 locations on the specimen for each wheel pass.

Permanent deformation curves were plotted using the data exported from the HWT system to characterize the rutting performance by showing the rut depth with respect to the increased number of wheel passes. In this test, the extreme points (control, 9% CC, and 9% SK) were tested.

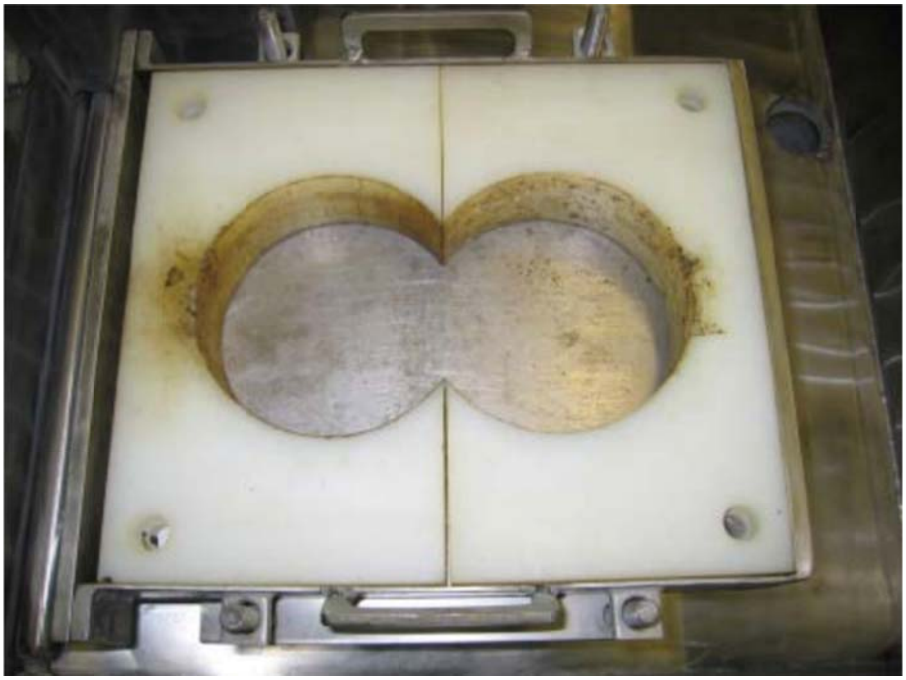


Figure 2. HWT test specimen mold.

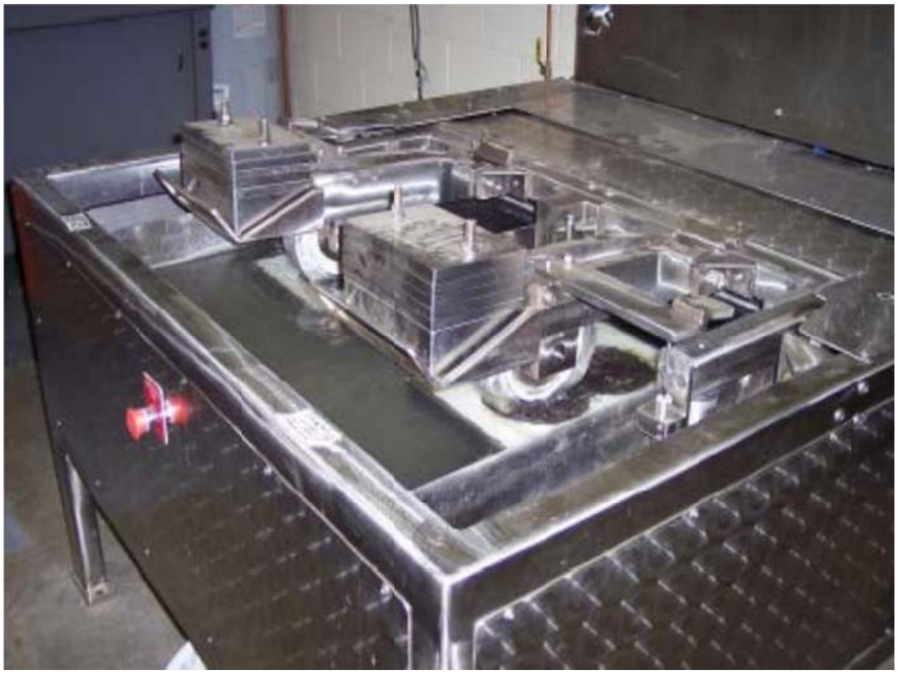
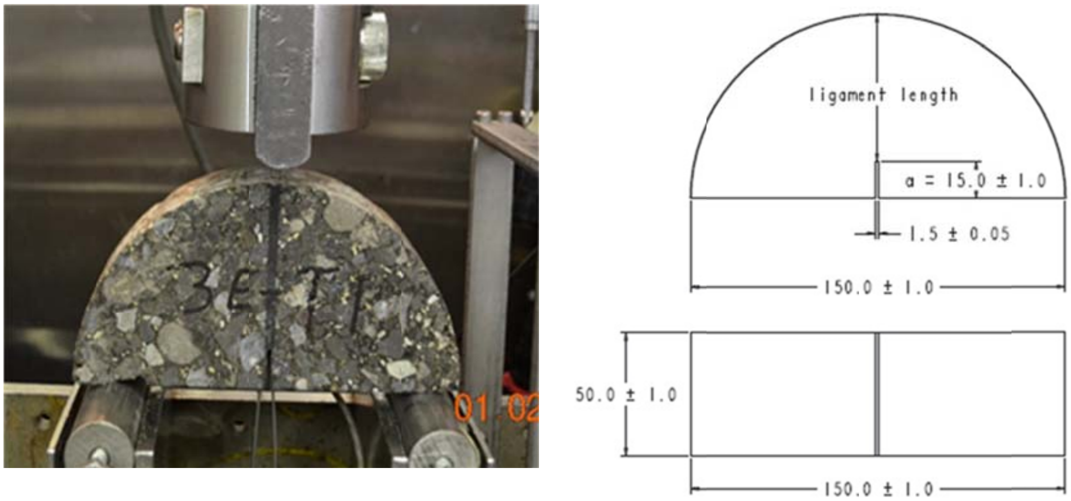


Figure 3. HWT test apparatus.

2.3.2 Semi-Circular Bending Beam Test

The semi-circular bending beam (SCB) test was used to determine the fracture energy and flexibility index of asphalt mixtures containing asphalt binder modified with ReOB. Fracture energy is defined as the area under the load-displacement curve. This test was conducted using a custom-designed SCB fixture that was placed in a servo-hydraulic asphalt testing machine (as shown in Figure 4). Two load cells with capacities of 44 kN and 97.8 kN (10 kips and 22 kips) were used for this test to measure the fracture load. Two types of fracture tests were conducted. First was the SCB fracture test at intermediate temperatures based on the standard protocols developed recently in ICT study R27-128, “Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS.” The intermediate-temperature SCB was linear variable differential transformer (LVDT)-controlled, tested at 25°C (77°F) with a monotonic load applied along the vertical diameter of the specimen at a displacement rate of 50 mm/min (1.96 in/min). The second fracture test was conducted at –12°C (10.4°F). At that temperature, the test was strain-controlled with a crack mouth opening displacement (CMOD) rate of 0.7 mm/min (0.028 in/min). The cracking load rate was slower in order to ensure stable crack growth during the test. Testing was conducted inside an environmental chamber that could maintain temperatures ranging from –40°C to 150°C (–40°F to 302°F), which helps to control and maintain the test’s temperature after conditioning the specimens.



(a) (b)

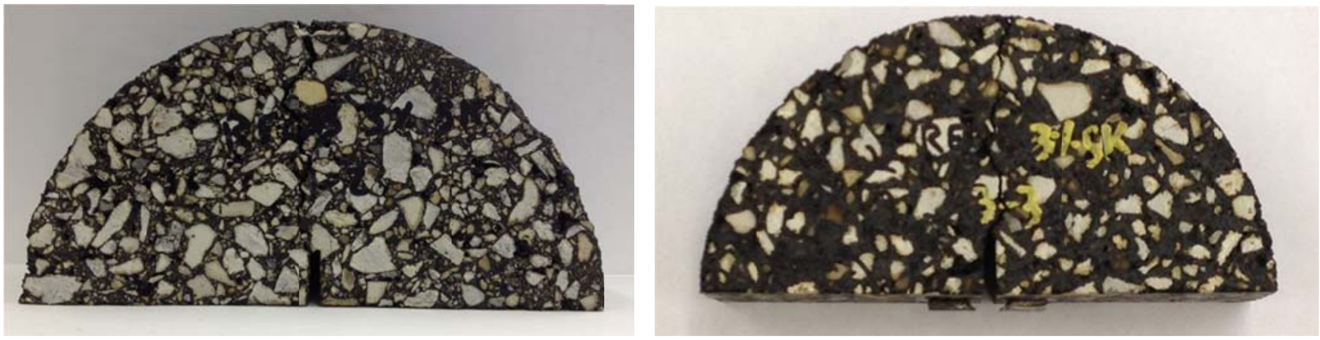
Figure 4. SCB test specimen and configuration (left) and geometry of specimen and fixture (right) with an external LVDT.

In this study, the SCB test was conducted under four different conditions as follows:

- Short-term aging (STA): asphalt mixtures were aged only during the production of the mix, and fabricated specimens were tested at 25°C (77°F).
- Low temperature (LT): asphalt mixtures were aged only during the production of the mix, and fabricated specimens were tested at –12°C (10.4°F).

- Long-term aging (LTA): asphalt mixtures were aged during the production of the mix and specimens were fabricated. Specimens were further aged for 5 days at 85°C (185°F) in the oven in accordance with AASHTO R30. Specimens were tested at 25°C (77°F).

- Extra-long-term aging (ELTA): asphalt mixtures were aged during the production of the mix, and specimens were fabricated. Specimens were further aged for 10 days at 85°C (185°F) in the oven. Fabricated specimens were tested at 25°C (77°F).



Short-term aged (STA)

Long-term aged (LTA)

Extra-long-term aged (ELTA)

Figure 5. SCB specimens after short-term aging (2 hr of oven conditioning at compaction temperature), long-term aging (5 days of oven conditioning at 85°C [185°F]), and extra-long-term aging (10 days of oven conditioning at 85°C [185°F]).

The SCB specimens were fabricated from 180.0 mm (7.0 in) gyratory-compacted specimens. Two slices, each with a thickness of 50.0 mm (20 in), were cut from the middle of the specimen as illustrated in Figure 6. The slices were cut in half and notched to produce four SCB specimens per each 180 mm (7 in) gyratory-compacted specimen. Specimens were dried after fabrication for 24 hr using an electric fan. LTA and ELTA specimens were aged for 5 days and 10 days, respectively, in an oven at 85°C (185°F) in accordance with AASHTO R30. Specimen geometry was checked before and after aging to assess any changes in dimensions while aging the specimens caused by potential creep. Thickness, radius, ligament, crack depth, and crack width were measured before and after aging the specimens. A difference of 0.1 to 0.8 mm (0.004 to 0.03 in), which corresponds to a 0.1% to 3% difference, was noticed. This was considered insignificant because specimens are allowed a 1.0 mm (0.04 in) margin of error per the test method. Gauge points were loaded on the specimens to control the CMOD while testing at low temperature. Dried specimens that were tested at 25°C (77°F) were conditioned in an environmental chamber until reaching the targeted temperature. Temperature was monitored using a thermocouple embedded in a dummy specimen. Specimens that were tested at –12°C (10.4°F) were conditioned in a freezer for 24 hours, and the targeted temperature was monitored with a similar thermocouple system.

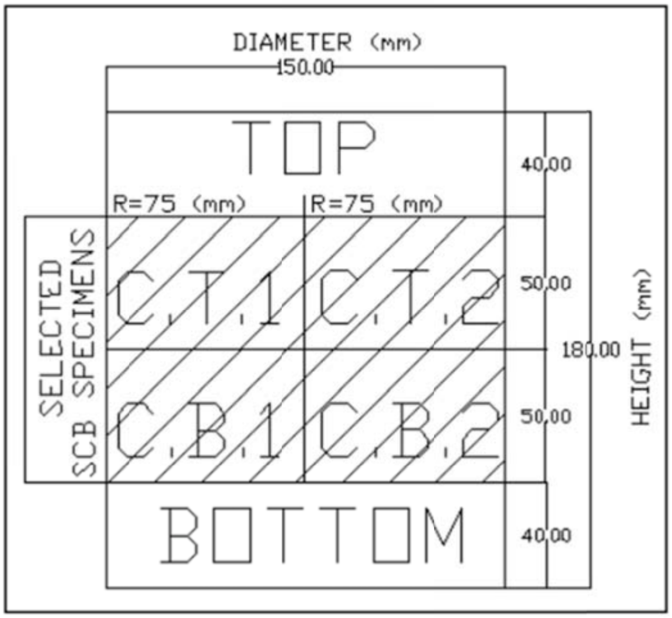


Figure 6. SCB specimen fabrication.

CHAPTER 3: ANALYSIS AND RESULTS

3.1 SCOPE OF LABORATORY TESTING

The results of the aforementioned tests were analyzed to evaluate the performance of asphalt binder using different percentages of ReOB. In addition, the results of the semi-circular bending beam (SCB) and the Hamburg wheel track (HWT) tests were analyzed to examine the impact of various materials and percentages of ReOB at the mixture level. A minimum of four replicates were tested in the SCB test and two replicates were tested for the HWT test to ensure statistical repeatability. The averages, standard deviations, and coefficient of variations were calculated for the results of the SCB test. The error bars based on the standard deviation were plotted on graphs.

3.1.1 Asphalt Binder Performance Grading

All asphalt binders with two types of ReOB (CC and SK) and various percentages of ReOB (3%, 6%, and 9%) were characterized using the SuperPave asphalt binder performance grading (PG) system. The asphalt binders were tested at three different aging levels using the original binder, the rolling thin film oven (RTFO) aging, and the pressure aging vessel (PAV) aging, per the requirements of AASHTO M320 specifications. Several tests at low, intermediate, and high temperatures were conducted on the studied binders; those tests were rotational viscosity (RV), dynamic shear rheometer (DSR), and the bending beam rheometer (BBR) test. The tests were run by three different institutions: Heritage Research Laboratories, North Central SuperPave Center, and the Illinois Department of Transportation’s Asphalt Binder Testing Laboratory. Figures 7 through 10 and Table 3 present the results of the tests and show a comparison between the results of the three different labs. All binders were graded as PG 58-28. The results from the three labs appeared to be consistent. A reduction in the stiffness between control and 9% ReOB samples was evident by the BBR test at –18°C (–0.4°F) and DSR test at an intermediate temperature of 19°C (66.2°F).

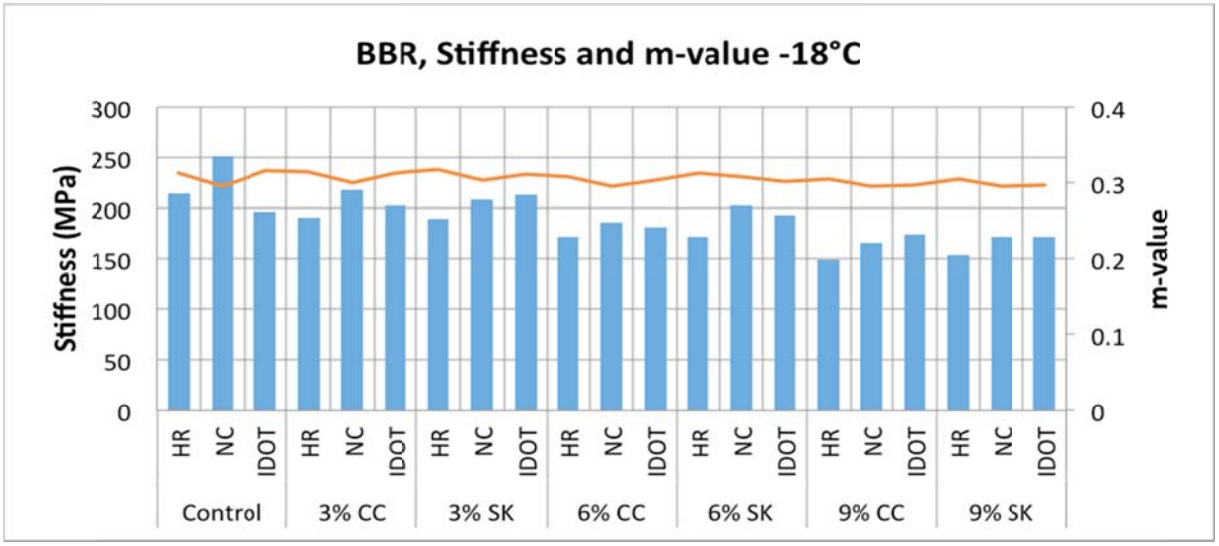


Figure 7. BBR stiffness and m-value results at –18°C (–0.4°F).

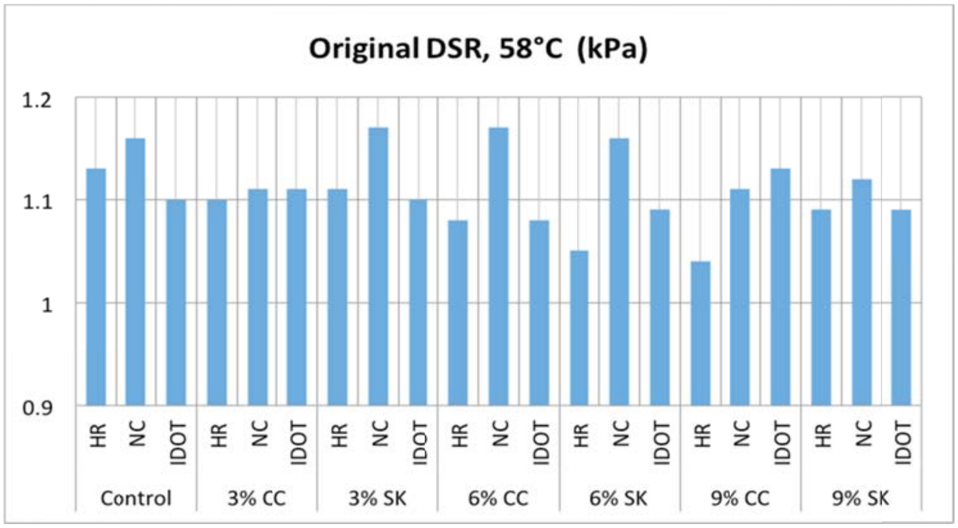


Figure 8. DSR results for original binder at 58°C (136°F).

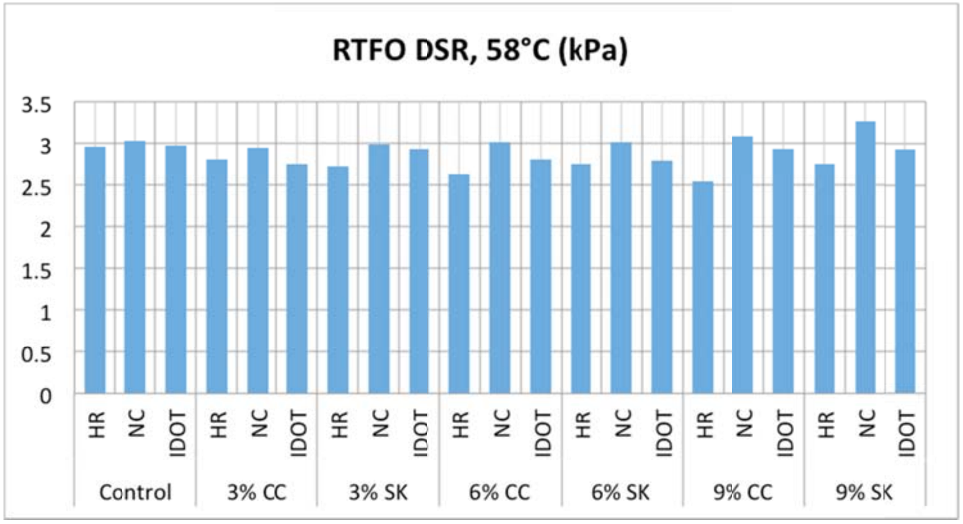


Figure 9. DSR results for RTFO binder at 58°C (136°F).

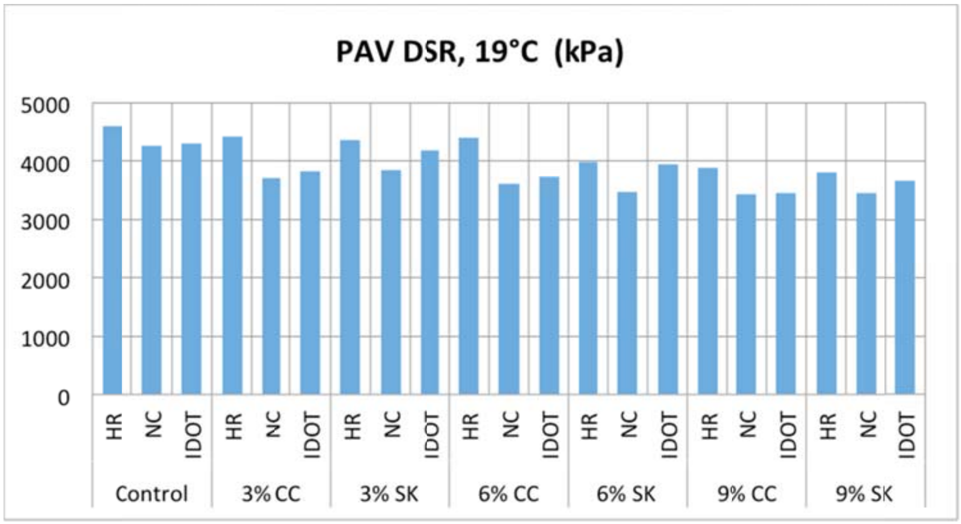


Figure 10. DSR results for PAV binder at 19°C (66°F).

Table 3. Summary of SuperPave Binder Grading Results

Material	**Control**			**3% CC**			**3% SK**			**6% CC**			**6% SK**			**9% CC**			**9% SK**		
Testing lab	**HR**	**NC**	**IDOT**	**HR**	**NC**	**IDOT**	**HR**	**NC**	**IDOT**	**HR**	**NC**	**IDOT**	**HR**	**NC**	**IDOT**	**HR**	**NC**	**IDOT**	**HR**	**NC**	**IDOT**
Original DSR, 58°C, kPa	1.13	1.16	1.1	1.1	1.11	1.11	1.11	1.17	1.1	1.08	1.17	1.08	1.05	1.16	1.09	1.04	1.11	1.13	1.09	1.12	1.09
RTFO DSR, 58°C, kPa	2.96	3.03	2.97	2.81	2.95	2.75	2.72	2.99	2.93	2.63	3.01	2.8	2.75	3.02	2.79	2.54	3.09	2.93	2.75	3.26	2.93
PAV DSR, 19°C, kPa	4597	4276	4300	4424	3702	3840	4359	3855	4180	4411	3603	3730	3983	3470	3950	3884	3431	3460	3817	3459	3670
BBR, m-value, –18°C	0.312	0.296	0.316	0.314	0.300	0.313	0.318	0.303	0.311	0.308	0.295	0.303	0.312	0.308	0.301	0.305	0.296	0.297	0.305	0.296	0.297
BBR, stiffness, –18°C, MPa	214	251	197	191	218	202	189	209	213	171	186	181	172	202	193	149	166	174	154	172	171
Pass/fail temperature, °C	58.9	59.2	58.7	58.7	58.8	58.9	58.8	59.2	58.7	58.6	59.2	58.6	58.4	59.2	58.6	58.3	58.8	58.9	58.7	59	58.7
	–29	–27.6		–29	–28		–29	–28.3		–28	–27.6		–29	–28.7		–28	–27.6		–28	–27.6	
Rot. Vis., 135° Pa-s		0.25	0.254		0.263	0.256		0.25	0.259		0.263	0.258		0.338	0.255		0.3			0.275	0.272
Mass loss RTFO, %	0.337	0.34	0.323	0.199	0.285	0.227	0.219	0.32	0.289	0.115	0.245	0.17	0.13	0.22	0.179	0.075	0.17	0.12	0.133	0.17	0.151
***Jnr* @ 3.2 kPa, RTFO, 1/kPa**		3.33	3.34		3.41	3.57		3.34	3.37		3.3	3.55		3.27	3.58		3.2	3.36		3.03	3.37
% *Jnr* difference, (between 0.1 & 3.2 kPa)		12.04	10.95		12.94	13.4		12.22	12.68		15.19	13.42		14.38	13.63		17.67	15.58		14.71	15.3
% recovery @ 3.2 kPa		0.39	0.22		0.37	0.11		0.4	0.3		0.59	0.16		0.59	0.23		0.76	0.51		0.93	0.55

HR: Heritage Research Laboratory

NC: North Central SuperPave Center

IDOT: IDOT BMPR’s Chemistry and Asphalt Binder Testing Laboratory

3.1.2 Ash Content

The ash content test was conducted on all seven binder blends in accordance with the standard specifications (ASTM D2939). Table 4 presents the calculated ash content. The ash content for all binders ranged from 0.05 to 0.72%. There was a consistent increasing trend in the ash content with increasing ReOB content.

Table 4. Ash Content Results

Sample	W crucible	W c+sample	W c+ash	W sample	W ash	Ash content	Average
0% Neat	42.686	44.422	42.686	1.736	0.000	0.000%	**0.053%**
	47.283	49.186	47.285	1.903	0.002	0.105%	
3% CC	40.657	41.777	40.658	1.120	0.001	0.089%	**0.081%**
	47.381	48.766	47.382	1.385	0.001	0.072%	
3% SK	47.456	49.305	47.461	1.849	0.005	0.270%	**0.288%**
	42.586	45.523	42.595	2.937	0.009	0.306%	
6% CC	47.870	51.377	47.887	3.507	0.017	0.485%	**0.512%**
	42.400	44.070	42.409	1.670	0.009	0.539%	
6% SK	47.461	49.021	47.466	1.560	0.005	0.321%	**0.325%**
	43.724	45.245	43.729	1.521	0.005	0.329%	
9% CC	42.588	44.661	42.601	2.073	0.013	0.627%	**0.638%**
	41.293	43.235	41.306	1.942	0.013	0.669%	
	42.402	45.638	42.422	3.236	0.020	0.618%	
9% SK	42.404	43.405	42.411	1.001	0.007	0.699%	**0.728%**
	47.870	49.456	47.882	1.586	0.012	0.757%	

3.1.3 Hamburg Wheel Track Test

The Hamburg wheel track tests were performed in this study on the asphalt mixture that had neat 58-28 asphalt binders, in addition to asphalt binders modified with 9% CC and 9% SK. All materials reached 20 mm (0.8 in) in rut depth before 20,000 cycles were completed, which terminated the test at the corresponding number of passes. Table 5 shows the maximum rut depths at the end of each test.

Table 5. HWT Test Results

Binder Type	Average Air Voids	Average VMA	Final Rut Depth (mm)	Number of Passes
Neat PG 58-28	7.29	17.86	20.0	11,003
PG 58-28 9% CC Blend	7.31	17.87	20.0	10,410
PG 58-28 9% SK Blend	7.38	17.93	20.0	11,050

Figure 11 illustrates the impact of ReOB on the permanent deformation performance of asphalt mixes. According to the results, mixes with ReOB up to 9% had a permanent deformation performance similar to that of the control mix. This finding indicates that the softening effect of the ReOB up to 9% was not evident in the rutting performance of asphalt mixtures. All mixes passed the IDOT rutting criteria for mixes with asphalt binder of PG 58-28 (12.5 mm [0.49 in] at 7,500 passes).

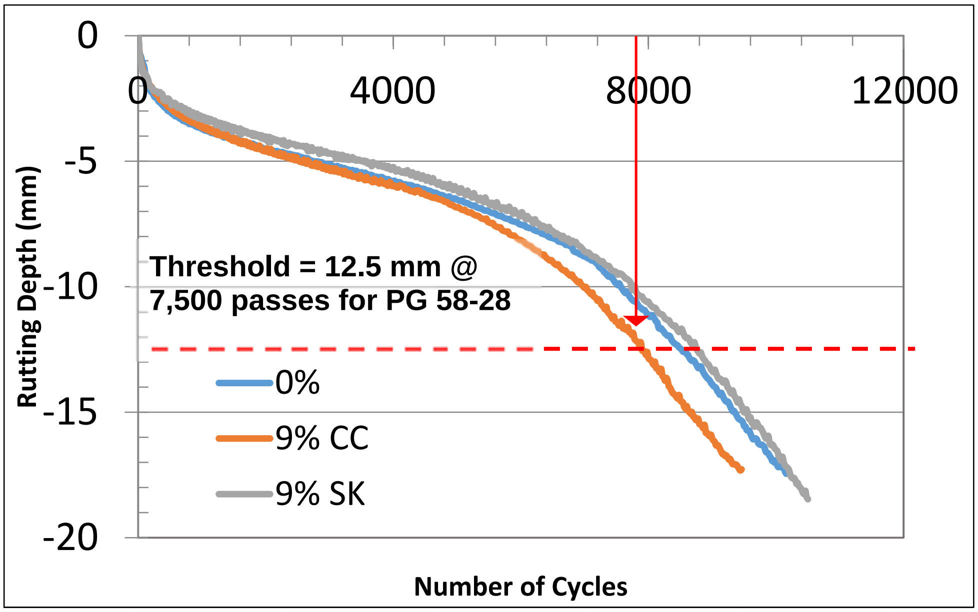


Figure 11. HWT test results.

3.1.4 Semi-Circular Bending Beam Test

The SCB fracture test was performed on asphalt mixes with various percentages of ReOB (3%, 6%, and 9%) and two ReOB materials (CC and SK). The mixes were tested at different conditioning and aging levels: short-term aged mixes conditioned at –12°C (10.4°F), **short-term aged mixes conditioned at 25°C (77°F), long-term aged mixes conditioned at 25°C (77°F), an**d extra-long-term aged mixes conditioned at 25°C (77°F). A minimum of four replicates was tested in all mixes; some mixes were tested with eight replicates. The average SCB parameters were calculated with a minimum of three replicates and more when data were available. The sample reduction technique consisted of removing outliers when the coefficient of variation was not satisfactory. Fracture energy was calculated using crack mouth opening displacement (CMOD) for low-temperature tests and the LVDT for intermediate-temperature tests. The peak load was recorded in addition to the displacement at failure. The SCB strength in MPa, the slope of the post-peak curve, and the slope's intercept with the x-axis were measured. In addition, the flexibility index (FI) was calculated to understand the change in flexibility with different levels of aging and various percentages of ReOB. The FI was calculated using the following equation:

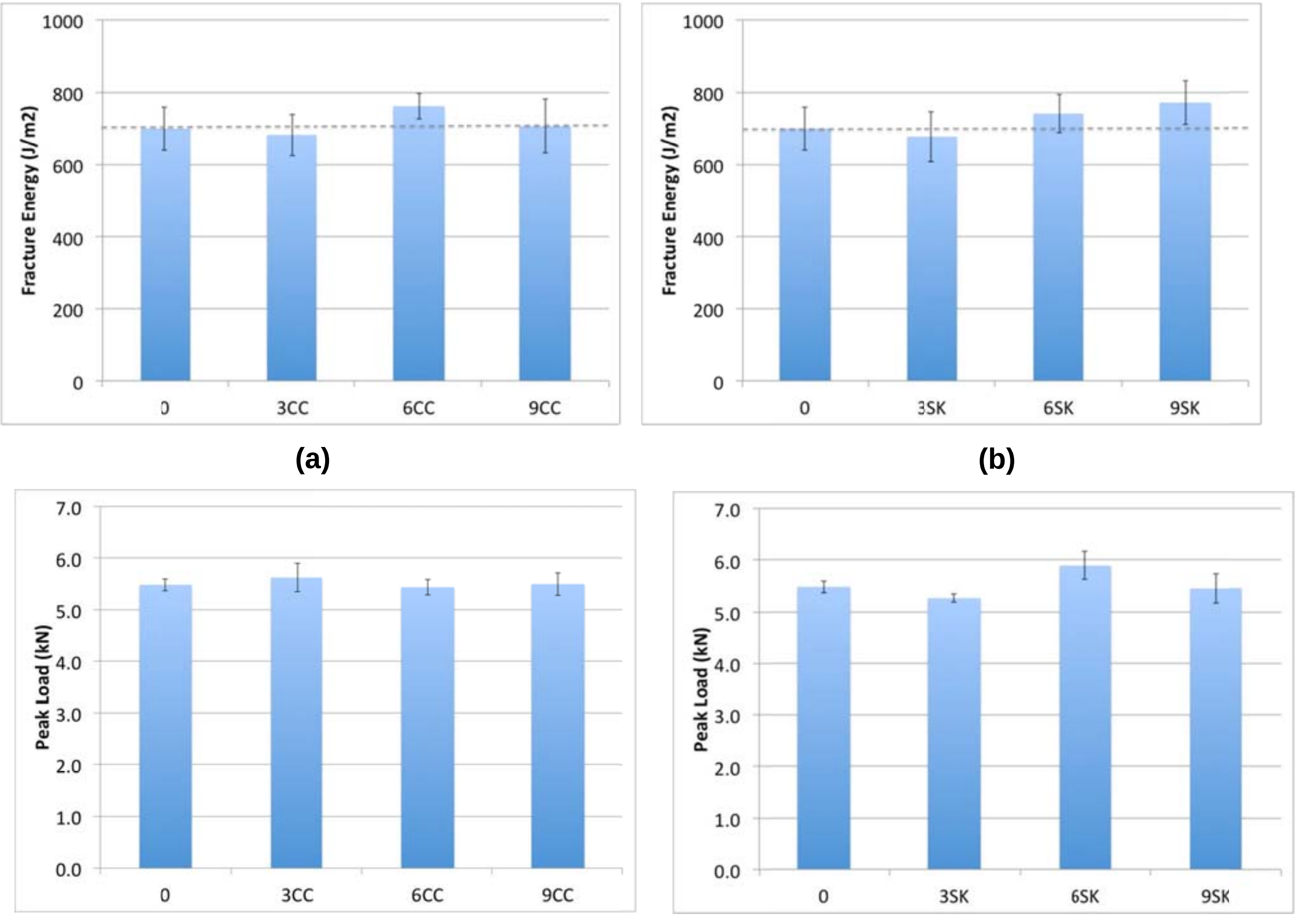
$$FI = A \times {}^{G_f}\!\big/_{abs(m)}$$

where G_f is fracture energy reported in J/m^2, and *m* is slope reported as kN/mm. Coefficient *A* is a unit conversion factor and scaling coefficient. *A* is 0.01 in this study.

This section presents the impact of the increased percentage of ReOB and the impact of aging on the strength performance of asphalt mixtures. This analysis was conduct based on the fracture energy, peak load, and the flexibility index.

3.1.4.1 *Impact of ReOB on Fracture Energy and Flexibility Index*

Figures 12 through 15 show the SCB fracture energy and peak load results for different mixes with two ReOB materials (CC and SK) and various percentages of ReOB (3%, 6%, and 9%) tested at different conditioning and aging levels. As shown in Figure 12, when the mixes were tested at low temperature, they exhibited insignificant differences in fracture performance in terms of fracture energy and peak load. The fracture energy for both ReOB materials at the studied percentages fluctuated around 700 J/m^2. Similarly, the peak load results for all the studied mixes fluctuated around 5.5 kN. The error bars on the figures show an insignificant statistical difference between different percentages of ReOB for both tested materials. This finding indicates that at low temperature, ReOB content up to 9% had an insignificant impact on the fracture performance of asphalt mixes. The results for both of the ReOB materials were similar.



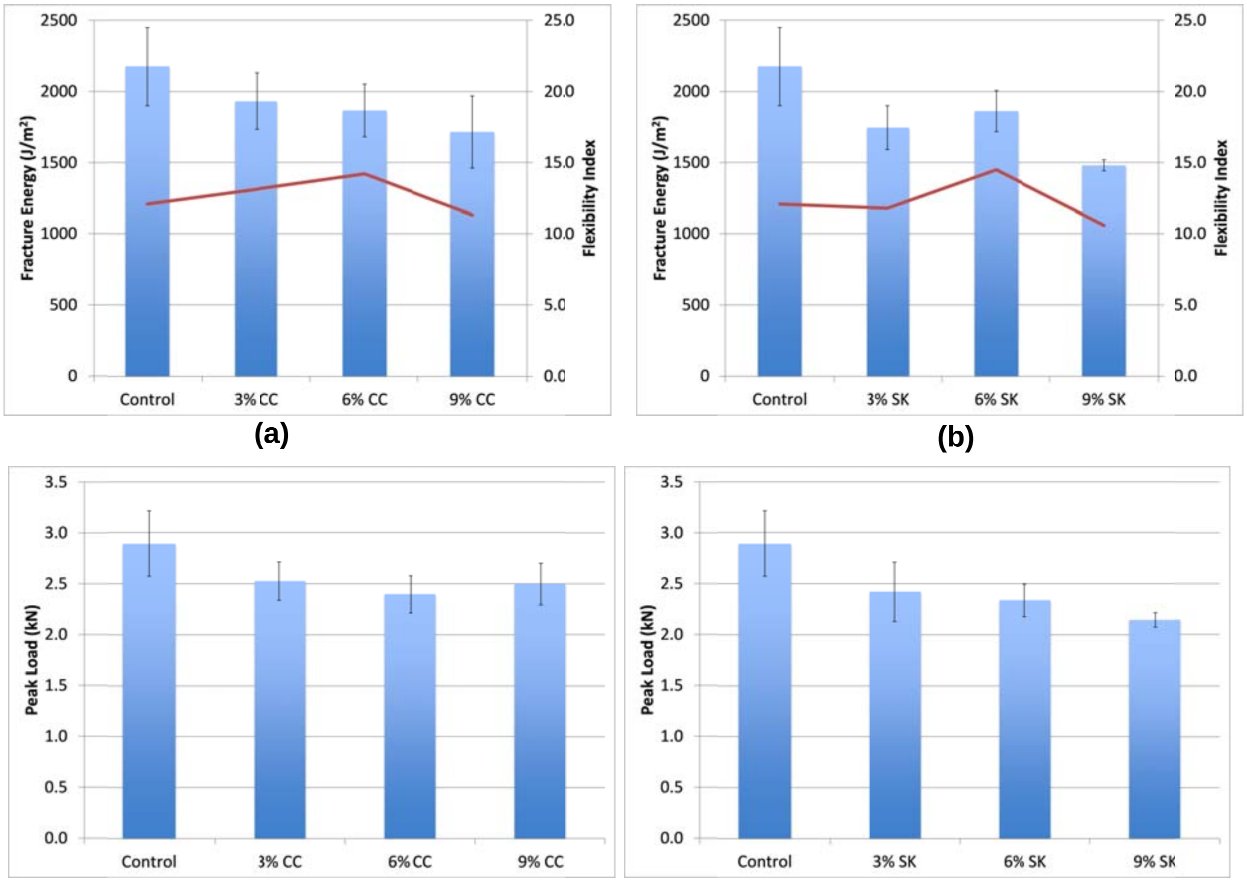
(a) (b)

(c) (d)

Figure 12. SCB results at –12°C (10.4°F).

Intermediate-temperature SCB test results are shown in Figure 13. A clear reduction in the fracture energy was observed when higher percentages of ReOB were used in asphalt binder. The peak loads showed a descending trend with higher percentages of ReOB for both products.

The FI showed an unclear trend because of two competing mechanisms, including loss of fracture energy and an increase in softening with higher percentages of ReOB. Unlike at low temperatures, asphalt mixes with ReOB at intermediate temperatures tended to decrease in fracture energy with higher percentages of ReOB and at the same time showed an increase in the slope of the post-peak curve. Because the FI is dependent on both the fracture energy and the post-peak slope, the FI values remained almost constant at the percentages of ReOB used in this study—fluctuating at around 13.0. The fracture energy increased at 25°C (77°F) compared with –12°C (10.4°F), while peak loads decreased as material exhibited more flexible behavior at intermediate temperature compared with low temperature. It is important to note that the average coefficient of variation for fracture energy and load was less than 10% for all testing conditions (low temperature and the three intermediate-temperature conditions) where the coefficient of variation for the FI was generally less than 20% (on average 15%, 20%, and 12% for the three aging conditions) for all specimens. Details about the statistics of the test results are provided in Appendix C.

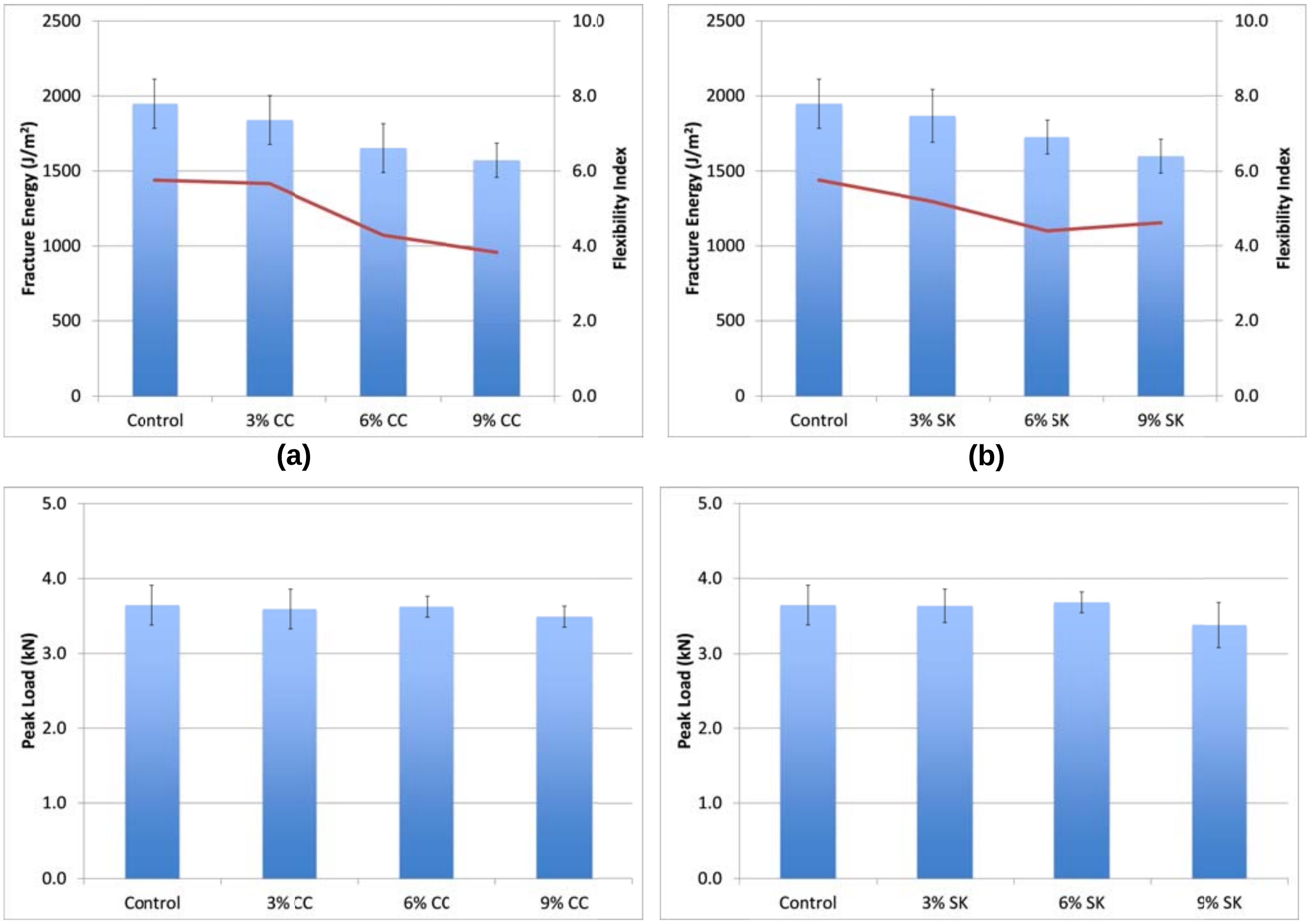


(a) (b)

(c) (d)

Figure 13. SCB results of short-term aging at 25°C (77°F): (a) fracture energy and FI of mixes prepared with CC-type ReOB; (b) fracture energy and FI of mixes prepared with SK-type ReOB; (c) peak load for mixes prepared with CC-type ReOB; (d) peak load for mixes prepared with SK-type ReOB.

Figure 14 presents the SCB results of long-term aging at 25°C (77°F). Fracture energy reduction with increasing ReOB was similar to that of short-term aged specimens. The peak loads increased with respect to the short-term-aged specimens and were around 3.5 kN as a result of the aging effect on the mixes. The softening effect of ReOB vanished once the material was aged according to the flexibility index results. The flexibility indexes decreased as higher percentages of ReOB were incorporated in the asphalt binder. As the fracture energy decreased and the slope of the post-peak curves increased, the result was a more brittle behavior and less-flexible material. This finding may indicate an increase over the long run in the brittleness of the mixtures modified with ReOB.

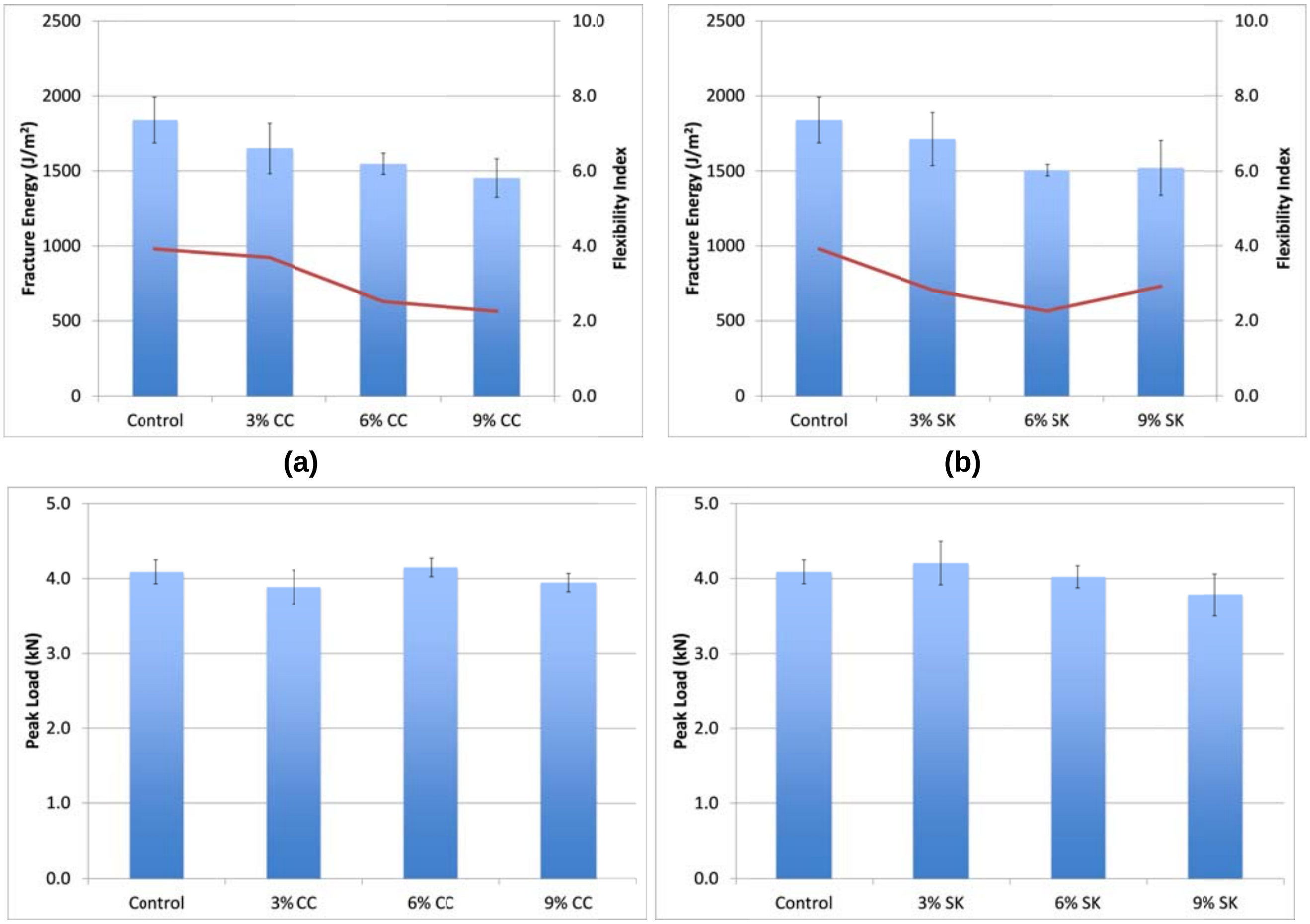


(a) (b)

(c) (d)

Figure 14. SCB results of long-term aging at 25°C (77°F): (a) fracture energy and FI of mixes prepared with CC-type ReOB; (b) fracture energy and FI of mixes prepared with SK-type ReOB; (c) peak load for mixes prepared with CC-type ReOB; (d) peak load for mixes prepared with SK-type ReOB.

The final aging level was the extra-long-term aging, as illustrated in Figure 15. A similar reduction trend in fracture energy and flexibility index was noticed as higher percentages of ReOB were incorporated in the asphalt mixes for both ReOB materials. The peak loads remained constant around 4.0 kN as the material was further aged—and thus exhibited a more brittle behavior compared with LTA. The drop in fracture energy with increasing ReOB content was also evident with ELTA specimens. Similar to the LTA specimens, the FI decreased with increasing ReOB content except in the mix prepared with 9% SK. When the general pattern of results is considered, this result may be considered an experimental anomaly.



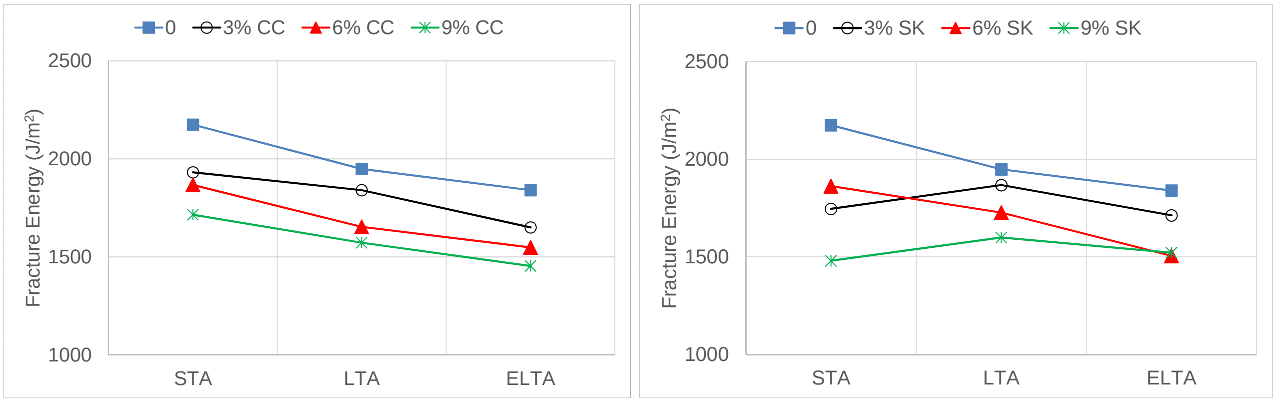
(a) (b)

(c) (d)

Figure 15. SCB results of extra-long-term aging at 25°C (77°F):
(a) fracture energy of mixes prepared with CC-type ReOB; (b) fracture energy of mixes prepared with SK-type ReOB; (c) peak load for mixes prepared with CC-type ReOB; (d) peak load for mixes prepared with SK-type ReOB.

3.1.4.2 Impact of Aging

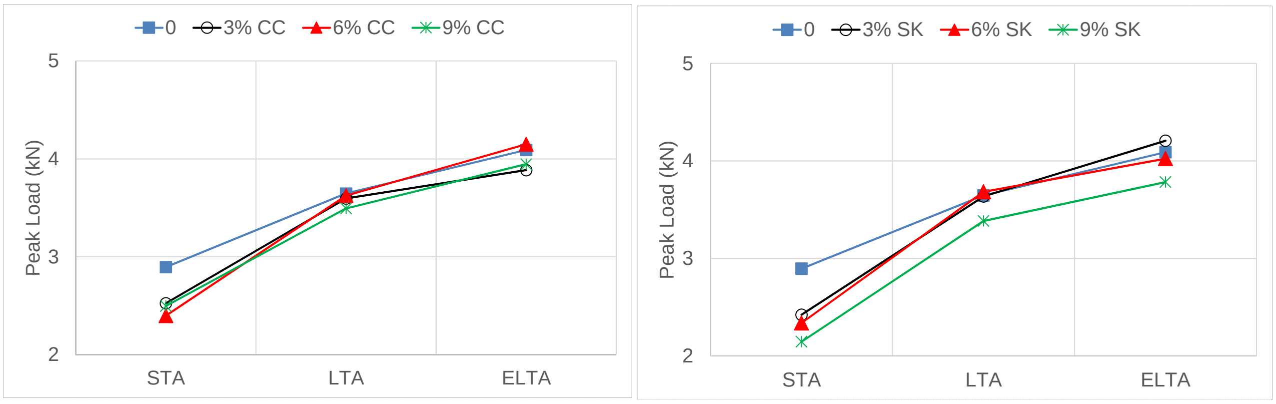
The results of the intermediate-temperature SCB testing were also used to evaluate the impact of aging. Initially, the effect of aging was shown with fracture energy results. The reduction trend with increased aging time was clear for all mixes. Figure 16 illustrates a relative comparison of fracture energy of mixes with ReOB compared with the control mix at all aging states.



(a) **(b)**

Figure 16. Impact of aging on fracture energy changing with aging condition for (a) mixes prepared with control and CC-type ReOB and (b) mixes prepared with control and SK-type ReOB.

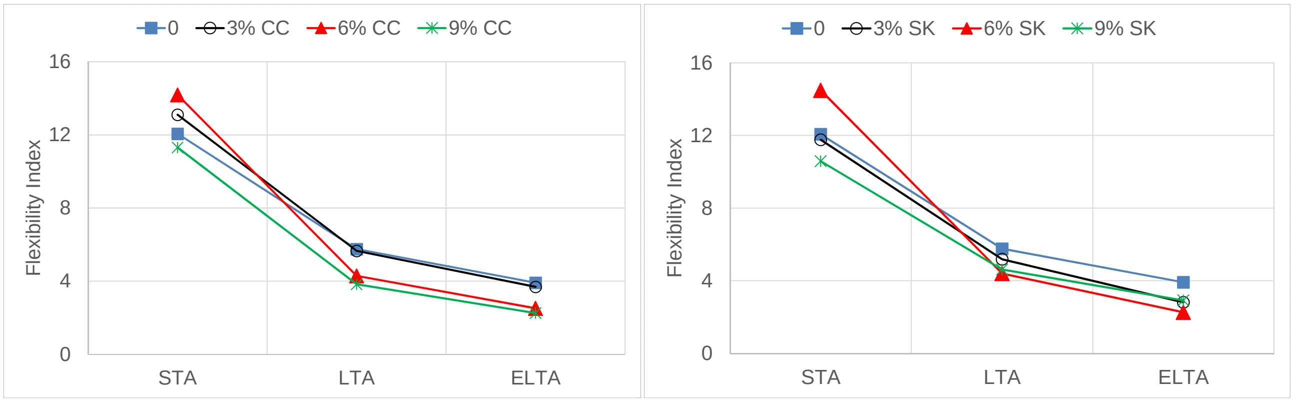
Figure 17 shows the aging effect using the peak load results from the intermediate-temperature SCB tests. Peak load (indicating tensile strength of asphalt concrete mixtures) increased with aging time. The increase in the first 5 days appeared to be more significant than that which occurred in the second 5 days of aging. The effect of aging was similar for all mixes regardless of ReOB content.



(a) **(b)**

Figure 17. Impact of aging on SCB peak load changing with aging condition for (a) mixes prepared with control and CC-type ReOB and (b) mixes prepared with control and SK-type ReOB.

Finally, the effect of aging on the FI is shown in Figure 18. Aging had a significant influence on the FI for all mixes. The index dropped about an order of magnitude with 10 days of aging. The decline was more rapid in the first 5 days of aging. After the end of 5 and 10 days of aging, flexibility indexes for specimens with 6% and 9% were clearly distinguished from the control specimens that had lower flexibility indexes. The results also show that the specimen with 3% SK-type ReOB had a low flexibility index after 10 days of aging, comparable with specimens with 6% or more ReOB.



(a) **(b)**

Figure 18. Impact on the FI of aging under different aging conditions for (a) mixes prepared with control and CC-type ReOB and (b) mixes prepared with control and SK-type ReOB.

Results obtained from all SCB tests are summarized in Tables 6 to 8. These tables present key properties from the SCB tests at low and intermediate temperatures, illustrating the effects of aging and ReOB content on those properties. The results did not show a consistent trend with increasing ReOB at low-temperature SCB tests. Low-temperature fracture energy either remained the same or slightly increased with increasing amounts of ReOB. According to the intermediate-temperature SCB tests, the drop in fracture energy with the addition of 9% ReOB was in the range of approximately 19% to 27% for the three aging conditions. Similarly, the reductions with 3% and 6% ReOB were in the range of approximately 5% to 15% and 13% to 17%, respectively. The percentage decrease in the intermediate-temperature fracture energy at the end of 10 days of aging was approximately 15% (except for the mixes with 3% ReOB [SK] and 9% ReOB [SK], which exhibited similar values).

Table 6. Summary of SCB Test Results for Fracture Energy, Illustrating the Percentage Changes with ReOB Content and Aging Condition

	Fracture Energy (J/m^2)				
	Low Temperature (LT)	**Intermediate-Temperature SCB**			**% Change after 10 Days of Aging**
		Short-Term Aged (STA)	Long-Term Aged (LTA)	Extra Long-Term Aged (ELTA)	
Control	700	2175	1949	1840	**–15**
3% CC	682	1932	1840	1650	**–15**
3% SK	677	1746	1868	1713	**–2**
% change for 3% ReOB	**–3**	**–15**	**–5**	**–9**	
6% CC	762	1867	1653	1548	**–17**
6% SK	741	1863	1726	1505	**–19**
% change for 6% ReOB	**7**	**-14**	**-13**	**-17**	
9% CC	707	1715	1572	1453	**–15**
9% SK	772	1480	1599	1521	**3**
% change for 9% ReOB	**6**	**–27**	**–19**	**–19**	

Tensile strength obtained from SCB tests are presented in Table 7. Low-temperature SCB results did not show any changes in the strength with varying ReOB. A reduction of approximately 20% was observed for the short-term aged samples tested at intermediate temperatures. This was generally consistent with the literature findings about the effects of ReOB. However, there was no evidence of strength decline after 5 and 10 days of aging with increasing ReOB. Aging had a dramatic effect on tensile strength of each mix. The increase in tensile strength with aging was in the range of 40% to 70%.

Table 7. Summary of SCB Test Results for SCB Tensile Strength Illustrating the Percentage Changes with ReOB Content and Aging Condition

	SCB Tensile Strength (MPa)				% Change After 10 Days of Aging
	Low Temperature (LT)	Intermediate-Temperature SCB			
		Short-Term Aged (STA)	Long-Term Aged (LTA)	Extra-long-Term Aged (ELTA)	
Control	0.73	0.39	0.49	0.55	**41**
3% CC	0.75	0.34	0.48	0.52	**54**
3% SK	0.70	0.32	0.48	0.56	**74**
% change for 3% ReOB	**–1**	**–15**	**–1**	**–1**	
6% CC	0.73	0.32	0.48	0.55	**73**
6% SK	0.79	0.31	0.49	0.54	**73**
% change for 6% ReOB	**3**	**–18**	**0**	**0**	
9% CC	0.74	0.33	0.47	0.53	**58**
9% SK	0.73	0.29	0.45	0.50	**75**
% change for 9% ReOB	**0**	**–20**	**–6**	**–6**	

[1] SCB tensile strength is calculated using the formula: *P*/ (2 * *r* * *t*) where *P*: peak load, *r*: radius (taken as 75 mm), *t*: thickness (taken as 50 mm).

Finally, the FI results are summarized in Table 8. The FI was calculated for intermediate-temperature results only. While there was no consistent trend noted in the FI with increasing ReOB for short-term aged specimens, a clear reduction in a range of approximately 20% to 30% was observed with increasing ReOB for long-term and extra-long-term aging conditions for specimens with 6% or more ReOB, with an exception of the specimen containing 3% SK-type ReOB. The specimen with 3% SK-type ReOB after 10 days of aging also showed a comparable reduction in the FI value. Considering the coefficient of variation for the FI (less than 20%), such a range of reductions can be statistically significant and indicate that, over the long run, the mixtures can potentially become more brittle and prone to overall cracking-related damage with increasing ReOB. Overall, the change in FI was substantial with aging time (in the range of approximately 70% to 80% at the end of 10 days of aging).

Table 8. Summary of SCB Test Results for FI Illustrating the Percentage Changes with ReOB Content and Aging Condition

	Flexibility Index				% Change After 10 Days of Aging
		Intermediate-Temperature SCB			
	Low Temperature SCB (LT)	Short-Term Aged (STA)	Long-Term Aged (LTA)	Extra-long-Term Aged (ELTA)	
Control	N/A	12.1	5.8	3.9	**–68**
3% CC	N/A	13.1	5.7	3.7	**–72**
3% SK	N/A	11.8	5.2	2.8	**–76**
% change for 3% ReOB		**3**	**–6**	**–17**	
6% CC	N/A	14.2	4.3	2.5	**–82**
6% SK	N/A	14.5	4.4	2.3	**–84**
% change for 6% ReOB		**19**	**–25**	**–39**	
9% CC	N/A	11.3	3.8	2.3	**–80**
9% SK	N/A	10.6	4.6	2.9	**–72**
% change for 9% ReOB		**–9**	**–27**	**–34**	

CHAPTER 4: SUMMARY OF FINDINGS AND CONCLUSIONS

In this study, the effect of re-refined oil bottoms (ReOB) on the performance of asphalt binder and the strength performance of one type of asphalt mixture was assessed. An experimental program was established to grade the different blends of asphalt binder, measure the ash content, study the permanent deformation and fracture performance of the studied asphalt mixture, and evaluate whether ReOB accelerates hardening of asphalt mixtures with aging. Two types of ReOB were included in this study at various percentages (0%, 3%, 6%, and 9%). Below is a summary of the experimental findings of this study:

- Mixes were designed and tested with increasing amounts of ReOB (3%, 6%, and 9%). During the mix design stage, it was observed that the voids in mineral aggregates (VMA) of mix with 9% ReOB were consistently lower than with the control mix (14.7 vs. 15.2) when aggregate gradation was kept the same.

- Standard binder grading tests indicated some reduction in the stiffness of binder at intermediate and low temperatures with increasing ReOB content, even though the binder grade remained the same.

- The Hamburg wheel track (HWT) test did not show any significant difference in the permanent deformation characteristics of mixes with 9% ReOB (both CC and SK) compared with the control mix. All of the mixes passed Illinois Department of Transportation (IDOT) standards (12.5 mm at 7,500 passes) with a small margin.

- Low-temperature semi-circular bending beam (SCB) tests did not show any trend for fracture energy and peak load with increasing ReOB content, with comparable fracture energy results for all mixes tested.

- Intermediate-temperature SCB tests for the short-term-aged specimens indicated a consistent decrease in fracture energy with increasing ReOB content. The drop in fracture energy with increasing ReOB content was in the range of approximately 15% to 27%. Similar observations can be made for both CC- and SK-type ReOBs.

- The flexibility index (FI) for short-term-aged specimens was in the range of 10 to 14, with no particular trend found between mixes. For short-term-aged laboratory-produced mixes, this range of FI is considered to be high—indicating cracking resistance of the mixes.

- With aging, the properties obtained from the intermediate-temperature SCB tests showed dramatic changes. Fracture energy dropped by approximately 15% at the end of 10 days of aging (referred to as extra-long-term aging in this report) with the exception of mixes with 3% ReOB (SK) and 9% ReOB (SK), which exhibited similar values. The increase in peak load (in the range of 40% to 70%) and decrease in FI (in the range of approximately 70% to 80%) at the end of 10 days of aging are valid signs of brittleness for all mixes.

- While the FI did not exhibit any consistent trend with increasing ReOB for short-term-aged specimens, it was observed that the flexibility index of specimens aged for 5 and 10 days was smaller (indicating brittleness and higher potential for damage with aging in the field) for mixes with higher percentages of ReOB. This also shows that the softening effects of ReOB vanished once the material was aged, according to the FI results. The reduction in the FI with increasing

ReOB was in a range of approximately 20% to 30% for mixes with increasing ReOB content—indicating that the ReOB may increase brittleness of mixes.

- This study exemplifies the significance of mixture aging in determining key laboratory performance properties obtained from the IL-SCB test. In this study, aging was applied on the fabricated specimens. Alternatively, loose-mixture aging at compaction temperatures can be applied to evaluate aging in the laboratory.
- The impact of ReOB on the mixes' fracture properties was evident at intermediate temperatures; however, the same impact was not observed at low temperatures for mixes with up to 9% ReOB.

According to the findings from the experimental program conducted in this study, the asphalt mixture with two types of ReOB products (up to 9%) had comparable rutting and low-temperature fracture properties with some reduction in fracture resistance, flexibility, and strength characteristics obtained at the intermediate-temperature SCB test. IL-SCB tests conducted at intermediate temperatures with long-term aging of the specimens indicated that mixes containing ReOB appeared to be less flexible compared with the control mixture; hence, they could possibly be more prone to overall cracking-related damage with increasing ReOB percentages in asphalt binder.

Similar experiments should be repeated with different types and grades of asphalt binder with different compositional characteristics (binders with higher asphaltene percentage) because the interaction of ReOB with binders having different compositional characteristics may vary (Johnson and Hesp 2014). Chemistry and compositional characteristics of ReOB blends should also be investigated with further rheological experiments with standard and extended aging. Given the increasing demand for softer-grade binders as well as the economic benefits in terms of initial production costs of using ReOB to modify binder properties to the desired grade, the future study should include life-cycle cost and an environmental assessment with a consideration of potential reduction in pavement performance.

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APPENDIX A: PG GRADING

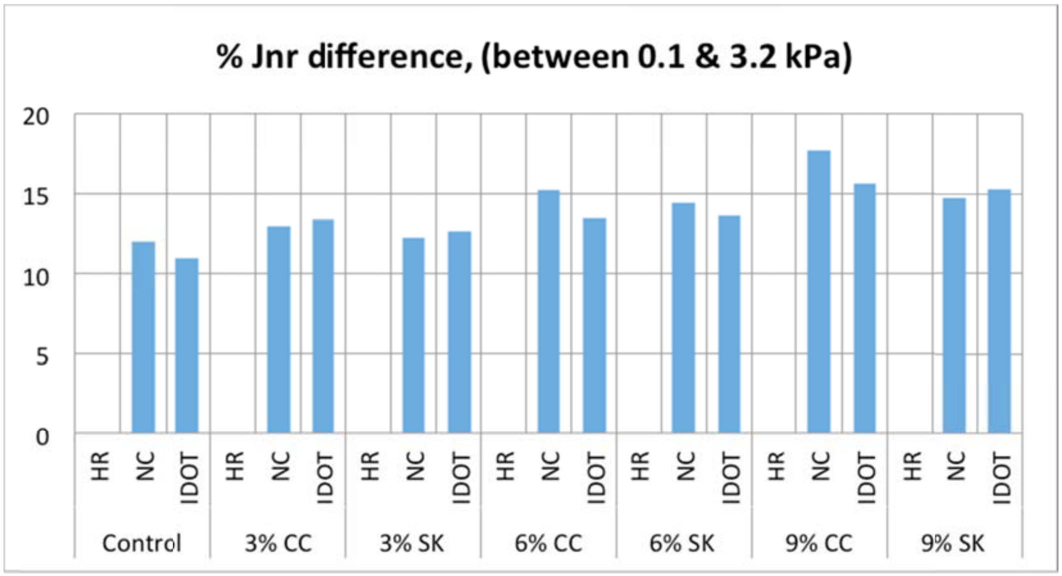

Figure A1. Percent Jnr difference.

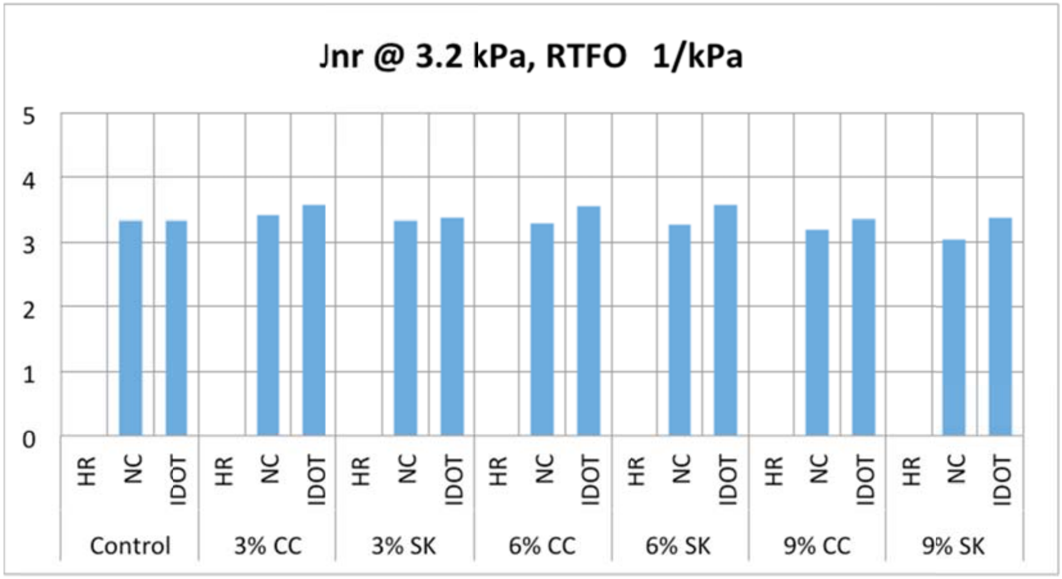

Figure A2. Jnr for RTFO binder.

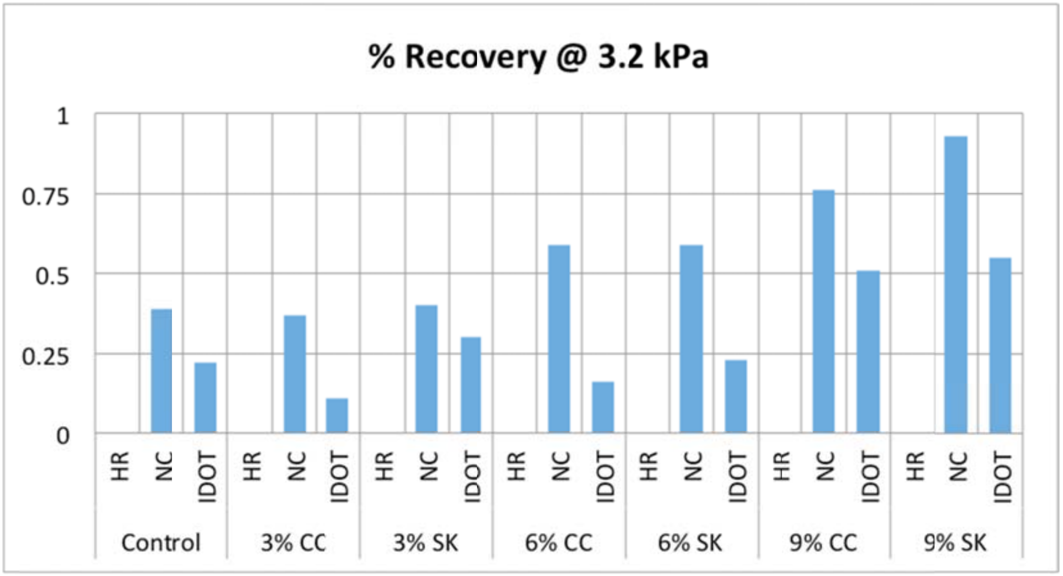

Figure A3. Percent recovery.

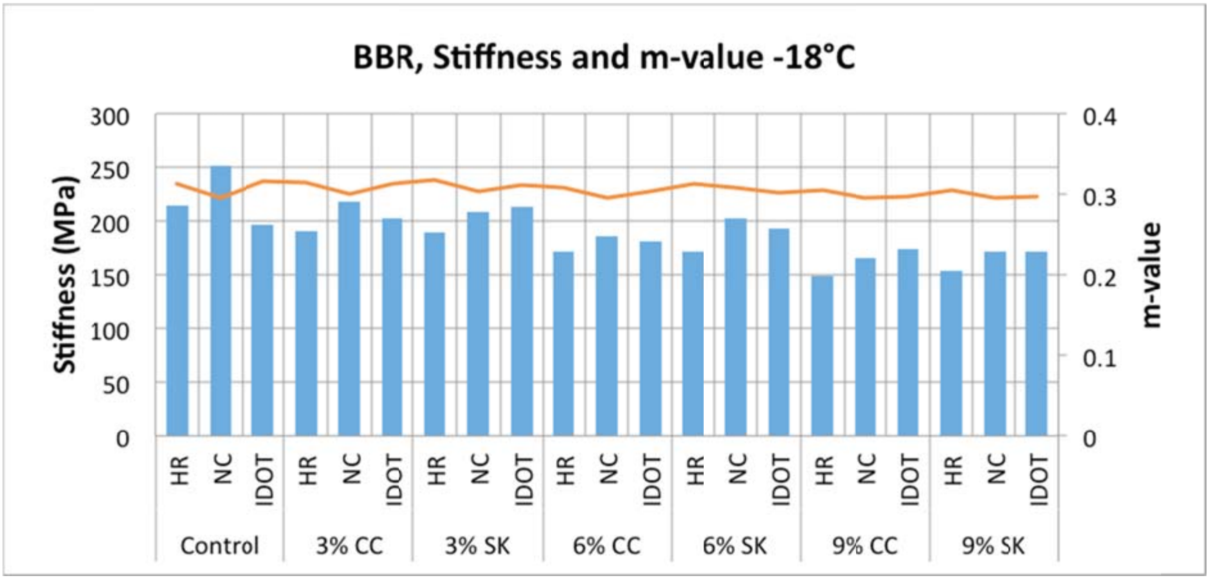

Figure A4. Bending beam rheometer data.

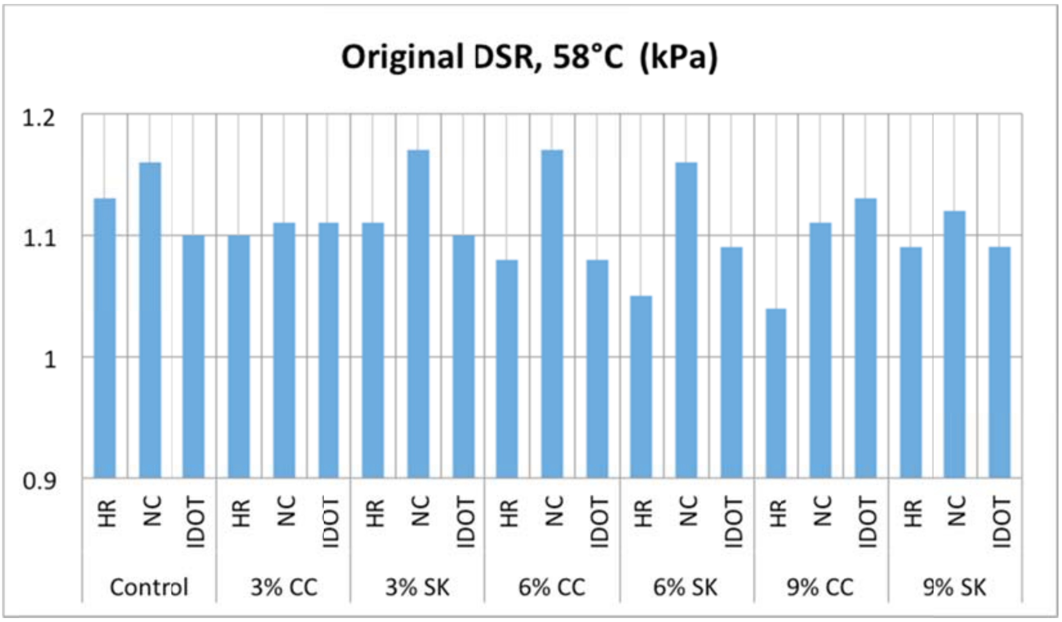

Figure A5. Dynamic shear rheometer data for original binder.

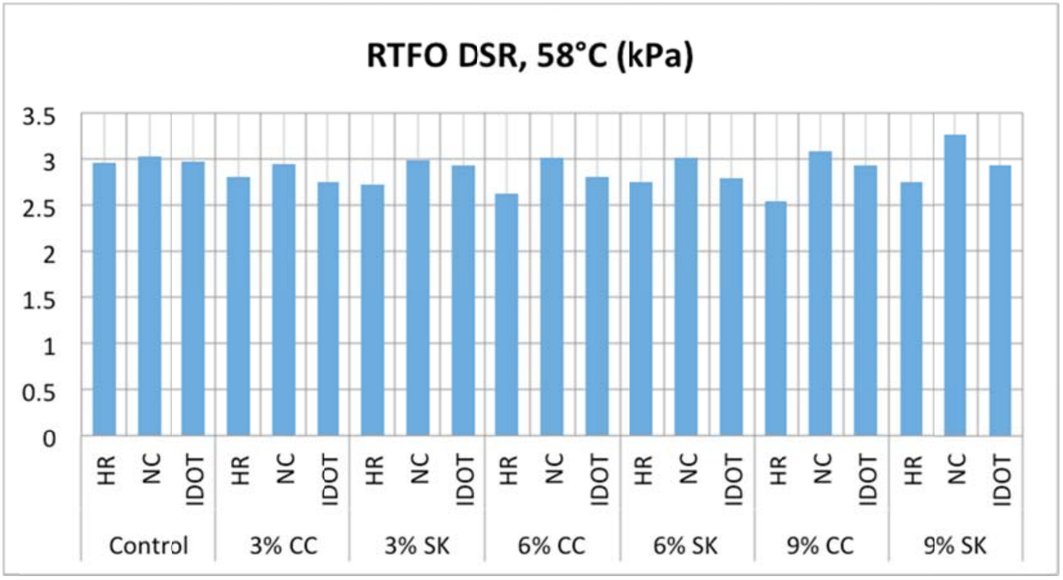

Figure A6. Dynamic shear rheometer data for RTFO binder.

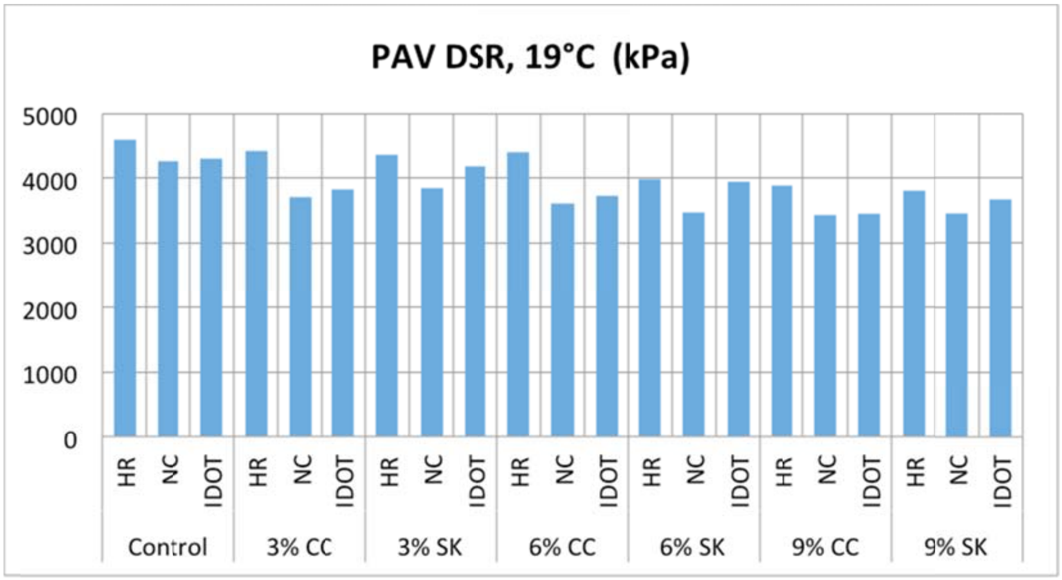

Figure A7. Dynamic shear rheometer data for PAV binder.

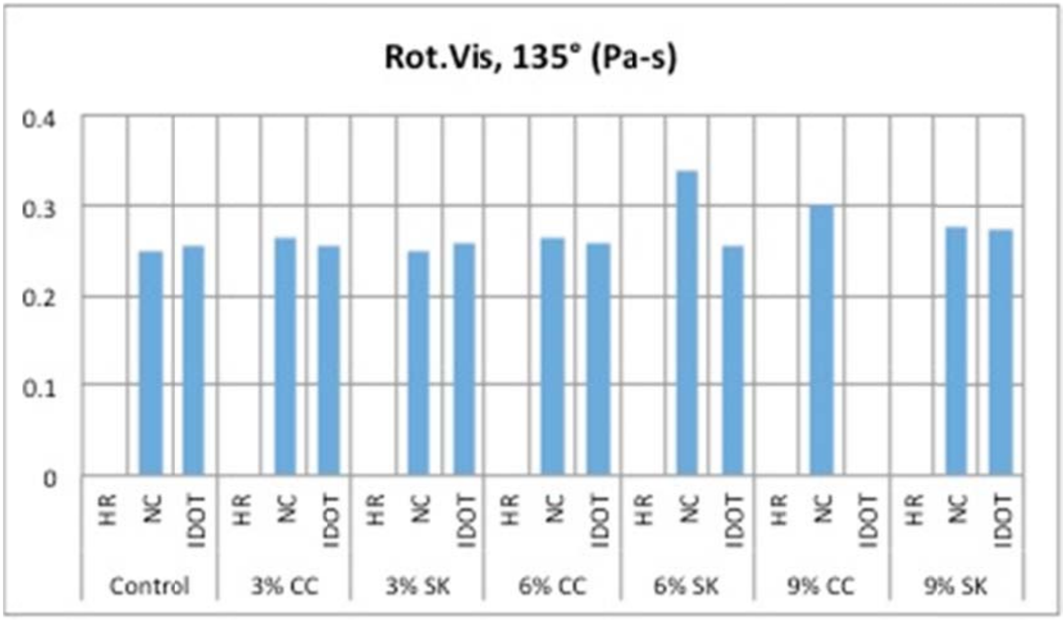

Figure A8. Rotational viscosity data.

APPENDIX B: VOLUMETRICS

Table B1. Volumetrics Data

Specimen	A	B	C	Gmb	Gmm	% Void	Gsb	VMA	Density	Date
ReOB-0%-HB-1-1	2423.7	2432.0	1372.8	**2.288**	2.461	**7.02**	2.608	**17.61**	**92.98**	1/29/15
ReOB-0%-HB-1-2	2343.3	2354.4	1323.4	**2.273**	2.461	**7.65**	2.608	**18.17**	**92.35**	1/29/15
ReOB-0%-HB-2-1	2387.1	2397.4	1353.3	**2.286**	2.461	**7.10**	2.608	**17.68**	**92.90**	1/29/15
ReOB-0%-HB-2-2	2348.4	2361.1	1330.5	**2.279**	2.461	**7.41**	2.608	**17.96**	**92.59**	1/29/15
ReOB-9%CC-HB-1-1	2355.7	2363.2	1334.9	**2.291**	2.461	**6.91**	2.608	**17.52**	**93.09**	1/29/15
ReOB-9%CC-HB-1-2	2387.3	2398.6	1348.8	**2.274**	2.461	**7.60**	2.608	**18.12**	**92.40**	1/29/15
ReOB-9%CC-HB-2-1	2368.0	2377.5	1337.7	**2.277**	2.461	**7.46**	2.608	**18.00**	**92.54**	1/29/15
ReOB-9%CC-HB-2-2	2397.7	2408.9	1358.1	**2.282**	2.461	**7.28**	2.608	**17.85**	**92.72**	1/29/15
ReOB-9%SK-HB-1-1	2348.0	2356.0	1327.6	**2.283**	2.461	**7.23**	2.608	**17.80**	**92.77**	1/29/15
ReOB-9%SK-HB-1-2	2416.9	2429.4	1366.8	**2.275**	2.461	**7.58**	2.608	**18.11**	**92.42**	1/29/15
ReOB-9%SK-HB-2-1	2390.5	2401.6	1351.3	**2.276**	2.461	**7.52**	2.608	**18.05**	**92.48**	1/29/15
ReOB-9%SK-HB-2-2	2374.7	2385.5	1345.8	**2.284**	2.461	**7.19**	2.608	**17.76**	**92.81**	1/29/15
ReOB-0%-2-1,2	2020.8	2026.0	1141.7	**2.285**	2.461	**7.14**	2.608	**17.72**	**92.86**	1/30/15
ReOB-0%-2-3,4	2009.4	2015.8	1133.2	**2.277**	2.461	**7.49**	2.608	**18.03**	**92.51**	1/30/15
ReOB-3%CC-2-1,2	2024.3	2029.3	1142.5	**2.283**	2.461	**7.24**	2.608	**17.81**	**92.76**	1/30/15
ReOB-3%CC-2-3,4	2024.9	2031.0	1141.4	**2.276**	2.461	**7.51**	2.608	**18.05**	**92.49**	1/30/15
ReOB-6%CC-2-1,2	2011.6	2017.9	1139.1	**2.289**	2.461	**6.99**	2.608	**17.58**	**93.01**	1/30/15
ReOB-6%CC-2-3,4	2012.2	2017.7	1136.1	**2.282**	2.461	**7.26**	2.608	**17.82**	**92.74**	1/30/15
ReOB-9%CC-2-1,2	2012.1	2019.5	1136.7	**2.279**	2.461	**7.39**	2.608	**17.94**	**92.61**	1/30/15
ReOB-9%CC-2-3,4	2010.9	2017.2	1136.8	**2.284**	2.461	**7.19**	2.608	**17.76**	**92.81**	1/30/15
ReOB-3%SK-2-1,2	1995.4	2003.5	1121.6	**2.263**	2.461	**8.06**	2.608	**18.54**	**91.94**	1/30/15
ReOB-3%SK-2-3,4	2014.5	2020.5	1139.2	**2.286**	2.461	**7.12**	2.608	**17.70**	**92.88**	1/30/15
ReOB-6%SK-2-1,2	2015.7	2025.1	1138.7	**2.274**	2.461	**7.60**	2.608	**18.12**	**92.40**	1/30/15
ReOB-6%SK-2-3,4	2018.4	2025.3	1139.2	**2.278**	2.461	**7.44**	2.608	**17.99**	**92.56**	1/30/15
ReOB-9%SK-2-1,2	1992.1	2000.5	1120.6	**2.264**	2.461	**8.00**	2.608	**18.49**	**92.00**	1/30/15
ReOB-9%SK-2-3,4	2000.2	2008.8	1132.8	**2.283**	2.461	**7.22**	2.608	**17.79**	**92.78**	1/30/15
ReOB-0%-3-3,4	2016.7	2022.4	1140.3	**2.286**	2.461	**7.10**	2.608	**17.68**	**92.90**	2/5/15
ReOB-3%CC-3-1,2	2022.9	2027.7	1144.4	**2.290**	2.461	**6.94**	2.608	**17.54**	**93.06**	2/5/15
ReOB-6%CC-3-1,2	2017.8	2022.7	1138.5	**2.282**	2.461	**7.27**	2.608	**17.84**	**92.73**	2/5/15

Specimen	A	B	C	Gmb	Gmm	% Void	Gsb	VMA	Density	Date
ReOB-9%CC-3-1,2	2031.1	2035.2	1149.9	**2.294**	2.461	**6.78**	2.608	**17.40**	**93.22**	2/5/15
ReOB-3%SK-3-1,2	2010.9	2015.3	1135.9	**2.287**	2.461	**7.08**	2.608	**17.67**	**92.92**	2/5/15
ReOB-6%SK-3-3,4	2004.2	2008.7	1130.2	**2.281**	2.461	**7.30**	2.608	**17.86**	**92.70**	2/5/15
ReOB-9%SK-3-3,4	2014.4	2020.3	1135.1	**2.276**	2.461	**7.53**	2.608	**18.07**	**92.47**	2/5/15
ReOB-0%-1-Repeat	7111.5	7148.0	4026.8	**2.278**	2.461	**7.42**	2.608	**17.97**	**92.58**	3/25/15
ReOB-3%CC-1-Repeat	7110.2	7144.5	4017.8	**2.274**	2.461	**7.60**	2.608	**18.12**	**92.40**	3/25/15
ReOB-9%CC-1-Repeat	7116.1	7143.1	4029.2	**2.285**	2.461	**7.14**	2.608	**17.72**	**92.86**	3/25/15
ReOB-9%SK-1-Repeat	7109.9	7145.3	4018.8	**2.274**	2.461	**7.60**	2.608	**18.12**	**92.40**	3/25/15
ReOB-E*-Pilot 2	7054.4	7109.1	3975.8	**2.251**	2.461	**8.52**	2.608	**18.94**	**91.48**	3/25/15
ReOB-E*-0%-1	7049.0	7097.5	3972.8	**2.256**	2.461	**8.33**	2.608	**18.78**	**91.67**	3/25/15
ReOB-0%-FR-1(1)	7109.0	7140.6	4020.1	**2.278**	2.461	**7.43**	2.608	**17.98**	**92.57**	4/23/15
ReOB-0%-FR-2(2)	7106.7	7144.8	4008.2	**2.266**	2.461	**7.93**	2.608	**18.42**	**92.07**	4/23/15
ReOB-0%-FR-3(3)	7120.5	7157.9	4028.7	**2.276**	2.461	**7.54**	2.608	**18.07**	**92.46**	4/23/15
ReOB-0%-FR-4(4)	7114.4	7142.7	4029.2	**2.285**	2.461	**7.15**	2.608	**17.73**	**92.85**	4/23/15
ReOB-9%CC-FR-1(5)	7111.0	7146.5	4028.7	**2.281**	2.461	**7.32**	2.608	**17.88**	**92.68**	4/23/15
ReOB-9%CC-FR-2(6)	7110.5	7144.1	4038.3	**2.289**	2.461	**6.97**	2.608	**17.57**	**93.03**	4/23/15
ReOB-9%CC-FR-3(7)	7116.0	7158.2	4041	**2.283**	2.461	**7.24**	2.608	**17.81**	**92.76**	4/23/15
ReOB-9%CC-FR-4(8)	7110.7	7143.2	4032	**2.286**	2.461	**7.13**	2.608	**17.71**	**92.87**	4/23/15
ReOB-6%CC-FR-1(9)	7120.4	7151.2	4035.7	**2.285**	2.461	**7.13**	2.608	**17.71**	**92.87**	4/23/15
ReOB-6%CC-FR-2(10)	7119.0	7152.8	4044.4	**2.290**	2.461	**6.94**	2.608	**17.54**	**93.06**	4/23/15
ReOB-3%SK-(1)	7057.1	7089.1	3992.8	2.279	2.461	**7.40**	2.608	**17.95**	**92.60**	11/25/15
ReOB-3%SK-(2)	7056.6	7087.2	3981.9	2.272	2.461	**7.68**	2.608	**18.20**	**92.32**	11/25/15
ReOB-3%SK-(3)	7057.5	7082.8	3977.6	2.273	2.461	**7.64**	2.608	**18.16**	**92.36**	11/25/15
ReOB-3%SK-(B)	7054.6	7085.9	3980.7	2.272	2.461	**7.68**	2.608	**18.20**	**92.32**	11/25/15
ReOB-3%SK-1T	2014.5	2018.6	1137.5	**2.286**	2.461	**7.10**	2.608	**17.68**	**92.90**	11/26/15
ReOB-3%SK-1B	2007.8	2010.4	1133.4	**2.289**	2.461	**6.97**	2.608	**17.57**	**93.03**	11/26/15
ReOB-3%SK-2T	2050.9	2054.6	1160.2	**2.293**	2.461	**6.82**	2.608	**17.44**	**93.18**	11/26/15
ReOB-3%SK-2B	2024.8	2029.1	1142.4	**2.284**	2.461	**7.21**	2.608	**17.78**	**92.79**	11/26/15
ReOB-3%SK-3T	2029.9	2033.7	1147.2	**2.290**	2.461	**6.96**	2.608	**17.56**	**93.04**	11/26/15
ReOB-3%SK-3B	2015.1	2018	1132.7	**2.276**	2.461	**7.51**	2.608	**18.05**	**92.49**	11/26/15
ReOB-3%SK-BT	2024.2	2028.1	1144	**2.290**	2.461	**6.97**	2.608	**17.57**	**93.03**	11/26/15
ReOB-3%SK-BB	1970.3	1973.4	1107.3	**2.275**	2.461	**7.56**	2.608	**18.09**	**92.44**	11/26/15

Specimen	A	B	C	Gmb	Gmm	% Void	Gsb	VMA	Density	Date
ReOB-3%SK-1T1	979.5	982.3	552.4	**2.278**	2.461	**7.42**	2.608	**17.97**	**92.58**	11/27/15
ReOB-3%SK-1T2	969.2	972.1	548.6	**2.289**	2.461	**7.01**	2.608	**17.60**	**92.99**	11/27/15
ReOB-3%SK-1B1	986.2	988.7	558	**2.290**	2.461	**6.96**	2.608	**17.56**	**93.04**	11/27/15
ReOB-3%SK-1B2	955.4	958.3	538.7	**2.277**	2.461	**7.48**	2.608	**18.02**	**92.52**	11/27/15
ReOB-3%SK-2T1	977.1	979.6	550.3	**2.276**	2.461	**7.52**	2.608	**18.05**	**92.48**	11/27/15
ReOB-3%SK-2T2	1006.9	1009.4	572.6	**2.305**	2.461	**6.33**	2.608	**17.00**	**93.67**	11/27/15
ReOB-3%SK-2B1	974.7	977.3	551.9	**2.291**	2.461	**6.90**	2.608	**17.50**	**93.10**	11/27/15
ReOB-3%SK-2B2	983.7	985.9	553.5	**2.275**	2.461	**7.56**	2.608	**18.11**	**92.42**	11/27/15
ReOB-3%SK-3T1	1001.6	1004.1	567	**2.291**	2.461	**6.89**	2.608	**17.50**	**93.11**	11/27/15
ReOB-3%SK-3T2	961.5	963.8	542.5	**2.282**	2.461	**7.26**	2.608	**17.83**	**92.74**	11/27/15
ReOB-3%SK-3B1	948.8	950.9	532.7	**2.269**	2.461	**7.81**	2.608	**18.31**	**92.19**	11/27/15
ReOB-3%SK-3B2	999.8	1002.3	563.2	**2.277**	2.461	**7.48**	2.608	**18.02**	**92.52**	11/27/15
ReOB-3%SK-BT1	963.8	966.3	546.9	**2.298**	2.461	**6.62**	2.608	**17.26**	**93.38**	11/27/15
ReOB-3%SK-BT2	994.6	996.7	560.5	**2.280**	2.461	**7.35**	2.608	**17.90**	**92.65**	11/27/15
ReOB-3%SK-BB1	971.9	974.7	545.9	**2.267**	2.461	**7.90**	2.608	**18.39**	**92.10**	11/27/15
ReOB-3%SK-BB2	933.7	936	526	**2.277**	2.461	**7.46**	2.608	**18.02**	**92.52**	11/27/15

APPENDIX C: SCB TEST RESULTS

Table C1. Short-Term-Aged SCB Test Results

Short-term Aged (STA)

Mix	Replicate ID	Energy (LLD) (J/m2)	AVERAGE	STD DEV	COV	Peak Load (kN)	Average Peak Load	STD DEV	COV	FI	AVERAGE	STD DEV	COV
REOB-0%	STA-1	2194	**2175**	**274**	**12.6**	3.32	**2.89**	**0.321**	**11.1**	10.2	**12.1**	**2.0**	**16.8**
	STA-2	1844				2.66				9.9			
	STA-3	2064				2.52				13.7			
	STA-4	2597				3.08				14.5			
REOB-3CC	STA-1	1921	**1932**	**197**	**10.2**	2.45	**2.53**	**0.190**	**7.5**	14.9	**13.1**	**1.2**	**9.3**
	STA-2	1926				2.66				11.6			
	STA-3	2218				2.74				13.4			
	STA-4	1661				2.25				12.5			
REOB-6CC	STA-1	2150	**1867**	**186**	**10.0**	2.41	**2.40**	**0.182**	**7.6**	18.8	**14.2**	**2.8**	**19.5**
	STA-2	1798				2.59				10.4			
	STA-3	1645				2.10				14.2			
	STA-4	1913				2.67				12.4			
	STA-5	2157				2.52				18.2			
	STA-6	1864				2.41				12.9			
	STA-7	1750				2.21				14.6			
	STA-8	1661				2.27				12.1			
REOB-9CC	STA-1	1553	**1715**	**255**	**14.9**	2.19	**2.50**	**0.203**	**8.1**	13.6	**11.3**	**2.4**	**21.1**
	STA-2	1489				2.57				8.4			
	STA-3	1678				2.49				9.5			
	STA-4	2141				2.75				13.8			
REOB-3SK	STA-1	1765	**1746**	**155**	**8.9**	2.6	**2.42**	**0.291**	**12.0**	10.9	**11.8**	**1.3**	**10.7**
	STA-3	1926				2.9				9.7			
	STA-5	1832				2.3				12.5			
	STA-6	1705				2.2				11.6			
	STA-8	1434				2.0				12.2			
	STA-9	1813				2.5				13.7			
REOB-6SK	STA-1	1720	**1863**	**146**	**7.8**	2.16	**2.34**	**0.158**	**6.8**	15.4	**14.5**	**1.3**	**9.3**
	STA-2	1786				2.33				11.9			
	STA-3	2094				2.65				13.7			
	STA-4	1761				2.35				14.7			
	STA-5	2035				2.34				15.5			
	STA-7	1779				2.20				15.7			
REOB-9SK	STA-2	1433	**1480**	**39**	**2.6**	2.07	**2.15**	**0.072**	**3.4**	10.5	**10.6**	**0.2**	**1.5**
	STA-3	1528				2.24				10.5			
	STA-4	1478				2.12				10.8			

Table C2. Long-Term-Aged SCB Test Results

Long-term Aged

Mix	Replicate ID	Energy (LLD) (J/m2)	AVERAGE	STD DEV	COV	Peak Load (kN)	Average Peak Load	STD DEV	COV	FI	AVERAGE	STD DEV	COV
REOB-0%	LTA-1	2196	**1949**	**164**	**8**	3.8	**3.6**	**0.265**	**7.3**	7.2	**5.8**	**1.1**	**19.9**
	LTA-2	2066				4.1				3.9			
	LTA-3	1849				3.6				5.5			
	LTA-5	1745				3.3				5.6			
	LTA-6	2047				3.6				7.1			
	LTA-7	1790				3.6				5.2			
REOB-3CC	LTA-1	1835	**1840**	**163**	**9**	3.6	**3.6**	**0.265**	**7.4**	6.1	**5.7**	**1.0**	**16.9**
	LTA-2	2024				4.0				6.6			
	LTA-3	1951				3.8				5.3			
	LTA-4	1710				3.9				4.0			
	LTA-5	1751				3.2				5.8			
	LTA-6	1729				3.2				6.0			
	LTA-7	2114				3.7				7.0			
	LTA-8	1606				3.4				4.5			
REOB-6CC	LTA-1	1724	**1653**	**163**	**10**	3.7	**3.6**	**0.139**	**3.8**	3.5	**4.3**	**0.9**	**20.9**
	LTA-2	1734				3.6				4.4			
	LTA-3	1731				3.6				5.2			
	LTA-6	1858				3.8				5.6			
	LTA-7	1389				3.3				4.0			
	LTA-8	1480				3.6				3.0			
REOB-9CC	LTA-1	1733	**1572**	**114**	**7**	3.6	**3.5**	**0.140**	**4.0**	4.4	**3.8**	**0.5**	**12.8**
	LTA-2	1556				3.6				3.2			
	LTA-3	1564				3.5				3.3			
	LTA-4	1715				3.7				4.2			
	LTA-5	1442				3.2				3.9			
	LTA-6	1407				3.5				3.4			
	LTA-7	1586				3.4				4.4			
	LTA-8												
REOB-3SK	LTA-1	1726	**1868**	**176**	**9**	3.7	**3.6**	**0.223**	**6.1**	4.5	**5.2**	**0.8**	**14.9**
	LTA-2	1858				3.6				5.0			
	LTA-3	2280				4.1				6.5			
	LTA-4	1740				3.8				4.8			
	LTA-5	1918				3.5				5.8			
	LTA-6	1678				3.5				4.3			
	LTA-7	1832				3.3				6.1			
	LTA-8	1910				3.7				4.6			
REOB-6SK	LTA-2	1751	**1726**	**113**	**7**	3.7	**3.7**	**0.139**	**3.8**	4.2	**4.4**	**1.4**	**30.7**
	LTA-3	1577				3.5				2.9			
	LTA-4	1851				3.9				6.2			
REOB-9SK	LTA-2	1666	**1599**	**113**	**7**	3.8	**3.4**	**0.301**	**8.9**	3.3	**4.6**	**1.0**	**21.7**
	LTA-3	1750				3.4				5.3			
	LTA-4	1683				3.8				4.1			
	LTA-5	1522				3.1				5.0			
	LTA-6	1560				3.1				6.3			
	LTA-8	1411				3.2				3.8			

Table C3. Extra-Long-Term-Aged SCB Results

Extra Long-Term Aged (ELTA)													
District ID	**Replicate ID**	**Energy (LLD) (J/m2)**	**AVERAGE**	**STD DEV**	**COV**	**Peak Load (kN)**	**Average Peak Load**	**STD DEV**	**COV**	**FI**	**AVERAGE**	**STD DEV**	**COV**
REOB-0%	ELTA-1	1962.5	**1840.1**	**152.5**	**8.3**	4.4	**4.1**	**0.2**	**3.9**	4.4	**3.9**	**0.6**	**14.9**
	ELTA-2	1917.2				4.0				4.3			
	ELTA-3	1972.0				4.0				4.0			
	ELTA-4	1798.4				4.2				3.3			
	ELTA-5	1913.5				4.2				3.3			
	ELTA-6	1515.2				3.8				3.1			
	ELTA-7	1690.3				4.1				4.0			
	ELTA-8	1952.1				4.0				4.9			
REOB-3CC	ELTA-2	2023.2	**1650.3**	**168.2**	**10.2**	4.3	**3.9**	**0.2**	**5.8**	4.7	**3.7**	**0.6**	**15.4**
	ELTA-3	1604.9				4.0				3.6			
	ELTA-4	1572.1				4.0				3.1			
	ELTA-5	1549.2				3.6				3.2			
	ELTA-7	1602.3				3.7				4.1			
	ELTA-8	1550.1				3.8				3.4			
REOB-6CC	ELTA-1	1447.9	**1548.0**	**70.5**	**4.6**	4.1	**4.1**	**0.1**	**3.0**	2.6	**2.5**	**0.3**	**13.1**
	ELTA-3	1636.0				4.4				2.2			
	ELTA-4	1595.8				4.1				3.0			
	ELTA-5	1610.6				4.2				2.8			
	ELTA-7	1476.5				4.1				2.0			
	ELTA-8	1521.5				4.1				2.4			
REOB-9CC	ELTA-1	1410.6	**1453.3**	**128.5**	**8.8**	3.9	**3.9**	**0.1**	**3.1**	2.2	**2.3**	**0.4**	**17.3**
	ELTA-2	1699.6				4.0				2.9			
	ELTA-5	1273.8				3.7				1.8			
	ELTA-6	1484.0				4.1				1.9			
	ELTA-7	1457.2				4.0				2.7			
	ELTA-8	1394.8				4.0				2.1			
REOB-3SK	ELTA-1	1523.8	**1713.1**	**177.9**	**10.4**	4.0	**4.2**	**0.3**	**6.9**	2.3	**2.8**	**0.8**	**29.4**
	ELTA-2	1594.1				4.2				2.6			
	ELTA-3	1456.7				4.3				2.0			
	ELTA-4	1890.2				3.9				4.8			
	ELTA-5	1996.6				4.8				2.4			
	ELTA-7	1867.0				4.6				2.1			
	ELTA-9	1908.9				4.2				3.8			
	ELTA-10	1564.8				3.8				2.9			
	ELTA-11	1676.1				4.3				2.5			
	ELTA-12	1653.2				4.1				2.6			
REOB-6SK	ELTA-1	1484.6	**1505.4**	**38.5**	**2.6**	3.9	**4.0**	**0.1**	**3.7**	2.2	**2.3**	**0.1**	**4.2**
	ELTA-2	1559.4				4.2				2.4			
	ELTA-4	1472.3				3.9				2.2			
REOB-9SK	ELTA-1	1656.1	**1520.6**	**183.4**	**12.1**	3.9	**3.8**	**0.3**	**7.2**	3.2	**2.9**	**0.3**	**8.9**
	ELTA-2	1646.4				4.1				3.1			
	ELTA-4	1285.9				3.8				2.4			
	ELTA-5	1299.4				3.2				3.0			
	ELTA-6	1468.5				3.7				2.7			
	ELTA-8	1767.4				4.0				3.1			

Table C4. Low-Temperature SCB Test Results

Low Temperature

Mix	Replicate ID	Energy (CMOD) (J/m2)	AVERAGE	STD DEV	COV	Peak Load (kN)	Average Peak Load	STD DEV	COV
REOB-0%	LT-1	662.4	**699.5**	**60.4**	**8.6**	5.6	**5.5**	**0.1**	**2.1**
	LT-2	667.7				5.4			
	LT-3	800.5				5.6			
	LT-4	779.4				5.4			
	LT-5	686.3				5.3			
	LT-6	622.2				5.5			
	LT-7	678.5				5.6			
REOB-3CC	LT-1	757.1	**681.9**	**57.5**	**8.4**	6.0	**5.6**	**0.3**	**4.9**
	LT-2	617.7				5.3			
	LT-3	670.7				5.6			
REOB-6CC	LT-1	712.4	**762.0**	**35.7**	**4.7**	5.3	**5.4**	**0.2**	**2.8**
	LT-2	794.7				5.7			
	LT-4	779.1				5.3			
REOB-9CC	LT-1	574.1	**706.7**	**75.1**	**10.6**	5.8	**5.5**	**0.2**	**4.0**
	LT-2	696.3				5.5			
	LT-3	706.8				5.5			
	LT-4	765.4				5.2			
	LT-5	790.7				5.6			
REOB-3SK	LT-1	634.6	**677.1**	**69.8**	**10.3**	5.4	**5.3**	**0.1**	**1.6**
	LT-2	584.6				5.3			
	LT-3	745.1				5.2			
	LT-4	744.0				5.2			
REOB-6SK	LT-1	785.8	**741.4**	**54.1**	**7.3**	5.9	**5.9**	**0.3**	**4.6**
	LT-2	665.3				5.6			
	LT-4	773.1				6.2			
REOB-9SK	LT-1	675.4	**772.0**	**61.0**	**7.9**	5.6	**5.5**	**0.3**	**5.2**
	LT-2	805.8				5.5			
	LT-3	817.6				5.8			
	LT-4	808.1				5.5			
	LT-5	827.7				5.8			
	LT-6	724.9				5.0			
	LT-7	687.1				5.2			
	LT-8	829.8				5.1			

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