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# DSR-Based Test Procedures and Specification Guidelines for Grading PG 58-XX and PG 64S-XX Asphalt Binders in Kansas

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Kansas Department of Transportation

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This report addresses a shortcoming of the Multiple Stress Creep Recovery (MSCR) test method and specification system for virgin PG 58-XX and blends of PG 58-XX with reclaimed asphalt pavement (RAP) binders. The MSCR specification system limits the non-recoverable compliance, Jnr, to less than 4.5 $kPa^{-1}$ for standard *S*-graded binders and disregards binders that do not satisfy this criterion. Also, the MSCR specification does not consider virgin binder grade adjustments when RAP is used. These binders, which are often blended with high percentages of RAP, have positively resulted in mostly a 64 °C high-temperature grade according to LTPPBind, with 98% reliability against rutting in Kansas.

This research blended PG 58-28 and PG 58-34 virgin binders with four RAP binders and conducted MSCR tests to investigate this issue. Results showed that the high-temperature grade of PG 58-XX binders increased to 64 °C when they were mixed with RAP binder percentages of 15% or more. Furthermore, MSCR test results showed that the addition of RAP binder decreased the Jnr value to the *S* criteria when the requirement of Jnr difference percentage was omitted. Results also showed that the RAP binder can be screened using the rotational viscosity test to ensure the blends of PG 58-XX and RAP binders result in high-temperature grade adjustments and satisfy the *S* grade. A comprehensive set of PG 58-XX, PG 64S-XX, and multiple RAP binders used in Kansas should be tested to develop sound specification criteria based on PG and MSCR grading specifications.

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Final Report

Prepared By

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The University of Kansas

A Report on Research Sponsored by

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

and

THE UNIVERSITY OF KANSAS
LAWRENCE, KANSAS

September 2020

# PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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# Abstract

This report addresses a shortcoming of the Multiple Stress Creep Recovery (MSCR) test method and specification system for virgin PG 58-XX and blends of PG 58-XX with reclaimed asphalt pavement (RAP) binders. The MSCR specification system limits the non-recoverable compliance, Jnr, to less than 4.5 $kPa^{-1}$ for standard *S*-graded binders and disregards binders that do not satisfy this criterion. Also, the MSCR specification does not consider virgin binder grade adjustments when RAP is used. These binders, which are often blended with high percentages of RAP, have positively resulted in mostly a 64 °C high-temperature grade according to LTPPBind, with 98% reliability against rutting in Kansas.

This research blended PG 58-28 and PG 58-34 virgin binders with four RAP binders and conducted MSCR tests to investigate this issue. Results showed that the high-temperature grade of PG 58-XX binders increased to 64 °C when they were mixed with RAP binder percentages of 15% or more. Furthermore, MSCR test results showed that the addition of RAP binder decreased the Jnr value to the *S* criteria when the requirement of Jnr difference percentage was omitted. Results also showed that the RAP binder can be screened using the rotational viscosity test to ensure the blends of PG 58-XX and RAP binders result in high-temperature grade adjustments and satisfy the *S* grade. A comprehensive set of PG 58-XX, PG 64S-XX, and multiple RAP binders used in Kansas should be tested to develop sound specification criteria based on PG and MSCR grading specifications.

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# Chapter 1: Background and Problem Statement

## 1.1 Background

Many new asphalt mixtures produced in the United States include various percentages of reclaimed asphalt pavement (RAP). Based on the Federal Highway Administration's (FHWA) recycled materials policy, materials used to construct original highways can also be used for applications such as repair and reconstruction. Although use of these recycled materials (i.e., RAP) has economic, environmental, and engineering benefits, specifying materials containing RAP is a major challenge.

Because the state of Kansas allows as high as 25% RAP in asphalt mixtures, this research estimated the Multiple Stress Creep Recovery (MSCR) grade of virgin binders blended with RAP binders. The MSCR test (AASHTO T350) was originally developed to supplement the traditional performance grading (PG) system based on $G^*/sin\ \delta$, where $G^*$ is the complex/dynamic shear modulus and $\delta$ is the phase angle; MSCR test protocol was originally developed to characterize rutting performance of asphalt mixtures. The MSCR test applies a repeated creep-recovery load at 0.1 kPa and 3.2 kPa stress levels for 1 second, followed by 9 seconds of rest to determine non-recoverable creep compliance (Jnr) and percent recovery (%R) parameters. The Jnr value correlates to the rutting resistance of asphalt binders, while MSCR %R represents binder capability to relax stresses and recover strains. Previous research has shown that the Jnr value correlates well with the rutting performance of asphalt mixtures (Bernier, Zofka, & Yut, 2012; D'Angelo, 2009; Wasage, Stastna, & Zanzotto, 2011; Zhang, Walubita, Faruk, Karki, & Simate, 2015).

Based on MSCR test parameters, the binder can be specified as Standard Designation (*S*) for traffic levels less than 10 million equivalent single-axle loads (ESALs), or roads with traffic speeds that exceed the standard traffic speed (>70 km/h). Binders with High Designation (*H*) can be used for traffic levels of 10–30 million ESALs or slow-moving traffic (20–70 km/h). Very High Designation (*V*) binders can be used for traffic levels greater than 30 million ESALs or standing traffic (<20 km/h). Finally, binders with Extremely High Designation (*E*) are suitable for traffic levels greater than 30 million ESALs and standing traffic (<20 km/h). For grade *S*, the maximum value for Jnr should be 4.5 kPa-1, and the value of Jnr cannot exceed 2.0 kPa-1 for grade *H*. As traffic volume increases, the Jnr of the asphalt binder must not exceed 1.0 kPa-1 for grade *V*, and the maximum value for Jnr is 0.5 kPa-1 for grade *E*. Because some asphalt binders may be overly sensitive to changes in shear stress, the difference between Jnr of 0.1 kPa and Jnr of 3.2 kPa was limited to a ratio of 75%. According to AASHTO T350, the %R values determine the elastic response of polymer modified and unmodified asphalt binders. AASHTO M332 (2014) includes %R requirements for *E*, *V*, and *H* designations but does not include %R requirements for *S* designations, although some *S*-graded binders in Kansas require modification with an elastomer.

Application of the MSCR test improves Superpave testing in many ways. The most important advantage of the test is that the Jnr value more accurately correlates to asphalt rutting performance than $G^*/\sin\delta$. Moreover, use of one MSCR test eliminates the need for additional PG Plus tests for modified binders, and MSCR recovery more efficiently determines elastic properties of the asphalt binder than PG Plus tests. However, the MSCR test disregards a wide range of binders, especially those used for roads with low traffic volume in Kansas.

## 1.2 Problem Statement

Most Kansas roadways with design traffic less than 3 million ESALs allow the use of PG 64S-XX or PG 58-XX asphalt binders. Although MSCR test parameters can effectively specify modified binders with *H*, *V*, or *E* designations, the test disregards asphalt binders with relatively high non-recoverable compliance, Jnr > 4.5 $kPa^{-1}$, and allows all binders with *S* designation to be used without elastomeric modification since MSCR %R criterion is not applicable. Many modified and current asphalt binders used in Kansas (e.g., PG 58-XX binders) do not satisfy Jnr criteria and are therefore disregarded and not included in the specification system. Furthermore, Kansas allows high percentages of RAP (typically 25%) in asphalt mixtures.

The Kansas Department of Transportation (KDOT) recently participated in a pooled-fund study to investigate the feasibility of implementing Dynamic Shear Rheometer (DSR)-based tests to grade or adjust the grade of asphalt binders (Bahia, Swiertz, & Lyngdal, 2016). However, the study did not investigate *S*-graded binders that must be polymer modified, and it did not address “soft” binders that do not satisfy the Jnr requirement for the *S*-grade designation. Because no clear guideline stipulates how to test and specify PG 58-XX, blends of PG 58-XX, and RAP binders using DSR-based tests, current research must investigate how the MSCR test and other DSR-based test parameters should be applied for grading and grade adjustment of these binders.

# Chapter 2: Research Scope

## 2.1 Materials Used

Table 2.1 lists the materials used in this research, including two virgin binders and four binders recovered from various RAP sources. KDOT provided all virgin and RAP binders.

**Table 2.1: Materials and sources**

| Material | Amount (gram) | Description |
|---|---|---|
| PG 58-28 | 15,715 | Virgin binder |
| PG 58-34 FHR-1 | 14,377 | Virgin binder |
| 50-24-KA-4396-01 | 1,784 | RAP binder recovered from Edwards County—west city limits of Kinsley, east to Stafford County line |
| 144-106-KA-4403-01 | 1,718 | RAP binder recovered from Haskell and Gray Counties—0.8 miles east of the US-83 junction, east to the US-56 junction |
| 83-28-KA-4393-01 | 890 | RAP binder recovered from Finney County—Haskell County line, north 7.9 miles |
| 27-38-KA4392-01 | 1,256 | RAP binder recovered from Hamilton County—west US-50 junction, north to Greeley County line |

## 2.2 Lab Tests

This research investigated how adding extracted and recovered RAP binder to a virgin binder affects PG at high temperatures. Tests were conducted on virgin binders blended with RAP binders into the following seven combinations:

1. 100% virgin binder
2. 10% RAP and 90% virgin binder
3. 15% RAP and 85% virgin binder
4. 20% RAP and 80% virgin binder
5. 25% RAP and 75% virgin binder
6. 30% RAP and 70% virgin binder
7. 100% RAP

Table 2.2 presents the testing matrix, including DSR-based tests, temperatures at which the tests were conducted, aging conditions, and the number of replicates. The testing matrix also included PG tests on PG 58-XX binders, RAP binders, and blends of PG 58-XX and RAP binders. These tests were conducted according to AASHTO T 315-10 on original and Rolling Thin-Film Oven (RTFO) residue. Test results were used to grade original and RAP binders based on AASHTO M 332-14 (2014). Furthermore, MSCR tests were conducted on all binders at 64 °C according to AASHTO T 350-14 with RTFO residues.

**Table 2.2: Testing matrix**

| Temperature | Selected Test Method | Aging Condition | Response | Replicate |
|---|---|---|---|---|
| 52, 58, 64, 70 °C | AASHTO T 315-10 | Original Binder[1] | G*/sin(δ) | 2 |
| 52, 58, 64, 70 °C | AASHTO T 315-10 | RTFO Residue[2] | G*/sin(δ) | 2 |
| 64 °C,<br>and the grading-required temperature | AASHTO T 350-14 | RTFO Residue[2] | $Jnr_{3.2}$<br>$\%R_{3.2}$<br>%Jnr Diff. | 2 |

AASHTO M 332-14
[1]Required original binder is 2 g for two samples of 25 mm mold
[2]Required RTFO is eight bottles (35 g each, resulting in 280 g each blend)

In addition to the tests listed in Table 2.2, a Brookfield viscometer (Figure 2.1) was used to conduct rotational viscosity tests at 135 °C on PG 58-XX binders and RAP binders based on ASTM D6373-16.


**Figure 2.1: Brookfield Viscometer used to measure rotational viscosity of binders**

## 2.3 Test Procedure

A Ross 100-L high shear laboratory mixer (Hauppauge, New York) was used in this project to ensure homogenous blending of PG-XX binders and RAP binders at various percentages. The following steps were used to thoroughly mix the virgin and RAP binders:

1. Use a hot spoon to obtain proper amounts of virgin and RAP binders based on the percentage of RAP binder.
2. Place the obtained binder in a deep steel container (Figure 2.2).
3. Heat the binder to the mixing temperature.
4. Place the heated mixture on a hot plate to avoid a sharp temperature drop during mixing.
5. Position the rotor-stator generator of the high shear mixer 2–3 head diameters from the bottom of the container.
6. Mix at 5,000 rpm for 2 min (5,000 rpm was determined to be the maximum speed without spillage).
7. Store the mixture for the next steps of testing or future tests.


**Figure 2.2: Ross (Hauppauge, New York) 100-L high-shear laboratory mixer set up**

### *2.3.1 Short-Term Aging of Binder Using RTFO*

The next step was to age the mixture using RTFO based on AASHTO T 240-13 to simulate short-term aging (Figure 2.3). The RTFO short-term aging protocol was selected to determine the effect of RAP binders on high-temperature grading. Short-term aging is required to simulate potential aging during mixing and compaction in the field.

Following AASHTO M 332-14, the material was heated and subjected to air flow for 85 min at 163 °C (325 °F). RTFO residue from this test was also used for additional testing, and mass loss was measured to determine binder volatility and mass changes due to oxidation.

**Figure 2.3: RTFO samples**

### 2.3.2 High-Temperature Grading Based on AASHTO T 315-10

AASHTO T 315-10 was used for high-temperature grading of all binders, including PG 58-XX, RAP binders, and blends of PG 58-XX and RAP binders. In this test, dynamic shear modulus and phase angle were measured at selected temperatures and frequencies, and with a parallel plate geometry set-up, in which a circular wafer of asphalt binder is sandwiched between two circular, parallel plates, was utilized (AASHTO, 2011). At constant temperature, one plate was oscillated with respect to the other plate at a prescribed frequency under stress-controlled conditions, and the resulting strain was measured. The complex shear modulus was the ratio of the maximum stress amplitude to maximum strain amplitude at the test temperature and testing frequency. The phase angle was derived from the difference in time at which the maximum stress and maximum strain occurred at the specified testing frequency. The complex shear modulus and phase angle were checked against criteria to determine the binder grade in accordance with AASHTO M 332-14 (2014). The starting temperature for each test was 52 °C, and the test continued at 58, 64, and 70 °C. DSR tests were conducted using a Kinexus Malvern instrument, as shown in Figure 2.4.

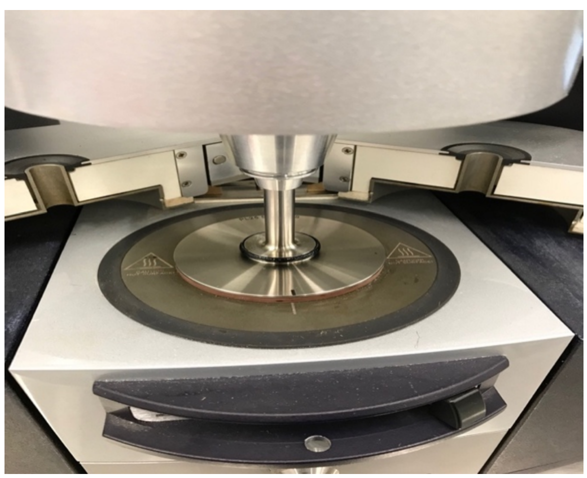


**Figure 2.4: DSR sample between parallel plates**

### *2.3.3 MSCR Test Based on AASHTO T 350-14*

One objective of this study was to investigate how the MSCR test could help determine virgin binder grade adjustments with RAP. RTFO residue was used to conduct the MSCR test, based on AASHTO T 350-14, at 64 °C since the LTPPBind program has shown a 98% reliability for Kansas at that temperature. Prescribed creep-recovery cycles were applied, and recoverable and non-recoverable strain components were measured. The recovered strain portion was expected to measure the binder's elastic behavior, and the non-recoverable portioDSRn was used to evaluate binder susceptibility to permanent deformation. Furthermore, the MSCR test was expected to determine the presence of an elastomeric polymer.

The MSCR test temperature should be similar to the actual pavement temperature. The MSCR test temperature was based on the yearly, 7-day average maximum pavement temperature measured 20 mm below the pavement surface. The outcome of the MSCR test includes non-recoverable creep compliance (Jnr) and percentage of recovery (%R) parameters. Low Jnr values reflect higher stiffness, and %R explains the delayed elastic response of the asphalt binder, indicating if the binder will recover after being subjected to stress. Binder samples with high amounts of delayed elastic response typically demonstrate significant elasticity at the test temperature.

The RTFO-aged asphalt binder was placed between the DSR plates and subjected to stress for 1 second, and then the load was removed for 9 seconds. Therefore, each cycle of creep and recovery lasted 10 seconds. Figure 2.5 and Figure 2.6 respectively illustrate the expected loading cycle and strain response from a single creep-recovery cycle.

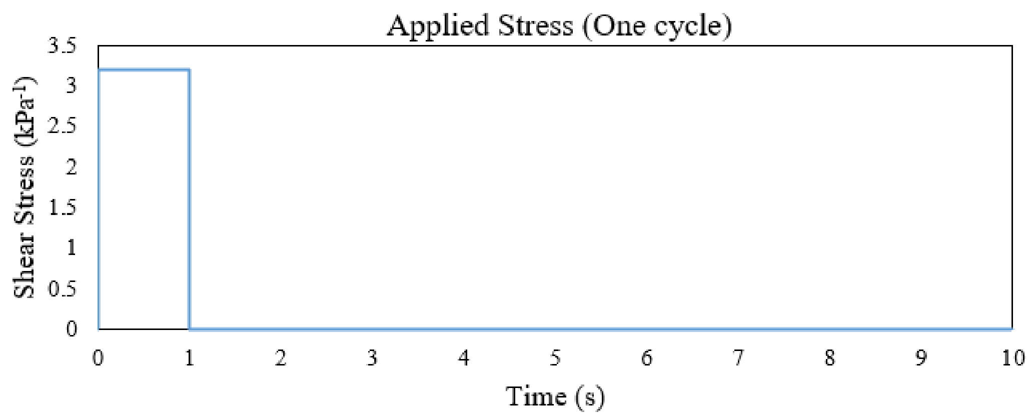



**Figure 2.5: Loading scenario of one cycle of the MSCR test**

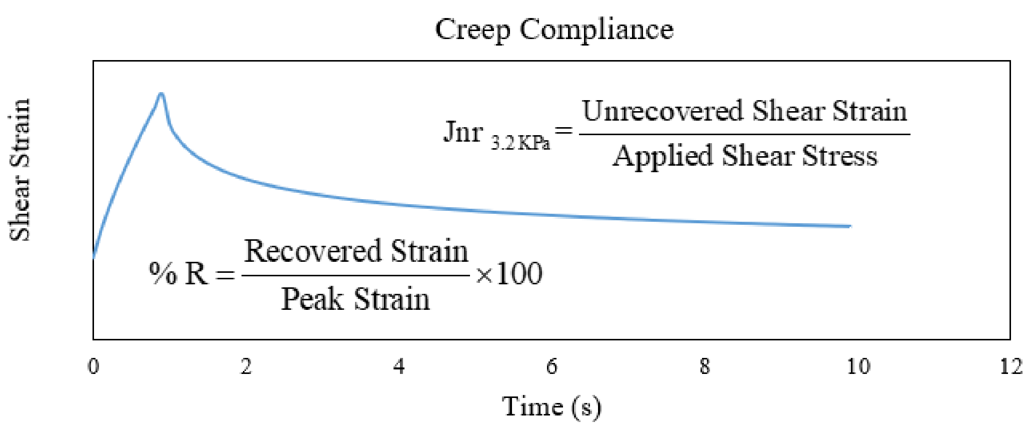



**Figure 2.6: Strain response during one cycle of the MSCR test**

The MSCR test initially applied a low stress level of 0.1 kPa as conditioning for 10 creep-recovery cycles and then continued with another 10 cycles at the same stress level. Then the stress was increased to 3.2 kPa, and another 10 loading cycles were performed (Figure 2.7) and sheer strain responses recorded (Figure 2.8). Each MSCR test included 30 creep-recovery cycles.

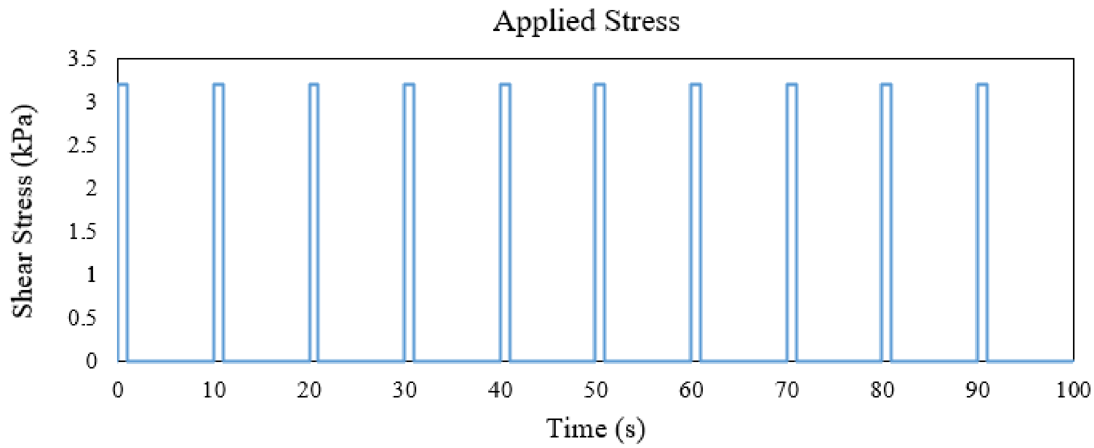



**Figure 2.7: Loading cycles of creep recovery during MSCR tests**

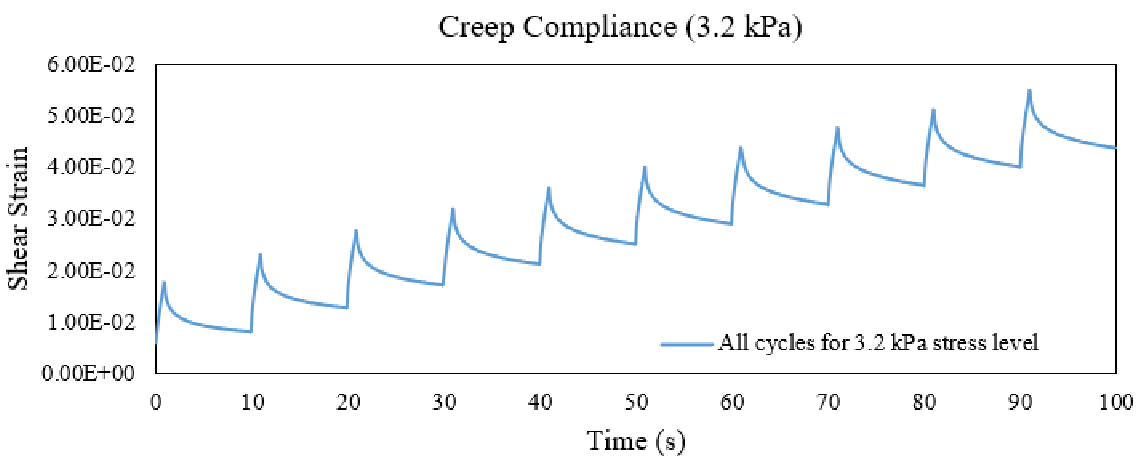



**Figure 2.8: Shear strain response during MSCR tests**

According to AASHTO T350, Jnr and %R determine the rutting susceptibility of asphalt mixtures and the elastic response of polymer modified and unmodified asphalt binders, respectively. Figure 2.9 illustrates the presence of an elastomeric polymer, which indicates the nonlinear viscoelastic behavior of the binder. Asphalt binders that fall below the curve have low elasticity, while binders above the curve demonstrate acceptable elastomeric properties.

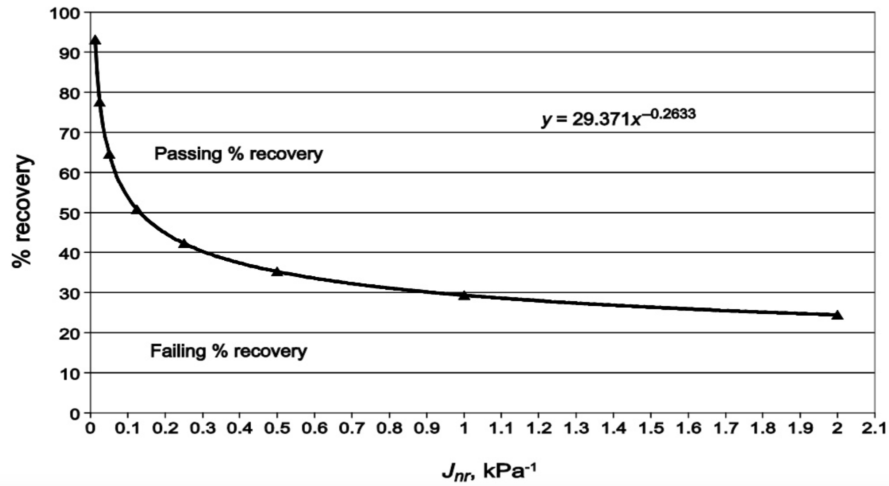



**Figure 2.9: MSCR criteria for binders with Jnr less than 2**

Performing the MSCR test improves the Superpave testing in different ways. The most important advantage of the MSCR test is related to the pavement's rutting issue. The Jnr value correlates to asphalt rutting more accurately as compared to the G*/sin δ. Moreover, additional PG Plus tests may be eliminated by performing a single MSCR test. The MSCR recovery is a quick and simple test method to determine elastic properties of the asphalt binder compared to the PG Plus tests.

# Chapter 3: Results and Discussion

## 3.1 Virgin Binders

KDOT provided two virgin binders, PG 58-28 and PG 58-34, for this research. First, the high-temperature grades of the binders were verified at the University of Kansas (KU), and then MSCR tests were conducted on the virgin binders to measure Jnr and %R. KDOT test results from similarly graded binders were extracted and compared to results of MSCR tests conducted at KU. Briefly, the following results were obtained:

1. High-temperature grades were verifiably identical to grades submitted by KDOT.
2. Because the virgin binders both failed the *S* grade, these binders should be disregarded based on MSCR specifications. Results of MSCR tests on binders modified with RAP showed that these binders can be used as *S* grades when blended with certain percentages of RAP binder.

This research first sought to verify grades of the provided virgin binders. Two replicates were tested based on AASHTO T 315-10. The tests were conducted on original binders and RTFO residue. Once the high-temperature grades were verified as PG 58-XX, MSCR test protocol was followed, based on AASHTO T 350-14, to measure MSCR test variables. MSCR tests were conducted on at least two replicates for the RTFO at 64 °C. Table 3.1 shows the results of tests conducted on the virgin binders (PG 58-XX) to verify their submitted grades, and Table 3.2 lists MSCR test results for RTFO specimens of virgin binders.

Figure 3.1 shows that results from tests conducted at KU were consistent with KDOT test results. Although Figure 3.1 shows that the PG 58-34 binder satisfied the *S* grade criteria, they did not meet the %JnrDiff of less than 75%. In fact, test results at KU showed the %JnrDiff for PG 58-34 virgin binders to be 103%, which is 28% higher than the designated 75% in the MSCR criteria.

**Table 3.1: High-temperature grades for KDOT PG 58-28 and PG 58-34 virgin binders**

| Grade Submitted as PG 58-28 | | | | | |
|---|---|---|---|---|---|
| | Replicate 1 | Replicate 2 | Test Temp. (°C) | Pass/Fail | Verified Binder Grade |
| *Tests on Original Binder* | | | | | **PG 58-XX** |
| **G*/sin(δ) kPa** | 0.61 | 0.64 | 64 | Fail | |
| | 1.30 | 1.37 | 58 | Pass | |
| | 2.95 | 3.13 | 52 | Pass | |
| *Tests on RTFO Residue* | | | | | |
| **G*/sin(δ) kPa** | 1.41 | 1.36 | 64 | Fail | |
| | 3.15 | 3.11 | 58 | Pass | |
| | 7.31 | **7.3** | **52** | Pass | |
| **Grade Submitted as PG 58-34** | | | | | |
| | Replicate 1 | Replicate 2 | Test Temp. (°C) | Pass/Fail | Verified Binder Grade |
| *Tests on Original Binder* | | | | | **PG 58-XX** |
| **G*/sin(δ) kPa** | 1.21 | 1.23 | 64 | Pass | |
| | 2.22 | 2.22 | 58 | Pass | |
| | 4.09 | 4.10 | 52 | Pass | |
| *Tests on RTFO Residue* | | | | | |
| **G*/sin(δ) kPa** | 2.00 | 2.02 | 64 | Fail | |
| | 3.67 | 3.68 | 58 | Pass | |
| | 4.00 | 4.10 | 52 | Pass | |

**Table 3.2: MSCR tests on RTFO specimens at 64 °C for virgin binders**

| Grade Submitted as PG 58-28 | | | | | |
|---|---|---|---|---|---|
| | Rep. 1 | Rep. 2 | Rep. 3 | Pass/Fail | Final MSCR Grade |
| *Tests on RTFO Binders* | | | | | **Fail *S* Grade Jnr Criteria** |
| Jnr 3.2 ($kPa^{-1}$) | 7.45 | 7.23 | – | Fail | |
| %R 3.2 | 0 | 0 | – | Fail | |
| %JnrDiff | 10.6 | 11.9 | – | Fail | |
| **Grade Submitted as PG 58-34** | | | | | |
| | Rep. 1 | Rep. 2 | Rep. 3 | Pass/Fail | Final MSCR Grade |
| *Tests on RTFO Binders* | | | | | **Fail *S* Grade %JnrDiff Criteria** |
| Jnr 3.2 ($kPa^{-1}$) | 3.06 | 2.94 | – | Fail | |
| %R 3.2 | 25.1 | 25.5 | – | Pass | |
| %JnrDiff | 103 | 103 | – | Pass | |

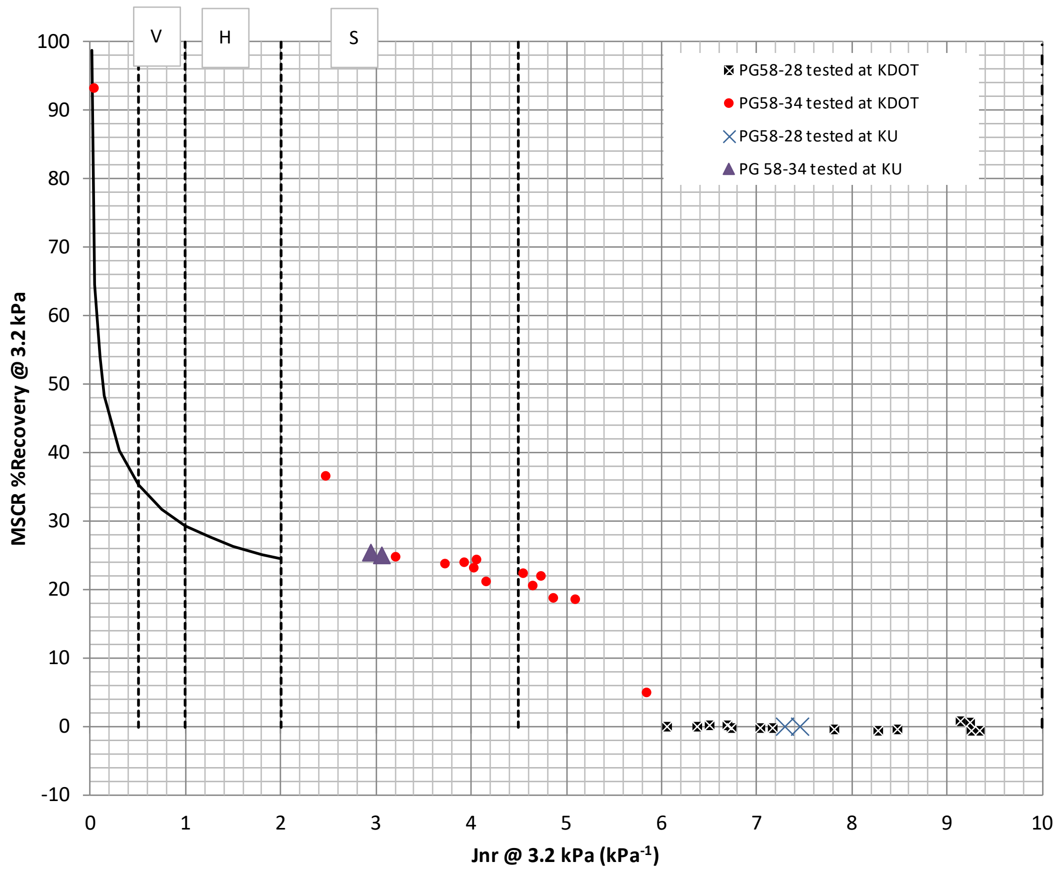



**Figure 3.1: Comparison of MSCR tests of virgin binders (KU and KDOT)**

## 3.2 Pure RAP Binders

In addition to virgin binders, pure RAP binders were also characterized based on AASHTO T 350-14 and AASHTO T 315-10. Pure RAP binders were initially tested to determine their PG grades, and then MSCR tests were conducted on pure RAP binders to determine MSCR test variables. This RAP binder test data and data on virgin binders were used to relate properties of virgin and pure RAP binders to mixture properties.

The four RAP binders were tested to determine their high-temperature PG grade. Table 3.3 and Table 3.4 show test results for the RAP binders. All results in this report are the average of at least two replicates with less than 7% deviation.

As shown in Table 3.3, the RAP 144-106 binder showed significantly lower high-temperature grade than the other RAP binders. Investigations on the source of RAP 144-106 revealed that RAP 144-106 was comprised of rubberized crack sealant, chip seal (lightweight aggregate and CRS-1HP), and hot mix asphalt (HMA) that was placed in 2009. Therefore, the conclusion was made that the CRS-1HP and the crack sealant caused the extracted RAP binder to be softer than expected. The results of this research reinforced this statement, and, in some cases, the data generated for binders modified with RAP 144-106 were neglected due to the softness of the RAP binder.

**Table 3.3: High-temperature PG grading of KDOT RAP binders**

| **100% RAP 50-24** | | |
|---|---|---|
| | G*/sin(δ) (kPa^) | PG Grade |
| Unaged RAP Binder | 1.118@ 100 °C | PG 100−XX |
| RTFO Residue | 3.143 @ 100 °C | |
| **100% RAP 27-38** | | |
| Unaged RAP Binder | 1.545 @ 94 °C | PG 94−XX |
| RTFO Residue | 3.290 @ 94 °C | |
| **100% RAP 83-28** | | |
| Unaged RAP Binder | 1.601 @ 106 °C | PG 106−XX |
| RTFO Residue | 2.673 @ 106 °C | |
| **100% RAP 144-106** | | |
| Unaged RAP Binder | 1.541 @ 82 °C | PG 82−XX |
| RTFO Residue | 4.381 @ 82 °C | |

**Table 3.4: MSCR tests on RTFO RAP binders at 64 °C**

| RAP Binder | $Jnr_{3.2}$ ($kPa^{-1}$) | %R $_{3.2}$ | %Jnr $_{Diff}$ |
|---|---|---|---|
| RAP 50−24 | 0.005935 | 77.5 | 22.9 |
| RAP 27−38 | 0.01282 | 80.5 | 81.1 |
| RAP 83−28 | 0.002951 | 77.2 | 75.5 |
| RAP 144−106 | 0.0925 | 36.9 | 10.20 |

## 3.3 Blend of PG 58-28 and RAP Binders

To investigate the effect of RAP binders on the high-temperature grade adjustment and MSCR variables, the two virgin binders were modified with 10%–30% RAP binders. For each virgin binder and RAP source, the following five combinations were considered:

1. 10% RAP + 90% virgin binder
2. 15% RAP + 85% virgin binder
3. 20% RAP + 80% virgin binder
4. 25% RAP + 75% virgin binder
5. 30% RAP + 70% virgin binder

The PG 58-28 virgin binder and RAP 50-24 binder were tested first, and then blends were tested according to AASHTO T 315-10 to determine the high-temperature PG grade of RAP modified binders (Table 3.5). At least two replicates were used for each test.

Table 3.5 shows that addition of at least 15% RAP changed the high-temperature grade of PG 58-XX (58 °C) to PG 64-XX (64 °C), a change that was considered the main criteria since Kansas is mostly a 64 °C state. In addition to changes in high-temperature grade, this research investigated how the addition of RAP binders would impact MSCR test results. Table 3.6 lists the results of PG 58-28 with various percentages of RAP 50-24. The objective was to determine which percentage of RAP binder would result in grade *S* according to MSCR specifications. It should be noted that the binders used in this research are primarily utilized in low traffic-volume roads for which the *S* grade is sufficient.

**Table 3.5: PG 58-28+RAP 50-24 test results based on AASHTO T 315-10 and ASTM D7175**

| % RAP | | Rep. 1 | Rep. 2 | Temp. (°C) | Pass/Fail | PG Grade |
|---|---|---|---|---|---|---|
| 10% RAP | *Tests on Unaged Binders* | | | | | PG 58-XX |
| | **G*/sin(δ)** | 0.872 | 0.858 | 64 | Fail | |
| | | 1.898 | 1.854 | 58 | Pass | |
| | | 4.281 | 4.264 | 52 | Pass | |
| | *Tests on RTFO Residue* | | | | | |
| | **G*/sin(δ)** | 2.049 | 2.054 | 64 | Fail | |
| | | 4.68 | 4.601 | 58 | Pass | |
| | | 11.108 | 10.732 | 52 | Pass | |
| 15% RAP | *Tests on Unaged Binders* | | | | | PG 64-XX |
| | **G*/sin(δ)** | 0.551 | 0.557 | 70 | Fail | |
| | | 1.146 | 1.136 | 64 | Pass | |
| | | 2.548 | 2.485 | 58 | Pass | |
| | *Tests on RTFO Residue* | | | | | |
| | **G*/sin(δ)** | 1.292 | 1.276 | 70 | Fail | |
| | | 2.781 | 2.741 | 64 | Pass | |
| | | 6.284 | 6.241 | 58 | Pass | |
| 20% RAP | *Tests on Unaged Binders* | | | | | PG 64-XX |
| | **G*/sin(δ)** | 0.582 | 0.571 | 70 | Fail | |
| | | 1.197 | 1.164 | 64 | Pass | |
| | | 2.644 | 2.532 | 58 | Pass | |
| | *Tests on RTFO Residue* | | | | | |
| | **G*/sin(δ)** | 1.404 | 1.364 | 70 | Fail | |
| | | 3.059 | 2.963 | 64 | Pass | |
| | | 7.075 | 6.798 | 58 | Pass | |
| 25% RAP | *Tests on Unaged Binders* | | | | | PG 64-XX |
| | **G*/sin(δ)** | 0.725 | 0.725 | 70 | Fail | |
| | | 1.494 | 1.492 | 64 | Pass | |
| | | 3.257 | 3.288 | 58 | Pass | |
| | *Tests on RTFO Residue* | | | | | |
| | **G*/sin(δ)** | 1.898 | 2.024 | 70 | Fail | |
| | | 4.167 | 4.434 | 64 | Pass | |
| | | 10.176 | 10.176 | 58 | Pass | |
| 30% RAP | *Tests on Unaged Binders* | | | | | PG 64-XX |
| | **G*/sin(δ)** | 0.934 | 0.916 | 70 | Fail | |
| | | 1.956 | 1.935 | 64 | Pass | |
| | | 4.329 | 4.331 | 58 | Pass | |
| | *Tests on RTFO Residue* | | | | | |
| | **G*/sin(δ)** | 1.349 | 1.345 | 76 | Fail | |
| | | 2.835 | 2.812 | 70 | Pass | |
| | | 6.075 | 6.15 | 64 | Pass | |

**Table 3.6: PG 58-28 + RAP 50-24 results based on AASHTO T 350-14**

| % RAP | Result Description | Rep. 1 | Rep. 2 |
|---|---|---|---|
| 0% RAP | Jnr 3.2 ($kPa^{-1}$) | 7.45 | 7.23 |
| | %R 3.2 | 0 | 0 |
| | %JnrDiff | 10.6 | 11.9 |
| 10% RAP | Jnr 3.2 ($kPa^{-1}$) | 5.288 | 5.308 |
| | %R 3.2 | 0 | 0 |
| | %JnrDiff | 13.7 | 12.6 |
| 15% RAP | Jnr 3.2 ($kPa^{-1}$) | 3.775 | 3.727 |
| | %R 3.2 | 0 | 0 |
| | %JnrDiff | 15.4 | 15.5 |
| 20% RAP | Jnr 3.2 ($kPa^{-1}$) | 3.386 | 3.397 |
| | %R 3.2 | 0.7 | 0 |
| | %JnrDiff | 16.2 | 17.6 |
| 25% RAP | Jnr 3.2 ($kPa^{-1}$) | 2.215 | 2.272 |
| | %R 3.2 | 1.2 | 1.3 |
| | %JnrDiff | 17 | 18 |
| 30% RAP | Jnr 3.2 ($kPa^{-1}$) | 1.448 | 1.357 |
| | %R 3.2 | 4 | 4 |
| | %JnrDiff | 20.7 | 20.2 |
| 100% RAP | Jnr 3.2 ($kPa^{-1}$) | 0.0062 | 0.0056 |
| | %R 3.2 | 77 | 78 |
| | %JnrDiff | 0 | 45.8 |

Figure 3.2 shows that at least 15% RAP satisfies grade *S* according to MSCR specifications. Although the addition of 30% or more RAP significantly decreased the Jnr value, it still did not meet %R and Jnr for *H* or *V* grades. The %JnrDiff binder grading criterion was not considered because %JnrDiff variations were significant.

Table 3.7 and Table 3.8 present the results of similar tests with PG 58-28 and other RAP binders.

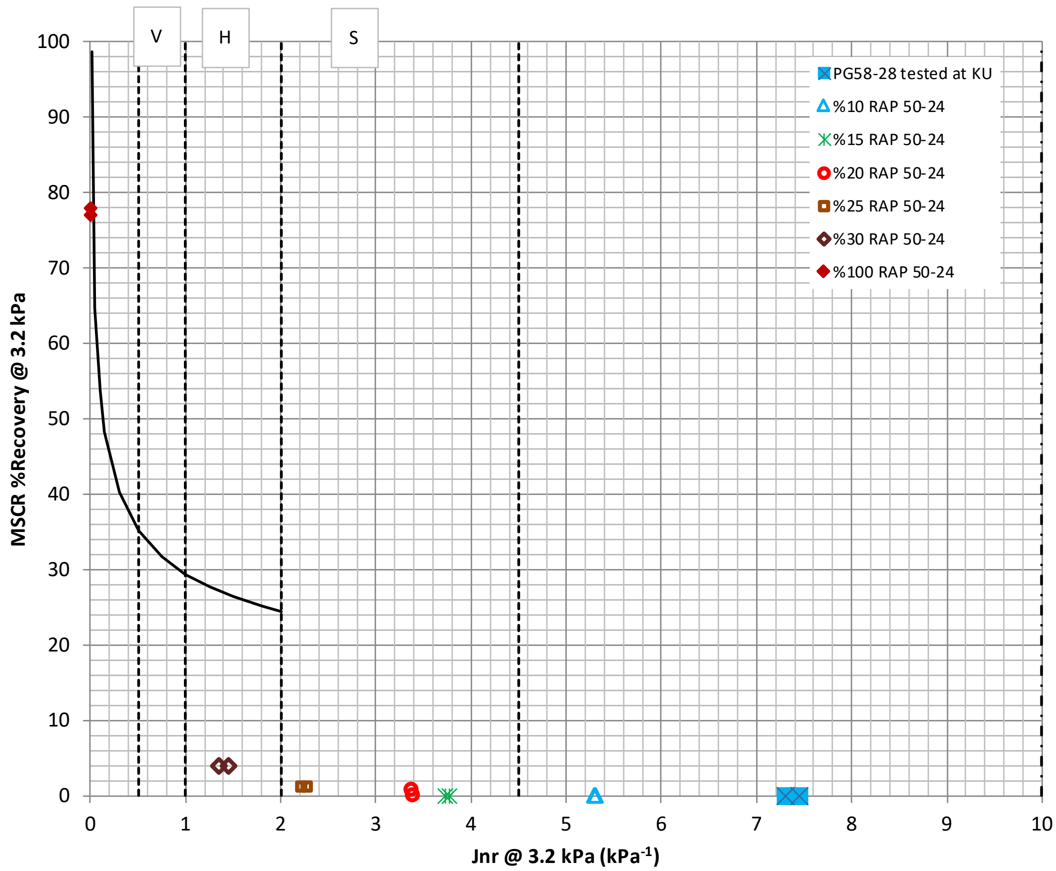



**Figure 3.2: Jnr versus %R for PG 58-28 modified with various percentages of RAP 50-24**

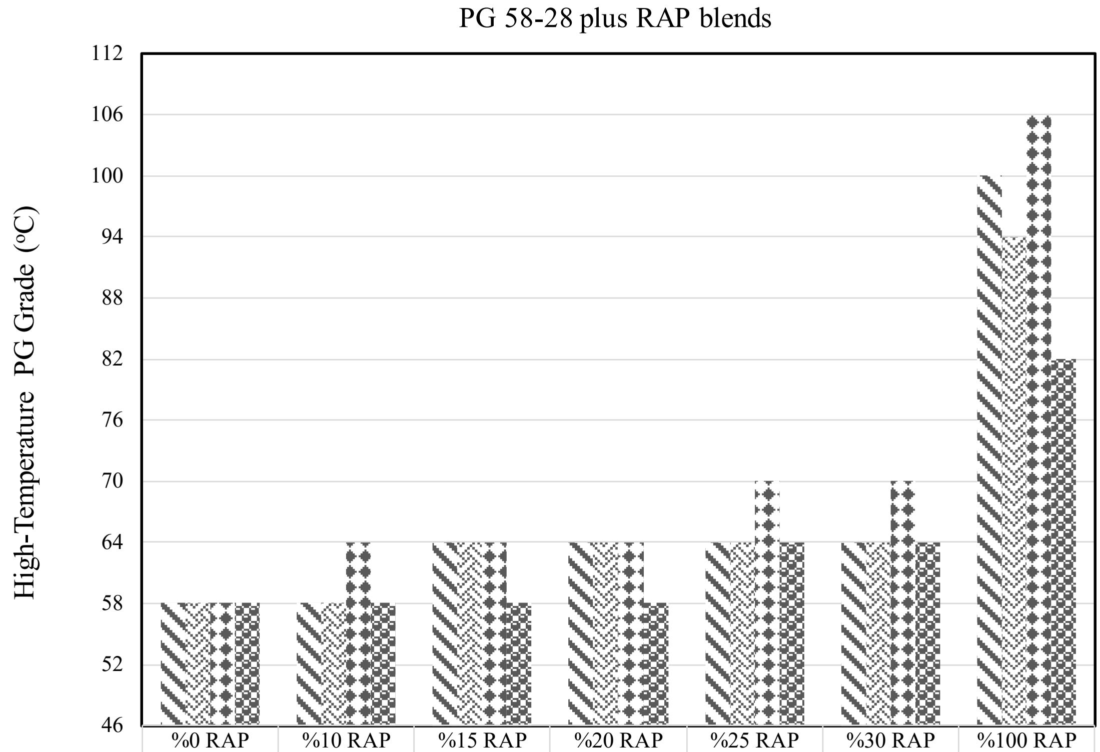
**Table 3.7: High-temperature grade of PG 58-28 modified with various percentages of RAP binders**

| Binder | Unaged G*/sin(δ) (kPa) | RTFO G*/sin(δ) (kPa) | PG grade |
|---|---|---|---|
| % RAP 50-24 | | | |
| 0 | 1.336 @ 58 °C | 3.125 @ 58 °C | 58 |
| 10 | 1.876 @ 58 °C | 4.641 @ 58 °C | 58 |
| 15 | 1.141 @ 64 °C | 2.761 @ 64 °C | 64 |
| 20 | 1.180 @ 64 °C | 3.011 @ 64 °C | 64 |
| 25 | 1.493 @ 64 °C | 4.300 @ 64 °C | 64 |
| 30 | 1.945 @ 64 °C | 2.823 @ 70 °C | 64 |
| 100 | 1.118 @ 100 °C | 3.143 @ 100 °C | 100 |
| % RAP 27-38 | | | |
| 0 | 1.336 @ 58 °C | 3.125 @ 58 °C | 58 |
| 10 | 1.870 @ 58 °C | 4.089 @ 58 °C | 58 |
| 15 | 1.022 @ 64 °C | 2.213 @ 64 °C | 64 |
| 20 | 1.185 @ 64 °C | 2.602 @ 64 °C | 64 |
| 25 | 1.573 @ 64 °C | 3.241 @ 64 °C | 64 |
| 30 | 1.863 @ 64 °C | 3.791 @ 64 °C | 64 |
| 100 | 1.545 @ 94 °C | 3.290 @ 94 °C | 94 |
| % RAP 83-28 | | | |
| 0 | 1.336 @ 58 °C | 3.125 @ 58 °C | 58 |
| 10 | 1.004 @ 64 °C | 2.377 @ 64 °C | 64 |
| 15 | 1.044 @ 64 °C | 2.838 @ 64 °C | 64 |
| 20 | 1.911 @ 64 °C | 4.242 @ 64 °C | 64 |
| 25 | 1.265 @ 70 °C | 2.712 @ 70 °C | 70 |
| 30 | 1.446 @ 70 °C | 3.707 @ 70 °C | 70 |
| 100 | 1.601 @ 106 °C | 2.673 @ 106 °C | 106 |
| % RAP 144-106 | | | |
| 0 | 1.336 @ 58 °C | 3.125 @ 58 °C | 58 |
| 10 | 1.602 @ 58 °C | 3.883 @ 58 °C | 58 |
| 15 | 1.123 @ 64 °C | 3.627 @ 58 °C | 58 |
| 20 | 1.240 @ 64 °C | 4.677 @ 58 °C | 58 |
| 25 | 1.218 @ 64 °C | 2.332 @ 64 °C | 64 |
| 30 | 1.640 @ 64 °C | 2.827 @ 64 °C | 64 |
| 100 | 1.541 @ 82 °C | 4.381 @ 82 °C | 82 |

**Table 3.8: Measured MSCR parameters for PG 58-28 binder modified with RAP binders**

| Binder | Jnr ($kPa^{-1}$) | %R | %Jnr Diff |
|---|---|---|---|
| % RAP 50-24 | | | |
| 0 | 7.372 | 0 | 11.25 |
| 10 | 5.298 | 0 | 13.15 |
| 15 | 3.751 | 0 | 15.45 |
| 20 | 3.391 | 0.35 | 16.9 |
| 25 | 2.243 | 1.4 | 17.5 |
| 30 | 1.402 | 4.45 | 20.45 |
| 100 | 0.005935 | 77.5 | 22.9 |
| % RAP 27-38 | | | |
| 0 | 7.372 | 0 | 11.25 |
| 10 | 5.622 | 0 | 14.3 |
| 15 | 4.909 | 0 | 19.85 |
| 20 | 3.780 | 0.5 | 19.4 |
| 25 | 3.099 | 1.2 | 20.2 |
| 30 | 2.444 | 2.05 | 25 |
| 100 | 0.01282 | 80.5 | 81.1 |
| % RAP 83-28 | | | |
| 0 | 7.372 | 0 | 11.25 |
| 10 | 4.503 | 0 | 12.3 |
| 15 | 3.693 | 0.2 | 20.5 |
| 20 | 2.380 | 1 | 15.3 |
| 25 | 1.517 | 2.35 | 15.2 |
| 30 | 1.065 | 4.65 | 14.65 |
| 100 | 0.002951 | 77.2 | 75.5 |
| % RAP 144-106 | | | |
| 0 | 7.372 | 0 | 11.25 |
| 10 | 6.056 | 0 | 13.25 |
| 15 | 5.894 | 0 | 11.80 |
| 20 | 4.917 | 0 | 11.40 |
| 25 | 4.213 | 0 | 13.70 |
| 30 | 3.692 | 0.10 | 13.60 |
| 100 | 0.0925 | 36.9 | 10.20 |

Figure 3.3 illustrates the high-temperature grade of PG 58-28 binder modified with various percentages of RAP binder. As expected, adding up to 20% of the soft RAP binder 144-106 did not change the high temperature of the blended binder. However, PG 58-28 blended with 15% of other RAP binders changed the high-temperature grade from 58 °C to at least 64 °C.




| | %0 RAP | %10 RAP | %15 RAP | %20 RAP | %25 RAP | %30 RAP | %100 RAP |
|---|---|---|---|---|---|---|---|
| RAP 50-24; PG 58-28 | 58 | 58 | 64 | 64 | 64 | 64 | 100 |
| RAP 27-38; PG 58-28 | 58 | 58 | 64 | 64 | 64 | 64 | 94 |
| RAP 83-28; PG 58-28 | 58 | 64 | 64 | 64 | 70 | 70 | 106 |
| RAP 144-106; PG 58-28 | 58 | 58 | 58 | 58 | 64 | 64 | 82 |

**Figure 3.3: High-temperature grade of PG 58-28 binder modified with various percentages of RAP binders**

To further evaluate this trend, MSCR parameters were determined for PG 58-XX and RAP binder blends. Results are plotted in Figure 3.4 based on the % RAP without mentioning the source of the RAP binder to determine the presence of a more general trend.

Figure 3.4 shows that, except for PG 58-28 blended with RAP 144-106, the addition of 15% or more RAP resulted in Jnr values less than 4.5 $kPa^{-1}$.

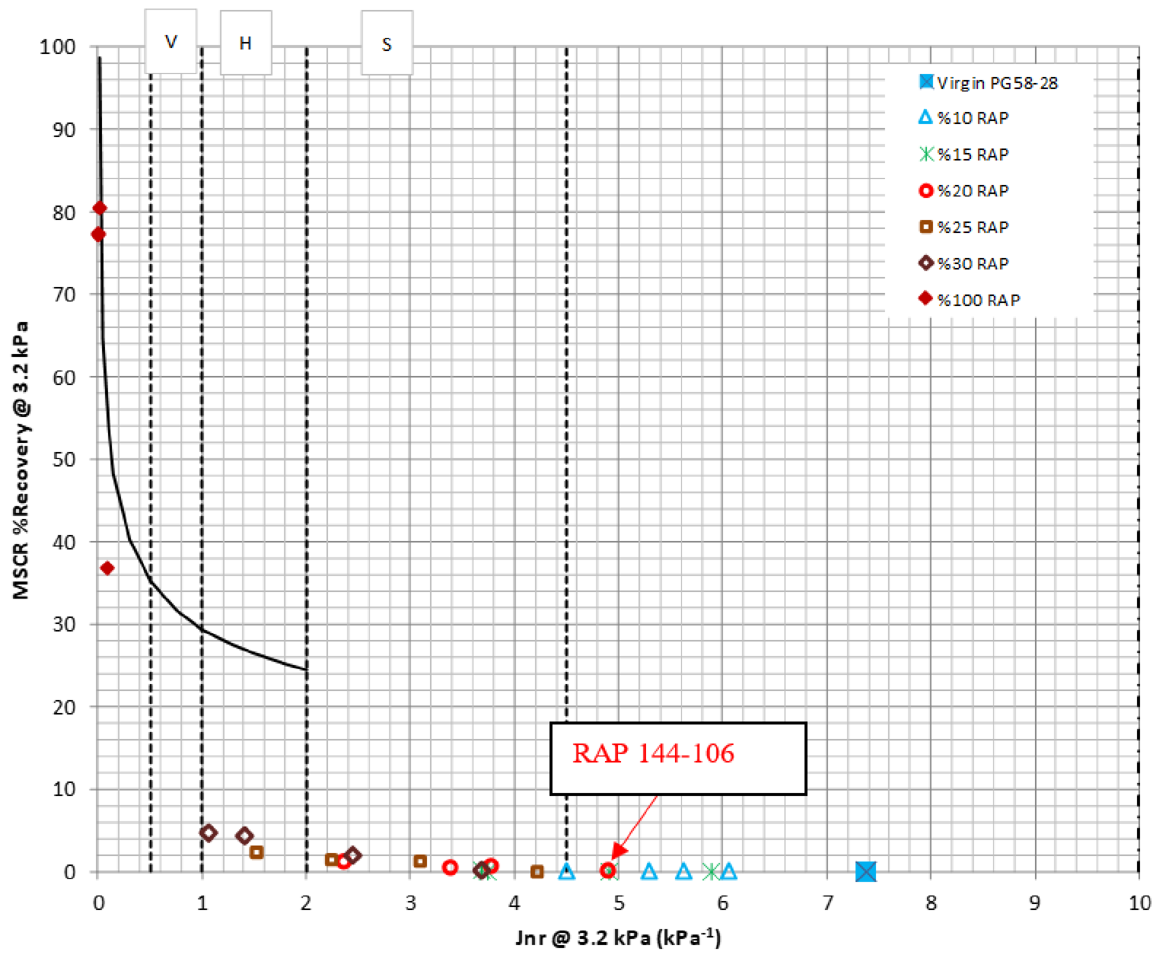



**Figure 3.4: Jnr versus %R for PG 58-28 modified with various percentages of RAP binders**

## 3.4 Blend of PG 58-34 and RAP Binders

Similar tests were conducted on the PG 58-34 binder blended with RAP binders. Table 3.9 and Table 3.10 show the results of high-temperature grading and MSCR parameters, respectively.

As shown in Figure 3.5, the addition of 15% or more of RAP increased the high-temperature grade of PG 58-34 binder blended with RAP from 58 ℃ to at least 64 ℃.

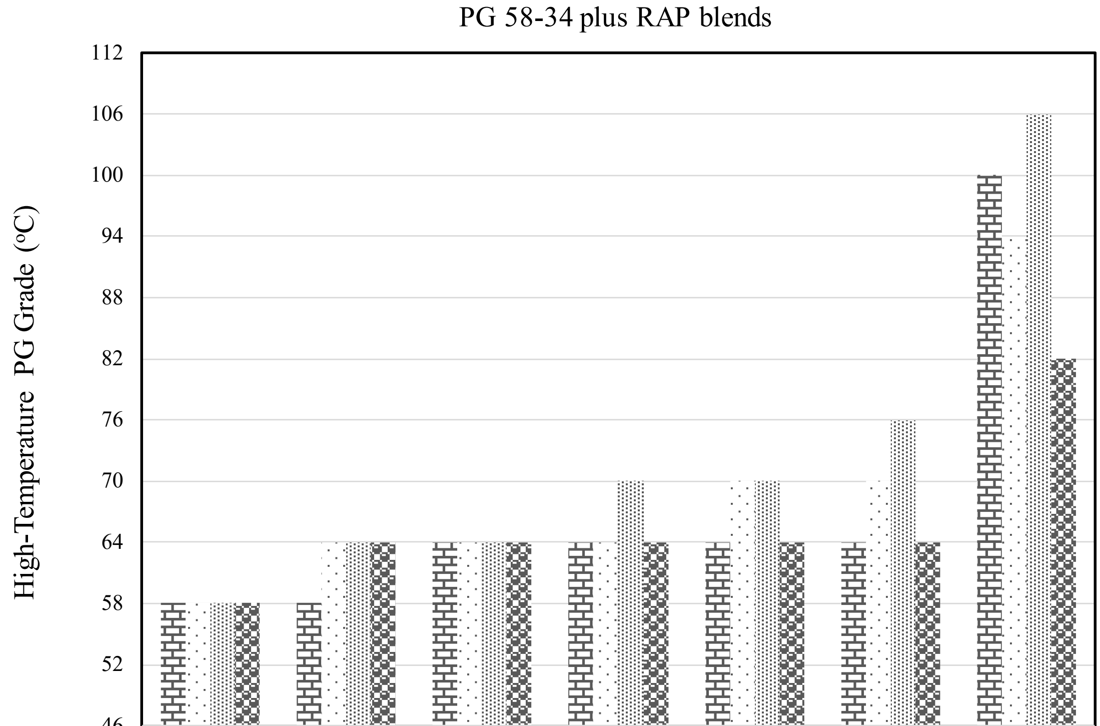
When considering MSCR parameters but not %JnrDiff, both the virgin binder and PG 58-34 blended with RAP binders satisfied at least the S grade (Figure 3.6).

**Table 3.9: High-temperature grade of PG 58-34 modified with various percentages of RAP binders**

| Binder | Unaged G*/sin(δ) (kPa) | Unaged G*/sin(δ) (kPa) | PG grade |
|---|---|---|---|
| % RAP 50-24 | | | |
| 0 | 1.336 @ 58 °C | 3.779 @ 58 °C | 58 |
| 10 | 1.389 @ 64 °C | 2.228 @ 64 °C | 64 |
| 15 | 1.209 @ 70 °C | 2.793 @ 64 °C | 64 |
| 20 | 1.420 @ 70 °C | 3.716 @ 64 °C | 64 |
| 25 | 1.611 @ 70 °C | 2.595 @ 70 °C | 70 |
| 30 | 1.784 @ 70 °C | 3.049 @ 70 °C | 70 |
| 100 | 1.118 @ 100 °C | 3.143 @ 100 °C | 100 |
| % RAP 27-38 | | | |
| 0 | 1.193 @ 64 °C | 3.779 @ 58 °C | 58 |
| 10 | 1.410 @ 64 °C | 2.702 @ 64 °C | 64 |
| 15 | 1.763 @ 64 °C | 3.154 @ 64 °C | 64 |
| 20 | 1.159 @ 70 °C | 3.533 @ 64 °C | 64 |
| 25 | 1.315 @ 70 °C | 2.294 @ 70 °C | 70 |
| 30 | 1.601 @ 70 °C | 2.763 @ 70 °C | 70 |
| 100 | 1.545 @ 94 °C | 3.290 @ 94 °C | 94 |
| % RAP 83-28 | | | |
| 0 | 1.193 @ 64 °C | 3.779 @ 58 °C | 58 |
| 10 | 1.718 @ 64 °C | 2.826 @ 64 °C | 64 |
| 15 | 1.163 @ 70 °C | 3.633 @ 64 °C | 64 |
| 20 | 1.617 @ 70 °C | 2.591 @ 70 °C | 70 |
| 25 | 1.139 @ 76 °C | 3.745 @ 70 °C | 70 |
| 30 | 1.384 @ 76 °C | 2.604 @ 76 °C | 76 |
| 100 | 1.601 @ 106 °C | 2.673 @ 94 °C | 106 |
| % RAP 144-106 | | | |
| 0 | 1.193 @ 64 °C | 3.779 @ 58 °C | 58 |
| 10 | 1.203 @ 64 °C | 2.303 @ 64 °C | 64 |
| 15 | 1.327 @ 64 °C | 2.610 @ 64 °C | 64 |
| 20 | 1.381 @ 64 °C | 3.121 @ 64 °C | 64 |
| 25 | 1.763 @ 64 °C | 3.267 @ 64 °C | 64 |
| 30 | 1.049 @ 70 °C | 3.641 @ 64 °C | 64 |
| 100 | 1.541 @ 82 °C | 4.381 @ 82 °C | 82 |

**Table 3.10: Measured MSCR parameters for PG 58-34 binder modified with RAP binders**

| Binder | Jnr ($kPa^{-1}$) | %R | %Jnr Diff |
|---|---|---|---|
| % RAP 50−24 | | | |
| 0 | 3.001 | 25.3 | 102.8 |
| 10 | 2.736 | 22.75 | 84.4 |
| 15 | 2.701 | 25.1 | 76.5 |
| 20 | 1.447 | 28.55 | 70.85 |
| 25 | 1.078 | 31.55 | 61.15 |
| 30 | 0.8275 | 34.95 | 54.8 |
| 100 | 0.005935 | 77.5 | 22.9 |
| % RAP 27−38 | | | |
| 0 | 3.001 | 25.3 | 102.8 |
| 10 | 2.159 | 24 | 91.3 |
| 15 | 1.730 | 28.3 | 79.8 |
| 20 | 1.533 | 30.55 | 86 |
| 25 | 1.181 | 33.7 | 77.4 |
| 30 | 0.8429 | 38.5 | 71.4 |
| 100 | 0.01282 | 80.5 | 81.1 |
| % RAP 83−28 | | | |
| 0 | 3.001 | 25.3 | 102.8 |
| 10 | 2.189 | 21.7 | 63.6 |
| 15 | 1.693 | 24.6 | 73.3 |
| 20 | 1.125 | 29.5 | 62.5 |
| 25 | 0.6469 | 35.7 | 48.8 |
| 30 | 0.4479 | 40.2 | 43.2 |
| 100 | 0.002951 | 77.2 | 75.5 |
| % RAP 144−106 | | | |
| 0 | 3.001 | 25.30 | 102.8 |
| 10 | 2.860 | 20.20 | 78.75 |
| 15 | 2.623 | 17.25 | 78.50 |
| 20 | 2.026 | 20.10 | 63.70 |
| 25 | 1.877 | 19.90 | 58.40 |
| 30 | 1.776 | 19.45 | 55.40 |
| 100 | 0.0925 | 36.9 | 10.20 |




| | %0 RAP | %10 RAP | %15 RAP | %20 RAP | %25 RAP | %30 RAP | %100 RAP |
|---|---|---|---|---|---|---|---|
| RAP 50-24; PG 58-34 | 58 | 58 | 64 | 64 | 64 | 64 | 100 |
| RAP27-38; PG 58-34 | 58 | 64 | 64 | 64 | 70 | 70 | 94 |
| RAP83-28; PG 58-34 | 58 | 64 | 64 | 70 | 70 | 76 | 106 |
| RAP 144-106; PG 58-34 | 58 | 64 | 64 | 64 | 64 | 64 | 82 |

**Figure 3.5: High-temperature grade of PG 58-34 binder modified with various percentages of RAP binders**

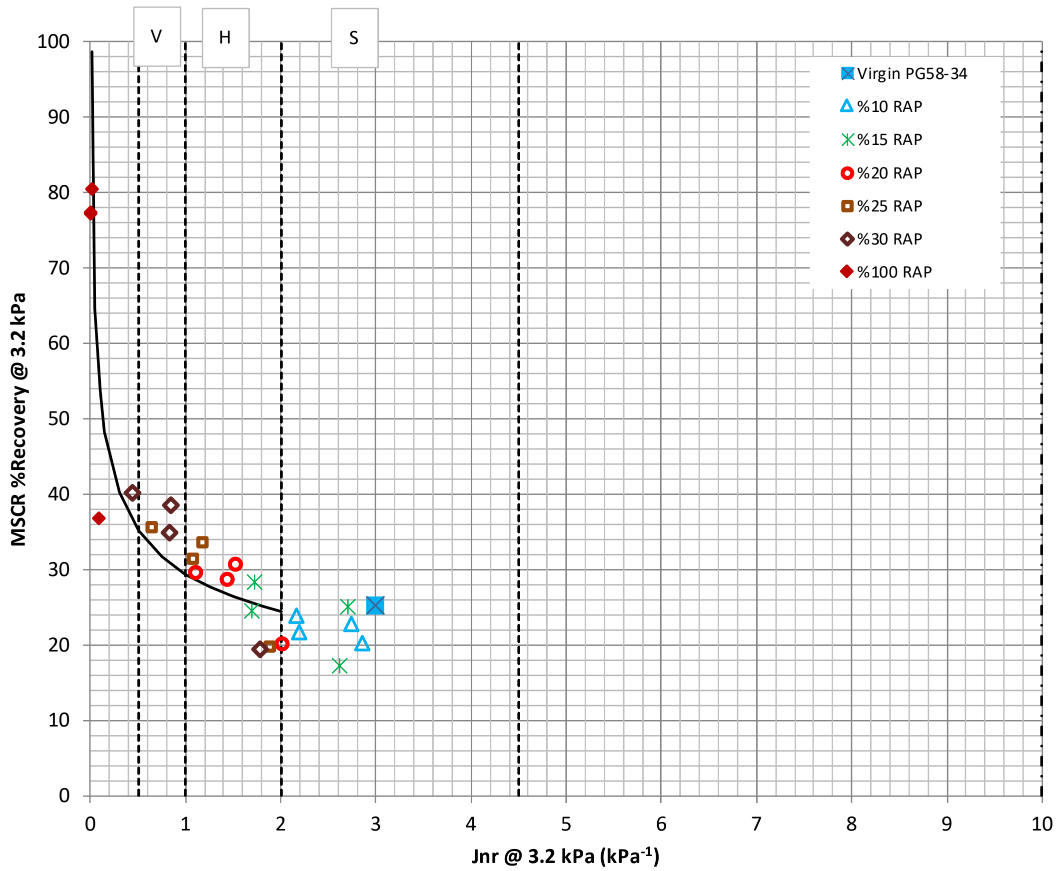



**Figure 3.6: Jnr Versus %R for PG 58-34 modified with various percentages of RAP binders**

### 3.5 Rotational Viscosity of Virgin and RAP Binders

As mentioned, binders modified with RAP 144-106, compared to other RAP sources, demonstrated unique behaviors. Rotational viscosity tests were conducted on virgin PG 58-XX and RAP binders at 135 °C to determine the minimum percentage of RAP that should be added to PG 58-XX binders to satisfy high-temperature grading of 64 °C and MSCR parameters for *S* grade binders. Results of the rotational viscosity test based on ASTM D6373-16 are listed in Table 3.11.

**Table 3.11: Rotational viscosity of virgin and RAP binders**

| Binder | Viscosity @ 135 °C (Pa.S) | Shear Stress (N/$cm^2$) | Strain (%) | Shear Rate ($S^{-1}$) |
|---|---|---|---|---|
| PG 58−34 | 0.762 | 52.7 | 6.1 | 6.8 |
| PG 58−28 | 0.35 | 23.8 | 2.7 | 6.8 |
| RAP 27−38 | 4.725 | 321.3 | 37.8 | 6.8 |
| RAP 50−24 | 4.5 | 307 | 36.2 | 6.8 |
| RAP 83−28 | 9.612 | 655.4 | 77 | 6.8 |
| RAP 144−106 | 0.7 | 46.8 | 5.5 | 6.8 |

Table 3.11 shows that the rotational viscosity of RAP 144-106 was almost an order of magnitude lower than other RAP binders. In fact, the rotational viscosity measured in the order of virgin PG 58-XX binders. Although the limited number of binders tested in this project prevented a conclusive judgement, this simple test may be used to screen RAP binders that satisfy the PG grade adjustment and the S grade condition when 15% RAP is mixed with PG 58-XX binders.

### 3.6 MSCR Parameters for PG 58-XX Blended with RAP Binders

Figure 3.7, Figure 3.8, and Figure 3.9 present the changes in MSCR parameters as the percentage of RAP modifications increased (30% maximum). Figure 3.7 shows that the Jnr value yielded a linear relationship with $R^2$ of nearly 0.9. However, no statistically meaningful trend was observed between %R and %JnrDiff with respect to percentage of RAP binder. Conclusions in this report were drawn with disregard of the %JnrDiff.

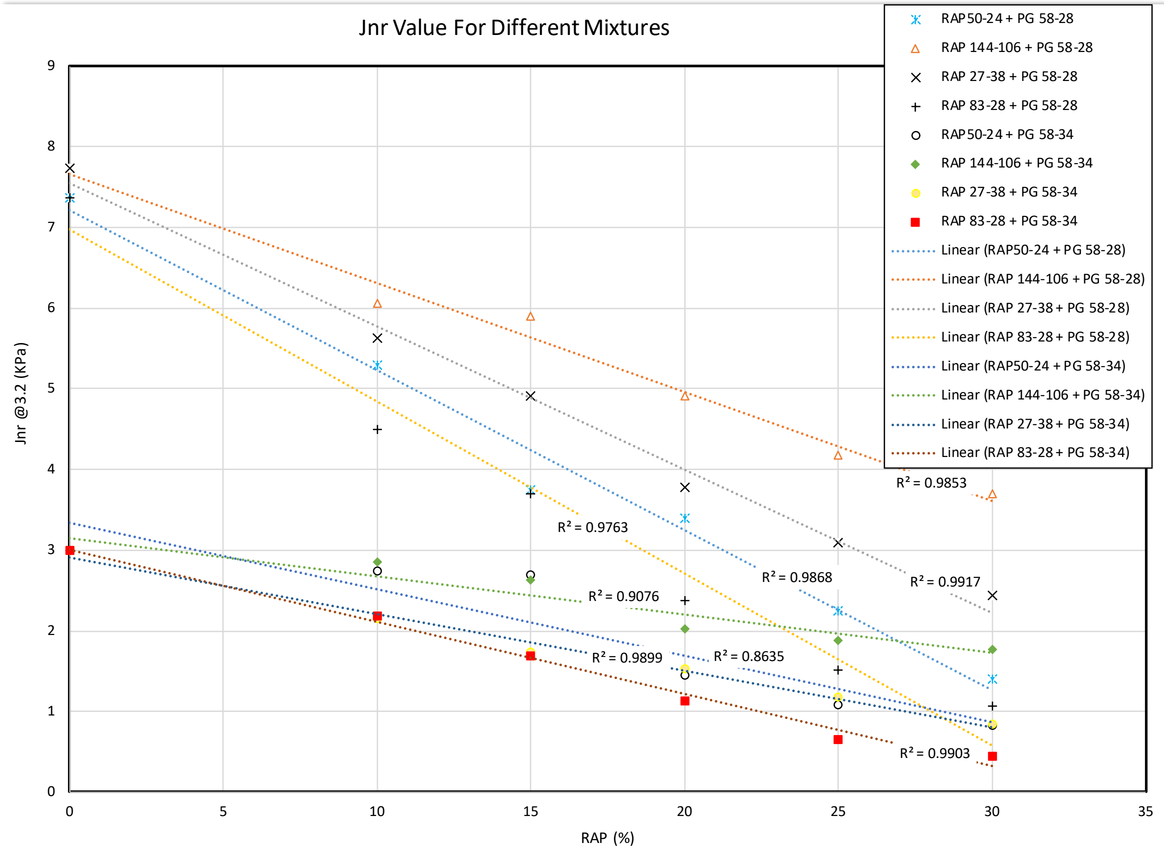



**Figure 3.7: Jnr of 3.2 kPa versus %RAP**

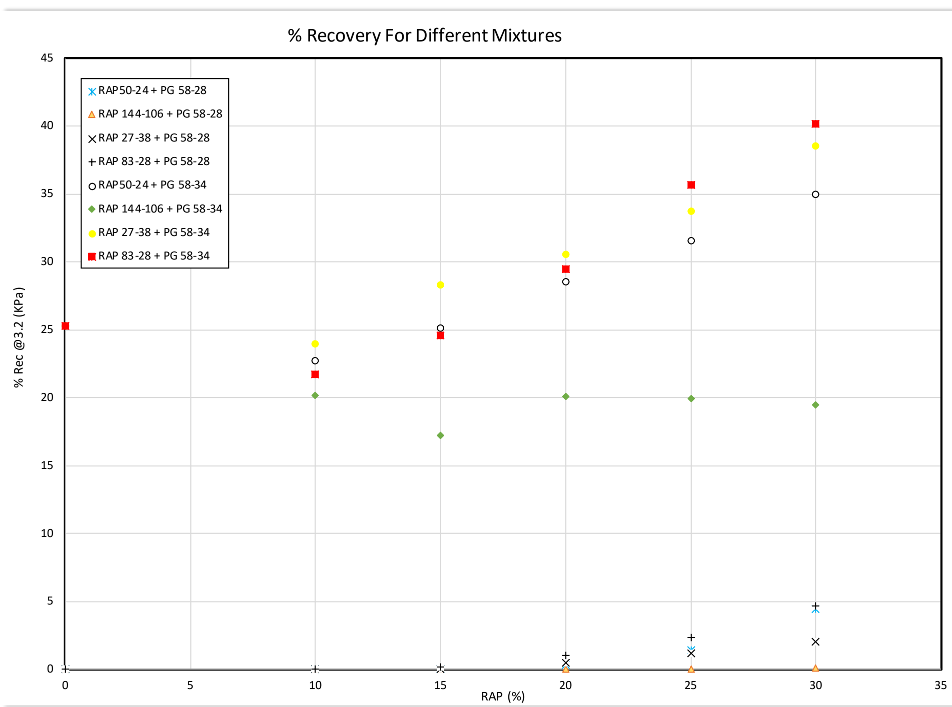



**Figure 3.8: %R versus %RAP**

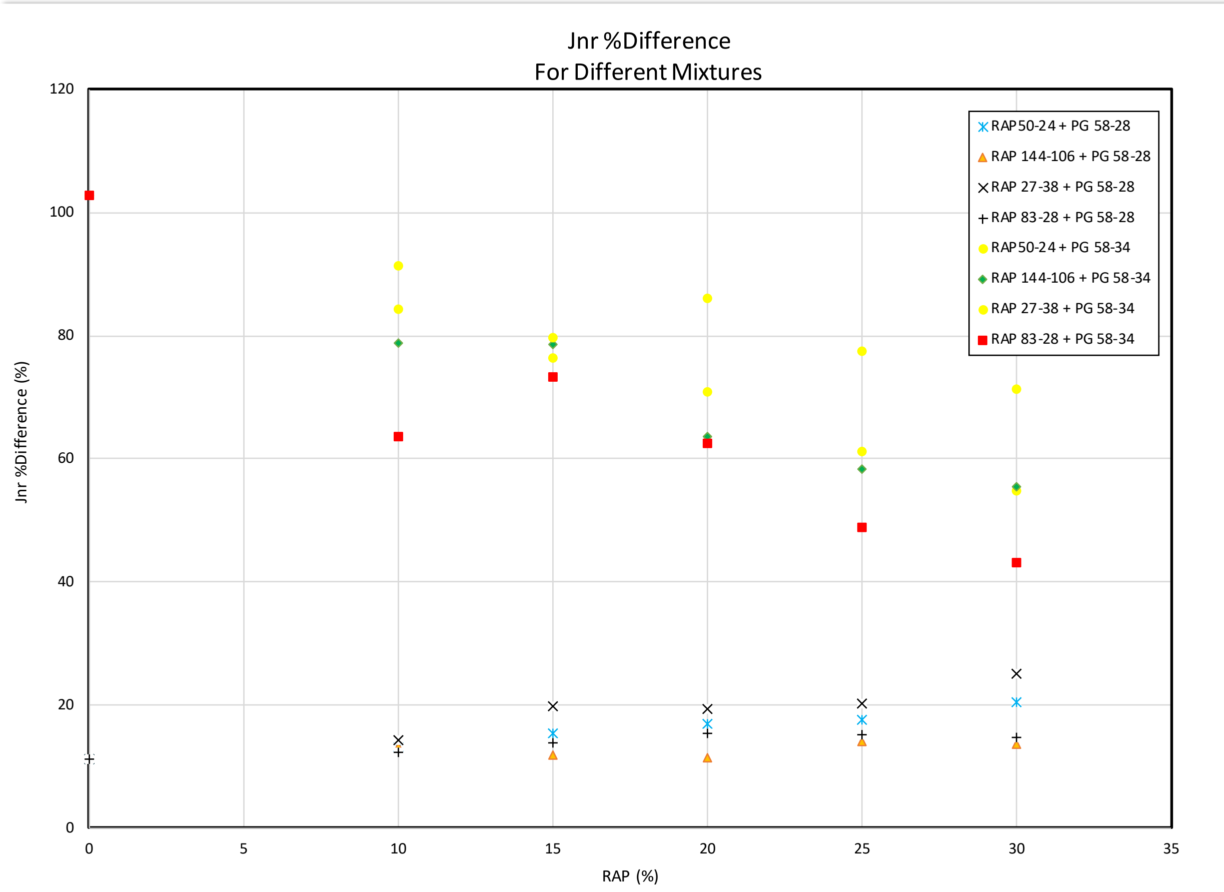
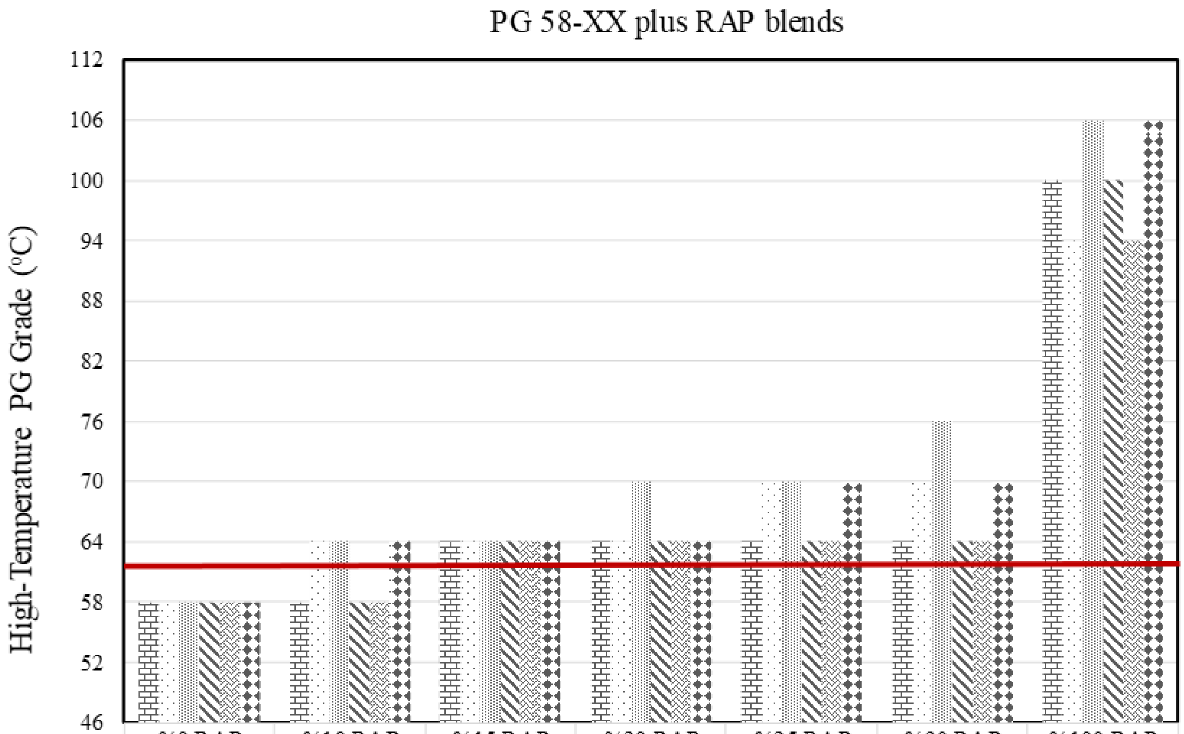



**Figure 3.9: Jnr %difference versus %RAP**

# Chapter 4: Conclusions and Recommendations

Based on the limited test results presented in this report, the following conclusions were drawn:

1. The rotational viscosity test can be used to determine whether RAP binders will improve the high-temperature grading and/or satisfy MSCR grading criteria when added to PG 58-XX binders.
2. Adding 15% or more RAP binders to virgin PG 58-XX will result in high-temperature grade adjustment from 58 °C to 64 °C, as shown in Figure 4.1. However, the RAP binder must be screened by studying the source or by conducting the rotational viscosity test to ensure the RAP binder is not too soft. RAP 144-106 results were excluded in Figure 4.1.
3. Adding 15% or more RAP binders to virgin PG 58-XX binders will satisfy the *S* grade condition based on the MSCR Jnr parameter, as shown in Figure 4.2. However, the RAP binder must be screened by studying the source or by conducting the rotational viscosity test to ensure the RAP binder is not too soft. RAP 144-106 results were excluded in Figure 4.2.




| | %0 RAP | %10 RAP | %15 RAP | %20 RAP | %25 RAP | %30 RAP | %100 RAP |
|---|---|---|---|---|---|---|---|
| RAP 50-24; PG 58-34 | 58 | 58 | 64 | 64 | 64 | 64 | 100 |
| RAP27-38; PG 58-34 | 58 | 64 | 64 | 64 | 70 | 70 | 94 |
| RAP83-28; PG 58-34 | 58 | 64 | 64 | 70 | 70 | 76 | 106 |
| RAP 50-24; PG 58-28 | 58 | 58 | 64 | 64 | 64 | 64 | 100 |
| RAP 27-38; PG 58-28 | 58 | 58 | 64 | 64 | 64 | 64 | 94 |
| RAP 83-28; PG 58-28 | 58 | 64 | 64 | 64 | 70 | 70 | 106 |

**Figure 4.1: High-temperature grade adjustment of PG 58-XX binders blended with various percentages of RAP binders**

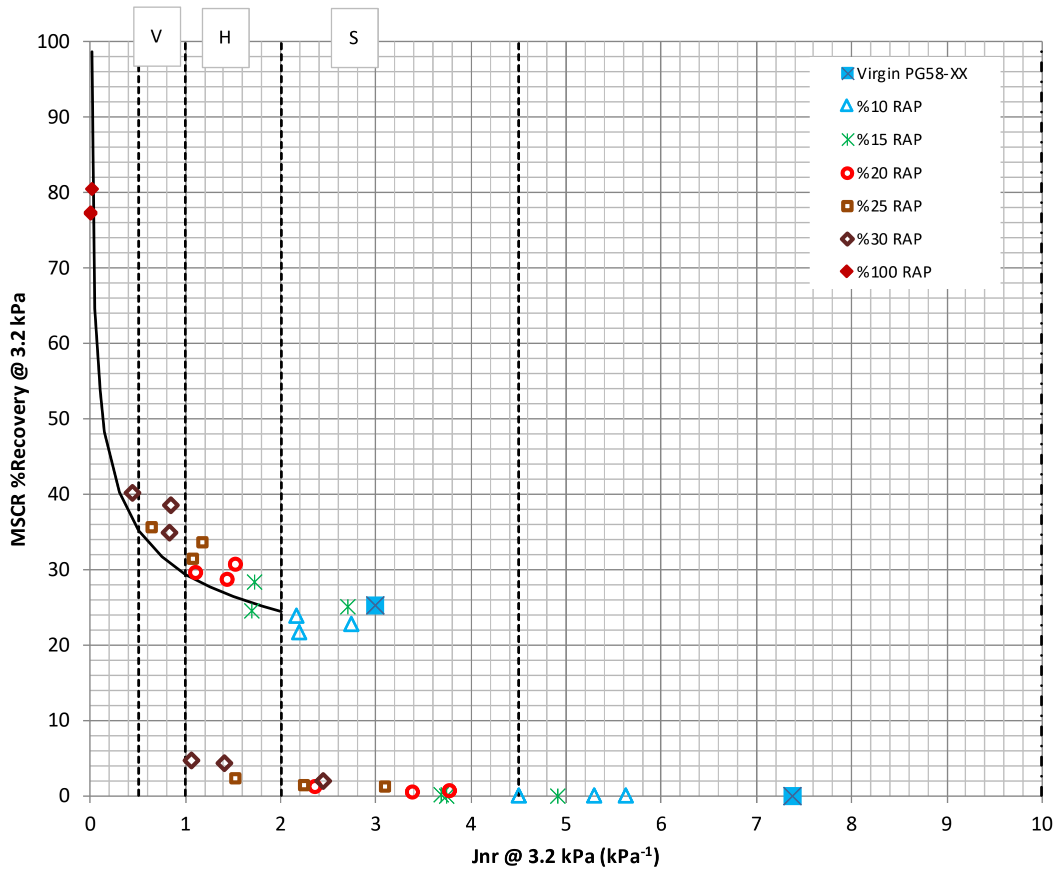



**Figure 4.2: Jnr versus %R of PG 58-XX binders blended with various percentages of RAP binders**

4. The test data show promising results regarding the effect of RAP binders on high-temperature grade adjustment of PG 58-XX blended with RAP sources. A comprehensive set of PG 58-XX virgin binders blended with RAP sources at various percentages should be tested to develop a unified specification guideline for grading and grade adjustment of these binders.
5. The test data show a high correlation between the MSCR Jnr value of virgin and RAP binder blends and the level of RAP modification. A comprehensive set of tests will allow statistically meaningful analysis to determine a relationship between MSCR parameters of the blended binders and %RAP.

6. The MSCR %R was discarded in the analysis of test data presented in this report. Therefore, blended binders should be tested for low-temperature grading and grade adjustment to determine how %R may correlate with low-temperature grading and grade adjustment.
7. This problem should be further investigated to preserve current PG performance grading with the MSCR protocol, enabling KDOT to preserve the current PG grading practice while incorporating the effect of MSCR parameters on grade adjustment of virgin and RAP-modified binders.

# References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AASHTO T 240-13. (2013). *Standard method of test for effect of heat and air on a moving film of asphalt binder (rolling thin-film oven test)*. Washington, DC: American Association of State Highway and Transportation Officials.

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