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IMPACT OF HIGH RAP CONTENT ON STRUCTURAL AND PERFORMANCE PROPERTIES OF ASPHALT MIXTURES

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16. Abstract

Currently, highway agencies in Illinois are exploring the feasibility of using of higher amounts of reclaimed asphalt pavement (RAP) in asphalt mixtures. Concerns about variability in aggregate gradation and higher stiffness of aged RAP binder have limited this use, however. This research project was designed to characterize the performance of hot-mix asphalt (HMA) with high amounts of RAP and to identify any special considerations that must be met to utilize these higher RAP contents.

Two material sources from two districts were used to prepare eight 3/4-in nominal maximum aggregate size (NMAS) N90 binder mix designs. The mix designs included a control mix with 0% RAP and three HMAs with 30%, 40%, and 50% RAP for each district. A base asphalt binder (PG 64-22) was used in the mix design process; a single-bumped binder (PG 58-22) and a double-bumped binder (PG 58-28) were also used to prepare specimens for performance testing. The tests conducted on the HMAs were moisture susceptibility, flow number, complex modulus, beam fatigue, semi-circular bending, and wheel tracking. All tested HMAs with RAP performed equal to or better than the mixtures prepared with virgin aggregate.

The study found that HMAs with high RAP content (up to 50%) can be designed with desired volumetrics. RAP fractionation proved to be very effective. Asphalt binder-grade bumping is vital for HMAs with 30% RAP content and above.

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Reclaimed Asphalt Pavement (RAP), High RAP, Mixture Volumetrics, Complex Modulus, Flow Number Test, Beam Fatigue Test, Fracture test, Wheel Tracking Test.

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EXECUTIVE SUMMARY

The national desire to move toward a sustainable pavement system has encouraged state DOTs to contemplate increasing the amount of reclaimed asphalt pavement (RAP) being used in asphalt pavements. Currently, the maximum amount of RAP that the Illinois Department of Transportation (IDOT) allows in high-volume roads is, on average, 15%. This research project provides data related to the laboratory performance characteristics of mixtures with high RAP content relative to mixtures with no RAP.

Several downsides have hindered the use of high RAP content in asphalt pavements, including high fines content, aging of asphalt binder, and variability in aggregate gradation. Special laboratory measures were undertaken to process RAP material before initiating the mix design process to make sure it was representative of the RAP stockpiles from which the RAP was sampled. Two aggregate and RAP sources were used to develop eight hot-mix asphalt (HMA) mix designs. The Bailey method of aggregate packing was used to design HMAs with 0% (control), 30%, 40%, and 50% RAP for each material source. Significant effort was put forth to achieve similar voids in mineral aggregates (VMA) in each mix. This ensured that the performance-testing results of the mechanical properties of the mixtures are independent of volumetrics and solely dependent on the mix designs and, hence, the percentage of RAP included.

In addition to evaluating the effect of RAP content, a testing program was designed to characterize the effect of single and double binder-grade bumping on the performance properties of the mixtures. Along with evaluating the moisture susceptibility of the prepared mixtures, performance tests—complex modulus, flow number, wheel tracking, semi-circular bending (SCB), and beam fatigue—were conducted.

The HMAs with high RAP content showed promising results and outperformed the control (0% RAP) mixtures on most tests. The results showed that the presence of RAP reduced the mixture rutting potential, improved fatigue behavior as measured by the conventional fatigue curve slope, and did not compromise mix resistance to moisture susceptibility. Single bumping PG 58-22 proved to be effective in improving fatigue behavior. The low-temperature fracture energy of the HMA decreased when 30% RAP or more was added compared to control mix. Hence, asphalt binder with grade bumping at low temperatures becomes necessary.

This study proved it is possible to design high-quality HMA with up to 50% RAP that meets IDOT’s desired volumetrics for binder mixtures and performs equal to or better than the control mixtures when appropriate asphalt binder is used.

In addition to appropriate mix design that meets volumetric requirements, RAP fractionation is necessary to achieve desired field performance. Both single and double binder-grade bumping are recommended to be used for HMA containing 30% RAP, depending on stiffness of aged binder. However, for HMA with higher RAP content, double or higher binder grade bumping may be necessary to reduce potential thermal cracking of the mixtures.

CONTENTS

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

During the past four decades, the demand for and use of reclaimed asphalt pavement (RAP) has continually increased. The desire to recycle the old pavement arises not only from the proven cost savings but also from an increase in environmental awareness. In an era in which every industry yearns to adopt greener and more sustainable approaches, asphalt recycling is a step forward in the direction of sustainable pavement systems.

Apart from hot-in-place recycling (HIPR) or cold-in-place recycling (CIPR), which can utilize 80% to 100% RAP, the percentage of RAP in conventional asphaltic mixture design seldom increases above 20% to 25%. One of the main reasons for RAP's limited use is the variability in aggregate gradation introduced with RAP especially when RAP stockpiles are not properly managed, separated, and processed to eliminate variability such as segregation. In addition, the high percentages of fines in RAP, increased stiffness of aged asphalt binder, and the need for overheating virgin aggregates in asphalt plants pose challenges to mixture design and production. The current economic crisis, coupled with environmental concerns, has forced departments of transportation (DOTs) in the United States to increase the amount of RAP up to 50% in flexible pavements. Apart from introducing complexities in mix designs, use of such a high amount of RAP (50%) has the potential to impact durability and structural performance of the pavements. Limited studies have been conducted to illustrate the impact of including a high amount of RAP on the fatigue, fracture, and permanent deformation characteristics of HMA.

Many researchers consider it proven that HMA mix designs with low RAP percentages (up to 15%) are not significantly affected by RAP variability (Bukowski 1997; Huang et al. 2004; Shah et al. 2007); however, higher RAP contents can considerably change the overall performance of the HMA mixture. Solaimanian and Tahmoressi (1996) observed that the use of a high percentage of RAP did not influence densities as much as it influenced the asphalt binder content of the plant mix. Projects with higher variation in the binder content of the RAP material also had higher variation in binder content of plant mix. Similarly, projects with higher variability in stiffness of RAP binder also showed higher variability in stiffness of plant mix binder. Moreover, numerous studies on RAP have indicated that the addition of the RAP in asphalt mixes changes the physical behavior of the mix. The increased stiffness of the RAP binder is believed to be the cause of increased modulus of asphalt mixes. Likewise, RAP also affects fatigue behavior and low-temperature cracking of the mixes (McDaniel et al. 2000; Shu et al. 2008).

Voids in mineral aggregates (VMA) play an important role in the performance of flexible pavements. Al-Qadi et al. (2009) observed that in one material, VMA decreased with increased RAP percentage, but for another material, VMA increased with increased RAP percentage. Inconsistent findings were reported by other researchers. West et al. (2009) and Kim et al. (2009) demonstrated similar results—that is, a decrease in optimum binder content and VMA with an increase in RAP percentage. Similar trends were observed by Mogawer et al. (2009) and Daniel and Lachance (2005). The Illinois Department of Transportation (IDOT) identified, quantified, and correctly adjusted the assumed aggregate (dry) bulk specific gravity (G_{sb}) for RAP in the early 2000s. This eliminated the use of effective specific gravity (G_{se}), which was leading to lower-than-desired optimum binder contents.

This report addresses the volumetric issues induced by inclusion of high percentages of RAP in HMA. The effects of single (PG 58-22) and double (PG 58-28) bumping of binder grade on the performance of HMAs with high RAP content were thoroughly investigated, and the results are presented herein. In this study, single binder-grade bumping corresponds to one grade reduction in the higher temperature grade, whereas double binder-grade bumping corresponds to one grade reduction at both the higher and lower temperature limit in the binder grade. For example, PG 58-22 and PG 58-28 represent single and double binder-grade bumps, respectively, with respect to PG 64-22.

1.2 RESEARCH OBJECTIVES AND SCOPE

The economics of asphalt concrete production are driving the desire to recycle higher percentages of RAP in HMA. It has long been thought that higher blending percentages (up to 50%) are achievable in the field. What has not been investigated until recently is whether any quantified difference in performance can be documented on high RAP mixtures compared to standard no-RAP HMA.

In a first-phase study on the residual binder of RAP (Al-Qadi et al. 2008), it was illustrated that the blending that occurred did not significantly impact the mix design procedure. Hence, the main objective of this study was to examine the impact of high RAP in HMA on the mix performance through the following main tasks:

- Characterize complex modulus, fracture, and fatigue properties of HMA with high RAP and compare to standard (no-RAP) mixes.
- Determine the need and impact of using single- and/or double-bumped asphalt binder.
- Evaluate durability of mixes with high RAP using wheel tracking tests, tensile strength ratio (TSR), and visual strip ratings.

1.3 RESEARCH METHODOLOGY

Agencies in Illinois are currently striving to use up to 50% RAP in HMA. Research activities undertaken in this project aimed to design and characterize the performance of HMA with high RAP content. To achieve the objectives of the study, a comprehensive literature review was conducted that focused on the use, production, and laboratory performance of HMA with high RAP. The detailed literature review is attached as Appendix A.

An experimental program was designed to determine structural and durability characteristics of HMA with high RAP and to compare results to HMA without RAP. Two control (0% RAP) HMAs and six mixtures with 30%, 40%, and 50% RAP were prepared. The Bailey method (Vavrik et al. 2002) of aggregate packing was used to develop all the mix designs. The performance of all the HMAs with RAP was determined using various performance tests, including complex modulus, beam fatigue, fracture, wheel tracking, and moisture susceptibility. The effect of softer binders on the performance of mixtures with RAP was also evaluated using two relatively softer binders (PG 58-22 and PG 58-28). All the properties were then compared with HMA made with virgin material (control mix).

This report includes five chapters. Chapter 1 is a brief introduction to the study. Chapter 2 presents a summary of the literature review conducted as part of the project. Chapter 3 focuses on details of the experimental program and the mix design procedure. Testing results are presented and discussed in Chapter 4. The summary and conclusions are provided in Chapter 5, as well as the recommendations based on the findings of the study.

CHAPTER 2 LITERATURE REVIEW (SUMMARY)

When asphalt concrete pavements reach the end of their service lives, the remaining materials can be salvaged and used for construction of new pavements. Apart from reducing the cost of the new asphalt pavement, asphalt recycling acts as an environmentally sound option for pavement rehabilitation. RAP is commonly mixed with various percentages of new aggregates and asphalt binders to produce new asphalt pavements. RAP can be used in the lower pavement layers (i.e., binder and base layers) to provide improved layer support for traffic loads as well as in wearing-surface layers. Extensive research has been published describing methods and strategies of asphalt recycling, their laboratory and field performances, and binder and mix properties. This chapter presents a summary of the detailed literature review in Appendix A.

Many states have had good experiences with RAP, but there are still many issues to be resolved regarding the use of high percentages of RAP in asphalt mix designs. Some of the major barriers and technical issues that keep states from using high percentages of RAP are stockpile management, availability of RAP, and asphalt binder and mix issues. Asphalt binder issues mainly deal with bumping grades and properties of the final binder blend. Mix issues can further be divided into mix design issues and mix performance issues. The key issues that need further investigation are contribution of asphalt binder from RAP (i.e., amount of blending), the volumetrics of asphalt mixtures containing RAP, and the need for additional testing to predict performance of mixes with RAP.

2.1 ASPHALT MIX DESIGN INCLUDING RECLAIMED ASPHALT PAVEMENT

Earlier practitioners who used RAP in HMA quickly realized a need for proper mix design. In 1989, the Asphalt Institute developed blending charts to incorporate RAP in HMA design. In 1997, Kandhal and Foo developed a procedure for selecting the performance grade (PG) of virgin asphalt binder to be used in recycled mixtures. Later in the same year, the Federal Highway Administration's (FHWA) RAP expert task force developed interim guidelines for the design of SuperPave™ HMA containing RAP (Bukowski 1997). The developed methodology was based on a tiered approach to determine the level of testing required in the design of HMA containing RAP. McDaniel and Anderson (2001) also recommended a tiered approached for incorporating RAP in HMA (see Table A-1 in Appendix A). The limits of these tiers depend on the RAP binder grade: with softer RAP binders, higher percentages of RAP can be used. Once the physical properties and critical temperatures of the recovered RAP binder are known, two blending approaches may be used. In the first approach, the percentage of RAP that will be used in an HMA is known, but the appropriate virgin asphalt binder grade for blending must be determined. In the second approach, the maximum percentage of RAP that can be used in an HMA while still using the same virgin asphalt binder grade must be determined.

One of the issues with designing RAP-containing HMA is the difficulty in precisely measuring the bulk specific gravity (G_{sb}) of the extracted RAP aggregate due to the changes in aggregate gradation and properties resulting from the extraction process. Many agencies use aggregate effective specific gravity (G_{se}) in lieu of G_{sb} for those reasons. The methodology recommended in NCHRP Report 452 (McDaniel and Anderson 2001) consists of assuming a value for the absorption of the RAP aggregate.

Some states estimate this value quite accurately based on past experience. Recently, Hajj et al. (2008) concluded that using G_{se} instead of G_{sb} resulted in overestimating both the combined aggregate G_{sb} and the VMA since, for a given aggregate, G_{sb} is always smaller than G_{se}. A test method for measuring the G_{sb} of RAP aggregates was introduced by Murphy Pavement Technology (Hajj et al. 2008). This method uses the binder content of the RAP material (P_b) and the maximum theoretical specific gravity (G_{mm}) of a RAP sample to determine G_{se}. The aggregate G_{sb} of the RAP aggregate is then calculated using an equation based on the local aggregate absorption and geological formations within each region or state. Kvasnak et al. (2010) also recommended determining RAP G_{sb} by using the G_{mm} method when a known regional absorption is available. If a regional absorption is not available, then the RAP G_{sb} should be determined from extracted aggregate. As stated earlier, IDOT identified, quantified, and correctly adjusted the assumed aggregate dry G_{sb} for RAP in the early 2000s. Anderson and Murphy (2004) presented the findings of a study at the World of Asphalt conference. The study showed, for the first time, that G_{sb} of RAP aggregate should be used instead for G_{se}.

Al-Qadi et al. (2009) observed that VMA at optimum asphalt content (AC) had opposite trends for two materials. For one material, VMA decreased with an increase in RAP percentage, but it showed the opposite trend for the other material. A study by West et al. (2009) VMA showed a decreasing trend with an increase of RAP percentage. The optimum asphalt content of the mixtures also decreased by 1% as RAP increased from 0% to 45%. Kim et al. (2009) also demonstrated similar results—that is, a decrease in optimum asphalt content and VMA with an increase in RAP amount. The study by Mogawer et al. (2009) showed the same trend as well. Daniel and Lachance (2005), however, observed some contrary results in their study on RAP. They found an increase in VMA and voids filled with asphalt (VFA) in the mixtures with 25% RAP and 40% RAP. They hypothesized that the difference between VMA values was the result of blending the RAP material with the virgin materials. Hajj et al. (2008) also observed similar increasing trends in VMA and VFA with an increase in RAP contents.

2.2 LABORATORY EVALUATION AND PERFORMANCE TESTING OF RAP MIXTURES

Considering the potential benefits and adverse effects of RAP, researchers have looked at various performance measures, including rutting and cracking, of mixtures with RAP. It is not only traffic loading that leads to pavement deterioration but also the aging of the asphalt binder. After the pavement is removed from the field, RAP materials may age even more during the stockpiling process because of exposure to air. Moreover, when RAP is added to HMA, the aged binder in the RAP mixes to some unknown degree with the virgin binder. This produces a composite effective binder system with unknown material properties and, hence, unpredictable pavement performance. Numerous studies on RAP have indicated that addition of the RAP in HMA changes the physical behavior of the mix. The increased stiffness of the RAP binder is believed to be the cause of increased modulus of HMA. Similarly, it also affects the mixtures' fatigue behavior and low-temperature cracking.

Daniel and Lachance (2005) observed that the complex modulus of the processed mixtures with RAP increased from the control to 15% RAP level, whereas the mixtures with 25% and 40% RAP had complex modulus curves similar to the control mixture for both tension and compression, which was an unexpected result. The creep compliance curves showed similar trends. A combination of gradation, asphalt content, and volumetric properties was identified as the cause of these unexpected trends. Similarly, Shah et al. (2007) reported that the results from complex modulus testing showed no increase in stiffness with the addition of 15% RAP compared with the control mix. However, the addition of 25% and 40% RAP resulted in an increase in the moduli.

Li et al. (2008) investigated the effect of RAP percentage and sources on the properties of HMA by performing complex modulus and semi-circular bending (SCB) tests. At high temperatures, the HMA containing 40% RAP was found to have higher or similar complex modulus compared to mixtures with 20% RAP. On the contrary, most mixtures containing 20% RAP were observed to have the highest complex modulus at lower temperatures or high frequencies. Fracture testing results indicated that mixtures with 20% RAP exhibited similar fracture resistance abilities to the control mixtures, which had the highest fracture energies. The addition of 40% RAP significantly decreased the low-temperature fracture resistance. Tam et al. (1992) studied thermal cracking of recycled hot mix (RHM) and confirmed the belief that RHM is less resistant than nonrecycled mixes to thermal cracking. The thermal cracking properties of laboratory and field mixes were analyzed using McLeod’s limiting stiffness criteria and the pavement fracture temperature (FT) method.

Gardiner and Wagner (1999) found that including RAP decreased the rutting potential and temperature susceptibility and increased the potential for low-temperature cracking. They also observed that an increase in RAP was accompanied by an increase in tensile strength ratio (TSR). Sondag et al. (2002) reported an increase in resilient moduli and no effect on TSR values with the addition of RAP. Widyatmoko (2008) prepared wearing and base course mixes with 10%, 30%, and 50% RAP. Contrary to what was found in most existing studies, Widyatmoko determined that mixtures containing RAP show lower resistance to permanent deformation compared with equivalent mixtures without RAP. Widyatmoko also found a reduction in stiffness as RAP content increased. This behavior was explained by the fact that with an increase of RAP percentage, more rejuvenators or softer binder is added to the mix, resulting in a softer mix. For the same reasons, the RAP mixes showed at least similar to or better fatigue resistance than mixes without RAP. It was also concluded that these mixes with RAP were not susceptible to moisture damage (stiffness ratio > 0.8).

Regarding fatigue life of the mixtures with RAP, tests conducted for the NCHRP 9-12 study confirmed that asphalt concrete with RAP content greater than 20% had a lower fatigue life than virgin mixes (McDaniel et al. 2000). Shu et al. (2008) observed that, based on the failure criterion of a 50% reduction in stiffness (obtained from beam fatigue tests), incorporating RAP increased the fatigue life of HMA. However, based on the plateau values from the beam fatigue test, incorporating RAP would cause input energy to turn into damage, which may result in shorter fatigue life.

2.3 SUMMARY

The purpose of asphalt mix design is to produce pavements that withstand rutting and fatigue, have thermal resistance, and show overall durability. Past research on RAP has focused on understanding the effect of RAP’s aged binder and gradation on the performance of HMA. The multi-tier system introduced by FHWA is generally used, with a few minor changes, throughout the United States. The amount of fines present in RAP limits the amount of RAP that can be incorporated in HMA. Use of higher percentages of RAP has been reported when RAP is fractionated into different sizes before adding it to virgin material. Currently, the volumetrics of the asphalt mix designs have been determined based on the assumption that RAP releases all the binder and fines material during the mixing process. However, it is not yet possible to measure the exact amount of fines and binder released by RAP for blending. This problem generates uncertainty in determining the VMA.

Although the stiffness of RAP tends to increase resistance of an asphalt mix to rutting, it decreases the mix’s resistance to thermal cracking. Conflicting observations have been made about the effect of RAP on fatigue performance of HMA. While some of the tests showed improvement in fatigue resistance, others showed a decrease.

Maximizing the use of RAP while maintaining the performance of the asphalt mixture comparable to virgin mixtures is the primary objective of research activities currently being carried out in the United States. Continuing increases in fuel prices, along with environmental concerns, limited natural resources, and the nation's current economic situation, demand that use of RAP be maximized in HMA pavements. In fact, initial spadework has been completed by FHWA to encourage use of high percentages of RAP. In 2007, an expert task group was formed by FHWA to explore the use of RAP in the construction and rehabilitation of flexible pavements for highways and roads. One of the goals of the task group is to initiate several field projects using high percentages of RAP (25% or more) to increase awareness of the benefits of RAP in asphalt mixture production and develop best practices for designing, processing, and handling RAP in asphalt mixtures (FHWA 2008).

The Illinois Department of Transportation (IDOT) also wants to increase use of RAP in asphalt mixture production. Accordingly, the current project was undertaken to address volumetric issues resulting from high percentages of RAP in HMA. Additionally, the effect of single and double bumping of binder grade on the performance of HMA with a high RAP content was investigated.

CHAPTER 3 EXPERIMENTAL PROGRAM

A laboratory experimental program was developed to characterize the effect of high RAP content on HMA. Table 3.1 shows the various mixtures examined in the study.

Table 3.1. Mix Design Matrix

Mix Type / RAP Source	RAP (%)				Total
	0	30	40	50	
District 1	1	1	1	1	4
District 5	1	1	1	1	4
Total	2	2	2	2	8

Two sources of aggregate and RAP material were used in the project. An asphalt binder (PG 64-22) was used in all the HMAs. A single-bumped binder (PG 58-22) and a double-bumped binder (PG 58-28) were used to fabricate the samples to capture the effects of softer asphalt binders on the performance of HMAs with high RAP.

3.1 MATERIALS

The virgin aggregate and RAP for this project were obtained from two source locations, District 1 and District 5. District 1 material was collected from Gallagher Asphalt Co. in Thornton, Illinois. Five aggregate gradations were collected from District 1: CM11, CM16, FM20, FM22, and mineral filler (baghouse fines). FM22 was obtained from Hanson Material Services in Thornton. Two gradations of 3/4-in (19-mm) nominal maximum aggregate size (NMAS) RAP [+3/8 and –3/8 in (9.5 mm)] were also obtained from the same source. Table 3.2 shows the stockpile gradation for District 1 aggregates.

Table 3.2. Stockpile Aggregate Gradation (District 1)

Sieve	CM11	CM16	FM20	FM22	Mineral Filler	+3/8-in RAP*	–3/8-in RAP*
1 in	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	90.9	100.0	100.0	100.0	100.0	96.9	100.0
1/2 in	43.5	100.0	100.0	100.0	100.0	81.5	100.0
3/8 in	18.8	98.4	100.0	99.6	100.0	64.8	98.9
No. 4	5.6	27.8	99.7	60.0	100.0	43.0	69.4
No. 8	4.2	5.2	81.0	14.0	100.0	31.4	47.0
No. 16	3.6	3.7	49.4	5.4	100.0	24.6	34.3
No. 30	3.3	3.2	31.0	4.2	100.0	19.8	26.2
No. 50	3.1	3.1	17.4	3.8	100.0	14.5	19.7
No. 100	3.0	3.0	10.3	3.6	95.0	9.3	12.9
No. 200	2.7	2.8	5.6	3.4	90.0	7.0	9.6
Binder Content (%)	—	—	—	—	—	4.2	5.1

*Extracted gradation

District 5 material was collected from Open Road Paving in Urbana. The source of the virgin aggregate was Vulcan in Kankakee. The material collected from District 5 was CM11, CM16, and FM20. The same FM22 used for District 1 HMA designs was used for District 5 HMA mix designs. Table 3.3 shows the stockpile gradation for District

5 aggregates. Open Road Paving also provided two gradations of 1/2-in NMAS RAP, +3/8 and –3/8 in.

Table 3.3. Stockpile Aggregate Gradations (District 5)

Sieve	CM11	CM16	FM20	FM22	Mineral Filler	+3/8-in RAP*	–3/8-in RAP*
1 in	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	82.1	100.0	100.0	100.0	100.0	99.3	100.0
1/2 in	39.1	100.0	100.0	100.0	100.0	90.8	100.0
3/8 in	19.0	97.3	100.0	99.6	100.0	78.6	99.3
No. 4	3.9	36.7	98.6	60.0	100.0	39.0	71.7
No. 8	2.7	6.8	74.6	14.0	100.0	26.5	48.6
No. 16	2.4	3.1	43.9	5.4	100.0	19.1	32.6
No. 30	2.2	2.3	24.6	4.2	100.0	14.8	24.2
No. 50	2.1	2.2	14.5	3.8	100.0	10.7	17.2
No. 100	2.1	2.1	9.7	3.6	95.0	7.7	12.7
No. 200	2.0	2.0	7.1	3.4	90.0	6.0	10.1
Binder Content (%)	—	—	—	—	—	3.9	5.5

*Extracted gradation

For all mixes, asphalt binders PG 64-22 and PG 58-22 were obtained from Emulsicoat Inc., Champaign, Illinois, and asphalt binder PG 58-28 was procured from Indiana. The true PGs for all binders, including the RAP binder, were determined in the lab. The PG grades for RAP binders were also determined, as shown in Table 3.4.

Table 3.4. PG Grades for Virgin and RAP Binders

Binder Type	True grades	PG grades
District 1 PG 64-22	66.7–24.2	64-22
District 5 PG 64-22	67.0–22.9	64-22
PG 58-22	62.3–22.4	58-22
PG 58-28*	61.4–27.4	58-22
District 1 RAP	82.4–13.7	82-10
District 5 RAP	89.3–14.9	88-10

*Not a true PG 58-28

Aggregate bulk specific gravities (G_{sb}) were determined for each RAP by IDOT's Bureau of Materials and Physical Research (BMPR). The theoretical maximum specific gravity (G_{mm}) was used to determine the RAP material's effective specific gravity (G_{se}). In this study, G_{sb} of the RAP aggregates was calculated using the following empirical relationship, Equation 3.1. IDOT, on the other hand, uses 0.1 as a reduction factor for slag RAP to determine G_{sb} of RAP aggregates. However, this study involved natural aggregate, so the value of 0.075 was used.

$$G_{sb}(RAP) = G_{se}(RAP) - 0.075 \tag{3.1}$$

3.2 ASPHALT MIX DESIGNS

Eight HMA mix designs were prepared for the study (Table 3.1); four mix designs were prepared for each district. The HMAs designed were binder course 3/4-in (19-mm) N90 mixtures with an air void content of 4.0%, minimum VMA of 13.0%, and VFA of 65% to 75%. For each source of material, a control mix design (0% RAP) and three mix designs with 30%, 40%, and 50% RAP, respectively, were developed. The Bailey method (Vavrik et al. 2002) was used to develop all mix designs. That method, based on the aggregate packing theory, is an efficient approach that can be used in HMA mix design. It provides useful insight into the aggregate packing effect on HMA volumetrics.

3.2.1 District 1 Asphalt Mix Designs

All virgin and RAP aggregates were fractionated in different sieve sizes and blended back to required average stockpile gradation listed for RAP in the mix design. Prior to fractionation, the RAP material was dried by heating it to 132°F (50°C) for 36 to 48 hr. The gradation obtained from fractionating the RAP ("apparent gradation") was then used to batch the samples for asphalt extraction and G_{mm} samples.

The gradation of the extracted aggregate was determined and then used in the HMA mix design to determine the final blends. A step-by-step procedure to determine apparent gradation is described elsewhere (Al-Qadi et al. 2008). The apparent and extracted gradations for the District 1 RAP material are presented in Table 3.5.

Table 3.5. Apparent and Extracted Gradations of District 1 RAP Aggregate

	Retained on Each Sieve (%)		Passing (%)	
	Apparent Gradation		Extracted/Actual Gradation	
Sieve	+3/8-in RAP	–3/8-in RAP	+3/8-in RAP	–3/8-in RAP
3/4 in	3.0	—	100.0	100.0
1/2 in	33.1	—	96.9	100.0
3/8 in	27.2	—	81.5	100.0
No. 4	17.9	43.3	64.8	98.9
No. 8	8.7	24.8	43.0	69.4
No. 16	—	15.2	31.4	47.0
No. 30	5.9	9.1	24.6	34.3
No. 50	—	—	19.8	26.2
No. 100	—	—	14.5	19.7
No. 200	—	—	9.3	12.9
Pan	4.3	7.6	7.0	9.6
Binder Content (%)	—	—	4.2	5.1

As previously explained, the Bailey method was used to determine all HMA mix designs. The unit weights of virgin aggregates—which take into account the effects of aggregate gradation, texture, shape and size, and compaction effort— were determined as part of the Bailey method. The unit weight test was not performed on RAP and mineral filler. Detailed information about the HMA design is provided in the following sections.

3.2.1.1 Aggregate Blend and Gradation

At the start of the study, a control (0% RAP) mix design was provided by IDOT, but due to the relative high specific gravities of procured virgin aggregate, the target blend was modified to achieve acceptable volumetrics, including air void (AV) contents and VMA. The aggregate blend for the control HMA mix is presented in Table 3.6.

After designing an HMA control mix, various percentages of RAP were added. The aggregate percentages, after including RAP, were altered such that the new blends containing RAP had the same percentage passing through the primary control sieve (PCS) as the control mix. The primary control sieve is defined as the closest sieve size to the product of 0.22 × NMAS. For example, for a 3/4-in (19-mm) NMAS mixture, the PCS is a No. 4 sieve.

To maintain the desired split of coarse and fine aggregate, the percentage that passed through the PCS were kept approximately the same for virgin and RAP blends. Moreover, coarse aggregate (CA) ratio values were kept the same because there were two coarse aggregates in virgin and RAP blends. In addition, the blend by mass of virgin fine aggregates in the virgin and RAP blends was the same [See Vavrik et al. (2002) for details about PCS and the Bailey method]. Initially, keeping the passing #200 material constant for all mix designs was considered, but the idea was dropped because of the presence of high amounts of fines (minus #200) in RAP. The HMA mix blends with RAP were finalized such that similar volumetrics were achieved for all HMAs.

Table 3.6 and Figure 3.1 show design aggregate blends, and Table 3.7 shows aggregate stockpile percentages for the District 1 control mix and the HMAs with 30%, 40%, and 50% RAP.

Table 3.6. Design Aggregate Blend for District 1 Asphalt Mix Designs

Sieve Size	Control	30%	40%	50%
1 in	100.0	100.0	100.0	100.0
3/4 in	96.1	96.1	96.4	96.6
1/2 in	75.6	75.9	77.8	79.1
3/8 in	64.5	63.7	65.6	66.6
No. 4	39.5	38.0	37.9	37.3
No. 8	27.5	23.2	22.5	21.7
No. 16	17.8	16.2	16.3	16.2
No. 30	12.3	12.4	12.8	13.1
No. 50	8.3	9.4	9.9	10.1
No. 100	6.2	6.8	7.1	7.2
No. 200	4.6	5.4	5.7	5.8

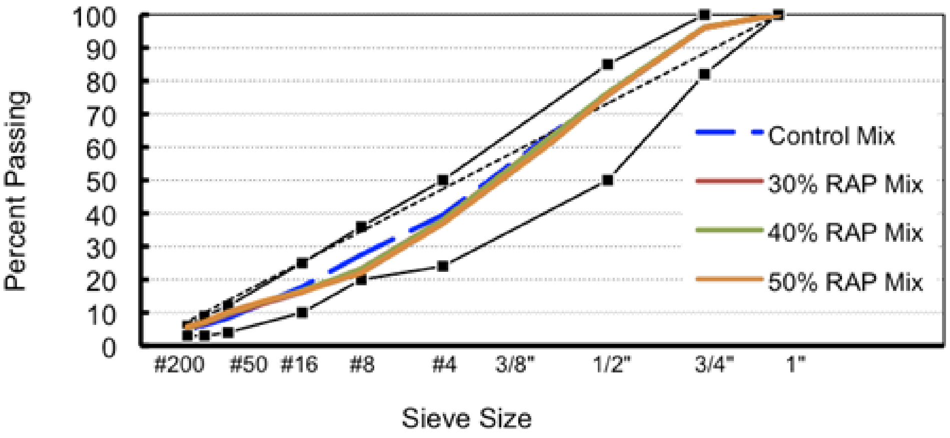


Figure 3.1. Aggregate blends for District 1 HMA designs.

3.2.1.2 Mix Design and Volumetrics

As described in the literature review, researchers have faced considerable difficulties in achieving the required VMA values with RAP mixes. Changes in VMA are the result of variation in RAP aggregate gradation and characteristics (i.e., shape, texture, and strength). By adopting a stringent approach for aggregate and RAP processing and using the Bailey estimation process, similar VMA values were achieved for all mixes, including the ones with various RAP contents. Therefore, any variation in mixture performance is independent of VMA. Table 3.7 shows the volumetrics, including VMA, for all District 1 mixes. Detailed volumetrics for each mix are in Appendix B.

Table 3.7. Stockpile Percentages and Volumetrics of District 1 Asphalt Mix Designs

	Control	30% RAP	40% RAP	50% RAP
CM11 (%)	43.2	37.7	31.0	25.5
CM16 (%)	27.1	12.5	13.3	14.0
FM20 (%)	28.5	8.5	4.0	0.0
FM22 (%)	—	10.5	11.0	10.0
+3/8-in RAP (%)	—	15.0	25.0	35.0
–3/8-in RAP (%)	—	15.0	15.0	15.0
Mineral Filler (%)	1.2	0.8	0.7	0.5
Binder Content (%)	4.9	4.9	5.1	5.0
Air Voids (%)	4.0	4.0	4.0	4.0
VMA (%)	13.7	13.6	13.7	13.7
VFA (%)	70.8	70.6	70.8	70.8

Table 3.8 presents a comparison between the design mix formula (DMF) and the extracted aggregate gradation of G_{mm} samples of HMAs with 30%, 40%, and 50% RAP. Stringent specimen preparation and RAP processing protocols helped ensure that gradation variability was insignificant.

Table 3.8. Comparison Between Target and Achieved Aggregate Gradations for District 1 Mixtures

	30% RAP		40% RAP		50% RAP	
Sieve	DMF	Extracted	DMF	Extracted	DMF	Extracted
1 in	100.0	99.5	100.0	100.0	100.0	100.0
3/4 in	96.1	95.9	96.4	96.2	96.6	97.4
1/2 in	75.9	76.3	77.8	77.9	79.1	79.7
3/8 in	63.7	64.8	65.6	65.8	66.6	67.4
No. 4	38.0	38.4	37.9	38.4	37.3	37.8
No. 8	23.2	23.4	22.5	22.7	21.7	22.0
No. 16	16.2	16.3	16.3	16.5	16.2	16.3
No. 30	12.4	12.6	12.8	13.1	13.1	13.4
No. 50	9.4	9.6	9.9	10.1	10.1	10.5
No. 100	6.8	7.0	7.1	7.5	7.2	7.6
No. 200	5.4	5.7	5.7	6.0	5.8	6.2

Optimum binder content was obtained by determining the volumetrics of mixtures at three different binder contents (at estimated optimum binder content, optimum + 0.5%, and optimum – 0.5%). In this study, asphalt mix designs with RAP were created assuming a 100% contribution of asphalt binder from RAP. In addition, IDOT's method of incorporating RAP was adopted—that is, the RAP percentages represents the actual RAP (including binder) not the RAP aggregate. For example, if 15% RAP is used with particular binder content, then the actual aggregate contribution by RAP to total aggregate blend will be less than 15%, based on the RAP binder content. Table 3.9 illustrates the actual percentages of virgin and aged RAP binders and aggregate contributed by RAP for various HMAs.

Table 3.9. Asphalt Binder and Aggregate Contribution from RAP for District 1 Mixtures

	Binder Contribution (%)			Aggregate Contribution (%)		
Mix Type	Virgin Binder	RAP Binder	Total	New Aggregate	RAP Aggregate	Total
Control Mix	100.0	0.0	100.0	100.0	0.0	100.0
30% RAP Mix	72.4	27.6	100.0	71.0	29.0	100.0
40% RAP Mix	65.4	34.6	100.0	61.1	38.9	100.0
50% RAP Mix	56.3	43.7	100.0	51.1	48.9	100.0

3.2.1.3 Moisture Susceptibility Test

IDOT's moisture susceptibility test (Illinois Modified AASHTO T 283-07; IDOT 2011) was conducted using PG 64-22 as part of the mix design evaluation. Six samples were compacted at 7 ± 0.5% air void content. The specimens prepared were 6 in (150 mm) diameter and 3.75 in (95 mm) height. The indirect tensile strength (ITS) test was performed on three dry specimens and three conditioned specimens. Visual stripping inspection was conducted after the ITS test. Figures 3.2 and 3.3 show the tensile strength and tensile strength ratios (TSRs) for each of the control and RAP mixtures respectively. Detailed results are tabulated in Appendix C.

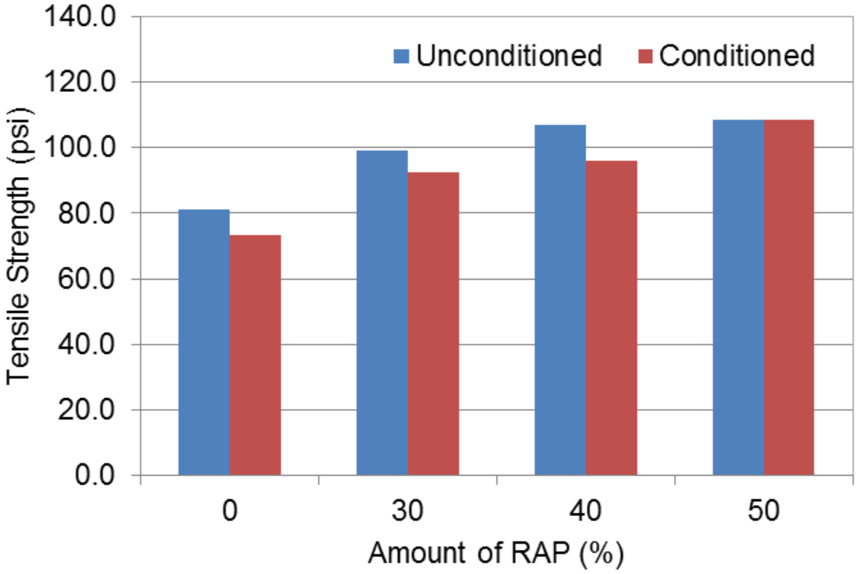


Figure 3.2. Tensile strength of District 1 conditioned and unconditioned specimens.

All the tested specimens passed IDOT's minimum requirement of 85% TSR. With the exception of mixtures with 40% RAP, TSRs increased with an increase in RAP content. This observation was similar to the trend noted in an earlier study by Al-Qadi et al. (2009). One of the factors contributing to the strength increase could be the presence of the aged binder because indirect tensile strength is a test that is relatively more dependent on asphalt binder.

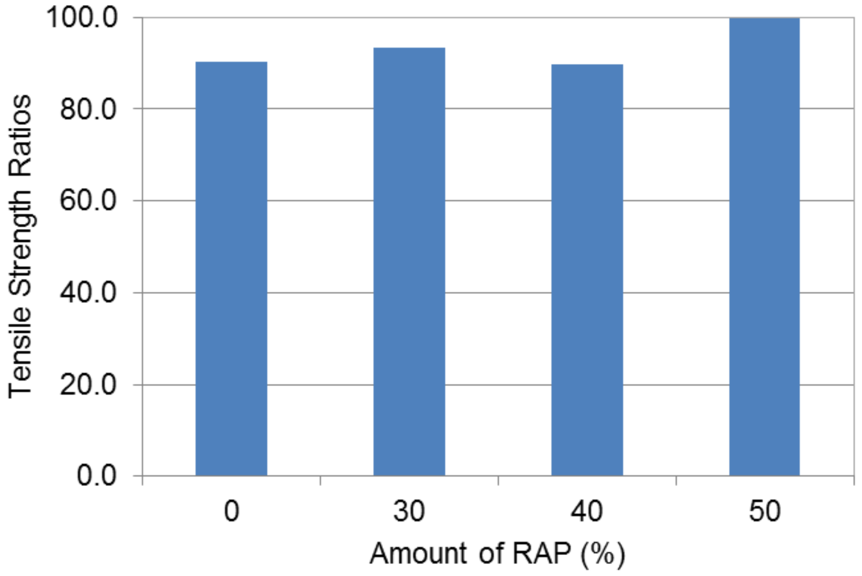


Figure 3.3. Tensile strength ratios (TSRs) for District 1 control and mixtures with RAP.

Visual inspection was carried out on split TSR specimens. The specimens revealed that the stripping susceptibility of mixtures with RAP remained similar to that of the control mixture (0% RAP), with the exception of specimens with 50% RAP—which showed the least resistance to stripping for the coarse aggregate. Table 3.10 shows the stripping rating for mixtures. A rating of 1 indicates no stripping, 2 indicates moderate stripping, and 3 indicates severe stripping. If a RAP used in the HMA wasn't exposed to moisture damage during its service life, it could strip during a moisture sensitivity test after being recoated with new asphalt binder. On the other hand, if it has been in the field for a long time without moisture damage, it most probably would not strip during the moisture sensitivity test.

Table 3.10. Stripping Rating for District 1 Control and Mixes with RAP

RAP (%)	0	30	40	50
Dry (coarse/fine)	1/1	1/1	1/1	1/1
Wet (coarse/fine)	2/2	2/2	2/2	3/2

3.2.2 District 5 Asphalt Mix Designs

3.2.2.1 Aggregate Blend and Gradation

Apparent gradations obtained after fractionating the District 5 RAP are shown in Table 3.11. The extraction and theoretical maximum specific gravity (G_{mm}) batches were made using the apparent gradation. The specimens were extracted at IDOT's facility in Springfield, and the values obtained were used to determine the bulk specific gravity (G_{sb}) of the RAP aggregates, utilizing Equation 3.1.

The extracted RAP aggregate gradations are also shown in Table 3.11. As discussed previously, the apparent gradation was used throughout the project for batching the samples in order to determine the extracted gradations shown in Table

3.11. Table 3.12 and Figure 3.4 show the design aggregate blend for District 5 control mix and for mixtures with RAP.

Table 3.11. Apparent and Actual Gradations of District 5 RAP Aggregate

Sieve	Retained on Each Sieve (%)		Passing (%)	
	Apparent Gradation		Extracted/Actual Gradation	
	+3/8-in RAP	–3/8-in RAP	+3/8-in RAP	–3/8-in RAP
3/4 in	3.4	—	99.3	100.0
1/2 in	17.6	—	90.8	100.0
3/8 in	22.0	1.5	78.6	99.3
No. 4	37.4	33.2	39.0	71.7
No. 8	9.7	29.4	26.5	48.6
No. 16	—	—	19.1	32.6
No. 30	6.1	28.7	14.8	24.2
No. 50	—		10.7	17.2
No. 100	—		7.7	12.7
No. 200	—		6.0	10.1
Pan	3.9	7.2	—	—
Binder Content (%)	—	—	3.9	5.5

Table 3.12. Design Aggregate Blend for District 5 Asphalt Mix Designs

Sieve	Control	30%	40%	50%
1 in	100.0	100.0	100.0	100.0
3/4 in	93.1	93.7	94.4	95.2
1/2 in	76.6	77.6	79.3	81.2
3/8 in	67.8	68.3	69.7	71.4
No. 4	38.7	39.5	39.3	39.9
No. 8	21.7	22.4	22.3	23.3
No. 16	13.6	14.6	14.8	15.6
No. 30	9.0	10.6	11.0	11.7
No. 50	6.8	7.9	8.2	8.6
No. 100	5.6	6.3	6.4	6.6
No. 200	4.9	5.3	5.4	5.4

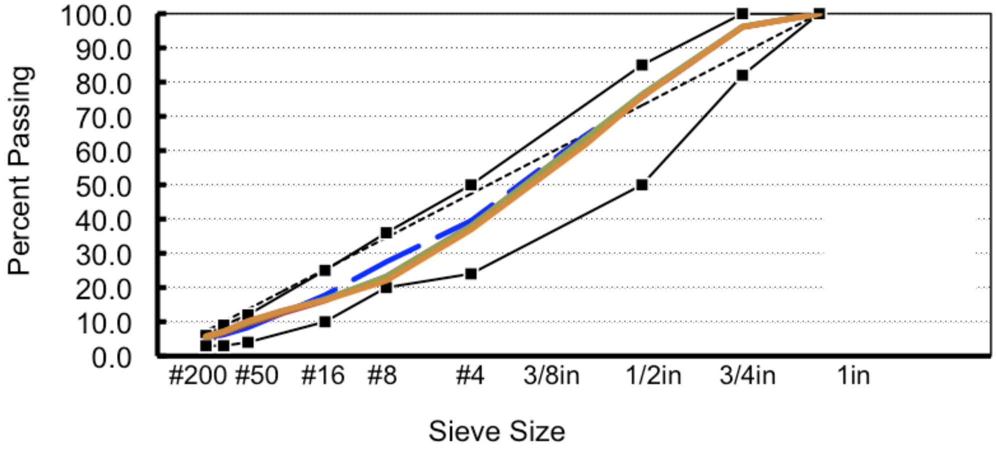


Figure 3.4. Aggregate blends for District 5 HMA designs.

3.2.2.2 Mix Design and Volumetrics

The District 5 control mix and RAP mixes were developed using PG 64-22, in accordance with IDOT specifications and using the Bailey method of aggregate packing. The District 5 control mix has already been used in the field. Slight modifications were applied to achieve the required volumetrics in the lab. Table 3.12 presents the designed aggregate blend for District 5 material; the stockpile percentages and volumetrics of all District 5 mix designs are shown in Table 3.13.

Table 3.13. Stockpile Percentages and Volumetrics of District 5 Asphalt Mix Designs

	Control	30% RAP	40% RAP	50% RAP
CM11 (%)	38.5	34.5	31.2	25.6
CM16 (%)	37.9	15.5	12.5	9.5
FM20 (%)	21.6	9.0	6.5	4.8
FM22 (%)	—	10.0	9.0	9.6
+3/8-in RAP (%)	—	15.0	25.0	35.0
–3/8-in RAP (%)	—	15.0	15.0	15.0
Mineral Filler (%)	2.0	1.0	0.8	0.2
Binder Content (%)	5.2	5.2	5.2	5.2
Air Voids (%)	4.0	4.0	4.0	4.0
VMA (%)	13.8	13.8	13.6	13.5
VFA (%)	71.0	71.0	70.8	70.4

Again, it is important to note that similar VMA has been achieved for all the mix designs. Since shape, texture, and strength of the RAP aggregates are usually different than those for virgin aggregates, matching the aggregate gradation of the RAP mixes to that of the control mixture does not provide the desired VMA. The targeted VMA could be achieved by slightly modifying the gradation of the trial fractionated RAP blends. The Bailey method was used, which reduced the number of trials to reach the desired volumetrics (detailed volumetrics of the final trial for each mix design are presented in Appendix B).

Table 3.14 presents the design mix formula (DMF) and the extracted aggregate gradation of G_{mm} or separate extraction samples for HMA with 30%, 40%, and 50% RAP. Table 3.15 shows the actual percentages of virgin and RAP asphalt binders and new and RAP aggregates for various HMAs.

Table 3.14. Comparison Between Target and Actual Aggregate Gradations for District 5 Mixtures

Sieve	30% RAP		40% RAP		50% RAP	
	DMF	Extracted	DMF	Extracted	DMF	Extracted
1 in	100	100.0	100.0	100	100.0	100.0
3/4 in	93.7	94.9	94.4	93.8	95.2	95.5
1/2 in	77.6	78.4	79.3	78.4	81.2	80.9
3/8 in	68.3	68.0	69.7	69.1	71.4	71.5
No. 4	39.5	39.4	39.3	39.2	39.9	40.1
No. 8	22.4	22.2	22.3	22.4	23.3	23.2
No. 16	14.6	15.1	14.8	14.8	15.6	15.4
No. 30	10.6	10.5	11.0	11.0	11.7	11.7
No. 50	7.9	7.7	8.2	7.9	8.6	8.6
No. 100	6.3	6.3	6.4	6.3	6.6	6.7
No. 200	5.3	5.3	5.4	5.3	5.4	5.6

Table 3.15. Asphalt Binder and Aggregate Contributions from RAP for District 5 Mixtures

Mix Type	Binder Contribution (%)			Aggregate Contribution (%)		
	Virgin Binder	RAP Binder	Total	New Aggregate	RAP Aggregate	Total
Control Mix	100.0	0.0	100.0	100.0	0.0	100.0
30% RAP Mix	73.9	26.1	100.0	71.0	29.0	100.0
40% RAP Mix	66.6	33.4	100.0	61.1	38.9	100.0
50% RAP Mix	59.2	40.8	100.0	51.1	48.9	100.0

3.2.2.3 Moisture Susceptibility Test

The moisture susceptibility of District 5 RAP mixtures was also evaluated. Figures 3.5 and 3.6 depict the tensile strength and TSRs of tested mixtures (detailed results are tabulated in Appendix C). An increase in tensile strength with an increase in RAP content was found for both conditioned and unconditioned specimens.

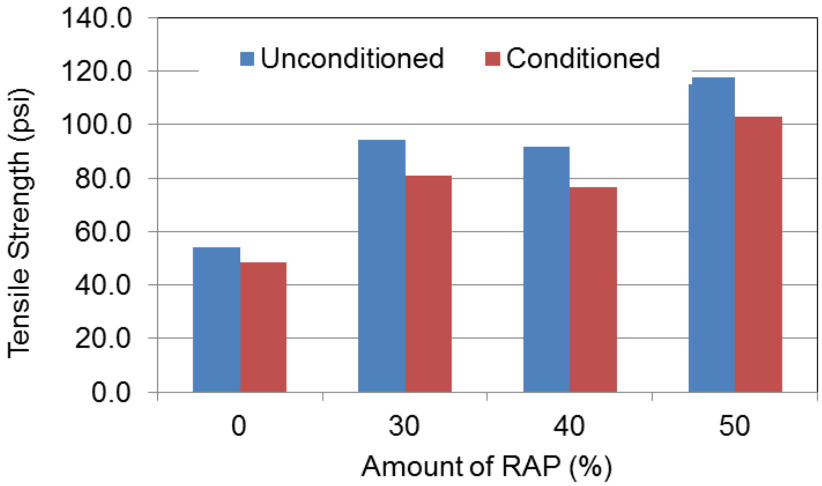


Figure 3.5. Tensile strength ratios (TSRs) of District 5 conditioned and unconditioned specimens.

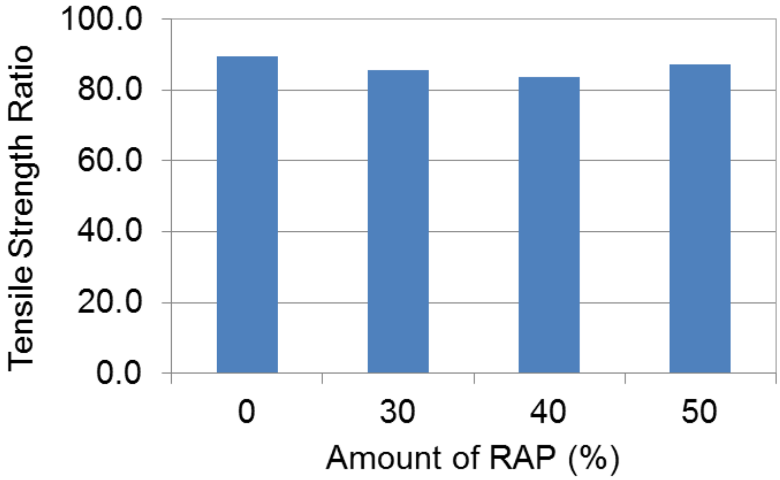


Figure 3.6. Tensile strength ratios (TSRs) for District 5 control and mixtures with RAP.

District 5 mixtures exhibited reductions in TSR values. The visual evaluation did not show any significant stripping, however. Table 3.16 presents the stripping ratings for District 5 mixtures. With the exception of the mixture with 40% RAP, all other mixtures passed IDOT’s minimum criterion of 85% TSR. It is important to note that the District 5 control mixture is known to be moisture susceptible (tensile strength less than 60 psi), which is evident in mixtures with RAP as well. Unlike the District 1 mixes, the addition of RAP did not bring any improvement in the TSR values, although an increase in the tensile strength was observed.

Table 3.16. Stripping Rating for District 5 Control and Mixtures with RAP

RAP (%)	0	30	40	50
Dry (coarse/fine)	1/1	1/1	1/1	1/1
Wet (coarse/fine)	1/2	2/2	2/1	2/2

3.3 LABORATORY PERFORMANCE TESTS

The following sections provide a description of the laboratory tests conducted to evaluate the impact of high RAP on HMA. These tests include complex modulus, flow, fatigue, wheel track, and fracture. The data analysis and discussion of the results from those tests are presented in Chapter 4.

3.3.1 Complex Modulus (E*) and Flow Number Tests

Complex modulus (E*) describes the modulus characteristics of HMA as a function of sinusoidal loading frequency and temperature. E* is a fundamental linear viscoelastic material property (in compression) and is used in the *Mechanistic Empirical Pavement Design Guide* (MEPDG) as a primary material input for pavement HMA layer thickness design. An E* test was conducted on specimens from both material sources. Sixty test specimens were fabricated based on the eight asphalt mix designs (i.e., mixes with 0%, 30%, 40%, and 50% RAP for both District 1 and District 5). Three binder types (PG 64-22, PG 58-22, and PG 58-28) were used.

Specimens were compacted in the SuperPave™ Gyratory Compactor (SGC) to obtain 7.0 ± 0.5% air void content level. SGC samples were then cored and cut to obtain specimens for E* tests. The tests were conducted at various frequencies and temperatures in accordance with AASHTO TP 62 specifications. Dynamic loading was adjusted to obtain an axial deformation of 50 microstrains. The matrix for the E* tests is presented in Table 3.17.

Table 3.17. E* Testing Matrix for Each Material Source

Temperatures (°F /°C)	RAP (%)				Total
	0	30	40	50	
14 / –10	3[1]	9[2]	9	9	30
39 / 4	3	9	9	9	30
70 / 21	3	9	9	9	30
100 / 38	3	9	9	9	30
129 / 54	3	9	9	9	30
Total	15	45	45	45	150

[1] The same three samples were tested at all temperatures and at the following frequencies: 0.1, 1, 5, 10, 25 Hz

[2] Three test sets (no binder bump, single bump, double bump)

Flow number (F_N) is used as a performance indicator for permanent deformation resistance of HMA. An F_N test is one of three SuperPave simple performance tests (SPT). It simulates different loading conditions by placing repetitive loading on a cylindrical sample. A specimen at the end of the test is shown in Figure 3.7. The flow numbers test was performed at 129°F (58°C) after the E* tests on the same specimens. The test was conducted until the completion of 10,000 cycles or 5% permanent strain, whichever occurred first.

Figure 3.7. A specimen at the conclusion of a flow number test.

3.3.2 Beam Fatigue Test

The flexural beam fatigue test is used to characterize the fatigue behavior of HMA at intermediate pavement operating temperatures. The test is believed to simulate the fatigue life of HMA pavements as a result of vehicular loading. In this study, a strain-controlled four-point beam fatigue test was conducted at 68°F (20°C) at levels of 1000, 800, 700, 500, 400, and 300 microstrains. A total of 120 beams were tested utilizing the eight HMAs from the two material and RAP sources (Districts 1 and 5) and three different asphalt binders. The failure criterion used in the study was the traditional 50% reduction in initial stiffness (i.e., the initial stiffness is the stiffness at the 50th load cycle).

A rolling wheel compactor (RWC) was used to compact the HMA beams to 14.8 in × 4.956 in × 2.953 in (376 mm × 125.9 mm ×75 mm). The weight of the mixtures was adjusted to achieve 7% air void content. Each compacted beam was cut into two smaller fatigue beams of 14.8 in × 2.48 in × 1.968 in (376 mm × 63 mm × 50 mm). Table 3.18 presents the beam fatigue test matrix for the project.

Table 3.18. Beam Fatigue Testing Matrix for Each Material Source

Strain Level (μ-strains)	Control	30% RAP	40% RAP	50% RAP
1000	1	3*	3	3
800	1	3	3	3
700	1	3	3	3
500	1	3	3	3
400	1	3	3	3
300	1	3	3	3
Total	6	18	18	18

*Three beams (no binder bump, single bump, double bump)

3.3.3 Wheel Tracking Test

A torture test (wheel tracking test) was conducted to evaluate the rutting potential of the control and the HMAs with various RAP contents. SGC specimens were compacted to 7.0% ± 1% air void content to create the test specimens. Although control mix (0% RAP) specimens were fabricated using only the base PG binder (PG 64-22), mixtures with RAP were tested with base, single-bumped (PG 58-22), and double-bumped (PG 58-28) binders. The wheel tracking test was performed on wet-conditioned (submerged in water) specimens at 122°F (50°C) for 20,000 passes of 150 lb (222 N) of steel wheel or until 0.5 in (12.5 mm) of deformation. The test matrix for the wheel tracking test is shown in Table 3.19.

Table 3.19. Wheel Tracking Testing Matrix for Each Material Source

Condition	RAP (%)				Total
	0	30	40	50	
Wet	3[1]	9[2]	9	9	30
Dry	3	9	9	9	30
Total	6	18	18	18	60

[1] Three replicates

[2] Three replicates × three binder types

3.3.4 Semi-Circular Bending (SCB) Fracture Test

Low-temperature fracture properties of the mixtures were determined using a semi-circular bending (SCB) test. The test setup is shown in Figure 3.8. A specimen 2 in (50 mm) thick was used instead of a 1-in (25-mm) specimen because 3/4-in (19-mm) NMAS was used in the study. To fabricate an SCB test specimen, a 2-in (50-mm) slice was cut from the middle of a 4.5-in (115-mm) gyratory specimen compacted at 7% air void content. The slice was cut into two halves, making semi-circular specimens of 2.91 in (74 mm) in radius, 5.9 in (150 mm) long, and 1.97 in (50 mm) thick.

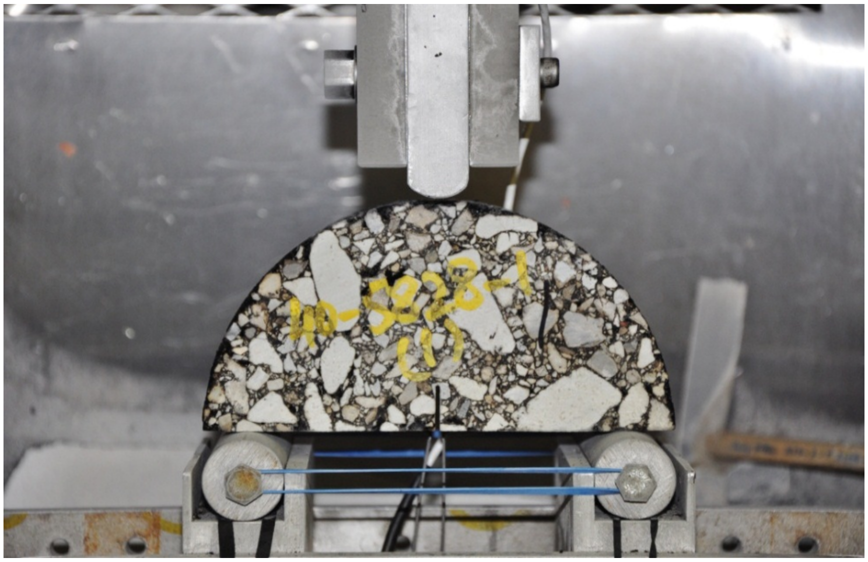


Figure 3.8. Semi-circular bending (SCB) test.

The test was conducted at two temperatures: 35.6°F (2°C) below and 50°F (10°C) above the lower limit of the base PG (64-22) grade. The two testing temperatures were –11.2°F (–24°C) and 10.4°F (–12°C) for the base PG grade, in accordance with a draft AASHTO test protocol. Table 3.20 presents the SCB test matrix for each material source.

Table 3.20. Semi-Circular Bending (SCB) Test Matrix for Each Material Source

Temperatures (°C)	RAP (%)				Total
	0	30	40	50	
2°C below Lower PG Grade (–24°C)[1]	3	9[2]	9	9	30
10°C above Lower PG Grade (–12°C)	3	9	9	9	30
Total	6	18	18	18	60

[1] Base PG grade: PG 64-22

[2] Three test sets (base binder, single bump, double bump)

A contact load of 22.5 lb (0.1 kN) was applied before starting the test. The test was controlled using the crack mouth opening displacement (CMOD) rate of 0.039 in/sec (0.1 mm/min). The test was stopped when the load level dropped to 22.5 lb (0.1 kN).

The parameter used to determine the fracture properties of the HMA was fracture energy (G_f); it is equal to the energy absorbed when the unit sectional area is fractured. Fracture energy is obtained by dividing fracture work by ligament area. (Fracture work is the area under the load-CMOD curve; ligament area is the product of ligament length and thickness of the specimen):

$$G_f = \frac{W_f}{A_{lig}} \tag{3.2}$$

where

W_f = fracture work; and

A_{lig} = area of a ligament.

Discussion of results from the aforementioned tests is presented in Chapter 4.

CHAPTER 4 RESULTS AND ANALYSIS

4.1 TEST RESULTS FOR DISTRICT 1 ASPHALT MIXTURES

4.1.1 Complex Modulus (E*) and Flow Number Tests

A complex modulus test was conducted on specimens obtained by cutting and coring the gyratory compacted samples prepared at 7.0 ± 0.5% air void content. Table 4.1 presents the air void contents of uncut gyratory samples for all E* samples.

Table 4.1. Air Void Contents of Uncut Gyratory Samples

	Air Void Content (%)								
Mix Type	PG 64-22			PG 58-22			PG 58-28		
Control	7.1	7.4	7.0	—	—	—	—	—	—
30% RAP	7.3	7.4	7.4	7.1	7.4	7.2	6.9	7.1	6.6
40% RAP	7.0	6.8	6.7	6.7	7.3	7.3	7.3	6.5	6.5
50% RAP	6.8	7.0	7.0	7.3	7.0	6.7	7.0	6.8	7.0

The complex modulus test results are presented in master curves, which were constructed using the time–temperature superposition principle at a temperature of 70°F (21°C). The master curves shown in Figure 4.1 illustrate the effect of adding RAP to mixes prepared with a base binder (PG 64-22). An increase in the modulus values was observed when RAP was added. Given that stringent quality control for aggregate gradation and volumetrics was imposed throughout the study, the increase in modulus values can only be attributed to stiffer RAP binder.

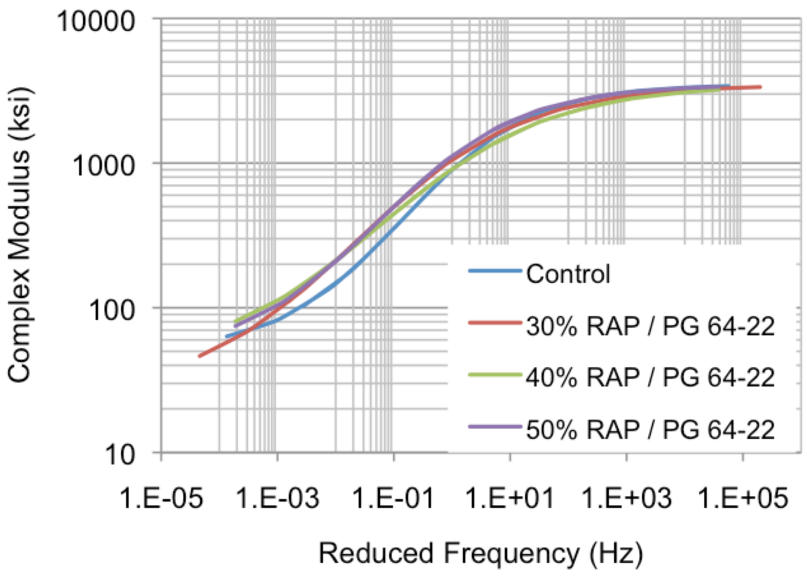


Figure 4.1. Master curves for District 1 control and HMA with RAP.

The control blend (0% RAP) had the lowest complex modulus over the reduced frequency. The HMA with 30% RAP showed an increase in the stiffness at both high and low frequencies. The 40% RAP showed inconsistent behavior: a higher modulus at a low frequency (high temperature) and a lower modulus at a high frequency (low temperature). The 50% RAP mixes consistently showed higher modulus values throughout the frequency spectrum.

The effect of softer binders was evaluated for the HMA mixes with RAP. Figure 4.2 shows that 30% RAP with the base binder PG 64-22 had a slightly higher modulus than the control mixture. While the complex modulus of the 30% RAP mix with PG 58-22 decreased to or below the modulus of the control mixtures, the lowest modulus values were obtained when double-bumped binder (PG 58-28) was used.

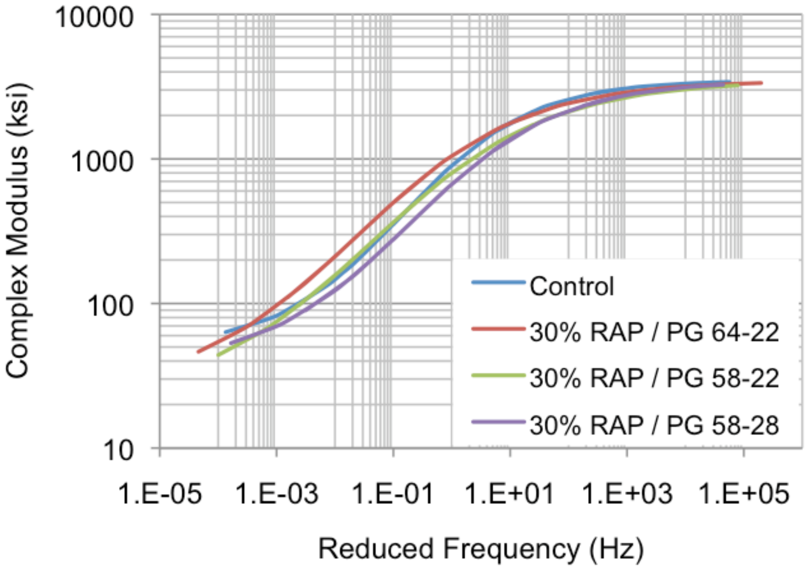


Figure 4.2. Effect of binder bumping on District 1 mixtures with 30% RAP.

The HMA with 40% RAP showed some erratic behavior, as illustrated in Figure 4.3. The control mix (0% RAP) had the lowest modulus at a low frequency (high temperature) but had the highest modulus at a high frequency. Although the modulus at a low frequency followed the expected trend, it showed an opposite trend on the other end of the curve. Figure 4.4 shows a considerable decrease in modulus for HMA with 50% RAP using PG 58-22 but no significant effect resulted from the use of double-grade bumping. The binder-grade bumping was found to be effective in reducing the moduli of mixtures with RAP to the moduli of the control mixtures and, in some cases, lower.

Overall, it is evident from the complex modulus test results that RAP increases the modulus values of the HMA due to the use of aged binder, especially at high temperatures. Although, the effect of single and double binder-grade bumping was visible from the master curves, statistical analyses were conducted on complex modulus data to evaluate whether the tested HMAs were statistically different from each other.

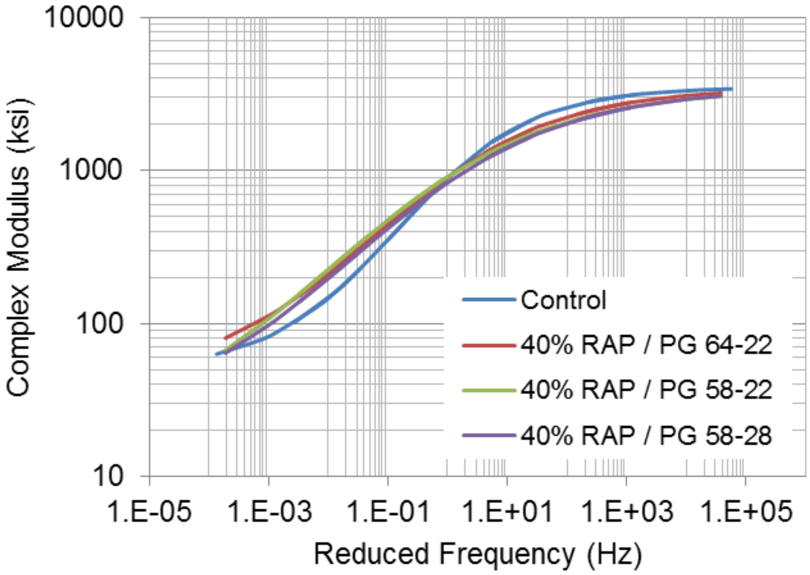


Figure 4.3. Effect of binder bumping on District 1 mixtures with 40% RAP.

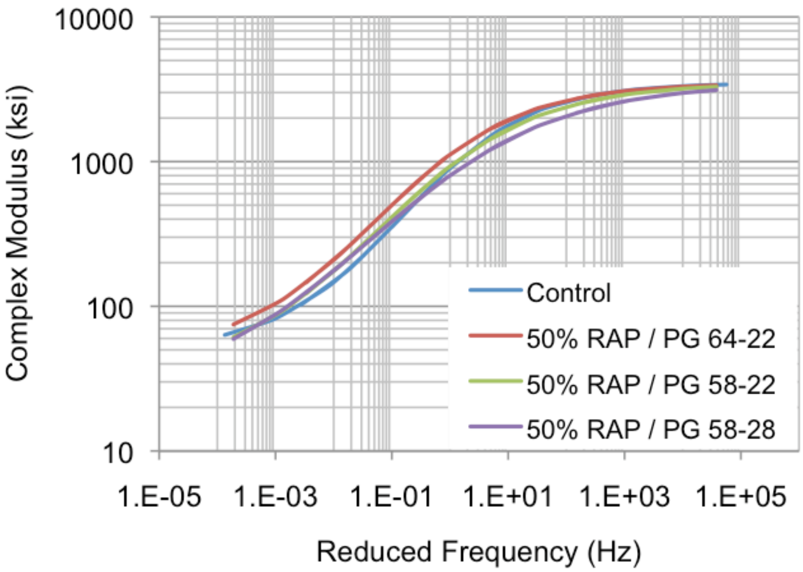


Figure 4.4. Effect of binder bumping on District 1 mixtures with 50% RAP.

A multiple-comparison procedure, Tukey's W procedure, was performed in conjunction with analysis of variance (ANOVA) to determine which means are significantly different from each other. Two population means are declared different if the difference between their sample means is greater than W, where W is dependent on the number of observations in each sample, degrees of freedom, and q, which is the upper-tail critical value of the Studentized range distribution (Ott and Longnecker 2010). All the analyses were completed using Statistical Analysis Software (SAS) v9.2. An example of an output file is presented at the end of Appendix C.

Different HMA and asphalt binder combinations were grouped and analyzed at two frequency levels (0.1 and 10 Hz) and three temperatures 14°F (–10°C), 70°F (21°C), and 129.2°F (54°C) for District 1 and District 5 HMAs. The alpha value used was 0.05. The following are the findings for District 1:

- When all the mixtures made with the base binder (PG 64-22) were grouped, none of the modulus values of HMAs with RAP were significantly different from the control mixture at any combination of frequency and temperature. This implies that the stiffening effect of RAP on District 1 HMA is not evident from E* results.
- To quantify the effect of binder-grade bumping, the control and HMA with 30% RAP were grouped. None of the HMAs with 30% RAP using different binders was significantly different from the control mixture. The HMA with 30% RAP and PG 58-28 was significantly different (softer) compared to mixtures with 30% RAP using PG 64-22 at 0.1 Hz and 70°F (21°C). At 10 Hz and 129.2°F (54°C), the HMAs with PG 58-22 and PG 58-28 were significantly different (softer) than the HMA with 30% RAP and PG 64-22. This clearly shows the effect of binder-grade bumping. At 14°F (–10°C), all HMAs behaved similarly, and no mix was significantly different from any other mix. It was noted that the effect of double bumping the binder was evident at intermediate temperatures, while at a high temperature, which is influenced by the high PG limit, the effect is similar to when a single-bump grade binder was used.
- The effect of binder-grade bumping on HMA with 40% RAP was analyzed. None of the HMAs consisting of 40% RAP with different binders was significantly different from the control mixture. The HMAs with PG 58-28, though, were significantly different from the HMAs with PG 58-22 only at 10 Hz and 129.2°F (54°C).
- For HMA with 50% RAP, none of the mixtures was significantly different from any other mixture at any temperature and frequency combination.

In summary, District 1 mixtures with RAP performed on par with the control mixture, based on E* test results. Although adding RAP stiffens HMA at high temperatures and improves complex modulus, steps should be taken to avoid possible block cracking due to increased asphalt binder stiffness. On the other hand, this test is insensitive at low temperatures because specimens are loaded in compression, while thermal cracking occurs in tension.

After performing the E* test, the same specimens were used for the flow number test. Figure 4.5 shows the average of three tests for each mix and binder type combination. The results reveal a consistent trend of increase in the flow number with an increase in RAP amount used in the HMA. Since a higher flow number implies higher resistance to permanent deformation, HMA with 50% RAP showed the highest resistance to rutting, followed by the mixtures with 40% and 30% RAP and the control mix.

The effect of grade bumping is also evident in Figure 4.5. Although the effect of softer binder is obvious and consistent in the flow number of the mixtures with RAP, the effect diminishes with an increase in RAP percentage in the mix. While the flow number of HMA with 30% RAP using PG 58-28 is 57.5% less than that with 30% RAP and PG 64-22, there is only an 11% reduction in the flow number of HMA with 50% RAP due to double-binder-grade bumping.

In summary, as RAP content increases, the flow number increases because the HMA becomes stiffer. The single-bump binder grade worked as expected and reduced the stiffness of the HMA. The stiffness could be reduced further when using a binder with a lower high PG limit. Double bumping the binder grade can further soften the HMA; however, it would be limited in this case because the test was conducted at a high temperature, 136.4°F (58°C).

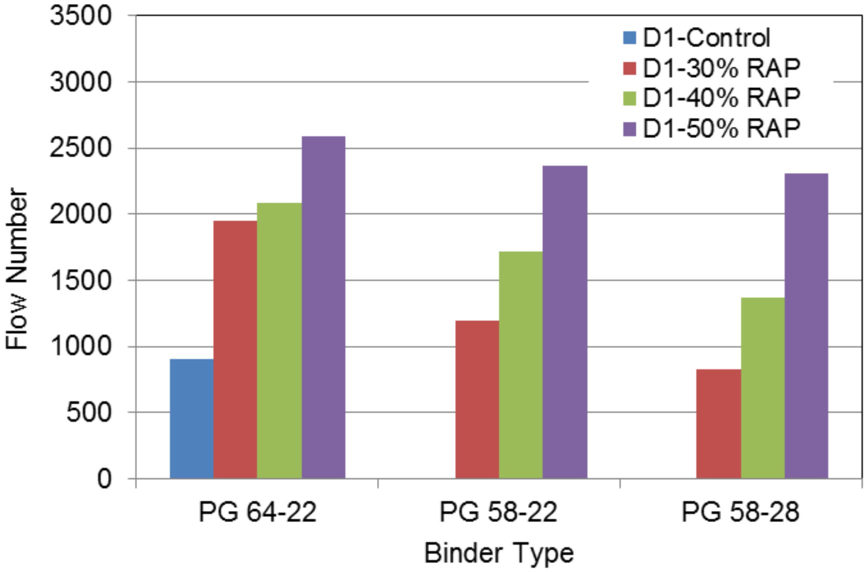


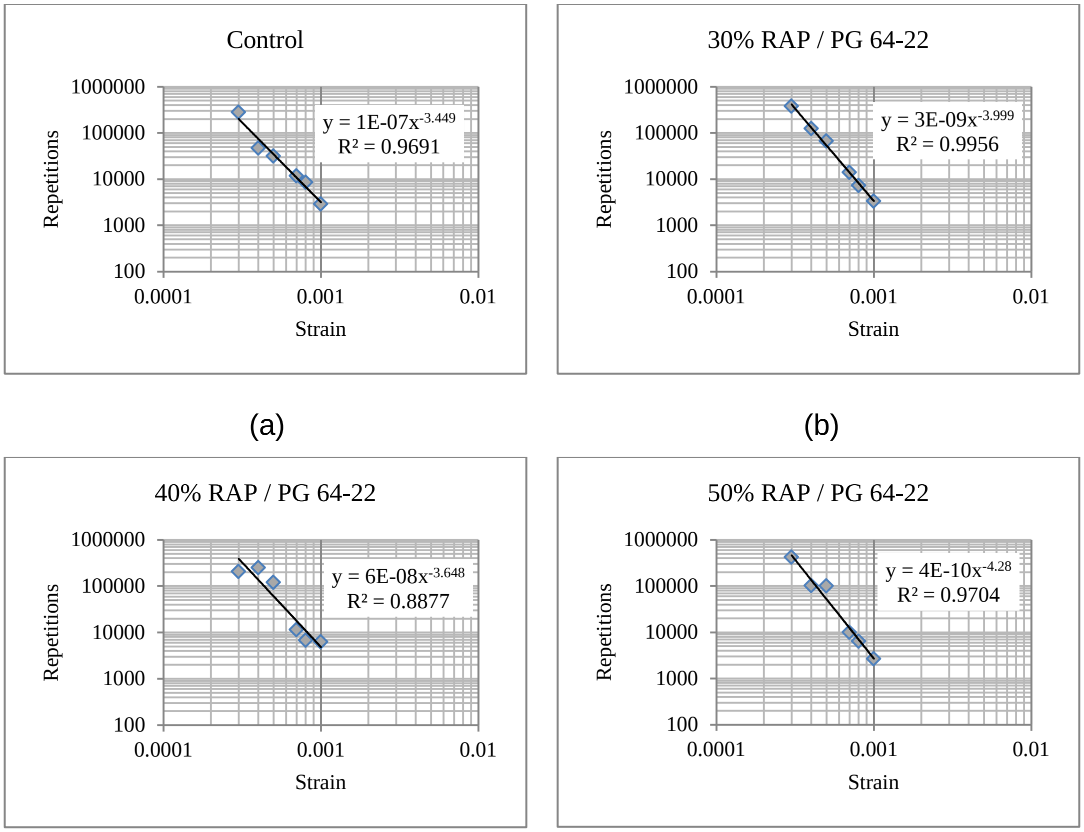
Figure 4.5. Flow number test results, District 1.

4.1.2 Beam Fatigue Test

The four-point beam fatigue test was conducted to determine the fatigue life of the HMA. The test was run at 68°F (20°C) at strain levels of 1000, 800, 700, 500, 400, and 300 microstrains. The failure criterion used in the study was the traditional 50% reduction in initial stiffness (i.e., the initial stiffness is the stiffness at the 50th load cycle). Equation 4.1 shows a typical relationship between the tensile strain at the bottom of the HMA layer (ε_o) and the number of load applications to crack appearance in the pavement (N_f).

$$N_f = K_1 \left(\frac{1}{\varepsilon_o}\right)^{K_2} \tag{4.1}$$

where K_1 and K_2 are the intercept and slope of a fatigue curve, respectively, and are dependent on the composition and properties of the HMA. The higher the absolute value of K_2, the better the fatigue behavior of the mix. Typical fatigue curves for District 1 HMA are shown in Figure 4.6. The values of flexural stiffness and K_2, obtained from the District 1 HMA fatigue testing, are presented in Table 4.2. In general, HMA flexure stiffness increased as RAP content in the mixture increased. The typical average K_2 value for Illinois HMA is 4.5 (Carpenter 2006), but IDOT uses a K_2 value of 3.5 for design purposes. Although the District 1 control HMA apparently performed acceptably, its fatigue behavior is at the lower end. Detailed results are presented in Appendix C.



(a) (b)

(c) (d)

Figure 4.6. Fatigue curves for District 1: (a) control mix, (b) HMA with 30% RAP, (c) HMA with 40% RAP, (d) HMA with 50% RAP.

The effect of RAP content was evaluated for HMA with each binder type. For PG 64-22, it was observed that HMA with 40% RAP showed insignificant changes in K_2. However, the HMAs with 30% and 50% RAP had an improved K_2 value. The flexural modulus (E_f) values showed an increase of approximately 22% when the RAP content increased from 0% to 30%. However, the flexural modulus did not change as the RAP content increased from 30% to 50%. Examining the effect of RAP when PG 58-22 binder was used, it was noted that the HMA with 30% RAP showed a significant increase in K_2 over the control mixture, while the 40% RAP showed moderate improvement. The HMA with 50% RAP had the most significant improvement. In addition, the flexural modulus showed an increase as RAP content increased from 30% to 50%.

The effect of RAP content on HMA with PG 58-28 was also examined relative to the control mix. The effect of RAP on HMAs' flexural modulus was evident, as it proportionally increased with RAP. For HMA with 30% RAP, the K_2 value was significantly improved, possibly due to the significantly lower flexural modulus (at constant strain, low modulus improves fatigue resistance). However, for HMAs with RAP contents of 40% and 50%, K_2 values dropped significantly relative to single bumping yet remained greater than the control mix value. This finding indicates that a double-grade binder bump does not provide improvement over a single bump, but it does provide slight improvement over the control HMA.

Table 4.2. Fatigue Beam Test Results for District 1 Mixtures

Sample	E_f (MPa)	K_2	E^{*1} (MPa)	(E_f/E^*)
0% RAP-PG 64-22	3500	3.45	10902	0.3
30% RAP-PG 64-22	4305	4.00	10802	0.4
30% RAP-PG 58-22	4042	4.42	9160	0.4
30% RAP-PG 58-28	2892	4.34	8000	0.4
40% RAP-PG 64-22	3492	3.65	9010	0.4
40% RAP-PG 58-22	4285	3.84	9813	0.4
40% RAP-PG 58-28	3683	3.56	7490	0.5
50% RAP-PG 64-22	4256	4.28	11477	0.4
50% RAP-PG 58-22	4495	4.98	9635	0.5
50% RAP-PG 58-28	3775	3.89	8870	0.4

[1] Complex Modulus values at 10 Hz and 21°C

The effect of binder bumping on fatigue life of HMA with the same amount of RAP was evaluated. For HMA with 30% RAP, binder bumping improved the K_2 values, primarily due to reduction in the modulus. For HMA with 40% RAP, the double bump appeared to lower the fatigue behavior compared to a single bump. For HMA with 50% RAP, it was evident that a single bump results in the best fatigue behavior. Although the double bump in binder grade significantly lowered fatigue behavior compared to the single bump, it was still an improvement over the control mixture. This reduction in K_2 value was observed in spite of a significantly lower modulus when the double-bumped binder was used, compared to HMA with PG 64-22 or PG 58-22. Again, fatigue life is a function of material stiffness (modulus and geometry) and level of strain applied.

4.1.3 Wheel Tracking Test

For the wheel tracking test, three replicates were tested for each HMA. None of the mixtures reached the 0.5-in (12.5-mm) criterion of failure. Figure 4.7 shows the effect of RAP on HMA permanent deformation. An improvement in rutting resistance was observed as RAP content increased from 0% to 40%. However, HMA with 50% RAP showed rutting resistance similar to that of HMA with 40% RAP.

The binder-grade bump effect on HMA with 30% RAP was evaluated, as presented in Figure 4.8. The rut depths of the HMA with 30% RAP increased when the virgin binder was softened. For HMA with 40% RAP (Figure 4.9), the effect of single- and double-grade binder bumping was similar, but it significantly increased rut depth compared to HMAs with PG 64-22. The rut depths remained less than those of the control mixture, even with double bumping.

Figure 4.10 shows rut depth for HMA with 50% RAP. While single-grade bump did not affect rut depths, double bumping increased rut depth slightly—but still less than with the control mixture. Overall, wheel tracking data showed improvement in permanent deformation with an increase in RAP content. The single and double bumping was effective in reducing the stiffness increase induced by the addition of aged RAP binder. Figure 4.11 shows average rut depths for all combinations of mixtures and binders.

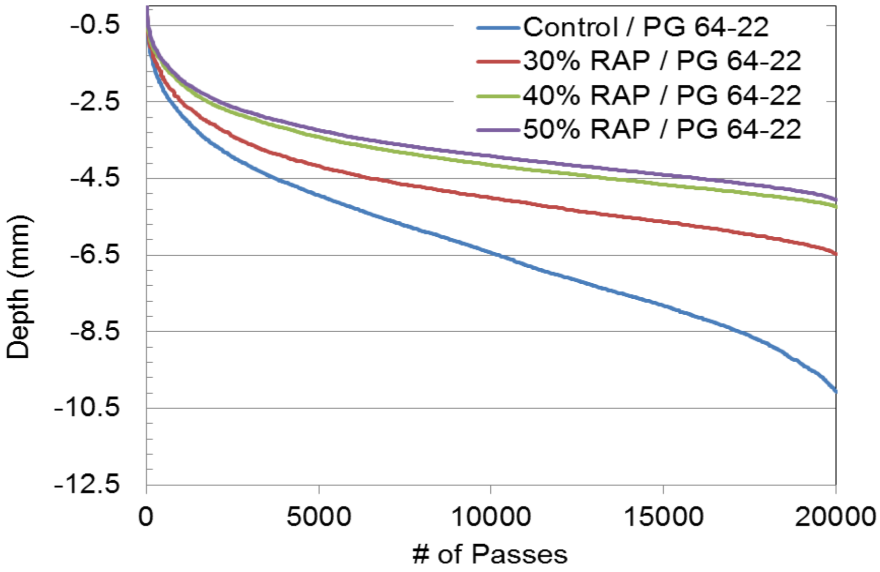


Figure 4.7. Average rut depths for District 1 mixtures: effect of RAP.

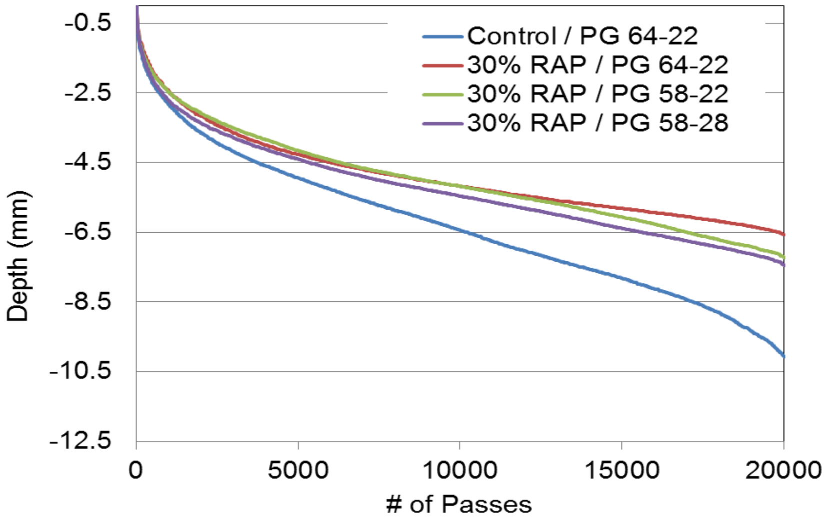


Figure 4.8. Average rut depths for District 1 mixtures with 30% RAP: effect of binder bumping.

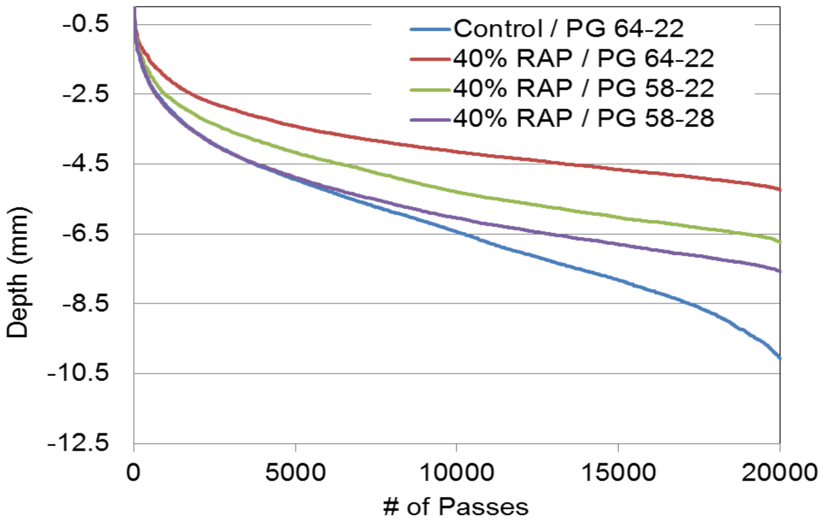


Figure 4.9. Average rut depths for District 1 mixtures with 40% RAP: effect of binder bumping.

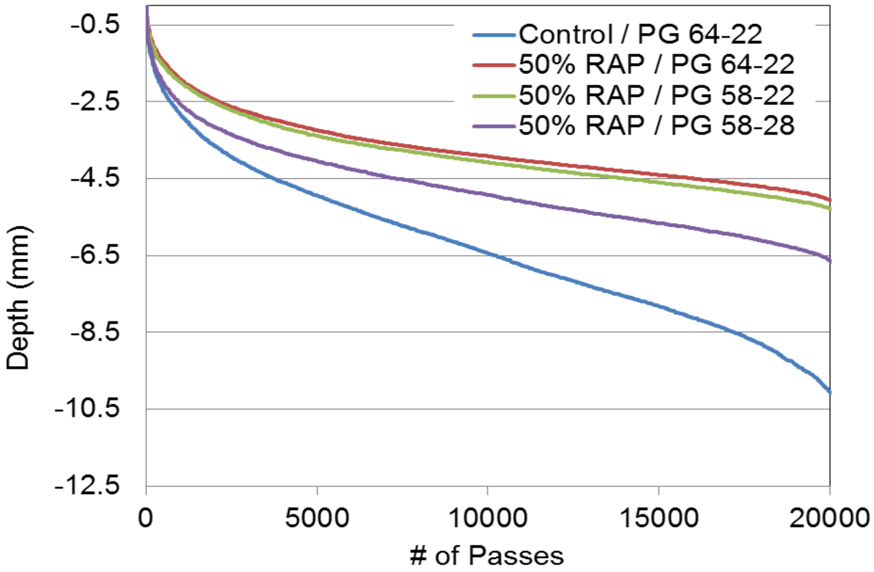


Figure 4.10. Average rut depths for District 1 mixtures with 50% RAP.

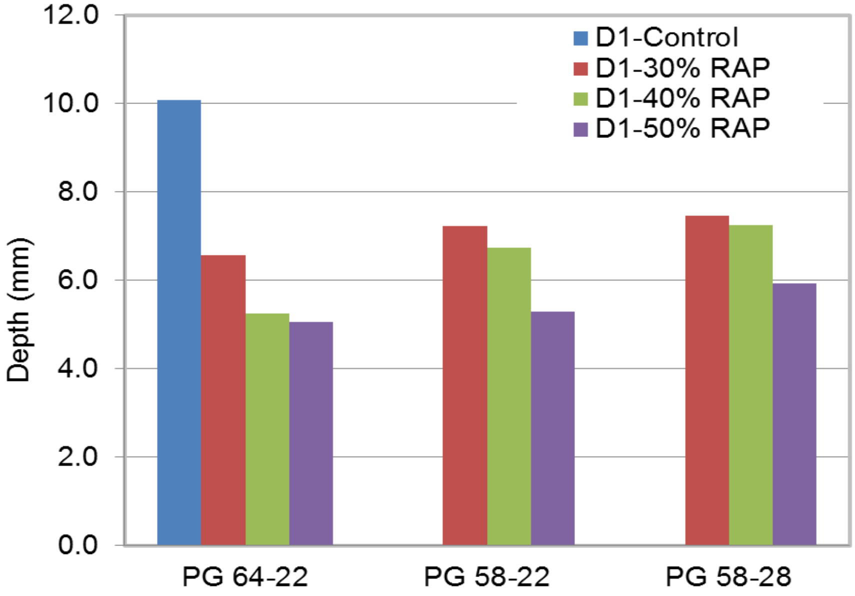


Figure 4.11. Average rut depths for all District 1 mixtures.

4.1.4 Semi-Circular Bending (SCB) Test

To better understand thermal cracking, glassy transition temperatures (T_g) were measured for four binders—that is, base binders (PG 64-22) and extracted RAP binders for both Districts 1 and 5. The T_g were measured with a differential scanning calorimeter (DSC). The binder samples were cooled to –94°F (–70°C) from 32°F (0°C) at a rate of 10°C/min. The T_g for the binders are presented in Table 4.3.

As explained in Chapter 3, the semi-circular bending (SCB) test was performed at two temperatures: 10.4°F (–12°C) and –11.2°F (–24°C). The test was performed at a crack mouth opening displacement (CMOD) rate of 0.003937 in/min (0.1 mm/min). Detailed results are presented in Appendix C.

Table 4.3. Glassy Transition Temperatures (T_g)

Sample No.	Binder	T_g (°C)	
		Onset*	Peak
1	District 1, PG 64-22	–9.9	–16.3
2	District 1, extracted RAP Binder	–12.1	–14.5
3	District 5, PG 64-22	–11.8	–16.1
4	District 5, extracted RAP binder	–10.2	–14.7
5	PG 58-22	–16.1	–18.3
6	PG 58-28	–17.2	–18.2

*The temperature at the onset of the spike; 1°F = 1.8 × Temperature (°C) + 32

Figure 4.12 shows the effect of RAP content on HMA fracture energy. Higher fracture energy suggests that more energy is required to create a unit surface area of a crack. Therefore, the lower the fracture energy, the greater the potential for thermal cracking.

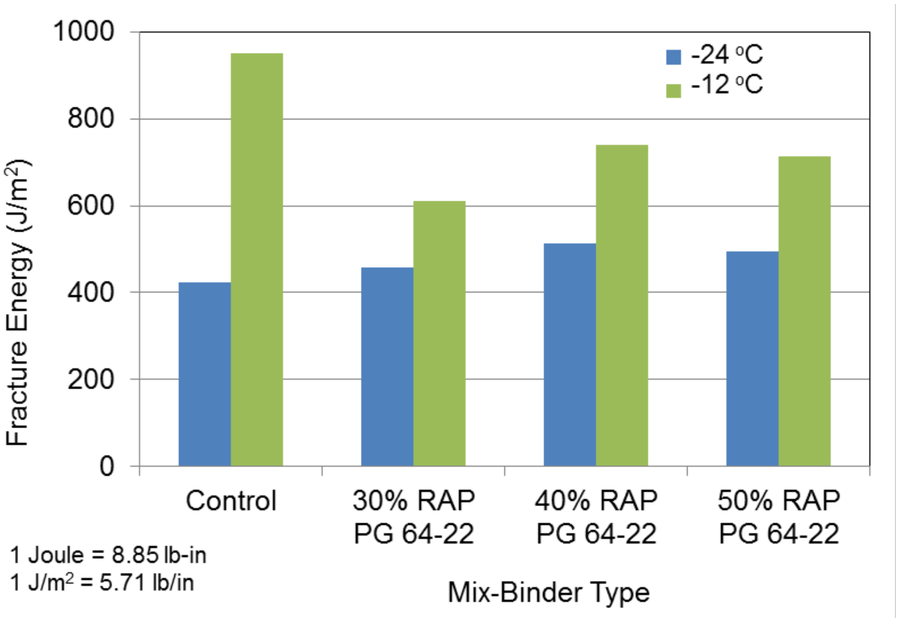


Figure 4.12. Fracture energy for District 1 mixtures: effect of RAP.

First, the effect of RAP on fracture energy was analyzed for asphalt mixtures prepared with the base binder (PG 64-22). Apart from the control mixture, HMAs with RAP showed a similar trend at both temperatures: At –11.2°F (–24°C), the fracture energy of the HMA steadily increased as the RAP amount increased from 0% to 40%; however, the fracture energy for HMA with 50% RAP slightly decreased. At 10.4°F (–12°C), the control mixture showed the highest fracture energy. Fracture energy sharply plummeted for the HMA with 30% RAP. The HMAs with RAP showed a similar trend as that seen at 10.4°F (–12°C). Fracture energies were greater at 10.4°F (–12°C) compared to –11.2°F (–24°C), possibly because the asphalt binder is relatively ductile and still within the viscoelastic range as shown by the T_g values. Hence, the creep effect was more pronounced, which consequently required more energy to initiate and propagate a crack. In addition, at relatively low temperatures, the crack tended to propagate in a straight path irrespective of the presence of aggregate and mastic, whereas at higher temperatures, the cracks were more likely to circumnavigate the aggregate particles and propagate through the softer mastic.

Figure 4.13 shows the effect of binder-grade bumping on the fracture energy of mixtures with 30% RAP. The fracture energy increased, at both temperatures, when PG 58-22 was used, whereas double bumping the binder grade (PG 58-28) resulted in no difference from that of HMA with PG 58-22. However, the double bump showed improved fracture energy over the control mixture.

For mixtures with 40% RAP (Figure 4.14), with the exception of HMA with 40% RAP and PG 58-22 at –11.2°F (–24°C), HMA fracture energy increased when the binder became softer. This increase in fracture energy is expected because the binder becomes more ductile and resistant to cracking when it is softer.

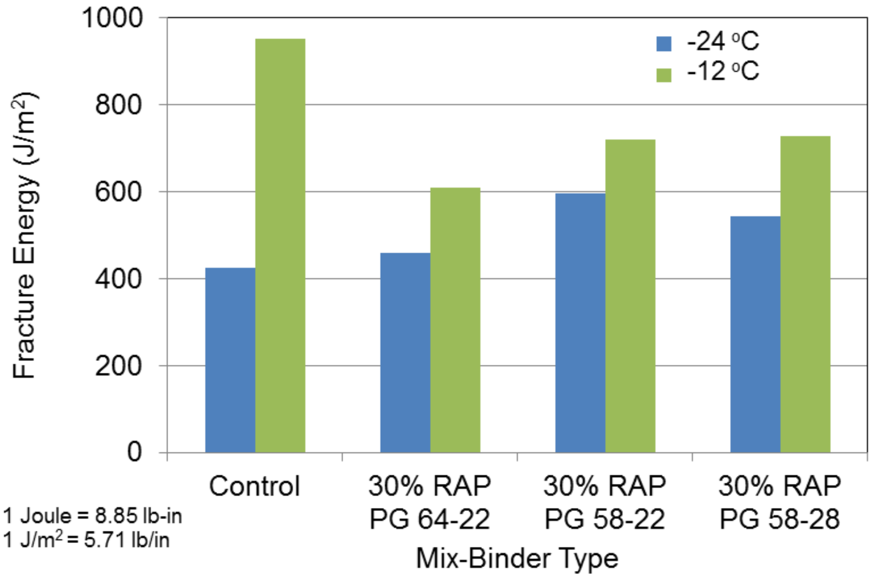


Figure 4.13. Fracture energies for District 1 mixtures with 30% RAP: effect of binder bumping.

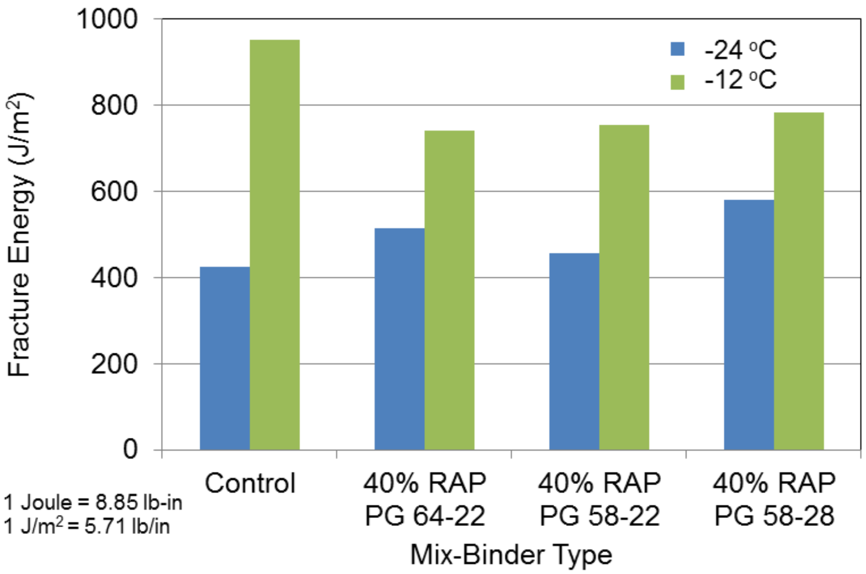


Figure 4.14. Fracture energy for District 1 mixtures with 40% RAP: effect of binder bumping.

For mixtures with 50% RAP, at –11.2°F (–24°C), a steady increase in fracture energy was observed when the binder changed from no bumping to double bumping, as shown in Figure 4.15. At 10.4°F (–12°C), the fracture energy decreased when single bumping was applied and then increased when double bumping was used. This is expected because single bumping affects binder behavior at a higher temperature range. The variation in fracture behavior between binders at 10.4°F (–12°C) and –11.2°F (–24°C) is primarily due to the change in binder phase, as indicated by the measured T_g values.

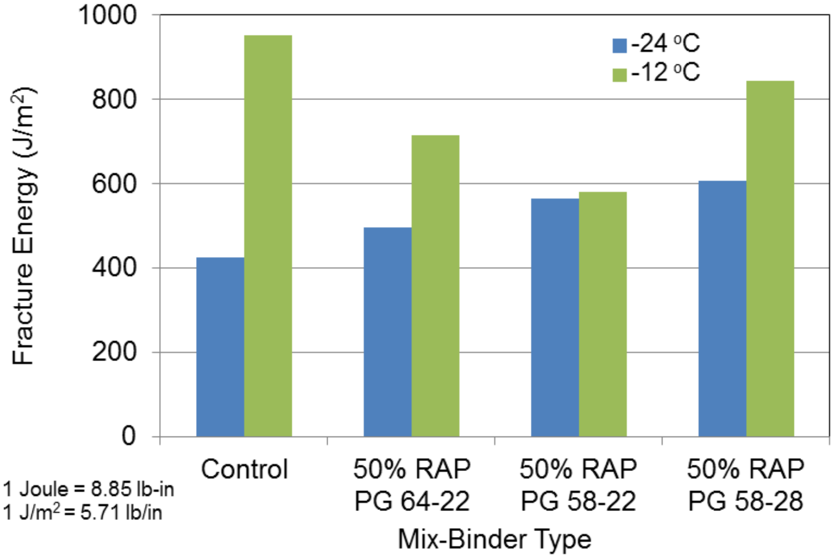


Figure 4.15. Fracture energy for District 1 mixtures
with 50% RAP: effect of binder bumping.

In general, the stiffening effect of RAP aged binder and softening effect of bumped binder is more pronounced at 10.4°F (–12°C) than at –11.2°F (–24°C). The softening effect when using single and double binder-grade bumping did not appear to be significant most of the times at –11.2°F (–24°C). The fracture energy test results at –11.2°F (–24°C) appeared to be unable to capture the effect of aged and softer binders because new and aged binders behave similarly at that temperature, which is well below the T_g. At 10.4°F (–12°C), on the other hand, fracture energy was significantly reduced by the addition of RAP with respect to the control mix, which can be improved by using a softer binder.

4.2 TEST RESULTS FOR DISTRICT 5 ASPHALT MIXTURES

4.2.1 Complex Modulus (E*) and Flow Number Tests

The E* master curves were generated for District 5 mixtures. At low frequencies (or high temperatures), HMAs with RAP exhibited stiffer behavior (i.e., higher moduli) compared to the control mix. However, it is hard to differentiate the HMAs with RAP from each other. As shown by the master curves in Figure 4.16, HMAs with 30%, 40%, and 50% RAP showed similar behaviors. The HMA with 30% RAP (the master curves in Figure 4.17) showed a decrease in moduli values with softer binder grades.

For HMAs with 40% RAP, no significant effect of binder-grade bumping was observed on moduli , as shown in Figure 4.18. For HMAs with 50% RAP, single and double binder-grade bumping showed similar amount of reduction in the moduli (Figure 4.19).

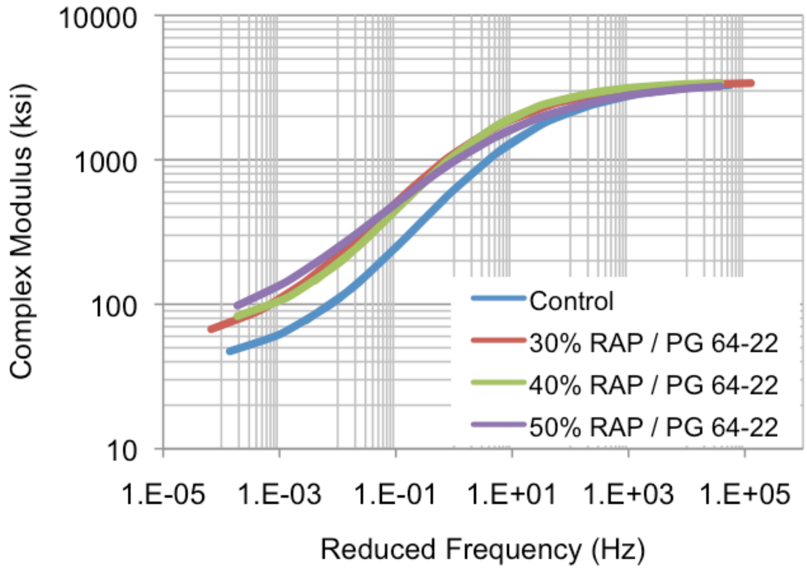


Figure 4.16. Master curves for District 5 control and RAP mixtures.

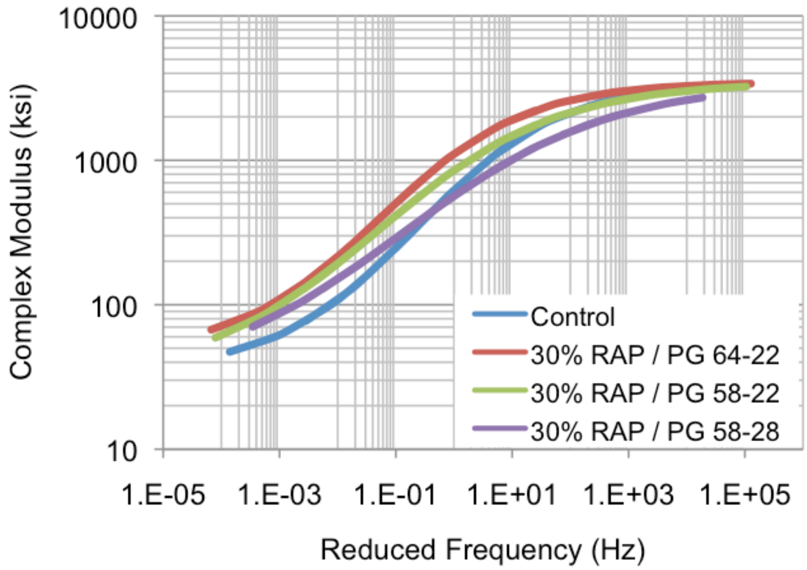


Figure 4.17. Effect of binder bumping on District 5 mixtures with 30% RAP.

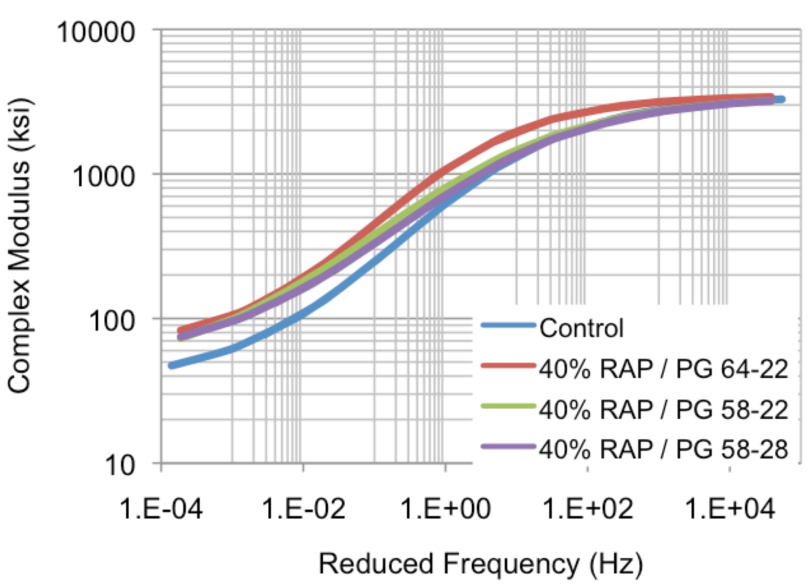


Figure 4.18. Effect of binder bumping on District 5 mixtures with 40% RAP.

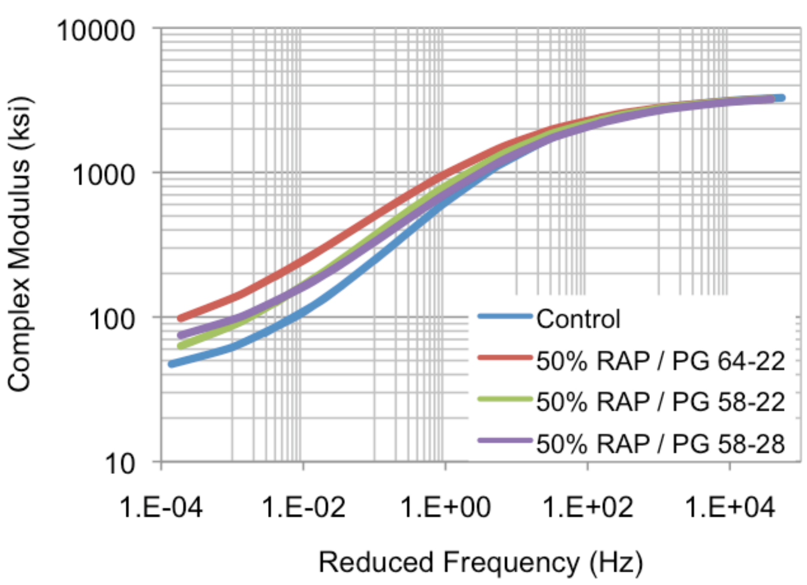


Figure 4.19. Effect of binder bumping on District 5 mixtures with 50% RAP.

To cover a wide range of temperatures and frequencies, statistical analyses were performed on District 5 complex modulus data at 0.1 and 10 Hz at temperatures of 14°F (–10°C), 70°F (21°C), and 129.2°F (54°C). The findings from the statistical analyses were as follows:

- At 0.1 Hz and 70°F (21°C) and 10 Hz and 129.2°F (54°C), all HMAs containing RAP with the base binder were significantly different from the control mixture, whereas no difference was found among the HMAs with

RAP. At 10 Hz and 70°F (21°C), the control mixture was significantly different from the 30% and 40% RAP mixtures. No significant difference between the RAP mixtures and the control mixture was found at 14°F (–10°C).

- The effect of binder bumping was analyzed by grouping the control mix with all of the HMAs with 30% RAP:
    - At 0.1 Hz and 70°F (21°C), the control mix was significantly different (softer) than the HMA with 30% RAP and PG 64-22 and PG 58-22. The double-bumped mixture (30% RAP with PG 58-28) was not significantly different from the control mix. The HMA mix with 30% RAP and PG 58-28 was significantly different from the HMA with 30% RAP and PG 64-22.
    - At 14°F (–10°C), at both 0.1 and 10 Hz, HMA with PG 58-28 were significantly different (softer) than the control mix and HMA with 30% RAP and PG 64-22, indicating that double bumping reduced the modulus and made those HMAs softer than the control mix.
    - At 10 Hz and 70°F (21°C), both the control and the HMA mix with 30% RAP and PG 58-28 were significantly different from the HMA mix with 30% RAP and PG 64-22.
    - At 10 Hz and 129.2°F (54°C), the control was significantly different from the HMAs with 30% RAP with PG 64-22.
- For HMA with 40% RAP, the control mix was significantly different from the rest of the mixes at 0.1 Hz and 70°F (21°C). At 10 Hz at both 70°F (21°C) and 129.2°F (54°C), the control mix was significantly different from HMA with 40% RAP and PG 64-22. The effect of binder bumping is prominent at higher temperatures, but at 14°F (–10°C), none of the mixtures was significantly different from others.
- For HMA with 50% RAP, at 0.1 Hz and 70°F (21°C), the control mix was significantly different (softer) from the rest of the mixes. At 0.1 Hz and 129.2°F (54°C), the control mix was significantly different from HMA with 50% RAP. At 10 Hz, the only significant difference between the control and the HMA with 50% RAP using PG 64-22 was shown at 129.2°F (54°C). Since the HMA with 50% RAP and PG 58-22 and PG 58-28 were not significantly different from the control mix, it was concluded that binder-grade bumping was effective to soften the mix. At 14°F (–10°C), none of the mixtures was significantly different than others.

Flow number results for District 5 HMAs are shown in Figure 4.20. The effect of increasing RAP is obvious in mixes using the base binder grade (PG 64-22). An increase in the flow number was observed as RAP content in HMA increased. When softer binder was used in HMAs with RAP, the F_N was reduced. The reduction in the flow number of HMAs with RAP was more pronounced when double-bumped binder was used. Overall, the trends are clear and consistent enough to show the effect of RAP and binder bumping.

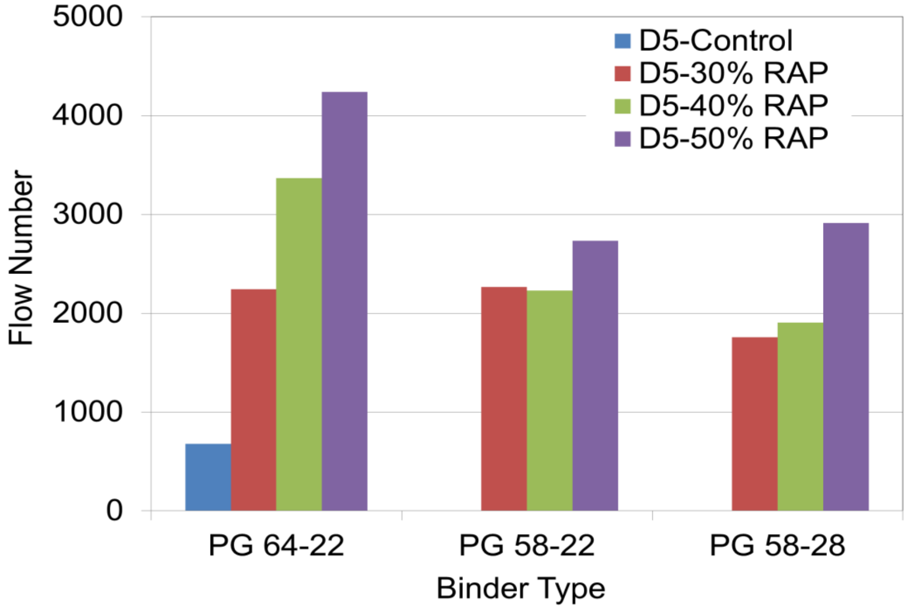


Figure 4.20. Flow number test results, District 5.

4.2.2 Beam Fatigue Test

Examining the District 5 fatigue data revealed that, similar to District 1 HMAs, a positive effect was observed in fatigue trends when adding RAP. As shown in Table 4.4, K_2 for PG 64-22 values increased as RAP increased up to 40%; the mix with 50% RAP showed a slight decrease in the K_2 value but was still higher than the mix with 30% RAP. Analysis of the effect of RAP on fatigue behavior for the mixtures with the bumped binders (PG 58-22 and PG 58-28) showed that all HMAs with RAP had significant improvement in fatigue behavior. The E_f and K_2 values increased as RAP content increased.

The effect of binder-grade bumping was also evaluated; for single-bumped binder (PG 58-22), the behavior of HMA with 30% RAP remained approximately the same as that of the mixtures with PG 64-22. The HMAs with 40% and 50% RAP, however, showed significant (20%) improvement. Again, the double-bumped binder (PG 58-28) showed a decrease in fatigue behavior relative to the single-bumped binder; the K_2 value for the asphalt mixture with 30% RAP was below the assumed design value (3.5) of typical Illinois mixtures (Carpenter 2006). The double-bumping effect was not that pronounced for HMAs with 40% and 50% RAP; there was still a reduction in K_2 values compared to the single bumping results. It is important to note that bumping is very effective in restoring the flexural modulus to that of the control mix values. In addition, fatigue testing is performed at normal temperatures, whereas the effect of double bumping is more pronounced at low temperature.

Tables 4.2 (see Section 4.1.2) and 4.4 show that the average ratio of flexural to complex modulus values was 0.40 for both District 1 and District 5 materials, which is within the range of the tested materials in Illinois. This indicates that all the mixtures prepared in the study had a good structural mix and consistent composition and were not different from normal virgin mixtures. The tensile behavior, which potentially could be the most negatively impacted by high RAP content, did not show significant difference with respect to normal mixes. These mixes were of similar quality as a virgin mix, and adding RAP did not have a negative impact.

Table 4.4. Fatigue Beam Test Results for District 5 Mixtures

Sample	E_f (MPa)	K_2	E* (MPa)	(E_f/E*)
0% RAP-PG 64-22	3314	3.64	7477	0.4
30% RAP-PG 64-22	4327	3.88	11390	0.4
30% RAP-PG 58-22	3579	3.80	9549	0.4
30% RAP-PG 58-28	3322	3.31	7222	0.5
40% RAP-PG 64-22	4864	4.55	11579	0.4
40% RAP-PG 58-22	4158	4.42	9410	0.4
40% RAP-PG 58-28	3695	4.24	8964	0.4
50% RAP-PG 64-22	5089	3.98	9903	0.5
50% RAP-PG 58-22	4175	4.78	8929	0.5
50% RAP-PG 58-28	4224	4.50	10071	0.4

[1] Complex Modulus values at 10 Hz and 21°C

4.2.3 Wheel Tracking Test

For District 5, Figure 4.21 shows that the control mix had very high potential for rutting and exceeded the failure criterion threshold of 0.5 in (12.5 mm). Introduction of RAP increased rutting resistance remarkably. For the base binder (PG 64-22), the HMA with 30% RAP appeared to improve rutting resistance. The asphalt mixture with higher RAP (i.e., 40% and 50%) behaved almost similarly to the asphalt mixture with 30% RAP having PG 64-22. For softer grades (PG 58-22 and PG 58-28), an increase in rutting resistance was observed with an increase in RAP content.

Analyzing the effect of binder-grade bumping, it appears that softer binders affect the mixtures with lower RAP content the most. For all District 5 mixtures with RAP, single and double bumping did not appear to produce different results. For 30% and 40% RAP, as shown in Figures 4.22 and 4.23, respectively, rutting resistance decreased with single-grade binder bumping, but double bumping did not decrease it further.

For HMA with 50% RAP, there was a minimal effect of binder bumping, as shown in Figure 4.24. In short, with an increase in RAP content, the binder effect was reduced slightly. This is similar to the trend observed for District 1 HMAs and may be attributed to the fact that less virgin binder is added as the RAP content increases. Figure 4.25 summarizes the test data that explains the effect of RAP as well as that of binder bumping.

Overall, the addition of RAP increased rutting resistance of the District 5 HMAs, and the performance was not compromised by using softer binder grades.

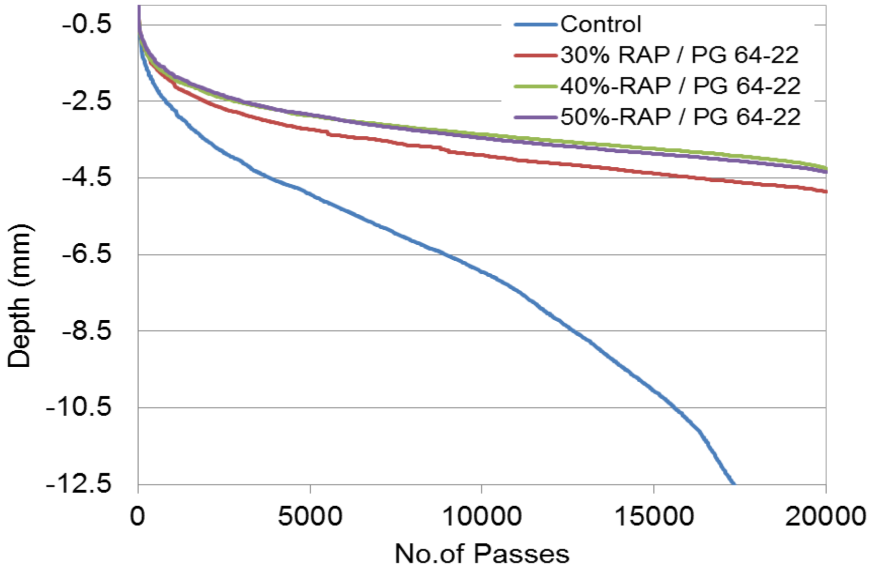


Figure 4.21. Average rut depths for District 5 mixtures: effect of RAP.

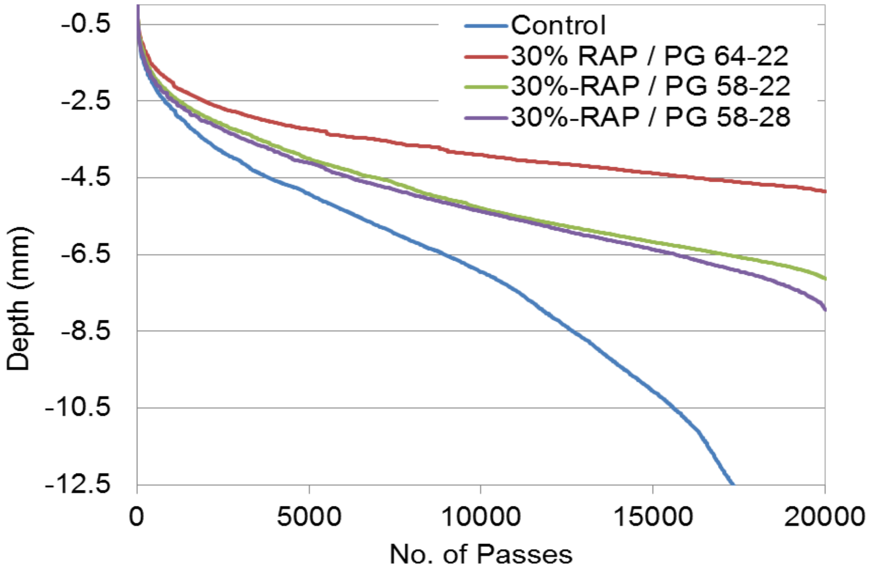


Figure 4.22. Average rut depths for District 5 mixtures with 30% RAP: effect of binder bumping.

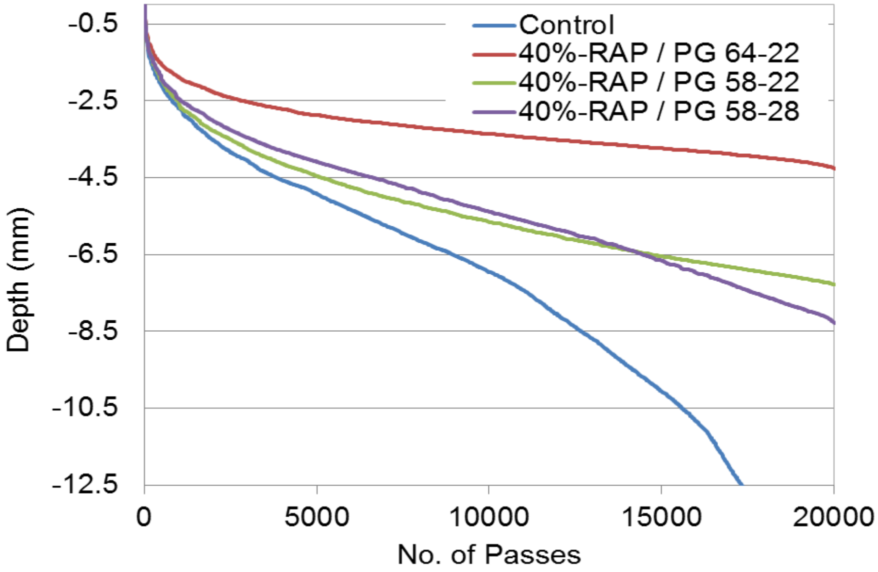


Figure 4.23. Average rut depths for District 5 mixtures with 40% RAP: effect of binder bumping.

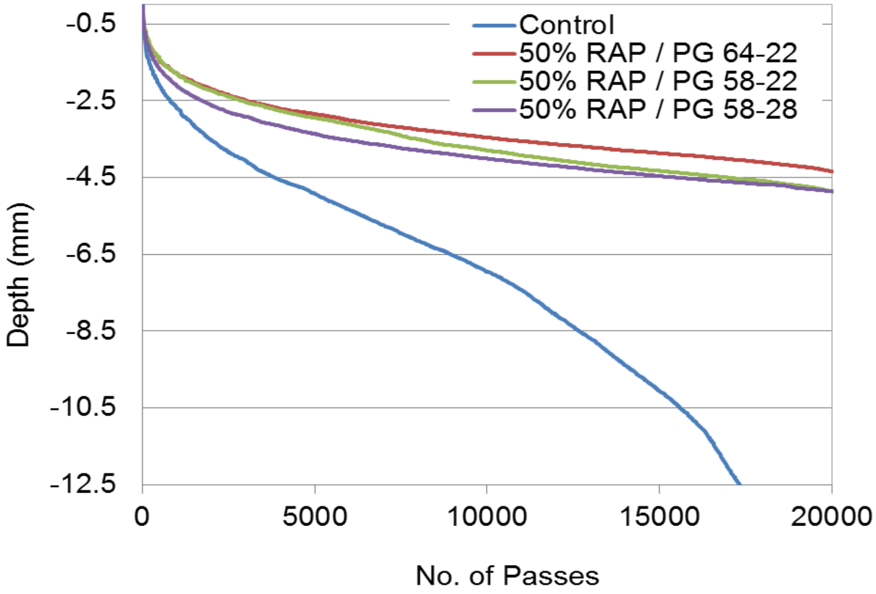


Figure 4.24. Average rut depths for District 5 mixtures with 50% RAP: effect of binder bumping.

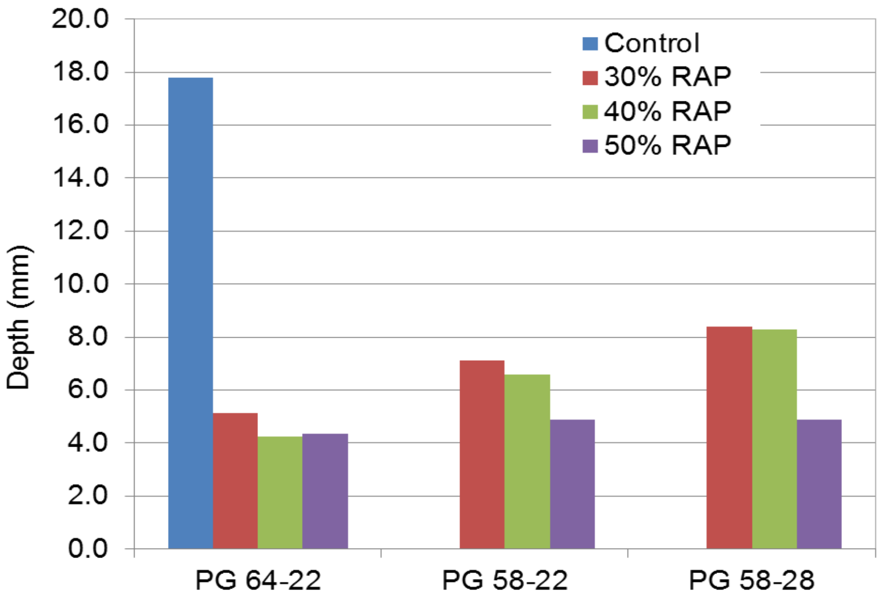


Figure 4.25. Average rut depths of all District 5 mixtures.

4.2.4 Semi-Circular Bending (SCB) Test

For District 5, SCB test results showed that fracture energies are similar at both temperatures, as shown in Figure 4.26 (detailed results are tabulated in Appendix C). Also, the effect of RAP on fracture behavior was not manifested from the data. At –11.2°F (–24°C), fracture energy slightly increased with addition of 30% RAP, whereas it decreased for the HMA with 40% RAP. The data showed an increase in fracture energy of 50% RAP relative to 40% RAP. At 10.4°F (–12°C) though, a slight decreasing trend was exhibited as the RAP content increased.

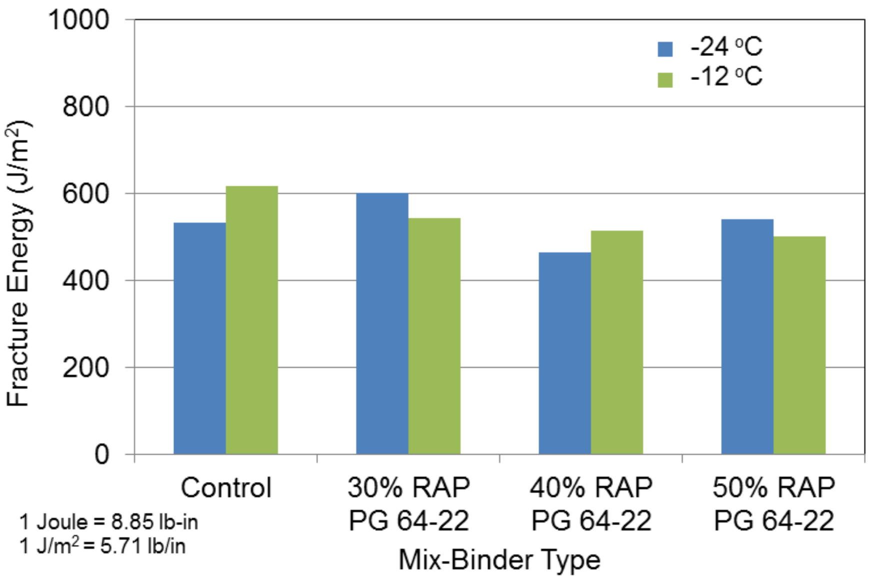
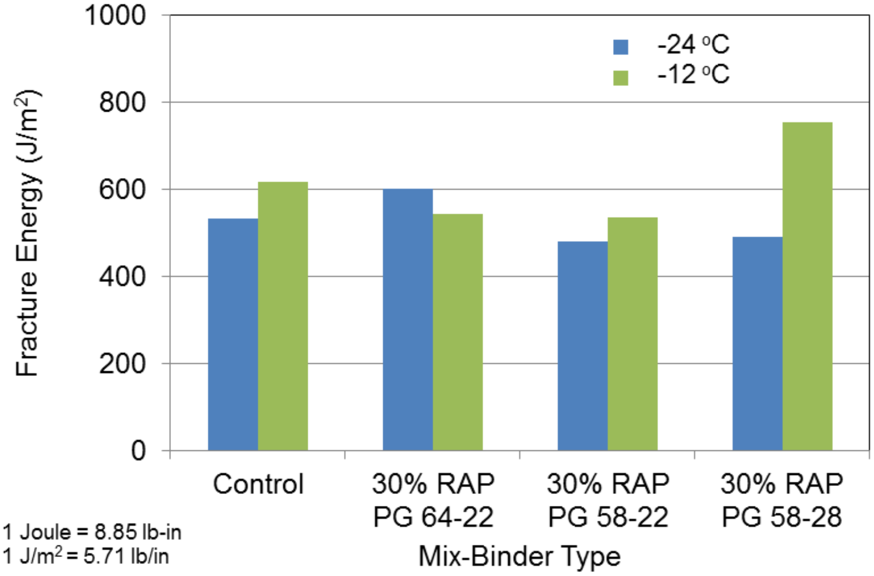


Figure 4.26. Fracture energies for District 5 mixtures: effect of RAP.

For HMA with 30% RAP, fracture energy decreased with single bumping at both temperatures, as shown in Figure 4.27. The double bumping did not affect the fracture energy at –11.2°F (–24°C), whereas a sharp increase was observed at 10.4°F (–12°C). As noted for the test results obtained on District 1 HMAs, testing below transition temperature (T_g) could not manifest the effect of adding aged binder.



1 Joule = 8.85 lb-in
1 J/m^2 = 5.71 lb/in

Figure 4.27. Fracture energies for District 5 mixtures with 30% RAP: effect of binder bumping.

For HMA with 40% RAP, fracture energy increased with single bumping at both temperatures, as shown in Figure 4.28. For double binder-grade bumping, the mixtures showed an increase in fracture energy at –11.2°F (–24°C), whereas, little change was observed at 10.4°F (–12°C).

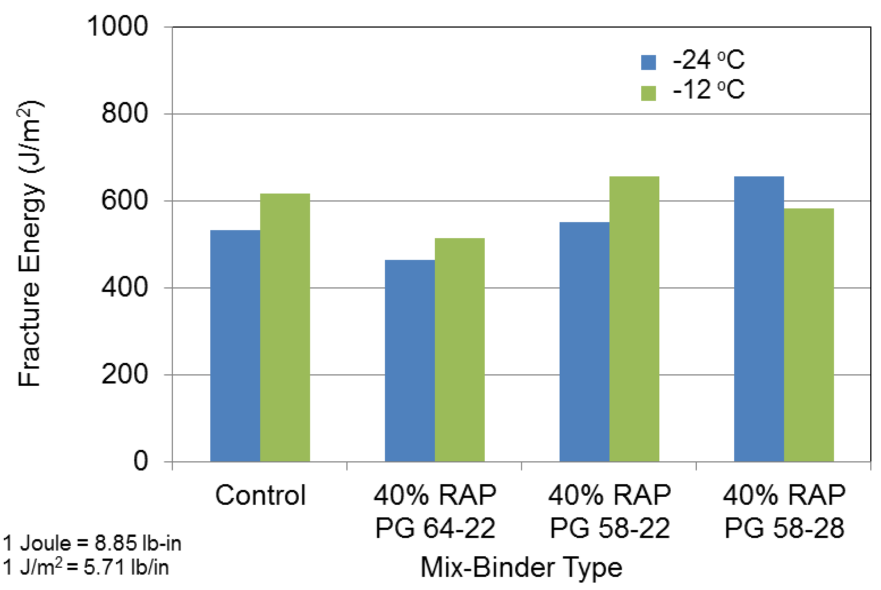


Figure 4.28. Fracture energies for District 5 mixtures with 40% RAP: effect of binder bumping.

Figure 4.29 shows that HMA with 50% RAP did not result in considerable difference in the fracture energies for no, single, and double bumping, although double binder-grade bumping resulted in the highest fracture energy. Other tests, such as flow number and wheel tracking, showed that binder bumping has the least effect on HMA with 50% RAP mixtures due to a lesser amount of virgin binder being used in them.

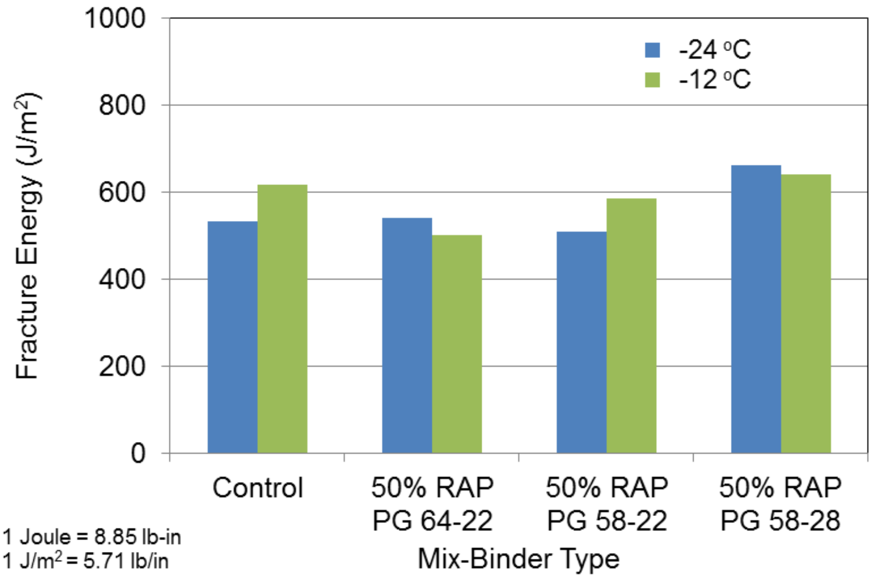


Figure 4.29. Fracture energies for District 5 mixtures with 50% RAP: effect of binder bumping.

Overall, fracture test data for District 5 mixtures did not differentiate between the mixtures. As discussed for the District 1 fracture test results at –11.2°F (–24°C), no clear trend emerged in the District 5 data. It appears that the aggregate skeleton of these 19-mm NMAS HMAs had a strong effect on fracture behavior. However, it was clear that the double-bumped binder would increase the fracture energy, but softer binder (at the low temperature) may need to be considered for HMA with 40% RAP and greater.

CHAPTER 5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 SUMMARY

The main objective of this study was to characterize and evaluate the stability and durability characteristics of nonpolymer-modified virgin HMAs with up to 50% RAP. The effect of RAP content as well as the effect of binder-grade bumping on the laboratory performance of HMA was evaluated. The effectiveness of single and double binder-grade bumping was also evaluated to determine what level of bumping is necessary at the various RAP contents to maintain the virgin mix characteristics.

Virgin aggregates and RAP materials were collected from two Illinois Department of Transportation (IDOT) administrative districts, District 1 and District 5. The RAP material was obtained in two sizes: +3/8 in (+9.5 mm) and –3/8 in (–9.5 mm). PG 64-22 binder was used as the base binder for designing the HMA. Two softer binder grades (PG 58-22 and PG 58-28) were used to evaluate the effect of binder-grade bumping on the performance of the HMA with RAP relative to the control mixtures. Four 3/4-in (19-mm) nominal maximum aggregate size (NMAS) binder mix designs ($N_{des} = 90$) were developed for both material sources, for a total of eight mix designs. The mix designs included a control mix with 0% RAP and mixtures with 30%, 40%, and 50% RAP for each district. The Bailey method of aggregate packing was used to design all the asphalt job mix formulae (JMF).

To control variability caused by the RAP gradation, each RAP material [+3/8 in (+9.5 mm) and –3/8 in (–9.5 mm)] was fractionated, over various sieve sizes, similar to virgin aggregate. Prior to fractionation, the RAP material was dried by heating it to 132°F (50°C) for 36 to 48 hr. The apparent gradation, obtained by fractionating the RAP, was then blended to prepare the extraction and Rice gravity (G_{mm}) samples. Fractionating the RAP aggregate resulted in achieving good control of mixture gradation. Consequently, similar VMA values were achieved for all mixes. This ensured that the performance testing results of the HMA were independent of volumetrics and solely related to changes in RAP content and/or binder type.

5.2 FINDINGS

The tests conducted on the HMA, designed to meet IDOT volumetric requirements for air voids, VMA, and VFA for N90, 3/8-in (19.0-mm) binder course mixture, included the following: IDOT-modified moisture susceptibility, complex modulus, flow, wheel tracking, beam fatigue, and SCB. The most important findings of the study were as follows:

- In general, tensile strength and tensile strength ratio (TSR) of the HMA increased as RAP content increased. Apart from District 5 HMAs with 40% RAP, all tested HMAs exceeded IDOT’s minimum TSR criterion of 85%. However, District 5’s control mix failed to pass the minimum tensile strength criterion of 60 psi (414 kPa). Visual inspections conducted on failed split TSR specimen faces showed similar stripping behavior between the control and mixtures with RAP.
- The complex modulus (E*) data for District 1 HMAs showed a nominal increase in modulus as RAP content increased, whereas for District 5 HMAs,

the increase in the complex moduli was more pronounced with the increase in RAP content.

- The flow number data clearly showed a reduction in rutting potential as the RAP content increased for all HMA mixes.
- Fatigue life of the HMA slightly improved with the addition of RAP for both mixture types. This is based on the slope (K_2) of the fatigue curve criterion.
- The wheel tracking test results for both HMA types were in agreement with the flow test data. The results suggested that increasing RAP content would reduce rutting potential.
- It was evident that RAP addition would increase the potential for thermal cracking (fracture energy was decreased). That was evident for both HMA types when 30% RAP was added. Additional RAP (above 30%) did not show significant difference on fracture behavior with respect to the HMA with 30% RAP, while the fracture energies still remained lower than those of the control mix.
- When single-bumped binder grade was used (compared to the same mix using PG 64-22), the following effects were observed:
  - The complex moduli (E*) were reduced for both District 1 and District 5 HMAs, regardless of the RAP content, but they were still greater than those for the control mixture. Complex moduli were considered at various loading frequencies and temperatures.
  - Rutting potential increased, as evident from flow and wheel tracking test results, but remained less than that for the control mixture.
  - Fatigue behavior improved for both HMA materials.
  - In general, low-temperature fracture behavior marginally improved for the mixes (single bumping might not have an impact at low temperature). Testing temperature is critical, and binder transition temperature (T_g) should be considered when analyzing data.
- When double-bumped binder grade was used, the following effects were observed:
  - In general, the complex moduli (E*) were reduced for all HMA types compared to the same HMAs with RAP made with base (PG 64-22) and single-bumped binder (PG 58-22). Complex moduli were considered at various loading frequencies and temperatures.
  - The rutting potential increased with respect to single bumping, as indicated by both flow and wheel tracking test results.
  - Fatigue behavior did not show improvement with respect to the HMA using a single-bumped binder grade, but it did show improvement over the control mixture. It is important to note that, in general, all mixtures with RAP had K_2 values greater than IDOT's assumed typical design value of 0.35.
  - In general, low-temperature fracture behavior improved over no bumping and showed slight improvement with respect to HMA using single-bumped binder grade for both HMA types.

In general, both single and double binder-grade bumping had significant effects on HMA with 30% RAP. For HMA with 40% and 50% RAP, though, the grade-bumping effect became less pronounced as RAP binder contribution increased.

5.3 CONCLUSIONS

Based on the findings of this study, it is concluded with confidence that it is possible to design high-quality HMA with up to 50% RAP that meets the required volumetrics and desired performance criteria. The HMA with RAP performed equal to or better than the mixtures produced with virgin aggregate.

While the benefit of binder-grade bumping at the upper PG temperature could be measured through tests conducted at high temperature (such as complex modulus, flow number, and wheel tracking) and at intermediate temperatures (such as tensile strength, complex modulus, and beam fatigue testing), only the facture energy increase shown in the SCB test provided an indication of the benefit of bumping the low PG limit (i.e., double bump). The double-bumped asphalt binder grade was found effective in counteracting the RAP stiff residual asphalt binder and in helping to retain the original properties of the virgin mixture.

Proper processing and fractionation of the RAP material at asphalt plants is strongly recommended to ensure consistent, high quality production of HMA with RAP.

5.4 RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made for practical applications and future research:

- RAP fractionation should be recommended as a best practice for all HMAs that include RAP.
- The laboratory performance of the nonpolymer-modified HMA with high RAP content can be designed to be on par with the performance of HMA produced with new aggregates. This suggests the potential of using 50% RAP in the field. However, attention should be given to potential increase in thermal cracking.
- Double bumping the binder grade is recommended for mixtures with 30% or more RAP to ensure performance equal to or better than HMA with single bumping binder. This approach would reduce thermal cracking potential.
- If modulus, tensile strength, and potential rutting criteria are desired to be maintained as those of nonpolymer-modified HMA without RAP, use of a softer binder grade, such as PG 52-28 should be explored when the RAP content exceeds 30%. Use of softening or rejuvenating agents may also be explored as an alternative.
- To investigate the cost effectiveness of single- versus double-bumping binder grade, a future cost analysis study should look at polymer-modified PG asphalt binders and RAP binder replacement with single- and double-bumping binder grade. A base PG 58-28 with single- and double-bumping binder grade should also be considered.
- A future study is recommended to evaluate the performance of HMA with high RAP content in the field or under accelerated pavement loading tests. This will help compare laboratory performance of these mixtures with their field performance.

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APPENDIX A LITERATURE REVIEW

A.1 INTRODUCTION

When hot mix asphalt (asphalt mixture) pavements reach the end of their service lives, the materials existing in them can be salvaged and used to construct new pavements. For the past four decades, the material obtained from old pavements, known as reclaimed asphalt pavement (RAP), has been recycled to produce new asphalt pavements. RAP is commonly mixed with various percentages of new aggregates and asphalt binders to produce fresh asphalt mixture pavements. It can also be used in the lower pavement layers (i.e., binder and base layers) to provide improved layer support for traffic loads. Apart from reducing the cost of the new asphalt pavement, asphalt recycling is also an environmentally sound option for pavement rehabilitation.

In the United States, interest in asphalt mixture recycling began in the 1970s, when the nation was hit by an oil embargo. Before that time, the cost involved in removing the existing section and crushing was more than the cost of using virgin material, but the arrival of advanced milling machinery changed the economic balance in favor of recycling. Since then, a number of studies have reported that pavements incorporating RAP performed almost similar to—or even better than—pavements made without RAP (Epps et al. 1997; Kandhal et al. 1995).

Many states have had good experiences with using RAP, but there are still many issues that need to be resolved before deciding to use high percentages of RAP in HMA. Some of the major barriers and technical issues that prevent various states from using high percentages of RAP are stockpile management, availability of RAP, and binder and mix issues. Binder issues are related primarily to bumping grades and properties of the final blend. Mix issues can be further divided into mix design issues and mix performance issues. The contribution of asphalt binder from RAP (i.e., the amount of blending), the volumetrics of asphalt mixture containing RAP, and requirements of any additional testing to predict performance of RAP mixes are the key problems that need further investigation.

Asphalt is a viscoelastic material. It behaves like an elastic material at very low temperatures and like a viscous material at high temperatures. At service temperatures, it exhibits characteristics of both materials, which makes it a more complicated material to understand. As asphalt ages, it becomes harder and stiffer. Although this stiffening increases the resistance of asphalt mixture to deformation, it also becomes prone to thermal and fatigue cracking from increased brittleness. Roberts et al. (1996) described six major mechanisms that contribute to asphalt aging and hardening during its construction and service. These factors include oxidation, volatilization, polymerization, thixotropy, syneresis, and separation.

Asphalt binder properties have a significant influence on asphalt mixture properties. Binder viscosity needs to be sufficiently low at high temperatures to allow the material to be moved through the asphalt mixture plant. It also needs to be sufficiently stiff at the average maximum high in-service temperature so that load-induced deformation (rutting) is minimized. At the same time, the binder needs to be flexible (ductile) at cold temperatures so that thermal cracking is minimized by the material's ability to dissipate stresses through deformation. Incorporation of RAP into asphalt mixture mixes brings with it all the complications related to aged binder.

An extensive amount of work has been published describing methods and strategies of asphalt recycling, their laboratory and field performances, and the binder and mix properties. This literature review focuses on issues related to mix design and performance testing of hot mix asphalt (asphalt mixture) incorporating high percentage of RAP. The literature review is divided into two sections; the first section addresses the incorporation of RAP into asphalt mixture design, and the second section focuses on laboratory performance testing of RAP mixes.

A.2 ASPHALT MIX DESIGN USING RECLAIMED ASPHALT PAVEMENT

An asphalt mixture with RAP poses significant challenges in the design procedure. These challenges arise from the variability of asphalt mixture mixes, aged binder, unknown amount of working binder, and other factors. Though high percentages of RAP have been used with in-place asphalt recycling, there are limits to the percentage of RAP that should be used with in-plant recycling. Except for in-place asphalt recycling on small/country roads, high percentages of RAP are not commonly used in practice because of the variability in RAP.

This variability not only arises from asphalt binder aging but also from finer gradation of RAP aggregates. During the milling process or ripping and crushing, the coarse material gets broken and results in an increase in fine material. The gradation of RAP material is determined by conducting a sieve analysis on the recovered RAP aggregate after binder extraction. When RAP in its original form is added to virgin material, it does not release all of its binders and fine aggregate. Fine aggregate may remain attached to the coarse aggregate and may not contribute to the mix properly. This uncertainty of how much binder and fine aggregate is being released by RAP creates considerable problems in determining the precise volumetrics of asphalt mixture.

The potentially adverse effects of the milling operation can present a problem in meeting SuperPave™ fine graduation requirements. A large amount of fines is detrimental because it can result in insufficient asphalt film thickness, which has been associated with poor mixture durability. The size reduction of the larger aggregate also increases mixture susceptibility to rutting and decreases fatigue life. Currently, this problem is addressed by placing restrictions on the maximum amount of RAP that may be used in the mixture and by blending in virgin aggregate.

It has been suggested by Gardiner and Wagner (1999) that RAP could be split into a coarse and fine fraction to keep a large amount of the dust fraction out of the mix, thereby allowing a higher percentage of RAP to be used. In that study, the finer RAP fraction was used in an above-the-restricted zone, 12.5-mm SuperPave gradation. RAP from two sources (Georgia and Minnesota) was split on a 1.2-mm (No. 16) sieve. Two 12.5-mm SuperPave gradations were selected: one below and the other above the restricted zone. It was observed that screening the RAP allowed up to 40% of the coarse RAP fraction to be used while still meeting the restricted zone SuperPave gradation requirements. This was primarily due to the significant reduction in the finer aggregate fractions, especially the minus 0.075-mm material. The addition of coarser fraction reduced the virgin asphalt requirement by approximately 18% to 33% at different RAP content levels. Although the use of minus No. 16 sieve reduced the virgin asphalt requirement by about 25% for minimum RAP content (15%), it can only be used in limited percentages to produce SuperPave gradation. A maximum of 15% of the fine RAP fraction was used to produce an acceptable above-the-restricted-zone SuperPave gradation.

According to many researchers (Bukowski 1997; Huang et al. 2004; Shah et al. 2007), asphalt mixture designs with low RAP percentages (up to 15%) are not significantly affected by RAP variability; however, higher percentages of RAP can considerably change the overall performance of the asphalt mixture.

Solaimanian and Tahmoressi (1996) wanted to identify the variability in different stockpiles of RAP material and the variability in plant-produced asphalt mixture containing 20% to 50% RAP. Different tests, such as the Hveem stability test, asphalt content determination (Abson recovery and nuclear gauges), gradation of RAP material, density of field cores, theoretical maximum gravity, viscosity, and penetration were conducted. The asphalt mixture projects with a high percentage of RAP studied in that research exhibited a larger variation in asphalt content, gradation, air voids, and stabilities compared with typical asphalt mixture projects without RAP material. The use of a high percentage of RAP did not influence densities as much as it influenced the asphalt content of the plant mix. Projects with higher variation in asphalt binder content of RAP material also had higher variation in asphalt binder of plant mix. Similarly, projects with higher variability in stiffness of RAP binder also showed higher variability in stiffness of plant mix binder. The RAP binder with a higher coefficient of variation in penetration also resulted in a higher coefficient of variation in penetration of plant mix binder. In general, production gradation was finer than the job mix formula target gradation, possibly because of aggregate crushing during the milling operation. It was recommended that high RAP not be used in asphalt mix designs unless variability is controlled.

As described previously, asphalt recycling became more predominant in the 1970s because of the oil embargo. Initially, agencies used RAP as an aggregate source, but the erratic performances of asphalt mixture mixes with RAP soon created the need to determine the proper design of these mixes. In 1989, the Asphalt Institute developed blending charts for incorporating RAP in asphalt mixture design. One of the shortcomings of the SuperPave mix design method was that it did not specifically provide for the use of RAP in mix design. In 1997, Kandhal and Foo developed a procedure for selecting the performance grade (PG) of virgin asphalt binder to be used in recycled mixtures. They recommended using specific-grade blending charts instead of temperature-sweep blending charts. The information necessary to construct a specific-grade blending chart is the $G^*/\sin\delta$ of both the aged asphalt binder and the virgin asphalt binder at the high pavement service temperature.

In 1997, based on past experiences, the Federal Highway Administration's RAP expert task force developed interim guidelines for the design of SuperPave asphalt mixture containing RAP (Bukowski 1997). The developed methodology was based on a tiered approach to determine the level of testing required in the design of asphalt mixture containing RAP. For RAP content less than 15%, there was no adjustment in the virgin binder grade to compensate for the RAP binder's stiffness. For RAP content ranging from 16% to 25%, FHWA suggested using a virgin binder one grade lower (for both high- and low-temperature grades) than the required binder grade. For RAP content greater than 25%, it was recommended that blending charts be used to select the appropriate binder grade. It was also suggested that RAP be handled as aggregate and that RAP binder be considered part of the blended binder. These guidelines are supported by the findings of NCHRP Project 9-12 (McDaniel et al. 2000), which was undertaken to develop guidelines to incorporate RAP in SuperPave mix design. The RAP binder evaluation and mix design using the Superpave system according to this project (McDaniel and Anderson 2001) is detailed next.

A.2.1 SuperPave Mix Design Method

Under the recommended guidelines for using RAP in Superpave mixtures are three tiers of RAP usage. Table 1 shows recommended tiers for Superpave RAP mixtures and the appropriate changes to the binder grade. The limits of these tiers depend on the RAP binder grade. With softer RAP binders, higher percentages of RAP can be used. The first tier establishes the maximum amount of RAP that can be used without changing the virgin binder grade. The second tier shows the percentages of RAP that can be used when the virgin grade is decreased by one grade (a 6-degree increment) on both the high- and low-temperature grades. The third tier is for higher RAP contents. For these higher contents, it is necessary to extract, recover, and test the RAP binder and to construct a blending chart (McDaniel and Anderson 2001).

Table A-1. Binder Selection Guidelines for RAP Mixtures
(McDaniel and Anderson 2001)

	RAP Percentage Recovered RAP Grade		
Recommended virgin asphalt binder grade	PG xx-22 or lower	PG xx-16	PG xx-10 or higher
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG-64-22 would normally be used)	20%–30%	15%–25%	10–15%
Follow recommendations from blending charts	>30%	>25%	>15%

The desired final binder grade, the physical properties (and critical temperatures) of the recovered RAP binder, and the physical properties (and critical temperatures) of the virgin binder, or the percentage of RAP in the mixture are needed to construct a blending chart.

Once the RAP binder has been extracted and recovered, it must be tested in the dynamic shear rheometer (DSR) at a high temperature as if it were an original, unaged binder. This results in a critical high temperature (T_c) at which G*/sinδ is equal to 1.00 kPa:

$$T_c(High) = \left(\frac{\log(1.0) - \log(G_1)}{a} \right) + T_1 \qquad \text{(A-1)}$$

where

G_1 = G*/sinδ at temperature T_1; and

a = slope of the stiffness-temperature curve as Δlog (G*/sinδ)/ΔT.

Then the remaining RAP binder is aged in the rolling thin film oven (RTFO) and is tested in the DSR and bending beam rheometer (BBR). RTFO aged binder is again tested in the DSR to obtain T_c(High) at which G*/sinδ is equal to 2.2 kPa:

$$T_c(High) = \left(\frac{\log(2.2) - \log(G_1)}{a} \right) + T_1 \qquad \text{(A-2)}$$

The high-temperature performance grade of the recovered RAP binder is then determined based on this single critical high temperature. The critical high temperature of the recovered RAP binder is the lower of the original DSR and RTFO DSR critical temperatures. The RTFO+pressure aging vessel (PAV) aged binder is used in determining the critical intermediate temperature $T_c(\text{Int})$ at which G* sinδ is equal to 5000 kPa:

$$T_c(Int) = \left(\frac{\log(5000) - \log(G_1)}{a} \right) + T_1 \qquad \text{(A-3)}$$

where

G_1 = G*sinδ at temperature T_1; and

a = slope of the stiffness–temperature curve as Δlog (G*sinδ)/ΔT.

The RTFO+PAV aged binder is then tested in the BBR to determine the critical low temperature, $T_c(S)$ or $T_c(m)$, based on BBR stiffness or m-value.

$$T_c(S) = \left(\frac{\log(300) - \log(S_1)}{a} \right) + T_1 \qquad \text{(A-4)}$$

$$T_c(m) = \left(\frac{0.300 - m_1}{a} \right) + T_1 \qquad \text{(A-5)}$$

where

S_1 = S-value at temperature T_1;

m_1 = m-value at temperature T_1; and

a = slope of the stiffness-temperature curve as Δlog (S)/ΔT.

The higher of the two low critical temperatures $T_c(S)$ and T_c (m) is selected to represent the low critical temperature for the recovered asphalt binder, $T_c(\text{Low})$. The low-temperature performance grade of the recovered RAP binder is determined based on this single critical low temperature.

Once the physical properties and critical temperatures of the recovered RAP binder are known, two blending approaches may be used. In the first approach, the percentage of RAP that will be used in an asphalt mixture is known, but the appropriate virgin asphalt binder grade for blending must be determined. In the second approach, the maximum percentage of RAP that can be used in an asphalt mixture while still using the same virgin asphalt binder grade must be determined. These two approaches are explained briefly in the following subsections (McDaniel and Anderson 2001).

A.2.2 Blending with a Known RAP Percentage (Virgin Binder Grade Unknown)

If the final blended binder grade, percentage of RAP, and recovered RAP properties are known, then the properties of an appropriate virgin asphalt binder grade can be determined. Using the following equation for the high, intermediate, and low critical temperatures separately, the properties of the virgin asphalt binder necessary to satisfy the assumptions can be determined.

$$T_{Virgin} = \frac{T_{Blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)} \qquad \text{(A-6)}$$

where

T_{Virgin} = critical temperature of the virgin asphalt binder;

T_{Blend} = critical temperature of the blended asphalt binder (final desired);

%RAP = percentage of RAP expressed as a decimal (i.e., 0.30 for 30%); and

T_{RAP} = critical temperature of recovered RAP binder.

A blending chart, shown as Figure A-1, can be used instead of Equation A-6.

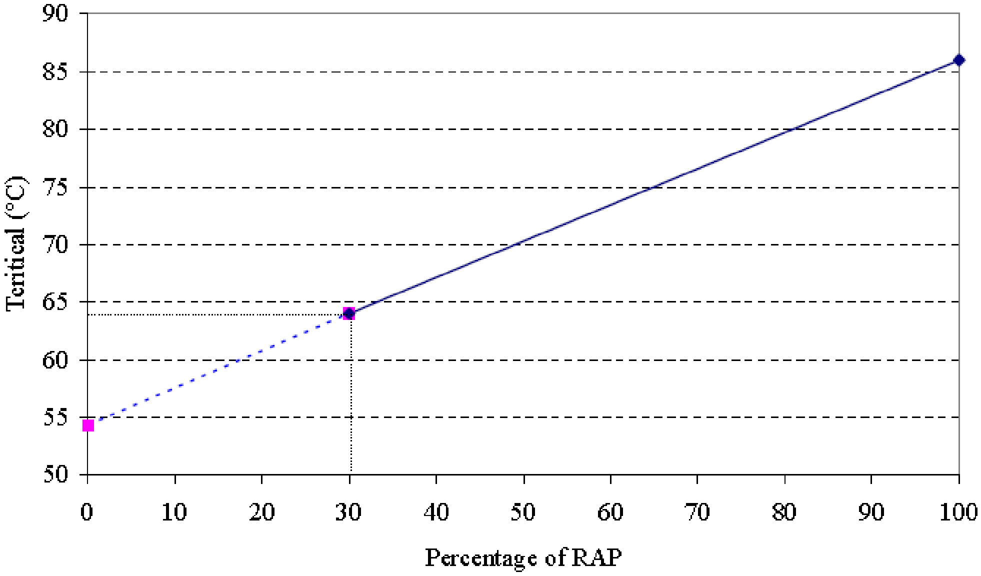

Figure A-1. High-temperature blending chart (RAP percentage known) (McDaniel et al. 2000)

A.2.3 Blending with a Known Virgin Binder Grade (RAP Percentage Unknown)

If the binder grade is fixed based on economics and availability or on the specifications for a given project, it is necessary to determine the amount of RAP that can be used with the specific virgin binder grade and still meet the final blended binder properties. The construction of a blending chart to determine RAP content is described next.

If the final blended binder grade, virgin asphalt binder grade, and recovered RAP properties are known, then the appropriate amount of RAP to use can be determined. Using the following equation for the high, intermediate, and low critical temperatures separately, the percentage of RAP required to satisfy the assumptions can be determined.

$$\%RAP = \frac{T_{Blend} - T_{Virgin}}{T_{RAP} - T_{Virgin}} \qquad \text{(A-7)}$$

where all terms are as previously defined.

Figure A-2 shows the graphical method for determining the RAP percentage to be used in asphalt mixture mix.

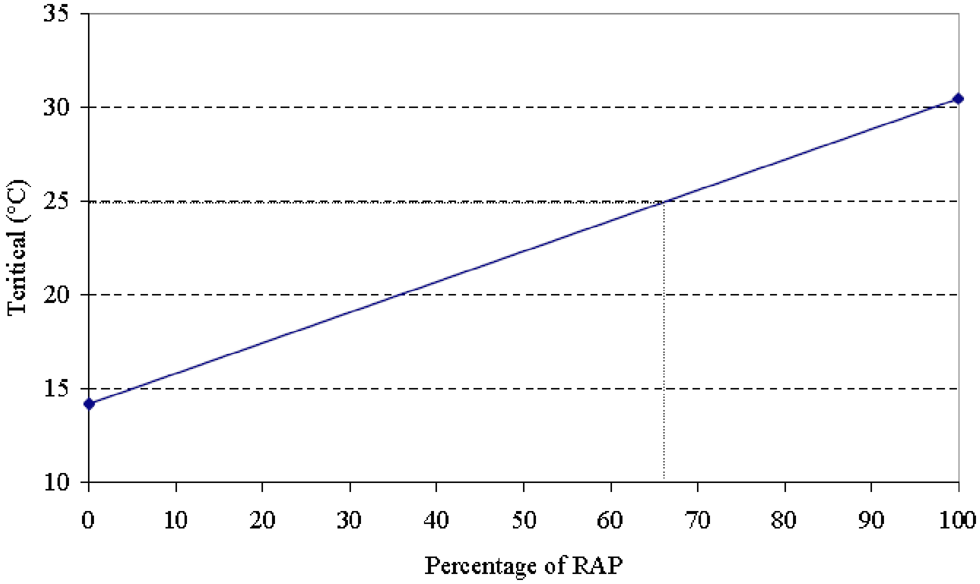

Figure A-2. Intermediate temperature blending chart (RAP percentage unknown) (McDaniel et al. 2000)

A.2.4 Developing the Mix Design

The amount of RAP to be included in the new asphalt mixture may be limited by two main factors: material-related factors and production-related factors. These factors include specification limits for mix type; plant type; gradation; aggregate consensus properties; binder properties; heating, drying, and exhaust capacity of the plant; moisture content of the RAP and virgin aggregates; temperature to which the virgin aggregate must be superheated; ambient temperature of the RAP; and virgin aggregate (McDaniel and Anderson 2001).

Overall, however, the process of using RAP in SuperPave mixtures is similar to that of using RAP in Marshall or Hveem mixtures. The blend of materials has to meet certain properties, and the plant must be capable of drying and heating the materials. Many of the techniques used to evaluate the RAP are similar to previous techniques. A detailed procedure for developing mix design involving RAP, along with examples, is described in NCHRP Report 452 (McDaniel and Anderson 2001).

To account for the presence of binder in the RAP material, the weight of RAP aggregate is calculated as follows (McDaniel and Anderson 2001):

$$M_{dry(RAP)} = \frac{M_{RAP(Agg)}}{(100 - P_b)} \times 100 \qquad \text{(A-8)}$$

where

$M_{dry(RAP)}$ = mass of dry RAP;

$M_{RAP(Agg)}$ = mass of RAP aggregate (including RAP binder); and

P_b = RAP binder content.

Equation A-8 is used when the amount (percentage) of RAP used in a mix is taken as the amount of RAP aggregate instead of the RAP (including binder) itself. It is important to note that in the study, IDOT's method of incorporating RAP was adopted (i.e., the percentage of RAP represents the actual RAP, including binder, not the RAP aggregate). For example, if 15% RAP is used with a particular asphalt content, then the actual aggregate contribution by RAP to the total aggregate blend will be less than 15%.

A.2.5 Issues with Specific Gravities and VMA

The bulk specific gravity of each aggregate stockpile, including the RAP aggregate, must be determined in order to calculate the bulk specific gravity of the combined aggregates. It is difficult to precisely measure the bulk specific gravity of the extracted RAP aggregate because of changes in aggregate gradation and properties due to the extraction process. NCHRP Report 452 (McDaniel and Anderson 2001) noted that few states used RAP effective specific gravity (G_{se}) instead of bulk specific gravity. G_{se} is determined using following equation:

$$G_{se} = \frac{100 - P_b}{\dfrac{100}{G_{mm}} - \dfrac{P_b}{G_b}} \qquad \text{(A-9)}$$

where

G_{mm} = theoretical maximum specific gravity;

$G_{b(RAP)}$ = specific gravity of RAP binder;

$P_{b(RAP)}$ = RAP binder content;

G_{se} = effective specific gravity of aggregate;

G_{sb} = bulk specific gravity of aggregate.

The methodology recommended in NCHRP Report 452 (McDaniel and Anderson 2001) consists of assuming a value for absorption of the RAP aggregate. Some states estimate this value quite accurately based on past experience. The G_{sb} of the RAP aggregate can be calculated based on this assumed absorption using Equation A-10. This G_{sb} value can then be used to estimate the combined aggregate bulk specific gravity and to calculate VMA.

$$G_{sb} = \frac{G_{se}}{\left(\dfrac{P_{ba}G_{se}}{100G_b} + 1\right)} \qquad \text{(A-10)}$$

where

P_{ba} = absorbed binder, percentage by weight of aggregate.

Recently, Hajj et al. (2008) concluded that using G_{se} instead of G_{sb} resulted in overestimating both the combined aggregate bulk specific gravity and the VMA, since for a given aggregate G_{sb} is always smaller than G_{se}. For instance, when the G_{se} of RAP is used in lieu of G_{sb}, the calculated VMA value will often change by 0.3% per 10% of RAP used, a one-tenth reduction in the optimum binder content, leading to dry mixes when designing to minimum VMA. This introduced error will be greater when higher percentages of RAP are used. For this reason, some states that allow the use of G_{se} for the RAP aggregate also increase their minimum VMA requirements to account for this error. Kvasnak et al. (2010) also recommended determining RAP G_{sb} by using the G_{mm} method when a known regional absorption is available. If a regional absorption is not available, then the RAP G_{sb} should be determined from extracted aggregate.

The following is a summary of a test method for measuring the bulk specific gravity of RAP aggregates. The method is used by IDOT and was introduced by Murphy Pavement Technology.

After determining the binder content of the RAP material (P_b) according to AASHTO T164, the maximum theoretical specific gravity (G_{mm}) of a RAP sample is determined after mixing with a 1% virgin asphalt binder by dry weight of RAP. The 1% asphalt binder is added to the RAP mixture to ensure a uniform coating of all particles. Then the adjusted P_b of the RAP mixture is calculated to account for the 1% virgin asphalt binder added. The effective specific gravity (G_{se}) of the RAP aggregate is calculated using Equation A-11.

$$G_{se} = \frac{100 - Adjusted\ P_b}{\dfrac{100}{G_{mm}} - \dfrac{Adjusted\ P_b}{1.040}} \tag{A-11}$$

The aggregate bulk specific gravity (G_{sb}) of the RAP aggregate is then calculated using Equation A-12.

$$G_{sb}(RAP) = G_{se}(RAP) - 0.100 \tag{A-12}$$

Hajj et al. (2008) recommended that if the test method proposed by Murphy Pavement Technology is used, then the proposed equation that correlates G_{sb} to G_{se} (Equation 12) must first be validated since it will be most likely influenced by aggregate absorption and geological formations within each region/state.

Al-Qadi et al. (2009) investigated the effect of the amount of reclaimed asphalt pavement (RAP) on the volumetric and mechanical properties of hot-mix asphalt (HMA). Six different job mix formulae (JMFs) were designed with two materials to investigate the effect of RAP variation on asphalt mixtures. It was observed that optimum asphalt content for mix designs with different percentages of RAP was not significantly changed. VMA at optimum asphalt content had opposite trends for two materials. For one material, VMA decreased with an increase in RAP percentage, but it showed an opposite trend for the other material. In another study, by West et al. (2009), VMA showed a decreasing trend with an increase of RAP percentage. The optimum asphalt contents of the mixtures were also decreased by 1% with an increase in RAP from 0% to 45%. Kim et al. (2009) also demonstrated the similar results (i.e., a decrease in optimum asphalt content and VMA with an increase in RAP amount). The study by Mogawer et al. (2009) showed the same trend.

Daniel and Lachance (2005) observed some contrary results in their study on RAP. They observed that the VMA and VFA of the RAP mixtures increased at 25% and 40% levels. They hypothesized that the difference between VMA values was due to the extent of blending of the RAP material with the virgin materials. They observed that there is an optimum heating time for the RAP material to allow for the greatest extent of blending between the virgin and RAP materials. The influence of pre-heating time of asphalt mixture with RAP on the volumetric properties of mixes was also evaluated. The VMA decreases by 0.5% when the heating time increases from 2 to 3.5 hr and then increases by almost 3% with a heating time of 8 hr. At the shorter heating time, the RAP is not heated enough to allow RAP particles to break up into smaller pieces and blend with the virgin materials. With the longer heating time, the RAP has likely aged further, its particles have hardened, and even fewer of them are able to break down and blend with the virgin material. They concluded that a RAP mixture may not meet the SuperPave VMA requirements when the RAP is heated for a particular amount of time, but the mixture may meet the requirements if the RAP is heated for a different amount of time. Hajj et al. (2008) also observed similar increasing trends in VMA and VFA with an increase in RAP percentages.

The purpose of the above discussion was to highlight asphalt mix design problems. Conflicting results from different studies show that emphasis should be put on studying the variation in volumetrics when using RAP in an asphalt mixture.

A.3 LABORATORY EVALUATION AND PERFORMANCE TESTING OF RAP MIXTURES

To determine the potential benefits and adverse effects of RAP, researchers looked at various performance measures of RAP mixtures, such as rutting and cracking. HMA pavements are designed to resist traffic and environmental loading for a specific period of time. Traffic loading as well as aging of the asphalt binder lead to deterioration of pavement and significantly affect pavement performance. After pavement is removed from the field, RAP materials age even further during the stockpiling process due to the exposure to air. Moreover, when RAP is added to HMA, the aged binder in the RAP mixes to some unknown degree with the virgin binder. This produces a composite effective binder system with unknown material properties and, hence, unpredictable pavement performance.

Huang et al. (2005) investigated the uncertainties caused by the unknown degree of blending of RAP binder with virgin binder. A lab study was conducted in which the blending process of RAP with virgin mixture was analyzed through controlled experiments. One type of screened RAP was blended with virgin (new) coarse aggregate at different percentages. A blended mixture containing 20% of screened RAP was subjected to staged extraction and recovery. The results from this experiment indicated that only a small portion of aged asphalt in RAP actually participated in the remixing process; other portions formed a stiff coating around RAP aggregates and RAP functionally acted as “composite black rock.” The resulting composite layered structure was desirable in improving the performance of the asphalt mixture.

Numerous studies on RAP have indicated that addition of RAP to an asphalt mixture changes the physical behavior of the mix. The increased stiffness of the RAP binder is believed to be the cause of increased modulus of asphalt mixture mixes. Similarly, it also affects the fatigue behavior and low-temperature cracking of the mixes. The effect of added RAP on asphalt mixture laboratory performance has been studied by many researchers. In the Gardiner and Wagner (1999) discussed above, low-temperature properties were tested using the SuperPave indirect tensile creep test at 0°C, –10°C, and –20°C. The rutting potential was also determined with an Asphalt Pavement Analyzer (APA). They also used a resilient modulus test to evaluate temperature susceptibility of the mixes at three temperatures (4°C, 25°C, and 40°C). They found that inclusion of RAP decreased rutting potential and temperature susceptibility and increased the potential for low-temperature cracking. The addition of RAP approximately doubled the stiffness at warmer temperatures, but this increase was minimal at lower temperatures. They observed that the increase in RAP was also accompanied by an increase in tensile strength ratio (TSR).

Tam et al. (1992) looked into the thermal cracking of recycled hot mix (RHM) and confirmed that RHM is less resistant than nonrecycled mixes to thermal cracking. The thermal cracking properties of laboratory and field mixes were analyzed using McLeod's limiting stiffness criteria and the pavement fracture temperature (FT) method. When the induced stress or strain, because of temperature drop, exceeds the failure stress or strain, cracking is expected to occur. The corresponding temperature is called the FT. The higher the FT of a material, the lower its resistance to thermal cracking. RHM specimens were produced from plant mixes and individual mix components in the laboratory. Tam et al. (1992) came up with a few suggestions to minimize low-temperature cracking and more accurately predict fracture temperature. They suggested limiting recycling ratios to 50:50 and selecting an appropriate virgin asphalt binder for a desirable recovered mix penetration.

To compare mixtures compacted with only virgin materials to those compacted with varying amounts of RAP, Sondag et al. (2002) measured the resilient modulus for 18 different mix designs. These mixtures incorporated three different asphalt binders, two sources of RAP, and varying amounts of RAP. The RAP from one source (District 6) was coarser than the other (District 8). The study showed that at 25°C, adding 40% District 6 RAP to a PG 58-28 control mixture resulted in a 74% increase in stiffness and a 164% increase with a PG 46-40 control mixture. A similar increase was observed with the addition of District 8 RAP. Therefore, the addition of RAP increased the resilient modulus. The RAP source also affected the resilient modulus results. The District 8 RAP binder had a higher PG grade than the District 6 RAP, and accordingly yielded a higher resilient modulus.

McDaniel and Shah (2003) and McDaniel at el. (2002) conducted a laboratory study to determine if the tiered approach of the FHWA and SuperPave RAP specifications are applicable to Midwestern materials obtained from Indiana, Michigan, and Missouri. The experimental program consisted of first comparing laboratory mixtures to plant-produced mixes containing the same RAP content and source, virgin aggregates, and binder. Additional samples were prepared in the laboratory with a RAP content of up to 50% to determine the effect of recycled materials on the mix performance. Prepared mixes were tested using the SuperPave Shear Tester (SST). Results of this study indicated that plant-produced mixes were similar in stiffness to laboratory mixtures at the same RAP content for the Michigan and the Missouri samples. The plant-produced mixes from Indiana were significantly stiffer than the lab mixes. Analysis of the SST data also indicated an increase in stiffness and decrease in shear deformation as the RAP content increased, but it also increased the potential for fatigue and thermal cracking. This indicates that higher RAP content mixtures (with no change in binder grade) would exhibit more resistance to rutting, provided that the aggregates are of acceptable quality. Testing conducted for the NCHRP 9-12 study confirmed that recycled mixtures with RAP content greater than 20% had a lower fatigue life than virgin mixtures (McDaniel et al. 2000). Decreasing the virgin binder grade may be an option to improve the mixture fatigue performance, especially at high RAP content. The authors also emphasized that designing mixtures that conform to SuperPave specifications may not be feasible at a RAP content greater than 40% to 50% due to the high fine content in RAP materials.

In a study by Pereira et al. (2004), the repeated simple shear test at constant height (RSST-CH) and four-point bending fatigue test were used to determine the rutting and fatigue behavior of 50% RAP mix and a control mix (no RAP). The RSST-CH tests were conducted at 50°C. Of the three asphalt contents (4.5%, 5%, and 5.5%), the HMA with RAP having 4.5% binder content exhibited the maximum resistance to permanent deformation. Generally, all the recycled mixes showed better behavior than the control mix without RAP. The authors observed improvement in fatigue resistance of RAP mixtures with 5% asphalt content compared to 4.5% asphalt content, but no further improvement was noticed with asphalt content of 5.5%. Thus, it was concluded that an increase in bitumen content did not significantly increase fatigue resistance.

Huang et al. (2004) evaluated fatigue resistance of HMA containing No. 4 sieve-screened RAP. A typical surface mixture commonly used in Tennessee was evaluated at 0%, 10%, 20%, and 30% RAP content. Fatigue characteristics of mixtures were evaluated with the indirect tensile strength test, semi-circular bending (SCB) test, semi-circular fatigue test, and semi-circular notched specimen fracture test. They found that long-term aging influenced the ranking of fatigue characteristics for mixtures containing different percentages of RAP. Generally, long-term aged mixtures more closely resembled the properties of field mixtures that had been in service for several years. Also, inclusion of RAP into the limestone surface mixture generally increased tensile strength, reduced post-failure tenacity, increased the mixture's modulus (stiffness), and reduced viscosity characteristics. In the study, total dissipated energy to failure at 20% of SCB tensile strength also indicated that inclusion of RAP generally increased fatigue life for unaged mixtures, whereas for long-term aged mixtures, dissipated energy increased with inclusion of 20% RAP and dropped to the same level as the mix without RAP. The inclusion of RAP in the mixtures improved the mixtures' resistance to fracture failure. The inclusion of less than 20% of RAP material had very limited influence on mixture stiffness and indirect tensile strength characteristics. The inclusion of a high percentage (30%) of RAP tended to significantly change the mixtures' fatigue cracking characteristics.

Focusing on the same objective to determine the effect of adding RAP on the volumetric and mechanistic properties of HMA, Daniel and Lachance (2005) conducted a study on different HMAs with RAP. They used a 19-mm SuperPave mixture containing no RAP as a control mix for evaluating properties of mixes containing 15%, 25%, and 40% RAP. Testing included complex modulus in tension and compression, creep compliance in compression, and creep flow in compression. The complex modulus of the processed RAP mixtures increased from the control to the 15% RAP level. Unexpectedly, however, the 25% and 40% RAP mixtures had complex modulus curves similar to the control mixture in both tension and compression. The creep compliance curves showed similar trends. A combination of gradation, asphalt content, and volumetric properties was identified as the cause of these unexpected trends.

To assess the feasibility of utilizing a high proportion of RAP in asphalt mixture, Widyatmoko (2008) prepared wearing and base course mixes with 10%, 30%, and 50% RAP. One of the asphalt mixture properties measured was deformation resistance, for which two tests were carried out. The repeated load axial test (RLAT) was carried out at 40°C (104°F) in the Nottingham Asphalt Tester (NAT). The wheel track test (WTT) was carried out under a wheel load of magnitude 520 N (117 lb) at 60°C (140°F). Contrary to norm, it was found that mixtures containing RAP show lower resistance to permanent deformation (i.e., greater WTT rut depth, WTT rut rate, and/or RLAT strain) compared with equivalent mixtures without RAP. They also noticed a reduction in stiffness with an increase in RAP content. This behavior was explained by the fact that with an increase of RAP percentage, more rejuvenators or softer binder are added to the mix—resulting in a softer mix. For same reasons, the RAP mixes showed at least similar or better fatigue resistance than mixes without RAP. It was also concluded that these mixes with RAP were not susceptible to moisture damage (stiffness ratio > 0.8).

Chehab and Daniel (2006) studied the sensitivity of the predicted performance of RAP mixtures to the assumed binder. This was accomplished with Mechanistic-Empirical Pavement Design Guide (MEPDG) software to predict performance of a specific flexible pavement structure with a RAP-modified asphalt mixture surface layer. In the study, RAP content and effective binder PG grade were the main variables. They found that alligator cracking was not significant in the analysis, possibly due to a thick test section and low truck traffic. The RAP mixes showed a lower predicted amount of longitudinal cracking after 10 yr than the asphalt mixture mix, but none reached the failure limit. The amount of cracking was higher for 40% RAP than for the other two RAP mixes. It was predicted that increasing the amount of RAP would result in more transverse cracking. The authors observed a slight increase in rutting with an increase in RAP content from 15% to 25%, which may be due to the higher asphalt content in the 25% RAP mixture, which offset the increase in stiffness. For the mix with 40% RAP, the amount of rutting was lowest, as expected. The authors also concluded that the assumed PG binder grade, particularly the high temperature grade, for the RAP mixtures had a significant influence on the predicted amount of thermal cracking and rutting performances. The results emphasized the importance of determining the effective binder grade of RAP mixtures.

Shah et al. (2007) conducted a study to investigate the effects of RAP content on virgin binder grade and to determine the properties of plant-produced mixtures. RAP was added at 15%, 25%, and 40% levels to an asphalt mixture with PG 64-22 and at 25% and 40% levels to an asphalt mixture with PG 58-28 binder. In addition, control mixture samples with PG 64-22 and no RAP were collected and tested for comparison. The results from complex modulus (|E*|) testing showed no increase in stiffness with the addition of 15% RAP compared with the control mix. However, the addition of 25% and 40% RAP resulted in an increase in the modulus. No significant change in stiffness was observed from a change in binder grade at higher RAP levels except for a slight lowering in moduli with respect to the control mix at higher frequencies. Indirect tensile strength results showed that mixes with higher strength also generally showed higher stiffness values. The mix with the highest RAP content had the highest strength and stiffness, and, hence, the warmest critical temperature. It was also observed that the stiffness of the binder changed only 3%, not the 40% (RAP added), which showed that combined properties of the binder did not change linearly based on the proportion of old and new binders as claimed earlier (McDaniel et al. 2000).

Carter and Gardiner (2007) developed a simple indirect tension stress relaxation test method and analysis approach for assessing binder-related asphalt mixture properties. The objective was to evaluate the effect of adding RAP to HMA on relaxation modulus and rate of relaxation. A total of 160 different asphalt mixture combinations of binders, aggregates, and RAP were compacted and tested using indirect tension stress relaxation at 5°C and 22°C. Two experiments were conducted. The first experiment was developed to compare binder stress relaxation modulus to the asphalt mixture indirect tension (IDT) stress relaxation modulus. Constant strain parallel plate testing was used to develop stress relaxation master curves for the virgin binders (PG 64-22 and PG 76-22). The asphalt mixture stress relaxation modulus was determined using a test method developed for the study. The binder relaxation master curves were compared to those for the HMA. The second experiment was designed to determine if the asphalt mixture indirect tension stress relaxation approach (developed and refined during the first experiment) was sensitive to changes in the mix binder, such as those anticipated with increasing percentages of RAP. Two relaxation characteristics from a power law fit through the data were used to define the effect of RAP on properties related to asphalt mixture binder: the initial modulus at 1 s (regression constant) and the curvature coefficient (regression exponent). The results showed a nonlinear relationship between both the initial modulus and the curvature coefficient and the percentage of RAP from 0% to 100% RAP. A linear relationship could be obtained only between the properties and the percentage of RAP between 0% and 50%. There is little change in either the initial modulus or curvature coefficient for asphalt mixture mixes with 50% or more RAP.

Li et al. (2008) investigated the effect of RAP percentage and sources on the properties of HMA by performing complex modulus and semi-circular beam (SCB) tests. Ten laboratory-prepared HMAs were studied using three RAP percentages (0%, 20%, and 40%). The mixes were fabricated using two RAP sources and two asphalt binders (PG 58-28 and PG 58-34). One of the RAPs had a single source; the other consisted of RAP collected from different pavements and blended in a single pile at the mixing plant. The authors observed that the HMAs containing RAP had higher complex modulus values than the control mixtures containing no RAP. At high temperatures, the HMAs containing 40% RAP were found to have higher or similar complex moduli as mixtures with 20% RAP. On the contrary, most mixtures containing 20% RAP were observed to have the highest complex modulus at lower temperatures or high frequencies. To explain the behavior of asphalt mixture at low temperatures, the authors hypothesized that the aged and brittle binder in the RAP resulted in the formation of microcracks. The stiffer asphalt binder was found to result in a higher complex modulus for both the control and the RAP-modified mixtures. Experimental data also showed that the RAP source was not a significant factor for complex modulus values at low temperatures, though it significantly affected the complex modulus values at high temperatures. The fracture resistance was significantly affected by the testing temperature and the percentage of RAP in the mixtures. Fracture testing results indicated that 20% RAP-modified mixtures exhibited similar fracture resistance abilities to the control mixtures, which had the highest fracture energies. The addition of 40% RAP significantly decreased low-temperature fracture resistance. At low temperatures, RAP source did not significantly affect fracture resistance of the HMA. Finally, no significant statistical relationship between complex modulus and fracture energy was found.

To evaluate and compare fatigue performance of HMA with RAP, Shu et al. (2008) prepared four asphalt mixtures consisting of 0%, 10%, 20%, and 30% RAP with one source of aggregate (limestone) and one type of binder (PG 64-22). The fatigue properties tested included indirect tensile strength (ITS), failure strain, toughness index (TI), resilient modulus, dissipated creep strain energy ($DCSE_f$), energy ratio, plateau value, and load cycles to failure. They observed that inclusions of RAP into HMA generally increased tensile strength and reduced post-failure tenacity in indirect tensile strength tests. The inclusion of RAP also generally decreased the $DCSE_f$ threshold and energy ratio calculated from IDT tests, which may result in the short fatigue life of HMA. Lower $DCSE_f$ values mean that the energy required to fracture the asphalt mix mixtures decreased as RAP percentage increased. The energy ratio concept is more reasonable than $DCSE_f$ for characterizing the cracking resistance of HMA because it takes into account both the energy required to fracture HMA and the dissipated energy accumulation in HMA under certain loading conditions. Based on the failure criterion of 50% reduction in stiffness (obtained from the beam fatigue test), incorporation of RAP increased the fatigue life of HMA, whereas based on plateau values from the beam fatigue test, inclusion of RAP would turn more input energy into damage, which may result in the shorter fatigue life. The plateau value failure criterion appeared more reasonable in evaluating fatigue performance of HMA. It was concluded that both SuperPave IDT and beam fatigue test results agreed in ranking fatigue resistance of mixtures when proper procedures were followed.

One of the primary concerns about using RAP is its effect on mixture durability. Moisture susceptibility is regarded as the main cause of poor mixture durability. Moisture susceptibility can be evaluated by performing stability, resilient modulus, or tensile strength tests on unconditioned and moisture conditioned samples. Gardiner and Wagner (1999) used the tensile strength ratio (ratio of unconditioned tensile strength and moisture-conditioned tensile strength) to evaluate moisture sensitivity. They showed that the inclusion of coarse RAP decreased moisture susceptibility. Sondag et al (2002) used the tensile strength ratio to evaluate the moisture sensitivity for 18 different mix designs incorporating three different asphalt binders, two sources of RAP and varying amounts of RAP. He found that the addition of RAP to a mixture had no positive or negative influence on the mixture moisture susceptibility. The properties of aged binder are also affected by the level of moisture damage on the existing pavement prior to recycling. In principle, stripped asphalt mixture should not be recycled due to the probability of reoccurrence of this distress in the new asphalt mixture (Karlsson and Isacsson 2006). However, when a small percentage of RAP is used (15 to 20%) together with an anti-strip agent, samples with moisture-damaged asphalt mixture provided a comparable strength and moisture resistance to samples made with virgin materials (Amirkhanian and Williams 1993).

APPENDIX B MIXTURE DESIGN

Table B-1. Job Mix Formula for District 1 Control (0% RAP) Mix

High RAP D1 N90 Control Mix	Design Target 4	1-point	Binder Opt. (–0.5%)	Binder Opt. (Optimum)	Binder Opt. (+0.5%)
Blend Percentages					
Adjusted for DCF?	No	Yes (0.4)	—	—	—
CM11	43.2	43.4	43.4	43.4	43.4
CM16	27.1	27.2	27.2	27.2	27.2
FM20	28.5	28.6	28.6	28.6	28.6
FM22	—	—	—	—	—
+3/8-in RAP	—	—	—	—	—
–3/8-in RAP	—	—	—	—	—
Mineral Filler	1.2	0.8	0.8	0.8	0.8
Total Aggregate	100.0	100.0	100.0	100.0	100.0
Percent Asphalt		4.8	4.5	5.0	5.5
Percent Aggregate	100.0	95.2	95.5	95.0	94.5
Bulk Specific Gravities					
CM11	2.711	2.711	2.711	2.711	2.711
CM16	2.659	2.659	2.659	2.659	2.659
FM20	2.697	2.697	2.697	2.697	2.697
FM22	—	—	—	—	—
+3/8-in RAP	—	—	—	—	—
–3/8-in RAP	—	—	—	—	—
Mineral Filler	2.900	2.900	2.900	2.900	2.900
Combined G_{sb}	2.695	2.695	2.695	2.695	2.695
Percent Passing from Washed Gradations					
1 in	100.0	100.0	100.0	100.0	100.0
3/4 in	96.1	96.1	96.1	96.1	96.1
1/2 in	75.6	76.2	76.1	76.1	76.1
3/8 in	64.5	65.3	65.4	65.4	65.4
No. 4	39.5	40.8	40.9	40.9	40.9
No. 8	27.5	28.0	28.2	28.2	28.2
No. 16	17.8	18.3	18.5	18.5	18.5
No. 30	12.3	12.8	13.1	13.1	13.1
No. 50	8.3	8.7	8.8	8.8	8.8
No. 100	6.2	6.2	6.2	6.2	6.2
No. 200	4.6	4.7	4.7	4.7	4.7

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Table B-1 (continued). Job Mix Formula for District 1 Control (0% RAP) Mix

Volumetrics					
G_{mb} 1 Dry Wt.	—	4912.1	4909.1	4931.3	4954.8
G_{mb} 1 Submerged Wt.	—	2888.4	2902.7	2926.8	2941.7
G_{mb} 1 SSD Wt.	—	4928.8	4922.2	4940.0	4960.3
G_{mb} 2 Dry Wt.	—	4916.2	4908.5	4931.6	4950.6
G_{mb} 2 Submerged Wt.	—	2896.7	2900.8	2923.5	2944.4
G_{mb} 2 SSD Wt.	—	4929.7	4920.8	4941.5	4958.2
G_{mb} 1	—	2.407	2.431	2.449	2.455
G_{mb} 2	—	2.418	2.430	2.444	2.458
Average G_{mb}	—	2.413	2.430	2.447	2.456
G_{mm} 1 Dry Wt.		2612.9	2605.5	2621.1	2632.0
G_{mm} 1 Pyc in Water Wt.		7657.3	7657.3	7657.3	7657.3
G_{mm} 1 Pyc + Sample in Water Wt.		9247.1	9245.9	9246.9	9247.0
G_{mm} 2 Dry Wt.		2611.2	2606.5	2622.6	2632.5
G_{mm} 2 Pyc in Water Wt.		7657.3	7657.3	7657.3	7657.3
G_{mm} 1 Pyc + Sample in Water Wt.		9244.4	9249.1	9247.5	9245.8
G_{mm} 1		2.554	2.562	2.541	2.525
G_{mm} 2		2.550	2.569	2.540	2.522
Average G_{mm}			2.565	2.541	2.524
G_b		1.03	1.03	1.03	1.03
G_{se}			2.759	2.754	2.757
Voids			5.2	3.7	2.7
VMA		14.8	13.9	13.7	13.9
VFA			62.2	73.0	80.7
Dust / Binder			1.0	0.9	0.9
P_{ba}			0.9	0.8	0.9
Effective Binder			3.7	4.2	4.7
Dust / Effective Binder			1.3	1.1	1.0
$N_{initial}$			8.0	8.0	8.0
N_{design}			90.0	90.0	90.0
Height 1 at $N_{initial}$					
Height 2 at $N_{initial}$					
Average Height at $N_{initial}$			—	—	—
Height 1 at N_{design}					
Height 2 at N_{design}					
Average Height at N_{design}			—	—	—
% of G_{mm} at $N_{initial}$			—	—	—

Table B-2. Volumetrics for District 1
Control Mix Design

D1-Control Mix Design Volumetrics Summary		
Volumetrics		IDOT Specifications
Binder (%)	4.9	—
Air Voids (%)	4.0	4
VMA (%)	13.7	13 (minimum)
VFA (%)	70.8	65–75
G_{mm}	2.546	—
G_{mb}		—
G_{se}	2.756	—

Table B-3. Job Mix Formula for District 1 30% RAP Mix

High RAP D1 N90 30% RAP Mix	Design Target	Binder Opt. (0.5%)	Binder Opt. (Optimum)	Binder Opt. (+0.5%)
Blend Percentages				
Adjusted for DCF?	Yes			
CM11	37.7	37.7	37.7	37.7
CM16	12.5	12.5	12.5	12.5
FM20	8.5	8.5	8.5	8.5
FM22	10.5	10.5	10.5	10.5
+3/8-in RAP	15.0	15.0	15.0	15.0
–3/8-in RAP	15.0	15.0	15.0	15.0
Mineral Filler	0.8	0.8	0.8	0.8
Total Aggregate	100.0	100.0	100.0	100.0
Percent Asphalt		4.3	4.8	5.3
Percent Aggregate	100.0	95.7	95.2	94.7
Bulk Specific Gravities				
CM11	2.711	2.632	2.632	2.632
CM16	2.659	2.620	2.620	2.620
FM20	2.697	2.635	2.635	2.635
FM22	2.669	2.669	2.669	2.669
+3/8-in RAP	2.687	2.627	2.627	2.627
–3/8-in RAP	2.671	2.641	2.641	2.641
Mineral Filler	2.900	2.900	2.900	2.900
Combined G_{sb}	2.691	2.691	2.691	2.691

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Table B-3 (continued). Job Mix Formula for District 1 30% RAP Mix

1 in	100.0	99.5	99.5	99.5
3/4 in	96.1	95.9	95.9	95.9
1/2 in	75.9	76.3	76.3	76.3
3/8 in	63.7	64.8	64.8	64.8
No. 4	38.0	38.4	38.4	38.4
No. 8	23.2	23.4	23.4	23.4
No. 16	16.2	16.3	16.3	16.3
No. 30	12.4	12.6	12.6	12.6
No. 50	9.4	9.6	9.6	9.6
No. 100	6.8	7.0	7.0	7.0
No. 200	5.4	5.7	5.7	5.7
Volumetrics				
G_{mb} 1 Dry Wt.	—	4821.0	4840.2	4863.9
G_{mb} 1 Submerged Wt.	—	2853.3	2871.1	2882.9
G_{mb} 1 SSD Wt.	—	4836.2	4853.7	4873.8
G_{mb} 2 Dry Wt.	—	4819.9	4846.7	4868.8
G_{mb} 2 Submerged Wt.	—	2843.9	2873.0	2885.6
G_{mb} 2 SSD Wt.	—	4837.8	4856.4	4875.6
G_{mb} 1	—	2.431	2.441	2.443
G_{mb} 2	—	2.417	2.444	2.447
Average G_{mb}	—	2.424	2.442	2.445
G_{mm} 1 Dry Wt.		2560.2	2572.6	2586.2
G_{mm} 1 Pyc in Water Wt.		7657.3	7657.3	7657.3
G_{mm} 1 Pyc + Sample in Water Wt.		9219.8	9219.7	9223.4
G_{mm} 2 Dry Wt.		2567.1	2572.9	2589.4
G_{mm} 2 Pyc in Water Wt.		7657.3	7657.3	7657.3
G_{mm} 1 Pyc + Sample in Water Wt.		9221.3	9220.9	9223.5
G_{mm} 1	—	2.566	2.547	2.535
G_{mm} 2	—	2.559	2.549	2.531
Average G_{mm}	—	2.563	2.548	2.533
G_{b}	—	1.03	1.03	1.03
G_{se}	—	2.747	2.753	2.758
Voids	—	5.4	4.2	3.5
VMA	—	13.8	13.6	14.0
VFA	—	60.7	69.4	75.1
Dust / Binder	—	1.3	1.2	1.1
P_{ba}		0.78	0.86	0.94
Effective Binder		3.6	4.0	4.4

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Table B-3 (continued). Job Mix Formula for District 1 30% RAP Mix

Dust / Effective Binder		1.6	1.4	1.3
$N_{initial}$		8.0	8.0	8.0
N_{design}		90.0	90.0	90.0
Height 1 at $N_{initial}$		130.98	131.12	132.09
Height 2 at $N_{initial}$		132.47	130.96	131.17
Average Height at $N_{initial}$		131.725	131.04	131.63
Height 1 at N_{design}		116.55	116.56	117.06
Height 2 at N_{design}		118.19	116.63	116.55
Average Height at N_{design}		117.37	116.595	116.81
% of G_{mm} at $N_{initial}$		84.3	85.3	85.7

Table B-4. Volumetrics for District 1 Mix Design with 30% RAP

D1-30% RAP Mix Design Volumetrics Summary		
Volumetrics		IDOT Specifications
Binder (%)	4.9	—
Air Voids (%)	4.0	4
VMA (%)	13.6	13 (minimum)
VFA (%)	70.7	65–75
G_{mm}	2.545	—
G_{mb}	2.444	—
G_{se}	2.752	—

Table B-5. Job Mix Formula for District 1 40% RAP Mix

High RAP D1 N90 40% RAP Mix	Design Target 3	Binder Opt. (–0.5%)	Binder Opt. (Optimum)	Binder Opt. (+0.5%)
Blend Percentages				
Adjusted for DCF?	Yes	Yes	Yes	Yes
CM11	31.0	31.0	31.0	31.0
CM16	13.3	13.3	13.3	13.3
FM20	4.0	4.0	4.0	4.0
FM22	10.9	10.9	10.9	10.9
+3/8-in RAP	25.0	25.0	25.0	25.0
–3/8-in RAP	15.0	15.0	15.0	15.0
Mineral Filler	0.8	0.8	0.8	0.8
Total Aggregate	100.0	100.0	100.0	100.0
Percent Asphalt		4.5	5.0	5.5
Percent Aggregate	100.0	95.5	95.0	94.5
Bulk Specific Gravities				
CM11	2.711	2.632	2.632	2.632
CM16	2.659	2.620	2.620	2.620
FM20	2.697	2.635	2.635	2.635
FM22	2.669	2.669	2.669	2.669
+3/8-in. RAP	2.687	2.627	2.627	2.627
–3/8-in RAP	2.671	2.641	2.641	2.641
Mineral Filler	2.900	2.900	2.900	2.900
Combined G_{sb}	2.688	2.688	2.688	2.688
Percent Passing from Washed Gradations				
1 in	100.0	100.0	100.0	100.0
3/4 in	96.4	96.2	96.2	96.2
1/2 in	77.8	77.9	77.9	77.9
3/8 in	65.6	65.8	65.8	65.8
No. 4	37.9	38.4	38.4	38.4
No. 8	22.5	22.7	22.7	22.7
No. 16	16.3	16.5	16.5	16.5
No. 30	12.8	13.1	13.1	13.1
No. 50	9.9	10.1	10.1	10.1
No. 100	7.1	7.5	7.5	7.5
No. 200	5.7	6.0	6.0	6.0

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Table B-5 (continued). Job Mix Formula for District 1 40% RAP Mix

Volumetrics				
G_{mb} 1 Dry Wt.		4814.2	4835.1	4859.1
G_{mb} 1 Submerged Wt.		2848.2	2864.3	2882.1
G_{mb} 1 SSD Wt.		4828.2	4846.0	4869.7
G_{mb} 2 Dry Wt.		4812.3	4837.7	4766.2
G_{mb} 2 Submerged Wt.		2844.7	2867.9	2826.1
G_{mb} 2 SSD Wt.		4826.3	4848.9	4775.8
G_{mb} 1	—	2.431	2.440	2.445
G_{mb} 2	—	2.428	2.442	2.445
Average G_{mb}	—	2.430	2.441	2.445
G_{mm} 1 Dry Wt.		2556.9	2570.8	2581.2
G_{mm} 1 Pyc in Water Wt.		7657.3	7657.3	7657.3
G_{mm} 1 Pyc + Sample in Water Wt.		9223.5	9218.6	9215.6
G_{mm} 2 Dry Wt.		2564.3	2554	2584.2
G_{mm} 2 Pyc in Water Wt.		7657.3	7657.3	7657.3
G_{mm} 1 Pyc + Sample in Water Wt.		9223.4	9208.2	9217.8
G_{mm} 1	—	2.581	2.547	2.523
G_{mm} 2	—	2.569	2.546	2.524
Average G_{mm}	—	2.575	2.546	2.524
G_b		1.03	1.03	1.03
G_{se}	—	2.771	2.760	2.757
Voids	—	5.6	4.1	3.1
VMA	—	13.7	13.7	14.0
VFA	—	58.8	70.0	77.7
Dust / Binder Content	—	1.3	1.1	1.0
P_{ba}		1.14	0.99	0.95
Effective Binder Content		3.4	4.1	4.6
Dust / Effective Binder Content		1.8	1.5	1.3
$N_{initial}$		8.0	8.0	8.0
N_{design}		90.0	90.0	90.0
Height 1 at $N_{initial}$		130.9	131.57	131.79
Height 2 at $N_{initial}$		130.74	130.68	128.51
Average Height at $N_{initial}$		130.82	131.125	130.15
Height 1 at N_{design}		116.12	116.43	117.19
Height 2 at N_{design}		116.27	116.05	114.5
Average Height at N_{design}		116.195	116.24	115.845
% of G_{mm} at $N_{initial}$		83.8	85.0	86.2

Table B-6. Volumetrics for District 1 Mix Design with 40% RAP

D1-40% RAP Mix Design Volumetrics Summary		
Volumetrics		IDOT Specifications
Binder (%)	5.1	—
Air Voids (%)	4.0	4
VMA (%)	13.8	13 (minimum)
VFA (%)	70.9	65–75
G_{mm}	2.546	—
G_{mb}	2.442	—
G_{se}	2.762	—

Table B-7. Job Mix Formula for District 1 50% RAP Mix

High RAP D1 N90 50% RAP Mix	Design Target 3	Binder Opt. (–0.5%)	Binder Opt. (Optimum)	Binder Opt. (+0.5%)
Blend Percentages				
Adjusted for DCF?	Yes	Yes	Yes	Yes
CM11	25.5	25.5	25.5	25.5
CM16	14.0	14.0	14.0	14.0
FM20	0.0	0.0	0.0	0.0
FM22	10.3	10.3	10.3	10.3
+3/8-in RAP	35.0	35.0	35.0	35.0
–3/8-in RAP	15.0	15.0	15.0	15.0
Mineral Filler	0.2	0.2	0.2	0.2
Total Aggregate	100.0	100.0	100.0	100.0
Percent Asphalt		4.5	5.0	5.5
Percent Aggregate	100.0	95.5	95.0	94.5
Bulk Specific Gravities				
CM11	2.711	2.711	2.711	2.711
CM16	2.659	2.659	2.659	2.659
FM20	2.697	2.697	2.697	2.697
FM22	2.669	2.669	2.669	2.669
+3/8-in RAP	2.687	2.687	2.687	2.687
–3/8-in RAP	2.671	2.671	2.671	2.671
Mineral Filler	2.900	2.900	2.900	2.900
Combined G_{sb}	2.685	2.685	2.685	2.685

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Table B-7 (continued). Job Mix Formula for District 1 50% RAP Mix

Percent Passing from Washed Gradations				
1 in	100.0	100.0	100.0	100.0
3/4 in	96.6	97.4	97.4	97.4
1/2 in	79.1	79.7	79.7	79.7
3/8 in	66.6	67.4	67.4	67.4
No. 4	37.2	37.8	37.8	37.8
No. 8	21.5	22.0	22.0	22.0
No. 16	16.0	16.3	16.3	16.3
No. 30	12.8	13.4	13.4	13.4
No. 50	9.8	10.5	10.5	10.5
No. 100	6.9	7.6	7.6	7.6
No. 200	5.5	6.2	6.2	6.2
Volumetrics				
G_{mb} 1 Dry Wt.	—	4788.1	4806.8	4802.0
G_{mb} 1 Submerged Wt.	—	2826.8	2842.9	2845.2
G_{mb} 1 SSD Wt.	—	4807.0	4817.2	4814.4
G_{mb} 2 Dry Wt.	—	4787.0	4808.8	4832.2
G_{mb} 2 Submerged Wt.	—	2820.1	2848.6	2863.4
G_{mb} 2 SSD Wt.	—	4808.4	4816.2	4842.6
G_{mb} 1	—	2.418	2.435	2.439
G_{mb} 2	—	2.408	2.444	2.441
Average G_{mb}	—	2.413	2.439	2.440
G_{mm} 1 Dry Wt.		2547.3	2562.6	2572.0
G_{mm} 1 Pyc in Water Wt.		7657.3	7657.3	7657.3
G_{mm} 1 Pyc + Sample in Water Wt.		9212.4	9210.0	9210.0
G_{mm} 2 Dry Wt.		2552.2	2563.0	2571.4
G_{mm} 2 Pyc in Water Wt.		7657.3	7657.3	7657.3
G_{mm} 2 Pyc + Sample in Water Wt.		9213.1	9212.3	9211.2
G_{mm} 1		2.567	2.537	2.523
G_{mm} 2		2.561	2.543	2.527
Average G_{mm}		2.564	2.540	2.525
G_b		1.03	1.03	1.03
G_{se}		2.758	2.752	2.758
Voids		5.9	4.0	3.4
VMA		14.2	13.7	14.1
VFA		58.4	71.1	76.2
Dust / Binder Content		1.4	1.2	1.1
P_{ba}		1.0	0.9	1.0
Effective Binder Content		3.5	4.1	4.5

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Table B-7 (continued). Job Mix Formula for District 1 50% RAP Mix

Dust / Effective Binder Content		1.7	1.5	1.4
$N_{initial}$		8.0	8.0	8.0
N_{design}		90.0	90.0	90.0
Height 1 at $N_{initial}$		131.7	131.0	130.8
Height 2 at $N_{initial}$		132.0	130.6	130.7
Average Height at $N_{initial}$		131.9	130.8	130.7
Height 1 at N_{design}		117.1	116.3	116.0
Height 2 at N_{design}		117.2	116.1	116.3
Average Height at N_{design}		117.1	116.2	116.2
% of G_{mm} at $N_{initial}$		83.6	85.3	85.9

Table B-8. Volumetrics for District 1 Mix Design with 50% RAP

D1-50% RAP Mix Design Volumetrics Summary		
Volumetrics		IDOT Specifications
Binder (%)	5.0	—
Air Voids (%)	4.0	4
VMA (%)	13.7	13 (minimum)
VFA (%)	71.0	65–75
G_{mm}	2.543	—
G_{mb}	2.440	—
G_{se}	2.756	—

Table B-9. Job Mix Formula for District 5 Control (0%) RAP Mix

High RAP D5 N90 Control Mix	Open Road's Target Blend (85BIT2893 - 19532)	Open Road's Actual Blend (85BIT2893 - 19532)	Design Target 2	Verification
Blend Percentages				
Adjusted for DCF?	—	—	No	Yes (0.6)
CM11	42.0	42.0	38.5	38.7
CM16	37.3	37.3	37.9	38.2
FM20	19.5	19.5	21.6	21.8
FM22	—	—	—	—
Mineral Filler	1.2	1.2	2.0	1.3
Total Aggregate	100.0	100.0	100.0	100.0
Percent Asphalt	5.4	5.4	—	5.2
Percent Aggregate	94.6	94.6	—	94.8
Bulk Specific Gravities				
CM11	2.636	—	2.632	2.632
CM16	2.627	—	2.620	2.620
FM20	2.617	—	2.635	2.635
FM22			2.551	2.551
Mineral Filler	2.800	—	2.900	2.900
Combined G_{sb}	2.631	2.631	2.633	2.633
Percent Passing from Washed Gradations				
1 in	100.0	100.0	100.0	100.0
3/4 in	95.0	96.0	93.1	93.1
1/2 in	76.9	78.0	76.6	76.6
3/8 in	67.1	68.0	67.8	67.8
1/4 in	—	—	—	—
No. 4	40.0	42.0	38.7	38.7
No. 8	21.4	22.0	21.7	21.7
No. 16	12.7	13.0	13.6	13.6
No. 30	8.3	9.0	9.0	9.0
No. 50	6.3	7.0	6.8	6.8
No. 100	5.4	6.0	5.6	5.6
No. 200	4.9	5.3	4.9	4.9

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Table B-9 (continued). Job Mix Formula for District 5 Control (0%) RAP Mix

Volumetrics				
G_{mb} 1 Dry Wt.	—	—		4709.2
G_{mb} 1 Submerged Wt.	—	—		2754.8
G_{mb} 1 SSD Wt.	—	—		4722.1
G_{mb} 2 Dry Wt.	—	—		4708.7
G_{mb} 2 Submerged Wt.	—	—		2756.6
G_{mb} 2 SSD Wt.	—	—		4718.7
G_{mb} 1	—	—		2.394
G_{mb} 2	—	—		2.400
Average G_{mb}	2.398	2.398	—	2.397
G_{mm} 1 Dry Wt.	—	—		2625.1
G_{mm} 1 Pyc in Water Wt.	—	—		1383.8
G_{mm} 1 Pyc + Sample in Water Wt.	—	—		2957.8
G_{mm} 2 Dry Wt.	—	—		2624.0
G_{mm} 2 Pyc in Water Wt.	—	—		1383.8
G_{mm} 1 Pyc + Sample in Water Wt.	—	—		2957.4
G_{mm} 1	—	—		2.497
G_{mm} 2	—	—		2.498
Average G_{mm}	2.497	2.497	—	2.498
Gb	1.037	—		1.030
G_{se}	2.717	—	—	2.710
Voids	4.0	4.0	—	4.0
VMA	13.8	13.8	—	13.7
VFA	71.0	71.0	—	70.5
Dust / Binder Content	0.91	—	—	0.9
P_{ba}	—	—		1.1
Effective Binder Content	—	—		1.0
Dust / Effective Binder Content	—	—	—	0.9
$N_{initial}$	10.0	—	—	1.1
N_{design}	90.0	90.0	—	5.1
Height 1 at $N_{initial}$	—	—	—	1.0
Height 2 at $N_{initial}$	—	—	—	8.0
Average Height at $N_{initial}$	—	—	—	90.0
Height 1 at N_{design}	—	—	—	—
Height 2 at N_{design}	—	—	—	—
Average Height at N_{design}	—	—	—	—
% of G_{mm} at $N_{initial}$	—	—	—	—

Table B-10. Volumetrics for District 5 Control Mix Design

D5-Control Mix Design Volumetrics Summary		
Volumetrics		IDOT Specifications
Binder (%)	5.2	—
Air Voids (%)	4.0	4
VMA (%)	13.8	13 (minimum)
VFA (%)	71.0	65–75
G_{mm}	2.497	—
G_{se}	2.710	—

Table B-11. Job Mix Formula for District 5 mixture with 30% RAP

High RAP D5 N90 30% RAP Mix	Design Target 2	1-point	Binder Opt. (–0.5%)	Binder Opt. (Optimum)	Binder Opt. (+0.5%)
Blend Percentages					
Adjusted for DCF?	No	Yes (0.6)			
CM11	34.5	34.7	34.7	34.7	34.7
CM16	15.5	15.6	15.6	15.6	15.6
FM20	9.0	9.1	9.1	9.1	9.1
FM22	10.0	10.1	10.1	10.1	10.1
+3/8-in RAP	15.0	15.0	15.0	15.0	15.0
–3/8-in RAP	15.0	15.0	15.0	15.0	15.0
Mineral Filler	1.0	0.5	0.5	0.5	0.5
Total Aggregate	100.0	100.0	100.0	100.0	100.0
Percent Asphalt		5.1	4.8	5.3	5.8
Percent Aggregate	100.0	94.9	95.2	94.7	94.2
Bulk Specific Gravities					
CM11	2.632	2.632	2.632	2.632	2.632
CM16	2.620	2.620	2.620	2.620	2.620
FM20	2.635	2.635	2.635	2.635	2.635
FM22	2.669	2.669	2.669	2.669	2.669
+3/8-in RAP	2.627	2.627	2.627	2.627	2.627
–3/8-in RAP	2.641	2.641	2.641	2.641	2.641
Mineral Filler	2.900	2.900	2.900	2.900	2.900
Combined G_{sb}		2.637	2.637	2.637	2.637

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Table B-11 (continued). Job Mix Formula for District 5 mixture with 30% RAP

Percent Passing from Washed Gradations					
1 in	100.0	100.0	100.0	100.0	100.0
3/4 in	93.7	94.7	94.9	94.9	94.9
1/2 in	77.6	77.8	78.4	78.4	78.4
3/8 in	68.3	68.8	68.0	68.0	68.0
No. 4	39.5	39.5	39.4	39.4	39.4
No. 8	22.4	22.4	22.2	22.2	22.2
No. 16	14.6	15.1	15.1	15.1	15.1
No. 30	10.6	10.6	10.5	10.5	10.5
No. 50	7.9	7.9	7.7	7.7	7.7
No. 100	6.3	6.4	6.3	6.3	6.3
No. 200	5.3	5.5	5.3	5.3	5.3
Volumetrics					
G_{mb} 1 Dry Wt.	—	4630.6	4618.8	4641.2	4659.7
G_{mb} 1 Submerged Wt.	—	2706.5	2696.1	2718.0	2738.1
G_{mb} 1 SSD Wt.	—	4642.3	4637.4	4652.3	4667
G_{mb} 2 Dry Wt.	—	4636.2	4621.2	4643.0	4662.7
G_{mb} 2 Submerged Wt.	—	2714.0	2698.1	2717.4	2730.1
G_{mb} 2 SSD Wt.	—	4648.8	4633.5	4651.3	4670.8
G_{mb} 1	—	2.392	2.379	2.399	2.416
G_{mb} 2	—	2.396	2.388	2.401	2.403
Average G_{mb}	—	2.394	2.383	2.400	2.409
G_{mm} 1 Dry Wt.		2585.8	2579.1	2595.9	2604.9
G_{mm} 1 Pyc in Water Wt.		1563.1	1563.1	1563.1	1563.1
G_{mm} 1 Pyc + Sample in Water Wt.		3117.4	3119.1	3118.8	3115.2
G_{mm} 2 Dry Wt.		2587.2	2584.2	2594.8	2606.4
G_{mm} 2 Pyc in Water Wt.		1563.1	1563.1	1563.1	1563.1
G_{mm} 1 Pyc + Sample in Water Wt.		3117.6	3120.9	3118.2	3117.2
G_{mm} 1	—	2.507	2.521	2.496	2.474
G_{mm} 2	—	2.505	2.518	2.496	2.477
Average G_{mm}	—	2.506	2.519	2.496	2.476
G_b	—	1.03	1.03	1.03	1.03
G_{se}	—	2.715	2.717	2.712	2.710
Voids	—	4.5	5.4	3.8	2.7
VMA	—	13.8	14.0	13.8	13.9
VFA	—	67.7	61.4	72.2	80.6
Dust / Binder	—	1.0	1.1	1.0	0.9
P_{ba}		1.12	1.15	1.08	1.05
Effective Binder		4.0	3.7	4.3	4.8

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Table B-11 (continued). Job Mix Formula for District 5 mixture with 30% RAP

Dust / Effective Binder		1.4	1.4	1.2	1.1
$N_{initial}$			8.0	8.0	8.0
N_{design}			90.0	90.0	90.0
Height 1 at $N_{initial}$			128.15	127.15	126.06
Height 2 at $N_{initial}$			127.69	126.68	127.21
Average Height at $N_{initial}$			127.92	126.915	126.635
Height 1 at N_{design}			113.51	112.99	112.77
Height 2 at N_{design}			113.09	112.83	112.9
Average Height at N_{design}			113.3	112.91	112.835
% of G_{mm} at $N_{initial}$			83.8	85.5	86.7

Table B-12. Volumetrics for District 5 Mixture with 30% RAP

D5-30% RAP Mix Design Volumetrics Summary		
Volumetrics		IDOT Specifications
Binder (%)	5.2	—
Air Voids (%)	4.0	4
VMA (%)	13.8	13 (minimum)
VFA (%)	71.0	65–75
G_{mm}	2.501	—
G_{se}	2.713	—

Table B-13. Job Mix Formula for District 5 40% RAP Mix

High RAP D5 N90 40% RAP Mix	Design Target 3	1-point	Binder Opt. (–0.5%)	Binder Opt. (Optimum)	Binder Opt. (+0.5%)
Blend Percentages					
Adjusted for DCF?	No	Yes (0.67)			
CM11	31.2	31.4	31.4	31.4	31.4
CM16	12.5	12.6	12.6	12.6	12.6
FM20	6.5	6.6	6.6	6.6	6.6
FM22	9.0	9.1	9.1	9.1	9.1
+3/8-in RAP	25.0	25.0	25.0	25.0	25.0
–3/8-in RAP	15.0	15.0	15.0	15.0	15.0
Mineral Filler	0.8	0.4	0.4	0.4	0.4
Total Aggregate	100.0	100.0	100.0	100.0	100.0
Percent Asphalt		5.2	4.8	5.3	5.8
Percent Aggregate	100.0	94.8	95.2	94.7	94.2
Bulk Specific Gravities					
CM11	2.632		2.632	2.632	2.632
CM16	2.620		2.620	2.620	2.620
FM20	2.635		2.635	2.635	2.635
FM22	2.669		2.669	2.669	2.669
+3/8-in RAP	2.627		2.627	2.627	2.627
–3/8-in RAP	2.641		2.641	2.641	2.641
Mineral Filler	2.900		2.900	2.900	2.900
Combined G_{sb}	2.636	2.636	2.636	2.636	2.636
Percent Passing from Washed Gradations					
1 in	100.0	100.0	100.0	100.0	100.0
3/4 in	94.4	94.3	93.8	93.8	93.8
1/2 in	79.3	79.4	78.4	78.4	78.4
3/8 in	69.7	69.7	69.1	69.1	69.1
1/4 in	—	—	—	—	—
No. 4	39.3	39.2	39.2	39.2	39.2
No. 8	22.3	22.7	22.4	22.4	22.4
No. 16	14.8	15.1	14.8	14.8	14.8
No. 30	11.0	11.2	11.0	11.0	11.0
No. 50	8.2	8.1	7.9	7.9	7.9
No. 100	6.4	6.5	6.3	6.3	6.3
No. 200	5.4	5.5	5.3	5.3	5.3

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Table B-13 (continued). Job Mix Formula for District 5 40% RAP Mix

Volumetrics					
G_{mb} 1 Dry Wt.		4623.2	4609.8	4626.2	4641.5
G_{mb} 1 Submerged Wt.		2708.9	2695.2	2710.5	2727.9
G_{mb} 1 SSD Wt.		4635.8	4626.6	4635.9	4650.8
G_{mb} 2 Dry Wt.		4623.6	4611.2	4627.9	4639.2
G_{mb} 2 Submerged Wt.		2705.8	2696.0	2714.9	2726.2
G_{mb} 2 SSD Wt.		4638.9	4629.2	4639.7	4648.5
G_{mb} 1	—	2.399	2.387	2.403	2.414
G_{mb} 2	—	2.392	2.385	2.404	2.413
Average G_{mb}	—	2.396	2.386	2.404	2.414
G_{mm} 1 Dry Wt.		2581.7	2575.7	2582.1	2596.8
G_{mm} 1 Pyc in Water Wt.		1563.1	1563.1	1563.1	1563.1
G_{mm} 1 Pyc + Sample in Water Wt.		3113.1	3115.0	3110.9	3109.8
G_{mm} 2 Dry Wt.		2583.3	2571.8	2585.2	2591.7
G_{mm} 2 Pyc in Water Wt.		1563.1	1563.1	1563.1	1563.1
G_{mm} 1 Pyc + Sample in Water Wt.		3113.9	3114.1	3110.8	3108.4
G_{mm} 1	—	2.502	2.516	2.496	2.473
G_{mm} 2	—	2.502	2.519	2.492	2.477
Average G_{mm}	—	2.502	2.518	2.494	2.475
G_b		1.03	1.03	1.03	1.03
G_{se}	—	2.715	2.716	2.710	2.709
Voids	—	4.2	5.2	3.6	2.5
VMA	—	13.8	13.8	13.6	13.7
VFA	—	69.4	62.1	73.5	82.1
Dust / Binder	—	1.0	1.1	1.0	0.9
P_{ba}			1.15	1.06	1.05
Effective Binder			3.7	4.3	4.8
Dust / Effective Binder			1.4	1.2	1.1
$N_{initial}$			8.0	8.0	8.0
N_{design}			90.0	90.0	90.0
Height 1 at $N_{initial}$			127.5	126.78	127.01
Height 2 at $N_{initial}$			127.93	127.04	126.82
Average Height at $N_{initial}$			127.715	126.91	126.915
Height 1 at N_{design}			113.37	112.45	112.45
Height 2 at N_{design}			113.69	112.59	112.45
Average Height at N_{design}			113.53	112.52	112.45
% of G_{mm} at $N_{initial}$			84.2	85.5	86.4

Table B-14. Volumetrics for District 5 Mix Design with 40% RAP

D5-40% RAP Mix Design Volumetrics Summary		
Volumetrics		IDOT Specifications
Binder (%)	5.2	—
Air Voids (%)	4.0	4
VMA (%)	13.6	13 (minimum)
VFA (%)	70.8	65–75
G_{mm}	2.500	—
G_{se}	2.711	—

Table B-15. Job Mix Formula for District 5 50% RAP Mix

High RAP D5 N90 50% RAP Mix	Design Target 4	1-point	Binder Opt. (–0.5%)	Binder Opt. (Optimum)	Binder Opt. (+0.5%)	1-point
Blend Percentages						
Adjusted for DCF?	No	Yes (0.5)				
CM11	25.6	25.8	25.8	25.8	25.8	25.8
CM16	9.5	9.6	9.6	9.6	9.6	9.6
FM20	4.8	4.8	4.8	4.8	4.8	4.8
FM22	9.6	9.7	9.7	9.7	9.7	9.7
+3/ 8in. RAP	35.0	35.0	35.0	35.0	35.0	35.0
–3/8-in RAP	15.0	15.0	15.0	15.0	15.0	15.0
Mineral Filler	0.5	0.2	0.2	0.2	0.2	0.2
Total Aggregate	100.0	100.0	100.0	100.0	100.0	100.0
Percent Asphalt		5.3	4.7	5.2	5.7	5.2
Percent Aggregate	100.0	94.7	95.3	94.8	94.3	94.8
Bulk Specific Gravities						
CM11	2.632					
CM16	2.620					
FM20	2.635					
FM22	2.669					
+3/8-in RAP	2.627					
–3/8-in RAP	2.641					
Mineral Filler	2.900					
Combined G_{sb}	2.635	2.635	2.635	2.635	2.635	2.635

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Table B-15 (continued). Job Mix Formula for District 5 50% RAP Mix

Percent Passing from Washed Gradations						
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	95.2	95.6	95.2	95.2	95.2	95.5
1/2 in	81.2	81.8	81.8	81.8	81.8	80.9
3/8 in	71.4	71.6	72.1	72.1	72.1	71.5
1/4 in	—	—	—	—	—	—
No. 4	39.9	40.3	40.5	40.5	40.5	40.1
No. 8	23.3	23.3	23.4	23.4	23.4	23.2
No. 16	15.6	15.7	15.9	15.9	15.9	15.4
No. 30	11.7	11.9	11.8	11.8	11.8	11.7
No. 50	8.6	8.7	8.5	8.5	8.5	8.6
No. 100	6.6	6.8	6.7	6.7	6.7	6.7
No. 200	5.4	5.7	5.6	5.6	5.6	5.6
Volumetrics						
G_{mb} 1 Dry Wt.	—	4613.0	4590.0	4605.3	4625.0	4605.6
G_{mb} 1 Submerged Wt.	—	2708.5	2689.6	2701.8	2716.4	2694.4
G_{mb} 1 SSD Wt.	—	4628.2	4615.2	4615.4	4635.1	4617.9
G_{mb} 2 Dry Wt.	—	4613.1	4588.3	4612.5	4624.2	4606.6
G_{mb} 2 Submerged Wt.	—	2704.0	2687.1	2706.5	2714.7	2701.3
G_{mb} 2 SSD Wt.	—	4625.2	4613.6	4622.2	4632.8	4616.2
G_{mb} 1	—	2.403	2.384	2.407	2.410	2.394
G_{mb} 2	—	2.401	2.382	2.408	2.411	2.406
Average G_{mb}	—	2.402	2.383	2.404	2.411	2.400
G_{mm} 1 Dry Wt.		—	2563.5	2575.0	2585.5	2570.4
G_{mm} 1 Pyc in Water Wt.		—	1563.1	1563.1	1563.1	1563.1
G_{mm} 1 Pyc + Sample in Water Wt.		—	3108.8	3109.3	3106.6	3105.9
G_{mm} 2 Dry Wt.		—	2561.6	2572.8	2587.5	2571.8
G_{mm} 2 Pyc in Water Wt.		—	1563.1	1563.1	1563.1	1563.1
G_{mm} 1 Pyc + Sample in Water Wt.		—	3107.9	3106.4	3107.7	3106.2
G_{mm} 1			2.519	2.503	2.481	2.501
G_{mm} 2			2.519	2.499	2.481	2.500
Average G_{mm}			2.519	2.501	2.481	2.501
G_b		1.03	1.03	1.03	1.03	1.03
G_{se}			2.712	2.714	2.712	2.714
Voids			5.4	3.9	2.8	4.0
VMA		13.7	13.8	13.5	13.7	13.7

(continued, next page)

Table B-15 (continued). Job Mix Formula for District 5 50% RAP Mix

VFA			60.9	71.3	79.4	70.5
Dust/Binder			1.2	1.1	1.0	1.1
P_{ba}			1.1	1.1	1.1	1.1
Effective Binder			3.6	4.1	4.7	4.1
Dust / Effective Binder			1.5	1.3	1.2	1.4
$N_{initial}$			8.0	8.0	8.0	8.0
N_{design}			90.0	90.0	90.0	90.0
Height 1 at $N_{initial}$			126.1	126.4	125.8	126.3
Height 2 at $N_{initial}$			126.6	126.8	125.9	126.1
Average Height at $N_{initial}$			126.4	126.4	125.8	126.2
Height 1 at N_{design}			112.4	112.1	111.9	112.2
Height 2 at N_{design}			112.9	111.5	112.0	111.9
Average Height at N_{design}			112.6	111.9	111.9	112.1
% of G_{mm} at $N_{initial}$			84.3	85.1	86.4	85.2

Table B-16. Volumetrics for District 5 Mix Design with 50% RAP

D5-50% RAP Mix Design Volumetrics Summary		
Volumetrics		IDOT Specifications
Binder (%)	5.2	—
Air Voids (%)	4.0	4
VMA (%)	13.5	13 (minimum)
VFA (%)	70.4	65–75
G_{mm}	2.505	—
G_{se}	2.713	—

APPENDIX C TEST RESULTS

Table C-1. Semi-Circular Bending (SCB) Test Results at –24°C for District 1

	Mix-Binder Type	Fracture Energy (J/m^2)	Avg.	Std Dev	COV	Peak Load	Avg.	Std dev	COV
1	0-6422-1	410	425	28	7	5.6	5.7	0.2	3.2
2	0-6422-2	407				5.9			
3	0-6422-3	457				5.5			
4	30-6422-1	408	459	49	11	5.1	5.3	0.2	4.3
5	30-6422-2	505				5.1			
6	30-6422-3	463				5.5			
7	40-6422-1	385	513	112	22	6.2	6.1	0.4	6.9
8	40-6422-2	590				6.4			
9	40-6422-3	565				5.6			
10	50-6422-1	419	496	109	22	5.9	6.2	0.3	5.0
11	50-6422-2	572				6.3			
12	50-6422-3	1196*				6.5			
1	30-5822-1	520	595	159	27	7.3	6.4	1.0	15.9
2	30-5822-2	488				5.3			
3	30-5822-3	778				6.6			
4	40-5822-1	403	456	49	11	5.3	5.6	0.3	5.8
5	40-5822-2	463				5.9			
6	40-5822-3	500				5.8			
7	50-5822-1	624	564	170	30	4.9	5.6	0.6	10.2
8	50-5822-2	373				5.8			
9	50-5822-3	696				5.9			
1	30-5828-1	510	542	109	20	5.6	6.2	0.6	10.2
2	30-5828-2	663				6.9			
3	30-5828-3	453				6.3			
4	40-5828-1	630	581	85	15	6.6	6.8	0.9	12.8
5	40-5828-2	629				7.8			
6	40-5828-3	483				6.1			
7	50-5828-1	434	606	162	27	5.0	5.8	0.7	12.3
8	50-5828-2	754				6.4			
9	50-5828-3	631				6.1			

* Outlier

Table C-2. Semi-Circular Bending (SCB) Test Results at –12°C for District 1

	Mix-Binder Type	Fracture Energy (J/m^2)	Avg.	Std Dev	COV	Peak Load	Avg.	Std Dev	COV
1	0-6422-1	617	950	312	33	5.3	5.3	0.2	2.9
2	0-6422-2	1233				5.5			
3	0-6422-3	1001				5.2			
4	30-6422-1	532	610	72	12	5.3	5.4	0.7	12.2
5	30-6422-2	675				6.1			
6	30-6422-3	622				4.8			
7	40-6422-1	747	741	157	21	6.0	5.6	0.6	9.9
8	40-6422-2	582				5.0			
9	40-6422-3	894				5.9			
10	50-6422-1	755	713	60	8	5.9	6.2	0.5	7.8
11	50-6422-2	671				6.0			
12	50-6422-3	1080*				6.8			
1	30-5822-1	713	718	6	1	5.3	5.5	0.2	4.3
2	30-5822-2	717				5.5			
3	30-5822-3	724				5.8			
4	40-5822-1	695	753	180	24	5.8	5.9	0.1	2.0
5	40-5822-2	955				6.0			
6	40-5822-3	610				6.0			
7	50-5822-1	514	581	66	11	5.7	5.8	0.2	3.6
8	50-5822-2	582				6.1			
9	50-5822-3	646				5.7			
1	30-5828-1	572	728	184	25	5.5	5.5	0.3	5.8
2	30-5828-2	681				5.9			
3	30-5828-3	932				5.2			
4	40-5828-1	655	783	168	21	6.1	6.2	0.4	6.4
5	40-5828-2	974				6.7			
6	40-5828-3	720				5.9			
7	50-5828-1	695	842	204	24	5.6	5.9	0.3	5.1
8	50-5828-2	756				5.9			
9	50-5828-3	1075				6.2			

* Outlier

Table C-3. Semi-Circular Bending (SCB) Test Results at –11.2°F (–24°C) for District 5

	Mix-Binder Type	Fracture Energy (J/m^2)	Avg.	Std Dev	COV	Peak Load	Avg.	Std Dev	COV
1	0-6422-1	456	531	146	27	6.6	6.3	0.7	11.0
2	0-6422-2	699				6.8			
3	0-6422-3	439				5.5			
4	30-6422-1	601	602	63	11	6.7	6.2	0.4	7.2
5	30-6422-2	539				5.9			
6	30-6422-3	666				6.0			
7	40-6422-1	427	465	38	8	6.4	5.7	0.6	11.1
8	40-6422-2	503				5.6			
9	40-6422-3	465				5.1			
10	50-6422-1	410	541	120	22	4.8	6.0	1.1	18.6
11	50-6422-2	567				7.0			
12	50-6422-3	646				6.3			
1	30-5822-1	372	479	99	21	5.4	6.0	0.5	8.8
2	30-5822-2	567				6.2			
3	30-5822-3	499				6.4			
4	40-5822-1	514	550	33	6	5.9	6.3	0.4	7.2
5	40-5822-2	558				6.1			
6	40-5822-3	579				6.8			
7	50-5822-1	560	509	50	10	7.9	6.5	1.2	18.7
8	50-5822-2	461				5.9			
9	50-5822-3	506				5.8			
1	30-5828-1	489	491	31	6	5.0	5.7	0.7	12.2
2	30-5828-2	462				6.4			
3	30-5828-3	523				5.8			
4	40-5828-1	617	656	138	21	6.7	6.3	0.4	6.0
5	40-5828-2	694				5.9			
6	40-5828-3	427				6.2			
7	50-5828-1	631	662	148	22	8.0	6.9	1.2	17.1
8	50-5828-2	823				7.1			
9	50-5828-3	532				5.7			

Table C-4. Semi-Circular Bending (SCB) Test Results at –12°C for District 5

	Mix-Binder Type	Fracture Energy (J/m^2)	Avg.	Std Dev	COV	Peak Load	Avg.	Std Dev	COV
1	0-6422-1	651	617	30	5	4.8	5.1	0.4	7.4
2	0-6422-2	591				5.0			
3	0-6422-3	609				5.5			
4	30-6422-1	417	542	156	29	5.6	5.2	0.3	6.2
5	30-6422-2	717				5.1			
6	30-6422-3	492				4.9			
7	40-6422-1	530	514	15	3	5.8	6.1	0.4	6.1
8	40-6422-2	510				6.5			
9	40-6422-3	501				5.9			
10	50-6422-1	566	501	56	11	6.1	5.6	0.4	7.2
11	50-6422-2	466				5.3			
12	50-6422-3	472				5.4			
1	30-5822-1	458	534	106	20	4.0	4.4	0.5	10.9
2	30-5822-2	609				4.7			
3	30-5822-3	0				0.0			
4	40-5822-1	819	657	144	22	5.8	6.0	0.6	10.1
5	40-5822-2	544				5.5			
6	40-5822-3	608				6.7			
7	50-5822-1	451	585	128	22	5.0	4.8	0.4	8.5
8	50-5822-2	601				5.1			
9	50-5822-3	705				4.4			
1	30-5828-1	896	754	125	17	5.1	5.3	0.3	5.7
2	30-5828-2	661				5.7			
3	30-5828-3	705				5.3			
4	40-5828-1	697	583	119	20	5.4	5.3	0.2	4.2
5	40-5828-2	460				5.0			
6	40-5828-3	592				5.5			
7	50-5828-1	551	567	127	22	4.8	5.6	0.9	15.4
8	50-5828-2	785				6.5			
9	50-5828-3	583				5.6			

Table C-5. Four-Point Beam Fatigue Test Data for District 1

Sample ID	Strain (μ Strain)	Initial Stiffness (S)	Nf
0-6422-1000	1000	3262	2870
0-6422-800	800	3339	8490
0-6422-700	700	3172	11820
0-6422-500	500	3483	31320
0-6422-400	400	3650	47290
0-6422-300	300	4094	279580
30-6422-1000	1000	3724	3350
30-6422-800	800	4238	7290
30-6422-700	700	4120	13890
30-6422-500	500	4120	67000
30-6422-400	400	4586	124840
30-6422-300	300	5044	380740
30-5822-1000	1000	3424	3060
30-5822-800	800	3641	9270
30-5822-700	700	3534	19190
30-5822-500	500	4417	47650
30-5822-400	400	4286	115670
30-5822-300	300	4948	979310
30-5828-1000	1000	2472	11790
30-5828-800	800	2927	8810
30-5828-700	700	1870	35230
30-5828-500	500	3192	176050
30-5828-400	400	3422	329740
30- 5828-300	300	3468	1465230
			(continued, next page)

Table C-5 (continued). Four-Point Beam Fatigue Test Data for District 1

Sample ID	Strain (µ Strain)	Initial Stiffness (S)	Nf
40-6422-1000	1000	2954	6290
40-6422-800	800	4053	6780
40-6422-700	700	4181	11540
40-6422-500	500	3670	121030
40-6422-400	400	4483	250930
40-6422-300	300	3164	207150
40-5822-1000	1000	3659	4480
40-5822-800	800	4122	5570
40-5822-700	700	3780	13720
40-5822-500	500	4641	81450
40-5822-400	400	4940	197060
40-5822-300	300	4565	243870
40-5828-1000	1000	2875	10510
40-5828-800	800	3534	13330
40-5828-700	700	3444	19740
40-5828-500	500	4387	80850
40-5828-400	400	4093	302670
40-5828-300	300	3765	471380
50-6422-1000	1000	3565	2680
50-6422-800	800	3575	6460
50-6422-700	700	3641	9940
50-6422-500	500	4998	100800
50-6422-400	400	4744	102480
50-6422-300	300	5015	423130
50-5822-1000	1000	3786	2220
50-5822-800	800	4062	9560
50-5822-700	700	4335	7010
50-5822-500	500	4767	34930
50-5822-400	400	5328	142460
50-5822-300	300	4689	1261060
50-5828-1000	1000	3244	5820
50-5828-800	800	3307	23280
50-5828-700	700	3894	19050
50-5828-400	400	4133	274430
50-5828-300	300	4295	645180

Table C-6. Four-Point Beam Fatigue Test Data for District 5

Sample ID	Strain (μ Strain)	Initial Stiffness (S)	Nf
0-6422-1000	1000	2409	6450
0-6422-800	800	2882	15740
0-6422-700	700	3369	22880
0-6422-500	500	3664	66370
0-6422-400	400	3450	184140
0-6422-300	300	4108	544630
30-6422-1000	1000	3794	5250
30-6422-800	800	4134	10930
30-6422-700	700	4178	15730
30-6422-500	500	4182	53350
30-6422-400	400	4403	278540
30-6422-300	300	5269	404420
30-5822-1000	1000	3115	10400
30-5822-800	800	3111	15150
30-5822-700	700	3273	31060
30-5822-500	500	3700	220180
30-5822-400	400	4054	345440
30-5822-300	300	4220	654210
30-5828-1000	1000	2778	9950
30-5828-800	800	2966	11730
30-5828-700	700	3120	45440
30-5828-500	500	3400	78630
30-5828-400	400	3626	322460
30-5828-300	300	4041	361260

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Table C-6 (continued). Four-Point Beam Fatigue Test Data for District 5

Sample ID	Strain (μ Strain)	Initial Stiffness (S)	Nf
40-6422-1000	1000	4108	3450
40-6422-800	800	4657	9030
40-6422-700	700	4394	8560
40-6422-500	500	5022	59850
40-6422-400	400	5181	129160
40-6422-300	300	5820	916710
40-5822-1000	1000	3311	7640
40-5822-800	800	3933	10330
40-5822-700	700	3928	28440
40-5822-500	500	4209	77050
40-5822-400	400	4585	746830
40-5822-300	300	4981	863570
40-5828-1000	1000	2924	7930
40-5828-800	800	3259	6990
40-5828-700	700	3750	49340
40-5828-500	500	3585	47740
40-5828-400	400	4298	421300
40-5828-300	300	4352	974050
50-6422-1000	1000	4487	4100
50-6422-800	800	4820	5140
50-6422-700	700	4672	8940
50-6422-500	500	5271	29990
50-6422-400	400	5537	229440
50-6422-300	300	5745	266420
50-5822-1000	1000	3215	5700
50-5822-800	800	3833	7730
50-5822-700	700	3548	15820
50-5822-500	500	4529	161940
50-5822-400	400	5159	193350
50-5822-300	300	4767	1521430
50-5828-1000	1000	3547	3240
50-5828-800	800	3543	14090
50-5828-700	700	4139	19510
50-5828-500	500	4734	51930
50-5828-400	400	4796	337190
50-5828-300	300	4587	797990

Table C-7. Moisture Susceptibility Test Data for District 1

Mix Type	Sample No.	Unconditioned Samples		Conditioned Samples		TSR
		Tensile Strength (psi)	Air Voids	Tensile Strength (psi)	Air Voids	
Control	1	68.6	6.8	71.5	6.5	90.2
	2	84.6	6.9	71.2	7.5	
	3	90.7	6.5	77.3	6.5	
	Average	81.3	6.7	73.3	6.8	
30% RAP	1	105.3	6.5	93.7	6.5	93.4
	2	94.0	7.3	92.8	6.8	
	3	98.1	6.5	91.3	6.8	
	Average	99.1	6.8	92.6	6.7	
40% RAP	1	110.9	6.8	92.5	6.9	89.7
	2	111.4	7.4	104.8	7.1	
	3	99.0	6.6	90.7	6.7	
	Average	107.1	6.9	96.0	6.9	
50% RAP	1	86.8	7.1	104.1	6.6	99.9
	2	116.0	7.4	102.5	7.0	
	3	122.8	6.6	118.6	7.1	
	Average	108.5	7.0	108.4	6.9	

Table C-8. Moisture Susceptibility Test Data for District 5

Mix Type	Sample No.	Unconditioned Samples		Conditioned Samples		TSR
		Tensile Strength (psi)	Air Voids	Tensile Strength (psi)	Air Voids	
Control	1	50.6	6.8	51.5	6.7	89.5
	2	53.3	7.2	48.1	7.2	
	3	55.1	6.8	48.9	7.1	
	Average	54.2	6.9	48.5	7.0	
30% RAP	1	90.0	7.0	76.0	6.9	85.7
	2	100.8	6.5	82.8	6.8	
	3	91.9	6.9	83.6	6.6	
	Average	94.2	6.8	80.8	6.8	
40% RAP	1	92.4	6.9	81.1	7.1	83.7
	2	92.8	7.2	74.9	7.1	
	3	89.4	7.1	74.0	7.0	
	Average	91.6	7.1	76.7	7.1	
50% RAP	1	118.8	7.2	99.9	6.9	87.3
	2	113.6	6.8	102.8	7.1	
	3	121.1	7.0	106.0	6.9	
	Average	117.8	7.0	102.9	7.0	

A typical SAS output file.

```
The SAS System                                                          1

The GLM Procedure

                Class Level Information

Class         Levels    Values

Mixtures           4    0-6422 40-5822 40-5828 40-6422


Number of Observations Read          12
Number of Observations Used          12

The SAS System                                                          2

The GLM Procedure

Dependent Variable: values

                                    Sum of
Source                     DF      Squares   Mean Square  F Value  Pr > F

Model                       3   32508386803   10836128934     5.54  0.0236

Error                       8   15644177931    1955522241

Corrected Total            11   48152564734


R-Square     Coeff Var      Root MSE    values Mean

0.675112      22.39153      44221.29       197491.2


Source                     DF     Type I SS   Mean Square  F Value  Pr > F

Mixtures                    3   32508386803   10836128934     5.54  0.0236


Source                     DF   Type III SS   Mean Square  F Value  Pr > F

Mixtures                    3   32508386803   10836128934     5.54  0.0236
```

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```
The GLM Procedure

Tukey's Studentized Range (HSD) Test for values

NOTE: This test controls the Type I experimentwise error rate, but it
generally has a higher Type II error rate than REGWQ.


Alpha                                   0.05
Error Degrees of Freedom                   8
Error Mean Square                   1.9555E9
Critical Value of Studentized Range  4.52881
Minimum Significant Difference        115626
```

Means with the same letter are not significantly different.

```
Tukey
Groupi
  ng            Mean      N    Mixtures

     A        268163      3    40-6422
     A
B    A        203012      3    40-5822
B    A
B    A        197528      3    40-5828
B
B             121261      3    0-6422
```

```
The GLM Procedure
Least Squares Means
Adjustment for Multiple Comparisons: Tukey

                  values      LSMEAN
Mixtures          LSMEAN      Number

0-6422        121260.667           1
40-5822       203012.333           2
40-5828       197528.333           3
40-6422       268163.333           4


          Least Squares Means for effect Mixtures
            Pr > |t| for H0: LSMean(i)=LSMean(j)

                 Dependent Variable: values

i/j              1             2             3             4

   1                      0.1859        0.2280        0.0152
   2       0.1859                       0.9986        0.3379
   3       0.2280         0.9986                      0.2793
   4       0.0152         0.3379        0.2793
```

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