USE OF HIGH-VOLUME RECLAIMED ASPHALT PAVEMENT (RAP) FOR ASPHALT PAVEMENT REHABILITATION

by

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Abstract

Because of recent rises in asphalt binder prices, state agencies and contractors are now willing to use higher volumes of reclaimed asphalt pavement (RAP). In this project, the effects of increasing RAP percentage and using fractionated RAP (FRAP) in hot-mix asphalt (HMA) mixtures have been studied. Fractionation involved processing and separating of RAP materials into at least two sizes, typically a coarse fraction and a fine fraction. This study evaluated the effects of increasing the proportions of RAP and FRAP on moisture resistance, rutting, and fatigue cracking of Superpave mixtures. Furthermore, the effect of using different sources of RAP in the mix has been investigated. HMA mixtures with five varying RAP and FRAP contents (20, 30, and 40% RAP, and 30 and 40% FRAP) were studied. The Hamburg wheel-tracking device (HWTD) test (TEX-242-F), the Kansas standard test method no. 56 (KT-56), or modified Lottman test, and the dynamic modulus test (AASHTO TP: 62-03) were used to predict moisture damage, rutting potential, and fatigue cracking resistance of the mixes. HMA specimens were made based on Superpave HMA mix design criteria for 12.5-mm (1/2-inch) nominal maximum aggregate size (NMAS) and compacted using the Superpave gyratory compactor. For the first source of RAP, results of this study showed that although mixture performance declined as the percentage of RAP increased, mixtures with even 40% RAP met minimum performance requirements. The second source of RAP, however, almost failed to meet minimum requirements even at 20% RAP. Results proved the maximum percentage of RAP allowed in the mix is highly influenced by its source. Although some improvements have been observed, especially for the second source of RAP, when RAP is compared to FRAP, FRAP does not seem to considerably affect performance of the HMA mixture.

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Dedication

This thesis is dedicated to my mother Jaleh Mohammadi, because everything she has done for me in life. A special dedication also goes to all my teachers.

Chapter 1 - Introduction

1.1 Introduction

The immense highway network that connects the entire continental United States is undoubtedly the most critical infrastructure in the country. In 2005, approximately 94 percent (almost 2.4 million miles) of the paved roads had asphalt surfaces. Construction of hot-mix asphalt (HMA) pavements requires large quantities of virgin aggregates and asphalt binder. According to the European Asphalt Pavement Association (EAPA), total production of HMA in the United States and Europe had reached 500 and 342 million tons, respectively (EAPA 2007). In the early 1990s, the Federal Highway Administration (FHWA) and Environmental Protection Agency (EPA) estimated that more than 90 million tons of asphalt pavement were reclaimed every year and more than 80 percent of reclaimed asphalt pavement (RAP) was recycled, making asphalt pavement the most recycled product in the United States. According to National Asphalt Pavement Association (NAPA) , the current annual production of new asphalt pavement material in the United States is approximately 500 million tons per year, which includes about 60 million tons of reclaimed materials that are reused or recycled directly into pavement. As of 2007, about 40 million tons of RAP is reused or recycled into other pavement-related applications every year for a total use of more than 100 million tons of RAP each year. This is an increase from 72 million tons of RAP used each year in the early 1990s. There is no doubt these quantities are required to maintain current infrastructures or reconstruct new pavements, but it is also of great importance to consider their future re-usage. Besides sustainability/environmental-related reasons for using RAP in constructing new pavements, such as saving resources and disposal costs, the rapidly increasing price of crude oil and lack of quality aggregates at different locations are other prevalent reasons to use RAP in HMA pavements (Zofka et al. 2010).

Recycling is beneficial in most cases by reducing the consumption of virgin materials, but the performance of the highway should not be compromised for cost reduction (Mohammad, Cooper and Elseifi 2011). It has been accepted that RAP can be a feasible constituent in HMA pavements and if properly designed and constructed, HMA mixtures with RAP can perform as well as conventional mixtures (Huang, Shu and Vukosavljevic 2011). The only issue is to what extent RAP should be allowed in different HMA mixes without sacrificing durability for lower initial cost. The average use of RAP across the United States is currently estimated at 12 percent of the mix; however, based on agencies' specifications, there is the potential to use up to 30 percent RAP in the intermediate and surface layers of pavement (FHWA HRT-11-021 2010). There are some concerns about long-term performance and durability of asphalt pavements containing RAP, especially in the major load-carrying and surface layers of asphalt pavements. Generally, as the result of having some long-term aged binder in asphalt mixes containing RAP, asphalt cement tends to be stiffer. The advantage of having a stiffer mix is its being less susceptible to permanent deformation or rutting, and its disadvantage is being less resistant to fatigue and thermal cracking.

Because of the aforementioned concerns, many state transportation agencies have limited the maximum amount of RAP used in surface layers, certain mixture types, and, in some instances, large or critical projects. Traditionally, the amount of RAP was typically limited to 15 percent or lower because there were no binder-grade changes or additional tests needed for such low percentages in Superpave mixtures. Besides, there was no significant economic incentive for using larger percentages of RAP. In 2006 and again in 2008, however, there were sharp increases in asphalt binder costs and as a result, RAP usage spiked as indicated by greater percentages of RAP now being allowed or used (Fig. 1.1). Furthermore, stricter environmental regulations, and an emphasis on "green" technologies [e.g., warm mix asphalt (WMA)], and sustainable pavements, highway agencies are more open to allowing higher percentages of RAP in HMA pavements. However, there is a lack of guidance on use of high percentages of RAP (high RAP) in mixtures, as well as information on the performance of these mixtures.

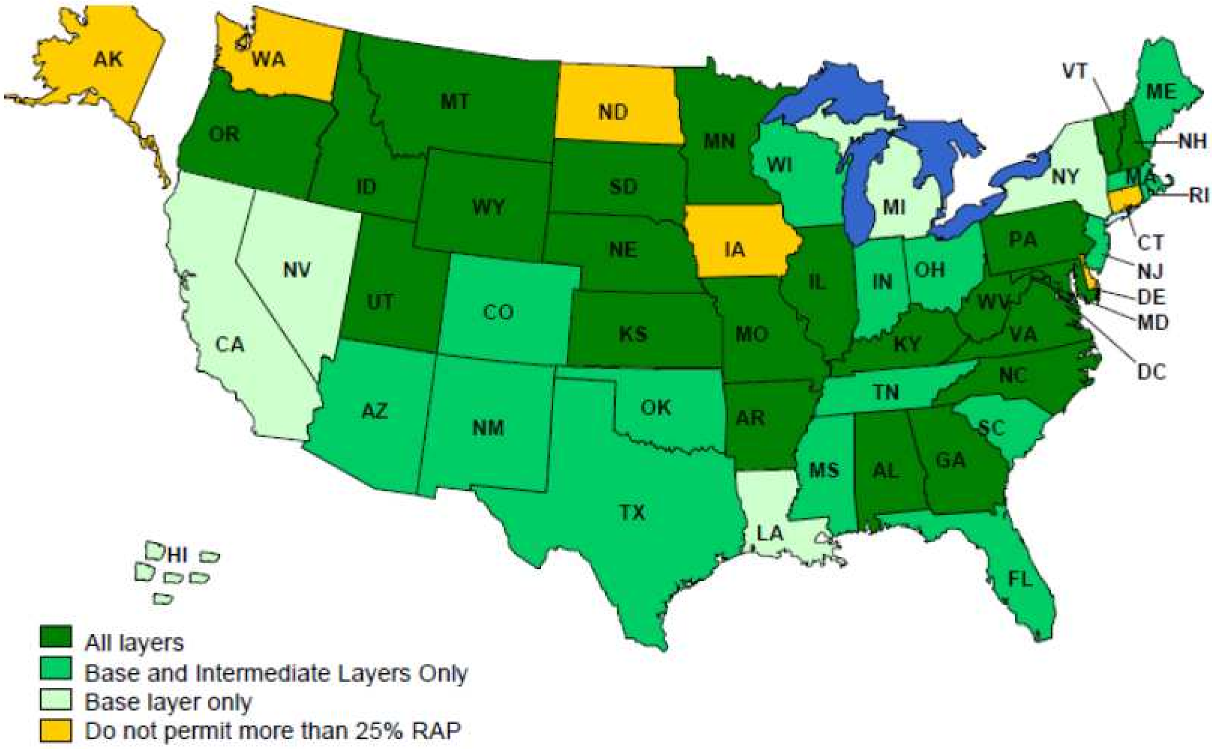


Figure 1.1 States that allow more than 25 percent of RAP in HMA mixtures (Copeland 2010)

1.2 Problem Statement

There are three main reasons for RAP to be favored over virgin materials: the increasing cost of crude oil and asphalt binder, scarcity of quality aggregates, and the pressing need to preserve the environment. Many state agencies have also reported significant savings when RAP is used. Considering material and construction costs, it has been estimated that use of RAP provides savings ranging from 14 to 34% for RAP content varying between 20 and 50%. Because of recent increases in asphalt binder prices, contractors are willing to use high percentages of RAP in HMA. The current national guideline, AASHTO M 323, for determining the binder-grade adjustment in HMA mixes, is shown in Table 1.1. The table shows a softer binder will be required if more than 15% RAP is going to be used in the HMA mix. Softer binders are more expensive and in the recent past, contractors were not willing to pay that extra amount. Nevertheless, as the asphalt price is rising, they are opting for higher percentages of RAP in Superpave mixtures.

Table 1.1 Binder selection guidelines for RAP mixtures according to AASHTO M 323

Recommended Virgin Asphalt Binder Grade	RAP Percentage
No change in binder selection	<15
Select virgin binder one grade softer than normal	15-25
Follow recommendations from blending charts	>25

One of the Superpave mix design requirements is control of the gradation of aggregates. Due to segregation in RAP stockpiles, and its influences on asphalt and dust content in the final mix, gradation control has been very difficult with RAP, especially when higher percentages of RAP were being added to the mix. The problem with segregated RAP is that the finer fraction will contain higher asphalt content, due to higher surface area, and that makes air void control in the mix very difficult. Fractionation is a process in which RAP is separated into at least two sizes, typically a coarse fraction, plus 12.5 or 9.5mm (1/2 or 3/8 inch), and a fine fraction, minus 12.5 or 9.5mm, in order to ensure the required consistency in RAP. In the United States, while some states are drafting specifications for fractionated RAP (FRAP), some others allow higher percentages of FRAP in the mix in compared to RAP. However, as of now, no systematic studies have been performed to look at the effects of FRAP on Superpave surface recycled (SR) mixtures.

1.3 Objectives

The main objectives of this research were to accomplish the following:

a) Evaluate the effect of increasing the percentage of RAP on the performance of Superpave mixtures, especially in terms of permanent deformation, fatigue cracking, and moisture susceptibility;

b) Evaluate the effect of using fractionated RAP as a replacement for RAP on the performance of Superpave mixtures; and

c) Evaluate the effect of RAP sources on the performance of RAP and FRAP Superpave mixtures.

1.4 Organization of Thesis

This thesis is divided into five chapters, including this introductory chapter (Chapter 1). Chapter 2 provides a literature review on reclaimed asphalt pavement (RAP), its benefits, and its challenges. Chapter 3 describes the methodology and laboratory testing. Chapter 4 discusses test results and related analysis, and Chapter 5 presents conclusions based on this study and recommendations for further studies.

Chapter 2 - Literature Review

2.1 Introduction

Reclaimed asphalt pavement (RAP), is the old, existing asphalt pavement that will be milled and stored in order to be used as a part of the new pavement. RAP can be obtained whenever an old existing pavement needs to be replaced or whenever a part of pavement needs to be cut in order to reach the underground utilities. If the existing old pavement is satisfactorily reclaimed, meaning milled and stored in a proper way, the aggregate in it can be used as a valuable source when quality aggregate is scarce. Besides, the existing binder in RAP can make up for some of the required binder in the hot-mix asphalt (HMA) mixture.

2.2 Benefits of Recycling Asphalt Pavement

Not being different from any other material, recycling asphalt pavement helps with having less disposals and preservation of environment. It also can reduce the construction and transportation costs, save aggregates and asphalt binder, and preserve the existing pavement geometry.

Figure 2.1 Milled reclaimed asphalt pavement


Figure 2.2 RAP Stockpiles at Shilling asphalt concrete production plant in Manhattan, KS

2.3 Hurdles in Using Higher RAP Contents in Hot-Mix Asphalt

Although RAP is allowed up to 30 percent in HMA mix in most states, its current average usage is only 12 percent. Less than 50 percent of the state departments of transportation add more than 20 percent RAP to the HMA mix. Many states, including Kansas, are either experimenting using higher percentages of RAP in the mix or routinely using higher percentages of RAP in HMA mixtures (FHWA-HRT-11-021).

There are some minor differences between producing RAP and virgin HMA mixtures including installation of scalping screen or any other device to hold large RAP particles before being mixed with the rest of aggregates in the drum or the need for RAP to be introduced to the mix away from the flame. Otherwise the production steps are similar in general and it is unknown why more than half of the states still hesitate to use higher percentages of RAP (FHWA-HRT-11-021).

The behavior of asphalt residue in RAP has a great influence on the final HMA mix performance. The two extreme possibilities for the behavior of binder residue in RAP are complete blending and no blending at all. Complete blending means that the contribution of the binder in RAP to the total binder required in the mix is 100 percent. No blending, on the other hand, means that the binder in RAP will remain as a "black rock "and does not blend with virgin binder at all. Besides affecting the performance, the level of blending guarantees RAP competitiveness. With high prices for asphalt binder, one of the reasons for RAP popularity is its contribution to the required binder in the mixture (FHWA-HRT-11-021).

It is accepted that in reality, the blending between residue asphalt in RAP and virgin binder is somewhere between 0 to 100 percent, but there exists no specific method to precisely determine the percentage of blending. One way to find out about the blending quantity is to conduct property tests such as dynamic modulus and compare the predicted results with actual results (FHWA-HRT-11-021).

In order to achieve the right asphalt PG grade for high RAP mixtures, blending charts, recommended by the state department of transportation, should be used. Development of blending charts is based on the assumption that 100 percent blending occurs between the virgin binder and the asphalt residue in RAP. If the basic assumption is not true, and 100 percent blending does not occur, serious concern might arise when as much as 40 percent RAP is being added to the mix. This can establish even more uncertainties about using higher percentages of RAP in HMA mixtures (Al-Qadi et al. 2007).

According to a NCDOT survey in 2009, the restrictions imposed by state transportation departments, on using higher percentages of RAP in the HMA mixture, are only one part of the problem. The other part of the problem involves contractors, who might not be always willing to use higher percentages of RAP. The reservations of the state transportation departments with high RAP fraction were based on uncertainties about the quality of RAP source and RAP consistency (RAP might lose its consistency if it is not stored properly), inaccuracies in binder grades and blending that takes place between RAP and virgin binder, the probable required changes in mix design when higher percentages of RAP are being introduced to the mix, problems with controlling the Superpave volumetric requirements, uncertainties about the long-term performance of mixtures with higher percentages of RAP, and finally concerns about using polymers. Among the contractors however, unwillingness to add higher percentages of RAP raises basically from the specification imposed by state transportation departments, problems with controlling RAP consistency, difficulties in obtaining required dust and moisture content, and finally excessive quality control (QC) requirements (FHWA-HRT-11-021).

2.4 RAP Characteristics to be Considered in Mix Design

As mentioned earlier, RAP is existing asphalt pavement which will be milled and stored in order to be used as a part of the new pavement. RAP contains valuable quantities of aggregates and binder. During years of service, both aggregates and binder were subject to changes affecting their qualities. To make sure that these changes are not going to negatively affect the HMA performance, specific considerations need to be taken (McDaniel and Anderson 2001).

2.4.1 Binder Characteristics

The most important thing is to know how much asphalt binder is still in the RAP. The binder content of RAP is important because it can be deducted from the total required binder for the HMA mixture. Once the binder quantity is known, it is time to consider the changes in physical and rheological properties of the binder residue in RAP due to oxidation during years of service. The aged binder is harder and it resembles higher binder PG grades. Due to lack of enough aged hardened binder to affect the final mix properties, it might not be necessary to test the properties of residue binder in RAP when lower percentages of RAP are introduced into the mix. For mixtures with more than 20 percent RAP, however, the properties of residue binder in RAP should be tested and considered in the mix design process. The recommended process is to extract and recover the binder in RAP and conduct performance grade (PG) tests on it. The extraction method is explained in AASHTO T 319, Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures. AASHTO T 319 is recommended because the extraction process used affects binder properties less than other methods (McDaniel and Anderson 2001).

2.4.2 Aggregate Characteristics

In Superpave HMA mix design, RAP is considered as a source of binder and aggregate, but the contribution of residue binder and aggregates are considered separately. Once the properties of binder in RAP are obtained, it is time to obtain the aggregate properties. Gradation is the most important characteristic of aggregates obtained from RAP and is obtained using Kansas test method KT-2 (AASHTO T 27).

Once the aggregate gradation was obtained, the bulk specific gravity (G_{sb}) of RAP aggregate should be obtained. If the history of RAP aggregates exists, the G_{sb} of original aggregates in the RAP can be used in mix design. If the G_{sb} of original aggregates does not exist but the effective specific gravity (G_{se}) records are available, the G_{se} can be replaced by G_{sb}. Replacing G_{se} for G_{sb} will not cause any problem because G_{se} is always greater than G_{sb} and the substitution will over estimate the bulk specific gravity of the blend (the combination of virgin aggregates and RAP). In case that no records exist for G_{se} or G_{sb} of the original aggregates in RAP or when higher percentages of RAP are introduced into the mix (causing non-negligible errors if G_{sb} is substitute by G_{se}), a typical value for the asphalt absorption will be assumed and RAP G_{sb} will be calculated using the G_{se}. The assumption for asphalt absorption should be based on experiences obtained during mix designs ate similar locations (FHWA-HRT-11-021).

2.5 RAP Fractionation

Due to segregation in RAP stockpiles and its influences on asphalt and dust content in the final mix, gradation control has been very difficult with RAP, especially when higher percentages of RAP are being added to the mix. The problem with segregated RAP is that the finer fraction will contain higher asphalt content, because of higher surface area, making the air-void control in the mix very difficult.

Fractionated RAP (F-RAP) is RAP that is separated into at least two different sizes in order to have a better control over consistency of the mix and gradation of the aggregates. Typical sizes for coarser and finer fraction are, respectively, +1/2 or +3/8 inches (+12.5 or +9.5 mm) and -1/2 or -3/8 inches (FHWA-HRT-11-021).

According to a survey in 2008 that received responses from 29 states, three states (South Carolina, Texas, and Alabama) had specifications for fractionating RAP, and three other states (Ohio, Wisconsin, and Illinois) were drafting specifications for fractionating RAP. These six states would allow higher amounts of RAP if it had been fractionated. A 2009 survey showed that if FRAP is used, 10 state transportation departments, Arizona, Georgia, Illinois, Kansas, North Carolina, Ohio, Texas, Utah, Wisconsin, and Washington, D.C., will allow a five percent increment of binder replacement for the surface mixes. It should be mentioned that crushing and screening RAP over a single screen is not fractionation and the product will not be called FRAP. As already mentioned, RAP fractionation is supposed to improve the consistency of the mix, but data collected from the contractors across United States by NCAT in 2008 and 2009, showed that FRAP stockpiles were no more consistent than the processed RAP stockpiles (FHWA-HRT-11-021).

2.6 Mix Design Consideration with High Percentages of RAP

One of the advantages of Superpave is the flexibility of mix design that allows adding different additives, such as RAP, to the HMA mix as long as the specified gradation can be achieved. There are two methods to select the percentages of RAP in the mix. The first method includes deciding about the expected contribution of RAP towards the total mix based on the RAP weight (as a percentage of total mix by weight). The second method includes deciding about the expected contribution of the residue binder in the RAP towards the total binder in the mix (as a percentage of total required binder by weight) while meeting volumetric properties requirements.

The Superpave mix design requirements for mixes with higher percentages of RAP are similar to the mix designs containing all virgin materials. Once the RAP has been characterized, it can be combined with the virgin aggregates to form a uniform blend gradation for mix design purposes. To satisfy gradation requirements, the selected blend must pass between the control points. Mixture volumetric requirements that need to be met for all Superpave mixes include voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), dust proportion, and 4% air voids at the N_{design} level. As result of being milled and crushed, RAP usually contains notably higher percentages of material passing a 0.075-mm (US No. 200) sieve. This limits the amount of RAP that can be used in a mix design while meeting the volumetric properties. The percentage of asphalt binder in the RAP should also be considered when determining asphalt binder content. Asphalt binder content of the total mix includes virgin and reclaimed asphalt binder. The RAP material should not be heated to the same temperature as for the aggregates and need to be heated separately at much lower temperatures (about 140^{0}F) than that needed for mixing and compaction (about 320^{o}F). To make up for the lower temperature of RAP, especially when added to the mix at high percentages, virgin aggregates are heated to a higher temperature so that when mixed, the mix temperature is within the required mixing temperature range. The philosophy behind not heating RAP to very high temperatures is to prevent additional aging of the existing binder in RAP. The recycled HMA should meet all test procedures and criteria as required for the virgin HMA (Al-Qadi et al. 2007, Brown et al. 2009).

To make up for the aged and hardened binder in RAP, a softer virgin binder needs to be add to the mix, especially when higher than 15 percent RAP is being added to the mix. In order to find the right binder PG grade for high RAP mixtures, a blending chart or blending equation is frequently used. The blending charts or equations can be used if the virgin binder PG grade is already chosen and the percentage of RAP in the mix is to be determined, or if the percentage of RAP to be added to the mix is known and binder PG grade for the virgin binder is to be determined. Procedures for using a blending chart are provided in the appendix of AASHTO M 323. In order to find the required binder PG grade according to AASHTO M 323, three critical temperatures including critical high temperature ($Tc_{(High)}$), intermediate critical temperature ($Tc_{(Int)}$), and low critical temperature ($Tc_{(Low)}$) should be obtained. The $Tc_{(High)}$ will be determined based on the original DSR and rolling thin film oven (RTFO) DSR. The high-temperature PG of the recovered binder is the minimum of DSR and RTFO DSR critical temperatures. The ($Tc_{(Int)}$) is determined by conducting intermediate-temperature DSR testing on the RTFO-aged recovered RAP binder as if the RAP binder were pressure-aging vessel-aged. The critical low temperature ($Tc_{(S)}$ or $Tc_{(m)}$) is determined based on the bending-beam rheometer tests on the RTFO-aged recovered RAP binder, or m-value. The low critical temperature ($Tc_{(Low)}$) is the higher of the two low critical temperatures, $Tc_{(S)}$ or $Tc_{(m)}$. The low- temperature PG of the recovered RAP binder is based on this low critical-temperature value.

Once the physical properties and critical temperatures of the recovered RAP binder are known, two existing approaches for blending are as follows (FHWA-HRT-11-021):

- Blending at a known RAP percentage, and
- Blending with a known virgin binder grade.

2.6.1 Blending at a Known RAP Percentage

When the desired final blended binder grade, the desired percentage of RAP, and the recovered RAP binder properties are known, the required properties of a virgin binder grade can then be obtained at each temperature (high, intermediate, and low) separately as follows:

$$\boldsymbol{T_{virgin}} = \frac{\boldsymbol{T_{blend}} - (\%\boldsymbol{RAP} \times \boldsymbol{T_{RAP}})}{(\mathbf{1} - \%\boldsymbol{RAP})} \tag{2.1}$$

where

T_{Virgin} = Critical temperature of virgin asphalt binder (high, intermediate, or low);

T_{Blend} = Critical temperature of blended asphalt binder (final desired) (high, intermediate, or low);

%RAP = Percentage of RAP expressed as a decimal; and

T_{RAP} = Critical temperature of recovered RAP binder (high, intermediate, or low).

2.6.2 Blending with a Known Virgin Binder Grade

When the final blended binder grade, the virgin asphalt binder grade, and the recovered RAP properties are known, the allowable RAP percentage can be determined as follows:

$$\%\boldsymbol{RAP} = \frac{\boldsymbol{T_{blend}} - \boldsymbol{T_{virgin}}}{\boldsymbol{T_{RAP}} - \boldsymbol{T_{virgin}}} \tag{2.2}$$

The RAP percentage should be determined at high, intermediate, and low temperatures. The RAP content or range of contents meeting all three temperature requirements should be selected. NAPA, in partnership with AASHTO and FHWA, has published a guide for designing HMA mixtures with high RAP percentages (Copeland 2010). The guide includes information on evaluating RAP material, mix design, plant verification, and quality control (QC).

2.7 Performance of HMA Mixtures with RAP

McDaniel (2002) did a comprehensive evaluation to determine if the tiered approach (table 1.1) of the Federal Highway Administration and Superpave RAP specifications is applicable to the materials obtained from Indiana, Michigan, and Missouri. In that study, laboratory mixtures were compared to the plant-produced mixtures with the same materials at RAP contents between 15 and 25%. Additional mixtures were designed and tested in the laboratory, with RAP content up to 50%, to determine the effect of recycled materials on mix performance. Results showed that plant-produced mixes were similar in stiffness to the laboratory mixtures at the same RAP content for the Michigan and Missouri samples. Furthermore, mixtures with up to 50% RAP could be designed with Superpave, provided RAP gradation and aggregate quality were sufficient. Linear blending charts were found to be appropriate in most cases. It was observed that increasing RAP content in a mixture increased stiffness and decreased shear strain, indicating increased resistance to rutting. It was concluded that when RAP properties are appropriately accounted for in the material selection and mix design process, Superpave mixtures with RAP can perform very well (McDaniel 2002).

Another study investigated short- and long-term performance of RAP mixes and compared them with the virgin HMA overlays used on flexible pavements. Data from 18 projects, ranged in age from eight to 17 years, from the long-term pavement performance (LTPP) program in North America were analyzed. . Distress parameters considered were roughness, rutting, and fatigue cracking. Structural performance of the overlaid sections was also evaluated with the deflection data. Results of the analysis of variance indicated the performance of RAP mixes and virgin HMA were not statistically different. Statistical similarity of deflections showed that RAP overlays can provide structural improvement that is equivalent to the virgin HMA overlays (Carvalho et al. 2010).

While rutting performance has typically been improved using RAP, fatigue and thermal performance has been inconsistent. Typically fatigue resistance is improved due to the stiffer nature of the aged binder in a recycled mixture, but this is only found in constant strain testing, and no consistent level of improvement has been reported. At higher blending percentages, the results are unpredictable. Low temperature thermal resistance is typically lowered because of the stiffer nature of the recycled mixtures.

2.8 RAP Cost Efficiency

As mentioned earlier, one of the most important reasons to use RAP in HMA mix is its cost efficiency. The following example is to provide some general ideas on how much RAP contributes to the cost reduction of the HMA mix. The source for all prices provided in this section is NAPA.

The basic assumptions in this analysis are: RAP asphalt content is 5.8 percent, cost of virgin asphalt is \$350/ton, and cost of virgin aggregates is \$10/ton.

Value of asphalt binder in RAP = 350×0.058 = \$20.3/ton **Equation 2.3**

Value of aggregates in RAP = 10× (1- 0.058) = \$9.42/ton **Equation 2.4**

Total value of RAP = 9.42+20.3 = \$29.72/ton **Equation 2.5**

Table 2.1 shows the RAP contribution to the mix for different percentages of RAP added to the mix. As shown in table 2.1, as the RAP percentage increases in the mix, it can provide better economic contribution to the HMA mix, and the price will decrease.

Table 2.1 RAP cost analysis for different mix designs and its contribution to the mix

Considered items	Price (\$)
Value of RAP	*29.72*
Plant cost for extra equipment	*-0.75*
Trucking cost	*-3*
Processing and handling cost	*-5*
Extra quality control cost	*-0.25*
Total savings	*20.72*
Savings for 20% RAP mix	*4.14 (14%)*
Savings for 30% RAP mix	*6.21 (21%)*
Savings for 40% RAP mix	*8.28 (28%)*

2.9 Summary

Attaining the goal of recycling, most importantly to achieve good performance in fatigue, rutting, thermal resistance, and overall durability while optimizing the amount of RAP utilized, poses problems for the asphalt materials engineer. Considerable research into the effects of mixture characterizations, aggregate properties and gradation, and binder properties of the RAP has given inconsistent results at times. This is especially true at high RAP blending percentages. The three- tier system of FHWA provides good recycled mixtures at low- to- moderate blend percentages. Aggregate gradation concerns become significant at higher RAP blend percentages, mainly due to high fines content and uncertain binder properties. To address this problem, fractionated RAP has been introduced and already used in many states.

More than 80 million tons of HMA recycled every year make asphalt the number one recycled product in United States. Use of RAP in hot-mix asphalt (HMA) has gained renewed interest because of high crude oil prices and environmental concerns, and higher proportions of RAP in HMA are being considered now. However, such mixtures tend to have some mixture design and performance challenges, especially due to variability in the source and material itself. In general, pavements with RAP mixes perform as well as the pavements with virgin mixes, provided RAP quantities and qualities are under control.

Chapter 3 - Laboratory Testing

3.1 Experimental Design and Methodology

To achieve the objectives of the study, all tests have been conducted on two different sources of RAP in order to control the effect of the RAP source on HMA performance. The first and second RAP sources were, respectively, obtained from Shilling Construction Company, a locally owned company in Manhattan, Kansas, and Konza construction, a construction company in Junction City, Kansas. For each RAP source, five different mixes with 20, 30, and 40% RAP, and 30, and 40% FRAP, were made and performance tests, conducted. Five different mix designs for each source of RAP were developed in the laboratory using 12.5-mm nominal maximum aggregate size (NMAS) design criteria. To be able to compare the effect of RAP source on HMA performance, same virgin aggregates were used for all Superpave mixtures. The designed Superpave mixes were then tested for performance in terms of rutting using the Hamburg wheel-tracking device (HWTD), moisture sensitivity by modified Lottman tests (KT-56), and resistance to fatigue cracking and permanent deformation by the dynamic modulus test.

3.1.1 RAP and PG Binder Selection

According to AASHTO M 323, due to the stiffening effect of the aged binder in the RAP, the specified binder grade of the virgin binder needs to be adjusted for asphalt mixes containing more than 15% RAP. The adjustments in this study were made using the blending chart developed by the Kansas Department of Transportation (KDOT). In order to use the KDOT blending chart, it is required to know the PG asphalt binder grade for the RAP and virgin asphalts. For both sources, the RAP PG grade was acquired through a set of tests conducted by KDOT and the virgin PG grade was derived based on the climatic conditions and 20-year design traffic of the project.

For the first source of RAP, knowing the RAP PG grade was 84-16 and the virgin binder PG grade was 70-28, based on KDOT's blending chart, the low sides of PG limits were -26 and -23 for 20% and 40% RAP, respectively. Consequently, -28 was chosen as the lower limit for the PG binder in this study. The high sides were 73 and 76 for 20 and 40% RAP, respectively, which resulted in PG 70 for the binder grade high side. Therefore, PG 70-28 was chosen for all HMA mixes containing 20 to 40% RAP for the first source of RAP.

For the second source of RAP, knowing the RAP PG grade was 91-10, based on KDOT's blending chart, the low sides of PG limits were -24 and -21 for 20% and 40% RAP, respectively. Consequently, -28 was chosen as the lower limit for the PG grade. The high sides were 74 and 78 for 20 and 40% RAP, respectively, which resulted in PG 70 for the binder grade high side. Therefore, PG 70-28 was chosen again for all HMA mixes containing 20 to 40% RAP for the second source of RAP. Figures 3.1 and 3.2 show the Excel sheets used to determine higher and lower limits for the PG grade, and Figure 3.3 shows the gradation of the first and second sources of RAP.

3.1.2 Virgin Aggregates and RAP

Five different virgin aggregates with 12.5-mm nominal maximum aggregate size (NMAS) obtained from Shilling Construction Company were mixed with three different percentages of RAP and selected virgin binder quantity. The combined blend had five different virgin aggregates: coarse-crushed limestone (CS-1), fine-crushed limestone (CS-1A), manufactured sand (MSD-1), crushed gravel (CG-5), and natural/river sand (SSG). The percentages of RAP added to the mix were 20%, 30%, and 40%. Furthermore, 30% and 40% FRAP mixes were made and tested to control the effect of RAP consistency on its performance.

Table 3.1 shows the gradation of various aggregates used in this study. Table 3.2 shows their percentages in each blend, and Table 3.3 shows the percentage of fine (minus 12.5 mm) and coarse aggregates (plus 12.5 mm) in the mixes containing FRAP. Since the RAP mix had a nominal maximum aggregate size (NMAS) of 9.5 mm (3/8 in), a higher fraction of fine materials was used.

Figures 3.3 and 3.4 show the 0.45-power chart for all five different aggregates used in mix design and for two sources of RAP, respectively. Table 3.4 shows the square-mesh sieve analysis results for both sources of RAP.

KDOT BLENDING CHART CALCULATION

Low Side of The Binder

Project Number		
RAP & Virgin Binder Inputs		
Temperatures	PG_{upper}	PG_{lower}
PG_{RAP}	84	-16
PG_{virgin}	70	-28

RAP Percent in Mix Design*		20.0
Blended Low Grade of Binder:		-26

High Side of The Binder

Project Number		
RAP & Virgin Binder Inputs		
Temperatures	PG_{upper}	PG_{lower}
PG_{RAP}	84	-16
PG_{virgin}	70	-28

RAP Percent in Mix Design*		40.0
Blended High Grade of Binder:		73

* If utilizing FRAP insert total FRAP percent (coarse and fine) in Mix Design

Blending Chart Calculations

%RAP	PG_{blend} =
0.00	-28
5.00	-27
10.00	-27
15.00	-26
20.00	-26
25.00	-25
30.00	-24
35.00	-24
40.00	-23
45.00	-23
50.00	-22
55.00	-21
60.00	-21

Blending Chart Calculations

%RAP	PG_{blend} =
0	70
5	71
10	71
15	72
20	73
25	74
30	74
35	75
40	76
45	76
50	77
55	78
60	78

Figure 3.1 KDOT's blending charts for PG grade adjustments for first source of RAP

KDOT BLENDING CHART CALCULATION

Low Side of The Binder

Project Number		
RAP & Virgin Binder Inputs		
Temperatures	**PG_{upper}**	**PG_{lower}**
PG_{RAP}	91	-10
PG_{virgin}	70	-28

RAP Percent in Mix Design*		20.0
Blended Low Grade of Binder:		-24

High Side of The Binder

Project Number		
RAP & Virgin Binder Inputs		
Temperatures	**PG_{upper}**	**PG_{lower}**
PG_{RAP}	91	-10
PG_{virgin}	70	-28

RAP Percent in Mix Design*		40.0
Blended High Grade of Binder:		74

* If utilizing FRAP insert total FRAP percent (coarse and fine) in Mix Design

Blending Chart Calculations

%RAP	**PG_{blend} =**
0.00	-28
5.00	-27
10.00	-26
15.00	-25
20.00	-24
25.00	-24
30.00	-23
35.00	-22
40.00	-21
45.00	-20
50.00	-19
55.00	-18
60.00	-17

Blending Chart Calculations

%RAP	**PG_{blend} =**
0	70
5	71
10	72
15	73
20	74
25	75
30	76
35	77
40	78
45	79
50	81
55	82
60	83

Figure 3.2 KDOT's blending charts for PG grade adjustments for second source of RAP

Table 3.1 Aggregate gradation

Material	CS-1	CS-1A	MSD-1	CG-5	SSG	1st RAP	2d RAP
Sieve Size	**% Passing**						
3/4	100					100	100
1/2	55	100	100	100	100	98	96
3/8	17	100	100	100	100	94	92
#4	0	26	99	94	96	80	78
#8	0	1	57	71	81	64	64
#16	0	0	28	43	57	47	48
#30	0	0	14	24	35	33	35
#50	0	0	5	12	14	20	21
#100	0	0	2	5	2	13	15
#200	0	0	0	0	0	10	12

Table 3.2 Aggregate percentages in different mixes

RAP (%)	CS-1 (%)	CS-1A (%)	MSD-1 (%)	CG-5 (%)	SSG (%)
20	20	12	12	16	20
30	16	15	13	12	14
40	12	13	13	12	10

Table 3.3 Percentage of fine and coarse aggregates in FRAP

% of FRAP in Mix	% of RAP plus 12.5mm (1/2 inch)		% of RAP minus 12.5mm (1/2 inch)	
	1st source	2d source	1st source	2d source
30	9	5	21	25
40	12	8	28	32

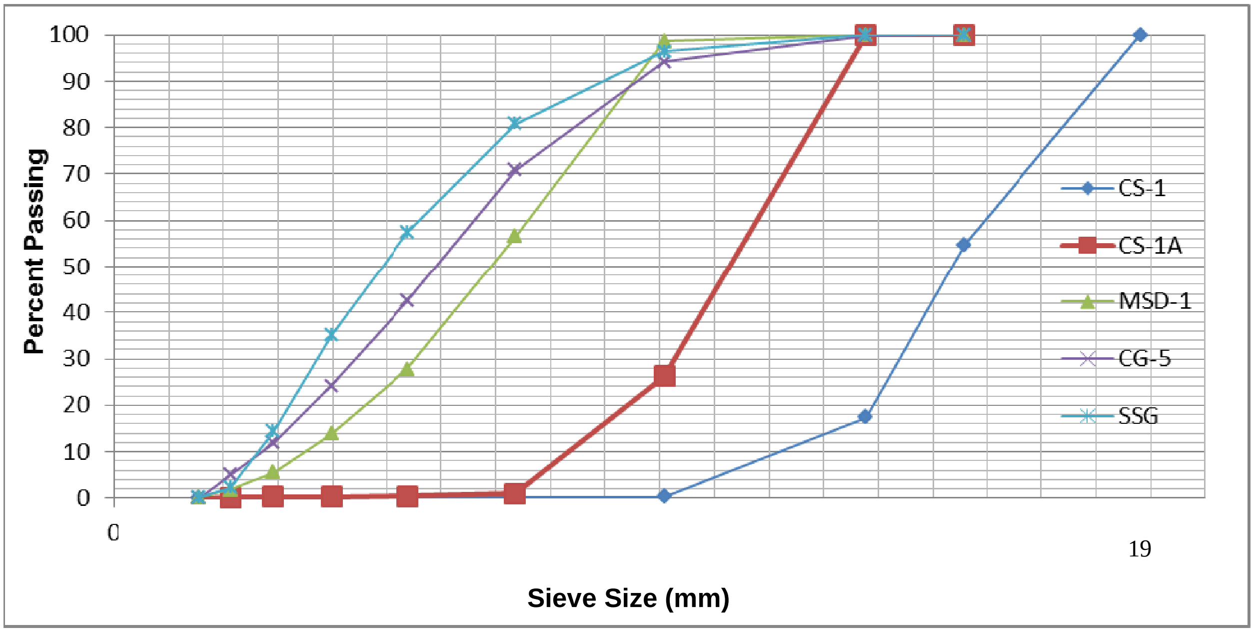


Figure 3.3 0.45-power chart for aggregates used in mix design

Figure 3.4 0.45-Power chart for the RAP sources used in mix design

Table 3.4 Square-mesh sieve analysis results for both sources of RAP

Sieve Sizes (mm)	% Retained		Cumulative % Retained		% Passing	
	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP
19	0	0	0	0	100	100
12.5	2	4	2	4	98	96
9.5	4	4	6	8	94	92
4.75	14	14	20	22	80	78
2.36	16	14	36	36	64	64
1.18	17	14	53	52	47	48
0.6	14	13	67	65	33	35
0.3	13	14	80	79	20	21
0.15	7	6	87	85	13	15
0.075	3	2	90	87	10	12

Table 3.5 Aggregates blending and KDOT requirements for three different percentages of RAP used in the mix

Sieve size (mm)	20% RAP		30% RAP		40% RAP		KDOT requirements
	1st RAP %	2d RAP	1st RAP %	2d RAP	1st RAP %	2d RAP	
19	0	0	0	0	0	0	0
12.5	9	10	8	8	6	7	0-10
9.5	18	18	15	16	12	13	10 Min
4.75	35	35	34	35	31	32	
2.36	53	53	53	53	50	50	42-61
1.18	69	69	69	69	67	66	
0.60	81	80	80	80	79	78	
0.30	91	90	90	89	88	88	
0.15	96	95	95	94	94	93	
0.075	98	97	97	96	96	95	90-98

3.2 Laboratory Mix Designs

In this study, mix designs were developed in the laboratory to meet the requirements of Superpave 12.5-mm NMAS mixtures using two RAP sources, one asphalt binder (PG 70-28), three different percentages of RAP (20%, 30%, and 40%), and two different percentages of

FRAP (30% and 40%). Superpave mixtures were developed meeting Superpave volumetric mixtures in Kansas as shown in Table 3.6. Design asphalt content was selected based on KDOT-specified volumetric criteria at 4.0 percent air voids at N_{des} level of 75 gyrations. Virgin aggregates were blended, heated, and finally mixed with the heated binder and RAP. Binder was heated to the recommended mixing temperature (309 - 320 ^{0}F) based on the virgin PG binder grade, and RAP was heated to 122 ^{0}F. To make up for the low temperature of RAP, virgin aggregates were heated to 350 ^{0}F before being mixed with the binder and RAP. All mixes were aged at the recommended compaction temperature (270 - 281 ^{0}F) for two hours before compaction in the Superpave gyratory compactor. Bulk specific gravity and unit weight of compacted asphalt mixtures (G_{mb}), and theoretical maximum specific gravity of asphalt mixtures (G_{mm}) were determined based on AASHTO T-166 (KT-15) and AASHTO T-209 (KT-39) test methods, respectively. Table 3.6 shows the volumetric properties of all five different mixes and KDOT requirements for 12.5-mm nominal maximum aggregate Size (NMAS). All mixes in this study met these requirements. In general, total asphalt content for these mixtures were lower than Superpave mixes with all virgin materials. This is due to the fact that most coarse aggregates in Kansas are soft limestone with high absorption. Use of 20 to 40% RAP and FRAP considerably reduces total asphalt content used for the recycled mixes. This is reinforced by the fact that the mixtures containing 40% RAP and 40% FRAP have the lowest asphalt content.

3.3 Performance Tests on Laboratory Mixtures

Performance tests were conducted in this research to evaluate the performance of designed mixtures containing RAP and FRAP. The performance of HMA mixtures in terms of rutting, moisture susceptibility, and fatigue cracking were analyzed and evaluated to determine the effect of increasing RAP percentage in the mix and replacing RAP with FRAP. Specimens fabricated by the Superpave gyratory compactor at target air voids were used to conduct laboratory performance tests. A brief description of the tests follows.

Table 3.6 Volumetric properties of five different mixes and KDOT requirements

Mix Design	Total asphalt content (%)		Virgin asphalt added (%)		Asphalt contained in RAP (%)		%Airvoid @ Ndes		%VMA		%VFA		Dust to binder ratio		% Gmm @ Nini		% Gmm @ Ndes	
	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP
20% RAP	*4.7*	*4.3*	3.6	3.50	1.1	0.80	3.9	4.0	14.1	14.0	71.6	71.5	0.6	0.61	88.5	88.5	96.0	96.0
30% RAP	*4.8*	*4.4*	3.1	3.20	1.7	1.20	4.0	3.9	14.0	14.1	71.3	71.7	0.6	0.62	88.0	88.0	96.0	96.0
40% RAP	*4.3*	*4.1*	2.1	2.50	2.2	1.60	4.0	4.0	14.2	14.0	71.9	71.3	0.7	0.61	87.9	87.8	96.0	96.0
30% FRAP	*4.3*	*4.4*	2.6	3.20	1.7	1.20	4.0	4.0	14.1	14.0	71.6	71.3	0.7	0.63	87.7	87.9	96.0	96.0
40% FRAP	*4.4*	*4.2*	2.1	2.60	2.3	1.60	4.1	4.1	14.3	14.0	72.0	71.3	0.7	0.6	87.8	87.8	96.0	96.0
KDOT Superpave volumetric mix design requirements for 12.5 MNAS									**Minimum 14**		**65-78**		**0.6 - 1.2**		**Maximum 90.5**		**Maximum 98**	

3.3.1 Hamburg Wheel-Tracking Device

The Hamburg wheel-tracking device (HWTD) is a common tool to assess stripping and rutting susceptibility of HMA mixtures. This test was used in this study to see how higher percentages of RAP and FRAP affect rutting and stripping susceptibility of Superpave mixtures containing RAP/FRAP. The tests were performed following the Tex-242-F test method of the Texas Department of Transportation (TxDOT). The samples were made using the Superpave gyratory compactor following AASHTO T-324 specifications. The Hamburg wheel tracking device (HWTD), manufactured by PMW, Inc. of Salina, Kansas, was used in this study (Figure 3.5). This device can test two specimens simultaneously and is operated by rolling a pair of steel wheels across the surface of specimens submerged in a water bath held at 50°C. The wheels have a diameter of 204 mm (8 inches) and width of 47 mm (1.85 inches). The device operates at approximately 50 wheel passes/min and the load applied by each wheel is approximately 705±22 N (158±5 lbs). Specimens used in this test were compacted to 7±1 percent air voids using a Superpave gyratory compactor. The specimens were 150 mm (6 inches) in diameter and 62 mm (2.4 inches) in height. Rut depth was measured automatically and continuously at 11 different points along the wheel path of each sample with a linear variable differential transformer (LVDT) with an accuracy of 0.01 mm (0.0004 inch). HWTD automatically stops the test if the preset number of cycles is reached or if the rut depth measured by the LVDTs reaches the value of 20 mm (0.8 inch) for an individual specimen.

Figure 3.5 Hamburg wheel-tracking device (HWTD) test setup

Once the test is completed, performance of the HMA is evaluated to determine failure susceptibility of the HMA as interpreted from the various parameters derived from the typical test output shown in Figure 3.6. These parameters are assumed to describe HMA failure due to weakness in the aggregate structure, inadequate binder stiffness, and/or moisture damage.

The post-compaction consolidation is the deformation in millimeters at 1,000 wheel passes and occurs rapidly during the first few minutes of the test. This parameter is referred to as the post-compaction consolidation because it is assumed the wheel is densifying the mixture within the first 1,000 wheel passes. The creep slope is the inverse of the deformation rate within the linear region of the deformation curve after post compaction and prior to stripping (if stripping occurs). The creep slope measures rutting susceptibility. It measures the accumulation of permanent deformation primarily due to a mechanism other than moisture damage. The stripping slope is the inverse of the deformation rate within the linear portion of the deformation curve, after the stripping began. The stripping inflection point is the number of wheel passes corresponding to the intersection of the creep slope and the stripping slope. The stripping slope measures the accumulation of permanent deformation due to moisture damage. It is used to estimate the relative resistance of the HMA sample to moisture-induced damage. In other words, this is the number of wheel passes at which moisture damage starts to dominate performance. The lower the inverse stripping slope, the more severe the moisture damage (Yildirim et al 2007).

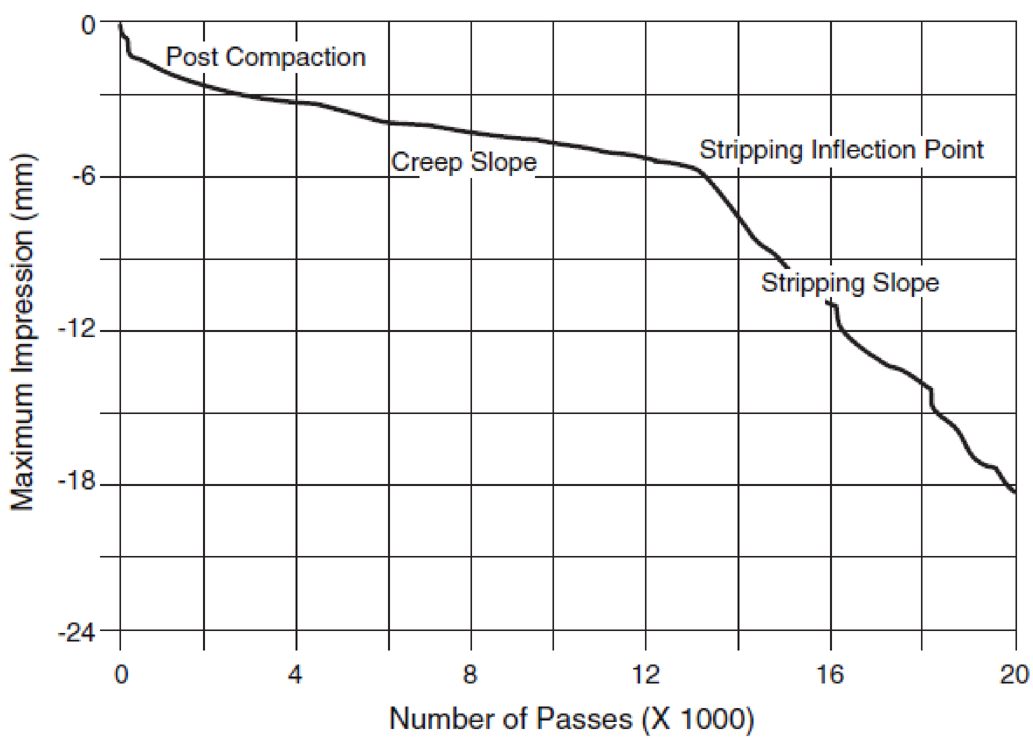


Figure 3.6 Typical Hamburg test curve and its major characteristics

3.3.2 Moisture Susceptibility Test

The moisture susceptibility test evaluates the effect of saturation and accelerated water conditions on compacted HMA samples utilizing freeze-thaw cycles. Kansas Test Method KT-56, Resistance of Compacted Asphalt Mixtures to Moisture- Induced Damage, commonly known as the modified Lottman test in Kansas, was used to evaluate moisture susceptibility in this study. For this test, specimens should be 150 mm (6 inches) in diameter and 95 mm (3.75 inches) in height. Six specimens were compacted to 7±0.5 percent air voids using the Superpave gyratory compactor. After compaction and air void determination, the six specimens were subdivided into two subsets of three samples so that average air void content of the two subsets were approximately equal. Diameter and thickness of the specimens were measured before further testing. Three specimens were selected as a control set and tested dry (without conditioning). The other subset of three specimens was conditioned by being subjected to a partial vacuum saturation of 70 to 80% of air voids, by placing them in a vacuum container filled with water in a way that at least 25 mm (1 inch) of water is covering them. A partial vacuum of 250 to 650 mm of Hg was applied to the container for a short time. After the degree of saturation for each specimen had been verified as meeting the test protocol, the conditioned samples were individually wrapped in a plastic film, and placed and sealed in a zip-lock bag with 10mL water. Samples are then placed in a freezer for a minimum of 16 hours at -18±3^{o}C. After freezing, the samples were thawed by being placed in a hot water bath for 24±1 hrs at 60±1^{o}C. The conditioned samples were then removed from the hot water bath and kept in a 25±1^{o}C water tank for two hours. Once the two hours was over, saturated surface dry (SSD) mass and mass under water was recorded for each plug. Unconditioned specimens (sealed in plastic wrap) were placed in a water bath for two hours at 25°C before their tensile strength were tested. Final diameter and thickness of conditioned samples was measured after removing them from the water bath and before testing. Both conditioned and unconditioned specimens were tested at a loading rate of 51 mm/minute till they broke and peak loads were recorded. Tensile strength was computed using equation 3.1 (Hossain et al. 2010). Figure 3.7 shows the different steps in this test method.

$$S = \frac{2000P}{\Pi t D} \tag{3.1}$$

where

S = tensile strength (kPa),

P = maximum load (N),

t = specimen thickness (mm), and

D = specimen diameter (mm).

Tensile strength ratio (TSR) is used to denote HMA resistance to the detrimental effects of moisture. It is defined as the ratio of average tensile strength retained after freeze-thaw conditioning (average tensile strength of conditioned specimens) to average tensile strength of unconditioned samples. Percent tensile strength ratio is computed using Equation 3.2.

$$\mathrm{TSR} = \frac{S_2}{S_1} \times 100 \qquad (3.2)$$

where:

S_1 = average tensile strength of unconditioned subset, and

S_2 = average tensile strength of conditioned subset.

(a)

(b)

(c)

(d)

Figure 3.7 Modified Lottman test steps: (a) vacuum Saturation, (b) specimens in freezer, (c) specimens in hot water bath, and (d) Specimen in testing frame

3.3.3 Dynamic Modulus Test

The HMA resistance to permanent deformation, or rutting and fatigue cracking, can be characterized using the dynamic modulus and phase angle of HMA. In order to measure the dynamic modulus $|E^*|$ and phase angle (δ) a sinusoidal axial compressive load was applied to the cylindrical specimen at a sweep of testing frequencies. $|E^*|$ was calculated by dividing the peak-to- peak stress by the peak-to-peak strain as shown in Figure 3.8. For mixtures to be rut resistant and exhibit higher stiffness at high temperature, a greater $|E^*|$ value and a lower phase angle are desirable (FHWA-HRT-11-021 2010).

The dynamic modulus test was conducted on specimens cored and trimmed to the size of 4 inches in diameter and 6 inches in height from a sample 6 inches in diameter and 11inches in height. The taller samples were fabricated using the gyratory compactor and were compacted to an air void level of 7±1 %. The 7±1 % was the core air void and was chosen to make the comparison between HWTD and dynamic modulus test results possible (as mentioned earlier, Hamburg specimens were compacted in 7±1 % air void).

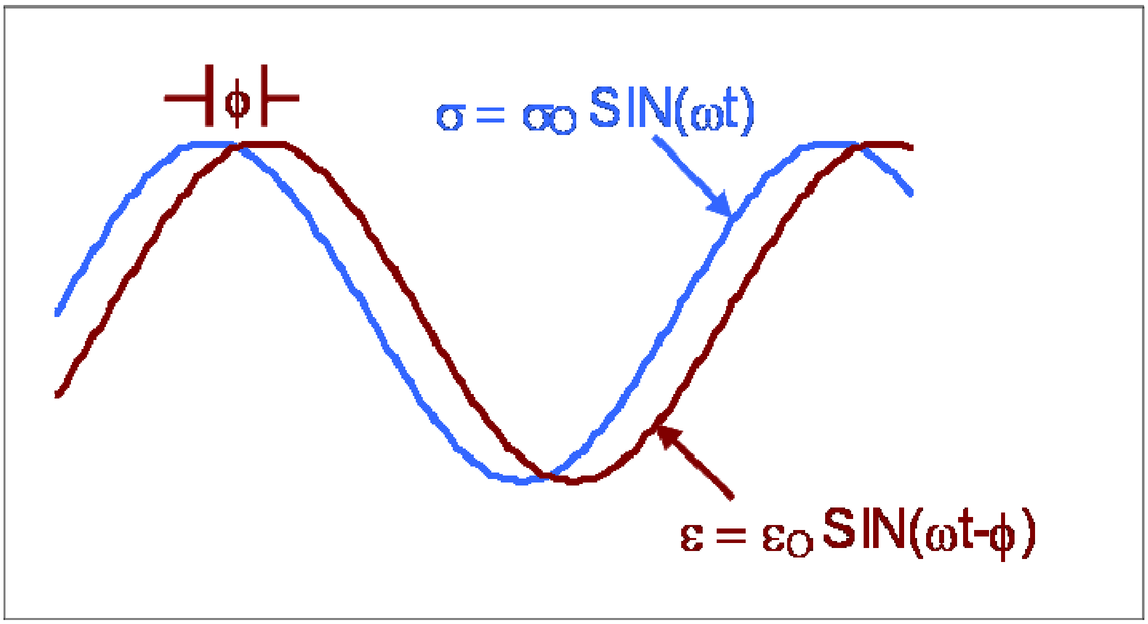


Figure 3.8 Sinusoidal loading in dynamic modulus test

Figure 3.9 shows a tall sample that has been fabricated in the Superpave gyratory compactor and a Dynamic modulus test sample that was cored and trimmed from it. The dynamic load ranged between 10 and 690 KPa (1.5 to 100 psi), and a higher load was used for lower test temperatures. The effective test temperature varied and the design frequency ranged between 0.1 and 25 Hz. The dynamic load was adjusted to obtain axial strains between 50 and 150 micro-strains.

Specimen ends were treated to reduce friction. The specimen was then placed in the testing chamber at the desired test temperature, and was left to stabilize before the sample was tested. The test specimen was first preconditioned with 200 cycles at 25 Hz using the target dynamic load. Then the specimen was loaded in specified temperature, frequency, and number of cycles. The loading stress and recoverable axial strain were computed for each frequency. Dynamic modulus and the phase angle were then calculated.

Figure 3.9 Superpave gyratory compactor sample, and cored and trimmed sample

In this study, dynamic modulus samples were tested using a universal testing machine (UTM-25) and an asphalt-mixture performance tester (AMPT) for the first and second source of RAP, respectively, following AASHTO TP: 62-03 (Standard Test Method for Determining Dynamic Modulus of Hot Mix Asphalt Concrete Mixtures). To accomplish the dynamic modulus test, three linear variable differential transducers (LVDTs) were used for axial deformation data collection, providing an estimated limit of accuracy of 13.1%. Fig 3.10 shows specimen setup and LVDT connections.

Some minor modifications to test temperatures were made because at the highest temperature (54^{o}C), glue and the samples start softening and LVDTs could not remain attached to the samples, whereas at the lowest temperature (-10^{o}C) UTM and LVDTs start freezing. As a result, in this study, the highest and lowest temperatures were excluded and three temperatures (4, 21, and 37^{o}C) and six loading frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) were used.

Figure 3.10 Sample set up in UTM machine with attached LVDTs

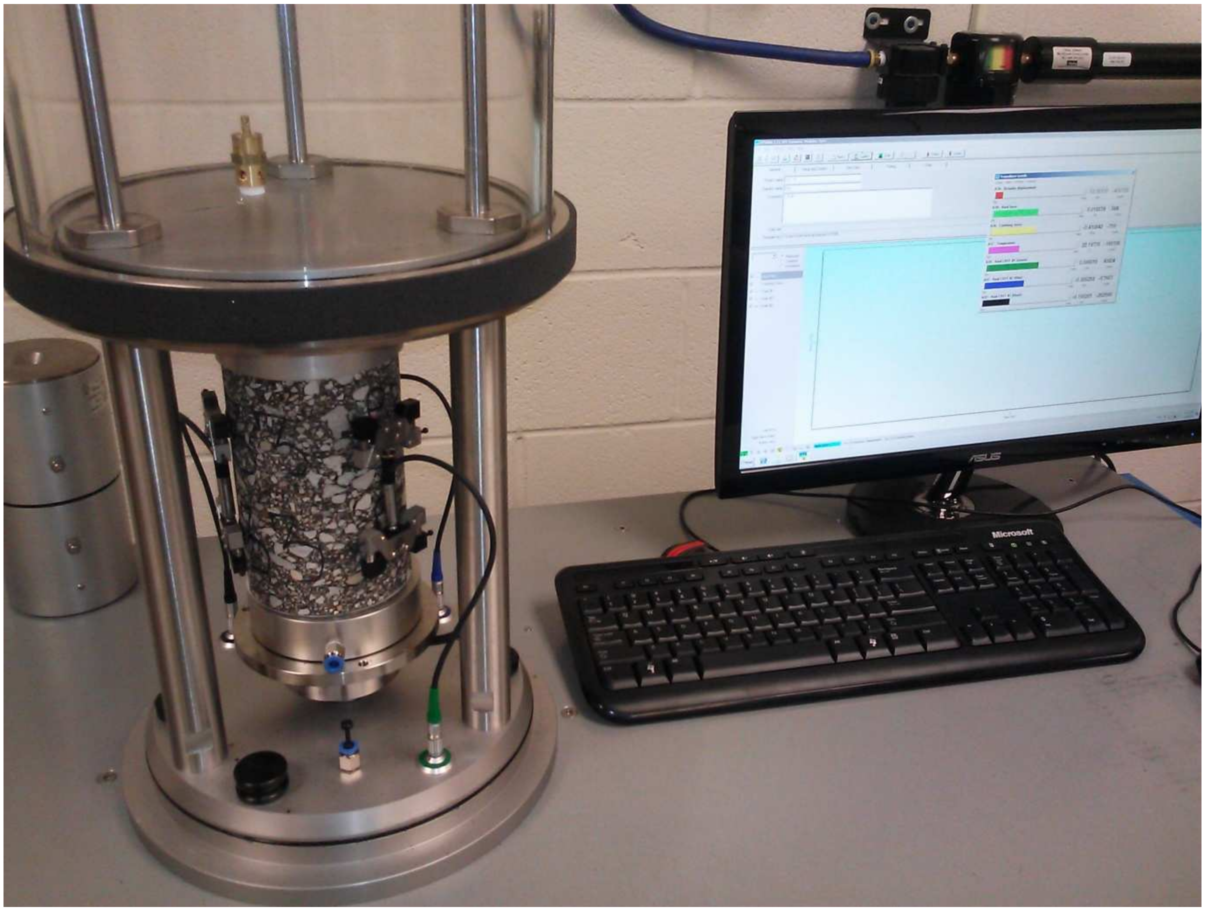


Figure 3.11 Sample set up in AMPT machine with attached LVDT’s

Chapter 4 - Results and Analysis

4.1 Hamburg Wheel-Tracking Device Test Results

The Hamburg wheel-tracking test was conducted on three replicate specimens for each mix, and results for all 15 tests for each source of RAP are provided in Appendix A. Tables 4-1 and 4-2 list the number of passes for each mix at failure for the first and second source of RAP, respectively. All mixes being tested in this study either failed before 40,000 passes or reached 40,000 passes with rut depth very close to 20 mm. For the second replicates of 20% RAP and 40% FRAP, the rut depth at 40,000 passes was very low (3.5 mm and 12.6 mm, respectively) when compared to other replicates of the same mix. Thus, those results were not taken into consideration. Besides, the machine stopped due to a power failure when one replicate of 30% FRAP samples was being tested and as the result, the final number of passes could not be obtained.

4.1.1 Hamburg Wheel-Tracking Device Test Outputs (Creep Slope, Stripping Slope, and Stripping Inflection Point)

To better understand HWTD performance test results, test outputs other than number of passes to failure, shown in table 4.1, need to be studied too. Figures 4.1 through 4.4 show number of wheel passes, creep slope, stripping slope, and stripping inflection points, respectively, for the mixes in this study for both sources of RAP. Figure 4.1 shows that the mix with 20% RAP had the highest number of passes and then the number of passes decreased as the RAP percentage increased in the mix. In contrast to the RAP, when FRAP was added to the mix, the number of passes at 40% FRAP was considerably higher than 30% FRAP. However, the number of passes with 30% and 40% FRAP were lower than the mixture with 20% RAP.

In HWTD outputs, there were two points that needed to be investigated further, creep slope (CS) and striping inflection point (SIP). Although the number of wheel passes was higher for 40% FRAP when compared to 30% FRAP (Figure 4.1), the CS and SIP decreased with an increased percentage of FRAP. This may indicate that the mixture with the higher percentage of FRAP was more vulnerable to rutting failure. When equal percentages of RAP and FRAP were compared, the number of wheel passes before failure was higher for FRAP mixtures, and all other HWTD outputs were either not affected or improved by replacing FRAP for RAP in the mix.

Table 4.1 Number of passes in HWTD test for five different mixes for both sources of RAP

Mix design	First run			Second run			Third run			Avrg of 3 Runs
	Number of passes			Number of passes			Number of passes			
	Left Wheel	Right Wheel	Avrg	Left Wheel	Right Wheel	Avrg	Left Wheel	Right Wheel	Avrg	
20% 1st RAP	40,000	40,000	40,000	-			28,871	24,829	26,850	33,425
30% 1st RAP	38,449	32,575	35,512	30,078	23,056	26,567	23,208	24,292	23,750	28,610
40% 1st RAP	20,600	21,200	20,900	31,700	34,167	32,934	23,822	21,800	22,811	25,548
30% 1st FRAP	30,290	27,860	29,075	-	29,275	29,275	24,385	-	24,385	27,578
40% 1st FRAP	39,800	27,762	33,781	-			31,820	28,292	30,056	31,919
20% 2d RAP	16,747	17,339	17,043	19,702	28,640	24,171	22,900	22,324	22,612	21,275
30% 2d RAP	10,404	13,476	11,940	15,300	18,000	16,650	14,200	16,144	15,172	14,587
40% 2d RAP	14,441	13,300	13,871	13,938	9,920	11,929	14,666	14,300	14,483	13,428
30% 2d FRAP	17,150	19,000	18,075	17,150	19,100	18,125	17,700	15,150	16,425	17,542
40% 2d FRAP	20,435	20,717	20,576	19,196	17,600	18,398	17,108	22,858	19,983	20,280

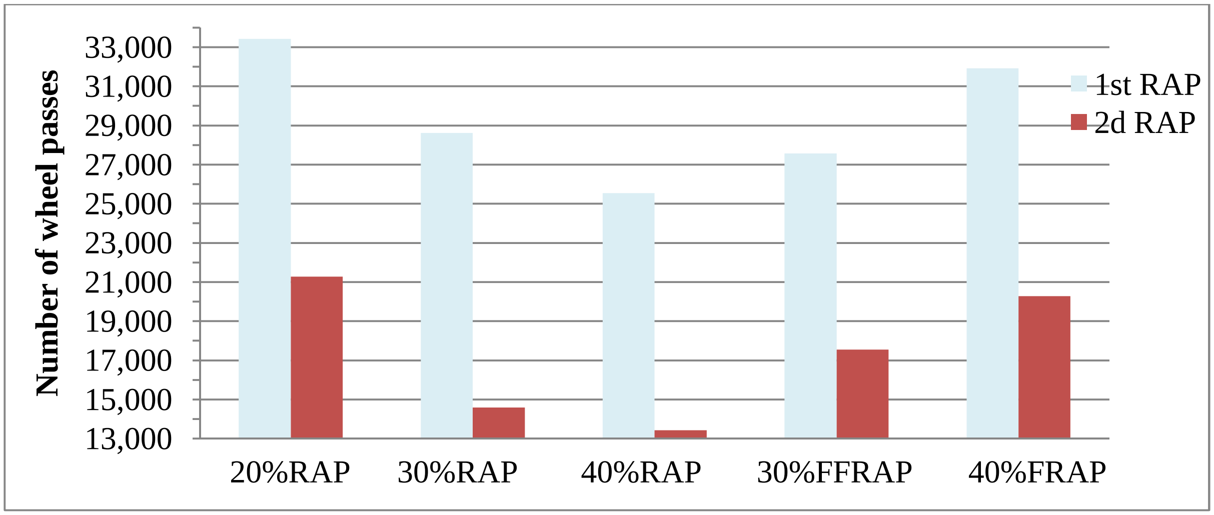


Figure 4.1 Comparison of average number of wheel passes for five different mixes

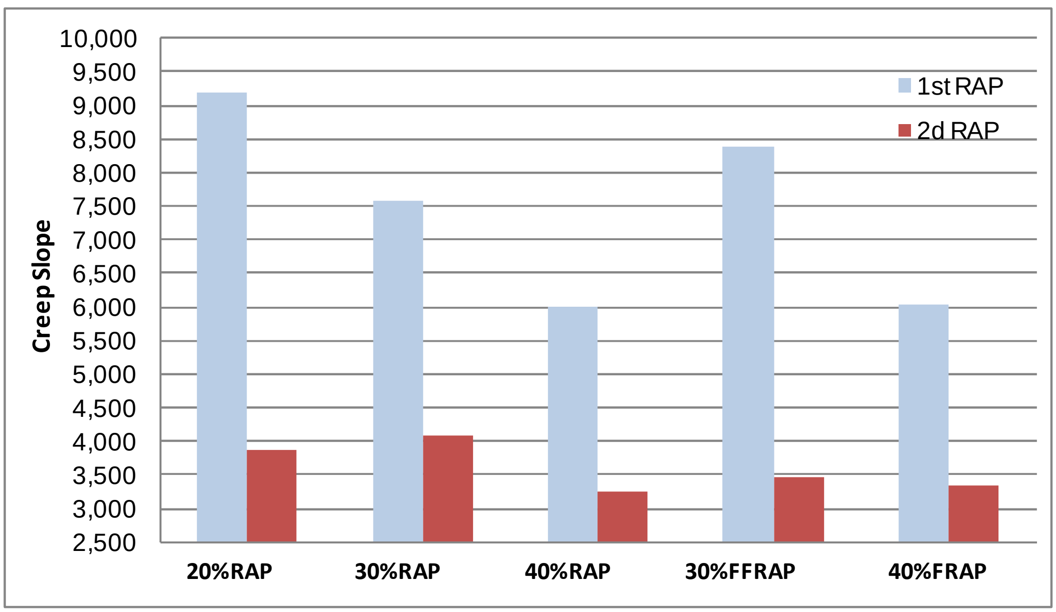


Figure 4.2 Effect of varying RAP percentage on Creep Slope (Passes/mm) for both sources of RAP

Figures 4.5 and 4.6 show the effect of increasing RAP percentage and replacing it with FRAP on creep slope, stripping inflection point, and stripping slope for first and second sources of RAP, respectively.

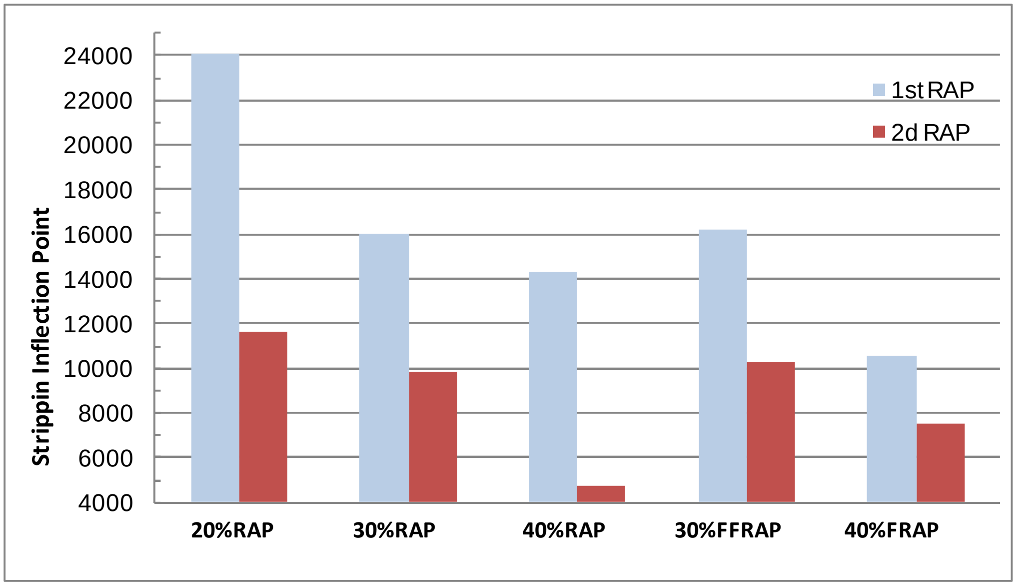


Figure 4.3 Effect of varying RAP percentage on Stripping Slope for both sources of RAP

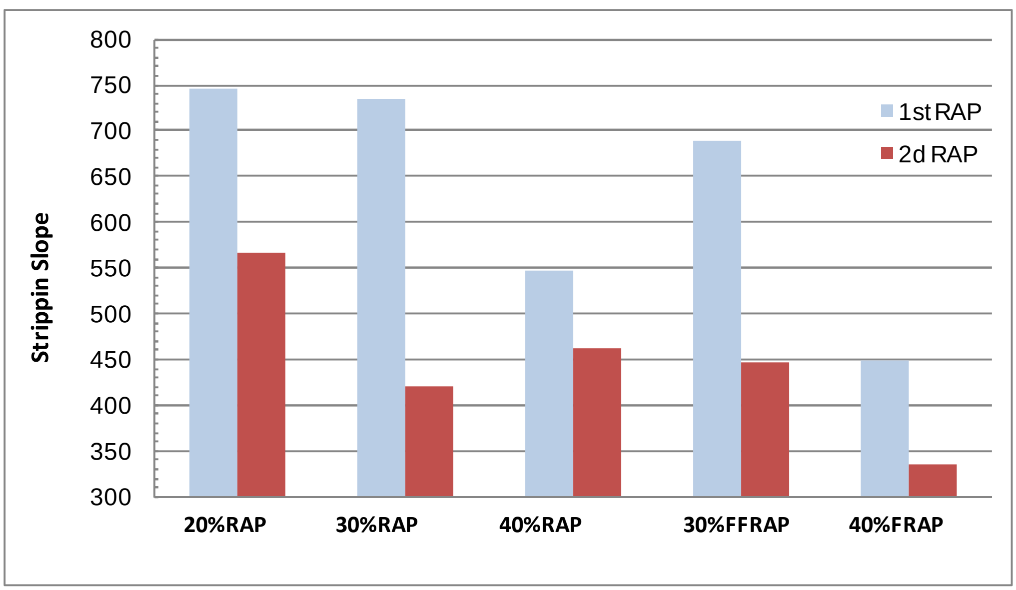


Figure 4.4 Effect of varying RAP percentage on Stripping Inflection Point

Figures 4.7 to 4.9 show the number of wheel passes and HWTD output parameters based on the percentage of virgin binder added to the mix. The results indicate that the amount of virgin binder plays a role in the rutting and stripping resistance of the mixture containing RAP or

FRAP. The best performance in terms of wheel passes to 20-mm rutting was obtained for the mixture containing the highest amount of virgin binder. Figure 4.8 illustrates the creep slopes of all mixes. It appears the best rutting resistance was obtained by the mixture with the highest amount of virgin binder. The two sources of RAP did not follow the same trend when it comes to stripping inflection point in Figure 4.9. While the worst performance belonged to 40% FRAP in first source of RAP, for the second source of RAP, the mix with 30% RAP showed a poor performance in stripping.

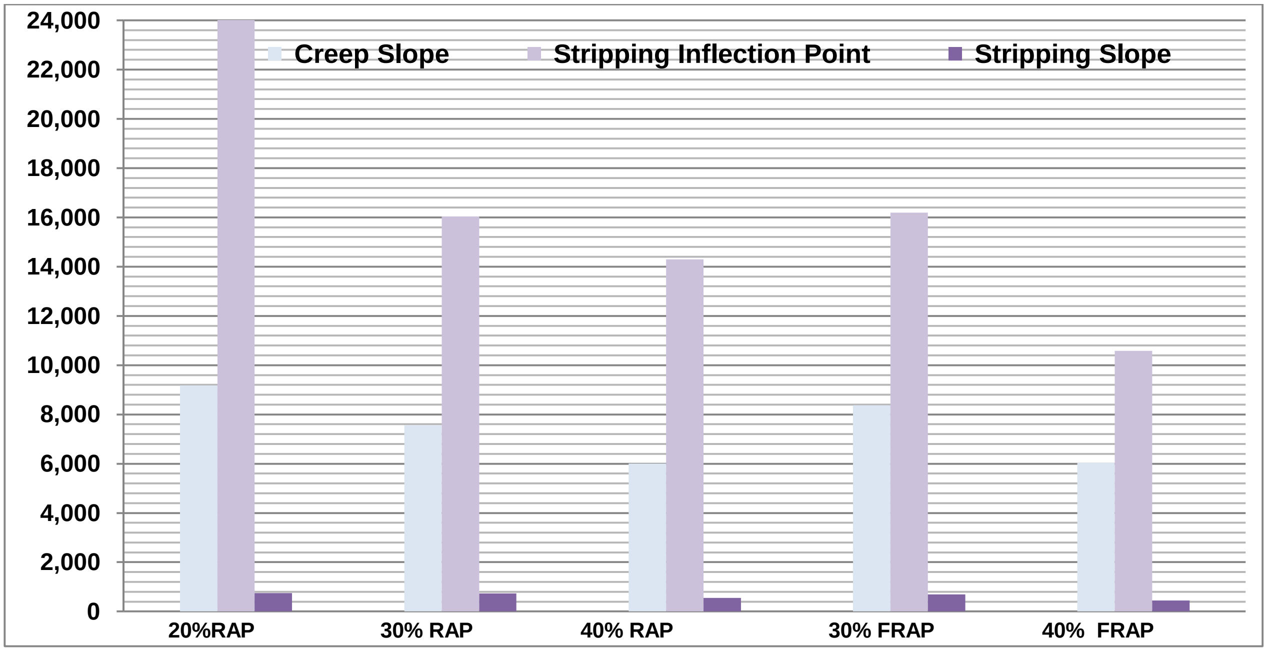


Figure 4.5 Effect of varying RAP percentage on HWTD output parameters (1st source of RAP)

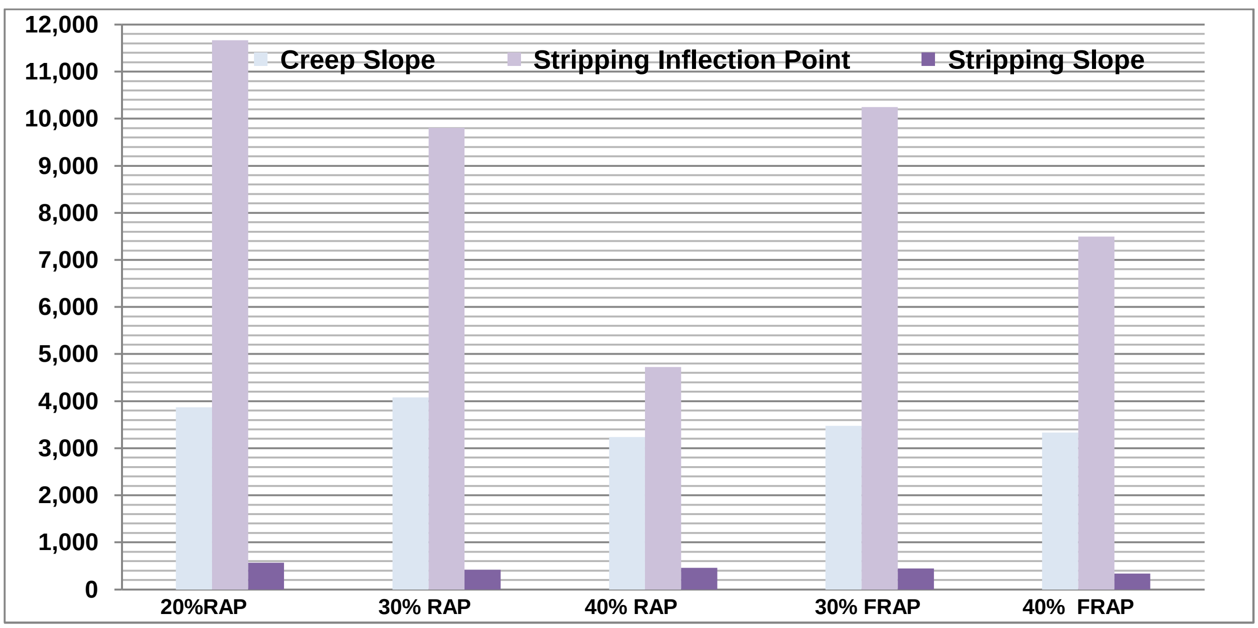


Figure 4.6 Effect of varying RAP percentage on HWTD output parameters (2d source of RAP)

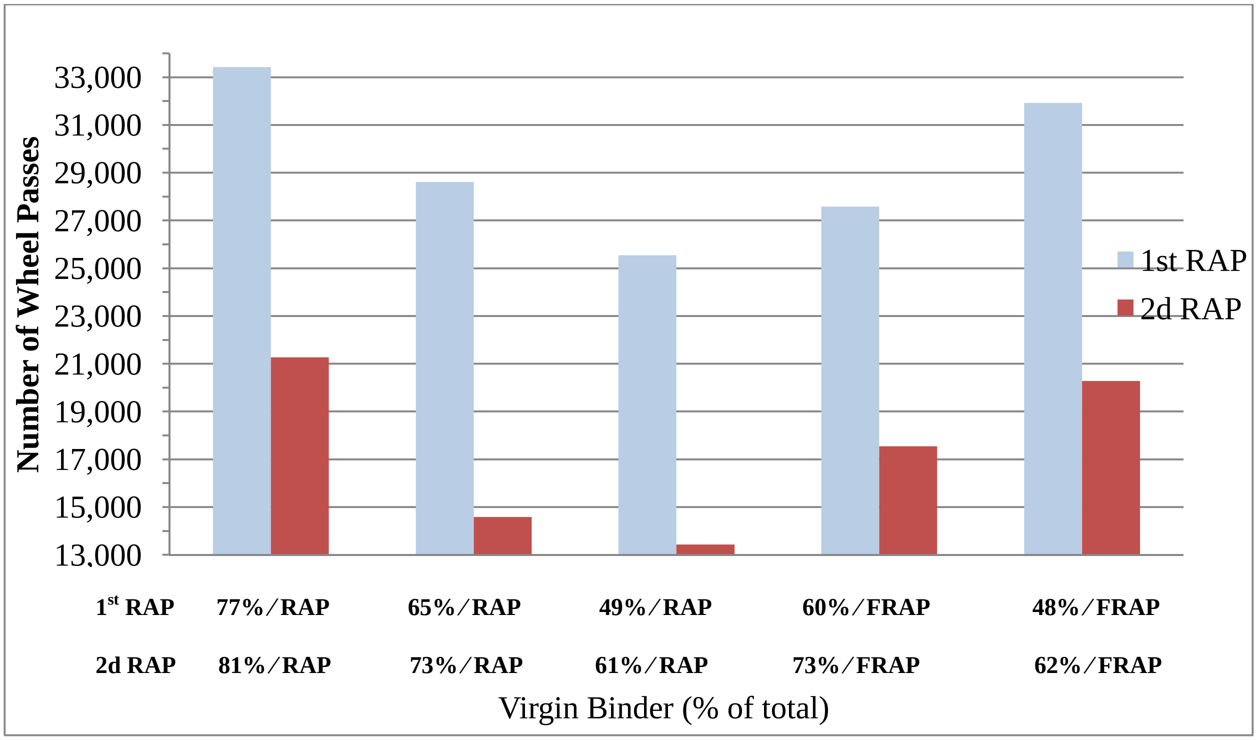


Figure 4.7 Number of wheel passes based on virgin binder contribution to the mix

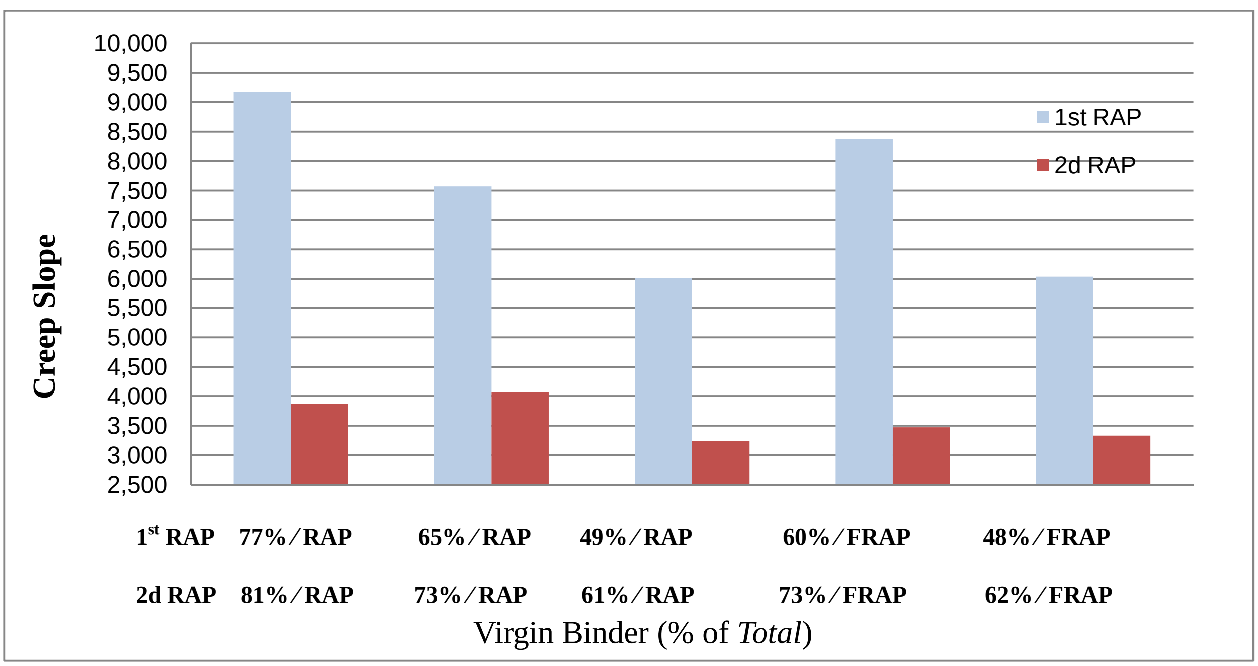


Figure 4.8 Creep slope (passes/mm) based on virgin binder contribution to the mix

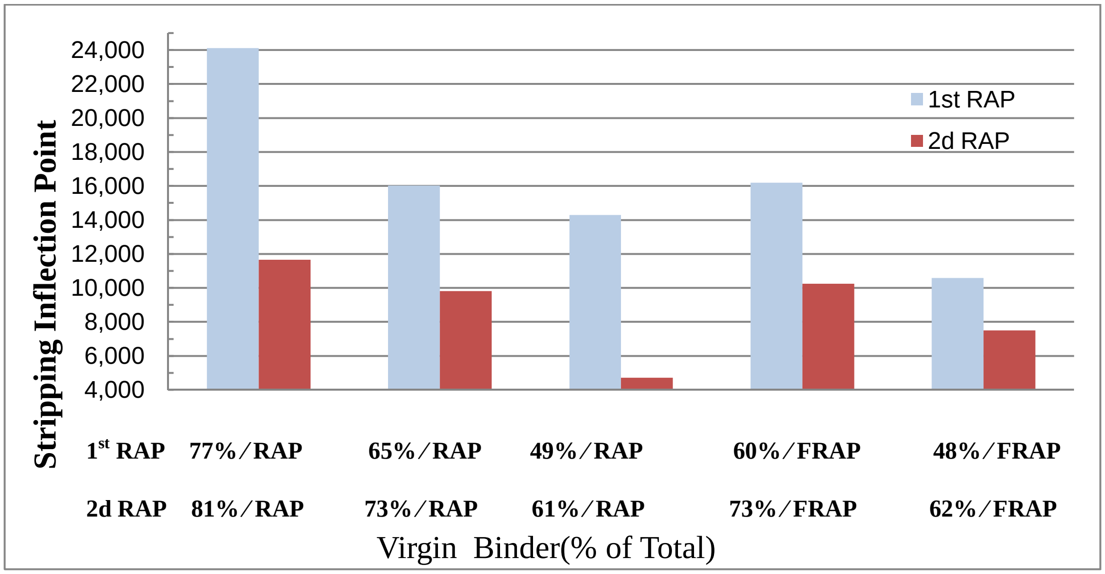


Figure 4.9 Stripping inflection point based on virgin binder contribution to the mix

4.1.2 Statistical Analysis of HWTD Output Data

The analysis of variance (ANOVA) was conducted by taking all the parameters in the HWTD as response variables and by taking the different mixes as "treatments." Statistical analysis software, SAS, was used for this purpose. Table 4.2 shows the summary results. These results showed that overall the effect of mixture type on the total number of wheel passes was not significant i.e., the mixture performance in the HWTD test could not be explained only by the mixture type. However, there were significant differences between the number of wheel passes to failure for mixtures with 20% RAP and 40% RAP. Both creep slope and stripping slope were also unaffected by mixture type, but there was significant difference in creep slopes between 20% and 40% RAP, and between 40% RAP and 40% FRAP. However, treatment type did significantly affect the stripping inflection point, or point when stripping starts in the HWTD test. The mixture with 20% RAP showed significantly different behavior than other mixtures with RAP and FRAP.

Table 4.2 Treatment vs. response variable in ANOVA

Treatment	Response Variable	Significant @ α = 0.1	Significant @ α = 0.05	Significant Difference between Treatments Ho: $\mu_i = \mu_j$
20% RAP **30% RAP** **40% RAP** **30% FRAP** **40% FRAP**	No. of Wheel Passes	N p value = 0.2844>0.1	N p value = 0.2844>0.05	20% RAP & 40% RAP (p value<0.1)
20% RAP **30% RAP** **40% RAP** **30% FRAP** **40% FRAP**	Creep Slope	N p value = 0.2426>0.1	N p value = 0.2426>0.05	20% RAP & 40% RAP 40% RAP & 40% FRAP (p value<0.1)
20% RAP **30% RAP** **40% RAP** **30% FRAP** **40% FRAP**	Stripping Inflection Point	Y p value = 0.0445<0.1	Y p value = 0.0445<0.05	20% RAP & 30% RAP 20% RAP & 40% RAP 20% RAP & 30% FRAP 20% RAP & 40% FRAP (p value<0.1)
20% RAP **30% RAP** **40% RAP** **30% FRAP** **40% FRAP**	Stripping Slope	N p value = 0.5455>0.1	N p value = 0.5455>0.05	None

4.2 Moisture Susceptibility Test (KT-56) Results

Table 4.3 presents tensile strength and tensile strength ratios (TSRs) for different percentages of RAP and FRAP in the mix. The Kansas Department of Transportation (KDOT) criterion for acceptable TSR is 80% and above. This means that if the average tensile strength of conditioned plugs is greater than or equal to the 80% of the average tensile strength of un-conditioned plugs, then the set has passed the minimum requirement. The TSR is not the only important parameter in the indirect tensile strength test. It is also of significant importance to compare conditioned and unconditioned sets in each mix design to find out how increasing the RAP percentage and adding FRAP will affect the HMA performance. Table 4.3 and Figure 4.10 show how the HMA performance was affected by increasing RAP percentage and by adding FRAP to the mix.

Table 4.3 shows that as the percentage of RAP increased in the mix, the TSR decreased and mixed with FRAP and performed either very close to or worse than the mixes with RAP. The increment of TSR implies that mixes with high RAP will not perform well in freeze-thaw conditions and are susceptible to moisture damage. It should be mentioned that although the TSR decreased as the RAP percentage increased, all mixes with RAP passed the KDOT criteria for the KT-56 test. The TSR for 30% RAP and 30% FRAP was exactly the same, and the TSR was slightly lower for 40% FRAP in comparison to 40% RAP and the mixture with 40% FRAP failed to meet the minimum required value (80%). The same thing cannot be said for the second source of RAP. Though the same trend has been observed as the percentage of RAP or FRAP increases in the mix, none of the mixes met KDOT requirements for the moisture susceptibility test.

The indirect tensile strength, however, increased as the RAP percentage increased in the mix, and it was the highest at 40% RAP and 40% FRAP for the first and second source of RAP, respectively. When RAP and FRAP were compared, mixes were behaving comparably and FRAP performed slightly better in the second source of RAP.

The lower TSR and higher tensile strength can be explained due to the nature of RAP. Because of the aged binder, mixes made with high percentages of RAP tend to be stiffer and fail only at very high tensile strengths where no moisture exists, but due to aging in years of service, the asphalt binder covering the aggregates gets cracked at different places, making the HMA mixture highly vulnerable to moisture. The cracked-binder film can explain high- and low-tensile strengths for unconditioned and conditioned samples.

Table 4.3 Indirect tensile strength results for conditioned and unconditioned plugs

Mix Dsgn	Smpl ID	Conditioned	Unconditioned	% Air Voids @ N des		Tensile Strength (lbs)		Average Tensile Strength (lbs)		Tensile Strength Ratio (%)		Passed		Failed	
				1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP
20% RAP	*a*			7.17	6.72	4,023	3,170	3,990	3,249	90	73	√			√
	b			7.09	6.97	3,930	3,220								
	c			7.42	6.98	4,018	3,358								
	e			7.12	6.80	4,431	4,432	4,430	4,473						
	f			7.22	7.45	4,428	4,083								
	g			7.26	6.57	4,431	4,904								
30% RAP	*a*			6.69	6.96	4,199	3,093	4,257	3,307	86	67	√			√
	b			6.83	6.58	3,817	3,533								
	c			6.96	6.82	4,756	3,295								
	e			7.06	6.83	4,402	4,859	4,964	4,906						
	f			6.53	6.51	5,259	4,682								
	g			6.67	7.06	5,231	5,177								
40% RAP	*a*			6.53	7.20	4,559	3,143	4,425	3,255	82	52	√			√
	b			6.52	7.10	4,277	3,290								
	c			6.85	6.70	4,440	3,332								
	e			6.56	6.80	5,221	6,531	5,391	6,235						
	f			6.48	7.20	5,654	5,847								
	g			6.81	6.80	5,297	6,326								
30% FRAP	*a*			6.96	7.20	3,777	3,300	3,963	3,107	86	62	√			√
	b			6.87	7.30	4,136	2,900								
	c			6.54	6.80	3,976	3,121								
	e			7.04	7.20	4,512	5,024	4,616	5,051						
	f			6.76	7.20	4,447	5,117								
	g			6.54	7.20	4,890	5,011								
40% FRAP	*a*			7.13	6.98	4,115	3,615	3,872	3,381	78	54			√	√
	b			6.74	7.26	3,772	3,673								
	c			6.66	7.14	3,730	2,853								
	e			6.96	7.33	5,105	6,538	4,934	6,303						
	f			6.86	6.76	5,151	6,526								
	g			6.78	7.33	4,547	5,844								

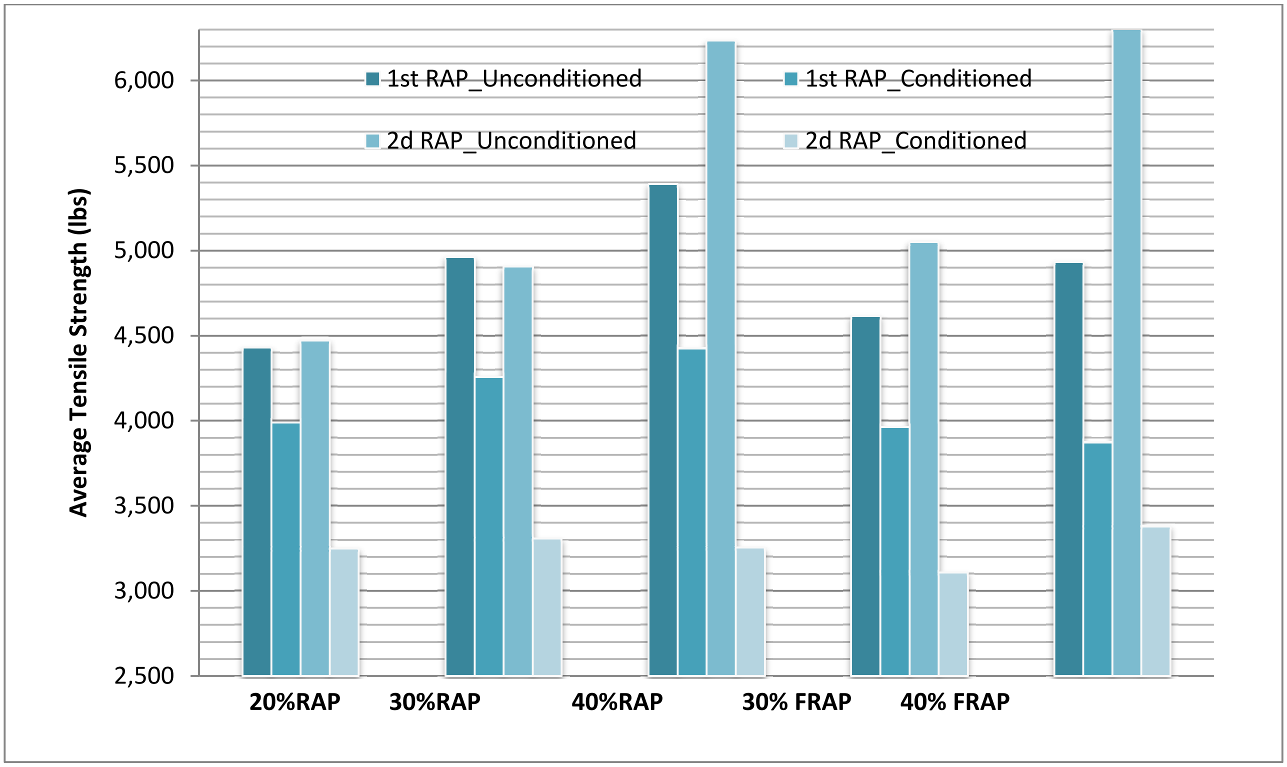


Figure 4.10 Tensile strength results for five different mixes

4.3 Dynamic Modulus Test Results

The dynamic modulus test results were automatically recorded with the operation of software in the UTM-25 and AMPT machines for first and second source of RAP, respectively. For each mix, three replicates were made and tested. Figure 4.11 shows the typical outputs of UTM and AMPT, and Figures 4.12 through 4.17 show the dynamic modulus test results for both sources of RAP.

The dynamic modulus and phase angle were affected by both temperature and loading frequencies. At low temperature and high loading frequency, the asphalt mixture was elastic and had a high dynamic modulus. At high temperature and low loading frequency, the asphalt mixture was more viscous and had a low elastic modulus. As was expected, dynamic modulus values were higher at lower temperature and lower at higher temperature. It was also observed that dynamic modulus decreased as the loading frequency changed from 25 Hz to 0.1 Hz.

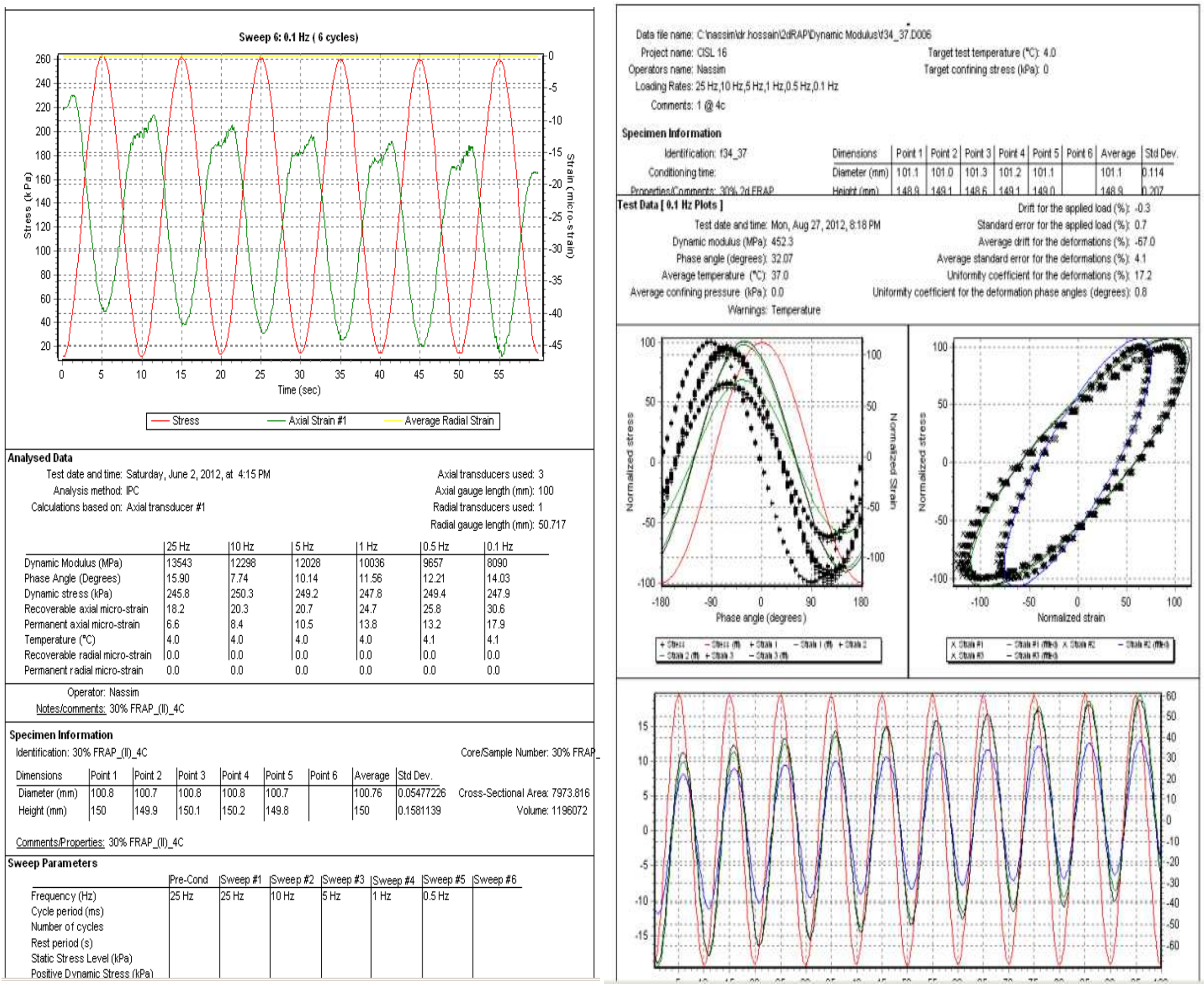


Figure 4.11 Typical outputs of UTM (left side) and AMPT (right side)

The behavior observed in two different sources of RAP were completely different from each other in the dynamic modulus test results and did not follow the same pattern as the temperature changed. For the first source, 20% RAP had the highest dynamic modulus, at 4^{o}C and 37^{o}C, being followed by either 30% RAP or FRAP, and leaving only third place for 40% RAP or FRAP. For the first source, RAP and FRAP behaved very similarly for equal percentage.

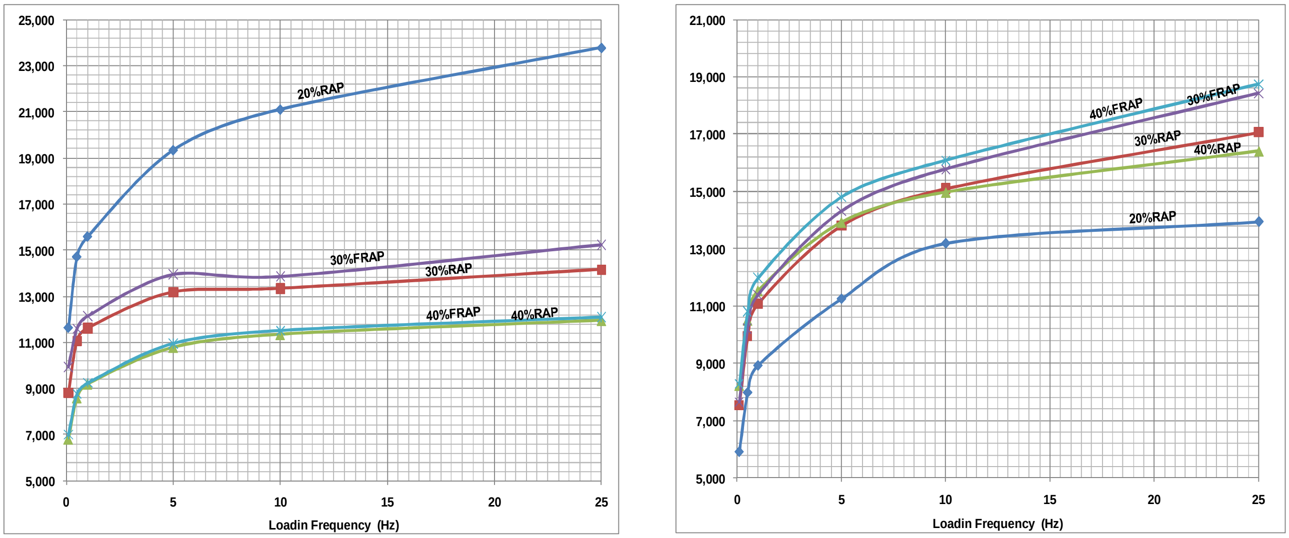


Figure 4.12 Dynamic modulus test results for first (left) and second (right) source of RAP at 4^{o}C

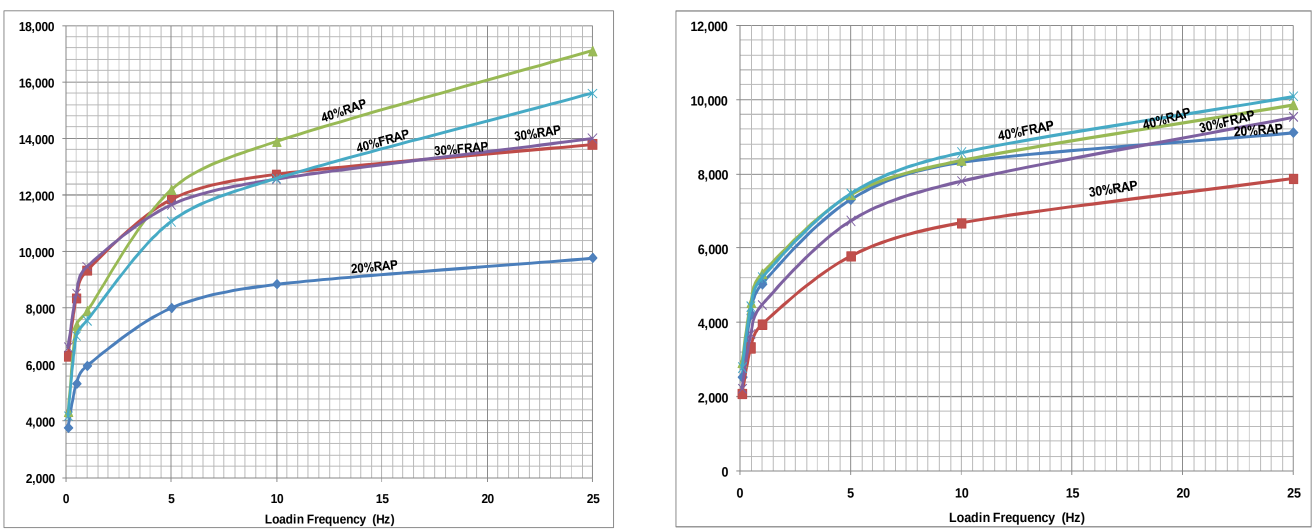
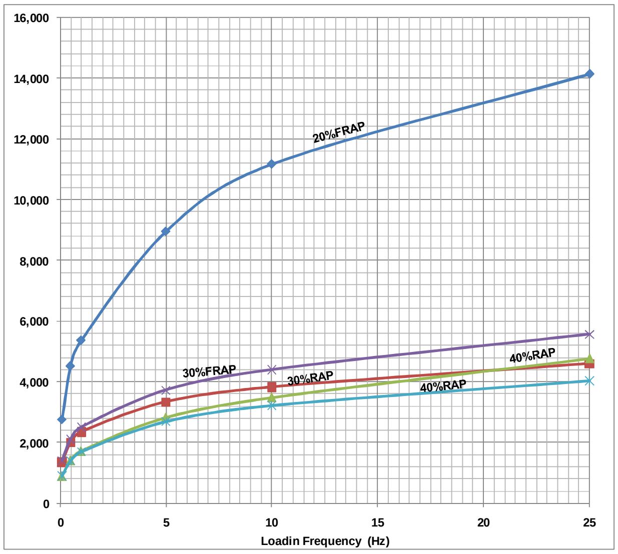


Figure 4.13 Dynamic modulus test results for first (left) and second (right) source of RAP at 21^{o}C



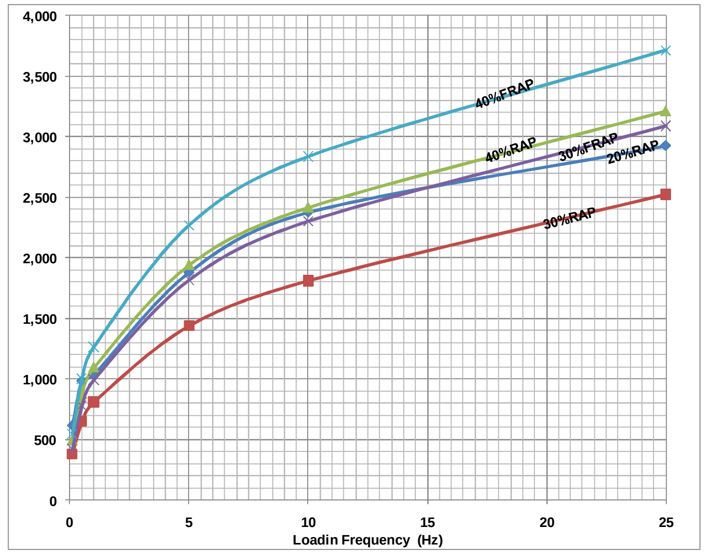


Figure 4.14 Dynamic modulus test results for first (left) and second (right) source of RAP at 37^{o}C

Tables 4.4 through 4.7 show the dynamic modulus and phase angle for all five mixes at three different temperatures for each source of RAP.

Table 4.4 Dynamic modulus results (MPa) for five different mixes at three different temperatures for the first RAP source

Mix Design	Sample ID	4℃						21℃						37℃					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
20% RAP	*S1*	27,740	24,816	23,171	18,935	18,013	15,024	8,074	7,084	6,452	4,945	4,401	3,114	18,524	13,604	10,746	6,274	5,327	3,035
	S2	25,607	21,587	19,295	15,518	14,645	11,354	7,177	6,463	5,874	4,508	4,044	2,872	14,773	10,122	7,754	4,005	3,315	1,790
	S3	17,989	16,897	15,544	12,311	11,457	8,509	14,072	12,999	11,698	8,423	7,553	5,322	9,073	9,746	8,313	5,774	4,869	3,400
	Average	23,779	21,100	19,337	15,588	14,705	11,629	9,774	8,849	8,008	5,959	5,333	3,769	14,123	11,157	8,938	5,351	4,504	2,742
	SD	5,126	3,982	3,814	3,313	3,278	3,266	3,749	3,608	3,209	2,145	1,931	1,350	4,759	2,127	1,591	1,192	1,055	844
	C.V%	0.22	0.19	0.20	0.21	0.22	0.28	0.38	0.41	0.40	0.36	0.36	0.36	0.34	0.19	0.18	0.22	0.23	0.31
30% RAP	*IV-I*	10,199	9,287	9,583	8,297	7,693	6,121	13,564	13,468	13,009	11,168	9,480	8,143	4,159	3,587	3,111	2,124	1,786	1,156
	IV-II	11,431	10,755	10,298	8,940	8,696	7,285	13,764	11,601	10,412	7,731	7,052	4,850	7,354	5,842	5,100	3,644	3,155	2,163
	S2	20,818	19,935	19,631	17,578	16,797	13,038	14,013	13,109	12,078	9,049	8,509	5,879	2,266	2,033	1,786	1,279	1,062	719
	Average	14,149	13,326	13,171	11,605	11,062	8,815	13,780	12,726	11,833	9,316	8,347	6,291	4,593	3,821	3,332	2,349	2,001	1,346
	SD	5,808	5,771	5,606	5,183	4,992	3,704	225	991	1,316	1,734	1,222	1,685	2,572	1,915	1,668	1,198	1,063	741
	C.V%	0.41	0.43	0.43	0.45	0.45	0.42	0.02	0.08	0.11	0.19	0.15	0.27	0.56	0.50	0.50	0.51	0.53	0.55
40% RAP	*S2*	11,015	10,541	10,056	8,730	8,240	6,642	27,598	21,013	18,608	12,342	11,786	7,191	6,099	3,864	2,999	1,769	1,431	865
	S(2-1)	11,223	10,834	10,218	8,546	7,948	6,125	14,723	12,898	10,942	6,546	6,036	3,090	2,937	2,276	1,864	1,180	964	646
	S(2-2)	13,589	12,632	12,055	10,281	9,596	7,649	8,984	7,757	6,989	4,776	4,317	2,650	5,264	4,309	3,612	2,228	1,858	1,194
	Average	11,942	11,336	10,776	9,186	8,595	6,805	17,102	13,889	12,180	7,888	7,380	4,310	4,767	3,483	2,825	1,726	1,418	902
	SD	1,430	1,132	1,110	953	879	775	9,532	6,683	5,908	3,958	3,912	2,504	1,639	1,069	887	525	447	276
	C.V%	0.12	0.10	0.10	0.10	0.10	0.11	0.56	0.48	0.49	0.50	0.53	0.58	0.34	0.31	0.31	0.30	0.32	0.31
30% FRAP	*S1*	21,551	19,611	19,849	18,000	17,240	15,401	14,025	12,682	11,915	10,127	9,195	7,661	2,665	2,353	2,105	1,588	1,346	995
	SII	13,543	12,298	12,028	10,036	9,657	8,090	14,808	12,233	10,871	8,173	7,566	5,145	8,200	6,537	5,709	4,023	3,504	2,353
	SIII	10,600	9,665	9,967	8,397	7,903	6,321	13,144	12,765	12,157	10,072	8,760	7,016	5,801	4,279	3,344	1,880	1,451	853
	Average	15,231	13,858	13,948	12,144	11,600	9,937	13,992	12,560	11,648	9,457	8,507	6,607	5,555	4,390	3,719	2,497	2,100	1,400
	SD	5,667	5,153	5,213	5,137	4,962	4,814	832	286	683	1,113	843	1,307	2,776	2,094	1,831	1,330	1,217	828
	C.V%	0.37	0.37	0.37	0.42	0.43	0.48	0.06	0.02	0.06	0.12	0.10	0.20	0.50	0.48	0.49	0.53	0.58	0.59
40% FRAP	*S1*	10,794	10,287	9,757	8,307	7,869	6,159	13,688	11,065	9,478	6,267	5,791	3,277	4,217	3,184	2,567	1,468	1,178	761
	S2	13,175	12,431	11,766	9,922	9,364	7,409	24,992	19,652	17,523	12,084	11,465	6,992	5,199	4,206	3,465	2,161	1,788	1,101
	S(2-2)	12,314	11,826	11,344	9,479	9,068	7,395	8,087	7,000	6,147	4,299	3,739	2,280	2,683	2,254	2,021	1,446	1,192	827
	Average	12,094	11,515	10,956	9,236	8,767	6,988	15,589	12,572	11,049	7,550	6,998	4,183	4,033	3,215	2,684	1,692	1,386	896
	SD	1,206	1,105	1,059	834	792	718	8,611	6,459	5,849	4,048	4,002	2,483	1,268	976	729	407	348	180
	C.V%	0.10	0.10	0.10	0.09	0.09	0.10	0.55	0.51	0.53	0.54	0.57	0.59	0.31	0.30	0.27	0.24	0.25	0.20

Table 4.5 Phase angle (degrees) results for five different mixes at three different temperatures for the first RAP source

Mix Design	Sample ID	4℃						21℃						37℃					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
20% RAP	*S1*	7.62	10.18	14.88	13.73	15.89	18.51	10.41	13.41	15.33	18.25	21.47	24.57	32.67	40.92	40.72	37.76	41.24	39.35
	S2	26.08	11.15	11.37	11.33	11.96	13.14	7.33	13.37	14.94	18.04	20.91	24.35	68.14	50.52	53.94	50.92	52.61	47.93
	S3	14.54	16.06	22.19	19.79	20.66	21.86	15.04	19.63	24.90	23.31	25.81	27.70	29.28	33.67	36.33	36.90	38.94	39.32
	Average	16.08	12.46	16.15	14.95	16.17	17.84	10.93	15.47	18.39	19.87	22.73	25.54	43.36	41.70	43.66	41.86	44.26	42.20
	SD	9.33	3.15	5.52	4.36	4.36	4.40	3.88	3.60	5.64	2.98	2.68	1.87	21.52	8.45	9.17	7.86	7.32	4.96
	C.V%	0.58	0.25	0.34	0.29	0.27	0.25	0.36	0.23	0.31	0.15	0.12	0.07	0.50	0.20	0.21	0.19	0.17	0.12
30% RAP	*IV-I*	3.76	12.60	10.06	11.72	14.16	17.66	5.47	21.05	23.72	24.98	27.91	26.45	13.68	25.45	26.36	27.07	31.37	31.69
	IV-II	15.96	10.30	10.17	14.06	14.98	16.99	8.22	10.90	13.97	16.60	19.75	21.99	19.59	24.79	26.60	28.94	33.50	35.72
	S2	2.39	3.23	5.07	6.68	8.43	11.02	11.30	12.41	16.74	19.38	21.69	23.43	13.00	18.83	22.15	24.14	28.39	29.12
	Average	7.37	8.71	8.43	10.82	12.52	15.22	8.33	14.79	18.14	20.32	23.12	23.96	15.42	23.02	25.04	26.72	31.09	32.18
	SD	7.47	4.88	2.91	3.77	3.57	3.66	2.92	5.48	5.02	4.27	4.26	2.28	3.62	3.65	2.50	2.42	2.57	3.33
	C.V%	1.01	0.56	0.35	0.35	0.28	0.24	0.35	0.37	0.28	0.21	0.18	0.10	0.23	0.16	0.10	0.09	0.08	0.10
40% RAP	*S2*	0.67	6.37	7.89	10.58	12.24	15.97	22.69	21.73	21.22	23.52	28.20	30.09	25.60	25.80	27.45	28.48	32.30	29.70
	S(2-1)	0.48	5.24	7.42	9.88	12.35	15.87	39.65	21.23	29.13	33.49	38.06	41.48	21.70	27.83	29.55	28.69	31.82	28.48
	S(2-2)	10.15	12.62	14.82	16.88	18.15	20.95	9.74	16.53	17.78	21.69	26.20	29.03	22.07	27.37	27.99	28.68	32.78	30.43
	Average	3.77	8.08	10.04	12.45	14.25	17.60	24.03	19.83	22.71	26.23	30.82	33.53	23.12	27.00	28.33	28.62	32.30	29.54
	SD	5.53	3.98	4.14	3.86	3.38	2.90	15.00	2.87	5.82	6.35	6.35	6.90	2.15	1.06	1.09	0.12	0.48	0.99
	C.V%	1.47	0.49	0.41	0.31	0.24	0.17	0.62	0.14	0.26	0.24	0.21	0.21	0.09	0.04	0.04	0.00	0.01	0.03
30% FRAP	*S1*	8.74	11.90	12.39	13.34	14.70	15.82	11.67	13.13	14.40	16.11	18.15	19.47	10.14	15.36	17.81	20.57	25.61	27.40
	SII	15.90	7.74	10.14	11.56	12.21	14.03	7.70	10.44	14.20	17.67	19.97	23.14	19.73	25.34	26.07	29.39	33.46	35.69
	SIII	3.76	12.5	8.77	12.1	14.07	17.23	4.82	15.85	19.21	21.35	24.54	25.26	30.22	36.45	38.54	38.73	41.10	35.75
	Average	9.47	10.71	10.43	12.33	13.66	15.69	8.06	13.14	15.94	18.38	20.89	22.62	20.03	25.72	27.47	29.56	33.39	32.95
	SD	6.10	2.59	1.83	0.91	1.29	1.60	3.44	2.71	2.84	2.69	3.29	2.93	10.04	10.55	10.44	9.08	7.75	4.80
	C.V%	0.64	0.24	0.18	0.07	0.09	0.10	0.43	0.21	0.18	0.15	0.16	0.13	0.50	0.41	0.38	0.31	0.23	0.15
40% FRAP	*S1*	2.24	6.52	8.72	10.90	12.50	15.98	19.52	23.66	26.19	30.69	34.70	38.39	25.18	32.72	33.20	32.48	36.25	31.65
	S2	10.22	13.36	15.01	16.46	18.43	21.09	21.24	20.60	21.85	24.11	28.46	30.17	20.59	26.11	27.40	28.81	32.68	29.81
	S(2-2)	1.33	6.56	8.12	10.72	12.50	16.50	11.80	17.44	19.36	22.92	27.77	30.03	12.99	21.16	23.34	24.61	30.84	29.97
	Average	4.60	8.81	10.62	12.69	14.48	17.86	17.52	20.57	22.47	25.91	30.31	32.86	19.59	26.66	27.98	28.63	33.26	30.48
	SD	4.89	3.94	3.82	3.26	3.42	2.81	5.03	3.11	3.46	4.19	3.82	4.79	6.16	5.80	4.96	3.94	2.75	1.02
	C.V%	1.06	0.45	0.36	0.26	0.24	0.16	0.29	0.15	0.15	0.16	0.13	0.15	0.31	0.22	0.18	0.14	0.08	0.03

Table 4.6 Dynamic modulus results (MPa) for five different mixes at three different temperatures for the second RAP source

Mix Design	Sample ID	4℃						21℃						37℃					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
20% RAP	*21*	14,480	14,747	11,823	9,510	8,557	6,386	8,748	7,555	6,630	4,603	3,868	2,348	5,137	3,312	2,578	1,402	1,125	641
	22	13,397	11,625	10,681	8,346	7,420	5,460	9,478	9,079	7,990	5,462	4,575	2,717	2,630	1,440	1,183	667	847	596
	S3	17,989	16,897	15,544	12,311	11,457	8,509	14,072	12,999	11,698	8,423	7,553	5,322	9,073	9,746	8,313	5,774	4,869	3,400
	Average	13,939	13,186	11,252	8,928	7,989	5,923	9,113	8,317	7,310	5,033	4,222	2,533	3,884	2,376	1,881	1,035	986	619
	SD	766	2,208	808	823	804	655	516	1,078	962	607	500	261	1,773	1,324	986	520	197	32
	C.V%	5.49	16.74	7.18	9.22	10.06	11.05	5.66	12.96	13.16	12.07	11.84	10.30	45.65	55.71	52.45	50.23	19.95	5.14
30% RAP	*31*	12,978	11,217	10,260	8,119	7,213	5,320	6,596	5,571	4,777	3,171	2,623	1,555	1,988	1,318	1,013	541	425	240
	33	18,790	17,412	16,268	13,668	12,503	9,911	9,502	8,049	7,047	5,000	4,294	2,864	3,493	2,602	2,135	1,262	1,039	621
	34	19,438	16,691	14,909	11,474	10,099	7,364	7,502	6,399	5,498	3,659	3,017	1,776	2,083	1,508	1,167	626	491	272
	Average	17,069	15,107	13,812	11,087	9,938	7,532	7,867	6,673	5,774	3,943	3,311	2,065	2,521	1,809	1,438	809	652	378
	SD	3,557	3,388	3,151	2,795	2,649	2,300	1,487	1,262	1,160	947	874	701	843	693	608	394	337	211
	C.V%	20.84	22.43	22.81	25.21	26.65	30.54	18.90	18.90	20.09	24.02	26.38	33.93	33.43	38.30	42.29	48.71	51.72	55.91
40% RAP	*42*	17,158	15,598	14,537	12,119	11,041	8,664	9,424	7,739	7,108	5,035	4,281	2,729	3,199	2,427	1,948	1,100	880	494
	43	16,400	14,932	13,845	11,394	10,374	8,142	10,785	9,042	7,887	5,701	4,888	3,191	3,504	2,638	2,138	1,225	985	556
	44	15,664	14,381	13,383	11,069	10,080	7,840	9,355	8,293	7,292	5,180	4,418	2,822	2,925	2,178	1,736	958	762	427
	Average	16,407	14,970	13,922	11,527	10,498	8,215	9,855	8,358	7,429	5,305	4,529	2,914	3,209	2,414	1,941	1,094	876	492
	SD	747	609	581	538	492	417	806	654	407	350	318	244	290	230	201	134	112	64
	C.V%	4.55	4.07	4.17	4.66	4.69	5.07	8.18	7.82	5.48	6.60	7.03	8.39	9.02	9.54	10.36	12.22	12.74	13.06
30% FRAP	*f31*	16,265	13,638	12,122	9,671	8,680	6,475	7,402	5,561	4,742	3,054	2,520	1,491	2,648	1,957	1,535	829	650	355
	f32	22,938	19,481	17,768	14,073	12,595	9,428	12,051	10,063	8,673	5,684	4,587	2,757	3,352	2,496	1,956	1,062	826	456
	f34	16,050	14,185	13,021	10,413	9,362	7,046	9,126	7,788	6,781	4,665	3,928	2,412	3,263	2,451	1,963	1,087	854	452
	Average	18,418	15,768	14,304	11,386	10,212	7,650	9,526	7,804	6,732	4,468	3,678	2,220	3,088	2,301	1,818	993	777	421
	SD	3,916	3,227	3,034	2,357	2,091	1,566	2,350	2,251	1,966	1,326	1,056	654	383	299	245	142	111	57
	C.V%	21.26	20.47	21.21	20.70	20.48	20.48	24.67	28.84	29.20	29.68	28.71	29.48	12.42	12.99	13.48	14.32	14.23	13.60
40% FRAP	*f42*	14,284	12,645	11,601	9,314	8,338	6,342	8,440	7,148	6,220	4,340	3,677	2,306	2,924	2,212	1,781	1,006	808	450
	f43	26,074	21,482	19,732	15,970	14,482	11,103	12,632	10,747	9,386	6,539	5,582	3,548	3,311	2,556	2,062	1,148	913	500
	f44	15,869	14,128	13,075	10,658	9,628	7,388	9,186	7,828	6,803	4,737	4,004	2,501	4,902	3,735	2,961	1,631	1,282	692
	Average	18,742	16,085	14,803	11,981	10,816	8,278	10,086	8,574	7,470	5,205	4,421	2,785	3,712	2,834	2,268	1,262	1,001	547
	SD	6,399	4,732	4,332	3,520	3,240	2,502	2,236	1,912	1,685	1,172	1,019	668	1,048	799	616	328	249	128
	C.V%	34.14	29.42	29.27	29.38	29.95	30.23	22.17	22.30	22.56	22.51	23.04	23.98	28.24	28.18	27.18	25.97	24.90	23.33

Table 4.7 Phase angle (degrees) results for five different mixes at three different temperatures for the second RAP source

Mix Design	Sample ID	4℃						21℃						37℃					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
20% RAP	*21*	9.99	10.59	11.87	14.62	16.02	19.58	17.16	18.53	20.08	23.79	25.10	28.46	34.80	49.38	50.64	36.63	35.82	15.57
	22	21.83	13.53	12.83	15.76	17.08	20.52	26.07	40.63	39.88	31.14	32.21	33.73	31.56	33.97	34.03	32.87	30.63	32.80
	S3	14.54	16.06	22.19	19.79	20.66	21.86	15.04	19.63	24.90	23.31	25.81	27.70	29.28	33.67	36.33	36.90	38.94	39.32
	Average	15.91	12.06	12.35	15.19	16.55	20.05	21.62	29.58	29.98	27.47	28.66	31.10	33.18	41.68	42.34	34.75	33.23	24.19
	SD	8.37	2.08	0.68	0.81	0.75	0.66	6.30	15.63	14.00	5.20	5.03	3.73	2.29	10.90	11.75	2.66	3.67	12.18
	C.V%	52.62	17.24	5.50	5.31	4.53	3.32	29.15	52.83	46.70	18.92	17.55	11.98	6.90	26.15	27.74	7.65	11.05	50.38
30% RAP	*31*	11.92	11.53	12.52	15.24	16.73	20.10	17.44	21.05	22.58	26.20	27.27	30.07	31.55	33.60	33.48	32.77	31.45	29.96
	33	7.85	8.47	9.40	11.26	12.19	14.85	17.60	18.44	19.56	22.54	23.46	25.98	28.23	29.79	29.87	30.64	29.92	29.46
	34	21.55	35.55	35.08	26.03	27.21	29.15	20.45	20.84	22.32	25.97	27.13	30.09	34.29	34.76	34.45	33.81	32.54	30.88
	Average	13.77	18.52	19.00	17.51	18.71	21.37	18.50	20.11	21.49	24.90	25.95	28.71	31.36	32.72	32.60	32.41	31.30	30.10
	SD	7.04	14.83	14.01	7.64	7.70	7.23	1.69	1.45	1.67	2.05	2.16	2.37	3.03	2.60	2.41	1.62	1.32	0.72
	C.V%	51.08	80.09	73.75	43.64	41.17	33.85	9.16	7.21	7.79	8.23	8.32	8.24	9.68	7.95	7.40	4.99	4.20	2.39
40% RAP	*42*	9.93	9.02	9.75	11.81	12.74	15.76	18.14	18.13	19.21	22.95	24.26	27.97	30.31	31.69	32.11	33.25	32.51	31.87
	43	9.23	9.81	10.57	12.76	13.76	16.71	15.08	16.79	18.27	21.86	23.19	27.02	29.84	31.07	31.71	33.24	32.73	32.45
	44	9.42	9.81	10.51	12.65	13.73	16.79	18.21	17.71	19.23	22.95	24.28	27.97	31.20	32.73	33.20	34.06	33.23	32.14
	Average	9.53	9.55	10.28	12.41	13.41	16.42	17.14	17.54	18.90	22.59	23.91	27.65	30.45	31.83	32.34	33.52	32.82	32.15
	SD	0.36	0.46	0.46	0.52	0.58	0.57	1.79	0.69	0.55	0.63	0.62	0.55	0.69	0.84	0.77	0.47	0.37	0.29
	C.V%	3.80	4.78	4.45	4.19	4.33	3.49	10.43	3.91	2.90	2.79	2.61	1.98	2.27	2.64	2.38	1.40	1.12	0.90
30% FRAP	*f31*	0.72	13.50	12.32	14.85	16.10	19.66	19.06	23.27	24.63	27.98	28.67	30.55	32.07	32.76	32.75	32.52	31.41	29.80
	f32	20.89	35.59	34.22	25.29	26.33	28.49	29.00	42.34	41.48	32.70	33.68	34.16	30.89	31.39	31.53	31.44	30.38	28.70
	f34	9.4	11.16	12.14	14.87	16.14	19.64	19.39	20.02	21.49	25.22	26.37	29.50	31.24	32.49	32.58	33.10	32.41	32.07
	Average	10.34	20.08	19.56	18.34	19.52	22.60	22.48	28.54	29.20	28.63	29.57	31.40	31.40	32.21	32.29	32.35	31.40	30.19
	SD	10.12	13.48	12.70	6.02	5.89	5.10	5.65	12.06	10.75	3.78	3.74	2.44	0.61	0.73	0.66	0.84	1.02	1.72
	C.V%	97.88	67.12	64.91	32.84	30.19	22.59	25.11	42.25	36.82	13.21	12.64	7.78	1.93	2.25	2.05	2.60	3.23	5.69
40% FRAP	*f42*	10.57	11.14	12.00	14.54	15.71	19.05	17.30	18.96	20.36	24.20	25.48	29.28	30.82	32.28	32.79	34.21	33.51	32.96
	f43	22.43	34.09	33.47	24.25	25.14	27.15	14.16	40.57	39.86	31.13	32.15	33.88	30.87	32.37	32.71	33.89	33.19	32.60
	f44	9.75	10.32	11.08	13.44	14.63	18.01	17.57	18.88	20.40	24.27	25.59	29.41	36.22	48.79	46.55	36.11	35.64	34.24
	Average	14.25	18.52	18.85	17.41	18.49	21.40	16.34	26.14	26.87	26.53	27.74	30.86	32.64	37.81	37.35	34.74	34.11	33.27
	SD	7.10	13.49	12.67	5.95	5.78	5.00	1.90	12.50	11.25	3.98	3.82	2.62	3.10	9.51	7.97	1.20	1.33	0.86
	C.V%	49.80	72.87	67.21	34.17	31.26	23.38	11.60	47.82	41.85	15.00	13.77	8.49	9.51	25.14	21.33	3.45	3.90	2.59

As can be seen in Figures 4.12 through 4.14 and Tables 4.4 through 4.7, at all three different temperatures, the highest dynamic modulus was obtained by 40% FRAP with the second source of RAP, followed by 40% RAP. The 20% RAP has the lowest dynamic modulus in tests performed at 4^{o}C and 21^{o}C, and was slightly better at 37^{o}C.

In dynamic modulus test results, for the first source of RAP tested at 4^{o}C and 37^{o}C, the highest dynamic modulus was obtained by 20% RAP, followed by 30%RAP or FRAP, and then 40% RAP or FRAP, with RAP and FRAP mixes behaving similarly. The samples made with the second source of RAP showed the best performance at 40% FRAP, followed by 30% FRAP at 4^{o}C and 40% RAP at 21^{o}C, due to the stiffer binder (higher PG grade) in RAP. As the binder started softening at 37^{o}C, there was still enough aged binder in 40% FRAP and RAP mixtures to make up for the temperature-softening effect, letting these still show the best performance. The same thing was not true about 30% FRAP and RAP mixtures, with 30% FRAP still performing better than 30% RAP, but worse than 20% RAP at 37^{o}C.

The binder PG grades for the first and second source of RAP were 84-16 and 91-10, respectively, making the second RAP stiffer than the first one. Besides, as it was shown in Table 3.3 (in Chapter 3), first and second FRAP mixes had 21and 25% passing the 12.5-mm sieve for 30% FRAP, and 28% and 32% aggregates passing the 12.5 mm-sieve for 40% FRAP, respectively. The first source of RAP had a coarser gradation and based on the nature of the source, fewer fine aggregates were introduced to the mix which in combination with having a softer binder caused the RAP and FRAP to behave very similarly to each other. Having finer gradation (higher surface area and higher binder content) and stiffer binder, the second source RAP and FRAP mixes did not behave similarly.

4.3.1 Possible Effect on Pavement Performance

The possible effect of these RAP and FRAP mixes can be understood by studying the performance models in the newly released Mechanistic-Empirical Pavement Design Guide (MEPDG) for flexible pavements.

4.3.1.1 Permanent Deformation Models

MEPDG offers models for predicting permanent deformation in each pavement layer. The average vertical resilient strain in each layer/sublayer is computed for each analysis period of the entire design period, with a linear elastic analysis program for each axle load configuration (NCHRP 2004). The rutting distress is predicted in absolute terms. The incremental distress is computed for each analysis period and is directly accumulated over the entire design life of the pavement. The model used to predict rutting of the asphalt mixes is based upon a field-calibrated statistical analysis of repeated permanent deformation laboratory test results. The model as follows:

$$\boldsymbol{\varepsilon_p / \varepsilon_r = k_1 * 10^{-3.4488} * T^{1.5606} * N^{0.479244}} \qquad \textbf{Equation 4.1}$$

$$\boldsymbol{k_1 = (C_1 + C_2 * depth) * 0.328196^{depth}} \qquad \textbf{Equation 4.2}$$

$$\boldsymbol{C_1 = -0.1039 * h_{ac}^2 + 2.4868 * h_{ac} - 17.342} \qquad \textbf{Equation 4.3}$$

$$\boldsymbol{C_2 = 0.0172 * h_{ac}^2 - 1.7331 * h_{ac} + 27.428} \qquad \textbf{Equation 4.4}$$

where

ε_0, β, and ρ are material properties,

ε_r = Resilient strain of the asphalt material as a function of mix properties, temperature and time rate of loading (in/in);

ε_p = Accumulated plastic strain at N repetitions of load (in/in);

T = Temperature (deg F);

N = Number of traffic repetitions; and

h_{ac}= Thickness of the layer/sublayer.

The final calibrated model parameters were derived from the permanent deformation data collected on 88 LTPP sections in 28 states (NCHRP 2004). The model developed above was derived based on observed deformation of in-service pavement structures and hence, is empirical. However, a desirable feature is that it includes the effect of temperature on the dynamic modulus for the asphalt concrete layers.

Equation (4.1) indicates that accumulated plastic strain due to load repetitions is directly proportional to the resilient strain of the asphalt material that in turn, is a function of mix properties, temperature, and time rate of loading (in/in). For a given temperature and rate of loading, higher stiffness or dynamic modulus of asphalt mixture will result in lower resilient strain. Rutting is usually considered critical at higher service temperature of the pavement and while aggregates carry a heavier weight on rutting resistance of a pavement, binder gives only some contribution. As the results of conducted tests in this study show, the softer aged binder in the first source of RAP does not help with the rutting resistance and at 37^{o}C performance declines as the percentage of RAP increases in the mix. The stiffer aged binder in the second source of RAP, however, contributes a lot to the rutting resistance of the HMA mix by giving the mixture enough stiffness to have the highest dynamic modulus results at 40% FRAP followed by 40% RAP for the tests conducted at 37^{o}C.

4.3.1.2 Load-Associated Cracking Models

Load-associated cracking is one of the most common asphalt concrete pavement distresses. The repeated traffic loads result in repeated tensile stresses in the bound layers. Under these repeated strains, fatigue cracks initiate at locations where the largest tensile strains and stresses develop. These critical locations depend on many factors such as pavement structural configuration, layer stiffness, and load configuration (area of load distribution, magnitude of stresses at the tire-pavement interface, etc.). After crack initiation at critical locations, the repeated traffic-load effect causes the cracks to propagate throughout the entire layer. These cracks allow water infiltration, thereby reducing overall performance of the pavement. Many pavement structural models assume that cracks initiate at the bottom of the asphalt concrete surface layer and then propagate upward. These cracks are named bottom-up fatigue cracks. MEPDG considers the alligator cracking as bottom-up fatigue cracking (NCHRP 2004). MEPDG also takes another type of fatigue cracking, now known as top-down cracking, which are longitudinal cracks in the wheel path. The cause of top-down cracking is hotly debated but they do seem to exist, especially in hot-weather locales.

MEPDG adopted Miner's hypothesis to estimate fatigue damage (NCHRP 2004):

$$D = \sum_{i=1}^{T} \frac{n_i}{N_i}$$ **Equation 4.5**

where

D = damage,

T = total number of periods,

n_i = actual traffic for period i, and

N_i = allowable repetitions to failure under conditions prevailing in period i.

The most commonly used model to predict the number of repetitions to fatigue cracking involves both tensile strain and mix stiffness. One well-known model proposed by the Asphalt Institute is based on a constant-stress criterion. The final fatigue model used in MEPDG can be obtained by numerical optimization and other modes of comparison as below:

$$N_f = 0.00432 * k_1^{'} * C(1/\varepsilon_t)^{3.9492} (1/E)^{1.281}$$ **Equation 4.6**

where

$C = 10^M$ and $M = 4.84*[V_b / (V_a+V_b) - 0.69]$,

V_b = effective binder volumetric content (%), and

V_a = air voids (%).

The parameter $k_1^{'}$ was introduced to account for different asphalt-layer thicknesses and is given by below for bottom-up cracking.

$$k_1^{'} = \frac{1}{0.000398 + [0.003602/(1+e^{(11.02-3.49*h_{ac})})]}$$ **Equation 4.7**

For top-down cracking, it is given by:

$$k_1^{'} = \frac{1}{0.01 + [12.00/(1+e^{(15.676-2.8186*h_{ac})})]}$$ **Equation 4.8**

Finally, the transfer function to estimate fatigue cracking from fatigue damage is expressed as in the equations below for bottom-up and top-down cracking respectively.

Bottom-up cracking

$$F.C. = \left(\frac{6000}{1 + e^{(C_1 * C'_1 + C_2 * C'_2 * \log 10(D*100))}} \right) * \left(\frac{1}{60} \right)$$

Equation 4.9

where

F.C. =bottom-up fatigue cracking, percent lane area,

D= bottom-up fatigue damage,

C_1 = 1.0,

C_2 = 1.0,

C'_1= -2 * C'_2, and

C'_2 = -2.40874-39.748*$(1+h_{ac})^{-2.856}$.

Top-down cracking

F.C. = 1000*10.56 / [1+ $e^{(7 - 3.5*\log 10\ (100*D))}$] **Equation 4.10**

where

F.C. = top-down fatigue cracking, ft/mile, and

D= top-down fatigue damage.

The fatigue cracking model for asphalt concrete was calibrated based on data from 82 LTPP sections located in 24 states, using 441 observations for alligator cracking and 408 data points for longitudinal cracking. The bottom-up cracking was calculated as a percentage of lane area, while the longitudinal cracking was expressed in terms of linear feet per mile of pavement (NCHRP 2004).

Equation (4.7) indicates that for a given tensile strain and volumetric properties of an asphalt mix, the number of repetitions to fatigue cracking is inversely related to the stiffness of an asphalt mix.

Fatigue cracking is considered a normal-to-low temperature phenomenon, and Figure 4.13 illustrates the dynamic modulus results at 21^{o}C for the five mixes in this study. Based on the conducted dynamic modulus tests, it seems like the mixture performance is in contradiction with what is assumed about stiffer binder and fatigue cracking, because the stiffer binder in RAP has helped with fatigue cracking. For both sources of RAP at 21^{o}C, Superpave mixtures are showing their best performances with 40% RAP and FRAP, followed by 30% RAP and FRAP. For the second source of RAP, the same thing is true for the tests conducted at 4^{o}C.

Chapter 5 - Conclusions and Recommendations

5.1 Conclusions

The objective of this research was to determine the impact of having higher percentages of RAP and FRAP on mixture performance for given Superpave mix designa. The following conclusions can be drawn based on this study:

1) Superpave mixtures with 20% RAP carried the highest number of wheel passes before reaching 20-mm rut depth in the Hamburg wheel-tracking device (HWTD) test. The number of passes decreases as the RAP percentage increases in the mix. When FRAP is replaced by RAP in the mix, the number of passes bumps up especially for 40% FRAP, still being less than mixes made with 20% RAP. Besides, other parameters obtained from the HWTD test outputs consistently indicate that a mixture with 20% RAP performs the best and there are no discernible differences in performance of RAP and FRAP mixtures for the first source of RAP. For the second source of RAP, however, better performances can be observed where RAP is being replaced by FRAP. These observations were largely supported by the statistical analysis of HWTD test outputs. This was also confirmed by analyzing the results in terms of virgin binder content. Given the large difference in performance between the mixtures with 20% RAP (76% virgin binder) and those with 30% RAP (62% virgin binder) or 30% FRAP, it can be surmised that minimum virgin binder content for the mixtures with RAP or FRAP should be about 75%. This finding may support the specifications of some state departments of transportation that require a minimum of 70% virgin binder.

2) The modified Lottman test results indicate that as the percentage of RAP increases in the mix, the tensile strength ratio (TSR) decreases and mixes with FRAP to perform worse than the mixes with RAP. The TSRs for 30% RAP and 30% FRAP are exactly the same, and the TSR is slightly lower for 40% FRAP when compared to 40% RAP. The mixture with 40% FRAP failed to meet the minimum required TSR value (80%). The indirect tensile strength, however, increases as the RAP percentage increases in the mix, and it is the highest at 40%

RAP. When RAP and FRAP are compared, FRAP mixes have slightly lower indirect tensile strength.

3) The dynamic modulus test results are different for the two sources of RAP. The first source of RAP tested at 4^{o}C and 37^{o}C; the highest dynamic modulus was obtained at 20% RAP followed by 30%RAP or FRAP, and then 40% RAP or FRAP with RAP and FRAP mixes behaving very similar. The behavior suggests that as the percentage of aged binder increases in the mix, the rutting performance diminishes.

4) Based on the dynamic modulus tests conducted, the observed performance is in contradiction with what is assumed about stiffer binder and fatigue cracking. The stiffer binder in RAP has helped with the fatigue cracking. For both sources of RAP at 21^{o}C, Superpave mixtures best performed with 40% RAP and FRAP followed by 30% RAP and FRAP. For second source of RAP, the same thing is true for the tests conducted at 4^{o}C.

5.2 Recommendations

1. Only two sources of RAP have been studied in this project. Multiple RAP sources should be investigated to find a more reliable assessment of high RAP Superpave mixtures.

2. Some form of cracking test, such as semi-circular bending test, Texas overlay test, etc., should be investigated to assess cracking susceptibility of high RAP mixtures and to dig deeper into the general concepts about the influences of stiffer aged binder in the HMA mix.

3. Life of pavements incorporated with high RAP mixtures should be assessed using MEPDG or a similar tool in order to find about life expectancy and predict future HMA pavement performance.

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Appendix A - Laboratory Mix Design and Performance Test Data

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Test Data (2011.0046.00704)

Sample #: 2011.0046.00704
Product: PG 70-28 FHR-1
Specification: Omaha - Weekly - IA, KS, NE - Spec Comp
Analysis Site: COE PINE BEND LAB
Sent By: OMAHA, NE
Collection Point: Autosampler
Sampled Date: 05/09/2011
Tested Date: 05/19/2011

Test Parameter		Result / UOM	Agency Min	Agency Max
General Sample Information - (Unspecified)				
Tank Number		1/2/011		
Lot Number		5W2		
Date Sample Received		5/11/11		
Date Begin Testing		5/16/11		
Date Complete Testing		5/19/11		
Rotational Viscosity (AASHTO) - T 316				
Temperature		135 °C		
Viscosity	C	*1.255* Pa.s		3.000
Rotational Viscosity @ 165C (AASHTO) - T 316				
Viscosity	C	*0.335* Pa.s		
Separation 2 day (R&B) - D 7173				
R&B Top	C	*73.5* °C		
R&B Bottom	C	*73.7* °C		
R&B Difference	C	*0.2* °C	-2.0	2.0
Flash Point, COC (AASHTO) - T 48				
Flashpoint, COC		308 °C	230	
DSR Unaged (AASHTO) - T 315				
Temperature		70 °C		
G*		1.422 kPa		
Phase angle		66.2 °		75.0
G/sin delta*	C	*1.55* kPa	1.00	
RTFO Mass Change (AASHTO) - T 240				
Mass Change	C	*-0.395* %	-1.000	1.000
DSR RTFO (AASHTO) - T 315				
Temperature		70 °C		
G*		2.654 kPa		
Phase angle		63.5 °		
G/sin delta*	C	*2.97* kPa	2.20	
Multiple Stress Creep Recovery RTFO - TP 70				
Test Temperature		64 °C		
Percent Recovery at 0.1 kPa		74.270 %		
Percent Recovery at 3.2 kPa		73.080 %		
Jnr at 0.1 kPa		0.294 kPa		
Jnr at 3.2 kPa		0.313 kPa		
Jnr Percent Difference	C	*6.46* %		

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Figure A.1 Asphalt binder specifications

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Test Data (2011.0046.00704)

Test Parameter		Result / UOM	Agency Min	Agency Max
Elastic Recovery, RTFO Residue (AASHTO) - T 301				
Temperature		25 °C		
Elastic Recovery	*C*	*85 %*	65	
PAV (AASHTO) - R 28				
PAV Temperature		100 °C	100	100
DSR PAV (AASHTO) - T 315				
Temperature		25 °C		
G*		2375 kPa		
Phase angle		51.8 °		
G* x sin delta		1867 kPa		5000
BBR PAV (AASHTO) - T 313				
Temperature		-18 °C		
Stiffness	*C*	*201.5* MPa		300.0
Slope	*C*	*0.333*	0.300	
Recommended Laboratory Mixing & Compaction Temp - (Unspecified)				
Mixing low limit		316 °F		
Mixing high limit		331 °F		
Compaction low limit		270 °F		
Compaction high limit		281 °F		

Test data provided on this document is for informational purposes only and may be actual or typical data. It is not intended to represent certified test results.

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Figure A.1 Asphalt binder specifications (continued)

Table A.1 Aggregate blend gradation mix with 20% RAP from the first source

Material	CS-1		CS-1A		MSD-1		CG-5		SSG		RAP		Blend	Target
% Used	20		12		12		16		20		20			
Sieve Size	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch		
1.5														
1														
3/4	0										0		0	0
1/2	45	9	0	0	0	0	0	0			2		9	0-10
3/8	83	17	0	0	0	0	0	0	0	0	6	1	18	10min
#4	100	20	74	9	1	0	6	1	4	1	20	4	35	
#8	100	20	99	12	43	5	29	5	19	4	36	7	53	42-61
#16	100	20	100	12	72	9	57	9	43	9	53	11	69	
#30	100	20	100	12	86	10	76	12	65	13	67	13	81	
#50	100	20	100	12	95	11	88	14	86	17	80	16	91	
#100	100	20	100	12	98	12	95	15	98	20	87	17	96	
#200	100	20	100	12	100	12	100	16	100	20	90	18	98	90-98

Table A.2 Aggregate blend gradation mix with 30% RAP from the first source

Material	CS-1		CS-1A		MSD-1		CG-5		SSG		RAP		Blend	Target
% Used	16		15		13		12		14		30			
Sieve Size	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch		
1.5														
1														
3/4	0										0		0	0
1/2	45	7	0	0	0	0	0	0			2		7	0-10
3/8	83	13	0	0	0	0	0	0	0	0	6	2	15	10min
#4	100	16	74	11	1	0	6	1	4	1	20	6	34	
#8	100	16	99	15	43	6	29	3	19	3	36	11	53	42-61
#16	100	16	100	15	72	9	57	7	43	6	53	16	69	
#30	100	16	100	15	86	11	76	9	65	9	67	20	80	
#50	100	16	100	15	95	12	88	11	86	12	80	24	90	
#100	100	16	100	15	98	13	95	11	98	14	87	26	95	
#200	100	16	100	15	100	13	100	12	100	14	90	27	97	90-98

Table A.3 Aggregate blend gradation mix with 40% RAP from the first source

Material	CS-1		CS-1A		MSD-1		CG-5		SSG		RAP		Blend	Target
% Used	12		13		13		12		10		40			
Sieve Size	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch		
1.5														
1														
3/4	0										0		0	0
1/2	45	5	0	0	0	0	0	0			2		5	0-10
3/8	83	10	0	0	0	0	0	0	0	0	6	2	12	10min
#4	100	12	74	10	1	0	6	1	4	0	20	8	31	
#8	100	12	99	13	43	6	29	3	19	2	36	14	50	42-61
#16	100	12	100	13	72	9	57	7	43	4	53	21	67	
#30	100	12	100	13	86	11	76	9	65	6	67	27	79	
#50	100	12	100	13	95	12	88	11	86	9	80	32	88	
#100	100	12	100	13	98	13	95	11	98	10	87	35	94	
#200	100	12	100	13	100	13	100	12	100	10	90	36	96	90-98

Table A.4 Aggregate blend gradation mix with 20% RAP from the second source

Material	CS-1		CS-1A		MSD-1		CG-5		SSG		RAP		Blend	Target
% Used	20		12		12		16		20		20			
Sieve Size	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch		
1.5														
1														
3/4	0										0		**0**	**0**
1/2	45	9	0	0	0	0	0	0			4	1	**10**	**0-10**
3/8	83	17	0	0	0	0	0	0	0	0	8	2	**18**	**10 Min**
#4	100	20	74	9	1	0	6	1	4	1	22	4	**35**	
#8	100	20	99	12	43	5	29	5	19	4	36	7	**53**	**42-61**
#16	100	20	100	12	72	9	57	9	43	9	52	10	**69**	
#30	100	20	100	12	86	10	76	12	65	13	65	13	**80**	
#50	100	20	100	12	95	11	88	14	86	17	79	16	**90**	
#100	100	20	100	12	98	12	95	15	98	20	85	17	**95**	
#200	100	20	100	12	100	12	100	16	100	20	87	17	**97**	**90-98**

Table A.5 Aggregate blend gradation mix with 30% RAP from the second source

Material	CS-1		CS-1A		MSD-1		CG-5		SSG		RAP		Blend	Target
% Used	16		15		13		12		14		30			
Sieve Size	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch		
1.5														
1														
3/4	0										0		0	0
1/2	45	7	0	0	0	0	0	0			4	1	8	0-10
3/8	83	13	0	0	0	0	0	0	0	0	8	2	16	10 Min
#4	100	16	74	11	1	0	6	1	4	1	22	7	35	
#8	100	16	99	15	43	6	29	3	19	3	36	11	53	42-61
#16	100	16	100	15	72	9	57	7	43	6	52	16	69	
#30	100	16	100	15	86	11	76	9	65	9	65	20	80	
#50	100	16	100	15	95	12	88	11	86	12	79	24	89	
#100	100	16	100	15	98	13	95	11	98	14	85	26	94	
#200	100	16	100	15	100	13	100	12	100	14	87	26	96	90-98

Table A.6 Aggregate blend gradation mix with 40% RAP from the second source

Material	CS-1		CS-1A		MSD-1		CG-5		SSG		RAP		Blend	Target
% Used	12		13		13		12		10		40			
Sieve Size	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch	% Ret.	% Batch		
1.5														
1														
3/4	0										0		0	0
1/2	45	5	0	0	0	0	0	0			4	2	7	0-10
3/8	83	10	0	0	0	0	0	0	0	0	8	3	13	10 Min
#4	100	12	74	10	1	0	6	1	4	0	22	9	32	
#8	100	12	99	13	43	6	29	3	19	2	36	14	50	42-61
#16	100	12	100	13	72	9	57	7	43	4	52	21	66	
#30	100	12	100	13	86	11	76	9	65	6	65	26	78	
#50	100	12	100	13	95	12	88	11	86	9	79	32	88	
#100	100	12	100	13	98	13	95	11	98	10	85	34	93	
#200	100	12	100	13	100	13	100	12	100	10	87	35	95	90-98

Table A.7 Volumetric properties of HWTD test specimens with 20% RAP

Plug no	Gsb		% Binder		Gmb		Gmm		%Va		%VMA		%VFA	
	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP
I-1	2.612	2.608	4.7	4.3	2.273	2.295	2.456	2.468	7.45	7.01	17.07	15.79	56.35	55.59
I-2			4.7	4.3	2.275	2.302	2.456	2.468	7.37	6.73	17.00	15.53	56.64	56.69
I-3			4.7	4.3	2.279	2.289	2.456	2.468	7.21	7.25	16.85	16.01	57.23	54.69
I-4			4.7	4.3	2.284	2.278	2.456	2.468	7.00	7.70	16.67	16.41	57.98	53.08
II-1			4.7	4.3	2.272	2.276	2.451	2.457	7.30	7.37	17.11	16.48	57.30	55.31
II-2			4.7	4.3	2.268	2.309	2.451	2.457	7.47	6.02	17.25	15.27	56.72	60.56
II-3			4.7	4.3	2.266	2.293	2.451	2.457	7.55	6.67	17.32	15.86	56.43	57.91
II-4			4.7	4.3	2.290	2.303	2.451	2.457	6.57	6.27	16.45	15.49	60.06	59.54
III-1			4.7	4.3	2.266	2.285	2.463	2.456	8.00	6.96	17.32	16.15	53.83	56.89
III-2			4.7	4.3	2.265	2.284	2.463	2.456	8.04	7.00	17.36	16.19	53.69	56.74
III-3			4.7	4.3	2.269	2.287	2.463	2.456	7.88	6.88	17.21	16.08	54.24	57.20
III-4			4.7	4.3	2.273	2.304	2.463	2.456	7.71	6.19	17.07	15.46	54.80	59.96

Table A.8 Volumetric properties of HWTD test specimens with 30% RAP

Plug no	Gsb		% Binder		Gmb		Gmm		%Va		%VMA		%VFA	
	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP
I-1	2.627	2.613	4.8	4.4	2.298	2.273	2.486	2.461	7.56	7.64	16.72	16.84	54.78	54.63
I-2			4.8	4.4	2.303	2.284	2.486	2.461	7.36	7.19	16.54	16.44	55.50	56.24
I-3			4.8	4.4	2.304	2.296	2.486	2.461	7.32	6.70	16.51	16.00	55.64	58.09
I-4			4.8	4.4	2.314	2.299	2.486	2.461	6.92	6.58	16.14	15.89	57.14	58.57
II-1			4.8	4.4	2.303	2.284	2.477	2.465	7.02	7.34	16.54	16.44	57.53	55.33
II-2			4.8	4.4	2.301	2.277	2.477	2.465	7.11	7.63	16.61	16.69	57.23	54.31
II-3			4.8	4.4	2.300	2.287	2.477	2.465	7.15	7.22	16.65	16.33	57.08	55.77
II-4			4.8	4.4	2.301	2.300	2.477	2.465	7.11	6.69	16.61	15.85	57.23	57.77
III-1			4.8	4.4	2.302	2.296	2.465	2.463	6.61	6.78	16.58	16.00	60.11	57.62
III-2			4.8	4.4	2.299	2.273	2.465	2.463	6.73	7.71	16.69	16.84	59.64	54.19
III-3			4.8	4.4	2.294	2.283	2.465	2.463	6.94	7.31	16.87	16.47	58.87	55.64
III-4			4.8	4.4	2.303	2.277	2.475	2.463	6.95	7.55	16.54	16.69	57.99	54.76

Table A.9 Volumetric properties of HWTD test specimens with 40% RAP

Plug no	Gsb		% Binder		Gmb		Gmm		%Va		%VMA		%VFA	
	1st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP
I-1	2.63	2.621	4.3	4.1	2.307	2.326	2.476	2.480	6.83	6.21	16.05	14.89	57.48	58.31
I-2			4.3	4.1	2.310	2.323	2.476	2.480	6.70	6.33	15.94	15.00	57.95	57.81
I-3			4.3	4.1	2.298	2.320	2.476	2.480	7.19	6.45	16.38	15.11	56.11	57.31
I-4			4.3	4.1	2.301	2.326	2.476	2.480	7.07	6.21	16.27	14.89	56.56	58.31
II-1			4.3	4.1	2.299	2.318	2.479	2.486	7.26	6.76	16.34	15.19	55.57	55.50
II-2			4.3	4.1	2.305	2.327	2.479	2.486	7.02	6.40	16.13	14.86	56.47	56.95
II-3			4.3	4.1	2.300	2.320	2.479	2.486	7.22	6.68	16.31	15.11	55.72	55.82
II-4			4.3	4.1	2.312	2.329	2.479	2.486	6.74	6.32	15.87	14.78	57.55	57.28
III-1			4.3	4.1	2.303	2.328	2.472	2.482	6.84	6.20	16.20	14.82	57.80	58.13
III-2			4.3	4.1	2.311	2.332	2.472	2.482	6.51	6.04	15.91	14.67	59.06	58.82
III-3			4.3	4.1	2.311	2.330	2.472	2.482	6.51	6.12	15.91	14.75	59.06	58.47
III-4			4.3	4.1	2.304	2.329	2.484	2.482	7.25	6.16	16.16	14.78	55.17	58.30

Table A.10 Volumetric properties of HWTD test specimens with 30% FRAP

Plug no	Gsb		% Binder		Gmb		Gmm		%Va		%VMA		%VFA	
	1st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP
I-1	2.627	2.613	4.3	4.4	2.282	2.276	2.445	2.455	6.67	7.29	16.87	16.73	60.48	56.42
I-2			4.3	4.4	2.276	2.269	2.445	2.455	6.91	7.58	17.09	16.99	59.55	55.40
I-3			4.3	4.4	2.287	2.271	2.445	2.455	6.46	7.49	16.69	16.91	61.27	55.68
I-4			4.3	4.4	2.287	2.272	2.445	2.455	6.46	7.45	16.69	16.88	61.27	55.83
II-1			4.3	4.4	2.281	2.266	2.457	2.457	7.16	7.77	16.90	17.10	57.63	54.53
II-2			4.3	4.4	2.284	2.265	2.457	2.457	7.04	7.81	16.80	17.13	58.08	54.39
II-3			4.3	4.4	2.274	2.274	2.457	2.457	7.45	7.45	17.16	16.80	56.60	55.67
II-4			4.3	4.4	2.307	2.296	2.457	2.456	6.11	6.51	15.96	16.00	61.74	59.28
III-1			4.3	4.4	2.258	2.275	2.451	2.455	7.87	7.33	17.74	16.77	55.62	56.27
III-2			4.3	4.4	2.279	2.282	2.451	2.455	7.02	7.05	16.98	16.51	58.67	57.32
III-3			4.3	4.4	2.274	2.275	2.451	2.455	7.22	7.33	17.16	16.77	57.92	56.27
III-4			4.3	4.4	2.280	2.273	2.451	2.455	6.98	7.41	16.94	16.84	58.82	55.98

Table A.11 Volumetric properties of HWTD test specimens with 30% FRAP

Plug no	Gsb		% Binder		Gmb		Gmm		%Va		%VMA		%VFA	
	1st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP	1 st RAP	2d RAP
I-1	2.63	2.621	4.4	4.2	2.300	2.295	2.486	2.476	7.48	7.31	16.40	16.12	54.37	54.64
I-2			4.4	4.2	2.304	2.302	2.486	2.476	7.32	7.03	16.25	15.86	54.95	55.69
I-3			4.4	4.2	2.292	2.289	2.486	2.476	7.80	7.55	16.69	16.33	53.23	53.76
I-4			4.4	4.2	2.305	2.278	2.486	2.476	7.28	8.00	16.21	16.74	55.09	52.22
II-1			4.4	4.2	2.300	2.276	2.475	2.485	7.07	8.41	16.40	16.81	56.87	49.97
II-2			4.4	4.2	2.307	2.309	2.475	2.485	6.79	7.08	16.14	15.60	57.95	54.61
II-3			4.4	4.2	2.311	2.293	2.475	2.485	6.63	7.73	16.00	16.19	58.57	52.27
II-4			4.4	4.2	2.307	2.303	2.475	2.485	6.79	7.32	16.14	15.82	57.95	53.71
III-1			4.4	4.2	2.305	2.285	2.477	2.476	6.94	7.71	16.21	16.48	57.17	53.19
III-2			4.4	4.2	2.312	2.284	2.477	2.476	6.66	7.75	15.96	16.52	58.26	53.05
III-3			4.4	4.2	2.304	2.287	2.477	2.476	6.98	7.63	16.25	16.41	57.02	53.48
III-4			4.4	4.2	2.303	2.304	2.477	2.476	7.02	6.95	16.29	15.79	56.87	56.00

Table A.12 HWTD test output for different mix designs for first and second source of RAP

Mix design	First Run								Second Run								Third Run							
	Post Compaction (@1,000 Passses)		Creep Slope		stripping Inflection Point		Stripping Slope		Post Compaction (@1,000 Passses)		Creep Slope		stripping Inflection Point		Stripping Slope		Post Compaction (@1,000 Passses)		Creep Slope		stripping Inflection Point		Stripping Slope	
	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel	Left Wheel	Right Wheel
20% 1st RAP	1.23	1.22	13,333	11,111	30,347	27,957	1,250	690									2.33	2.07	5,600	6,667	20,845	17,320	580	459
30% 1st RAP	1.50	1.70	11,429	5,882	23,748	17,231	901	988	1.60	1.65	10,769	6,000	18,330	11,743	566	667	1.69	1.47	6,000	5,333	13,119	12,019	625	667
40% 1stRAP	1.23	1.23	4,580	5,000	10,952	11,750	435	545	1.33	1.42	6,932	9,091	16,949	21,803	822	143	1.49	1.33	5,000	5,455	12,700	11,589	735	597
30% 1stFRAP	1.63	1.55	9,231	9,231	16,986	17,218	784	714	-	1.45	-	9,231	-	17,218	-	714	1.49	-	6,667	-	14,267	-	606	-
40% 1st FRAP	-	1.00	-	7,273	-	13,617	-	625									1.04	1.44	13,333	8,333	22,882	13,383	673	769
20% 2d RAP	1.45	2.25	3,333	3,333	8,372	6,879	504	517	0.97	1.15	4,615	1,000	9,804	18,517	581	625	1.16	1.69	6,667	4,286	13,250	13,167	565	609
30% 2d RAP	0.97	1.62	3,529	5,000	10,606	10,997	400	426	1.51	1.42	3,750	5,000	8,127	10,529	426	541	1.42	1.69	3,333	3,846	8,907	9,673	331	400
40% 2d RAP	1.05	1.05	2,500	3,333	5,815	4,511	500	455	1.13	2.20	4,444	2,500	3,876	3,909	526	556	1.15	1.41	3,333	3,333	5,302	4,924	455	278
30% 2d FRAP	1.88	2.13	3,333	3,333	9,952	11,955	435	455	1.45	1.46	3,333	5,000	11,776	10,596	357	476	1.48	1.25	3,333	2,500	9,945	7,275	476	476
40% 2d FRAP	1.06	1.08	5,000	5,000	10,292	12,193	556	360	0.94	1.61	5,000	3,333	10,128	9,106	526	556	1.13	1.08	5,000	5,000	9,848	10,731	435	667

Table A.13 G_{mb}, G_{mm}, and %Va of KT-56 specimens for both sources of RAP

Mix Dsgn	Smpl ID	Conditioned	Unconditioned	Gmb 1st RAP	Gmb 2d RAP	Gmm 1st RAP	Gmm 2d RAP	% Binder 1st RAP	% Binder 2d RAP	% Va 1st RAP	% Va 2d RAP
20% RAP	*a*			2.265	2.302	2.440	2.468	4.70	4.30	7.17	6.72
	b			2.267	2.296	2.440	2.468			7.09	6.97
	c			2.271	2.293	2.453	2.465			7.42	6.98
	e			2.283	2.300	2.458	2.468			7.12	6.80
	f			2.276	2.284	2.453	2.468			7.22	7.45
	g			2.275	2.303	2.453	2.465			7.26	6.57
30% RAP	*a*			2.287	2.301	2.451	2.473	4.80	4.40	6.69	6.96
	b			2.290	2.314	2.458	2.477			6.83	6.58
	c			2.287	2.308	2.458	2.477			6.96	6.82
	e			2.278	2.304	2.451	2.473			7.06	6.83
	f			2.291	2.312	2.451	2.473			6.53	6.51
	g			2.294	2.302	2.458	2.477			6.67	7.06
40% RAP	*a*			2.306	2.309	2.467	2.487	4.30	4.10	6.53	7.20
	b			2.309	2.310	2.470	2.487			6.52	7.10
	c			2.326	2.312	2.497	2.477			6.85	6.70
	e			2.307	2.309	2.469	2.477			6.56	6.80
	f			2.309	2.308	2.470	2.487			6.48	7.20
	g			2.327	2.313	2.497	2.482			6.81	6.80
30% FRAP	*a*			2.300	2.280	2.472	2.456	4.30	4.40	6.96	7.20
	b			2.291	2.277	2.460	2.456			6.87	7.30
	c			2.299	2.285	2.460	2.453			6.54	6.80
	e			2.298	2.279	2.472	2.456			7.04	7.20
	f			2.305	2.276	2.472	2.453			6.76	7.20
	g			2.299	2.277	2.460	2.453			6.54	7.20
40% FRAP	*a*			2.307	2.316	2.484	2.490	4.40	4.20	7.13	6.98
	b			2.310	2.309	2.477	2.490			6.74	7.26
	c			2.312	2.312	2.477	2.490			6.66	7.14
	e			2.311	2.302	2.484	2.484			6.96	7.33
	f			2.307	2.316	2.477	2.484			6.86	6.76
	g			2.309	2.302	2.477	2.484			6.78	7.33

Table A.14 Diameter and thickness of KT-56 specimens for first source of RAP before and after conditioning

			a		b		c		e		f		g	
				Avg.		Avg.		Avg.		Avg.		Avg.		Avg.
20% RAP	Before	Diameter	149.99	150.08	149.67	149.93	150.88	150.49	150.45	150.36	150.39	149.79	150.54	150.58
			149.98		150.04		150.48		150.60		148.97		150.44	
			150.26		150.07		150.12		150.03		150.01		150.75	
		Thickness	94.89	94.75	94.59	94.33	94.26	94.55	94.60	94.66	94.37	94.50	94.81	94.58
			94.65		94.57		94.73		94.62		94.61		94.39	
			94.70		93.82		94.65		94.77		94.53		94.54	
	After	Diameter	151.09	150.64	150.33	150.53	150.42	150.54						
			150.37		150.40		150.85							
			150.47		150.86		150.35							
		Thickness	94.87	95.07	95.38	95.27	94.81	94.85						
			95.49		95.74		94.75							
			94.85		94.70		95.00							
30% RAP	Before	Diameter	150.20	150.24	150.20	150.16	150.18	150.15	150.25	150.37	150.16	150.16	149.99	150.05
			150.36		150.15		150.10		150.33		150.25		150.05	
			150.16		150.12		150.17		150.54		150.06		150.10	
		Thickness	94.70	94.60	94.71	94.65	94.68	94.63	94.52	94.64	94.53	94.55	94.90	94.80
			94.43		94.66		94.61		94.66		94.53		94.61	
			94.68		94.58		94.60		94.73		94.60		94.88	
	After	Diameter	150.43	150.38	150.26	150.26	150.33	150.35						
			150.37		150.29		150.34							
			150.33		150.23		150.37							
		Thickness	94.54	94.57	94.77	94.83	94.62	94.61						
			94.49		94.89		94.65							
			94.69		94.83		94.57							

Table A.14 Diameter and thickness of KT-56 specimens for first source of RAP before and after conditioning (Continued)

			a		b		c		e		f		g	
				Avg.		**Avg.**		**Avg.**		**Avg.**		**Avg.**		**Avg.**
40% RAP	**Before**	Diameter	149.91		150.03		150.08		150.04		150.15		149.96	
			149.98	149.95	150.00	150.03	150.05	150.04	150.03	150.04	150.04	150.09	150.01	150.00
			149.95		150.05		150.00		150.05		150.07		150.03	
		Thickness	94.83		94.81		94.90		94.56		94.62		94.89	
			94.90	94.85	94.83	94.86	94.72	94.81	94.77	94.60	94.77	94.68	94.98	94.90
			94.81		94.94		94.82		94.47		94.65		94.82	
	After	Diameter	150.15		150.26		150.37							
			150.12	150.16	150.28	150.28	150.30	150.29						
			150.21		150.29		150.19							
		Thickness	95.28		94.79		95.23							
			94.92	95.03	94.83	94.80	95.17	95.19						
			94.90		94.77		95.17							
30% FRAP	**Before**	Diameter	150.14		150.11		150.11		150.13		150.01		150.14	
			150.14	150.13	150.08	150.09	150.03	150.11	150.04	150.08	149.99	150.04	150.06	150.10
			150.10		150.08		150.20		150.07		150.13		150.11	
		Thickness	94.72		94.87		94.70		94.96		95.00		94.59	
			94.99	94.88	94.76	94.82	94.86	94.79	94.91	94.94	94.74	94.89	94.85	94.73
			94.92		94.83		94.80		94.95		94.92		94.75	
	After	Diameter	150.06		150.35		150.20							
			150.33	150.21	150.39	150.37	150.27	150.27						
			150.23		150.36		150.35							
		Thickness	94.85		94.87		94.87							
			94.93	94.88	94.94	94.82	97.79	95.88						
			94.85		94.66		94.99							

Table A.14 Diameter and thickness of KT-56 specimens for first source of RAP before and after conditioning (Continued)

			a		b		c		e		f		g	
				Avg.		Avg.		Avg.		Avg.		Avg.		Avg.
40% FRAP	Before	Diameter	150.03		150.03		150.00		150.00		149.95		150.08	
			150.03	150.00	150.05	150.05	149.91	149.97	149.89	149.95	149.98	149.98	150.00	150.03
			149.95		150.06		150.00		149.96		150.00		150.01	
		Thickness	95.20		95.01		94.93		94.85		94.69		94.59	
			94.84	94.93	94.70	94.91	94.87	94.85	94.78	94.82	94.70	94.68	94.74	94.67
			94.75		95.02		94.74		94.84		94.66		94.68	
	After	Diameter	150.37		150.33		150.34							
			150.29	150.32	150.30	150.29	150.28	150.33						
			150.30		150.24		150.38							
		Thickness	95.26		94.80		94.72							
			94.84	95.02	94.87	94.82	94.75	94.75						
			94.95		94.79		94.77							

Table A.15 Diameter and thickness of KT-56 specimens for second source of RAP before and after conditioning

			a	a Avg.	b	b Avg.	c	c Avg.	e	e Avg.	f	f Avg.	g	g Avg.
20% RAP	Before	Diameter	150.00	150.07	150.00	149.97	150.10	150.03	150.10	149.90	150.20	150.10	150.00	149.97
20% RAP	Before	Diameter	150.20		149.80		150.00		149.80		150.00		149.90	
20% RAP	Before	Diameter	150.00		150.10		150.00		149.80		150.10		150.00	
20% RAP	Before	Thickness	94.80	94.73	94.50	94.57	94.70	94.67	94.80	94.80	94.80	94.77	94.70	94.67
20% RAP	Before	Thickness	94.70		94.60		94.60		94.80		94.80		94.70	
20% RAP	Before	Thickness	94.70		94.60		94.70		94.80		94.70		94.60	
20% RAP	After	Diameter	150.20	150.27	150.20	150.10	150.40	150.37						
20% RAP	After	Diameter	150.40		150.10		150.30							
20% RAP	After	Diameter	150.20		150.00		150.40							
20% RAP	After	Thickness	94.70	94.67	94.60	94.67	94.80	94.83						
20% RAP	After	Thickness	94.60		94.70		94.90							
20% RAP	After	Thickness	94.70		94.70		94.80							
30% RAP	Before	Diameter	145.00	144.87	145.50	145.70	145.10	145.23	145.00	144.93	144.80	144.97	145.00	145.23
30% RAP	Before	Diameter	144.80		145.60		145.10		144.90		145.00		145.20	
30% RAP	Before	Diameter	144.80		146.00		145.50		144.90		145.10		145.50	
30% RAP	Before	Thickness	94.30	94.40	94.50	94.43	94.50	94.40	94.70	94.67	94.60	94.60	94.50	94.40
30% RAP	Before	Thickness	94.40		94.40		94.40		94.60		94.50		94.40	
30% RAP	Before	Thickness	94.50		94.40		94.30		94.70		94.70		94.30	
30% RAP	After	Diameter	150.10	150.20	150.10	150.17	150.20	150.17						
30% RAP	After	Diameter	150.20		150.20		150.20							
30% RAP	After	Diameter	150.30		150.20		150.10							
30% RAP	After	Thickness	94.70	94.77	94.50	94.60	94.40	94.50						
30% RAP	After	Thickness	94.80		94.60		94.50							
30% RAP	After	Thickness	94.80		94.70		94.60							

Table A.15 Diameter and thickness of KT-56 specimens for second source of RAP before and after conditioning (continued)

			a		b		c		e		f		g	
				Avg.		Avg.		Avg.		Avg.		Avg.		Avg.
40% RAP	Before	Diameter	150.10	150.00	150.00	149.97	150.00	149.97	150.00	149.97	150.00	149.87	150.00	149.93
			149.90		150.00		150.00		149.90		150.00		149.90	
			150.00		149.90		149.90		150.00		149.60		149.90	
		Thickness	94.60	94.63	94.70	94.73	94.90	94.60	95.00	94.63	94.90	94.70	94.70	94.57
			94.60		94.80		94.50		94.50		94.80		94.50	
			94.70		94.70		94.40		94.40		94.40		94.50	
	After	Diameter	150.57	150.50	150.32	150.30	150.42	150.47						
			150.45		150.23		150.43							
			150.48		150.35		150.57							
		Thickness	95.00	94.92	94.91	94.87	94.86	94.81						
			94.92		94.77		94.81							
			94.84		94.92		94.76							
30% FRAP	Before	Diameter	150.14	150.13	150.11	150.09	150.11	150.11	150.13	150.08	150.01	150.04	150.14	150.10
			150.14		150.08		150.03		150.04		149.99		150.06	
			150.10		150.08		150.20		150.07		150.13		150.11	
		Thickness	94.72	94.88	94.87	94.82	94.70	94.79	94.96	94.94	95.00	94.89	94.59	94.73
			94.99		94.76		94.86		94.91		94.74		94.85	
			94.92		94.83		94.80		94.95		94.92		94.75	
	After	Diameter	150.06	150.21	150.35	150.37	150.20	150.27						
			150.33		150.39		150.27							
			150.23		150.36		150.35							
		Thickness	94.85	94.88	94.87	94.82	94.87	95.88						
			94.93		94.94		97.79							
			94.85		94.66		94.99							

Table A.15 Diameter and thickness of KT-56 specimens for second source of RAP before and after conditioning (continued)

			a		b		c		e		f		g	
				Avg.		**Avg.**		**Avg.**		**Avg.**		**Avg.**		**Avg.**
40% FRAP	**Before**	Diameter	150.03	150.00	150.03	150.05	150.00	149.97	150.00	149.95	149.95	149.98	150.08	150.03
			150.03		150.05		149.91		149.89		149.98		150.00	
			149.95		150.06		150.00		149.96		150.00		150.01	
		Thickness	95.20	94.93	95.01	94.91	94.93	94.85	94.85	94.82	94.69	94.68	94.59	94.67
			94.84		94.70		94.87		94.78		94.70		94.74	
			94.75		95.02		94.74		94.84		94.66		94.68	
	After	Diameter	150.37	150.32	150.33	150.29	150.34	150.33						
			150.29		150.30		150.28							
			150.30		150.24		150.38							
		Thickness	95.26	95.02	94.80	94.82	94.72	94.75						
			94.84		94.87		94.75							
			94.95		94.79		94.77							

Table A.16 G_{mb}, G_{mm}, and %Va of dynamic modulus specimens for both sources of RAP

Mix Design	Sample ID		Gmb		Gmm		% Binder		% Va	
	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP	1st RAP	2d RAP
20% RAP	S1	21	2.278	2.285	2.463	2.462	4.70	4.30	7.51	7.19
	S2	22	2.292	2.267	2.463	2.462			6.94	7.92
	S3	S3	2.288	2.307	2.463	2.486			7.11	7.20
30% RAP	IV-1	31	2.290	2.259	2.455	2.438	4.80	4.40	6.72	7.34
	IV-2	33	2.297	2.252	2.455	2.438			6.44	7.63
	30-2	34	2.292	2.250	2.470	2.438			7.21	7.71
40% RAP	2	42	2.320	2.292	2.468	2.477	4.30	4.10	6.00	7.47
	2-1	43	2.307	2.301	2.454	2.484			5.99	7.37
	2-2	44	2.306	2.289	2.454	2.484			6.03	7.85
30% FRAP	30-I	f31	2.313	2.286	2.461	2.471	4.30	4.40	6.01	7.49
	30-II	f32	2.308	2.305	2.461	2.471			6.22	6.72
	30-III	f34	2.310	2.313	2.458	2.494			6.02	7.26
40% FRAP	40F(0)	f42	2.293	2.306	2.466	2.496	4.40	4.20	7.02	7.61
	S1	f43	2.292	2.302	2.471	2.473			7.24	6.91
	S2	f44	2.296	2.304	2.471	2.473			7.08	6.83

Table A.17 Diameter and thickness of dynamic modulus specimens for the first source of RAP

	20% RAP	30% RAP	40% RAP	30% FRAP	40% FRAP
	Sample # S1	Sample # IV-1	Sample # 2	Sample # 30-I	Sample # 40F
Diameter	101.49	100.90	100.90	100.50	100.80
Diameter	101.39	100.70	100.70	101.10	100.70
Diameter	101.52	100.90	100.90	100.60	100.80
Diameter	101.33	100.80	100.80	100.60	100.80
Diameter	101.44	100.70	100.70	101.40	100.90
Thickness	149.90	150.60	150.60	151.90	150.00
Thickness	151.10	150.40	150.40	152.00	149.80
Thickness	151.20	150.40	150.40	151.07	150.00
Thickness	151.20	150.30	150.30	151.70	150.08
Thickness	149.90	150.20	150.20	151.80	150.07
	Sample # S2	Sample # IV-2	Sample # 2-1	Sample # 30-II	Sample # S1
Diameter	101.70	100.80	100.90	100.80	100.60
Diameter	101.80	100.90	100.80	100.70	100.70
Diameter	101.90	100.70	100.80	100.80	100.80
Diameter	102.00	100.30	100.80	100.80	100.80
Diameter	101.80	100.90	100.90	100.70	100.70
Thickness	150.80	150.20	148.90	150.00	148.90
Thickness	150.30	149.70	148.40	149.90	148.70
Thickness	150.10	149.70	148.50	150.10	148.90
Thickness	150.70	150.10	148.70	150.20	148.80
Thickness	151.00	150.00	148.90	149.80	148.90
	Sample # S3	Sample # 30-2	Sample # 2-2	Sample # 30-III	Sample # S2
Diameter	101.20	100.80	100.90	100.90	100.60
Diameter	101.80	100.90	100.80	100.70	100.70
Diameter	102.00	100.80	100.80	100.60	100.80
Diameter	101.90	100.80	100.80	100.80	100.80
Diameter	101.30	100.70	100.90	100.70	100.70
Thickness	147.90	150.70	149.80	150.50	148.80
Thickness	148.50	150.80	150.70	150.40	148.70
Thickness	148.80	150.50	151.00	150.30	148.30
Thickness	148.90	149.80	149.70	150.20	148.50
Thickness	148.80	149.90	150.00	150.30	148.70

Table A.18 Diameter and thickness of dynamic modulus specimens for the second source of RAP

	20% RAP	30% RAP	40% RAP	30% FRAP	40% FRAP
	Sample # 21	**Sample # 31**	**Sample # 42**	**Sample # f31**	**Sample # f42**
Diameter	101.00	101.00	101.10	101.40	101.20
	101.10	101.20	100.90	101.80	101.20
	101.00	101.20	100.80	101.70	101.00
	101.10	101.90	101.00	101.50	101.10
	101.00	101.30	100.70	101.40	101.10
Thickness	149.50	151.30	152.00	152.00	151.60
	149.70	151.10	153.00	152.70	151.70
	150.10	151.10	152.70	151.90	151.80
	150.30	151.50	152.20	152.00	151.40
	150.40	151.50	151.50	151.90	151.50
	Sample # 22	**Sample # 33**	**Sample # 43**	**Sample # f32**	**Sample # f43**
Diameter	101.00	101.00	100.90	101.10	101.30
	101.10	101.80	100.90	100.90	101.20
	101.00	101.00	101.10	100.90	101.30
	101.10	101.30	101.00	101.00	101.20
	101.00	101.50	101.00	101.10	101.20
Thickness	149.50	150.80	151.10	149.60	150.90
	149.70	150.00	151.90	150.00	150.30
	150.10	149.80	151.60	150.20	150.00
	150.30	149.90	151.70	149.90	150.60
	150.40	150.00	151.80	149.80	150.40
	Sample # S3	**Sample # 34**	**Sample # 44**	**Sample # f34**	**Sample # f44**
Diameter	101.20	100.90	101.00	101.10	101.10
	101.70	100.70	101.10	101.00	100.90
	102.00	100.10	101.20	101.30	100.90
	101.90	100.00	101.90	101.20	101.20
	101.50	100.80	101.00	101.10	101.00
Thickness	148.00	151.90	150.80	148.90	150.70
	148.50	151.20	150.70	149.10	150.20
	148.80	150.50	150.60	148.60	149.90
	148.90	150.40	150.80	149.10	150.30
	148.70	151.00	150.80	149.00	150.40