OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

IMPLEMENTATION OF MEPDG FOR ASPHALT PAVEMENT WITH RAP

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16. ABSTRACT

This study explored the potential of using high reclaimed asphalt pavement (RAP) content with hot mix asphalt (HMA) in base and surface courses for conditions prevailing in Oklahoma. A total of eight Superpave mixes (four mixes for each of two field demonstration sites) containing different percentages of RAP namely, 25% RAP and 40% RAP for S3 base courses and 0% RAP and 10% RAP for S4 surface courses were designed and tested. Besides the evaluation of laboratory and plant mixes, cores and block samples collected from test sections were tested to examine their mechanistic performance and to estimate input parameters needed for the 2002 Mechanistic-Empirical Pavement Design Guide (MEPDG). Furthermore, rheological and chemical properties of virgin, recovered and blended (virgin binder mixed with the recovered binder from RAP) were evaluated. The mechanistic characteristics of mixes were evaluated by conducting creep compliance, dynamic modulus, Hamburg Wheel Track, and 4-point beam fatigue tests. The creep compliance results showed reduction in compliance of the mix due to increase in the RAP content. The dynamic modulus test results illustrated that the asphalt mix containing a higher amount of RAP has higher dynamic modulus values. The increase in RAP content reduced rutting susceptibility and improved moisture damage potential of both S3 and S4 mixes. Asphalt binder rheological test results reveal significant increase of viscosity, stiffness and performance grade (PG) of the blended binders compared to the virgin counterparts. Elemental analyses show significant increase in oxygen content in the blended binders, which are in agreement with the rheological characteristics of the binders. Findings of this study are expected to be useful for pavement professional in analyzing and designing HMA mixes with high RAP contents.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
LENGTH				
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
AREA				
in²	square inches	645.2	square millimeters	mm
ft²	square feet	0.0929	square meters	m²
yd²	square yards	0.8361	square meters	m²
ac	acres	0.4047	hectares	ha
mi²	square miles	2.590	square kilometers	km²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.0283	cubic meters	m³
yd³	cubic yards	0.7645	cubic meters	m³
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
TEMPERATURE (exact)				
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.448	Newtons	N
lbf/in²	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
AREA				
mm²	square millimeters	0.00155	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.196	square yards	yd²
ha	hectares	2.471	acres	ac
km²	square kilometers	0.3861	square miles	mi²
VOLUME				
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m³	cubic meters	35.315	cubic feet	ft³
m³	cubic meters	1.308	cubic yards	yd³
MASS				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
FORCE and PRESSURE or STRESS				
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in²

IMPLEMENTATION OF MEPDG FOR ASPHALT PAVEMENTS WITH RAP

**Final Report
OTCREOS10.1-45
June 30, 2013**

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EXECUTIVE SUMMARY

This study conducted laboratory and field evaluation of local reclaimed asphalt pavement (RAP) samples and virgin materials (aggregate and binders) for conditions prevailing in Oklahoma. To this end, two RAPs were collected for laboratory evaluation and stockpiled for the construction of two test sections. Different percentages (25% and 40% in base [S3] courses and 0% and 10% in surface [S4] courses) of each RAP were used to prepare S3 and S4 mixes. Virgin aggregates and binders used in the new HMA mixes were also collected from local sources and evaluated in the laboratory. Furthermore, in cooperation from two local contractors, two two-lane HMA test sections were constructed. One lane of each test section was constructed with the maximum allowable RAP (0% in S4 mix and 25% in S3 mix) and the other lane was constructed with high RAP (10% in S4 and 40% in S3). Cylindrical core and block samples were collected from the constructed pavement sections and evaluated (dynamic modulus, creep, and beam fatigue) in the laboratory. Also, the recovered binders from RAPs and blended (virgin binder mixed with recovered binder) binders were evaluated for viscosity, stiffness, PG grading and determination of MEPDG input parameters. Collected RAP samples were extracted using an NCAT Ignition Oven. The extracted aggregates were then evaluated in laboratory for mechanical and surface properties.

Rheological test results of asphalt binders reveal that the stiffness of the blended binder increases with an increase in the percentage of the RAP binder. With 10% RAP binder, there is no change in the PG grade of the virgin binder. On With 40% RAP binder, the high and low PG temperatures are about two grades and one grade, respectively, higher than those of the virgin binder. It is also noted that the viscosity and PG temperature do not change significantly with the addition of 0.5% anti-stripping agent. As expected, the complex modulus (G^*) value decreases but the δ value increases with increased testing temperature. Another trend is that the G^* value increases and the δ value decreases with an increase of the percentage of the RAP. The G^* and δ values of blended binders under RTFO-aged condition at the range of temperature presented in this report can be used as Mechanistic-Empirical Pavement Design Guide (MEPDG) Level 1 input parameters.

Aggregate test results reveals the L.A. abrasion loss values and the Micro-Deval loss values of the mixes meet the aggregate soundness requirements set by Oklahoma Department of Transportation (ODOT). However, aggregates extracted by an NCAT oven show more L.A. abrasion loss values and Micro-Deval loss values, compared to their virgin counterparts. Sand equivalent tests show that NCAT oven-extracted aggregates with high RAP result in a significant increase in sand equivalent values compared to its virgin counterpart. Insoluble test results indicate that RAP aggregates do not meet the ODOT solubility requirement. Mix volumetric data show that the voids in mineral aggregate (VMA) and voids filled with aggregate (VFA) of the RAP mixes increased with increasing percentage of RAP.

Mechanistic test results of the RAP mixes show that the dynamic modulus of the mix containing high RAP is significantly higher than that of the virgin counterpart (no RAP). From Hamburg Wheel Test results, it is observed that rutting resistance of RAP mixes increases with an increase in RAP content. For instance, at 10,000 passes the S3-25 (air void content = 7.1%) and the S3-40 (air void content = 7.1%) mixes showed a rut depth of approximately 4.95 mm and 3.72 mm, respectively. Four point beam fatigue test results show that the lower the RAP content, the higher the fatigue life, irrespective of mix type (S3 or S4). However, more favorable effects in terms of fatigue life were observed in the case of S4 mixes compared to the S3 mixes when RAP is added in the mix. Indirect tensile strength (IDT) in all tested mixes decreased with an increase in the RAP content. The test results also showed that IDT of S3 (base course) mixes are very sensitive to the RAP content. For instance, a 15% increase in RAP content in the S3 mixes, reduces the IDT values by 23%. Also, it was observed that the IDT value of the S4 mix with 25% RAP was about 5% less than that of S3 mix with the same RAP content. The creep compliance results showed an increase in the stiffness and a decrease in compliance of the mix due to increased RAP content.

The findings of this study have been shared with pavement professionals through formal and informal acidities, which include a technology transfer workshop, meetings and collaborations with three local transportation agencies, a design firm and two contractors, and technical publications and presentations (three journal articles, seven proceedings papers, and eleven platform and four poster presentations).

1   INTRODUCTION

1.1   Problem Statement

Asphalt recycling has become an important topic in recent years because of its enhanced use in the construction of asphalt concrete (AC) pavements. The increasing demand of reclaimed asphalt pavement (RAP) is mainly due to the increasing cost of asphalt binders and scarcity of quality virgin aggregates, as well as due to increasing environmental awareness. RAP has already become one the most widely used recycled materials in the United States.   Nationally, the use of RAP in new pavements is expected to be doubled by 2014 (NAPA, 2009). Even though the beneficial effects are high, several state agencies including Oklahoma Department of Transportation (ODOT) are not confident enough to use high percentages of RAP (more than 25% in base course and some RAP in surface course) on their roadways. The current state of practice for ODOT is to allow a maximum of 25% RAP in base courses and none in surface mixes. The current usage of RAP in roads of Oklahoma is significantly lower than the maximum allowable limit and is much lower than its neighboring states (Jones, 2008). This is partly because of the lack of mechanistic performance data and specifications of new hot mix asphalt (HMA) with RAP (Hossain et al., 2012; O'Rear et al., 2008). This study was undertaken to generate mechanistic performance data from laboratory testing on asphalt mixes containing higher amounts (up to 40% in base course and 10% in surface course) of RAP than currently used by ODOT. Also, as field demonstrations, two pavement sections were constructed using hot mix asphalt (HMA) containing these higher amounts of RAP.

1.2   Purpose

In the asphalt recycling process, the processed RAP is blended with virgin materials to produce new mixes. Consequently, the rheological and mechanistic characterization of recovered binders and aggregates from RAP is essential to attain proper blending in the mix design methods, and structural design and performance analysis of constructed pavements. The mechanistic properties of new mixes with RAP (amounts higher than currently used by ODOT, in this case) are important and necessary in input parameters in the Mechanistic-Empirical Pavement Design Guide

(MEPDG). Thus, the purpose of this study was to evaluate mechanistic properties HMA mixes with high RAP content.

1.3   Scope and Objectives

This study is limited to laboratory and field evaluation of local RAPs and virgin materials (aggregates and binders). To this end, bulk RAP samples were collected from two different sources for laboratory testing and also used to produce HMA for the construction of two test sections. Different percentages (25% and 40% in base courses and 0% and 10% in surface courses) of each RAP were blended with virgin aggregates and used to produce base and surface mixes. The mix design protocols were based on the specifications used by ODOT. Virgin aggregates and binders used in the new HMA mixes were collected from local sources and evaluated in the laboratory. Furthermore, in cooperation with two local contractors, two different test sections were constructed. One lane of each test these test sections was constructed with the maximum allowable RAP (0% in surface course and 25% in base course) while the other lane was constructed with high RAP (10% in surface course and 40% in base course). Cylindrical cores and block samples were collected from the constructed pavement sections and tested in the laboratory for dynamic modulus, creep, and beam fatigue.

The primary goal of this research is to evaluate the effect of RAP content on the properties and performance of the associated HMA mixes. Specifically, the following items were addressed: aggregate properties, volumetric mix design, dynamic modulus, creep compliance and indirect tensile strength. Two base mixes (S3-25 and S3-40) and two surface mixes (S4-0 and S-10) are used for this purpose, where S3-25 refers to a base mix with 25% RAP and S4-10 refers to a surface mix with 10% RAP. Specific objectives of the present study are given below:

- Collect field RAPs, virgin binders and aggregates for the design and construction of new HMA pavement sections.
- Evaluate the effects of different percentages (0%, 10%, 25%, and 40% RAP binder) of recovered binders from RAP on consistency values and performance grade (PG) (AASHTO M 320) of the virgin binders. Superpave binder test protocols, which include viscosity (AASHTO T 316), rotational thin film oven

(AASHTO T 240), pressure aging vessel (AASHTO R 28), dynamic shear rheometer (AASHTO T 315), and bending beam rheometer (AASHTO T 313) are used in the evaluation of the PG and flow behavior.

- Determine input parameters for virgin binders modified with different percentages of recovered binders from RAP in accordance with the MEPDG specifications.

- Examine the effects of different percentages of recover binders from RAP on the chemical compositions (Carbon, Hydrogen, Nitrogen and Oxygen) of the virgin binders through elemental analysis.

- Evaluate physical and mechanical properties of aggregates namely, gradation (AASHTO T 27 and T30), and specific gravity (AASHTO T84 and T85). The LA abrasion (AASHTO T96), the sand equivalent (AASHTO T 176), and insoluble residue (OHD L-25) are also assessed for each mix gradation used in this study.

- Perform volumetric mix designs of HMA containing RAP (namely, S3-25, S3-40 for base courses and S4-0 and S4-10 for surface courses), in accordance with the Superpave® test methods AASHTO M 323 and AASHTO R 35.

- Construct a field test section with these mix designs (namely, S3-25, S3-40 for base courses and S4-0 and S4-10 for surface courses).

- Collect core and block samples from the constructed field test sections and evaluate their performance, namely creep compliance and indirect tensile strength.

- Collect plant mixes used in the construction of the test section for laboratory testing, namely of dynamic modulus (E*), creep compliance and indirect tensile strength (IDT).

- Determine the input parameters for HMA mixes containing the aforementioned percentages of RAP for the implementation in M-EPDG Level 1 designs involving similar materials.

Asphalt recycling has become an important topic in recent years because of its enhanced use in the construction of asphalt concrete (AC) pavements. The increasing demand of reclaimed asphalt pavement (RAP) is mainly due to the increasing cost of asphalt binders and scarcity of quality virgin aggregates, as well as due to increasing

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- Determine the input parameters for HMA mixes containing the aforementioned percentages of RAP for the implementation in M-EPDG Level 1 designs involving similar materials.

2   BACKGROUND

2.1   MEPDG Input Parameters and Their Significance

The MEPDG evaluates pavement performance by using local material properties as input (NCHRP, 2004). In the hierarchical approach used in the MEDPG, laboratory test data of asphalt mixes and asphalt binder are required for obtaining the highest reliability (Level 1). For Level 1 analysis, dynamic modulus (E*), creep compliance, and indirect tensile strength of the asphalt mix are required. On the other hand, dynamic shear modulus (G*) and phase angle (δ) values of the asphalt binder are combined with E* values of the mixes to estimate E* master curves for the design life of the pavement. For the intermediate level (Level 2), the asphalt binder's rheological test data are combined with volumetric properties of the mix to evaluate performance of the pavements. At the lowest design reliability (Level 3), volumetric properties of the mix are combined with the asphalt binder's performance grade (PG) to predict the performance of the mix. Pertinent to the evaluation of the performance of HMA mixes with RAP and the determination of MEDPG input parameters, a comprehensive review of existing literature was conducted in this study. A summary of this literature review is given below:

2.2   Blending of Recovered and Virgin Binders

In a laboratory study, McDaniel and Shah (2003) prepared samples with a RAP content of up to 50% to determined the effect of recycled materials on the mix performance. Prepared mixes were tested using a Superpave shear tester. It was observed that addition of RAP materials stiffened the mixture properties as compared to virgin mixes. The increased stiffness may improve the rutting resistance of the mix but it can also increase the potential for fatigue and thermal cracking. Decreasing the PG grade of the virgin binder may be an option to improve the fatigue performance of the mix, especially at high RAP content. These researchers highlighted that designing asphalt mixes that conform to the Superpave specifications may not be feasible at a RAP content greater than 40 to 50% due to the high fine contents of the RAP materials.

Mohammad et al. (2003) investigated the recycling of polymer-modified asphalt using laboratory testing. A polymer-modified mix with a RAP content varying from 0 to

60% was prepared and tested using indirect tensile strength, indirect tensile creep, repeated shear test, asphalt pavement analyzer, and beam fatigue. It was observed that as the RAP content increased, the rutting resistance of the mix increased while its fatigue resistance decreased.

Daniel et al. (2010) studied selected plat mixes in New Hampshire with different amounts of RAP and evaluated the PG grading of the binders and their critical temperatures for cracking. The binders were recovered by centrifuge (using trichloroethylene as a solvent) in accordance with the Abson method. These researchers also used an additional procedure to remove the last traces of trichloroethylene, if any, from the recovered binder. The additional process consisted of placing 35-gm of recovered binder in a RTFO bottle, placing the bottle in the oven rack, and rotating the rack for 10 minutes at 163°C. The RTFO residue was then considered as the "original" condition of the binder tested in a DSR at desired temperatures. They also performed further RTFO and PAV aging of the "original" binder to maintain consistent testing procedures with the virgin binders. It was observed that the high PG temperature remained the same, or only increased by one grade for the various percentages of RAP but the low PG temperature remained the same, or only increased by one grade from the virgin mix. They also observed that the critical cracking temperatures only change by a few degrees as the RAP percentages increase.

Dong et al. (2010) studied two PG binders (PG 58-22 and PG 64-22) and an aged binder (recovered from RAP of unknown original binder grade) while evaluating the performance of additives in RAP. The aged binder was recovered from RAPs using the Abson method. They reported significant aging of the recovered binder in terms of kinematic viscosity and penetration, among others. For example, the kinematic viscosities of the recovered binder and the PG 64-22 binder at 135°C were found to be 5275 mPa.s and 412 mPa.s, respectively. Similarly, the penetration values of the recovered binder and the PG 64-22 binder at 25°C were found to be 16 mm and 64 mm, respectively.

2.3   Mechanistic Evaluation of RAP Mixes

In a laboratory study, Daniel and Lachance (2005) examined the effect of increased RAP on the volumetric and mechanistic properties of asphalt mixes. A 19-mm Superpave mix containing 0% RAP (no RAP) was used as the control for evaluating properties of mixes containing 15%, 25%, and 40% RAP. Two types of RAP, a processed RAP and an unprocessed RAP (grindings) were evaluated. Testing included dynamic modulus in tension and compression, creep compliance in compression, and creep flow in compression. Dynamic modulus and creep compliance master curves were constructed using the time–temperature superposition principle to describe the behavior of each mix over a range of temperature. The voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) of the RAP mix increased at 25% and 40% RAP contents, and there was also an influence of preheating time on the volumetric properties. The dynamic modulus of mixes containling processed RAPs increased from the control to 15% RAP level, but the dynamic modulus master curves of mixes containing 25% and 40% RAP were similar to that of the control mix in both tension and compression. The creep compliance curves showed similar trends.

Cross et al. (2007) evaluated dynamic modulus (E*) data of S3 mixes with up to 25% RAP for possible use in the MEDPG analysis by ODOT. It was reported that the presence of 25% RAP in a mixture had significant effects on the measured E* values. This study also reported that the binder's PG grade had a significant effect on the measured E* values. While comparing E* values of mixes with different PG grade binders, it concluded that that use of 25% RAP in a mix appeared to raise the PG grade of the new binder by approximately one grade. However, this study did not evaluate the PG grades or other MEPDG input parameters of asphalt binders.

Kim et al. (2007) studied the effect of RAP in HMA on creep compliance and indirect tensile (IDT) strength. In their study, four different percentages of RAP mixes namely, 0%, 25%, 35%, and 45% RAP, were designed. The control mix with 0% RAP was prepared with a virgin PG 67-22 binder. The 25% RAP mix was blended with a PG 64-22 binder, and the 35% and 45% RAP mixes were blended with a PG 58-28 binder. The Superpave IDT test and the energy ratio (ER) concept were used to assess the

cracking performance. The creep test was performed by applying a constant load for 1,000 seconds. Several parameters were determined from this test including creep compliance as a function of time. These properties were used to determine the mix's resistance to creep and damage. The IDT test was performed by subjecting a specimen to failure at a rate of 50 mm/min. The control mix showed a higher creep compliance rate than the mix containing 25% RAP. Although the 25% RAP mix was blended with a softer binder (PG 64-22), the RAP might have overcome the effect of the softer binder, resulting in a lower creep compliance rate than the control mix. However, the 35% RAP mix blended with a PG 58-28 binder showed a higher rate of creep compliance than the other mixes due to the softer asphalt binder. The 45% RAP mix with PG 58-28 binder had a reduced rate of creep compliance compared to the 35% RAP mix since it contained more RAP materials but the same virgin binder as the 35% RAP mix.

In a related study, Vargas (2007) tested the creep compliance and indirect tensile strength of HMA mixes containing RAP. Four types of RAP were combined at four levels (0%, 10%, 20% and 30%) with aggregates from four different sources. One source of virgin asphalt binder (PG 76-22) was used. The results showed an increase in creep compliance with temperature, as expected. Addition of RAP did not change the stiffness of the mix; no clear relationship between creep compliance and the RAP content was evident.

In another laboratory study, Li et al. (2008) investigated performance of ten asphalt mixes, including two different RAP sources, at three RAP contents (0, 20% and 40%) and two different asphalt binders (PG 58-28 and PG 58-34) by conducting dynamic modulus and semi-circular bending fracture tests. Results illustrated that the asphalt mixes containing RAP have higher dynamic moduli than those of the virgin mixes. The stiffer binder was found to result in higher dynamic modulus values for both the control and the RAP-modified mixes. Experimental data also show that the RAP source is not a significant factor for the dynamic modulus values at low temperatures, although it significantly affects dynamic modulus values at high temperatures. In addition to test temperature, the RAP content was found to significantly affect the semi-circular bending fracture resistance of mixes. However, at low temperature, the dynamic

modulus values for mixes containing a softer binder were higher than those of the mixes containing a stiffer binder.

Watson et al. (2008) studied the LA Abrasion loss of blended aggregates composed of different percentages (0%, 10%, 20% and 30%) of recycled SMA mixes and four virgin aggregates. Both RAP and virgin aggregates were granite materials used by the Georgia DOT. It was reported that properties of the blend such as LA abrasion loss was mainly influenced by the virgin aggregate source. The variation of the LA abrasion losses among RAP materials was found to be very small (within 3% difference). It was also observed that the angularity of aggregates in a RAP varied significantly from the original angularity due to brakeage during the original mix production, during milling, and during processing (crushing). It was concluded that up to 20% RAP can be used without significantly affecting the performance. The fatigue life is expected to reduce significantly with the addition of 30% RAP.

In a recent study, Tabaković et al. (2010) evaluated the physical properties of RAP and its influence on the mechanical performance of an asphalt mix. A series of mixes were designed containing varying percentages of RAP. A mix made from only virgin materials was selected as the control mix for the investigation. The effect of introducing RAP into the asphalt mix was evaluated through a series of laboratory tests including the Marshall test, the indirect tensile stiffness modulus test, the indirect tensile fatigue test and the water sensitivity test. A circular wheel track was developed in order to study the dynamic effects of a rolling wheel traveling over an asphalt pavement. The laboratory tests showed that the introduction of RAP to the mix resulted in an improvement in all mechanical properties. Specifically, it was found that the mix containing up to 30% RAP, exhibited improved fatigue resistance relative to the control mix manufactured from virgin materials.

Abdelrahman et al. (2010) investigated performance of a pavement base layer having a high RAP content using resilient modulus (M_r) as the primary indicator for base layer characterization. The test results indicated that M_r increases with RAP content, asphalt content and aggregate dry density. Overall, it was reported that RAP has a potential to be used in high percentages in pavement base layers than surface layers. In

another recent study, Alam et al. (2010) investigated the behavior of base course mixes containing different amounts. A mix was prepared by bleding RAP with varied quantities of local aggregates. Resilient modulus tests conducted on compacted spcimens showed that M_r value increases wih RAP contents.

In another recent study, McGraw et al. (2010) examined the effect of RAP on E^* of HMA. A total of 17 mixes containing various amounts of RAP (0%, 10%, 15%, 25% and 30%) were used with two types of binders (PG 58-28 and PG 51-34). It was found that the E^* increases with increasing RAP content and the differences are more pronounced at lower frequencies (high temperatures). The increase in E^* was noticeably higher in the mix containing 30% RAP than that of the control mix (0% RAP).

From the aforementioned studies, it is evident that many studies have focused on the performance of HMA mixes with lower percentages of RAP. In particular, there has been no doucmentation on the performance of HMA with high RAP contents in Oklahoma. The present study was pursued to address this weakness. It is also seen that a limited studies have evaluated the required MEPDG Level 1 input parameters for HMA mixes, espicially with high RAP contents. In particular, no comprehensive studies have addressed the implementation of the MEPDG for HMA mixes with high RAP contents. The present study attempts to address this research need.

3   MATERIALS AND METHODS

3.1   Selection of RAP Samples

In cooperation with ODOT and Oklahoma Asphalt Paving Association (OAPA) partners, two field RAP samples (RAP1 and RAP2) were collected. One of the RAPs was collected with the help of Silver Star Construction Co., located in Moore, OK. The second RAP sample (RAP2) was selected in cooperation with Schwartz Paving Co. in Oklahoma City, Oklahoma. The test sites are both city roads. Aggregates were extracted from RAP samples and the binder content was determined by using a NCAT Ignition Oven in accordance with OHD L-26 Method A (Methods of Test for Determination of Bitumen Content in Bituminous Paving Mixtures). Representative RAP samples were obtained in accordance with AASHTO T 168 (Sampling of Bituminous Paving Mixtures). About 800 gm of asphalt binder was recovered from each RAP sample in accordance with the Abson method, which is discussed later in this chapter. The recovery of asphalt binder was done at the Liquid Laboratory, ODOT Materials Division. The recovered binders from RAPs were evaluated for PG grading and determination of MEDPG input parameters. Collected RAP samples were extracted in accordance with the OHD L-26 Method using an NCAT Ignition Oven, which is discussed later in this chapter. The extracted aggregates were then evaluated for mechanical and surface properties such as durability, gradation and shape.

3.2   Recovery of Binder and Aggregate

3.2.1 The Abson Recovery Method

About 800 gm of asphalt binder is recovered from each RAP for further laboratory testing. At first, the asphalt binder in the RAP is extracted with trichloroethylene (TCE: C_2HCl_3) per AASHTO T 160 (AASHTO, 2008). In this method, the RAP is placed in a large, flat pan, and warmed in a 110 ± 5ºC oven until it can be separated. The loose RAP is then placed in a bowl along with the solvent sufficient to cover the RAP. Sufficient time is allowed (typically up to one hour) for the solvent to disintegrate the loose RAP. The bowl containing the RAP and solvent is then placed in the vacuum extraction apparatus. The extract is then collected and centrifuged. The

centrifuge is started slowly and the speed gradually increased to a maximum of 3600 rpm until the solvent stops flowing through the drain. At this stage 200 mL or more trichloroethylene is added and the procedure is repeated at least three times.

The binder is recovered using the Abson method (AASHTO, 2008) according to AASHTO T 170. The solution from the previous extraction is centrifuged for a minimum of 30 minutes at 770 times gravity in a 250-mL to 500-mL wide-mouth bottles. The extracted solution is concentrated by a primary distillation process. The residue is then transferred from the primary distillation flask, using several washes of solvent to rinse the residue into the distillation flask. Afterwards, carbon dioxide (CO_2) gas is introduced at a low rate (approximately 100 mL/min). This distillation process is continued until the temperature reaches 157ºC to 160ºC. The CO_2 gas flow is then increased to approximately 900 mL/minute. This flow rate and a temperature of 160ºC to 166ºC are maintained for 10 minutes before the process is considered complete.

3.2.2 The NCAT Ignition Oven Method

The NCAT Ignition Oven was used in accordance with OHD L-26 Method – A, for extraction of aggregates from RAP and HMA mixes. The amount of material for each batch of the extraction process was determined based on the nominal maximum size (NMAS). For instance, 2 kg of field RAP1 (FRAP1) sample was used during each extraction as its NMAS was 19 mm. Then the NCAT oven was preheated to 538°C, and an automated ignition process was initiated. The samples were burned until the measured weight loss did not exceed 0.1 gram for three consecutive minutes. The time required to achieve a constant weight was approximately 45 minutes. The extracted aggregate from the NCAT Ignition Oven are then set outside the oven to cool down naturally before handling for further testing.

3.3   Field Constructions

3.3.1 Test Site for RAP1

The test site for this study was selected in cooperation with Silver Star Construction Co. in Moore, Oklahoma. The RAP used in this project was milled from a section of I-35 (project number IMY-0035-2(311)088) and is located in McClain County

(near Purcell, Oklahoma). This I-35 section had a 1.5-inch overlay of HMA Type B with PMAC-1C binder in 1994 (Project Number: I-IR-35-2(198)081 Part 1) (Hobson, 2010). Before 1994, the section received a 2-in. of leveling course of HMA Type C with AC-3 binder in 1979 (Project Number: I-IR-35-2(133)082 Parts 1 and 2). The section also had an Open Graded Friction Surface Course (OGFSC) with the same AC-3 from Kerr McGee at Wynneewood, Oklahoma. The milling process started in the first week of August, 2010. The contractor (Silver Star Construction Co.) processed the collected asphalt millings by sizing and fractionating with a ¾-inch sieve as only the finer portion (passing ¾-inch sieve) would be used in the new HMA mix. Approximately, 2000 tons of processed asphalt millings were stockpiled separately for the construction of the test section in the present study. The test section was located on Franklin Road (near US-77) in Norman, Oklahoma.

Figures 3.1 (a) through 3.1(d) show photographic views of the processing and stockpiling of asphalt millings, a close view of millings and collection of processed millings (RAP) in bags. About 1200 lbs of the processed RAP were collected for laboratory evaluation. Henceforth, the processed (fractionated) millings noted above are RAP1. In addition to collection of RAP1, the research team collected four different types of virgin aggregates namely, #67 Rocks, 5/8-inch Chips, Screenings, Manufacture Sand, and Sand, to be used for the construction of the test section. Henceforth, the collected virgin aggregates will be called AGG1. A virgin PG 64-22 binder (from Valero Refinery at Ardmore, Oklahoma) was used for producing HMA nixes for the test section. This virgin binder was collected from the Silver Star Construction Company for laboratory evaluation.

The test site is a two-lane city road having a length of approximately 670 ft (Figure 3.2). Prior to paving, the existing silty clay subgrade was stabilized with 14% Cement Kiln Dust (CKD). The in-place density and water content of the stabilized subgrade was measured using a nuclear gauge in accordance with the ASTM D 6938 test method. At the end of the stabilization, the field density of the stabilized subgrade layer was reported to be 103.4% of the Standar Proctor density at a moisture content of 17.3%. The thickness of the subgrade soil was 6 in. Figures 3.3 through 3.7 show the

soil stabilization process. Figure 3.3 shows the right of way of the test site before the beginning of the soil stabilization process, while Figure 3.4 shows the pouring and mixing of the stabilizing agent (CKD) with the existing soil. Figure 3.5 shows the watering of the existing subgrade mix with the CKD, during the stabilization process. Figure 3.6 shows the leveling of the well-mixed subgrade with CKD before the beginning of compaction, while Figure 3.7 shows the stabilized subgrade after compaction and finish rolling.

Figure 3.1   (a) Processing of RAP1 millings, (b) Stockpile of RAP1 millings, (c) Close view of I-35 (RAP1) millings, and (d) Collection of I-35 (RAP1) millings

3.3.1.1   *Construction of South Lane (S3-25 and S4-0 mixes)*

The south lane of the test section was constructed with a S3-25 mix, overlaid by a S4-0 mix (current state of practice). The paving machine was equipped with an

electronic slope and grade control. The S3-25 layer was constructed in two lifts, each having a thickness of 3 in. (72 mm). On February 18, 2011, the first lift of S3-25 layer was constructed.

Figure 3.2   Test Site Location on York Drive.

Figure 3.3   Right of Way Before Soil Stabilization.

Figure 3.4   Process of Mixing CKD With the Subgrade.

Figure 3.5   Watering During the Stabilization Process.

Figure 3.6   Leveling of the Stabilized Soil.

Figure 3.7   Stabilized Subgrade.

The construction was behind the schedule because of a snow storm. After the laydown of the first lift (Figure 3.8), it was compacted using a vibratory compactor with steel drum roller (CAT PS-360B), as shown in Figure 3.9. The rolling pattern was

established on the basis of density readings obtained from a nuclear density gage (conducted by EST Inc., Norman, Oklahoma). Both density and temperature were recorded for each pass until the density started decreasing with the number of passes. During the trial compaction, it was found that three and a half passes would be enough to achieve the desired level of compaction. Therefore, it was decided to use only three passes for compaction. Following the vibratory compaction, a rubber-tire roller DYNAPAC CA-251 (Figure 3.10) was used to smoothen the surface. A total of five passes were made using this rubber-tire roller. Finally, the vibratory compactor (CAT PS-360B) was used again without any vibration for finish rolling. Only one pass was used this time. After the construction of the first lift, it's thickness was determined by taking three cores and measuring the thickness of each core. The thicknesses of these cores were 3.1 in., 2.9 in. and 3.0 in., with an average thickness of 3 in. Therefore, the same amount of mix (135 tons of material) was used to achieve the next 3 in. of the second lift. Due to the cold weather, the construction of the second S3 layer was postponed until February 21, 2011. Between the construction of the first and the second lifts of S3 layers, the Gutter Curb was constructed on February 19, 2011 using the curb machine (POWER CURBER 5700-C). On February 23, 2011, the second lift of the S3-25 layer was constructed using the same equipment and procedure as outlined above for the first lift.

Figure 3.8   Laydown Operation of S3-25 Layer (South Lane).

Figure 3.9   Compaction of S3-25 Layer with Steel Drum Roller

Figure 3.10 Compaction of S3-25 Layer With Rubber-Tire Roller.

After the construction of the S3 layers, a tack coat (SS-1HP) was sprayed on the S3 layer on February 26, 2011, before the construction of the S4 layers. The south lane of the test section was constructed with S4-0 mix (Figure 3.11 and Figure 3.12). During the paving of the S4-0 layer, paper was placed between the S3-25 and S4-0 layers at selected locations for the ease of extracting cores (Figure 3.13). Also, those selected locations were labeled after paving by using spray paint on the top of the S4-0 layer. After laydown, compaction was conducted using a vibratory compactor with steel drum (CAT PS-360B). As before, the rolling pattern was decided on the basis of density readings obtained from a nuclear density gage during trial rolling. Both density and temperature were recorded for each pass until the density started decreasing with the number of passes. It was found that approximately four passes are enough to achieve the desired level of compaction.

Figure 3.11   Laydown of S4-0 Layer (South Lane).

Figure 3.12   Laydown and Compaction of S4-0 Layer (South Lane).

Figure 3.13 Placement of Paper During Laydown of S4 Layers.

3.3.1.2   *Construction of the North Lane (S3-40 and S4-10 mixes)*

The North lane of the test section was constructed using the same equipment and procedure as outlined above for the South lane. This lane was constructed with a S3-40 mix overlaid by a S4-10 mix, and four passes were used to achieve the desired level of compaction for S3-40. The thickness of the first lift of S3-40 mix (Figure 3.14) was determined by taking three cores and measuring the thickness of each core. It was found that thicknesses of the cores are 3.1 in., 2.9 in. and 3.0 in., with an average thickness of 3 in. Henceforth, the same amount of mix (135 tons of material) was used to achieve the next 3 in. of the S3 layers. After the construction of the S3-40 layers, the S4-10 layer (Figure 3.15) was constructed. Five passes were used to achieve the desired level of compaction for this layer.

Figure 3.14   Laydown of S3-40 Layer (North Lane).

Figure 3.15   Laydown of S4-10 Layer Over S3-40 Layer (North Lane).

3.3.1.3　In-Situ Coring

The in situ coring was first performed on February 24, 2011, after the construction of the base layers and again on February 28, 2011, after the construction of the surface layers. A total of eighteen cores were extracted from the base layers, while fourteen cores were extracted from the surface layers. The location, the mix type and the thickness of all the cores are presented in Tables 3.1 and 3.2. The cores were extracted at a regular interval of fifty and seventy five feet from each other for the base and surface layers, respectively.

The core specimens were retrieved from both lanes between the expected wheel paths, as shown in Figure 3.16 and Figure 3.17. As shown in Figure 3.17, cores of same diameter (6 in. (152 mm)) were obtained. Each core was taken to full depth of the asphalt pavement layer. The average thicknesses of the cores were 6 in. (152 mm) and 3 in. (76.2 mm) for base and surface layers, respectively. After extraction, the cores were properly labeled and carefully wrapped so that they can be brought to the laboratory in good condition. After extraction, Silver Star Construction patched all the holes with HMA, followed by compaction with a plate compactor, as shown in Figures 3.18 and 3.19. The cores were cut in the laboratory to achive a diameter 6 in. and a height of 1.8 in., for testing.

Table 3.1　Descriptions of Cores from S3 Layers

Cores No	Distance from west end (ft.)	Mix Type	Thickness (in)
1	50	S3-25	5.875
2	100	S3-25	5.625
3	150	S3-25	5.75
4	200	S3-25	6.375
5	250	S3-25	6.25
6	300	S3-25	6.875
7	350	S3-25	6.625
8	400	S3-25	6.375
9	450	S3-25	6.25
10	50	S3-40	6.00
11	100	S3-40	5.625
12	150	S3-40	5.625
13	200	S3-40	5.875

14	250	S3-40	5.625
15	300	S3-40	6.00
16	350	S3-40	6.50
17	400	S3-40	6.75
18	450	S3-40	6.00

Table 3.2   Descriptions of Cores from S4 Layers

Cores Samples No.	Distance from west end (ft.)	Mix Type	Thickness
1	75	S-4 Virgin	3.125
2	112	S-4 Virgin	3.25
3	171	S-4 Virgin	3.125
4	208.5	S-4 Virgin	3.25
5	325	S-4 Virgin	3.125
6	464	S-4 Virgin	3.125
7	595.6	S-4 Virgin	3.125
8	103	S-4-10%	2.5
9	191	S-4-10%	3.0
10	267	S-4-10%	3.125
11	387.5	S-4-10%	3.125
12	458.7	S-4-10%	3.25
13	522.6	S-4-10%	3.625

Figure 3.16   Coring Operation S3-25 (South Lane).

Figure 3.17   Core locations.

Figure 3.18   Patching Process of the Holes.

Figure 3.19 Plate Compaction During Patching Holes.

3.3.2 Test Sites for RAP2

The test sites of RAP2 were selected in cooperation with Schwartz Paving Co. in Oklahoma City, Oklahoma and are located on 178 Street North May in Oklahoma City (Figure 3.20) and South Czech Hall Road in Mustang, Oklahoma. Both of these test sites are city roads.

Figure 3.20   Test Site Located on 178 Street North May, Oklahoma City.

3.3.2.1   Construction of 178 Street and N. May, Oklahoma City

This test section was constructed with S3-25 and S3-40 mixes. Thirty bags (approximately 600 lbs.) of each mix were collected and transported to Broce asphalt laboratory for testing. The paving machine was equipped with an electronic slope and grade control (Figure 3.21). The S3 layers were constructed in two lifts, each having a thickness of 3 in. On January 4, 2012, the first lift of the S3 layer was constructed (Figure 3.22). After the laydown of the first lift, it was compacted by using a vibratory compactor with steel drum roller (HAMM HD-110 HV), as shown in Figure 3.23. The in situ coring was first performed on January 5, 2012, after the construction of the base layers (Figure 3.24). A total of eight cores were extracted from the base layers. The core specimens were retrieved from the test section between the expected wheel paths, as shown in Figure 3.25. As shown in Figure 3.26, cores of same diameter (6 in. (152 mm)) were obtained for rut testing. Each core was taken to full depth of the constructed pavement. The average thicknesses of the cores were 6 in. (152 mm). After extraction, the cores were properly labeled and carefully wrapped so that they can be brought to the laboratory in good condition. After extraction, Schwartz Paving Co. patched all the holes with HMA, followed by compaction with a plate compactor.

Figure 3.21   The Paving Machine Used for Test Site 2.

Figure 3.22   Construction of S3 Lift for Test Site 2.

Figure 3.23   Compaction of S3 Lift for Site 2.

Figure 3.24   Coring in Progress for Test Site 2.

Figure 3.25   Obtained Cores from S3 Layer for Test Site 2.

3.3.2.2   Construction of South Czech Hall Rd., Mustang (S4-25 mix)

This test section was constructed with a S4-25 mix. Thirty bags (approximately 600 lbs.) of loose mix were collected and transported to Broce asphalt laboratory for testing. Collection of core samples was not possible for this site due reasons beyond the control of the research team.

3.4   Rheological Evaluation of Binders

3.4.1 Superpave Tests

The extracted aggregates and recovered binders from RAPs, virgin binders, and virgin aggregates used in producing HMA mixes were evaluated in the laboratory. Superpave binder test protocols were followed to evaluate the performance of the binders. PG grades of the binders were evaluated as per AASHTO M 320. Short-term and long-term simulations of the binders were conducted by using a rotational thin film oven (RTFO) as per AASHTO T 240 and a pressure aging vessel (PAV) as per AASHTO R 28. High and low PG temperatures were estimated by using a dynamic

shear rheometer (DSR) as per AASHTO T 315 and a bending beam rheometer (BBR) in accordance with AASHTO T 313, respectively. Rotational viscosity (RV) values of the binders were estimated in accordance with AASHTO T 316.

3.4.2 Elemental Analysis

Elemental analyses of the base and blended (10%, 25% and 40% of RAP1 and RAP2 binder) binders were determined by Gailbraith Laboratories, Inc. (GLI). The C, H, and N measurements were made using a Thermo Finnigan FlashEA™ 2000 Elemental Analyzer (GL, 2013a). The samples are burned in pure oxygen at 950°C under static conditions to produce as combustion products CO_2, H_2O, N_2, and SO_2. The FlashEA® 2000 separates the combustion gases by chromatography and measures the gases using a self-integrating steady state thermal conductivity analyzer.

Oxygen analysis is done using a Thermo Finnigan FlashEA™ 1112 Elemental Analyzer (Oxygen Modification) (GL, 2013b) which pyrolyzes the sample in helium. During the pyrolysis, nitrogen, hydrogen, and carbon monoxide are formed when they contact a nickel plated carbon catalyst, at 1060°C. The carbon monoxide, hydrogen, and nitrogen are separated by chromatography and the carbon monoxide measured with a thermal conductivity analyzer to obtain the oxygen percentage.

3.5   Mechanistic Evaluation of Asphalt Mixes

3.5.1 Hamburg Wheel Track Test

For determining rut and moisture damage (stripping), cores were tested by using Hamburg wheel-tracking machine in accordance with the OHD L 55 test method (ODOT 2010). Susceptibilities to rutting and moisture are based on pass/fail criteria (Cooley, 2000). The test procedure requires that the cores be secured in mounting tray using plaster of Paris. During testing, the 47 mm (1.85 in) wide wheel is tracked across a sample submerged in water bath for 20,000 passes or until a rut depth of 20 mm occurs (Figure 3.26 (a)). The load on the wheel is 705 N (158 lb) (Figure 3.26 (b)). The average speed of each wheel is approximately 1.1 km/h (0.68 mph); each wheel travels approximately 230 mm (9.05 inch) before reversing direction, and the device operates at approximately 53±2 wheel passes/min. The temperature of water bath was

maintained at 50±1°C (122±2°F). Rut depths were measured continuously with a series of LVDTs. Figures 3.26 (c) and (d) show sample before and after testing.

(a)

(b)

(c)

(d)
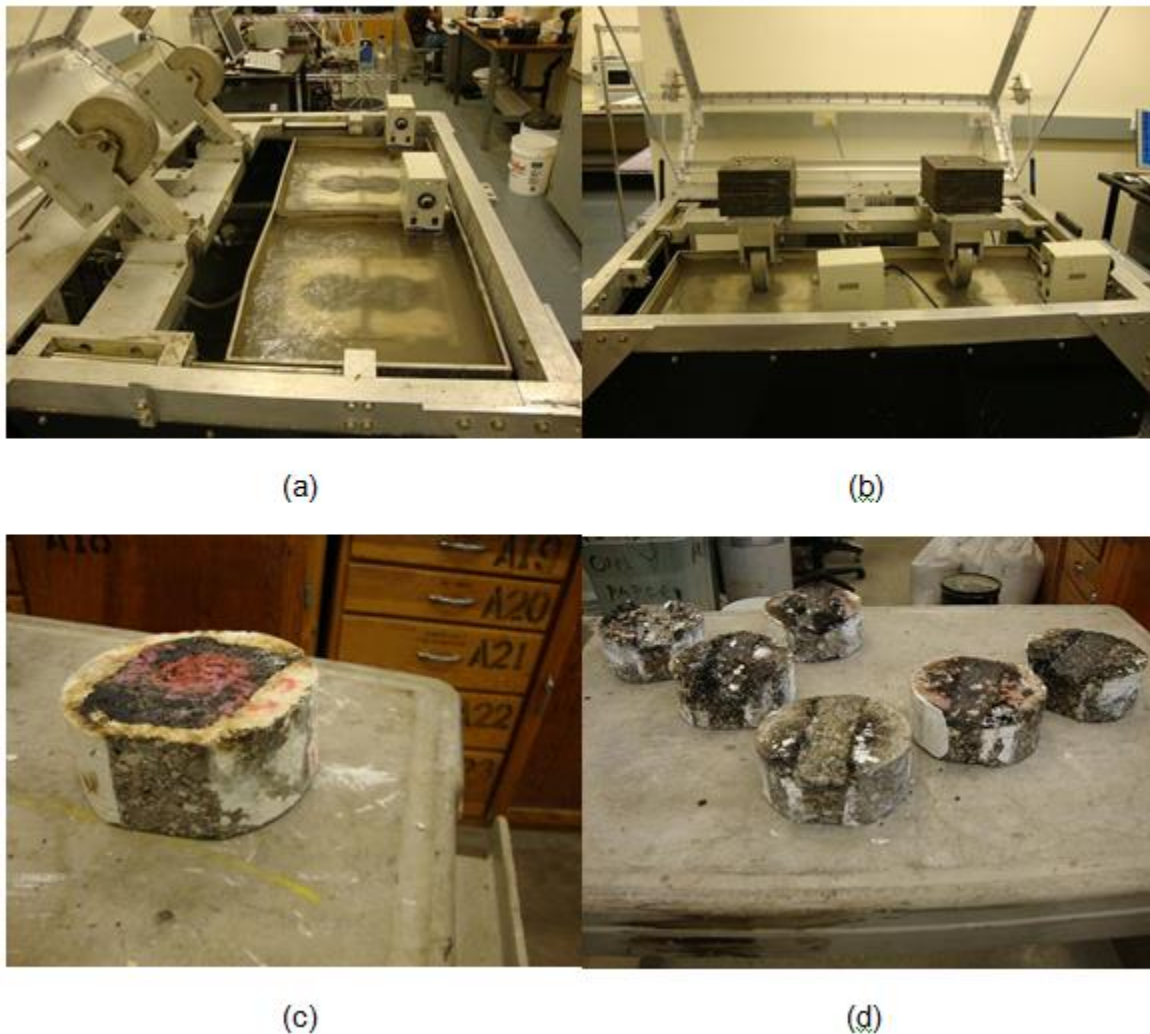
Figure 3.26 (a) Hamburg Test Setup (b) During Testing with Loaded Wheels (c) Specimen Before Test (d) Specimen After Test.

The LVDT measures the depth of the rut with an accuracy of 0.01 mm (0.0004 inch). From a typical test curve, three characteristic regions are generally defined. The following features are noted: post-compaction consolidation, creep slope, stripping slope, and stripping inflection point (Lu and Harvey, 2006; Yildirim et al., 2007). Texas Department of Transportation (TxDOT) has adopted this test and recommended a maximum allowable rut depth of 12.5 mm at 20,000 passes for PG-76 or higher, at 15,000 passes for PG-70 and at 10,000 passes for PG-64 or lower (Yildirim et al. 2007).

It is worth mentioning that the Hamburg wheel-tracking machine has been found to have excellent correlations with field performance (Williams and Prowell, 1999; Izzo and Tahmoressi, 1999; Yildirim et al. 2007). So, it was decided to conduct this test on mixes as an additional performance indicator.

3.5.2 Fatigue Test

The fatigue resistance or number of cycles to fatigue is determined by testing beam specimens (length = 15.0 in., width = 2.5 in., thickness = 2.0 in.) using a four-point beam fatigue apparatus (Figure 3.27). Test samples are prepared in the laboratory at a target air void of 7±0.5%. This test is conducted in a strain-controlled mode at 20°C and at 10 Hz loading frequency, as recommended by AASHTO T321 (AASHTO, 2009). The strain level for testing was selected based on a number of preliminary tests on samples and was selected as 200 micro-strain. A 1100-lbf. (5 kN) load cell was used to apply cycles of loading and unloading in the four-point fatigue apparatus. A LVDT with a maximum stroke length of 0.04 in. (±1mm) and mounted on a target glued at the center of the beam was used to measure the vertical deformation. The initial stiffness was determined at the 50th load cycle. The total number of load repetitions that causes a 50% reduction in initial stiffness is considered fatigue life (AASHTO, 2009).

Figure 3.27   AMPT ATM-100 Used for Fatigue Tests.

3.5.3 Dynamic Modulus

The dynamic modulus (AASHTO TP 62) testing was conducted at following five different temperatures: 14°F, 40°F, 70°F, 100°F and 130°F (-10.0°C, 4.4°C, 21.1°C, 37.8°C, 54°C)   starting at the lowest temperature and proceeding to the highest temperature. For each temeperature level, test was conducted at six different frequencies from the highest to lowest. The following frequencies were used: 25 Hz, 10 Hz, 5 Hz, 0.5 Hz, 0.1 Hz. Prior to testing, the sample was first conditioned by applying 200 cycles of load at a frequency of 25 Hz. The specimen was then placed in an environmental chamber and allowed to attain equilibrium at the specified test temperature (± 0.5). The magnitude of load was adjusted based on the material stiffness, air voids content, temperature, and frequency to keep the strain response within 50 – 150 microstrains (see Figure 3.28 (a) and (b)). The data were recorded for the last 5 cycles of each sequence.

(a)

(b)
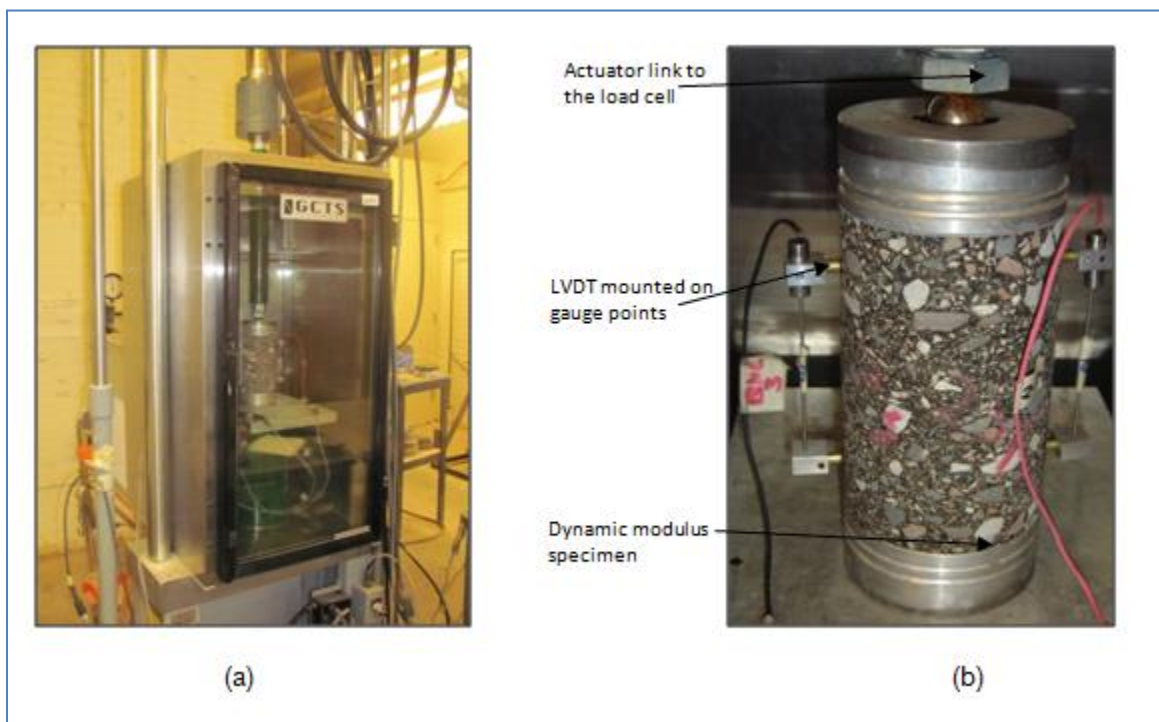
Figure 3.28   (a) Equipment setup for dynamic modulus, (b) E* specimen inside the Environmental Chamber.

The master curves for each mix (S3-25, S3-40, S4-0, and S-10) were generated at a reference temperature of 70°F (21.1°C) using the procedure outlined in Bonaquist and Christensen (2005). Equations 3.1 and 3.2 show the sigmoid function and shift factor used for fitting and the master curve, respectively. The default values of ASTM 'A' (i.e., 10.980) and 'VTS' (i.e., -3.680) for a typical PG 64 - 22 binder were taken from the new MEPDG (AASHTO, 2004). A nonlinear optimization program was used to solve for these unknown parameters simultaneously.

$$\log\left(E^*\right) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \left\{\log(\omega) + c\left[10^{A + VTS \log T_R - \log \eta_{70RTFOT}}\right]\right\}}}$$

(3.1)

The shift factor a(T) is given by:

$$a(T) = \frac{f_r}{f}$$

(3.2)

where,

E* = dynamic modulus,

a(T) = shift factor as a function of temperature and age,

$\delta, \beta, \alpha, and\ c$ = fitting parameters determined through numerical optimization of Equation 3.9,

$\eta_{70RTFOT}$ = viscosity at reference temeperature of interest of 70°F (21°C) and under rolling thin-film oven aged condition,

ω = loading frequency,

f_r = reduced frequency at the reference temeperature,

f = frequency at particular temeperature,

T_R = temperature in Rankine,

A = regression intercept, and

VTS = regression slope of viscosity-temeperature susceptibility.

3.5.4 Creep Compliance Test

In AASHTO T 322, the creep compliance is defined as "the time-dependent strain divided by the applied stress." In this study, creep compliance tests were conducted at -0.4° F, 14° F, 32° F, and 50° F on cylindrical cores having a diameter of 6.0 in. and a height of 1.8 in., in accordance with the AASHTO T 322 test method. The test method consists of applying a static load of fixed magnitude along the diametral axis of the specimen for 100 seconds. A 22,000 lbs. load cell was used for loading the specimen. The vertical and horizontal deformations were measured by two LVDTs having a stroke length of 0.2 in., and attached in the diametrically perpendicular direction. A gauge length of approximately 1.5 in. was used for mounting the LVDTs on one face of the specimen. The horizontal and vertical deformations measured near the center of the specimen were used for calculating the tensile creep compliance, as a function of time. The load level was selected to keep horizontal deformation in the linear viscoelastic range (0.000492 – 0.0007480 in.) during the creep test. Figures 3.29 (a) through (d) show the photographic view of the setup used for conducting creep test.

The creep compliance was calculated as a function of the horizontal and vertical deformations, the gauge length over which these deformations are measured, the dimensions of the test specimen, and the magnitude of the static load. The following steps are used in determining creep compliance, as defined in the AASHTO T 322 test method:

$$D(t) = \frac{\Delta X_{tm,t} D_{avg} b_{avg}}{P_{avg} GL} C_{cmpl} \qquad\qquad (3.3)$$

where,

$D(t)$ = creep compliance at time t $(kPa)^{-1}$,

GL = gauge length in inch (1.5 in., 38 mm),

D_{avg} = average diameter of the specimens,

b_{avg} = average thickness of all specimens,

$\Delta X_{tm,t}$ = trimmed mean of the normalized, horizontal deformations (nearest to 0.001 in.) of all specimens faces of the specimen at time t,

P_{avg} = average creep load (lb., kN), and

C_{cmpl} = correction factor that can be defined as follows:

$$C_{cmpl} = 0.6354 \left(\frac{X}{Y} \right)^{-1} - 0.332 \qquad \textbf{(3.4)}$$

where,

X/Y = absolute value of ratio of the normalized, trimmed mean of the horizontal deformations ($\Delta X_{tm,t}$) to the normalized, trimmed mean of the vertical deformations ($\Delta Y_{tm,t}$) at a time corresponding to ½ of the total creep compliance test time.

The range of the correction factor (Equation 3.4) is given by the following equation:

$$\left| 0.704 - 0.213 \left(\frac{b_{avg}}{D_{avg}} \right) \right| \le C_{cmpl} \le \left| 1.566 - 0.195 \left(\frac{b_{avg}}{D_{avg}} \right) \right| \qquad \textbf{(3.5)}$$

The master creep compliance curve was created by using the time-temperature superposition principle. The time and temperature-dependent material properties can be represented by using reduced time (t_r) (Richardson and Lusher, 2008). The creep compliance versus time curves obtained from several individual temperatures was shifted along the time or frequency axis to create one continuous, creep compliance versus reduced time master curve. For a constant temperature, the reduced time (t_r) is defined as follows:

$$t_r = t \times a_t \qquad \textbf{(3.6)}$$

where,

a_t = time-temperature shift factor, and

t = time (seconds).

The Poisson's ratio, ν, was calculated as follows:

$$\nu = -0.10 + 1.480 \left(\frac{X}{Y} \right)^2 - 0.778 \left(\frac{b_{avg}}{D_{avg}} \right)^2 \left(\frac{X}{Y} \right)^2 \qquad \textbf{(3.7)}$$

where,

D_{avg} = average diameter of the specimens,

b_{avg} = average thickness of all specimens, and $0.05 \leq \nu \leq 0.50$
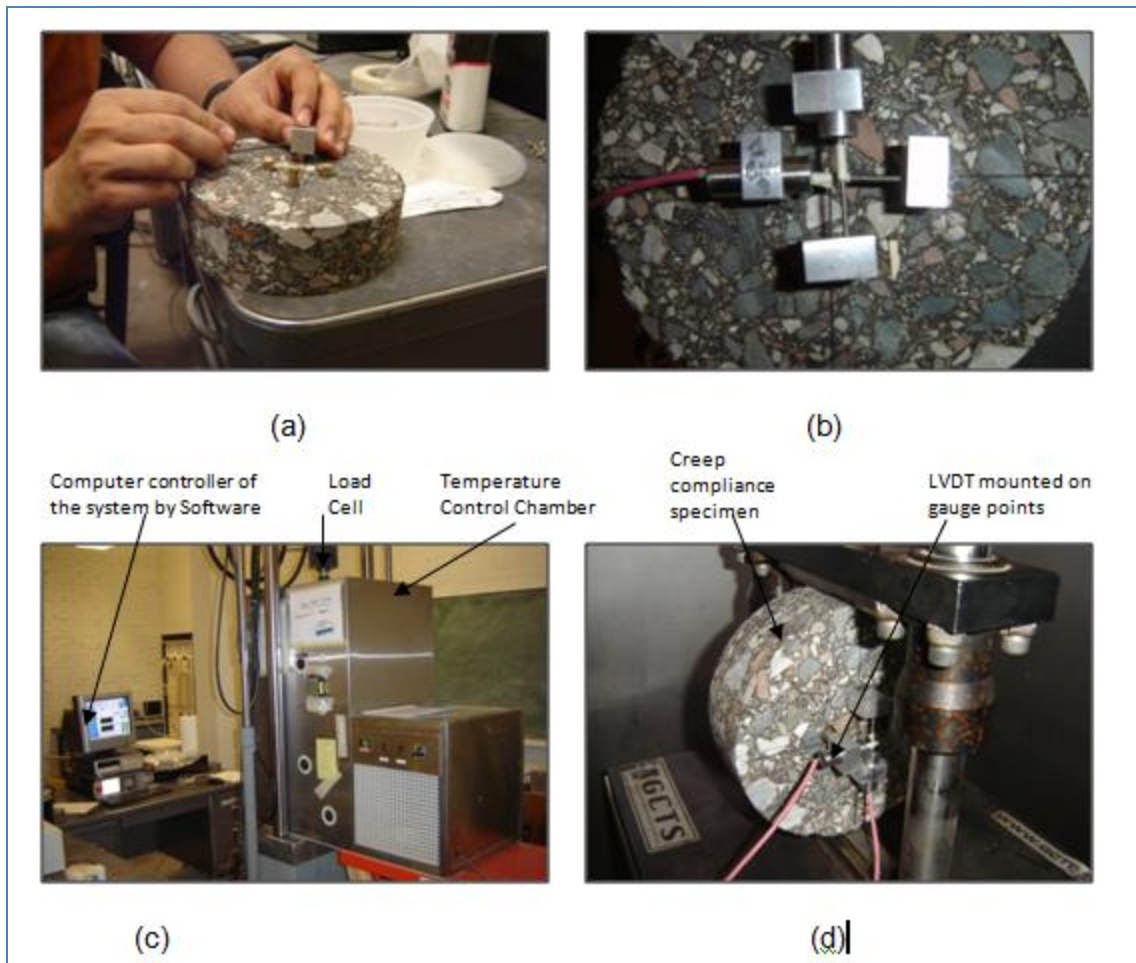
Figure 3.29 (a) Brass Gauge Points on Creep Specimen, (b) LVDT Mounted Onto the Brass Gauge Points, (c) Equipment Setup for Both Creep Compliance and Dynamic Modulus Testing, (d) Creep Compliance Specimen Inside the Environment Chamber.

3.5.5 Indirect Tensile Strength Test

After the completion of the creep compliance testing at specified temperatures, the environmental chamber was then set at 14° F at which the tensile strength testing was performed. The portion of T 322 related to the tensile strength testing is destructive. The specimen was loaded until failure occurs and the specimen cannot be used again. The specimen temeperature was stabilized first at the target temperature 14 ± 32.9°F

and then loaded at a rate (vertical movement) of 0.5 in. per minute. The tensile strength was calculated by using the following equation:

$$S_{t,m} = \frac{2xP_{f,n}}{\pi x b_n x D_n}$$

(3.8)

where,

$S_{t,n}$ = tensile strength of the specimen, n, and

$P_{f,n}$ = maximum load observed for specimen, n

4 ASPHALT BINDER TEST RESULTS

4.1 Performance Grading of Binders

Performance grade (PG) of the virgin binder with different percenatges (0%, 10%, 25%, 40%, and 100%) of RAP1 binder were determined as per AASHTO MP-1. To obtain the high PG temperatures of these binders, dynamic shear rheometer (DSR) tests on unaged and RTFO-aged binders were conducted as per AASHTO T 315. To evaluate the low PG temperatures of the blended binders, bending beam rheometer (BBR) tests on PAV-aged binder were conducted as per AASHTO T 313. As seen in Figure 4.1, the stiffness of the RAP1 binder is significanlty higher than the virgin binder, as expected. The high and low PG temperatures are about five grades and two grades, respectively, higher than those in the virgin PG 64-22 binder. The stiffness of the belended binder increases with an increase of the percentage of the RAP1 binder (Table 4.1). With 10% RAP1 binder, there is no noticable change in the PG grade of the virgin binder. With 40% RAP1 binder, the high and low PG temperatures are about two grades and one grade, respectively, higher than those of the virgin binder. The PG grades of blended binders (blends of virgin binder and RAP binder) can be used as the MEPDG Level 3 input parameters.
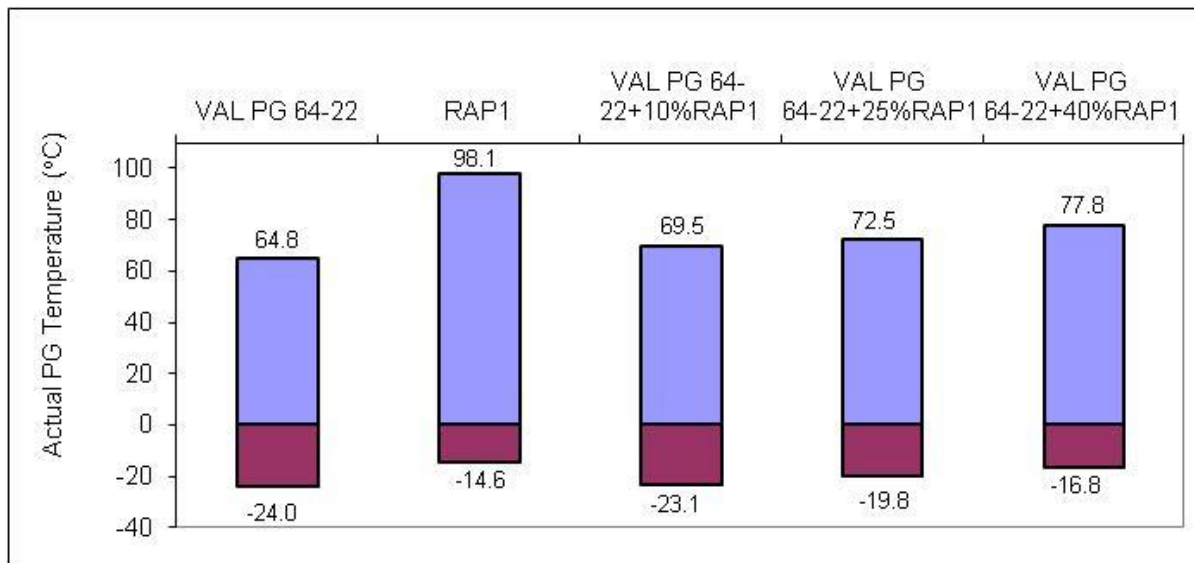
Figure 4.1   Performace Grade of the RAP1 Blended Binders.

The recovered binder from RAP2 was blended with a virgin PG 64-22 binder at different proportions (10%, 25% and 40% recovered binder) and their PG grades were evaluated. As shown in Figure 4.2, virtually there was no change in the Superpave PG grade (6^oC interval) due to the addition of 10% RAP binder. With 25% RAP binder, the PG grade has increased by one full grade (PG 70-16) at both ends. With further addition of RAP binder, the PG temperatures increases to some extent, however, the Superpave PG grade still remains as PG 70-16. The continuous PG grades of these binders are shown in Figure 4.2. It is noted that the PG temperature does not change significantly with the addition of 0.5% anti-stirpping agent.
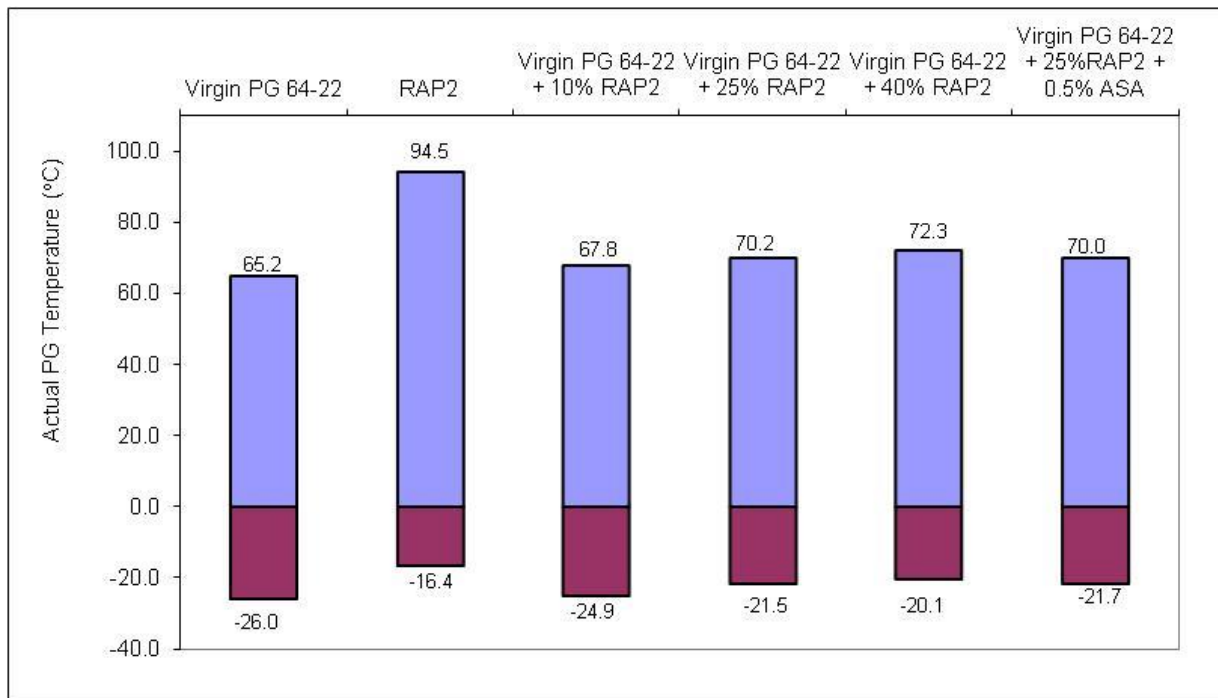
Figure 4.2   Performance Grade of RAP2 Blended Binders.

4.2   Rotational Viscosity

Rotational viscosity test (AASHTO T 316) results of RAP2 blended binders are shown in Figure 4.3. As seen in Figure 4.3, the viscosity of RAP1 binder is about 8 times higher than that of the virgin PG 64-22 binder. This is due to the fact that the RAP1 binder experienced oxidative hardening throughout its service life. With the addition of RAP1 binder in the virgin binder the viscosity increases, which is expected. The viscosity values of virgin binder with 10%, 25%, and 40% RAP1 were about 1.1,

1.25, and 2.2 folds, respectively, compared to the virgin binder. Such observations are in agrement with PG grades of blended binders discussed earlier.
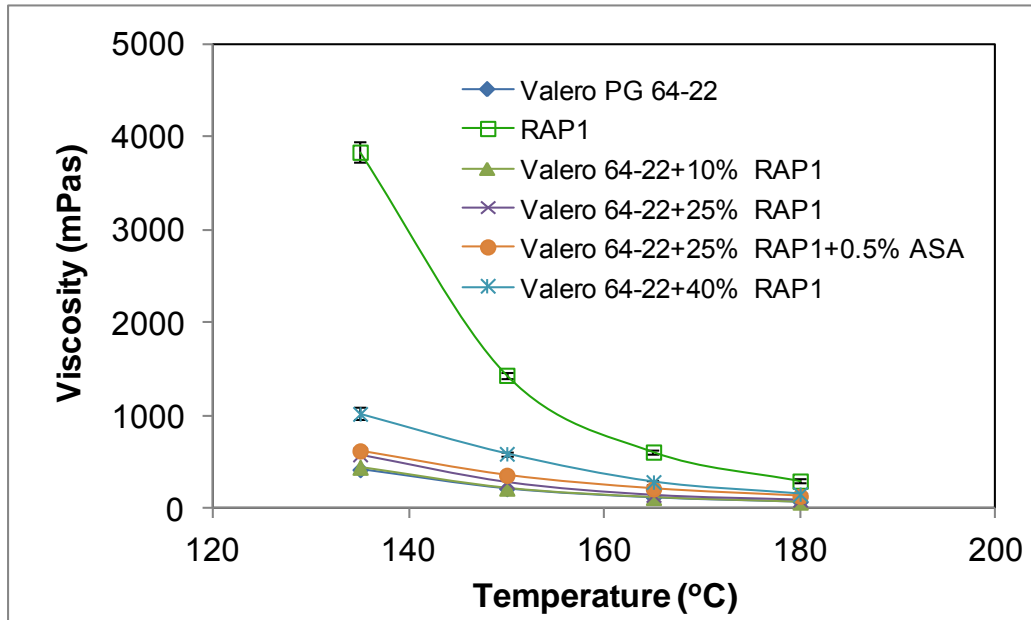
Figure 4.3   Viscosity Test Results of the Blended Binders.

Rotational viscoisty data of the RAP2 blended binders under unaged conditon are shown in Figure 4.4. As illustrated in Figure 4.4, the viscosity of the RAP2 binder is about 530% higher than the virgin PG 64-22 binder. With addition of 10%, 25% and 40% RAP2 binder in the virgin binder, the viscosity vlaues were found to be about 10% , 44%, and 119% higher, respectively, compared to the virgin binder. The anti-stripping agent does not seem to have any significant effects on the viscosity of 25% RAP blended binder.
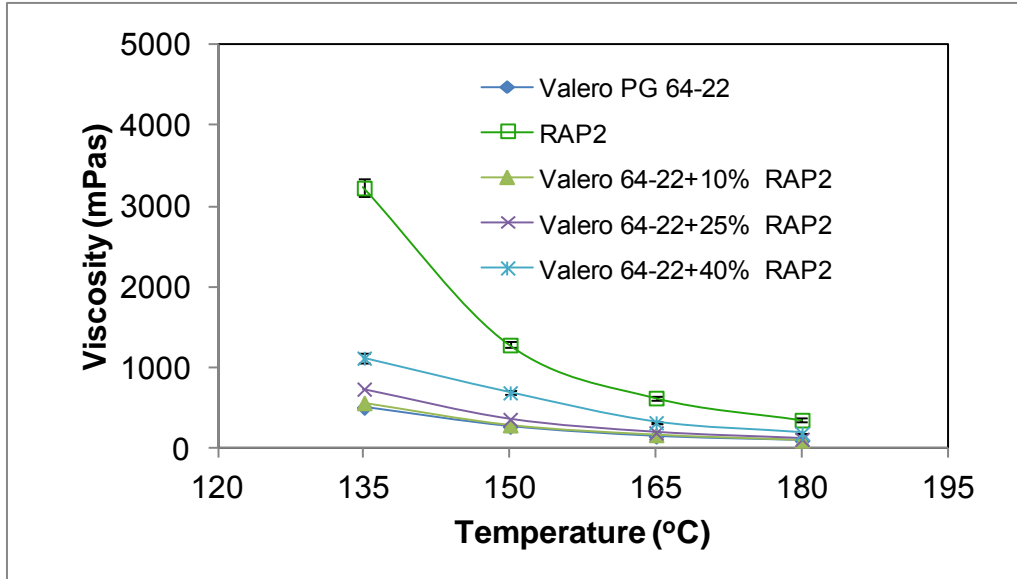
Figure 4.4   Rotational Viscosity Data of Blended Binders.

4.3   MEPDG Input Parameter for Binders with RAP

The MEPDG input parameters, dynamic moduls (G*) and phase angle (δ), of RTFO-aged blended binders (PG 64-22 with different percentages of RAP1 and RAP2) were evaluated by conducting DSR tests as per AASHTO T 315 over a range of temperatures (21.1^{o}C, 29.4^{o}C, 43.3^{o}C, 46.1^{o}C, and 54.4^{o}C). Values of G* and δ of RAP1 blended binders are presented in Figures 4.5 and 4.6, respectively. As expected, the G* value decreases but the δ value increases with increase in testing temperature. Another trend is that the G* value increases and the δ values decreases with an increase of the percentage of the RAP1 binder except for 25% RAP1 at 21.1^{o}C and 29.4^{o}C. This is due to the fact that the RAP1 binder has experienced oxidative hardening throughut its service life. As mentioned in earlier secitons, RAP binders are significanlty stiffer than their virgin counterparts. Thus, the higher the RAP content the stiffer the blended binder. Similar observations were made for RAP2 blended binders and the MEPDG Level 1 input parameters for these binders are presented in Figures 4.7 and 4.8.
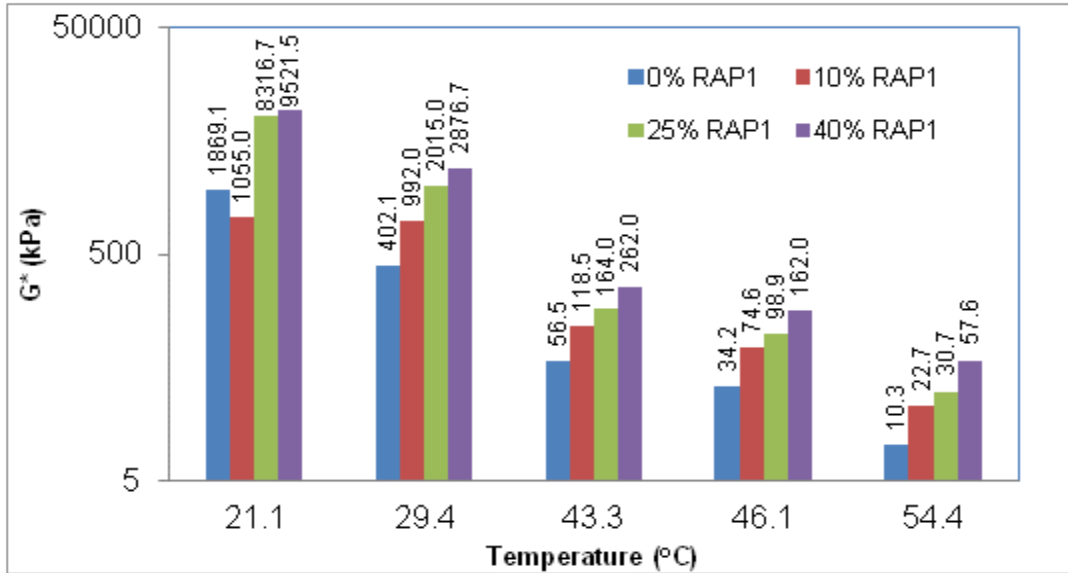
Figure 4.5   MEPDG Input Parameters (G*) of RAP1 Blended Binders.
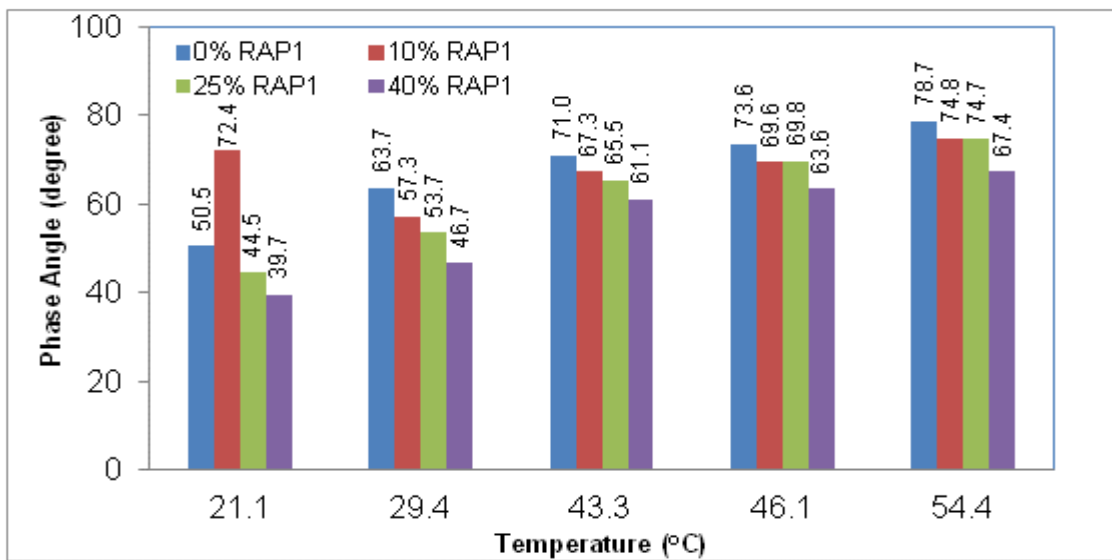
Figure 4.6   MEPDG Input Parameters (δ values) for RAP1 Blended Binders.

In the case of 25% RAP1 at 21.1^{o}C and 29.4^{o}C, a slight decrease of the G* value and an increase of the δ value were observed, compared to 10% RAP1.   Such observations are quite unexpected and uneplainable with limited laboratory data. It is suspected that some anomalies (e.g., sample triming, normal force, etc.) related to operator, machine, or combination of both factors played some roles behind such discrepencies in test result. It can also be mentioned that the MEPDG Level 1 input parameters for the 25% RAP blended binders modified with the anti-stripping agent was

not possible to evaluate due to the limited amount of recovered binders. However, based on PG grade and viscosity measurements, it is expected that 0.5% anti-stripping agent will not have any significant effects on the MEPDG Level 1 input parameters of 25% RAP modified binders.
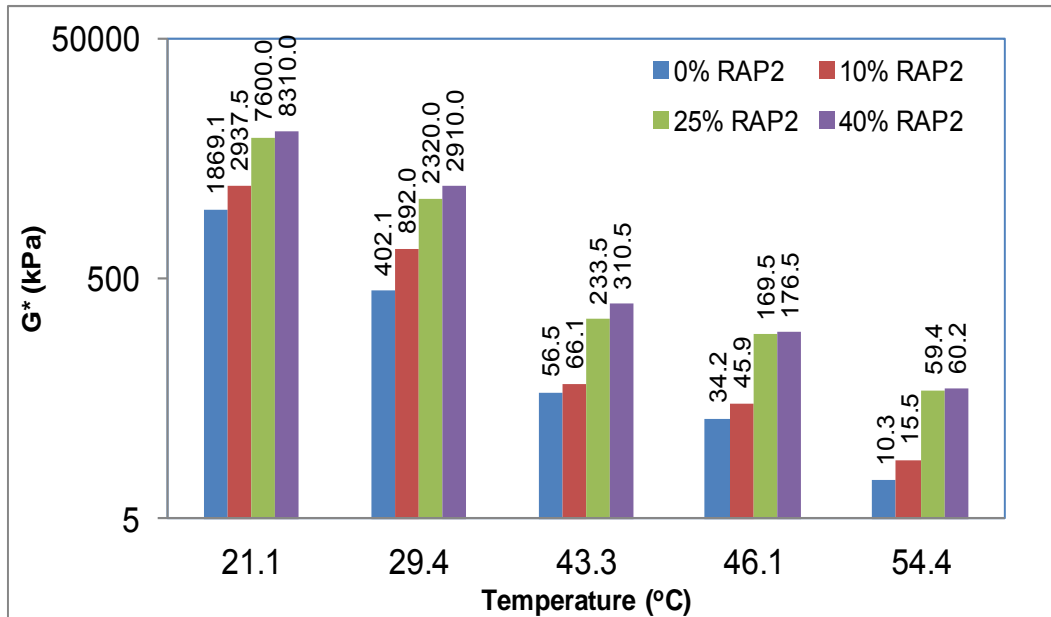
Figure 4.7   MEPDG Input Parameters (G*) of RAP2 Blended Binders.
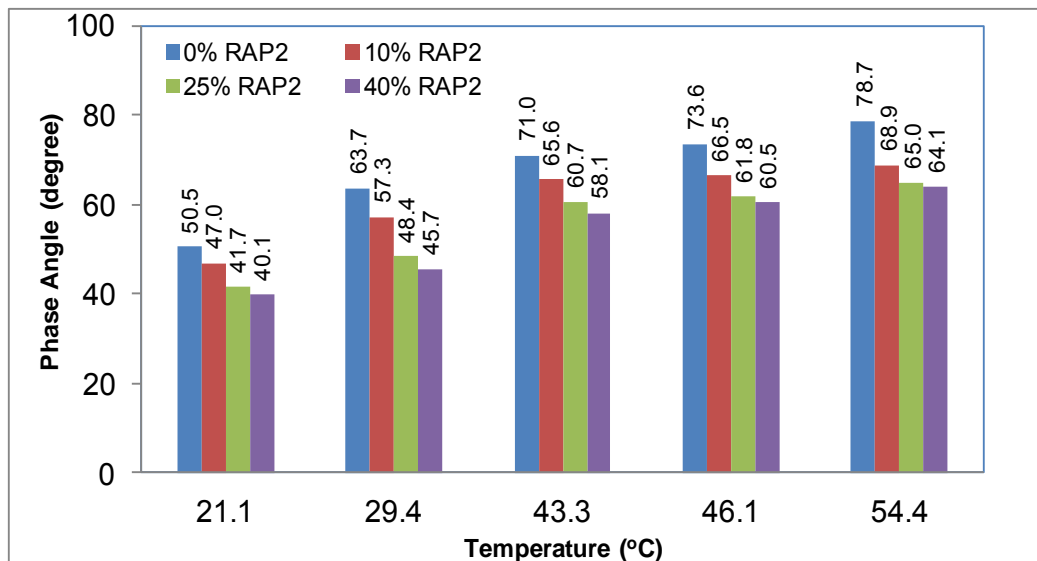
Figure 4.8   MEPDG Input Parameters (δ values) for RAP2 Blended Binders.

4.4   Chemical Analyses

Chemical analyses (Tables 4.2 and 4.3) of RAP blended binders show that there is more oxygen content in RAP binder compared to the virgin binder. Also, it is evident that the content of oxygen increases with an increase in the amount of RAP binder. Furthermore, the content of oxygen increases with the level of aging (RTFO versus PAV aging of samples with 25% RAP binder), indicating increased oxidative hardening in the case of PAV-aged binders. It should be noted than the elemental analysis used in this study was not capable of detecting any compounds smaller than 0.5%. Also, only C, H, N and O were attempted to detect in this study.

Table 4.1   Chemical Compositions of RAP1 Blended Binders

Binder Type	C%	H%	N%	O%
VAL PG 64-22-Unaged	85.06	10.43	0.69	0.81
VAL PG 64-22+10%RAP1-Unaged	84.78	10.21	0.66	0.74
VAL PG 64-22+25%RAP1-Unaged	84.51	10.26	0.77	<0.50
VAL PG 64-22+40%RAP1-Unaged	84.13	10.09	<0.5	0.60
VAL PG 64-22+40%RAP1-RTFO	83.37	10	0.69	1.14
RAP1-Unaged	83.59	10	0.65	2.19

Table 4.2   Chemical Compositions of RAP2 Blended Binders

Binder Type	C%	H%	N%	O%
VAL PG 64-22-Unaged	84.82	10.65	0.98	0.62
VAL PG 64-22+10%RAP2-Unaged	84.12	10.53	<0.5	0.86
VAL PG 64-22+25%RAP2-Unaged	84.27	10.35	<0.5	1.07
VAL PG 64-22+25%RAP2-RTFO	83.58	10.26	<0.5	1.44
VAL PG 64-22+25%RAP2-PAV	83.82	10.35	<0.5	1.50
VAL PG 64-22+40%RAP2-Unaged	83.65	10.34	<0.5	3.04
RAP2-Unaged	82.33	9.96	<0.5	2.24

5.   AGGREGATE PROPERTIES TEST RESULTS AND DISCUSSIONS

5.1   RAP1

5.1.1 Gradation

As noted earlier, bulk RAP1 materials were selected with the help of Silver Star Construction Co. in Moore, Oklahoma. The location of this RAP source was I-35 in McClain County (near Purcell), Oklahoma. The milling site consisted of a 1.5 in. (37 mm) overlay of HMA Type B with PMAC-1C binder. The overlay was constructed in 1994. Prior to 1994, the project received a 2 in. (50 mm) of leveling course of HMA Type C with AC-3 (viscosity grading) binder in 1979. In addition to collection of RAP, five different types of virgin aggregates, namely, #67 rocks, 5/8-in. chips, screenings, manufactured sand, and natural sand were collected for mix design and laboratory testing. The gradations of extracted and virgin aggregates were analyzed in accordance with AASHTO T 30 and AASTO T 27, respectively. Two samples were tested for each material and averaged for gradation. A summary of the gradation is presented in Table 5.1.

Table 5.1   Aggregates and RAP1 Gradations (Percent Passing)

Sieve Size	#67 from Martin Marietta	5/8" Chips from Hanson	Scrns. From Hanson	Manufac-tured Sand from Martin Marietta	Sand from GMI Sand OKC, OK 1402	Fine RAP from Contractor Site
1 in. (25 mm)	97	100	100	100	100	100
3/4 in. (19 mm)	88	100	100	100	100	97
1/2 in (12.5 mm)	59	96	100	100	100	90
3/8 in. (9.5 mm)	37	84	100	100	100	55
#4 (4.75 mm)	6	33	89	92	100	34
#8 (2.36 mm)	2	9	57	48	99	25
#16 (1.18 mm)	1	4	37	25	98	21
#30 (0.600 mm)	1	3	23	13	91	17
#50 (0.300 mm)	1	2	14	7	67	10
#100 (0.150 mm)	0	2	8	4	25	7
#200 (0.075 mm)	0.3	1.2	4.1	1.9	8.3	4.3

5.1.2 Specific Gravity

The specific gravity of aggregates was expressed as a bulk specific gravity. In this study, the bulk specific gravity tests of coarse aggregate and fine aggregate were conducted following the AASHTO T 85 and T 84 test methods, respectively. The coarse aggregate portion was defined as the portion that retains on a No. 4 (4.75 mm) sieve. For both coarse and fine aggregate portions, the samples were tested in individual size fractions as well as for a specific mix gradation.

5.1.2.1 *Coarse Aggregate Specific Gravity*

The coarse aggregate was first thoroughly mixed and then reduced to the required size in accordance with the AASHTO T 248 test method. The set of apparatus used to conduct the coarse specific gravity in the Broce Laboratory is shown in Figure 5.1. The sample, under an oven-dry condition, was soaked for fifteen to nineteen hours, as per specifications. After the soaking period, it was removed from the soaking water and placed in the specified wire mesh basket. The basket and sample were placed in water and agitated to remove any trapped air from the sample. The mass in water was recorded on a data sheet. The sample was then removed from the water and placed on a towel. The aggregate was moved around on the towel until the film of water on the surface of the aggregate particles was no longer visible. Care was taken not to make the aggregate particles too dry. The sample was then weighed, and the mass was recorded as the saturated-surface-dry (SSD) weight. Lastly, the sample was placed in an oven until a constant mass was reached. The constant mass was recorded as the oven-dry weight. The three recorded masses namely, oven-dry test sample in air, SSD test sample in air, and saturated test sample in water were used to calculate the bulk specific gravity (SSD) using Equation 5.1 and the results are presented in Table 5.2:

$$G_{sb} = \frac{A}{B-C} \qquad\qquad (5.1)$$

where,

G_{sb} = Bulk specific gravity,

A = Oven dry weight,

B = SSD weight, and

C = Weight in water.

Figure 5.1   Apparatus Used for determination of Specific Gravity of Coarse Aggregates.

5.1.2.2   *Fine Aggregate Specific Gravity*

The bulk specific gravity, apparent specific gravity and percent absorption of each fine aggregate sample were determined in accordance with the AASHTO T 84 test methods. Figure 5.2 presents the apparatus used to conduct the fine specific gravity test. The fine aggregate was first thoroughly mixed and then reduced to the required size in accordance with the AASHTO T 248 test method. The sample size for this procedure is approximately 2.2 lbs. (1,000 g) of material passing the No. 4 (4.75 mm) sieve. The test sample was dried to a constant weight in an oven set at 230 ± 9°F (110 ± 5°C), and then cooled at room temperature for one to three hours. Following the cooling period, the sample was soaked by maintaining it at a moisture content of at least 6% for a fifteen to nineteen-hour period. After the soaking period, the sample was spread on a flat non-absorbent surface, and dried to the Saturated Surface Dry (SSD) condition. The SSD condition is determined using a specified conical mold and a tamper. The material is placed in the cone, tamped twenty five times and the cone is

removed. If the material slumps, the SSD condition is reached, but if it does not slump, it is necessary to dry the sample further.

Figure 5.2   Apparatus Used for determination of Specific Gravity of Fine Aggregates.

After reaching the SSD condition, 1.1 ± 0.0022 lb (500 ± 1 g) of the sample is placed in a pycnometer charged with water. All air voids are removed by the hand agitation method and the pychnometer is filled with water to the calibration line and the mass is recorded. The material is then taken out and placed in an oven at a temperature of 230˚F (110˚C) for drying. The mass of the dry material is determined. The bulk specific gravity is then calculated using Equation 5.2 and the results are presented in Table 5.2.

$$G_{sb} = \frac{A}{B - S - C}$$ **(5.2)**

where,

G_{sb} = Bulk specific gravity,

A = Weight of oven dry sample,

B = Weight of flask filled with water to the calibration line,

C = Weight of flask, sample and water to the calibration line, and

S = Weight of SSD sample.

Table 5.2   Specific Gravity Values of Aggregates of RAP1 Mixes

Source/Producer	Martin-Marietta (Davis, OK)	Hanson Aggregate	Hanson Aggregate	Martin-Marietta	GMI Sand OKC, OK 1402
Type of Aggregates	#67	5/8" Chips	Scrns.	Man. Sand	Sand (Unlisted Source)
Coarse Aggregates G_{sb}	2.665	2.671	2.677	2.640	-
Fine Aggregates G_{sb}	2.546	2.595	2.558	2.630	2.622

5.1.3 L.A. Abrasion Test

The L.A. abrasion test was conducted on specific mixes with specific gradations in accordance with the ASTM C 131 test method. The L.A. abrasion test is most often used to evaluate the toughness and abrasion of the associated aggregates. The apparatus used to conduct the test is presented in Figure 5.3. When the L.A abrasion values are too high, excessive aggregate breakdown may occur during handling, compaction, and traffic, resulting in potential bleeding, rutting, or raveling (Wu et al., 1998). The gradation used in this study is the C gradation, in accordance with the criterion recommended in the ASTM C 131 test method.

Figure 5.3   Apparatus Used for L.A. abrasion Test.

The L.A. Abrasion test calls for 11 lbs (5000 gm) of aggregate test sample to be placed in a revolving drum along with a set number of steel balls averaging 1.84 in (46.8 mm) in diameter. The drum picks up and drops the sample and the balls 500 times by means of a shelf located inside the drum. The sample is then removed from the drum and sieved using a No. 12 (1.70 mm) sieve. The loss is calculated as the difference between initial mass and final mass. The loss is expressed to the nearest 1% of mass. The results are presented in Table 5.3 and Table 5.4. It is evident that all the mixes met the ODOT requirements for the L.A. abrasion loss (≤ 40 %). Regardless the mix type, the L.A. abrasion loss increases slightly with the increase in the RAP content. However, the percentage of RAP (up to 40% for S3 and 10% for S4) in the combined blend had a little effect on changes in the L.A. abrasion loss. The RAP aggregate may be beneficial since some of the rough, irregular edges would have been broken off during previous handling, placement and milling of materials (Han et al., 2011). In some cases, the proportion of RAP in the mixes actually improved the L.A. abrasion properties.

5.1.4 Micro-Deval

The Micro-Deval testing was conducted according to the ASTM D 7428 test method (Figure 5.4). The procedure consists of soaking a previously weighed 3.3 ± 0.011 lbs. (1500 ± 5 g) aggregate sample in two liters of water for one hour, and then placing the aggregate and the water in a small stainless steel drum with 11 lbs. (5000 g) of small steel balls with a diameter of 0.37 ± 0.02 in. (9.5 ± 0.5 mm). The drum is then sealed and rotated at 100 ± 5 revolutions per minute for a specified amount of time depending on the gradation used. Afterwards, the aggregate sample is removed and wet sieved over the No. 4 (4.75 mm) and No. 16 (1.19 mm) sieves. The total amount of aggregate retained on both sieves is collected and oven-dried to a constant mass at 230 ºF (110 ºC), or usually overnight. The loss is determined by calculating the percent loss as retained on the No. 16 (1.19 mm) sieve. The results are presented in Table 5.3 and Table 5.4 for S3 and S4 mixes, respectively.

Figure 5.4   Apparatus Used for Micro-Deval Test.

5.1.5 Sand Equivalent Test

The sand equivalent test is a consensus aggregate property specified in the Superpave® mix-design method (Prowell et al., 2005). In this study, the test was conducted on specific mix gradation in accordance with the AASHTO T176 test method. Figures 5.5 shows the apparatus used for conducting this test. Fine aggregates (passing the No. 4 (4.75 mm) sieve) are placed in a graduated, transparent cylinder that is filled with a mixture of water and a flocculating agent. After agitation and 20-min. of settling, the sand separates from the clay-like fines and the heights of sand and sand plus clay are measured. The sand equivalent is the ratio of the height of the sand to the height of sand plus clay times 100. A higher sand equivalent values indicate more sand and less clay and silt. The results are presented in Tables 5.3 through 5.6.

Table 5.3   Summary of Mix Gradation for S3-25 and S3-40 of RAP1 Mixes

Blended Material	S3-25	S3-40	Gradation (Sieve Size, mm)	% Passing for S3-25	% Passing for S3-40	Required[a]
#67 Rock	15%	12%	25	100	100	100
5/8" Chips	22%	25%	19	99	97	90-100
Screenings	17%	8%	12.5	89	90	≤ 90
Manufactured Sand	10%	15%	9.5	78	70	-
Natural Sand	11%	0%	4.75	56	43	-
Fine RAP	25%	40%	2.36	39	24	23-49
			1.18	31	16	-
			0.6	25	11	-
			0.3	18	7	-
			0.15	9.0	5	-
			0.075	5.2	2.7	2-8

[a] Required for 0.3-3M of Design ESAL; RAP: Recycled Asphalt Pavement; S3-25: mix containing 25% RAP; S3-40: mix containing 40% RAP.

Table 5.4   Summary of Aggregates Properties and Volumetric Properties of S3-25 and S3-40 of RAP1 Mixes

Volumetric and Aggregate Properties	S3-25	S3-40	Required[a]
G_{mm}	2.533	2.475	N/A
G_{se}	2.722	2.665	N/A
G_{sb}	2.671	2.628	N/A
G_b	1.01	1.01	N/A
Virgin Binder Type	PG 64-22	PG 64-22	N/A
Total Binder Content (%)	4.4	4.7	N/A
Virgin Binder Content (%)	2.9	2.9	N/A
VMA (%) (Required: ≥ 13.0)	14.5	15.2	N/A
VFA (%) (Required: 65-78)	67.2	73.6	N/A
DP (Required: 0.6-1.2)	1.4	0.8	N/A
LA Abrasion (%)	21	22	≤ 40
Micro Deval (%)	11.8	12.5	≤ 25
Sand Equivalent (%)	78	82	≥ 40
Fine Aggregates Angularity (%)	43.5	42	≥ 40
Tensile Strength Ratio	0.87	0.82	≥ 0.80
APA Rut (mm)	1.1	3.6	≤ 6 mm
Permeability (10^{-5} cm/s)	6.4	6.5	≤ 12.5

G_{mm}: Maximum Theoretical Specific Gravity; G_{se}: Effective Specific Gravity of Aggregates; G_{sb}: Bulk Specific Gravity of Aggregates; VMA: Void in Mineral Aggregates; VFA: Void Filled with Asphalt; DP: Dust Proportion; APA: Asphalt Pavement Analyzer

Table 5.5   Summary of Mix Gradation and Volumetric Properties for S4-0 and S4-10 of RAP1 Mixes

Blended Material	S4-0	S4-10	Gradation (Sieve Size, mm)	% Passing for S4-0	% Passing for S4-10	Required[a]
5/8" Chips	25%	30%	19	100	100	90-100
1/2" Chips	18%	0%	12.5	96	98	≤ 90
Screenings	42%	22%	9.5	88	90	-
Manufactured Sand	0%	33%	4.75	57	68	-
Natural Sand	15%	5%	2.36	35	39	23-49
Fine RAP	0%	10%	1.18	28	25	-
			0.6	23	17	-
			0.3	15	10	-
			0.15	7	6	-
			0.075	4.6	2.7	2-8

[a] Required for 0.3-3M of Design ESAL; RAP: Recycled Asphalt Pavement; S4-0: mix containing 0% RAP; S4-10: mix containing 10% RAP.

Table 5.6   Summary of Aggregates and Volumetric Properties for S4-0 and S4-10 of RAP1 Mixes

Volumetric and Aggregate Properties	S3-25	S3-40	Required[a]
G_{mm}	2.488	2.470	N/A
G_{se}	2.699	2.687	N/A
G_{sb}	2.670	2.605	N/A
G_b	1.01	1.01	N/A
Virgin Binder Type	PG 64-22	PG 64-22	N/A
Total Binder Content (%)	5.1	5.3	N/A
Virgin Binder Content (%)	5.1	4.8	N/A
VMA (%) (Required: ≥ 13.0)	15.8	15.9	N/A
VFA (%) (Required: 65-78)	69.6	73.3	N/A
DP (Required: 0.6-1.2)	0.97	0.6	N/A
LA Abrasion (%)	18	21	≤ 40
Micro Deval (%)	7.7	11.8	≤ 25
Sand Equivalent (%)	67	75	≥ 40
Fine Aggregates Angularity (%)	42.7	41.6	≥ 40
Tensile Strength Ratio	0.85	0.82	≥ 0.80
APA Rut (mm)	1.39	4.2	≤ 6 mm
Permeability (10^{-5} cm/s)	3	10.4	≤ 12.5

Volumetric and Aggregate Properties	S3-25	S3-40	Required[a]

G_{mm}: Maximum Theoretical Specific Gravity; G_{se}: Effective Specific Gravity of Aggregates; G_{sb}: Bulk Specific Gravity of Aggregates; VMA: Void in Mineral Aggregates; VFA: Void Filled with Asphalt; DP: Dust Proportion; APA: Asphalt Pavement Analyzer

5.1.6 Total Insoluble Residue

The acid insolubility of aggregate is an indicator of skid resistance of the pavement surface. The lower the acid insoluble residue, the lower the expected skid resistance of the pavement. The acid insoluble material in coarse aggregates was determined as per OHD L-25 (Method of Test for Total Insoluble Residue in Coarse Aggregate). The extracted aggregates were washed and those passing through a 1/2 inch (12.5 mm) sieve and retained on a No. 4 sieve were used to measure the insolubility in conc. hydrochloric acid (HCl).
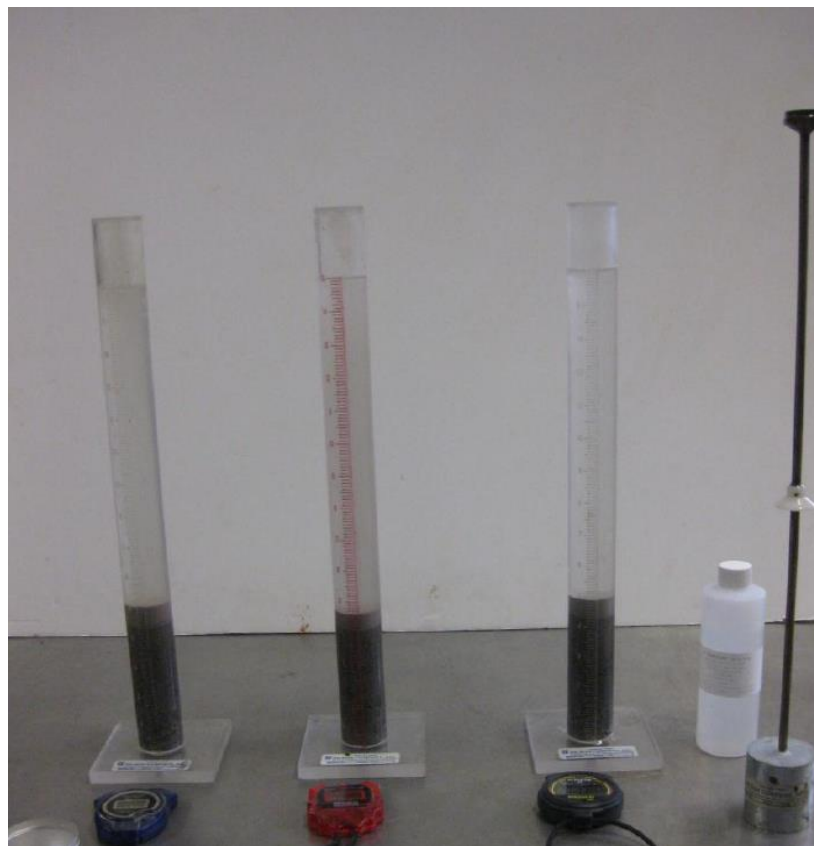
Figure 5.5   Sand Equivalent Test Setup.

In this test, 400 ml of water was added to 0.44 lb (200 gm) of coarse aggregate, then approximately 30 ml of concentrated hydrochloric acid was added per 1 oz (30 gm) of coarse aggregate. The mixture was stirred over a period of days until all reaction ceased. Then the insoluble free of excess ions were washed by filling jar with tap water and allowing the material to settle for about 48 hours and pouring off the clean solution. Procedure was repeated three times. After the third wash cycle, the insoluble were washed into a shallow pan and were rolled between thumb and fore finger to crumble any friable particles. Then they were washed over a No. 200 sieve, dried at 212°-221° F (100°-105° C) and weighed. Insolubles retained on a No. 200 sieve were reported as a percent of total sample used. Insoluble Residue values of selected RAP1 and virgin samples are presented in Table 5.7.

Table 5.7   Insoluble Residue Test Results of RAP1 Aggregates

Mix Type	Aggregate Type	Average Insoluble Residue (%)	Standard Deviation (%)
RAP1	NCAT Oven Extracted	31.1	1.3
S4+0%RAP1	NCAT Oven Extracted	88.8	N/A

5.2   RAP2

5.2.1 Gradation

As mentioned earlier, gradation or the particle size distribution of aggregates is one of the most important aggregate characteristics which highly affect the performance of asphalt mix as a pavement material. As noted previously, aggregates were extracted from the collected mixes and RAP samples and the binder content was determined by using a NCAT ignition oven, as per the AASHTO T 308 method (Standard Method of Test for Determining the Asphalt Binder Content of Hot Mix Asphalt by the Ignition Method). Representative samples of RAP2 were obtained as per AASHTO T 168 (Sampling of Bituminous Paving Mixtures). The moisture content of the representative sample was determined by oven drying it at 110°C until a constant mass was achieved.

Based on the nominal maximum size (NMAS) of RAP2 (19 mm), a 2000-gm sample was used in each test according to the AASHTO T 308 test method.

The extracted aggregates were analyzed in accordance with the AASHTO T 30 method (Mechanical Analysis of Extracted Aggregate) for gradation by using a series of sieves, as given in the original mixes. Gradations of aggregates extracted from RAPs were then compared with their virgin counterparts. Three replicates of each sample were sieved to find the average gradation. Aggregate gradations according to the mix designs, for the three RAP2 mixes, S3+25%RAP2, S3+40%RAP2, and S4+25%RAP2, are shown later in Appendix A (Figures A.13 through A.15). It was observed that the aggregates extracted from RAP2 fall within the S4 mix definitions according to ODOT Standard Specifications (ODOT 2009).

5.2.2 Specific Gravity

As shown in Table 5.8, the bulk specific gravity (BSG) and effective specific gravity (ESG) values of S3+25%RAP2 were found to be 2.698 and 2.680, respectively. The BSG and ESG values of S3+40%RAP2 were found to be 2.704 and 2.655, respectively. The BSG and ESG values of S4+25%RAP2 were observed as 2.674 and 2.605, respectively.

5.2.3 Durability

The LA Abrasion loss values of S3+25%RAP2, S3+40%RAP2, and S4+25%RAP2 were found to be 23.0, 22.0, and 24.2, respectively, which were well below the ODOT maximum limit of 40. The Micro-Deval loss value of S3+40%RAP2 was found to be 16.2, which was also well below the ODOT maximum allowable limit of 25. It should be noted that Micro-Deval tests were not conducted for aggregates for S3+25%RAP2 and S4+25%RAP2 mixes.

5.2.4 Sand Equivalent

As explained earlier in this chapter, the sand equivalent test is a measure of the relative proportions of fine dust or clay-like materials in fine aggregate and is an indicator of the dust or clay content in fine aggregate. Sand equivalent tests of RAP2 aggregates were conducted in accordance with the AASHTO T 176 (Plastic Fines in

Graded Aggregates and Soils by Use of the Sand Equivalent Test) standard test method. In regard to RAP2 mixes, sand equivalent tests were conducted on three types of aggregates: (1) NCAT oven extracted aggregates from field mixes: S3+25% RAP2, S3+40%RAP2 and S4+25% RAP2, (2) NCAT oven extracted aggregates from RAP2, and (3) Blended virgin aggregates according to the mix designs of field collected mixes.

The sand equivalent values obtained from Items 2 and 3 are mathematically combined to obtain the virgin sand equivalent value of each mix. This will help observe the effect of extraction of aggregates using the NCAT ignition oven on the sand equivalent value. Sand equivalent values obtained for different aggregates in this study are shown in Table 5.8. It should be noted that the sand equivalent values for virgin blended aggregates are the combination of the sand equivalent values of the virgin portion of the mix and the extracted aggregates from RAP2. It was observed that the sand equivalent values of all aggregates met the ODOT criterion (sand equivalent value >40%) for the construction of high volume roads (≥ 3M+ equivalent single axle load). However, this observation should be used cautiously as the excessive heat in the NCAT ignition oven may alter the sand equivalent values of RAP aggregates (Hossain et al., 2012). According to Table 5.8, this difference was no more than 4%.

Table 5.8   Sand Equivalent Test Results on Aggregates

Mix Type	Aggregate Type	Average Sand Equivalent (%)	Standard Deviation (%)
RAP2	NCAT Oven Extracted	70	1.33
S3+25%RAP2	NCAT Oven Extracted	80	2.12
	Virgin Blend	82	2.10
S3+40%RAP2	NCAT Oven Extracted	84	0.98
	Virgin Blend	88	1.20
S4+25%RAP2	NCAT Oven Extracted	81	3.51
	Virgin Blend	79	1.11

5.2.5 Insoluble Residue

Table 5.9 presents the average and standard deviation values derived from insoluble residue test results on three insoluble test trials of the NCAT oven extracted RAP2 aggregates and virgin blended and NCAT oven extracted aggregates from

S3+25%RAP2, S3+40%RAP2 and S4+25%RAP2 mixes. According to Table 5.9, the hydrochloric acid (HCl) insolubility of RAP2 aggregates was found to be 16.3 even though the original pavement was constructed as an insoluble mix with a required acid insolubility of greater than 40. Thus, RAP2 aggregates do not meet the ODOT solubility requirement anymore. Possible reasons for the loss in the percent insoluble residue could be degradation of particles under heavy traffic (3M+ equivalent axle load) and weathering actions. To verify the possible effect of the NCAT ignition oven on the acid insolubility of extracted aggregates, S3 and S4 NCAT oven extracted aggregate and their virgin counterparts were also tested and they were found to be extremely low (below 7.0), which were also in agreement with insoluble residue data available in ODOT Materials Division's database (ODOT 2010). A possible reason for virgin aggregates having extremely low insoluble residue was the source of aggregates. Currently aggregates in the quarry appear to be limestone. Limestone, which is composed largely of calcite ($CaCO_3$), is expected to react well with HCl. However, sandstone, which is primarily composed of quartz and/or feldspar, is not expected to react with HCl. Therefore, concentrated HCl acid used in the insoluble residue test was more reactive with carbonates in the limestone aggregates compared to sandstones. These findings reiterate the need for the evaluation of acid insoluble residue of RAP aggregates intended to be used in new mixes. It is very unlikely that the NCAT ignition oven processes change the fundamental mineralogy (chemicals composition) of aggregates, reflecting that the percent residue should not change. This was observed in Table 5.9, whereas NCAT extracted aggregates have a very similar insoluble residue values to their virgin counterparts.

Table 5.9   Insoluble Residue Results for Site 2 Aggregates

Mix Type	Aggregate Type	Average Insoluble Residue (%)	Standard Deviation (%)
RAP2	NCAT Oven Extracted	16.3	1.9
S3+25%RAP2	NCAT Oven Extracted	6.3	2.0
	Virgin Blend	3.6	1.7
S3+40%RAP2	NCAT Oven Extracted	5.1	2.1
	Virgin Blend	3.1	1.8

Mix Type	Aggregate Type	Average Insoluble Residue (%)	Standard Deviation (%)
S4+25%RAP2	NCAT Oven Extracted	7.0	1.9
	Virgin Blend	5.8	1.1

5.3   Summary

As discussed in Sections 5.2.1 to 5.2.4, testing on the aggregates extracted from mixes (S3-25% RAP2, S3-40% RAP2 and S4-25% RAP2) and those from the virgin blends of aggregates, the following summary can be concluded:

- Based on the L.A. abrasion loss values and the Micro Deval loss values, it can be observed that all of the mixes (including RAP2) meet the aggregate soundness requirements set by ODOT. However, NCAT oven extracted aggregates show more L.A. abrasion loss values and Micro Deval loss values, compared to their virgin counterparts.

- Sand equivalent tests show that the NCAT oven extraction process of S3 mixes (with 25% and 40% RAP) results in an increase in sand equivalent values. Similar observation has been made for the S4 mix with 25% RAP2.

- Insoluble test results indicate that RAP2 aggregates do not meet the ODOT solubility requirement. Also, S3 and S4 NCAT oven extracted aggregates and their virgin counterparts were tested and their corresponding insoluble values were found to be extremely low (below 7.0). This was in agreement with insoluble residue data available in the ODOT Materials Division's database.

6.   MIX TEST RESULTS AND DISCUSSIONS

Test results of volumetric mix designs of RAP1 and RAP2 mixes and relevant discussions are presented in the subsequent sections of this chapter.

6.1   RAP1

6.1.1 Volumetric Properties

The collected RAP millings were used for volumetric mix designs in accordance with the AASHTO M 323 test method. As discussed in Chapter 5, a total of four mix designs, namely, S3-25, S3-40, S4-0, and S4-10 were developed. A total of four and three mix trials were used for developing the volumetric mix designs for the S3-40 and S4-10 mixes, respectively. The mix designs for the S3-25 and S4-0 mixes were provided by Silver Star Construction Co. The trial designs prepared for the S3-40 and S4-10 mixes are presented in Appendix A (Figures A.1 through A.11). The procedure consisted of mixing different percentages of virgin aggregates, virgin binder, and RAP satisfying the gradation requirements. The prepared asphalt mix was then conditioned and used to prepare cylindrical samples in a Superpave® Gyratory Compactor (SGC) in accordance with the AASHTO T 312 test method. The final trials were found to satisfy the volumetric mix design requirements for the S3-40 and S4-10 mixes. The mixes were designed for an equivalent single axle load (ESAL) level of 0.3M – 3M. The S3-40 mix is a blend of aggregates containing 12%, 25%, 8%, and 15% of #67 rocks, 5/8-in chips, screening, and manufactured sand, respectively. The gradation of this blend is well within the minimum and maximum limits of the ODOT requirements for S3 mixes. Similarly, the S4-10 mix is a blend of 30%, 22%, 30%, and 8% of 5/8-in chips, screening, manufactured sand and natural sand, respectively, which are well within the limits of the ODOT requirements for S4 mixes.

6.1.2 Mix Performance

6.1.2.1   Rut and Moisture Resistance

The test results for S3 and S4 mixes tested at different air void contents are presented in Figures 6.1 and 6.2, respectively. It is evident from Figure 6.1 that the rut depth of S3-25 mix is higher than the rut depth of S3-40 mix. For example, at 10,000

passes S3-25 (air void content = 7.1%) and S3-40 (air void content = 7.1%) mixes showed a rut depth of approximately 4.95 and 3.72 mm, respectively. The behavior of rut with increase in RAP content in S4 mixes is not very clear due to significant difference in air void content of S4-0 (average air void content = 4.1%) and S4-10 (average air voids content = 8.4%) mixes. For example, the S4-10 mix with an air voids content of 7.8% showed lower rut values as compared to the S4-0 mix having an air voids content of 4.6%. On the other hand, the same S4-10 mix (air voids content = 7.8%) showed higher rut values as compared to S4-0 mix with an air voids content of 3.6% (Figure 6.2). It is important to note that both specimens from the S4-0 mix had significant lower air voids content (4.1%). Thus, lower rut values were expected in the case of S4-0 mix specimens (Hossain et al. 2010).
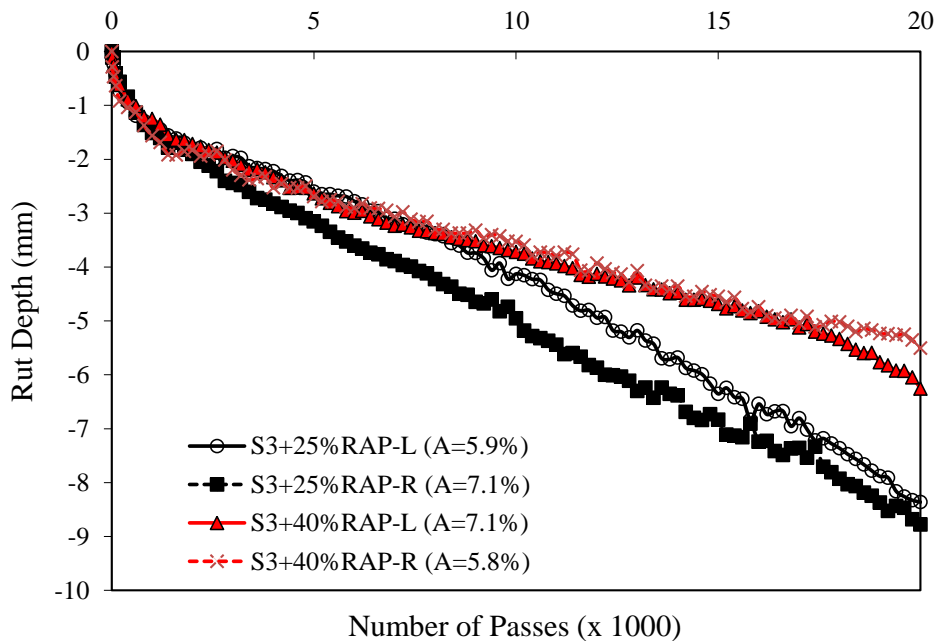
Figure 6.1   Hamburg Curves of S3 Mixes with RAP1.

For further evaluation of moisture susceptibility of mixes, the average rut values for each mix were calculated and plotted in Figure 6.3. As presented in Figure 6.3, all four characteristic regions are evident in S3-25 and S4-0 mixes. The stripping inflection points for S3-25, S4-0 and S4-10 mixes were found to be approximately 17,000, 15,700 and 15,000 passes, respectively. According to FHWA (2012), an inflection point below

10,000 wheel passes indicates significant moisture damage susceptibility of the mix. No stripping slope and inflection point were observed in S3-40 mix.
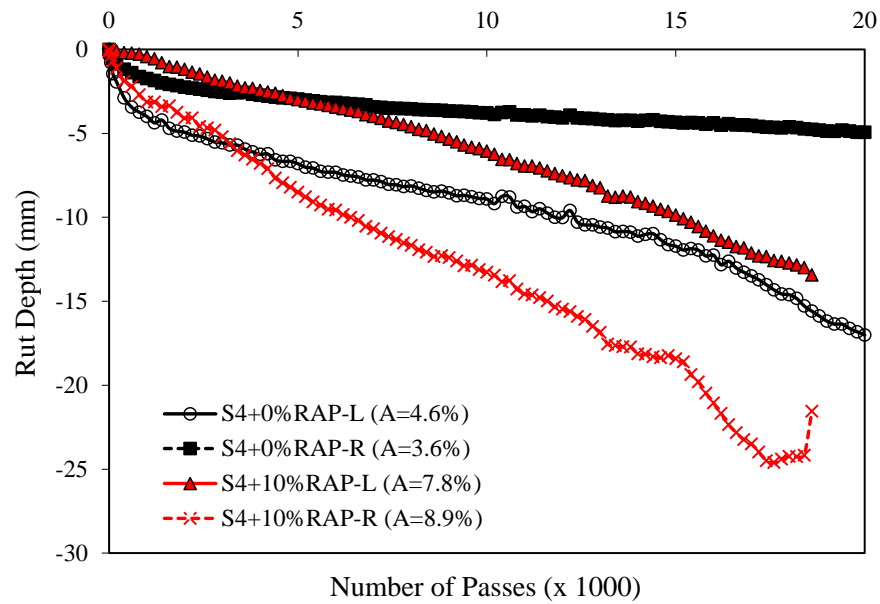
Figure 6.2   Hamburg Curves of S4 Mixes with RAP1.
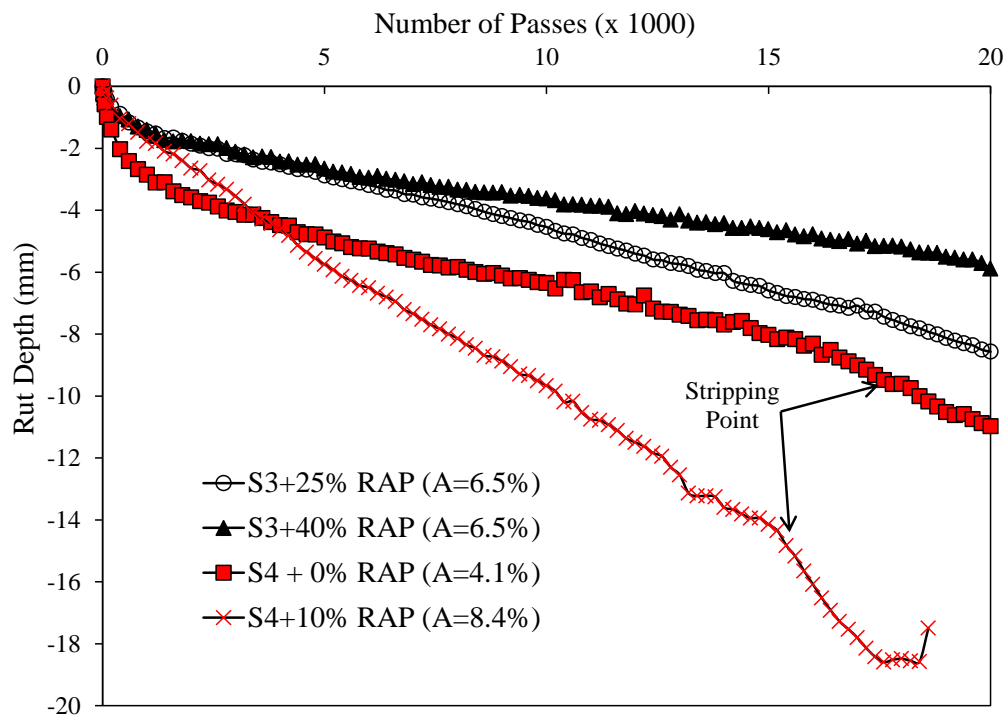
Figure 6.3   Average Hamburg Curves of S3 and S4 Mixes with RAP1.

6.1.2.2   Fatigue Life

Fatigue cracking as a result of repetitive stress and strain caused by traffic and environmental effects is considered a primary distress mechanism in asphalt pavements. Therefore, fatigue performance of the asphalt pavement is an important design parameter. Although existing design standards aim to ensure the quality of the HMA, the fatigue performance of HMA mixes containing RAP is not well understood. The mix design procedure currently used in Oklahoma is primarily intended to eliminate mixes that might be susceptible to rutting and moisture damage and fatigue performance is not directly evaluated in the mix design process. The fatigue life of an asphalt mix is its ability to withstand the repeated traffic loads without failure. Fatigue cracking becomes more important when RAP materials are used in producing HMA mixes. Historically it is believed that the use of RAP which contains aged binder will result in a brittle mix and therefore it is expected to be more prone to fatigue cracking. Therefore, the primary purpose of conducting fatigue tests in this project was to evaluate the effects of RAP content and gradation on the fatigue life of the HMA.

Four point beam fatigue tests (FTG) were conducted in OU Broce Asphalt Laboratory using a newly purchased high end Asphalt Mix Performance Tester (AMPT). This test was used as a valuable tool for accelerated laboratory testing of asphalt mixes for fatigue life under controlled-strain conditions. In this study, FTG tests were conducted according to the AASHTO T 321 test method, on two types of asphalt mixes: laboratory compacted and field compacted, asphalt beam samples. The slab samples collected from the field (from RAP 1 Site) were transported to the Broce Asphalt Laboratory and were cut to the desired beam size in accordance with the size requirements indicated in the AASHTO T321 test method. Collection of the slab samples from RAP 2 Site was found not to be feasible. Hence, the asphalt mixes collected from the RAP 2 Site was used for compaction of the slabs, using a linear kneading compactor. Compacted slabs were then cut to the desired sizes to obtain beam samples. FTG tests were conducted under a constant strain mode on the beam

samples. Flexural stiffness was measured at the beginning of the test (average stiffness from the first 50 cycles) and the stiffness decay at 50% of initial stiffness was targeted as the test termination criterion. The number of cycles giving 50% of initial stiffness was reported as the fatigue failure cycle.

Table 6.1 shows the FTG test results, conducted on the asphalt beam samples from the RAP 1 Site. As indicated in Table 6.1, the tests were conducted at a temperature of 20°C and at a constant frequency of 10 Hz. All the tests were conducted under a constant strain level of 300 micro strains. However, the FTG tests on the S3-40% RAP 1 mix was conducted at 200 micro strains, due to the limitations in the number of available samples. From Table 6.1, it is evident that S4-10% RAP 1 mix showed a higher average fatigue life (367,095 cycles, approximately 32%) compared to that of the S4-10% RAP 1 mix (279,071 cycles).

While interpreting the FTG results, the difference in air voids between these two mixes should also be taken into account. The beam samples prepared from the S4-0% RAP 1 mix have an average air voids of 3.8%. The corresponding air voids for beam samples prepared from the S4-10% RAP 1 mix was much higher (7.1%). Therefore, an improvement in the fatigue life is expected with the addition of 10% RAP 1 to the S4-0 mix if the samples have similar air voids.

Table 6.1   Fatigue Test Results Conducted on the Asphalt Mixes with RAP1

Mix Type	Sample No.	Air Voids (%)	Strain Level (µe)	T (°C)	f (Hz)	Initial Stiffness (MPa)	AASHTO - Failure Cycles @50% Initial	Average Failure Cycles @50% Initial Stiffness	COV (%)
S4-0% RAP1	S4-0-2-2	3.8	300	20	10	5486	261,705	279,071	9.3
	S4-0-4-1	3.8	300	20	10	5875	308,888		
	S4-0-4-2	3.7	300	20	10	5826	266,620		
S4-10% RAP1	S4-10-6-2	7.6	300	20	10	4549	375,910	367,095	22.3
	S4-10-7-1	7.0	300	20	10	4272	281,200		
	S4-10-7-2	6.8	300	20	10	3872	444,175		
S3-25% RAP1	S lab 2-1	7.7	300	20	10	4971	700,000	850,000	25.0
	S lab 2-2	6.2	300	20	10	5557	1,000,000		

Mix Type	Sample No.	Air Voids (%)	Strain Level (με)	T (°C)	f (Hz)	Initial Stiffness (MPa)	AASHTO - Failure Cycles @50% Initial	Average Failure Cycles @50% Initial Stiffness	COV (%)
S3-40% RAP1	S lab 1-1	6.1	200	20	10	8110	2,500,000		
	S lab 1-2	6.3	200	20	10	7324	1,700,000	2,433,333	28.9
	S lab 2-1	6.8	200	20	10	7951	3,100,000		

From Table 6.1, it is evident that due to the difference in the FTG testing strain levels between S3-25% RAP 1 and S3-40% RAP 1, no solid conclusions can be made on the effect of using RAP 1 on the fatigue life of S3 mixes. But, it was observed that S3-25% RAP 1 showed even a better fatigue performance (132% higher) compared to that of S4-10% RAP 1. Also, coefficients of variation (COV) of fatigue failure cycles for each mix type are shown in Table 6.1. It was observed that COV varies between 9.3% for S4-0% RAP 1 to 28.9% for S3-40% RAP 1 mix, which is well within the range of observation made by other researchers. Thus, it can be concluded that addition of RAP 1 to the mix has a favorable effect on fatigue life of the tested asphalt mixes from RAP 1 Site.

6.1.3 MEPDG Inputs

6.1.3.1 *Dynamic Modulus*

Table 6.2 summarizes air voids, bulk specific gravity (G_{mb}), maximum specific gravity (G_{mm}) and asphalt content for each E* test specimen. As shown in Table 6.1, two specimens were tested and averaged for each mix. It should also be noted that the air voids of all the specimens were in the range of 7% ± 0.5%, in accordance with the AASHTO TP 62 test method for dynamic modulus. The dynamic modulus values are presented in Tables 6.3 and 6.4. A statistical t-test was conducted on the results of the replicate specimens from each mix to determine the difference between the replicates. The results of the t-test show that there are no significant differences between the

replicate specimens (t-test ≥ 0.05). Plots generated from the dynamic modulus test results are presented in Figures 6.4 through 6.7.

It is evident from Table 6.3 (also from Figures 6.4 and 6.5) and Table 6.4 (also from Figures 6.6 and 6.7) that the dynamic modulus increases as the loading frequency increases, while it decreases as the testing temperature increases. For example, for the S3-25 mix, the dynamic modulus (E^*) values increase from 1002 psi (at 0.1 Hz) to 1860 psi (at 25 Hz) at a temperature of 40 °F, while it decreases from 2368 psi (at -0.4 °F) to 153 psi (at 130°F) at a constant frequency of 25Hz. This behavior is consistent with the observations made by Flintsch et al. (2008).

Table 6.2   Summary of Volumetric Characteristics of Specimens Tested for Dynamic Modulus with RAP1 at Project on York Drive

Mix Type	Specimen Number	Air Void (%)	G_{mm}	G_{mb}	Asphalt Content (%)
S3-25	#1	7.329	2.546	2.359	4.4
	#2	7.091		2.365	
S3-40	#1	6.878	2.535	2.377	4.7
	#2	7.147		2.354	
S4-0	#1	6.742	2.496	2.328	5.1
	#2	6.627		2.331	
S4-10	#1	6.772	2.498	2.329	5.3
	#2	6.976		2.324	
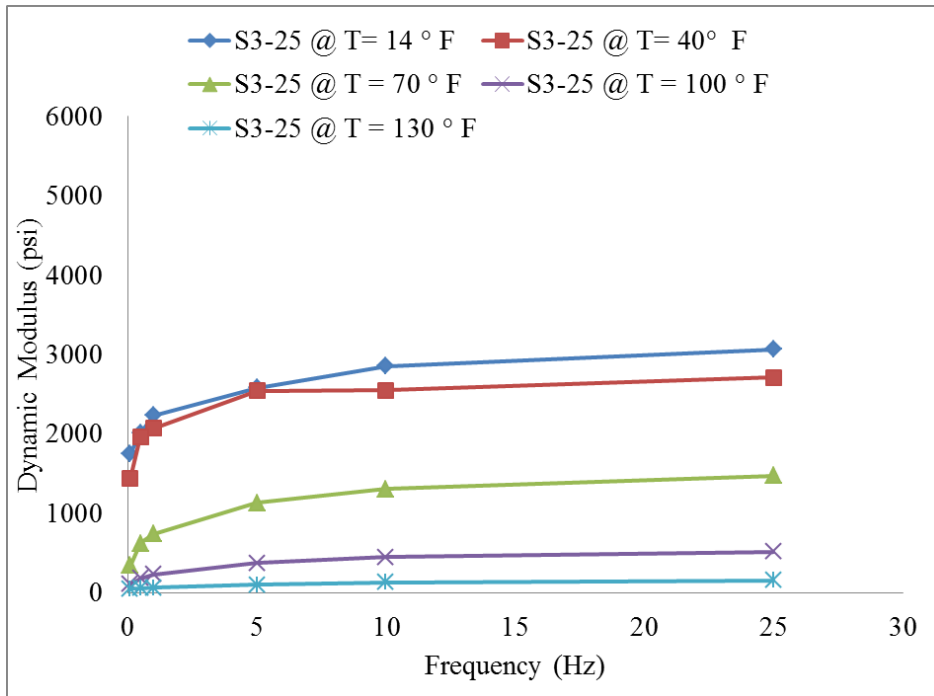
Figure 6.4   Plot of Average Dynamic Moduli for S3-25 Mix with RAP1.

Table 6.3   Dynamic Moduli of S3-25 and S3-40 Mixes with RAP1

Temp. (°F)	Freq. (Hz)	S3-25 Sample #1 (ksi)	S3-25 Sample #2 (ksi)	S3-25 Average (ksi)	S3-40 Sample #1 (ksi)	S3-40 Sample #2 (ksi)	S3-40 Average (ksi)
14	25	2368	3756	3062	5504	5512	5508
	10	2125	3578	2852	5337	5297	5317
	5	2223	2938	2580.5	5049	5077	5063
	1	2009	2456	2233	4543	4614	4579
	0.5	1915	2098	2007	4748	4242	4495
	0.1	1730	1770	1750	3657	3631	3644
40	25	1860	3559	2710	3429	3632	3531
	10	1721	3370	2546	3181	3475	3328
	5	1819	3271	2545	2952	3193	3073
	1	1522	2614	2068	2741	2624	2683
	0.5	1379	2544	1962	2337	2439	2388
	0.1	1002	1888	1445	1921	1664	1793
70	25	1284	1662	1473	1744	2027	1885.5
	10	1158	1451	1305	1652	1592	1622
	5	1082	1177	1130	1527	1446	1487
	1	735	747	741	1098	1080	1089
	0.5	632	616	624	850	943	897
	0.1	361	321	341	464	492	478
100	25	532	496	514	647	428	538
	10	445	449	447	581	331	456
	5	371	374	373	476	279	378
	1	236	227	232	301	165	233
	0.5	182	181	182	232	129	181
	0.1	105	108	107	143	85	114
130	25	153	160	157	190	191	191
	10	125	134	130	139	149	144
	5	101	99	100	114	114	114
	1	65	62	64	73	73	73
	0.5	56	54	55	59	68	64
	0.1	50	44	47	52	51	52
t-test Results Between Two Sets		0.130 (S3-25; Samples #1 and #2)			0.961 (S3-40; Samples #1 and #2)		

Table 6.4   Dynamic Moduli of S4-0 and S4-10 Mixes with RAP1

Temp. (°F)	Freq. (Hz)	S4-0 Sample #1 (ksi)	S4-0 Sample #2 (ksi)	S4-0 Average (ksi)	S4-10 Sample #1 (ksi)	S4-10 Sample #2 (ksi)	S4-10 Average (ksi)
14	25	3902	2972	3437	4323	4303	4313
	10	3721	2939	3330	4260	4236	4248
	5	3713	2870	3292	4002	4026	4014
	1	3117	2581	2849	3957	3956	3957
	0.5	2998	2469	2734	3858	3864	3861
	0.1	3247	2059	2653	3718	3785	3751.5
40	25	1611	2143	1877	2882	2661	2772
	10	1587	2040	1814	2707	2565	2636
	5	1443	1959	1701	2455	2535	2495
	1	1199	1533	1366	2084	2054	2069
	0.5	1052	1369	1211	1908	1754	1831
	0.1	675	908	792	1346	1332	1339
70	25	818	930	874	1213	1331	1272
	10	716	897	807	1098	1101	1099.5
	5	617	710	664	1030	1122	1076
	1	424	493	459	668	664	666
	0.5	328	395	362	577	489	533
	0.1	188	216	202	326	294	310
100	25	255	268	262	418	424	421
	10	203	221	212	328	355	341.5
	5	154	176	165	265	296	281
	1	88	101	95	153	174	163.5
	0.5	66	83	75	122	136	129
	0.1	47	56	52	84	94	89
130	25	57	84	71	156	133	145
	10	47	64	56	125	101	113
	5	35	50	43	111	87	99
	1	24	34	29	70	56	63
	0.5	15	28	22	56	47	52
	0.1	17	24	21	37	39	38
t-test Results Between Two Sets		0.854 (S4-0; Samples #1 and #2)			0.978 (S4-10; Samples #1 and #2)		
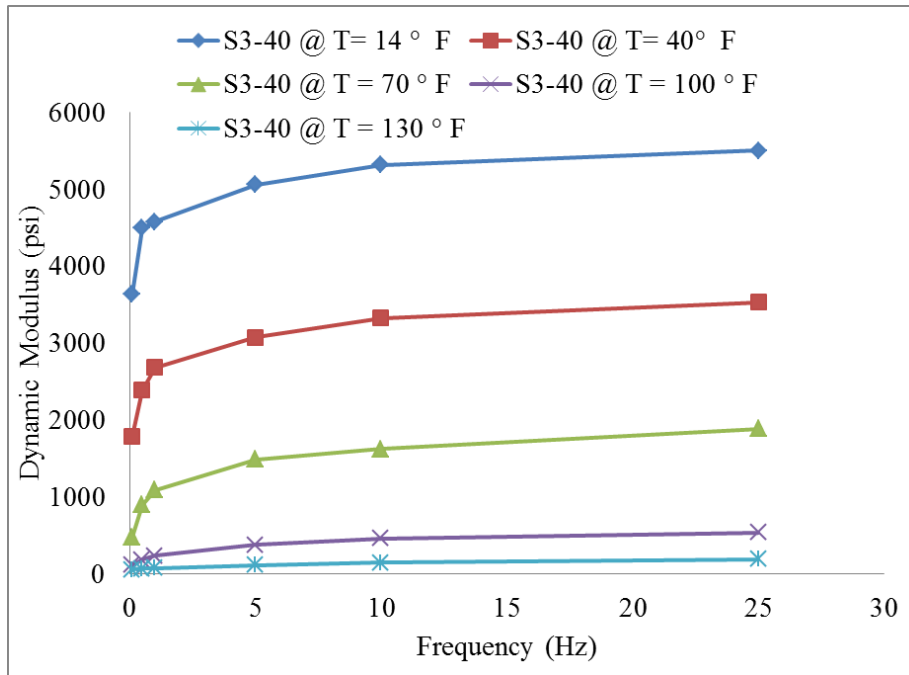
Figure 6.5   Plot of Average Dynamic Moduli for S3-40 Mix with RAP1.
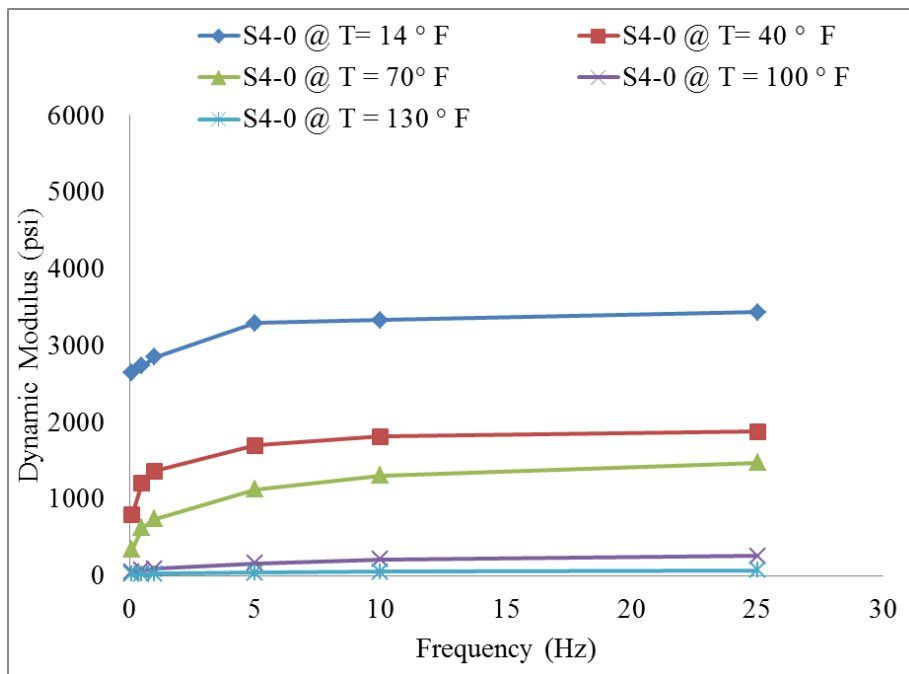
Figure 6.6   Plot of Average Dynamic Moduli for S4-0 Mix with RAP1.
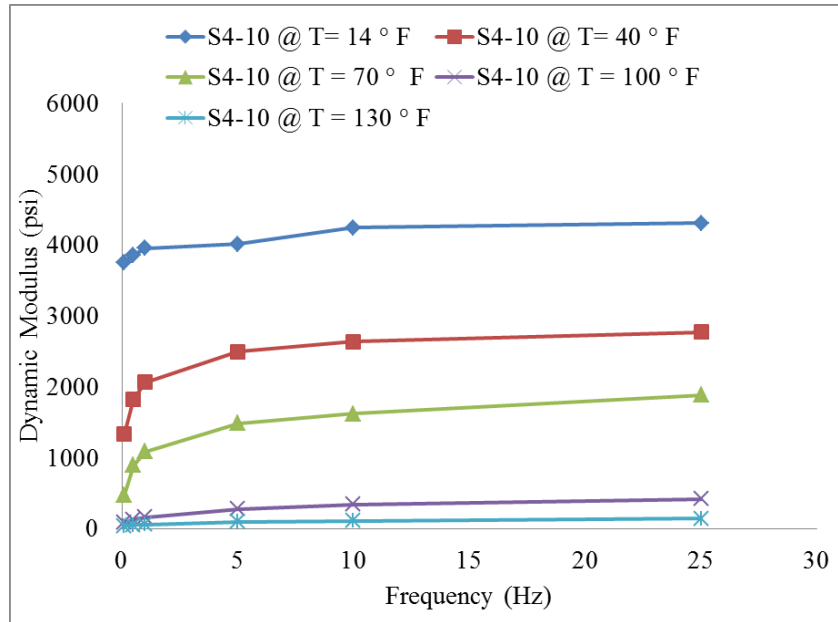
Figure 6.7   Plot of Average Dynamic Moduli for S4-10 Mix with RAP1.

The master curves for dynamic modulus were developed based upon the procedure described in Chapter 3. The master curves for S3 mixes (S3-25 and S3-40) and S4 mixes (S4-0 and S4-10) are plotted in Figures 6.8 and 6.9, respectively. From Figure 6.8, it is generally evident that the dynamic modulus of the mix containing 40% RAP (S3-40) is higher than that of the mix containing 25% RAP (S3-25). For example, the S3-40 mix produced dynamic modulus values approximately 35%, 40% and 65% higher at a reduced frequency of 10^{-7}, 1 and 10^{7} Hz, respectively, as compared to the corresponding S3-25 mix. This same trend is also evident in Figure 6.9, where the dynamic modulus of the mix containing 10% RAP (S4-10) is found to be higher than that of the mix containing 0% RAP (S4-0). For example, the S4-10 mix produced dynamic modulus values approximately 40%, 35% and 42% higher at a reduced frequency of 10^{-7}, 1 and 10^{7} Hz, respectively, as compared to the S4-0 mix. These observations are in agreement with previous results reported by other researchers (e.g., Stroup-Gardiner and Wagner, 1999; Li et al., 2008; McGraw et al., 2010). The master curves represent the stiffness of the material for a wide range of loading frequencies (or loading times, equivalently). The master curve of the dynamic modulus as a function of time (or frequency) describes the time (or loading rate) dependency of the material. The amount

of shifting at each temperature, required to form the master curve, depicts the temperature dependency of the HMA.
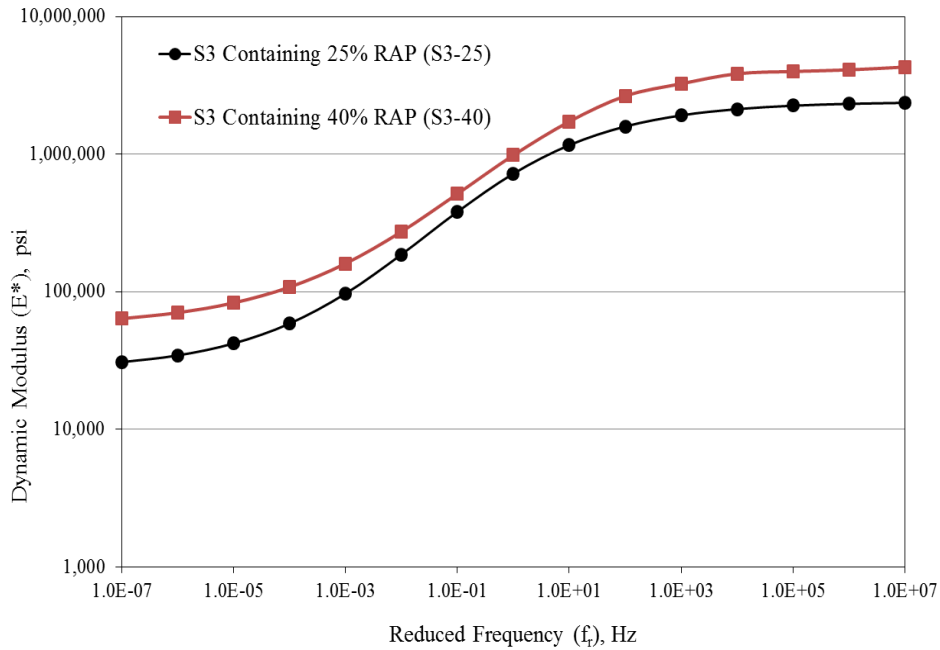
Figure 6.8   Comparison of Dynamic Moduli for S3-25 and S3-40 Mixes with RAP1.
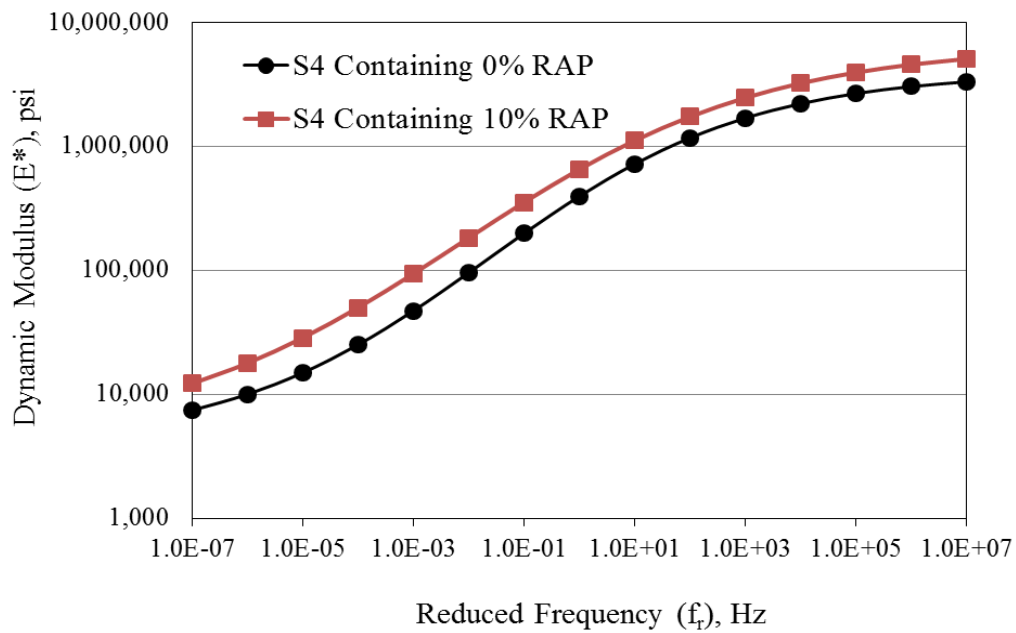
Figure 6.9   Comparison of Dynamic Moduli for S4-0 and S-10 Mixes with RAP1.

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The log of shift factors used for developing the master curves of S3 mixes (S3-25 and S3-40) and S4 mixes (S4-0 and S4-10) are presented in Figures 6.10 and 6.11, respectively. It is clear from Figures 6.10 and 6.11 that S3-25 and S3-40 mixes had similar magnitude (± 0.1) of shift factors up to the reference temperature (21.1°C). Above this reference temperature, the S3-40 mix exhibited a higher magnitude of shift factor as compared to the S3-25 mix at a comparable temperature. Below the reference temperature, the shift factors for S4 mixes exhibited a higher magnitude of shift for mixes with lower percentage of RAP (S4-0) (Figure 6.11). However, the shift factors of S4 mixes did not follow any particular trend above the reference temperature. Some researchers have reported that the differences between the modulus values due to RAP are more pronounced at higher temperature or lower frequencies (e.g., Li et al., 2008).
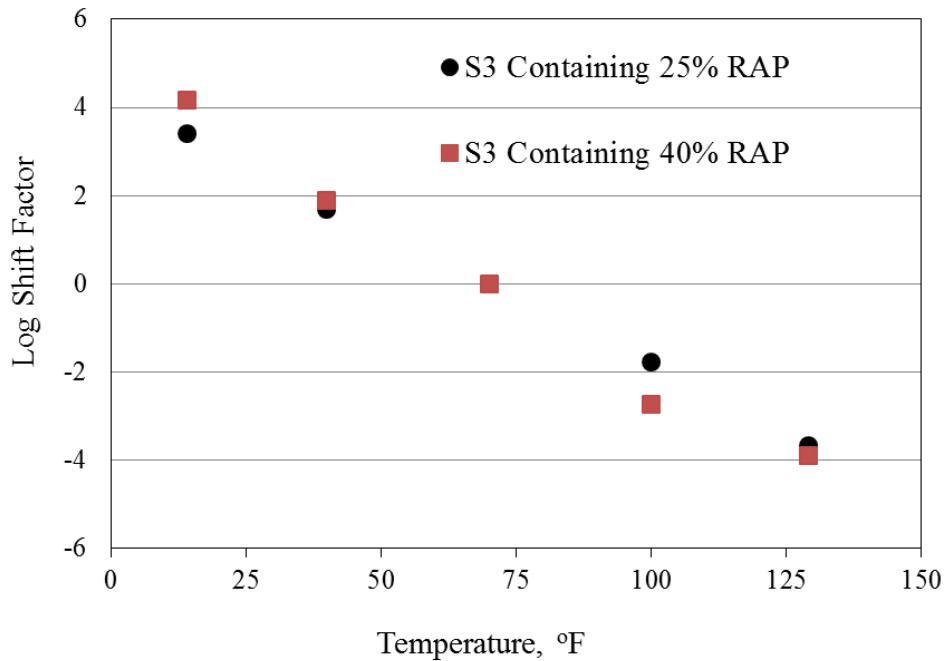
Figure 6.10 Comparison of Shift Factor Used for Generating Master Curves for S3-25 and S3-40 mixes with RAP1.
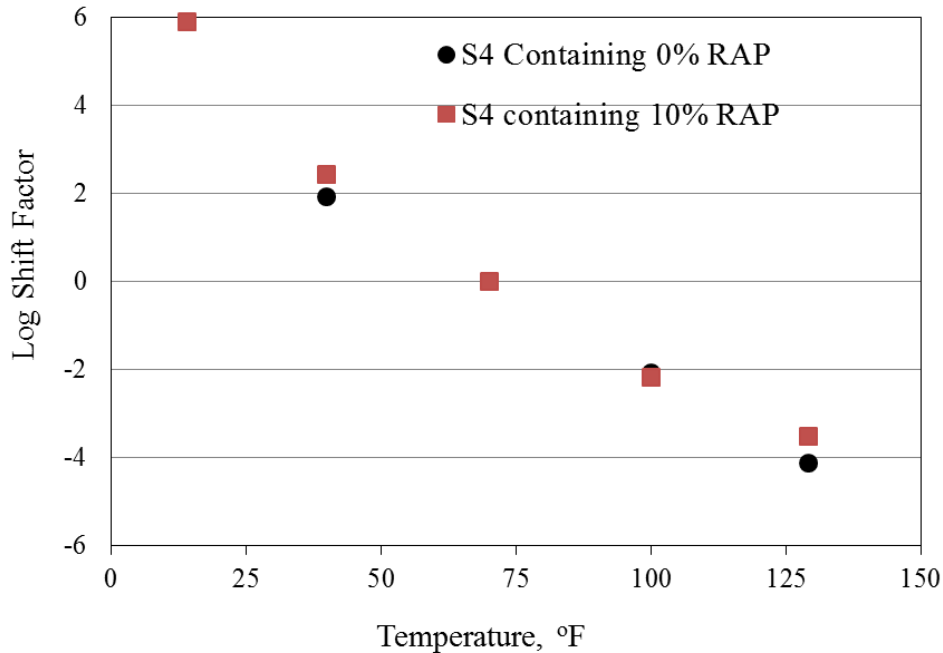
Figure 6.11 Comparison of Shift Factor Used for Generating the Master Curves for S4-0 and S4-10 Mixes with RAP1.

6.1.3.2 *Creep Compliance*

As noted earlier, the creep compliance test has been adopted in the M-EPDG to describe the mechanical behavior of HMA at low-temperature. It is the primary input for predicting thermal cracking in asphalt pavements over their service lives. In order to achieve the Level 1 M-EPDG design, creep compliance tests were conducted at -0.4°F, 14°F, 32°F, and 50°F (-18°C, -10°C, 0°C, and 10°C) on cylindrical cores having a diameter of 6.0 in. (150 mm) and a height of 1.8 in. (45 mm), in accordance with the AASHTO T 322 test method. The cylindrical cores used for the creep compliance were sawed from the cores extracted from the test site, as described in Chapter 3. Table 6.5 summarizes air voids, bulk specific gravity (G_{mb}), and maximum specific gravity of each creep compliance test specimen. As shown in Table 6.5, two replicates were tested for each mix. The creep compliance values at different loading times (i.e., 2 s, 5 s, 10 s, 20 s, 50 s, and 100 s) are presented in Table 6.6 through Table 6.9. A statistical t-test was conducted on the results of the two duplicate specimens of each mix to determine the difference between the replicates. The results from the t-test show that there is no

significant difference between duplicate specimens (t-test ≥ 0.05), except for the S3-40 mix at -0.4^{o}F (-18°C). The low level of confidence observed within the duplicate specimens of the S3-40 mix could be partly attributed to the relatively small deflections (4.84 x10^{-7} in. to 9.03x10^{-7} in.) at -0.4^{o}F (-18°C). Plots generated for the creep compliance test results are presented in Figures 6.12 through 6.17.

Table 6.5   Air Voids, G_{mb}, and G_{mm} of Specimens Tested for Creep Compliance of Project on York Drive

Mix Type	RAP Cont. (%)	Sample Number	Air voids (%)	G_{mb}	G_{mm}
S3	25	#1	5.56	2.416	2.546
S4	25	#2	5.48	2.345	
S4	40	#1	5.67	2.403	2.535
S4	40	#2	6.01	2.394	
S4	0	#1	5.95	2.35	2.496
S4	0	#2	6.48	2.323	
S4	10	#1	6.51	2.325	2.498
S4	10	#2	6.47	2.327	

Table 6.6   Creep Compliance (D(t) in 1/psi) values for S3-25 Mix with RAP1

Time (Sec)	D(t) at T = -0.4°F; Sample 1	D(t) at T = -0.4°F; Sample 2	D(t) at T = 14°F; Sample 1	D(t) at T = 14°F; Sample 2	D(t) at T = 32°F; Sample 1	D(t) at T = 32°F; Sample 2	D(t) at T = 50°F; Sample 1	D(t) at T = 50°F; Sample 2
2	4.84E-07	6.46E-07	5.89E-07	6.77E-07	9.19E-07	8.00E-07	2.34E-06	1.86E-06
5	5.40E-07	6.36E-07	6.03E-07	6.77E-07	1.03E-06	9.70E-07	3.09E-06	2.33E-06
10	5.51E-07	7.37E-07	6.87E-07	7.69E-07	1.19E-06	1.13E-06	3.92E-06	3.21E-06
20	5.73E-07	7.57E-07	8.00E-07	9.26E-07	1.38E-06	1.38E-06	4.91E-06	4.31E-06
50	6.28E-07	8.17E-07	8.54E-07	9.91E-07	1.92E-06	1.86E-06	6.95E-06	6.58E-06
100	6.95E-07	9.38E-07	1.06E-06	1.18E-06	2.41E-06	2.36E-06	9.35E-06	9.02E-06
Avg.	5.78E-07	7.55E-07	7.66E-07	8.70E-07	1.48E-06	1.42E-06	5.09E-06	4.55E-06
Stdev	7.38E-08	1.13E-07	1.80E-07	1.99E-07	5.77E-07	5.93E-07	2.63E-06	2.76E-06
t-test	0.08 (T=0.4°F; Sample #1 and #2)		0.37 (T=14°F; Sample #1 and #2)		0.87 (T=32°F; Sample #1 and #2)		0.74 (T=50°F; Sample #1 and #2)	

Table 6.7   Creep Compliance (D(t) in 1/psi) values for S3-40 Mix with RAP1

Time (Sec)	D(t) at T = -0.4°F; Sample 1	D(t) at T = -0.4°F; Sample 2	D(t) at T = 14°F; Sample 1	D(t) at T = 14°F; Sample 2	D(t) at T = 32°F; Sample 1	D(t) at T = 32°F; Sample 2	D(t) at T = 50°F; Sample 1	D(t) at T = 50°F; Sample 2
2	6.64E-07	4.00E-07	6.40E-07	4.82E-07	9.26E-07	9.71E-07	1.81E-06	1.37E-06
5	7.04E-07	4.41E-07	7.28E-07	5.70E-07	1.14E-06	1.01E-06	2.33E-06	2.33E-06
10	6.95E-07	4.54E-07	7.72E-07	6.09E-07	1.26E-06	1.15E-06	2.93E-06	2.44E-06
20	7.83E-07	5.22E-07	8.59E-07	6.57E-07	1.44E-06	1.39E-06	3.67E-06	2.87E-06
50	8.23E-07	5.66E-07	9.89E-07	7.59E-07	1.90E-06	1.79E-06	5.02E-06	4.29E-06
100	9.04E-07	6.05E-07	1.11E-06	7.88E-06	2.36E-06	2.34E-06	6.75E-06	6.13E-06
Average	7.62E-07	4.98E-07	8.49E-07	6.44E-07	1.50E-06	1.44E-06	3.75E-06	3.24E-06
Stdev	9.12E-08	7.94E-08	1.73E-07	1.16E-07	5.32E-07	5.34E-07	1.85E-06	1.70E-06
t-test	0.03* (T=0.4°F; Sample #1 and #2)		0.08 (T=14°F; Sample #1 and #2)		0.85 (T=32°F; Sample #1 and #2)		0.63 (T=50°F; Sample #1 and #2)	

*Indicate a significant difference between the replicates (t-test <0.05)

Table 6.8   Creep Compliance (D(t) in 1/psi) values for S4-0 Mix with RAP1

Time (Sec.)	D(t) at T = -0.4°F; Sample 1	D(t) at T = -0.4°F; Sample 2	D(t) at T = 14°F; Sample 1	D(t) at T = 14°F; Sample 2	D(t) at T = 32°F; Sample 1	D(t) at T = 32°F; Sample 2	D(t) at T = 50°F; Sample 1	D(t) at T = 50°F; Sample 2
2	4.52E-07	2.91E-07	4.76E-07	8.24E-07	8.02E-07	7.23E-07	2.19E-06	2.64E-06
5	4.92E-07	3.33E-07	5.47E-07	9.41E-07	9.09E-07	8.81E-07	2.78E-06	2.33E-06
10	4.92E-07	3.34E-07	6.55E-07	1.08E-06	1.15E-06	1.09E-06	3.91E-06	4.24E-06
20	6.02E-07	3.97E-07	6.08E-07	1.25E-06	1.38E-06	1.34E-06	5.29E-06	5.51E-06
50	6.26E-07	4.18E-07	9.04E-07	1.56E-07	1.90E-06	2.00E-06	8.05E-06	7.90E-06
100	7.35E-07	4.70E-07	1.05E-06	1.87E-06	2.49E-06	2.84E-06	1.09E-05	1.12E-05
Average	5.67E-07	3.74E-07	7.23E-07	1.25E-06	1.44E-06	1.48E-06	5.53E-06	5.63E-06
Stdev	1.07E-07	6.61E-08	2.16E-07	3.96E-07	4.35E-07	8.04E-07	3.37E-06	3.40E-06
t-test	0.06 (T=0.4°F; Sample #1 and #2)		0.06 (T=14°F; Sample #1 and #2)		0.92 (T=32°F; Sample #1 and #2)		0.96 (T=50°F; Sample #1 and #2)	

Table 6.9   Creep Compliance (D(t) in 1/psi) Values for S4-10 Mix with RAP1

Time (Sec.)	D(t) at T = -.4°F; Sample 1	D(t) at T = -0.4°F; Sample 2	D(t) at T = 14°F; Sample 1	D(t) at T = 14°F; Sample 2	D(t) at T = 32°F; Sample 1	D(t) at T = 32°F; Sample 2	D(t) at T = 50°F; Sample 1	D(t) at T = 50°F; Sample 2
2	3.81E-07	3.11E-07	5.82E-07	3.25E-07	8.73E-07	6.28E-07	1.21E-06	1.17E-06
5	4.06E-07	3.53E-07	6.77E-07	4.05E-07	1.01E-06	7.44E-07	1.68E-06	1.55E-06
10	4.36E-07	3.91E-07	7.28E-07	4.37E-07	1.21E-06	9.25E-07	2.09E-06	2.01E-06
20	4.72E-07	4.05E-07	8.57E-07	4.76E-07	1.49E-06	1.13E-06	2.60E-06	2.71E-06
50	5.02E-07	4.66E-07	1.12E-06	5.80E-07	2.04E-06	1.60E-06	3.88E-06	4.05E-06
100	6.12E-07	5.49E-07	1.39E-06	6.74E-07	2.83E-06	2.17E-06	5.32E-06	5.56E-06
Avg.	4.68E-07	4.12E-07	8.93E-07	4.83E-06	1.58E-06	1.20E-06	2.80E-06	2.84E-06
Stdev	8.26E-08	8.47E-08	3.08E-07	1.26E-07	7.42E-07	5.86E-07	1.54E-06	1.67E-06
t-test	0.28 (T=0.4°F; Sample #1 and #2)		0.06 (T=14°F; Sample #1 and #2)		0.35 (T=32°F; Sample #1 and #2)		0.96 (T=50°F; Sample #1 and #2)	

Table 6.10   Poisson's Ratio for S3 and S4 Mixes with RAP1

Temp (°F)	S3-25; Sample #1	S3-25; Sample #2	S3-40; Sample #1	S3-40; Sample #2	S4-0; Sample #1	S4-0; Sample #2	S4-10; Sample #1	S4-10; Sample #2
-4	0.127	0.125	0.208	0.198	0.213	0.235	0.201	0.211
14	0.146	0.151	0.223	0.235	0.254	0.265	0.238	0.244
32	0.168	0.178	0.235	0.239	0.315	0.378	0.308	0.324
50	0.222	0.236	0.298	0.302	0.321	0.345	0.381	0.375
t-test	0.837 (Sample #1 and #2)		0.935 (Sample #1 and #2)		0.506 (Sample #1 and #2)		0.909 (Sample #1 and #2)	

Table 6.11   Indirect Tensile Strength (psi) for S3 and S4 Mixes with RAP1

Sample Number	S3-25	S3-40	S4-0	S4-10
1	553	390	503	399
2	542	380	515	332
Average	548	385	509	366
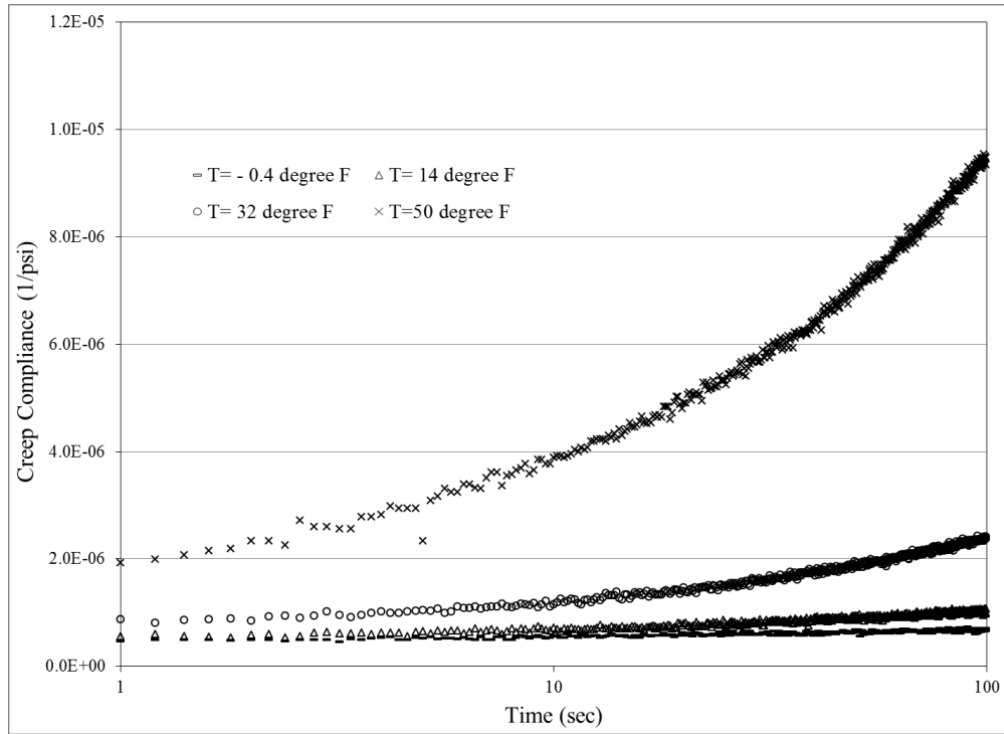
Figure 6.12 Variation of Creep Compliance of S3-25 Mix (RAP1) with Temperature.
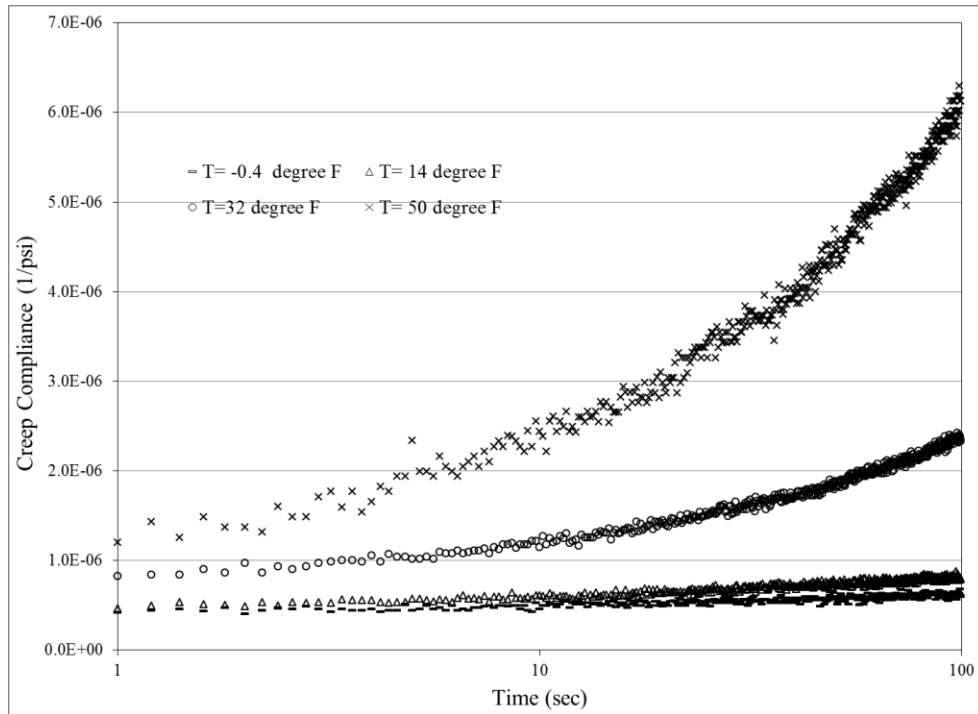
Figure 6.13 Variation of Creep Compliance of S3-40 Mix (RAP1) with Temperature.
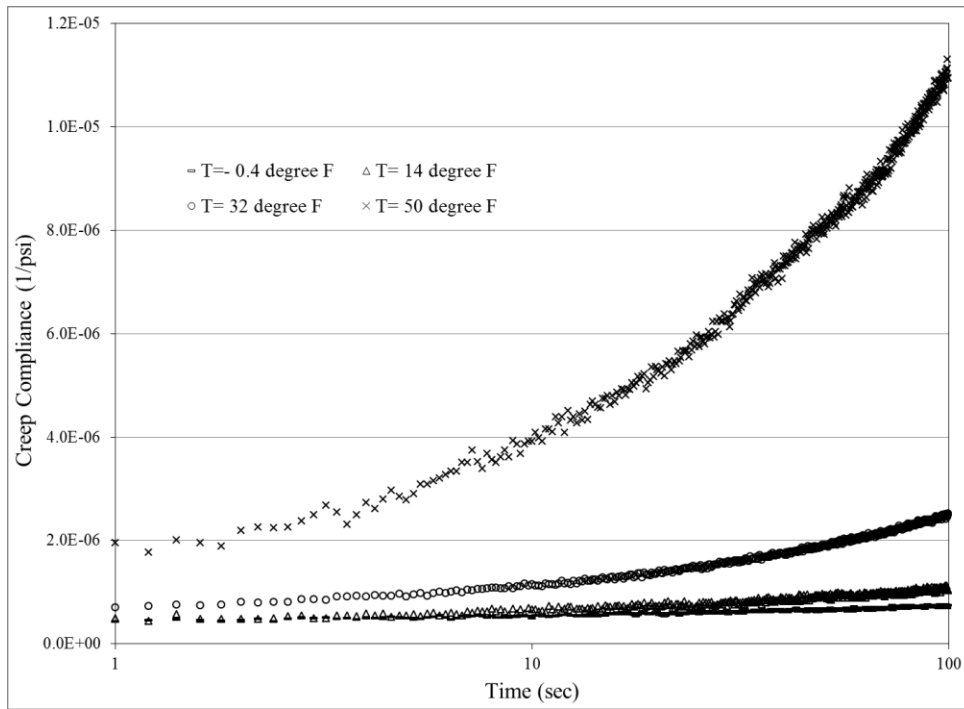
Figure 6.14   Variation of Creep Compliance for S4-0 Mix (RAP1) with Temperature.
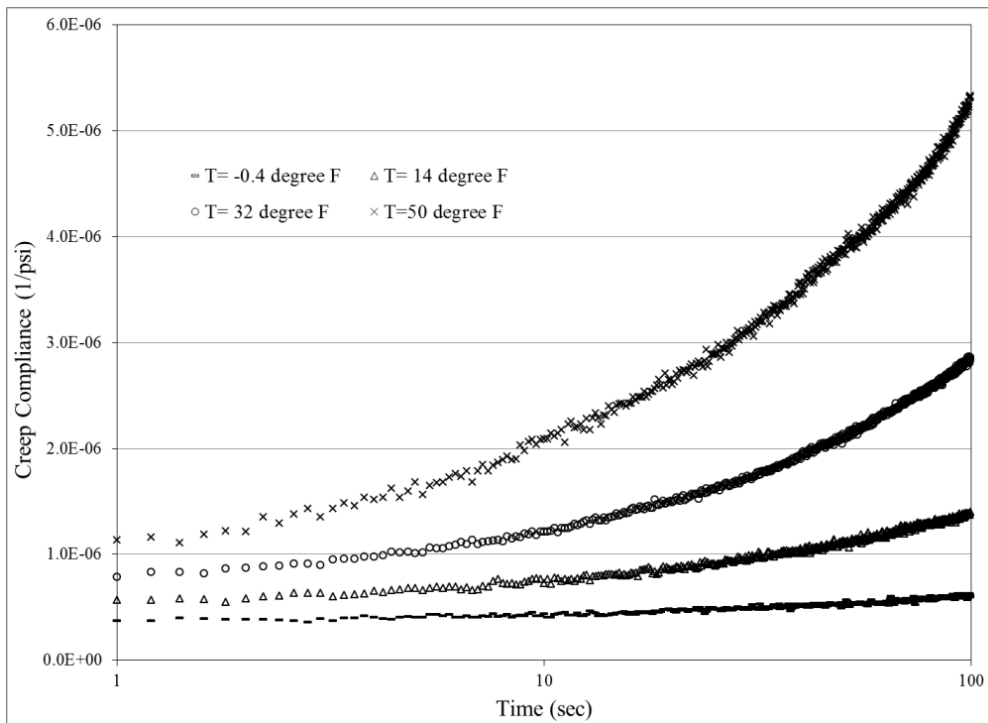
Figure 6.15   Variation of Creep Compliance of S4-10 (RAP1) with Temperature.
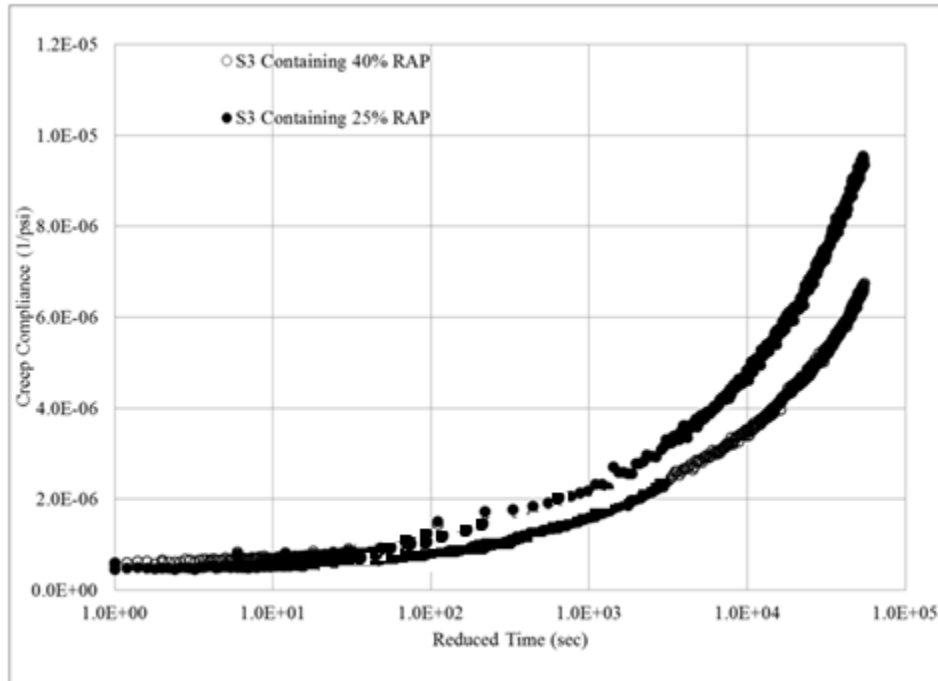
Figure 6.16   Comparison of Creep Compliance Master Curves for S3-25 and S3-40 with RAP1.
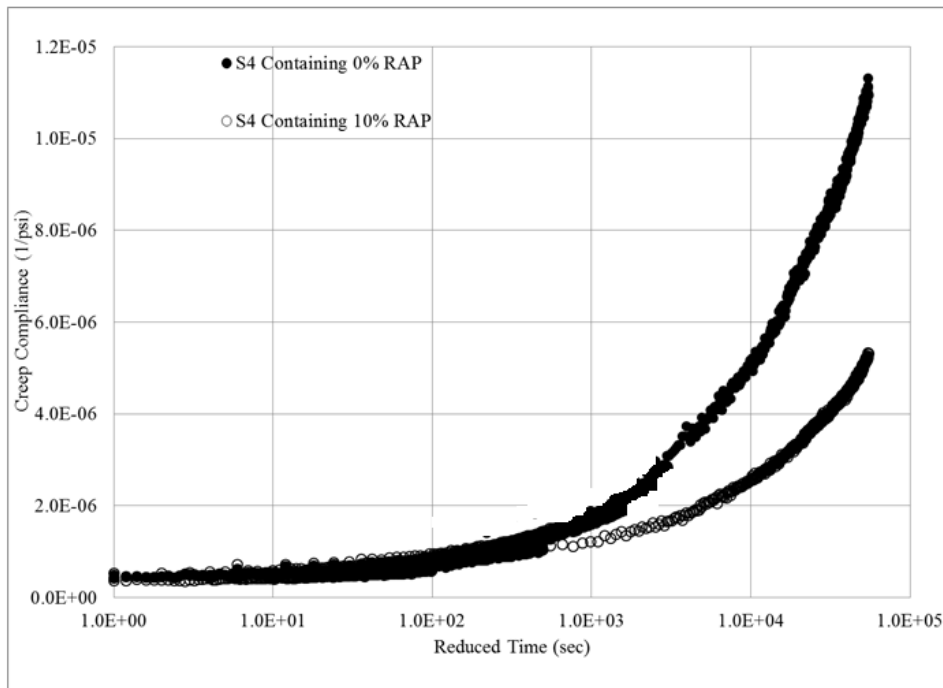
Figure 6.17   Comparison of Creep Compliance Master Curves for S4-0 and S4-10 with RAP1.

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It is evident from Figures 6.12 through 6.15 that creep compliance increases with an increase in temperature, as expected (Richardson and Lusher, 2008; Vargas, 2007). It is also evident from Figures 6.12 and 6.13 that the S3-25 mix is more sensitive to change in temperature as compared to the corresponding higher RAP containing mix (S3-40). For example, an increase in temperature by 82.4 ^{o}F (from -0.4^{o}F to +50°F) increased the creep compliance by approximately 709% and 465% for the S3-25 mix and the S3-40 mix (at 100 seconds), respectively. Also, an increase in temperature by 50°F (from 32°F to +50°F) increased the creep compliance by approximately 550% and 350% for the S3-25 mix and the S3-40 mix (at 100 seconds), respectively. Similarly, S4 mixes containing higher RAP content showed less sensitivity towards temperature (Figures 6.14 and 6.15). For example, an increase in temperature by 82.4^{o}F (from -0.4^{o}F to +50°F) increased the creep compliance by approximately 1730% and 835% for the S4-0 mix and the S4-10 mix (at 100 seconds), respectively.

Master curves for creep compliance were generated for both S3-25 and S3-40 mixes, as well as for both S4-0% and S4-10%, as shown in Figures 6.16 and 6.17, respectively. It is clear from Figure 6.16 that both S3-25 and S3-40 mixes show similar creep compliance values up to a reduced time of 10 seconds (low temperature), beyond which the S3-25 mix started showing higher creep as compared to the S3-40 mix. Also, differences in creep values between the S3-25 and S3-40 mixes are more pronounced at a higher reduced time or temperature. For example, at a reduced time of 100 seconds, the S3-25 mix had approximately 75% higher creep compliance values as compared to the S3-40 mix. However, the percentage difference between the S3-25 and S3-40 mixes increased by 134% at a reduced time of 10,000 seconds. A similar trend was also observed for the S4 mixes (Figure 6.17). For example, at a reduced time of 100 seconds, the S4-0 mix had approximately 30% higher creep compliance values as compared to the S3-40 mix. However, the percent difference between the S3-25 and S3-40 mixes increased by 80% at a reduced time of 10,000 seconds. This behavior of the S3 and S4 mixes with an increase in RAP content of the mixes, is consistent with the observations reported by other researchers (e.g., Daniel and Lachance, 2005;

Richardson and Lusher, 2008; Solanki et al., 2012). This behavior may be attributed to hardness of the binder in the RAP as compared to the virgin binder, thereby increasing the viscosity of the mix.

6.1.3.3   *Poisson's Ratio and Indirect Tensile Strength*

The indirect tensile strength (IDT) of HMA is one of two primary inputs for the low-temperature or thermal cracking module in the new M-EPDG software. IDT is defined as the strength of HMA when subjected to tension. Although Poisson's ratio is not an input in the M-EPDG thermal cracking modulus, it is an input property for asphalt materials in the M-EPDG and can be entered directly or estimated from other properties. Tables 6.10 and 6.11 show the Poisson's ratio and the IDT values in a tabular form. Also, plots of average values of Poisson's ratio and IDT are presented in Figures 6.18 and 6.19, respectively. A statistical t-test was conducted on the Poisson's ratio results from the two duplicate specimens of each mix to determine the difference between the results of the replicate (Table 6.10). The results from the t-test show that there is no significant difference between the results of the duplicate specimens (t-test ≥ 0.05).
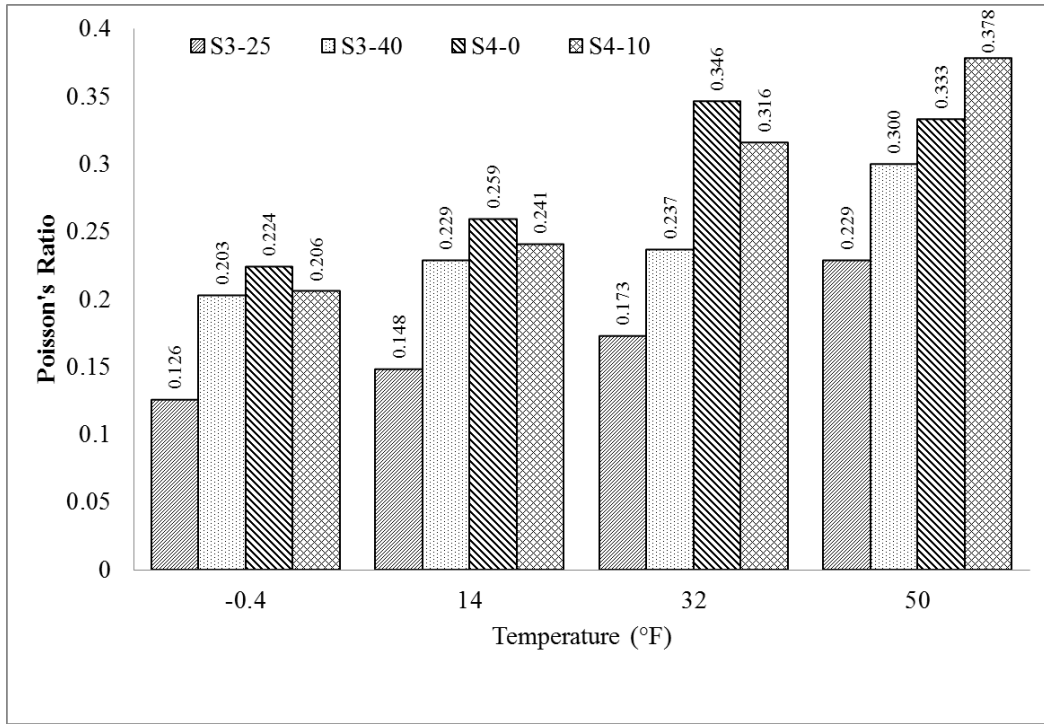
Figure 6.18   Poisson's Ratio of S3-25, S3-40, S4-0, and S4-10 Mixes with RAP1.

It is evident from Table 6.10 and Figure 6.18 that the Poisson's ratio values increase with increasing temperature, as expected (Richardson and Lusher, 2008). The results of the S3 mixes, present an increase in the Poisson's ratio values with an increase in the RAP content. For example, at -4°F, the value of Poisson's ratio increases from 0.127 to 0.208 for the S3-25 and S3-40 mixes, respectively. Comparatively, the results of the S4 mixes show a reduction in the Poisson's ratio values with an increase in the RAP content, except for the results at 50°F. Thus, the RAP content can increase the Poisson's Ratio as it is the case here for the S3 mixes and reported by Richardson and Lusher (2008) or decrease the Poisson's Ratio values of the HMA, as it is the case here for S4 mixes.

It is evident from Table 6.11 and the plots in Figure 6.19 that indirect tensile strength (IDT) in all of the mixes decreased with an increase in the RAP content. This trend is in accordance with results reported by Richardson and Lusher (2008). The results show that the IDT in the S3 mixes is more sensitive to the RAP content than in the S4 mixes. For instance, a 15% increase in RAP content in the S3 mixes and a 10% increase in the S4 mixes, reduces the IDT values by 30% and 27%, respectively.
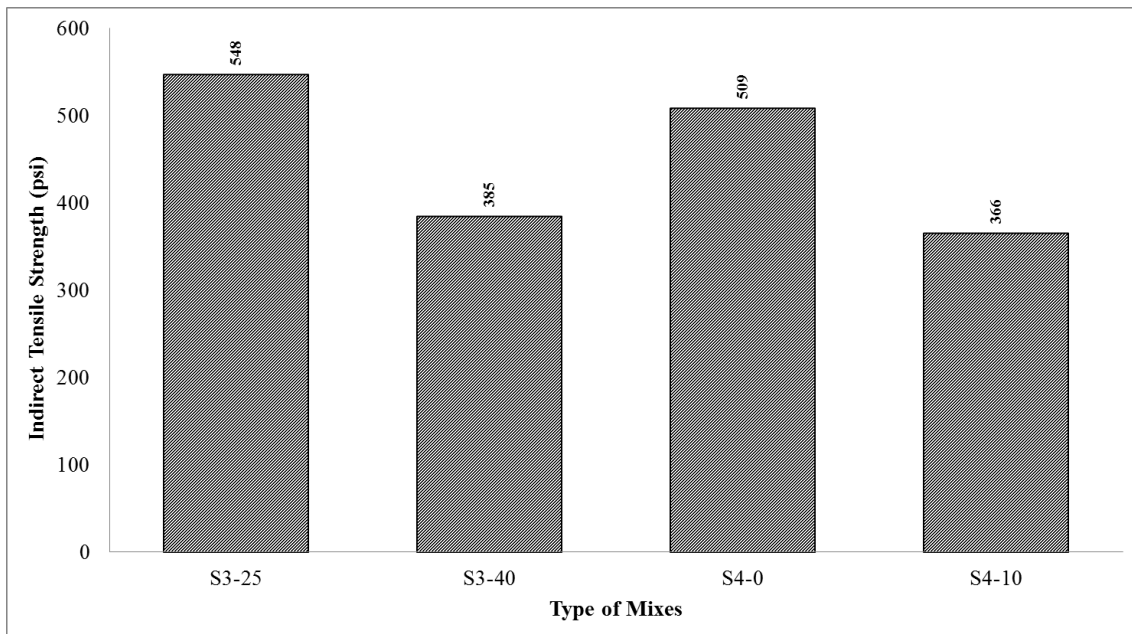
Figure 6.19 Indirect Tensile Strength of S3-25, S3-40, S4-0, and S4-10 Mixes with RAP1 at a Temperature of 14°F.

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6.2   RAP2

6.1.2   **Volumetric Properties**

The collected RAP materials from Site 2 were used for volumetric mix design in accordance with the AASHTO M 323 test method. Similar to Site 1, a total of four mix designs, namely, S3-25, S3-40, S4-0, and S4-10 were developed for Site 2. A total of six and five mix trials were used for developing the volumetric mix designs for the S3-40% RAP2 and S4-10% RAP2 asphalt mixes, respectively. The mix designs for the S3-25% RAP2 and S4-0 RAP2 mixes were provided by Schwarz Paving Co. However, due to construction problems, only S4-25% RAP2 was used in the construction, instead of S4-10% RAP2 and S4-0% RAP2 mixes. The mix design procedure consisted of mixing different percentages of virgin aggregates, virgin binder, and RAP2 satisfying the gradation requirements. The prepared asphalt mix was then conditioned and used to prepare cylindrical samples in the SGC in accordance with the AASHTO T 312 test method. The final trials were found to satisfy the volumetric mix design requirements for the S3-40 and S4-10 mixes. The mixes were designed for an equivalent single axle load (ESAL) level of 0.3 M – 3 M. The final volumetric mix design sheets for S3-25% RAP2, S3-40% RAP2, S4-10% RAP2 and S4-25% RAP2 asphalt mixes are presented in Appendix A (Figures A.12 through A.15).

6.2.2   Mix Performance

6.1.3   *Rut and Moisture Resistance*

The Hamburg Wheel Tracking (HWT) test results for the S3 and S4 mixes tested at different air void contents are presented in Figures 6.20 and 6.21. It is evident from Figure 6.20 and Figure 6.21 that the rut depth of S3-25 mix is higher than that of the S3-40 mix. For example, at 10,000 passes the S3-25 (air voids content = 6.6%) and the S3-40 (air voids content = 6.0%) mixes showed a rut depth of approximately 8.3 and 6.0 mm, respectively. Better rut resistance was observed in the case of the S4-25%RAP2 mix compared to the S3-25%RAP2 mix or the S3-40%RAP2 mix, up to approximately 13,000 wheel passes. For example, at 10,000 passes, the S4-25%RAP2 mix with an air voids content of 7.1% showed a rut depth of 4.4 mm, which is a lower rut values as compared to the S3-25%RAP2 and the S3-40%RAP2 mixes.
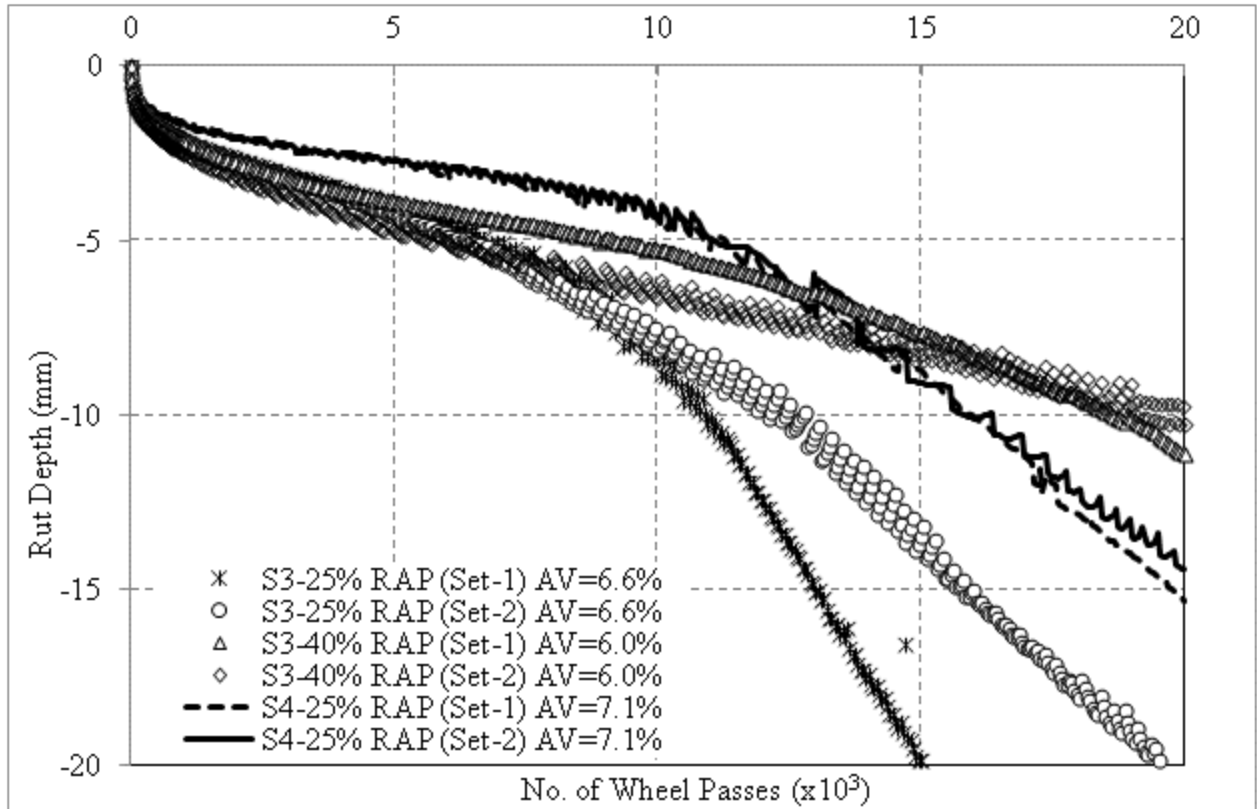
Figure 6.20 Hamburg Curves of S3 and S4 Mixes with RAP2.

Further, for evaluating the moisture damage susceptibility of mixes, according to Figure 6.21, all four characteristic regions are evident in the S3-25%RAP2 and S4-25%RAP2 mixes. The stripping inflection points for the S3-25%RAP2 and S4-25%RAP2 mixes were found approximately 10,567and 10,978 passes, respectively. According to FHWA (2012), an inflection point below 10,000 wheel passes indicates significant moisture damage susceptibility in the mix. No stripping slope and inflection point was observed in the S3-40%RAP2 mix.
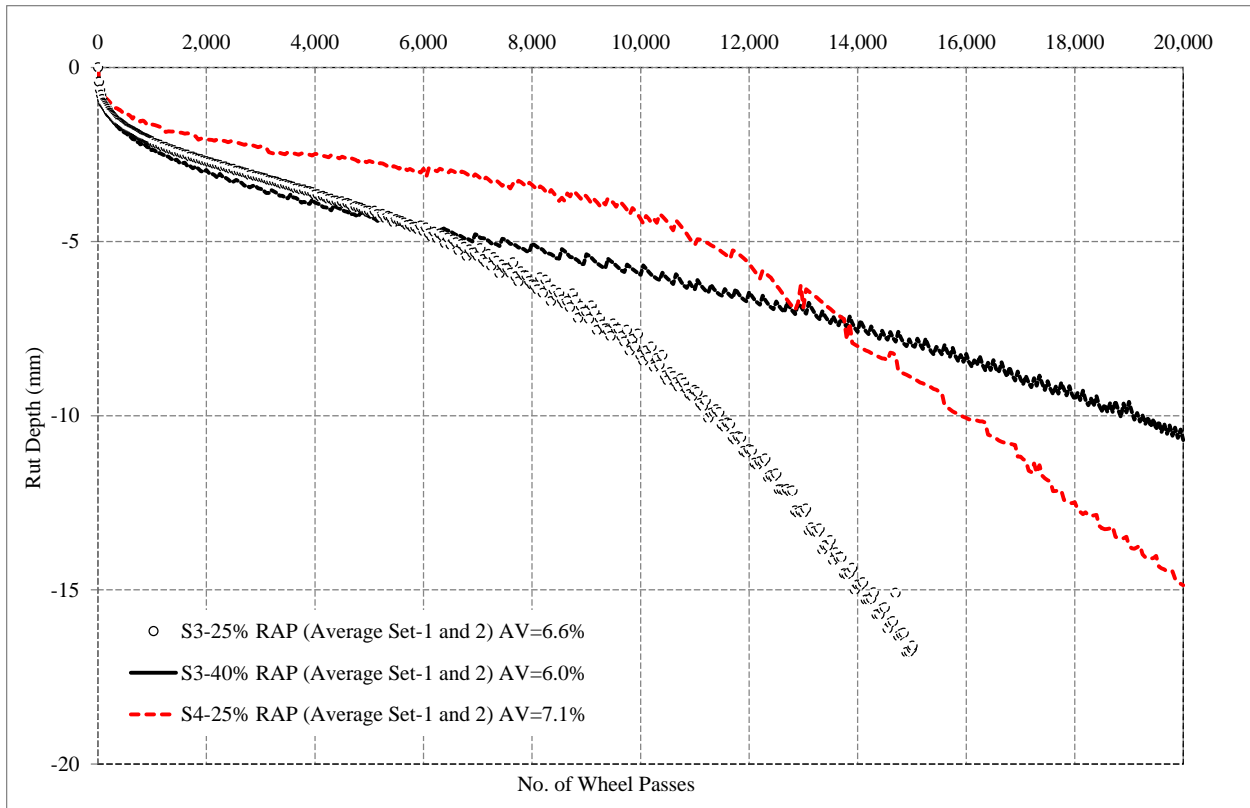
Figure 6.21 Average Hamburg Curves of S3 and S4 Mixes with RAP2.

6.2.3 Fatigue Life

Table 6.12 shows the FTG test results, conducted on the asphalt beam samples compacted from the mixes used at the RAP 2 Site. As indicated in Table 6.12, the tests were conducted at 20°C temperature and at a constant frequency of 10 Hz. All of the FTG tests on mixes from the RAP 2 Site were conducted at a constant strain of 300 micro strains. From Table 6.12, it is evident that S3-25% RAP 2 mix showed an approximately 96% higher average fatigue life (470,981 cycles) compared to that of the S3-40% RAP 2 mix (240,108 cycles). While interpreting the FTG results, the difference in air voids between these two mixes should also be taken into account. The beam samples compacted with the S3-40% RAP 2 have an average air voids of 7.0%. However, this value for beam samples compacted with the S3-25% RAP 2 mix was only 5.5%. Therefore a better fatigue performance observed in the S3-25% RAP 2 may be partially attributed to its lower air voids.

Table 6.12   Fatigue Test Results Conducted on the Asphalt Mixes from RAP 2 Site

Mix	Sample No.	Air Void (%)	Strain Level (με)	T (°C)	f (Hz)	Initial Stiffness (MPa)	AASHTO - Failure Cycles @50% Initial	Average Failure Cycles @50% Initial Stiffness	COV (%)
S4-25% RAP 2	S4-25%-3-1	4.2	300	20	10	8937.4	4,347,246	4,773,623	12.6
	S4-25%-4-1	4.1	300	20	10	8261.1	5,200,000		
S3-25% RAP 2	S3-25%-3-1	5.4	300	20	10	6588.5	453,899	470,981	5.1
	S3-25%-3-2	5.6	300	20	10	6365.5	488,063		
S3-40% RAP 2	S3-40%-5-2	7.3	300	20	10	5816.4	237,236	240,108	1.7
	S3-40%-8-1	6.8	300	20	10	6099.1	242,979		

From Table 6.12 one can say that the average fatigue life of the S4-25% RAP 2 (4,773,623 cycles) is approximately 10 and 20 times higher than those of the S3-40% RAP 2 and the S3-25% RAP 2 mixes, respectively. In other words, favorable effect of addition of RAP 2 on fatigue life of asphalt mixes is more observed in the case of the S4 mixes, compared to that of the S3 mix. Also, the coefficients of variation (COV) of fatigue failure cycles for each mix type are shown in Table 6.12. It was observed that the COV varies between 1.7%, for S3-40% RAP 2 to 12.6% for S4-25% RAP 2 mix, which is well within the range of observations made by other researchers.

6.2.3 MEPDG Inputs

6.2.3.1   Dynamic Modulus

The same testing procedure followed for conducting dynamic modulus testing on the RAP1 mixes was repeated for testing the RAP2 mixes, in accordance with the AASHTO TP 62 test method. The average dynamic modulus values at each testing frequency and temperature are presented in Table 6.13. Plots generated from the dynamic modulus test results are presented in Figures 6.22 through 6.24. From these figures, it is evident that the dynamic modulus increases as the loading frequency increases, while it decreases as the testing temperature increases. For example, for the

S3-25% RAP2 mix, the dynamic modulus (E*) values increase from 1100 ksi (at 0.1 Hz) to 2192 ksi (at 25 Hz) at a temperature of 40°F, while it decreases from 2,905 ksi (at 14 °F) to 148 ksi (at 130°F) at a constant frequency of 25Hz. This behavior is consistent with the observations made by Flintsch et al. (2008).

Table 6.13   Dynamic Moduli (ksi) of S3-25% RAP2, S3-45% RAP2 and S4-25% RAP2 Mixes

Mix Type	Frequency (Hz)	At 14°F	At 40°F	At 70°F	At 100°F	At 130°F
S3-25% RAP2	25	2905	2192	1239	475	148
	10	2812	2067	1037	358	114
	5	2735	1937	933	300	88
	1	2537	1596	640	180	52
	0.5	2443	1441	540	143	42
	0.1	2206	1100	335	97	36
S3-40% RAP2	25	6736	4360	2066	789	226
	10	6248	3553	1510	609	170
	5	5870	3327	1190	506	124
	1	4976	2853	885	331	83
	0.5	4590	2654	744	266	64
	0.1	3713	1978	463	170	42
S4-25% RAP2	25	3569	2146	1040	563	230
	10	3275	1903	861	427	181
	5	3055	1784	768	368	151
	1	2559	1482	539	236	99
	0.5	2354	1316	451	194	82
	0.1	1907	1107	294	137	59
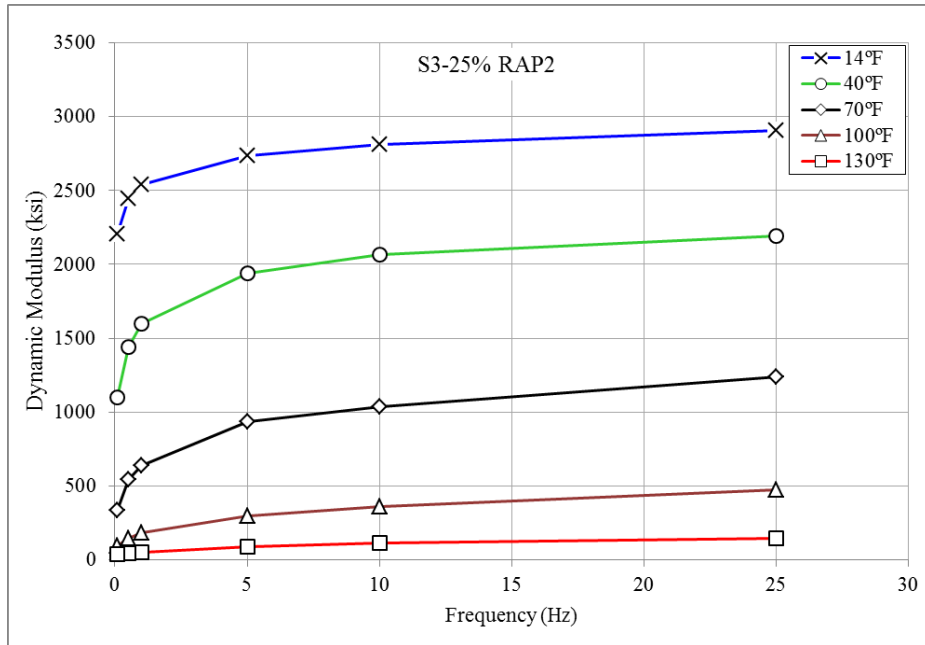
Figure 6.22   Plot of Average Dynamic Moduli for S3-25% RAP2 Mix.
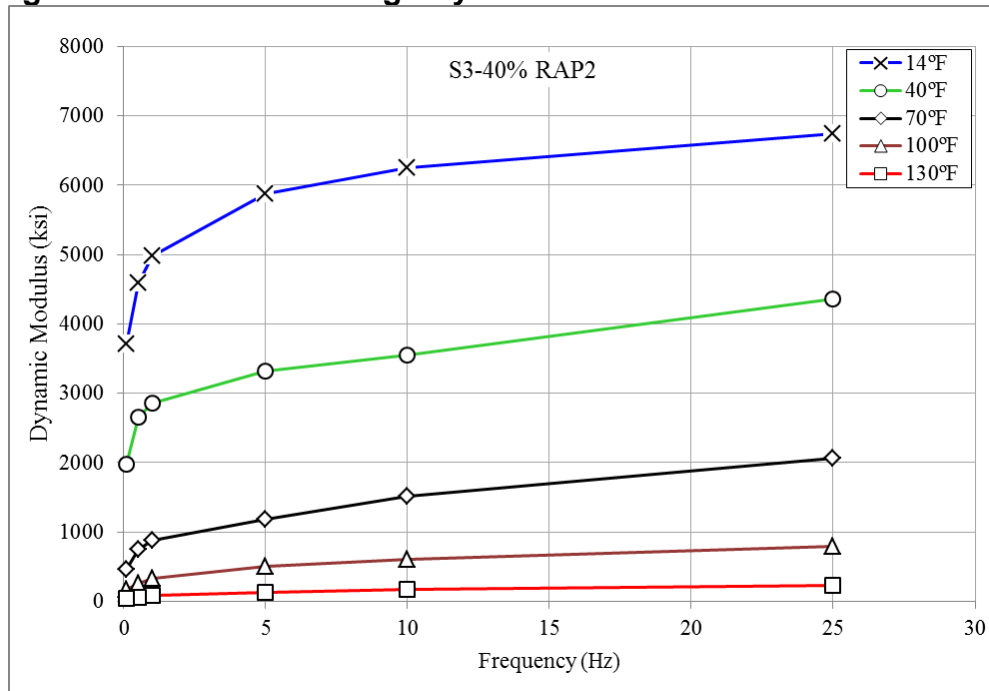
Figure 6.23   Plot of Average Dynamic Moduli for S3-40% RAP2 Mix.
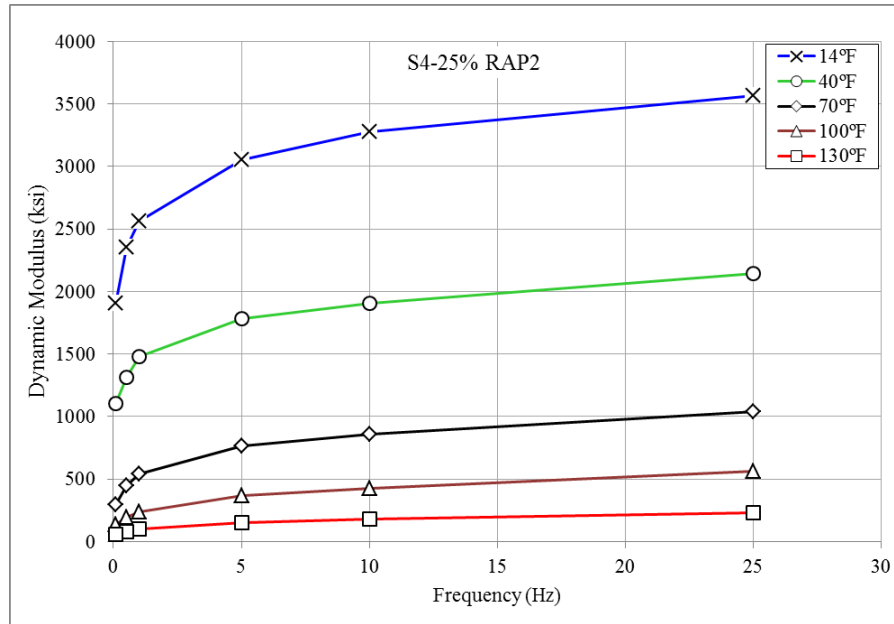
Figure 6.24 Plot of Average Dynamic Moduli for S4-25% RAP2 Mix.

The master curves for dynamic modulus were developed based upon the procedure described in Chapter 3. The master curves for the S3 mixes (S3-25% RAP2 and S3-40% RAP2) and the S4 mix (S4-25%RAP2) are plotted in Figures 6.25 and 6.26, respectively. It is evident that the dynamic modulus of the mix containing 40% RAP (S3-40% RAP2) is higher than that of the mix containing 25% RAP (S3-25% RAP2). However, this difference reduces at lower frequencies. This is attributed to the effect of aggregate type and shape which become dominant at a lower frequency (equivalent to higher temperature). For example, the S3-40% RAP2 mix produced dynamic modulus values approximately 26%, 68% and 90% higher at a reduced frequency of 0.1, 10 and 100 Hz, respectively, as compared to the corresponding S3-25% RAP2 mix. These observations are in agreement with previous results reported by other researchers (e.g., Stroup-Gardiner and Wagner, 1999; Li et al., 2008; McGraw et al., 2010). The master curves represent the stiffness of the material for a wide range of loading frequencies (or loading times, equivalently). Also, it was observed that the master curves developed for the S3-25% RAP2 and the S4-25% RAP2 mixes show a similar trend and values at different frequencies, which was expected. The master curve of the dynamic modulus as a function of time (or frequency), describes the time (or

loading rate) dependency of the material. The amount of shifting at each temperature, required to form the master curve, depicts the temperature dependency of the HMA.
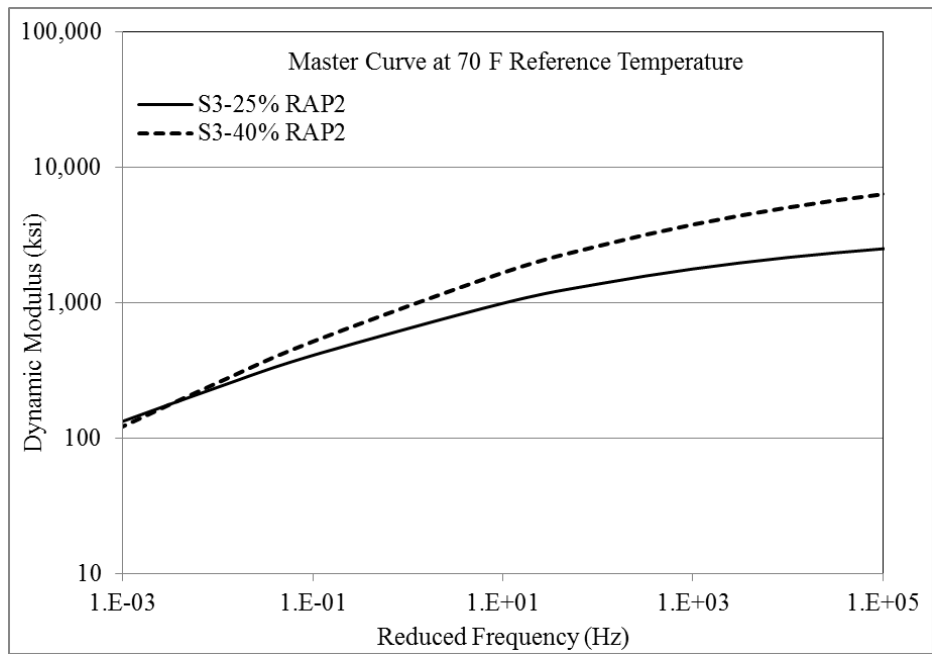
Figure 6.25 Dynamic Modulus Master Curves of S3-25% RAP2 and S3-40% RAP2 Mixes.
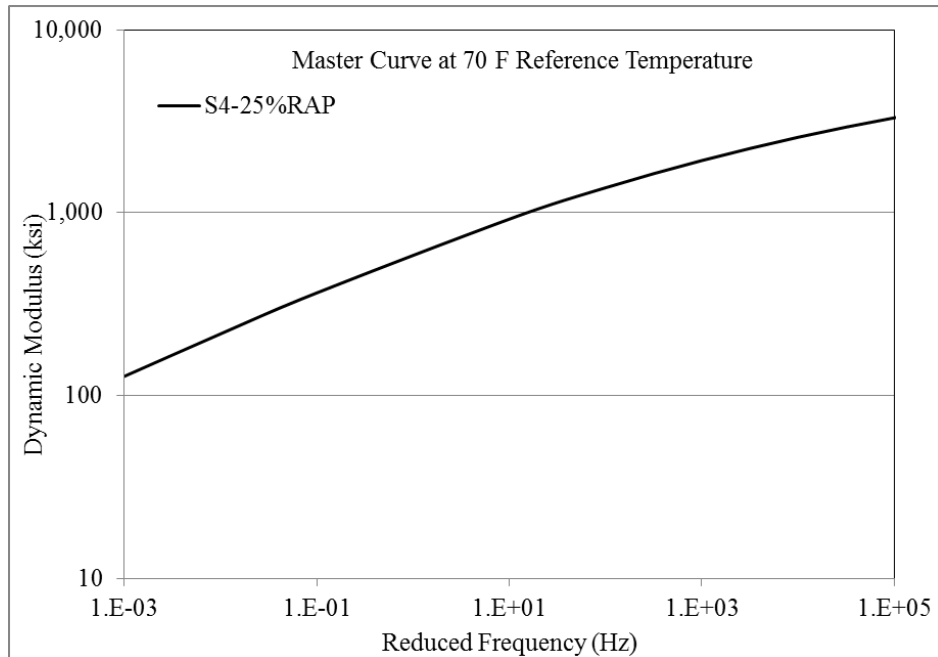
Figure 6.26 Dynamic Modulus Master Curve for S4-10% RAP2 Mix.

The log of shift factors used for developing the master curves of the S3 mixes (S3-25% RAP2 and S3-40% RAP2) and the S4 mix (S4-25% RAP2) are presented in Figures 6.27 and 6.28, respectively. It is clear from these figures that the S3-25% RAP2 had a lower shift factor compared to that of the S3-40% RAP2 mix up to the reference temperature (70°F). Above this reference temperature, the S3-40% RAP2 mix exhibited a higher magnitude of shift factor as compared to the S3-25% RAP2 mix at a comparable temperature. Some researchers have reported that the differences between the modulus values due to RAP are more pronounced at higher temperature or lower frequencies (e.g., Li et al., 2008).
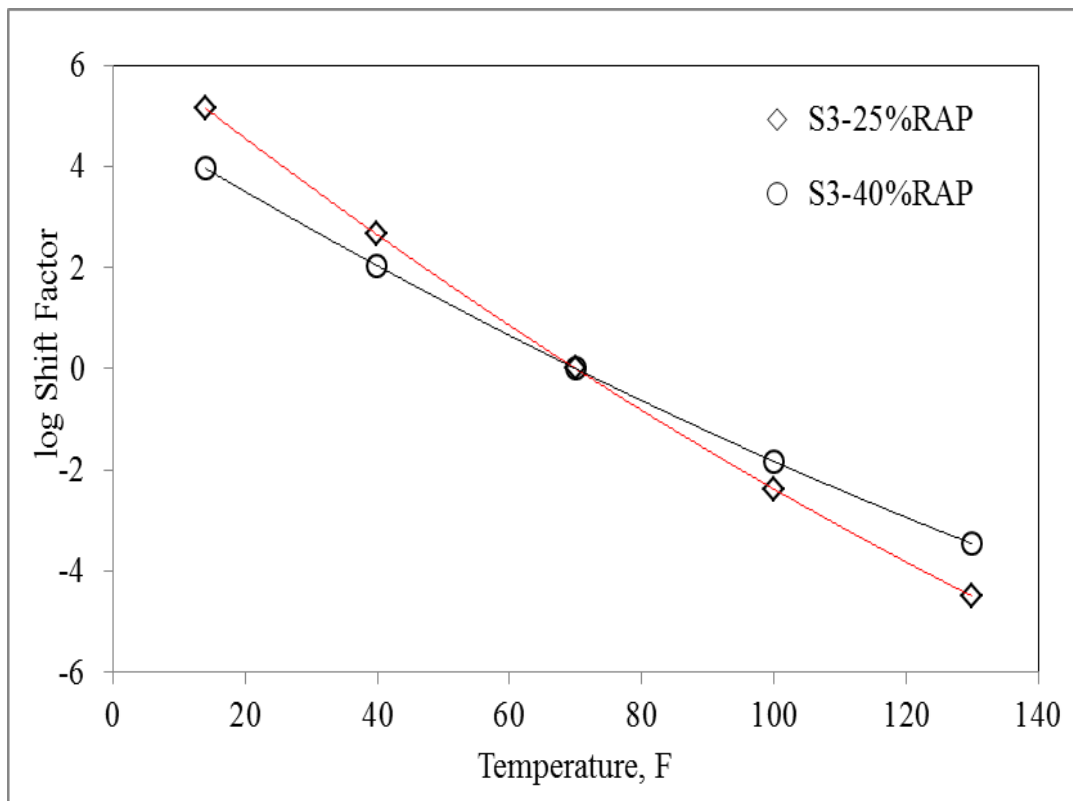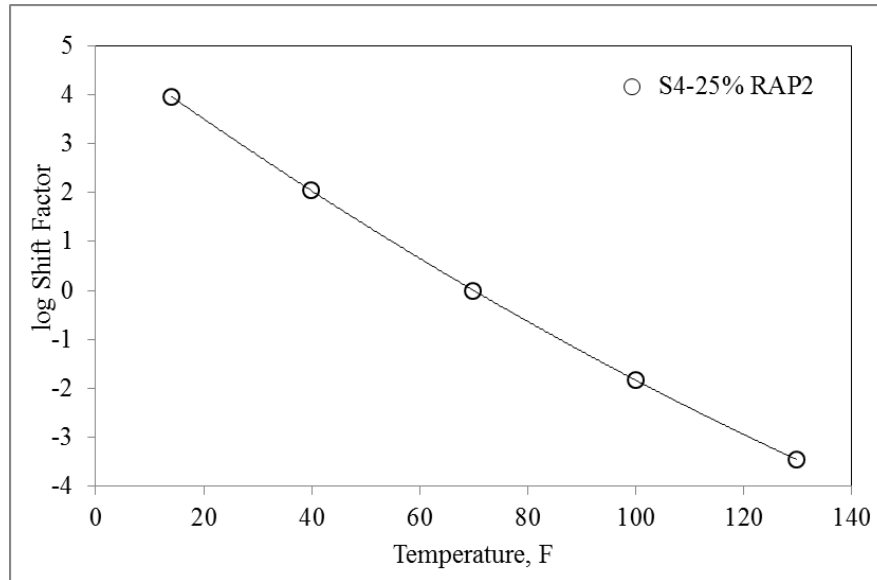
Figure 6.28 Shift Factor Used for Generating the Master Curve of S4-25% RAP2 Mix.

6.2.3.2   Indirect Tensile Strength

The M-EPDG software uses the indirect tensile strength (IDT) of HMA as one of two primary inputs for the low-temperature or thermal cracking module. The same methodology for conducting IDT tests used for the RAP1 Site was followed for the RAP2 Site. Table 6.14 shows the IDT values of the S3-25% RAP2, the S3-40% RAP2 and the S4-25% RAP2 mixes in a tabular form. Also, plots of average values of IDT are presented in Figure 6.29. It is evident that indirect tensile strength (IDT) values in all of the mixes decreased with an increase in the RAP content. This trend is in accordance with the results reported by Richardson and Lusher (2008). The results show that the IDT values in S3 mixes are sensitive to the RAP content. For instance, a 15% increase in RAP content in the S3 mixes, reduces the IDT values by 23%. Also, it was observed that the IDT value of the S4-25% RAP2 mix is 5% less than that of the S3-25% RAP2 mix.

Table 6.14   Indirect Tensile Strength for S3 and S4 Mixes

Sample No.	S3-25% RAP2	S3-40% RAP2	S4-25% RAP2
No. 1	438.7	360.4	417.4
No. 2	505.2	365.2	481.0

Sample No.	S3-25% RAP2	S3-40% RAP2	S4-25% RAP2
Average	472.0	362.8	449.2
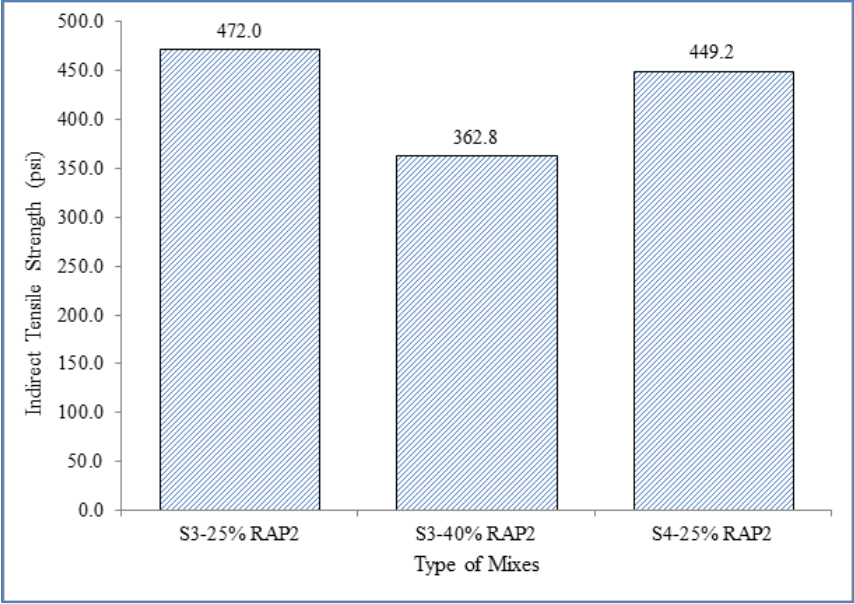
Figure 6.29 Indirect Tensile Strength of S3 and S4 Mixes at a Temperature of 14°F.

6.2.3.3   Creep Compliance

As noted earlier, the creep compliance test has been adopted in the M-EPDG to describe the mechanical behavior of HMA at low-temperature. The same methodology used for conducting the creep compliance tests on the mixes from RAP1 Site, was followed for the RAP2 Site. The creep compliance values at different loading times (i.e., 1 s, 2 s, 5 s, 10 s, 20 s, 50 s, and 100 s) for S3-25%RAP2, S3-40%RAP2 and S4-25%RAP2 are presented in Tables 6.15 through 6.17, respectively. Plots generated for the creep compliance test results are presented in Figures 6.30 through 6.32.

It is evident from Figures 6.30 through 6.32 that creep compliance increases with an increase in temperature, as expected (Richardson and Lusher, 2008; Vargas, 2007). It is also evident from Figures 6.30 and 6.31 that the S3-25% RAP2 mix is more sensitive to change in temperature as compared to corresponding mix containing higher RAP (S3-40% RAP2). For example, an increase in temperature by 82.4 ^{o}F (from -0.4^{o}F to +50°F) increased the creep compliance by approximately 1081% and 1000% for the S3-25% RAP2 mix and the S3-40% RAP2 mix (at 100 seconds), respectively. Also, an

increase in temperature from 32°F to +50°F increased the creep compliance by approximately 243% and 187% for the S3-25% RAP2 mix and the S3-40% RAP2 mix (at 100 seconds), respectively.

Table 6.15   Creep Compliance (D(t) in 1/MPa) values for S3-25% RAP2 Mix

Time (Sec.)	At T = -0.4°F; Sample 1	At T = -0.4 °F; Sample 2	At T = 14°F; Sample 1	At T = 14°F; Sample 2	At T = 32°F; Sample 1	At T = 32°F; Sample 2	At T = 50°F; Sample 1	At T = 50°F; Sample 2
1	3.31E-07	4.79E-05	3.05E-07	4.43E-05	4.61E-07	6.68E-05	1.23E-07	1.78E-05
2	3.38E-07	4.91E-05	3.52E-07	5.10E-05	5.33E-07	7.73E-05	6.88E-07	9.88E-05
5	3.53E-07	5.12E-05	4.01E-07	5.81E-07	5.60E-07	8.12E-05	1.30E-06	1.89E-04
10	3.69E-07	5.35E-05	4.18E-07	6.06E-05	7.37E-07	1.07E-04	1.55E-06	2.25E-04
20	3.89E-07	5.65E-05	4.69E-07	6.80E-05	9.15E-07	1.33E-04	2.36E-06	3.42E-04
50	4.28E-07	6.20E-05	5.62E-07	8.15E-05	1.28E-06	1.86E-04	3.76E-06	5.45E-04
100	4.68E-07	6.79E-05	6.60E-07	9.57E-05	1.61E-06	2.34E-04	5.53E-06	8.02E-04
Avg.	3.82E-07	5.54E-05	4.52E-07	6.56E-05	8.72E-07	1.26E-04	2.19E-06	3.17E-04
Stdev	5.02E-08	7.28E-06	1.23E-07	1.78E-05	4.32E-07	6.27E-05	1.89E-06	2.74E-04
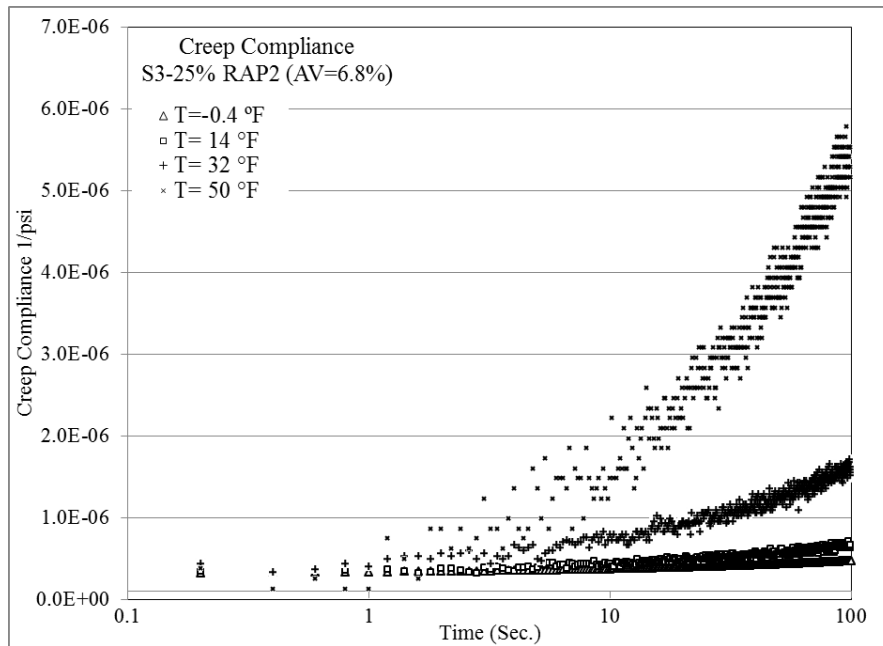
Figure 6.30 Variation of Creep Compliance for S3-25%RAP2 Mix with Temperature.
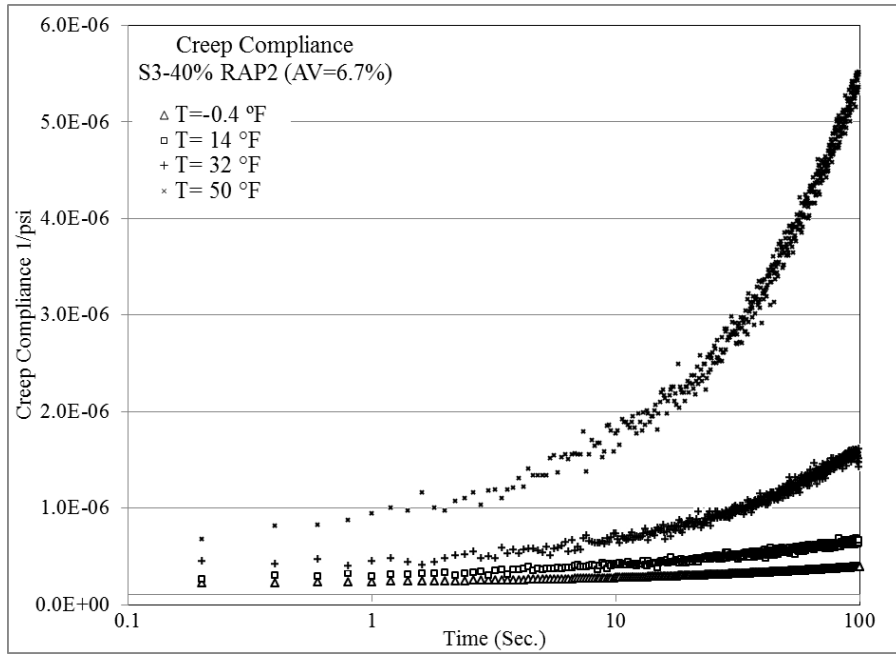
Figure 6.31   Variation of Creep Compliance for S3-40%RAP2 Mix with Temperature
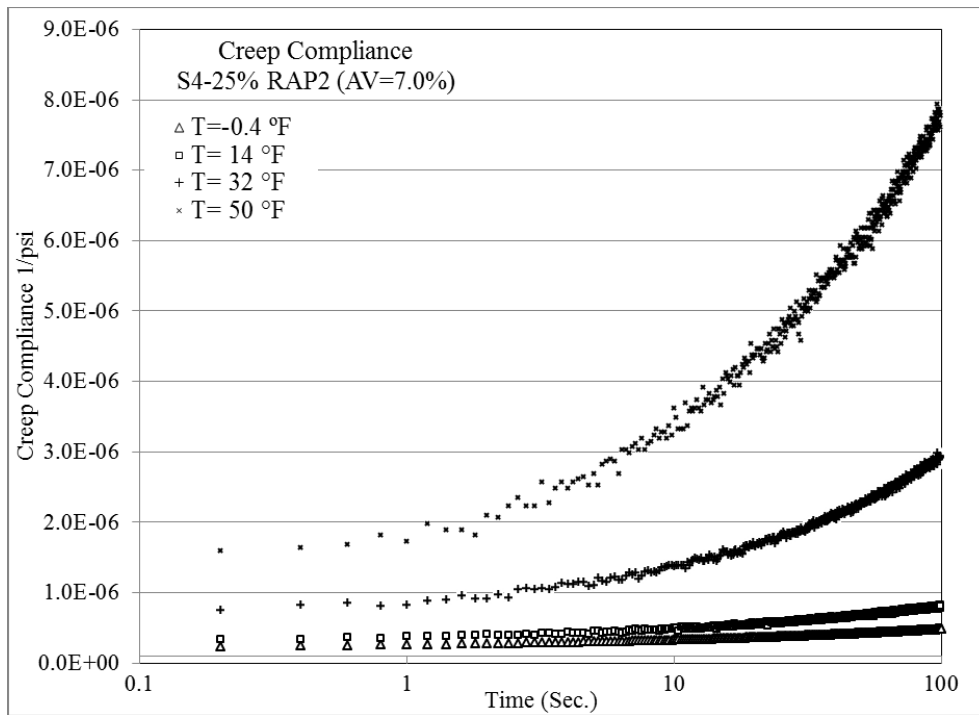
Figure 6.32   Variation of Creep Compliance for S4-25%RAP2 Mix with Temperature.

Table 6.16   Creep Compliance (D(t) in 1/MPa) values for S3-40% RAP2 Mix

Time (Sec.)	At T = -0.4°F; Sample 1	At T = -0.4 °F; Sample 2	At T = 14°F; Sample 1	At T = 14°F; Sample 2	At T = 32°F; Sample 1	At T = 32°F; Sample 2	At T = 50°F; Sample 1	At T = 50°F; Sample 2
1	2.35E-07	3.41E-05	2.52E-07	3.66E-05	3.23E-07	4.69E-05	8.49E-07	1.23E-04
2	2.44E-07	3.53E-05	3.18E-07	4.61E-05	4.70E-07	6.82E-05	1.06E-06	1.54E-04
5	2.60E-07	3.77E-05	3.64E-07	5.28E-05	5.55E-07	8.06E-05	1.37E-06	1.99E-04
10	2.77E-07	4.02E-05	4.14E-07	6.01E-05	6.98E-07	1.01E-04	1.72E-06	2.50E-04
20	3.00E-07	4.36E-05	4.50E-07	6.53E-05	8.47E-07	1.23E-04	2.28E-06	3.31E-04
50	3.44E-07	5.00E-05	5.54E-07	8.03E-05	1.19E-06	1.72E-04	3.70E-06	5.37E-04
100	3.92E-07	5.68E-05	6.87E-07	9.96E-05	1.50E-06	2.18E-04	4.31E-06	6.25E-04
Avg.	2.93E-07	4.25E-05	4.34E-07	6.30E-05	7.98E-07	1.16E-04	2.19E-06	3.17E-04
Stdev	5.72E-06	8.30E-06	1.47E-07	2.14E-05	4.20E-07	6.08E-05	1.34E-06	1.94E-04

Master curves for creep compliance were generated for both S3-25% RAP2 and S3-40% RAP2 mixes, as well as for the S4-25% RAP2 mix as shown in Figures 6.33 and 6.34, respectively. It is clear from Figure 6.33 that the S3-25% RAP2 mixes shows higher creep compliance values up to a reduced time of 4 seconds, compared to those of the S3-40% RAP2 mixes. However, both the S3-25% RAP2 and the S3-40% RAP2 mixes show similar creep compliance values at a reduced time span between 10 and 4000 seconds. Beyond this tims, the S3-25% RAP2 mix starts showing a higher creep as compared to the S3-40% RAP2 mix. Also, differences in creep values between the S3-25% RAP2 and S3-40 mixes are more pronounced at higher reduced time or temperature. For example, at a reduced time of 1 seconds, the S3-25% RAP2 mix had approximately 6% higher creep compliance values as compared to the S3-40% RAP2 mix. However, the percentage difference between the S3-25% RAP2 and S3-40% RAP2 mixes increased to 26% at a reduced time of 100,000 seconds. This behavior of mixes with high RAP content is consistent with the observations reported by other researchers (e.g., Daniel and Lachance, 2005; Richardson and Lusher, 2008; Solanki et al., 2012). This behavior may be attributed to hardness of the binder in the RAP as compared to the virgin binder. A harder binder increases the viscosity of the mix. From

Figure 6.34, it was also observed that creep compliance values of the S4-25% RAP2 mix are at the same range as its S3 counterpart.

Table 6.17   Creep Compliance (D(t) in 1/MPa) values for S4-25% RAP2 Mix

Time (Sec)	At T = -0.4°F; Sample 1	At T = -0.4°F; Sample 2	At T = 14°F; Sample 1	At T = 14°F; Sample 2	At T = 32°F; Sample 1	At T = 32°F; Sample 2	At T = 50°F; Sample 1	At T = 50°F; Sample 2
1	2.59E-07	3.76E-05	3.68E-07	5.34E-05	7.00E-07	1.02E-04	1.43E-06	2.07E-04
2	2.74E-07	3.97E-05	3.92E-07	5.69E-05	9.33E-07	1.35E-04	2.02E-06	2.92E-04
5	3.00E-07	4.35E-05	4.26E-07	6.18E-05	1.14E-06	1.66E-04	2.64E-06	3.83E-04
10	3.26E-07	4.73E-05	4.81E-07	6.98E-05	1.38E-06	2.01E-04	3.40E-06	4.93E-04
20	3.60E-07	5.22E-05	5.51E-07	7.99E-05	1.68E-06	2.43E-04	4.38E-06	6.35E-04
50	4.19E-07	6.08E-05	6.74E-07	9.78E-05	2.26E-06	3.28E-04	6.00E-06	8.70E-04
100	4.79E-07	6.94E-05	8.01E-07	1.16E-04	2.97E-06	4.30E-04	7.64E-06	1.11E-03
Avg.	3.45E-07	5.01E-05	5.28E-07	7.65E-05	1.58E-06	2.29E-04	3.93E-06	5.70E-04
Std. dev	7.99E-08	1.16E-05	1.60E-07	2.32E-05	7.98E-07	1.16E-04	2.24E-06	3.25E-04
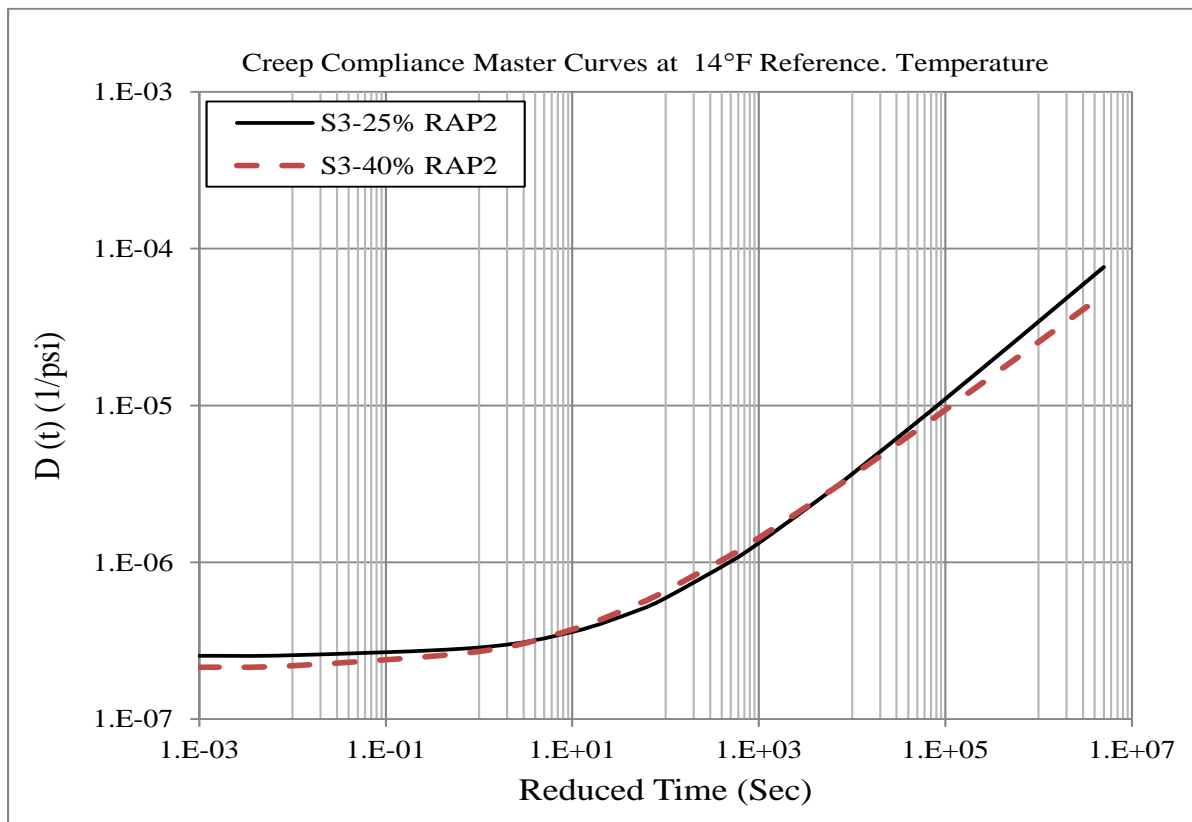
Figure 6.33 Creep Compliance Master Curves for S3-25% RAP2 and S3-4% RAP2.
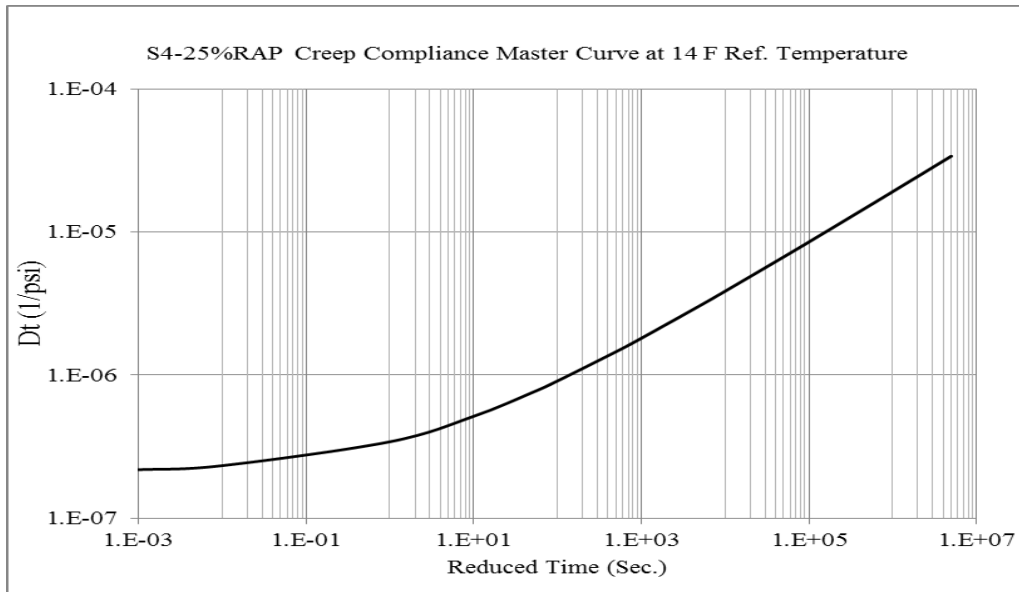
Figure 6.34 Creep Compliance Master Curves for S4-25% RAP2.

6.4   Summary

As explained in this chapter, the S3 (base course) and S4 (surface course) mixes with up to 40% RAP were tested in the laboratory for mechanistic performance. Two types of RAP (RAP1 and RAP2) were used to construct two test sections (Site 1 and Site 2), both located in Oklahoma. Site 1 had two lanes: one lane was paved by the contractor with traditional mixes (S3 mix with 25% RAP1 and S4 mix with 0% RAP1), and the other lane was constructed with custom mixes (S3 mix with 40% RAP1 and S4 with 10% RAP1). Site 2 was constructed in the same manner except that the custom mixes contained 25% RAP2 in the S4 mix. Findings from the performance data of tested mixes are summarized below:

- It was found that the voids in mineral aggregate (VMA) and voids filled with aggregate (VFA) of the RAP mixes increased with increasing percentage of RAP.
- The dynamic modulus test results illustrated that the asphalt mix containing higher amount of RAP has higher dynamic modulus values.
- From the Hamburg Wheel Test results it is observed that the rutting resistance of RAP mixes increases with an increase in RAP content. For instance, at 10,000

passes, the S3-25 (air void content = 7.1%) and S3-40 (air void content = 7.1%) mixes showed a rut depth of approximately 4.95 and 3.72 mm, respectively.

- Four-point beam fatigue test (FTG) test results show that the lower the RAP content the higher the fatigue life, irrespective of mix type (S3 or S4). However, more favorable effects in terms of fatigue life were observed in the case of S4 mixes compared to the S3 mixes when RAP is added in the mix.

- Indirect tensile strength (IDT) in all of tested mixes decreased with an increase in the RAP content. Test results also showed that IDT values of the S3 (base course) mixes are very sensitive to the RAP content. For instance, a 15% increase in RAP content in the S3 mixes, reduces the IDT values by 23%. Also, it was observed that the IDT values of the S4 (surface) mix with 25% RAP was about 5% less than that of S3 (base course) mix with the same RAP content.

- The creep compliance results showed an increase in the stiffness and a decrease in compliance of the mix due to an increase in RAP content. As expected, the creep compliance increases with an increase in temperature. It is also evident that the 25% RAP mix is more sensitive to change in temperature compared to corresponding mix containing higher RAP (40% RAP2) . Up to a reduced time of 4 seconds, it is oberseved that mixes with 25% show higher creep compliance values compared to the mixes with 40% RAP. However, at a reduced time span btween 10 to 4000 seconds, mixes with 25% and 40% RAP show similar creep compliance values.

7   SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1   Summary

This study was limited to laboratory and field evaluation of local RAPs and virgin materials (aggregate and binders). To this end, two RAP samples were collected for laboratory evaluation and stockpiled for the construction of two test sections. Different percentages (25% and 40% in base courses and 0% and 10% in surface courses) of each RAP sample were used to prepare base and surface mixes for conditions and specifications prevailing in Oklahoma. Virgin aggregates and binders used in the new HMA mixes were also collected from local sources and evaluated in the laboratory. Furthermore, in cooperation with two local contractors, two two-lane HMA test sections were constructed. One lane of each test section was constructed with the maximum allowable RAP (0% in surface course and 25% in base course) and the other lane was constructed with high RAP (10% in surface course and 40% in base course). Cylindrical core and block samples were collected from the constructed pavement sections and evaluated (dynamic modulus, creep, and beam fatigue) in the laboratory.

The recovery of asphalt binder was conducted at the Liquid Laboratory, ODOT Materials Division. The recovered binders from RAPs were evaluated for PG grading and determination of MEPDG input parameters. Collected RAP samples were extracted in accordance with the OHD L-26 Method using an NCAT Ignition Oven. The extracted aggregates were then evaluated in laboratory for mechanical and surface properties. Furthermore, virgin binders blended with RAP binder and virgin aggregates mixed with extracted aggregates from RAP were evaluated in laboratory. Findings of this study, presented in the next section, are expected to be useful to pavement professional in analyzing and designing HMA mixes with high RAP contents.

7.2   Conclusions

Based on the test results and findings of this study, the following conclusions are made:

- The stiffness of the belended binder increases with an increase in the percentage of the RAP binder. With 10% RAP binder, there is no change in the PG grade of the virgin binder. On With 40% RAP binder, the high and low PG temperatures are

about two grades and one grade, respectively, higher than those of the virgin binder. It is also noted that the PG temperature does not change significantly with the addition of 0.5% anti-stirpping agent.

- With addition of 10%, 25% and 40% RAP binder in the virgin binder, the viscosity vlaues were found to be about 10%, 44%, and 119% higher compared to the virgin binder. The anti-stripping agent does not seem to have any significant effects on the viscosity of the binder blended with 25% RAP binder.

- As expected, the G* value decreases but the δ value increases with increased testing temperature. Another trend is that the G* value increases and the δ value decreases with an increase of the percentage of the RAP. The G* and δ values of blended binders under RTFO-aged condition at the range of temperature presented in this report can be used as MEPDG Level 1 input parameter for analyzing new HMA pavemenets with RAP. Based on the L.A. abrasion loss values and the Micro-Deval loss values, it can be observed that all of the mixes meet the aggregate soundness requirements set by ODOT. However, aggregates extracted by an NCAT oven show more L.A. abrasion loss values and Micro-Deval loss values, compared to their virgin counterparts.

- Sand equivalent tests show that NCAT oven-extracted aggregates with high RAP result in a significant increase in sand equivalent values compared to its virgin counterpart.

- Insoluble test results indicate that RAP aggregates do not meet the ODOT solubility requirement. Furthermore, aggregates extracted from S3 and S4 mixes and their virgin counterparts were found to be extremely low (below 7.0), which were in agreement with insoluble residue data available in the database at the ODOT Materials Division.

- It was found that the voids in mineral aggregate (VMA) and voids filled with aggregate (VFA) of the RAP mixes increased with increasing percentage of RAP.

- The dynamic modulus test results show that the asphalt mixes containing high RAP have higher dynamic modulus values.

- From Hamburg Wheel Test results, it is observed that rutting resistance of RAP mixes increases with an increase in RAP content. For instance, at 10,000 passes the S3-25 (air void content = 7.1%) and the S3-40 (air void content = 7.1%) mixes showed a rut depth of approximately 4.95 mm and 3.72 mm, respectively.

- Four point beam fatigue test results show that the lower the RAP content, the higher the fatigue life, irrespective of mix type (S3 or S4). However, more favorable effects in terms of fatigue life were observed in the case of S4 mixes compared to the S3 mixes when RAP is added in the mix.

- Indirect tensile strength (IDT) in all tested mixes decreased with an increase in the RAP content. The test results also showed that IDT of S3 (base course) mixes are very sensitive to the RAP content. For instance, a 15% increase in RAP content in the S3 mixes, reduces the IDT values by 23%. Also, it was observed that the IDT value of the S4 (surface) mix with 25% RAP was about 5% less than that of S3 (base course) mix with the same RAP content.

- The creep compliance results showed an increase in the stiffness and a decrease in compliance of the mix due to increased RAP content. As expected, the creep compliance increases with an increase in temperature.

7.3   Recommendations

This study used bulk RAP samples collected from asphalt millings of unknown or little known history. Studying the effect of simulated RAPs of different ages (e.g., 10 years, 20 years, 30 years, etc.) is expected to provide the changes in mechanistic properties of evaluated materials with respect to aging. That was beyond the scope of this project and is a research need that may be considered by OkTC and ODOT in future. Furthermore, a comprehensive database of existing RAP stockpiles will be highly beneficial to pavement professionals in Oklahoma.

8. IMPLEMENTATION/TECHNOLOGY TRANSFER

8.1 Implementation and Technology Transfer Workshop

Technology transfer has occurred continuously during this project. It has occurred at a number of levels. First, at the local level, the research team worked very closely with a design firm, *EST Inc.* located in Moore, Oklahoma, to perform volumetric mix designs of HMA with high RAP contents (up to 10% RAP in surface courses and 40% RAP in base courses). Secondly, two local paving companies namely Silver Star Construction Co. in Moore, Oklahoma and Schwarz Paving Inc. in Oklahoma City, Oklahoma successfully constructed the HMA test sections with high RAP contents. The City of Norman and the City of Oklahoma City were well informed about these custom HMA mixes through formal and information communications pre- and post- construction phases of the project. The ODOT Research Panel members were informed about these custom HMA mixes and construction schedules during the bi-annual and final project meetings of the matching project (*ODOT SPR Item 2223*: *Test Methods for Use of Recycled Asphalt Pavement in Asphalt Mixes*). Furthermore, a presentation titled "*Recycled Asphalt Pavement Research at OU*," was made during the visit of ODOT Personnel to the University of Oklahoma on June 22, 2011. An invited lecture on "*Green Paving Technology*," was made to a group of about 35 individuals representing K-12 Middle School Teachers in Oklahoma on June 16, 2011.

In coordination with OkTC (Dr. Hagen), one technology transfer workshop (two hours), covering the benefits and findings of this study, was held at the ODOT Facility Office (Commission Room) in Oklahoma City on September 18, 2012. The research team discussed different phases (planning, design, construction) and presented the findings of this project to the workshop participants (about 25) that included executives, materials engineers and division engineers from ODOT, engineers from FHWA, personals from OkTC, members from OAPA, and researchers and students from OkTC-affiliated universities (OU, OSU and LU). Two professional development hours (PDH) were offered to the interested participants.

8.2   Journal and Proceedings Papers

The scale and breadth of this project have drawn national and international attention. The research team has published/submitted 3 journal articles and 7 proceedings papers, and made 11 platform and 4 poster presentations. Furthermore, test data from this project are integral part of a Master's thesis and two Ph.D. dissertations. The publication records of the research team related to the project are listed below:

8.2.1. Referred Journal Papers

- Solanki, P., Zaman, M., Hossain, Z., and Adje, D. "Effect of Recycled Asphalt Pavement on Thermal Cracking Resistance of Hot Mix Asphalt," in the *International Journal of Geomechanics (IJOG),* (Submitted August 2012; in Review).

- Hossain, Z., and Zaman, M., "Sensitivity of Oklahoma Binders on Dynamic Modulus of Asphalt Mixes and Distress Functions," in the *Journal of Materials in Civil Engineering*, August, 2012, Volume 24, No. 8, 1076–1088.

- Hossain, Z., Solanki, P., Zaman, M., Lewis, S., and Hobson, K. "Influence of Recovery Processes on Properties of Binders and Aggregates Recovered from Recycled Asphalt Pavement," in the *Journal of ASTM International (JAI),* Vol. 9, Issue 3, February 2012, Page Count: 18.

8.2.2. Referred Conference Papers

- Ghabchi, R., Singh, D., Zaman, M., Hossain, Z., Solanki, P., and Adje D. "A Laboratory Study to Evaluate the Effects of RAP Sources on Performance of Asphalt Mixes," *GeoCongress 2014* (Submitted February 2013, in Review).

- Hossain, Z., Zaman, M., and Doiron, C. "Mechanistic Empirical Pavement Design Guide Input Parameters for Unbound Aggregates in Oklahoma," *2nd IACGE International Conference on Geotechnical and Earthquake Engineering*, October 25-27, 2013 (Submitted February 2013, in Review).

- Pranshoo, S., P., Hossain, Z., Adje, D., Ghabchi, R., Singh, D., and Zaman, M. "Effect of Recycled Asphalt Pavement on Mechanistic Properties of Hot Mix Asphalt," *OkTC-ODOT Research Day*, October 4, 2012.

- Solanki, P., Hossain, Z., Zaman, M., and Adje, D., "Volumetric and Mechanistic Characteristics of Asphalt Mixes Containing Recycled Asphalt Pavement," *in Proc. of GeoCongress 2012*, March 25-29, 2012.

- Hossain, Z., Solanki, P., Zaman, M., "Mechanistic Evaluation of Recovered Materials from Recycled Asphalt Pavement," *in Proc. of GeoCongress 2012*, March 25-29, 2012.

- Hossain, Z., Buddhalla, A., O'Rear, A. O., Zaman, M., Laguros, J. L., and Lewis, S., "Recycled Asphalt Pavement in new Asphalt Mixtures: State of the Practice," in the 2nd *International symposium on Asphalt Pavement and Environment*, October 1-3, 2012, Fortaleza, Brazil.

- Pranshoo, S., P., Hossain, Z., Adje, D., and Zaman, M. "Effect of Recycled Asphalt Pavement on Thermal Cracking Resistance of Hot Mix Asphalt," *2nd International Symposium on Constitutive Modeling of Geomaterials: Advances and New Applications*, Beijing, China, October 15-16, 2012.

8.2.3.   Referred Conference Abstracts

- Hossain, Z., Zaman, M., and Solanki, P. "Prediction of Dynamic Modulus of Asphalt Mixes with Reclaimed Asphalt Pavement," *2013 Conference of the ASCE Engineering Mechanics Institute*, to be held August 4-7, 2013, Northwestern University, Evanston, IL

- Hossain, Z., Zaman, M., and Solanki, P. "State-of-the-Practice and Mechanistic Evaluation of New Asphalt Mixes with High Reclaimed Asphalt in Oklahoma," 2013 Summer Workshop of the TRB Committee ADC60 on *Sustainable Best Management Practices in Transportation*, to be held on July 14-17, 2013, Pittsburgh, PA

- Hossain, Z., Solanki, P., Zaman, M., Lewis, S., and Hobson, K., "Influence of Recovery Processes on Properties of Binders and Aggregates Recovered from Recycled Asphalt Pavement," In the *International Symposium on Testing and Specifications of Recycled Materials for Sustainable Geotechnical Construction*, February 2-4, 2011, Baltimore, Maryland.

- Hossain, Z., M. Zaman, C. Doiron, J. Autrey, A, Gupta, J. Laguros, "Influences of Recovery Methods on Properties of Binders and Aggregates Recovered from Recycled Asphalt Pavement," presented at *47th Petersen Asphalt Research Conference (PARC)*, Western Research Institute, July 12-15, 2010 in Laramie, Wyoming.

8.2.4. Posters

- Zaman, M., Hossain, Z., Solanki, P. , Ghabchi, R., Singh, D., and Lewis, S. "Mechanistic Evaluation Reclaimed Asphalt Pavement (RAP) for New Mixes," *ODOT-OTC Research Day*, Oklahoma City, October 4, 2012.

- Hossain, Z., Zaman, M., and Lewis, S. "Test Methods for the Evlaution of RAP," *ODOT-OTC Research Day*, Oklahoma City, October 14, 2011.

- Zaman, M., Hossain, Z., Solanki, P., Laguros, J., and Lewis, S. "Local Calibration of the MEPDG for Asphalt Pavements with RAP," *ODOT-OTC Research Day*, Oklahoma City, October 15, 2010.

- Zaman, M., and Hossain, Z. "Implementation of MEPDG for Asphalt Pavement with RAP," Research and Innovative Technology Administration (RITA) Site Visit, *Oklahoma Transportation Center (OTC),* Norman, March 30, 2010.

8.2.5. Thesis/Dissertation

- Ghabchi, R., "Laboratory Characterization of Recycled and Warm Mix Asphalt for Enhanced Pavement Applications," *Ph. D. Dissertation*, Department of Civil Engineering and Environmental Science, the University of Oklahoma, Norman, Oklahoma, 2014 (Expected), in Preparation, xx pages.

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- Hossain, Z., "Evaluation of Rheological Properties of Asphalt Binders for Pavement Design Applications," *Ph. D. Dissertation*, Department of Civil

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A. APPENDIX A: Trial Mix Designs for HMA Mixes

Trial and final mix design sheets of S3 and S4 mixes with different percentages of RAP1 and RAP2 are presented in this section.

Table A.1   Percent Passing of S3 Mix with 40% RAP1 and PG 64-22OK Binder: Trial #1

Sieve Size	#67 Rock	5/8" Chips	Screenings	Man. Sand	Sand	RAP	Combined
1 in	97	100	100	100	100	100	100
3/4 in	88	100	100	100	100	97	97
1/2 in	59	96	100	100	100	90	90
3/8 in	37	84	100	100	100	55	72
#4	6	33	89	92	100	34	51
#8	2	9	57	48	99	25	35
#16	1	4	37	25	98	21	28
#30	1	3	23	13	91	17	22
#50	1	2	14	7	67	10	14
#100	0	2	8	4	25	7	7
#200	0.3	1.2	4.1	1.9	8.3	4.3	3.6
%USED	14	10	15	10	11	40	100

Table A.2   Percent Passing of S3 Mix with 40% RAP1 and PG 64-22OK Binder: Trial #2

Sieve Size	#67 Rock	5/8" Chips	Screenings	Man. Sand	Sand	RAP	Combined
1 in	97	100	100	100	100	100	100
3/4 in	88	100	100	100	100	97	97
1/2 in	59	96	100	100	100	90	89
3/8 in	37	84	100	100	100	55	69
#4	6	33	89	92	100	34	46
#8	2	9	57	48	99	25	30
#16	1	4	37	25	98	21	22
#30	1	3	23	13	91	17	16
#50	1	2	14	7	67	10	10
#100	0	2	8	4	25	7	6
#200	0.3	1.2	4.1	1.9	8.3	4.3	3.1
%USED	17	13	12	13	5	40	100

Table A.3   Percent Passing of S3 Mix with 40% RAP1 and PG 64-22OK Binder: Trial #3

Sieve Size	#67 Rock	5/8" Chips	Screenings	Man. Sand	Sand	RAP	Combined
1 in	97	100	100	100	100	100	100
3/4 in	88	100	100	100	100	97	97
1/2 in	59	96	100	100	100	90	89
3/8 in	37	84	100	100	100	55	69
#4	6	33	89	92	100	34	43
#8	2	9	57	48	99	25	25
#16	1	4	37	25	98	21	17
#30	1	3	23	13	91	17	12
#50	1	2	14	7	67	10	7
#100	0	2	8	4	25	7	5
#200	0.3	1.2	4.1	1.9	8.3	4.3	2.7
%USED	16	20	12	12	0	40	100

Table A.4   Percent Passing of S3 Mix with 40% RAP1 and PG 64-22OK Binder: Trial #4

Sieve Size	#67 Rock	5/8" Chips	Screenings	Man. Sand	Sand	RAP	Combined
1 in	97	100	100	100	100	100	100
3/4 in	88	100	100	100	100	97	97
1/2 in	59	96	100	100	100	90	90
3/8 in	37	84	100	100	100	55	70
#4	6	33	89	92	100	34	43
#8	2	9	57	48	99	25	24
#16	1	4	37	25	98	21	16
#30	1	3	23	13	91	17	11
#50	1	2	14	7	67	10	7
#100	0	2	8	4	25	7	4
#200	0.3	1.2	4.1	1.9	8.3	4.3	2.7
%USED	12	25	8	15	0	40	100

Table A.5   Percent Passing of S4 Mix with 10% RAP1 and PG 64-22OK Binder: Trial #1

Sieve Size	#67 Rock	5/8" Chips	Screenings	Man. Sand	Sand	RAP	Combined
1 in	97	100	100	100	100	100	100
3/4 in	88	100	100	100	100	97	100
1/2 in	59	96	100	100	100	90	97.7
3/8 in	37	84	100	100	100	55	90
#4	6	33	89	92	100	34	67
#8	2	9	57	48	99	25	35
#16	1	4	37	25	98	21	20
#30	1	3	23	13	91	17	12
#50	1	2	14	7	67	10	7
#100	0	2	8	4	25	7	4
#200	0.3	1.2	4.1	1.9	8.3	4.3	2.4
%USED	0	32	22	36	0	10	100

Table A.6   Percent Passing of S4 Mix with 10% RAP1 and PG 64-22OK Binder: Trial #2

Sieve Size	#67 Rock	5/8" Chips	Screenings	Man. Sand	Sand	RAP	Combined
1 in	97	100	100	100	100	100	100
3/4 in	88	100	100	100	100	97	100
1/2 in	59	96	100	100	100	90	97.7
3/8 in	37	83	100	100	100	55	90.4
#4	6	33	89	92	100	34	68
#8	2	9	57	48	99	25	39
#16	1	4	37	25	98	21	24
#30	1	3	23	13	91	17	16
#50	1	2	14	7	67	10	10
#100	0	2	8	4	25	7	5
#200	0.3	1.2	4.1	1.9	8.3	4.3	2.8
%USED	0	30	22	33	5	10	100

Table A.7   Percent Passing for S4 Mix with 10% RAP1 and PG 64-22OK Binder: Trial #3

Sieve Size	#67 Rock	5/8" Chips	Screenings	Man. Sand	Sand	RAP	Combined
1 in	97	100	100	100	100	100	100
3/4 in	88	100	100	100	100	97	100
1/2 in	59	96	100	100	100	90	97.7
3/8 in	37	84	100	100	100	55	90.7
#4	6	33	89	92	100	34	69
#8	2	9	57	48	99	25	40
#16	1	4	37	25	98	21	27
#30	1	3	23	13	91	17	19
#50	1	2	14	7	67	10	12
#100	0	2	8	4	25	7	6
#200	0.3	1.2	4.1	1.9	8.3	4.3	3.0
%USED	0	30	22	30	8	10	100

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Oklahoma Department of Transportation Mix Design Report
(Submittal-For Acceptance Only)

Asphalt Concrete, Type S3 (PG 64-22 OK)   Mat'l. Code: asco009   Binder - Recycled   ID: B2
(Material Full Name and Material Code)   *(Design Type and Design Type ID)*

PMI-Silver Star   P/S # m00565   S3pv0261001000
(Producer/Supplier Name and Producer/Supplier Code)   *(Mix ID)*

PMI-Silver Star (Moore, OK) - 400TPH   PLANT ID # m00565-01
(Plant Name and Plant ID)   *(Project Number)*

(Job Piece Number)   *(Contract ID)*   *(County)*   *(Highway)*

(Contractor)   > 4 in. (100 mm)   0.3M+
                        (Depth From Surface)   *(ESALs)*

Aggregate	Producer/Supplier	% USED
#67 Rock	Martin-Marietta (Davis, OK) P/S # m002285005	12
5/8" Chips	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	25
Scrns.	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	8
Man. Sand	Martin-Marietta (Davis, OK) P/S # m002285005	15
Sand (Unlisted Source)	GMI Sand Okc, Ok 1402	0
Fine R.A.P.	Contractor / Project Site P/S # Contractor	40

Asphalt Additive, Anti-Strip   *(Product Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)*

Asphalt Cement: Asphaltic Cement Type PG 64-22 OK, acem003, Valero (Ardmore, OK), m00352
(Material Full Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)

For Acceptance Only
Not for production use

Sieve Size	#67 Rock	5/8" Chips	Scrns.	Man. Sand	Sand (Unlisted Source)	Fine R.A.P.	Comb. Agg.	JMF	Min.	Max.	% Tol. (±)
1 in (25 mm)	97	100	100	100	100	100	100	100	100	100	0
3/4 in (19 mm)	88	100	100	100	100	97	97	97	90	100	7
1/2 in (12.5 mm)	59	96	100	100	100	90	90	90	83	97	7
3/8 in (9.5 mm)	37	84	100	100	100	55	70	70	63	77	7
#4 (4.75 mm)	6	33	89	92	100	34	43	43	36	50	7
#8 (2.36 mm)	2	9	57	48	99	25	24	24	19	29	5
#16 (1.18 mm)	1	4	37	25	98	21	16	16	12	20	4
#30 (.600 mm)	1	3	23	13	91	17	11	11	7	15	4
#50 (.300 mm)	1	2	14	7	67	10	7	7	3	11	4
#100 (.150 mm)	0	2	8	4	25	7	5	5	2	8	3
#200 (.075 mm)	0.3	1.2	4.1	1.9	8.3	4.3	2.7	2.7	0.7	4.7	2
AC Content %						4.5		4.7	4.3	5.1	0.4

	°F (°C)	Required
Mix temperature @ discharge from mixer:	305 (152)	± 20 °F (± 10 °C)
Optimum roadway compaction temperature:	290 (143)	
Laboratory mixing temperature:	325 (163)	
Laboratory compaction temperature:	300 (149)	

Tests on Asphalt Cement   Found   For Acceptance Only / Not for production use
Specific Gravity @ 77 ° F   1.0100

Tests on Compressed Mixtures (@ Design AC)

	# Gyr.	% Density of Gmm	% Density Required
Nini	7	85.5	85.5 - 90.5
Ndes	75		96
Nmax	115	97.7	< 98.4

Tests on Aggregates		Required		Units
Durability Index	76	40	min.	%
F.A.A. %U	42	40	min.	%
Flat and Elongated	0	10	max.	%
Fractured Faces	100/100	65/65	min.	%
Insoluble Residue		N/A		
LA Abrasion	22	40	max.	%
Micro-Deval	12.5	25	max.	%
Permeability	6.5	12.5	max.	10^{-5}cm/s
Sand Equivalent	82	40	min.	%
IOC	0.18			%
Gse	2.665			
Gsb	2.628			
Specimen Weight	4704			g

Tests on Compressed Mixtures

%AC	Gmb	Gmm	% Density of Gmm	% Density Required min.	% Density Required max.	% VMA min.	% VMA Req. min.	% VFA min.	% VFA Required max.
4.3	2.319	2.490	93.1	95	97	15.6	13	55.8	65	78
4.8	2.343	2.471	94.8			15.1		65.6	
5.3	2.379	2.452	97.0			14.3		79.0	

Dust Prop.	DP Required min.	DP Required max.	
0.7			
0.6	0.6	1.6	
0.6			

ITS (PSI)   142.7   75 (min.)
TSR   0.82   Design (min.): 0.80   Field (min.): 0.75
Compacted Wt. (lbs/sy/1" thick) = 108.9   @   4.7 % Asphalt Cement
                                              2.9 % New Asphalt Cement

MEETS SPECIFICATION REQUIREMENTS

Comments: Prepared at the University of Oklahoma (Broce Laboratory) for Research Project entitled "Implementation of MEPDG for Asphalt Pavements with RAP"

Figure A.1   Mix Design Sheet for S3 Mix with 40% RAP1

Oklahoma Department of Transportation Mix Design Report
(Submittal-For Acceptance Only)

Asphalt Concrete, Type S4 (PG 64-22 OK)   Mat'l. Code: asco012   Binder - Recycled   ID: B2
(Material Full Name and Material Code)   *(Design Type and Design Type ID)*

PMI-Silver Star   P/S # m00565   S4pv0261001000
(Producer/Supplier Name and Producer/Supplier Code)   *(Mix ID)*

PMI-Silver Star (Moore, OK) - 400TPH   PLANT ID # m00565-01
(Plant Name and Plant ID)   *(Project Number)*

(Job Piece Number)   _(Contract ID)_   _(County)_   _(Highway)_

                                        > 4 in. (100 mm)   0.3M+
(Contractor)   _(Depth From Surface)_ _(ESALs)_

Aggregate	Producer/Supplier	% USED
#67 Rock	Martin-Marietta (Davis, OK) P/S # m002285005	0
5/8" Chips	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	30
Scrns.	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	22
Man. Sand	Martin-Marietta (Davis, OK) P/S # m002285005	33
Sand (Unlisted Source)	GMI Sand Okc, Ok 1402	5
Fine R.A.P.	Contractor / Project Site P/S # Contractor	10

Asphalt Additive, Anti-Strip   _(Product Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)_

Asphalt Cement: Asphaltic Cement Type PG 64-22 OK, acem003, Valero (Ardmore, OK), m00352
                     (Material Full Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)

Producer/Supplier:	Martin-Marietta (Davis, OK) P/S # m002285005	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	Martin-Marietta (Davis, OK) P/S # m002285005	GMI Sand Okc, Ok 1402	Contractor / Project Site P/S # Contractor							
									For Acceptance Only Not for production use				
Sieve Size	#67 Rock	5/8" Chips	Scrns.	Man. Sand	Sand (Unlisted Source)	Fine R.A.P.		Comb. Agg.	JMF	Min.	Max.	% Tol. (±)
3/4 in (19 mm)	88	100	100	100	100	97		100	100	100	100	0
1/2 in (12.5 mm)	59	96	100	100	100	90		98	98	91	100	7
3/8 in (9.5 mm)	37	83	100	100	100	55		90	90	83	97	7
#4 (4.75 mm)	6	33	89	92	100	34		68	68	61	75	7
#8 (2.36 mm)	2	9	57	48	99	25		39	39	34	44	5
#16 (1.18 mm)	1	4	37	25	98	21		25	25	21	29	4
#30 (.600 mm)	1	3	23	13	91	17		17	17	13	21	4
#50 (.300 mm)	1	2	14	7	67	10		10	10	6	14	4
#100 (.150 mm)	0	2	8	4	25	7		6	6	3	9	3
#200 (.075 mm)	0.3	1.2	4.1	1.9	8.3	4.3		2.7	2.7	0.7	4.7	2
AC Content %						4.5		5.3	5.3	4.9	5.7	0.4

	°F (°C)	Required
Mix temperature @ discharge from mixer:	305 (152)	± 20 °F (± 10 °C)
Optimum roadway compaction temperature:	290 (143)	
Laboratory mixing temperature:	325 (163)	
Laboratory compaction temperature:	300 (149)	

Tests on Aggregates		Required	Units
Durability Index	76	40 min.	%
F.A.A. %U	42	40 min.	%
Flat and Elongated	0	10 max.	%
Fractured Faces	100/100	65/65 min.	%
Insoluble Residue		N/A	
LA Abrasion	21	40 max.	%
Micro-Deval	11.8	25 max.	%
Permeability	10.4	12.5 max.	10⁻⁵cm/s
Sand Equivalent	75	40 min.	%

Tests on Asphalt Cement   Found
Specific Gravity @ 77 ° F   1.0100

For Acceptance Only Not for production use

Tests on Compressed Mixtures (@ Design AC)			
	# Gyr.	% Density of Gmm	% Density Required
Nini	7	86.4	85.5 - 90.5
Ndes	75		96
Nmax	115	98.0	< 98.4

IOC	0.18 %
Gse	2.687
Gsb	2.605
Specimen Weight	4680 g

Tests on Compressed Mixtures

%AC	Gmb	Gmm	% Density of Gmm	% Density Required		% VMA	% VMA Req.	% VFA	% VFA Required	
				min.	max.		min.		min.	max.
4.8	2.374	2.489	95.4			13.2		65.2		
5.3	2.380	2.470	96.4	95	97	13.5	14	73.3	65	78
5.8	2.408	2.451	98.2			12.9		86.0		

Dust Prop.	DP Required		ITS (PSI)	102.7	75 (min.)			
0.7	min.	max.	TSR	0.82	Design (min.): 0.80	Field (min.): 0.75		
0.6	0.6	1.6	Compacted Wt. (lbs/sy/1" thick) =	108.7	@	5.3	% Asphalt Cement	
0.6						4.8	% New Asphalt Cement	

MEETS SPECIFICATION REQUIREMENTS

Comments: Prepared at the University of Oklahoma (Broce Laboratory) for Research Project entitled "Implementation of MEPDG for Asphalt Pavements with RAP"

Figure A.2   Mix Design Sheet for S4 Mix with 10% RAP1

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Oklahoma Department of Transportation Mix Design Report

Asphalt Concrete, Type S3 (PG 64-22 OK) Mat'l. Code: asco009	Binder - Recycled ID: B2
(Material Full Name and Material Code)	*(Design Type and Design Type ID)*
PMI-Silver Star P/S # m00565	S3pv0260900800
(Producer/Supplier Name and Producer/Supplier Code)	*(Mix ID)*
PMI-Silver Star (Moore, OK) - 350TPH PLANT ID # m00565-01	0.3M+
(Plant Name and Plant ID)	*(ESALs)*

Aggregate	Producer/Supplier	% USED
#67 Rock	Martin-Marietta (Davis, OK) P/S # m002285005	15
5/8" Chips	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	22
Scrns.	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	17
Man. Sand	Martin-Marietta (Davis, OK) P/S # m002285005	10
Sand	General Materials Inc (OKC, OK) P/S # m001911402	11
Fine R.A.P.	Contractor / Project Site P/S # Contractor	25
Asphalt Cement:	Asphaltic Cement Type PG 64-22 OK, acem003, Valero (Ardmore, OK), m00352	
	(Material Full Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)	

Requires Form 93-E0 signed by the Department for production use.
-Oklahoma D.O.T. Materials-

Producer/Supplier: Sieve Size	#67 Rock *Martin-Marietta (Davis, OK) P/S # m002285005*	5/8" Chips *Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008*	Scrns. *Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008*	Man. Sand *Martin-Marietta (Davis, OK) P/S # m002285005*	Sand *General Materials Inc (OKC, OK) P/S # m001911402*	Fine R.A.P. *Contractor / Project Site P/S # Contractor*			Comb. Agg.	JMF	Min.	Max.	% Tol. (±)
1 in (25 mm)	100	100	100	100	100	100			100	100	100	100	0
3/4 in (19 mm)	91	100	100	100	100	100			99	99	92	100	7
1/2 in (12.5 mm)	53	81	100	100	100	99			89	89	82	96	7
3/8 in (9.5 mm)	34	52	100	100	100	94			78	78	71	85	7
#4 (4.75 mm)	3	17	80	92	99	74			56	56	49	63	7
#8 (2.36 mm)	2	3	52	52	99	54			39	39	34	44	5
#16 (1.18 mm)	1	3	36	30	97	41			31	31	27	35	4
#30 (.600 mm)	1	2	26	18	92	34			25	25	21	29	4
#50 (.300 mm)	1	2	19	10	60	25			18	18	14	22	4
#100 (.150 mm)	1	2	14	6	12	15			9	9	6	12	3
#200 (.075 mm)	0.8	1.7	10.7	3.4	1.7	9.5			5.2	5.2	3.2	7.2	2
AC Content %						5.8			4.4	4.4	4.0	4.8	0.4

Mix temperature @ discharge from mixer, °F (°C): 305 (152) **Required** ± 20 °F (± 10 °C)
Optimum roadway compaction temperature, °F (°C): 290 (143)

Tests on Asphalt Cement **Found**
Specific Gravity @ 77 ° F   1.0100

Tests on Compressed Mixtures (@ Design AC)

	# Gyr.	% Density of Gmm	% Density Required
Nini	7	88.1	85.5 - 90.5
Ndes	75		96
Nmax	115	96.6	< 98.4

Tests on Aggregates		**Req.**	
Durability Index	76	40	min.
F.A.A. %U	43.5	40	min.
Flat and Elongated	0	10	max.
Fractured Faces	100/100	65/65	min.
Insoluble Residue		N/A	
LA Abrasion	21	40	max.
Micro-Deval	11.8	25	max.
Permeability	6.4	12.5	max.
Sand Equivalent	78	40	min.
IOC	0.40%		
Gse	2.722		
Gsb	2.671		
Specimen Weight	4945		

Requires Form 93-E0 signed by the Department for production use.
-Oklahoma D.O.T. Materials-

Tests on Compressed Mixtures

%AC	Gmb	Gmm	% Density of Gmm	% Density Required min.	% Density Required max.	% VMA	% VMA Req. min.	% VFA	% VFA Required min.	% VFA Required max.
4.1	2.397	2.545	94.2			13.9		58.3		
4.6	2.437	2.525	96.5	95	97	13.0	13	73.1	65	78
5.1	2.463	2.505	98.3			12.5		86.4		

Dust Prop.	DP Required min.	DP Required max.
1.5	0.6	1.6
1.3		
1.2		

ITS (PSI)   198.8   75 (min.)
TSR   0.87   Design (min.): 0.80   Field (min.): 0.75
Compacted Wt. (lbs/sy/1" thick) =   111.4   @   4.4   % Asphalt Cement
2.9   % New Asphalt Cement

APA Rut Test Depth (mm):   0.96   6 max.

Comments:

Last Modified By: Schratwieser, Edward P.   eschratw   Date: 11/18/2009
(User Name and User ID)   *(mm/dd/yyyy)*

Figure A.3   Mix Design Sheet for S3 Mix with 25% RAP1 (Provided by the Contractor)

OKLAHOMA DEPARTMENT OF TRANSPORTATION Mix Design Report

Asphalt Concrete, Type S4 (PG 64-22 OK)	asco012	Insoluble
(Material Full Name and Material Code)		(Design Type)
PMI - Silver Star	m00565	s4pv0160792200
(Producer/Supplier and P/S Code)		(Mix ID)
		0.3M+
		(ESALs)

MATERIAL	SOURCE	%USED
5/8" Chips	Hanson Aggregates @ Davis, OK(5008)	25
1/2" Chips	Hanson Aggregates @ Davis, OK(5008)	18
Screenings	Hanson Aggregates @ Davis, OK(5008)	42
Sand	G.M.I. @ Oklahoma City, OK(1402)	15
Asphalt Cement (PG64-22OK)	Valero @ Ardmore, OK(m00352)	

Aggregate Percent Passing	5/8" Chips	1/2" Chips	Scrns	Sand	Combined Aggregate	Job Formula	JMF Tolerance
3/4"	100				100	100	± 0
1/2"	83	100			96	96	± 7
3/8"	58	93	100	100	88	88	± 7
No. 4	20	34	73	99	57	52	± 7
No. 8	3	7	45	95	35	34	± 5
No. 16	2	2	31	91	28	28	± 4
No. 30	2	2	23	83	23	23	± 4
No. 50	2	1	17	47	15	15	± 4
No. 100	2	1	13	6	7	7	± 3
No. 200	1.3	1.7	9.0	1.0	4.6	4.6	± 2
%AC Asphalt Cement (PG64-22OK)						5.1	± 0.4
Mix Temperature @ discharge from Mixer, °F						305	± 20
Optimum Roadway Compaction Temperature, °F						290	

Tests on Asphalt Cement:

	Found
Spec. Grav. @ 77 °F	1.0140

Tests on Aggregates:

	Found	Required
F.A.A..%U.	46.9	40 Min.
Sand Equivalent	67	40 Min.
L.A. Abrasion	18	40 Max.
Durability (DC)	75	40 Min.
IOC	0.72	
Insoluble Residue	88.8	30 Min.
Fractured Faces	100/100	75/75 Min.
Gse	2.699	
Gsb	2.670	
Specimen Wt.	4835	

Tests on Compressed Mixtures (at Design AC Content):

	SGC	Dens. % o Gmm	Dens. % of Gmm Req'd
Nini	7	87.1	85.5-90.5
Ndes	75	96	96
Nmax	115	96.8	< 98

Tests on Compressed Mixtures:

Percent Asphalt	Gmb	Gmm	Dens. % of Gmm	Dens. % of Req'd of Gmm	V.M.A. (%)	V.M.A. (Min.%)	%VFA	%VFA Req'd	%DP	%DP Req'd
4.6	2.335	2.507	93.1		16.6		58.5		1.09	
5.1	2.368	2.488	95.2	95-97	15.8	14	69.6	65-78	0.97	0.6-1.6
5.6	2.384	2.469	96.6		15.7		78.1		0.88	

Layer Depth: ≤ 4"
TSR: 0.85 0.80 Min. (0.75 Min. Field) Req'd
Compacted Wt. 108.9 lbs./sq.yd./1" thickness
Lab Permeability Test(cm/sec) - 3 x10⁻⁵ (Required: 12.5x10⁻⁵ Max.)
APA Rut Test(mm) - 1.39 (Required: 6 mm Max.)
MicroDeval (% Wear) - 7.7 (Required: 25 Max.)
ITS (psi) - 270.3 (Required: 75 psi Min.)

Figure A.4   Mix Design Sheet for S4 Mix without any RAP1 (Provided by the Contractor)

OKLAHOMA DEPARTMENT OF TRANSPORTATION Mix Design Report

Asphalt Concrete, Type S3 (PG64-22OK)   asco009   Binder-Recycle
_____(Material Full Name and Material Code)_____   _____(Design Type)_____
Schwarz Paving Co., Inc.   m00432   s3pv0160800901
_____(Producer/Supplier and P/S Code)_____   (Mix ID)
                                                                             3M+
                                                                             (ESALs)

MATERIAL	SOURCE	%USED
1 1/2" Rock	The Dolese Co. @ Davis, OK(5002)	10
5/8" Chips	Martin Marietta @ Davis, OK(5005)	22
Stone Sand	The Dolese Co. @ Davis, OK(5002)	23
Screenings	The Dolese Co. @ Davis, OK(5002)	10
Sand	The Dolese Co. @ Mustang, OK	10
Coarse R.A.P.	Stockpile @ Plantsite	25
Asphalt Cement (PG64-22OK)	Valero @ Ardmore, OK(m00352)	

Aggregate Percent Passing	1 1/2" Rock	5/8" Chips	Stone Sand	Scrns	Sand	R.A.P.	Combined Aggregate	Job Formula	JMF Tolerance
1"	100					100	100	100	± 0
3/4"	77	100				99	97	97	± 7
1/2"	41	72				96	87	87	± 7
3/8"	21	22		100		91	73	*81	± 7
No. 4	2	1	100	90		74	61	61	± 7
No. 8	1	1	71	59	100	57	47	47	± 5
No. 16	1	1	35	38	98	45	33	33	± 4
No. 30	1	1	14	26	91	37	24	24	± 4
No. 50	1	0	5	19	50	28	15	15	± 4
No. 100	1	0	3	15	7	16	7	7	± 3
No. 200	0.7	0.2	1.7	12.3	0.5	9.6	4.2	4.2	± 2
%AC (PG64-22OK)						5.0		4.2	± 0.4

Mix Temperature @ discharge from Mixer, °F 305   ± 20
Optimum Roadway Compaction Temperature, °F 290

Tests on Asphalt Cement:

	Found
Spec. Grav. @ 77 °F	1.01 Est.

Tests on Aggregates:

	Found	Required
F.A.A. %U	45.2	40 Min.
Sand Equivalent	81	45 Min.
L.A. Abrasion	23	40 Max.
Durability (DC)	74	40 Min.
IOC	0.19	
Fractured Faces	100/100	75/75 Min.
Gse	2.698	
Gsb	2.680	
Specimen Wt	4920	

Tests on Compressed Mixtures (at Design AC Content):

	SGC	Dens. % o Gmm	Dens. % of Gmm Req'd
Nini	8	88.8	85.5-89
Ndes	100	96	96
Nmax	160	96.8	< 98

Tests on Compressed Mixtures:

Percent Asphalt	Gmb	Gmm	Dens. % of Gmm	Dens. % of Req'd of Gmm	V.M.A. (%)	V.M.A. (Min.%)	%VFA	%VFA Req'd	%DP	%DP Req'd
4.1	2.419	2.525	95.8		13.4		68.8		1.08	
4.6	2.431	2.505	97.0	95-97	13.5	13	77.9	65-76	0.96	0.6-1.6
5.1	2.449	2.486	98.5		13.3		88.8		0.86	

Mix Layer Depth: > 4 in.
TSR - 0.80 0.80 Min. (0.75 Min. Field) Required
Compacted Wt. - 110.9 lbs/sq.yd/ 1" thickness
Lab Permeability Test(cm/sec) -2 x10⁻⁵ (Required: 12.5x10⁻⁶ Max.)
APA Rut Test Depth(mm) - 1.15 (Required: 5 mm Max.)
Recommended 3.0 % New Asphalt Cement
MicroDeval (% Wear) - 17.8 (Required: 25 Max.)
ITS (psi) - 275.0 (Required: 75 psi Min.)
*REVISED (GRAD.) Effective 7/14/08 per contractor's request.

MEETS SPECIFICATION REQUIREMENTS for 708-3(a-g)99 Rev. 6/3/04
                                       708-10(a-c)99 Rev. 6/3/04

Figure A.5   Mix Design of S3+25% RAP2

Oklahoma Department of Transportation Mix Design Report
(Submittal-For Acceptance Only)

Asphalt Concrete, Type S3 (PG 64-22 OK)   Mat'l. Code: asco009
(Material Full Name and Material Code)

Binder - Recycled   ID: B2
(Design Type and Design Type ID)

Schwarz Paving Co., Inc.   P/S # m00432
(Producer/Supplier Name and Producer/Supplier Code)

S3qc0071100100
(Mix ID)

Schwarz Paving (West OKC, OK) - 300TPH   PLANT ID # m00432-01
(Plant Name and Plant ID)

(Project Number)

(Job Piece Number)   *(Contract ID)*   *(County)*   *(Highway)*

(Contractor)

< or = 4 in. (100 mm)
(Depth From Surface)

3M+
(ESALs)

Aggregate	Producer/Supplier	% USED
1 1/2" Rock	Dolese Co (Davis, OK) P/S # m002745002	18
5/8" Chips	Dolese Co (Davis, OK) P/S # m002745002	42
Fine R.A.P.		40

Asphalt Additive, Anti-Strip
(Product Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)

Asphalt Cement: Asphaltic Cement Type PG 64-22 OK, acem003, Valero Energy Corp (Muskogee, OK), m00788
(Material Full Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)

For Acceptance Only
Not for production use

Producer/Supplier:	Dolese Co (Davis, OK) P/S # m002745002	Dolese Co (Davis, OK) P/S # m002745002							Comb. Agg.	JMF	Min.	Max.	% Tol. (±)
Sieve Size	1 1/2" Rock	5/8" Chips	Fine R.A.P.										
1 in (25 mm)	97	100	100						99	99	99	99	0
3/4 in (19 mm)	73	100	100						95	95	88	100	7
1/2 in (12.5 mm)	30	91	98						83	83	76	90	7
3/8 in (9.5 mm)	15	56	92						63	63	56	70	7
#4 (4.75 mm)	1	1	70						29	29	22	36	7
#8 (2.36 mm)	0	0	52						21	21	16	26	5
#16 (1.18 mm)	0	0	38						15	15	11	19	4
#30 (.600 mm)	0	0	30						12	12	8	16	4
#50 (.300 mm)	0	0	23						9	9	5	13	4
#100 (.150 mm)	0	0	14						6	6	3	9	3
#200 (.075 mm)	0.1	0.3	9.4						3.9	3.9	1.9	5.9	2
AC Content %			5.5						5.1	5.1	4.7	5.5	0.4

	°F (°C)	Required
Mix temperature @ discharge from mixer:	305 (152)	± 20 °F (± 10 °C)
Optimum roadway compaction temperature:	290 (143)	
Laboratory mixing temperature:	325 (163)	
Laboratory compaction temperature:	300 (149)	

Tests on Aggregates		Required		Units
Durability Index	74	40	min.	%
Flat and Elongated	0	10	max.	%
Fractured Faces	100/100	85/80	min.	%
LA Abrasion	22	40	max.	%
Micro-Deval	16.2	25	max.	%

Tests on Asphalt Cement	Found
Specific Gravity @ 77 ° F	1.0100

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Not for production use

Tests on Compressed Mixtures (@ Design AC)

	# Gyr.	% Density of Gmm	% Density Required
Nini	8	85.5	85.5 - 89.4
Ndes	100		96
Nmax	160	97.9	< 98.4

Gse	2.704
Gsb	2.655
Specimen Weight	4916 g

Tests on Compressed Mixtures

%AC	Gmb	Gmm	% Density of Gmm	% Density Required min.	% Density Required max.	% VMA	% VMA Req. min.	% VFA	% VFA Required min.	% VFA Required max.
4.5	2.391	2.514	95.1			14.0		65.0		
5.0	2.400	2.503	95.9	95	97	14.1	13	70.9	65	76
5.5	2.405	2.487	96.7			14.4		77.1		

Dust Prop.	DP Required min.	DP Required max.
1.0		
0.9	0.6	1.6
0.8		

ITS (PSI)   133.6   75 (min.)
TSR   0.86   Design (min.): 0.80   Field (min.): 0.75
Compacted Wt. (lbs/sy/1" thick) =   109.6   @   5.1   % Asphalt Cement
2.9   % New Asphalt Cement

MEETS SPECIFICATION REQUIREMENTS

Comments: Prepared at the University of Oklahoma (Broce Lab.) for research purpose.

Figure A.6   Mix Design of S3+40% RAP2

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Oklahoma Department of Transportation Mix Design Report
(Submittal-For Acceptance Only)

Asphalt Concrete, Type S4 (PG 64-22 OK) Mat'l. Code: asco012
(Material Full Name and Material Code)

Binder - Recycled ID: B2
(Design Type and Design Type ID)

Schwarz Paving Co., Inc. P/S # m00432
(Producer/Supplier Name and Producer/Supplier Code)

S4qc0071100100
(Mix ID)

Schwarz Paving (West OKC, OK) - 300TPH PLANT ID # m00432-01
(Plant Name and Plant ID)

(Project Number)

(Job Piece Number) *(Contract ID)* *(County)* *(Highway)*

(Contractor)

< or = 4 in. (100 mm)
(Depth From Surface)

3M+
(ESALs)

Aggregate	Producer/Supplier	% USED
5/8" Chips	Dolese Co (Davis, OK) P/S # m002745002	45
Scrns.	Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008	18
Stone Sand	Dolese Co (Davis, OK) P/S # m002745002	17
Sand		10
Fine R.A.P.		10

Asphalt Additive, Anti-Strip
(Product Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)

Asphalt Cement: Asphaltic Cement Type PG 64-22 OK, acem003, Valero Energy Corp (Muskogee, OK), m00788
(Material Full Name, Material Code, Producer/Supplier Name, Producer/Supplier Code)

Producer/Supplier:
Dolese Co (Davis, OK) P/S # m002745002
Hanson Aggregates, WRP Inc (Davis, OK) P/S # m001985008
Dolese Co (Davis, OK) P/S # m002745002

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Not for production use

Sieve Size	5/8" Chips	Scrns.	Stone Sand	Sand	Fine R.A.P.			Comb. Agg.	JMF	Min.	Max.	% Tol. (±)
3/4 in (19 mm)	100	100	100	100	100			100	100	100	100	0
1/2 in (12.5 mm)	91	100	100	100	98			96	96	89	100	7
3/8 in (9.5 mm)	56	100	100	100	92			79	79	72	86	7
#4 (4.75 mm)	1	100	100	100	70			52	52	45	59	7
#8 (2.36 mm)	0	78	77	100	52			42	42	37	47	5
#16 (1.18 mm)	0	50	42	100	38			30	30	26	34	4
#30 (.600 mm)	0	33	20	98	30			22	22	18	26	4
#50 (.300 mm)	0	21	8	74	23			15	15	11	19	4
#100 (.150 mm)	0	12	3	14	14			5	5	2	8	3
#200 (.075 mm)	0.3	6.9	1.6	1.1	9.4			2.7	2.7	0.7	4.7	2
AC Content %					5.5			5.8	5.8	5.4	6.2	0.4

	°F (°C)	Required
Mix temperature @ discharge from mixer:	305 (152)	± 20 °F (± 10 °C)
Optimum roadway compaction temperature:	290 (143)	
Laboratory mixing temperature:	325 (163)	
Laboratory compaction temperature:	300 (149)	

Tests on Aggregates	Required		Units
Durability Index	75	40 min.	%
Flat and Elongated	0	10 max.	%
Fractured Faces	100/100	85/80 min.	%
LA Abrasion	22	40 max.	%
Micro-Deval	14.3	25 max.	%

Tests on Asphalt Cement	Found
Specific Gravity @ 77 ° F	1.0100

For Acceptance Only
Not for production use

Tests on Compressed Mixtures (@ Design AC)

	# Gyr.	% Density of Gmm	% Density Required
Nini	8	88.3	85.5 - 89.4
Ndes	100		96
Nmax	160	97.1	< 98.4

Gse	2.703
Gsb	2.643
Specimen Weight	4942	g

Tests on Compressed Mixtures

%AC	Gmb	Gmm	% Density of Gmm	% Density Required		% VMA	% VMA Req.	% VFA	% VFA Required	
				min.	max.		min.		min.	max.
5.0	2.342	2.494	93.9	95	97	15.8	14	61.4	65	76
5.5	2.361	2.472	95.5			15.6		71.2		
6.0	2.372	2.456	96.6			15.6		78.2		

Dust Prop.	DP Required		ITS (PSI)	119.8	75 (min.)			
	min.	max.	TSR	0.69	Design (min.): 0.80	Field (min.): 0.75		
0.7	0.6	1.6	Compacted Wt. (lbs/sy/1" thick) =	108.4	@	5.8	% Asphalt Cement	
0.7						5.3	% New Asphalt Cement	
0.6								

MEETS SPECIFICATION REQUIREMENTS

Comments: Prepared at the University of Oklahoma (Broce Lab.) for research purpose. Use of anti stripping agent is recommended.

Figure A.7 Mix Design of S4+10% RAP2

A.D. No.	011-025-008	Mix Type S4 Recycle	Design #		S4PV0160802700	
Project #	Various Projects		Location	Various Projects	ESALs	3M+
Contractor	Schwarz Paving Co., Inc.			Producer	Schwarz Paving Co., Inc.	

Aggregate Type	Aggregate Used	% USED
5/8" Chips	Dolese @ Davis, Ok (5002)	30
Screenings	Dolese @ Davis, Ok (5002)	18
Stone Sand	Dolese @ Davis, Ok (5002)	17
Sand	Dolese @ Mustang, Ok	10
RAP	Plant Stockpile	25

PG 64-22 OK   Valero @ Ardmore, Okla.(m00352)

Sieve Size	5/8" Chips	Screenings	Stone Sand	Sand	RAP	Comb. Agg.	JMF	% Tol.
1 1/2"	100	100	100	100	100	100	100	0
1"	100	100	100	100	100	100	100	0
3/4"	100	100	100	100	99	100	100	± 7
1/2"	98	100	100	100	95	98	98	± 7
3./8"	69	100	100	100	87	87	87	± 7
No. 4	8	86	99	100	67	61	61	± 7
No. 8	2	58	67	100	54	46	46	± 5
No. 16	2	40	36	99	44	35	35	± 4
No. 30	1	28	19	95	36	27	27	± 4
No. 50	1	20	9	66	26	19	19	± 4
No. 100	1	16	4	16	16	9	9	± 3
No. 200	1.0	12.4	2.5	1.0	8.7	5.2	5.2	± 2
% Asphalt Cement					4.9		4.6	± 0.4
Mix Temperature @ discharge from Mixer, Deg. F							325	
Optimum RoadwayCompaction Temperature, Deg. F							305	

Tests on Asphalt Cement
pecific Gravity   1.01

Tests on Compressed Mixtures (at Design AC Content)

	SGC	Dens. % of Gmm	Dens. % of Gmm req'd
Nini	8	88.8	<89
Ndes	100	96.1	96
Nmax	160	97.4	<98

Tests on Aggregates		Req.
Sand Equivalent	80	40 min.
Fine Aggregate Angularity	45.0	45 min.
L.A. Abrasion	24.4	40 max.
Durability Index	74	40 min.
Insoluable Residue	40.4	40 min.
IOC	0.13%	
Fractured Faces	100/100	65/65
BSG	2.674	
ESG	2.695	
Specimen Weight	4885	
Flat and Elongated Particles	0	10 max.

Tests on Compressed Mixtures :

% AC	Gmb	Gmm	Dens. % of Gmm	Density Req.	V.M.A.	Air Voids	V.F.A.	V.F.A. Req'd	% DP	% DP Req.
4.6	2.405	2.503	96.1		14.2	3.9	72.6		1.21	
5.1	2.429	2.483	97.8	95-97	13.8	2.2	84.2	65-78	1.08	0.6-1.6
5.6	2.443	2.464	99.1		13.8	0.9	93.7		0.98	

Tensile Strength Ratio: 0.81   0.80 Min. (0.75 Min. Field) Required
kg/sq.m/25mm thickness   58.8   @   4.6   % Asphalt Cement
Mix Layer Depth: 100mm >

MEETS SPECIFICATION REQUIREMENTS

Figure A.8   Mix Design of S4+25%RAP2