Laboratory and Field Evaluation of Plant Produced Asphalt Mixtures Containing RAP in Hot Climate Areas

by

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ABSTRACT

The use of Reclaimed Asphalt Pavements (RAP) in newly produced asphalt mixtures has been gaining a wide attention from state Departments of Transportations (DOTs) during the past four decades. However, the performance of these mixtures in harsh and hot climate areas such as Phoenix, Arizona has not been carefully addressed. This research focuses on evaluating the laboratory and field performance of Hot Mix Asphalt Mixtures (HMA) produced with two different RAP contents 15%, and 25%. A road section was identified by the City of Phoenix where three test sections were constructed; the first being a control (0% RAP), the second and the third sections with 15% and 25% RAP contents, respectively. The 25% RAP mixture used a lower Performance Grade (PG) asphalt per local practices. During construction, loose HMA mixtures were sampled and transported to the laboratory for advanced material characterization.

The testing included Dynamic Modulus (DM) test to characterize the stiffness of the material, Flow Number (FN) test to characterize the rutting resistance of the mixtures, IDEAL CT test to characterize the crack initiation properties, C* Fracture test to investigate the crack propagation properties, Uniaxial Fatigue to evaluate fatigue cracking potential, and Tensile Strength Ratio test (TSR) to evaluate the moisture susceptibility. Field cores were obtained from each test section and were tested for indirect tensile strength characteristics. In addition, asphalt binder testing was done on the extracted and recovered binders.

The laboratory results, compared to the control mixture, indicated that adding 15% and 25% RAP to the mix did not have significant effect on the stiffness, improved the rutting potential, had comparable cracking potential, and gave an acceptable passing

performance against potential moisture damage. The binder testing that was done on the extracted and recovered binders indicated that the blended RAP binder yields a high stiffness. Based on results obtained from this study, it is recommended that the City of Phoenix should consider incorporating RAP in their asphalt mixtures using these low to moderate RAP contents. In the future implementation process, it is also recommended to include specifications where proper mixture designs are followed and supported with some of the laboratory tests outlined in this research.

This thesis is dedicated to my Mother Hanadi Dayekh, for her love, sacrifice, and dedication. Without her endless support and encouragement, I would not be here today

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TABLE OF CONTENTS

Page

CHAPTER Page

CHAPTER Page

LIST OF TABLES

Table Page

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

CHAPTER 1 INTRODUCTION

1.1- Background

The American Society of Civil Engineers ASCE (2017) report card graded the road network in the United States with a grade D. There are more than four million miles of roads in the US, in which 21% have a poor pavement condition. This poor pavement condition has cost the US motorist around 120.5 billion dollars in vehicle repairs in 2015 alone (ASCE, 2017).

The highway system in the US has been underfunded for years, causing an $836 billion of backlog in highway and bridge funding. Among this backlog, $420 billion are needed just for existing highways repair. Failure to spend this amount of money on the infrastructure, the economy will lose around $4 trillion in the Gross Domestic Product (GDP), resulting in a loss of 2.5 million jobs by 2025. This loss will cost each household a $3400 each year. Hot Mix Asphalt (HMA) pavements constitutes more than 90% of the road network in the US. The materials cost represents a large portion of the total asphalt pavement construction process, as seen in Figure 1 (Copeland, 2011). Thus, reducing the cost of HMA production will save a lot of money, and will allow the Departments of Transportation (DOTs) to make better use of their budgets in maintaining and rehabilitating the road network. The use of Reclaimed Asphalt Pavements (RAP) as a component in the new produced HMA will reduce the needed amount of virgin aggregates and virgin binder, which may lead to cost reduction and, more importantly, energy conservation and recyclability program, leading to sustainable pavements implementation. In order to have a successful use of RAP in HMA, the inclusion of RAP shouldn’t compromise the performance of the pavement.

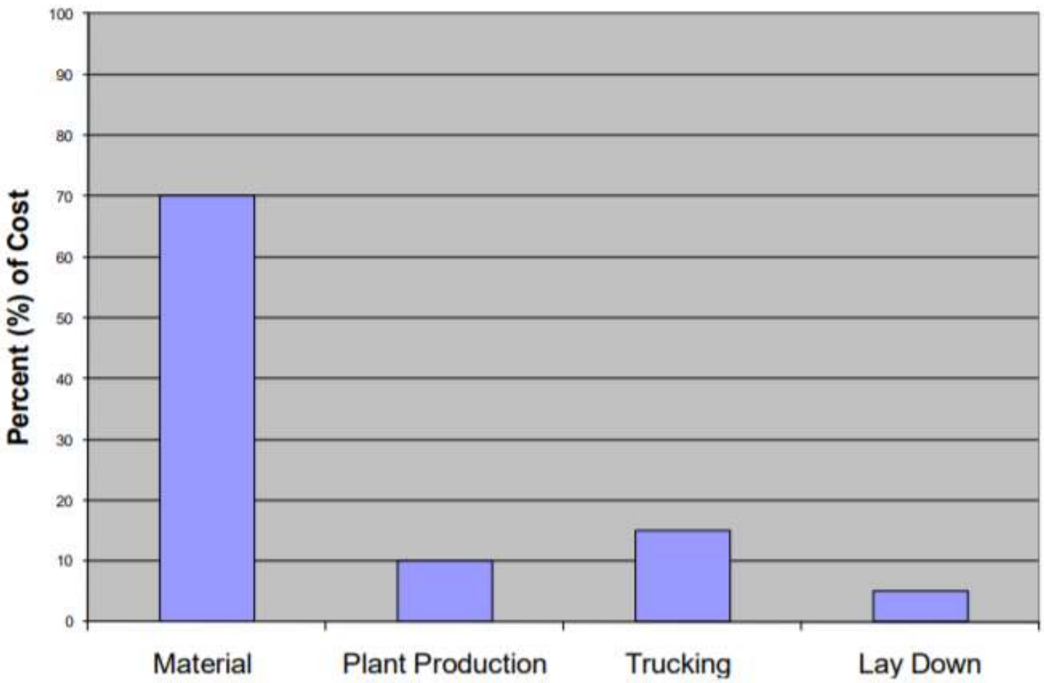


Figure 1. Cost of Different Pavement Construction Components (Adapted from Copeland, 2011)

According to the National Asphalt Pavement Association NAPA (2017), around 76.2 million tons of RAP were used in newly produced asphalt mixtures in 2017. This amount of RAP has reduced the need of 21.5 million barrels of asphalt binder, and more than 72 million tons of aggregates, which led to a saving of more than $2.1 billion.

Although asphalt is the most recycled material in the US, yet, 102.1 million tons of asphalt still stockpiled at the end of the 2017. Also, agencies have limited the use of RAP in their asphalt mixtures. There are concerns regarding increasing the RAP content in the newly produced asphalt mixtures by both state agencies and contractors. The most common challenges for the state DOTs in using more RAP are many; such as RAP quality and consistency, mix design procedure and volumetric requirements, degree of blending and binder selection, risk of compromising cracking performance and durability, and the use of RAP with polymers. Whereas, contractors are facing the following barriers in using more RAP: dust and moisture contents of RAP, the need to increase the quality control on the production and construction of pavements with RAP mixtures, the control of RAP properties, and most importantly, the limitations of State DOTs specifications. Figure 2 shows the most common factors that limit the increase of RAP contents. As the figure shows, the specification limits are the most common reported factor. The specification limits are usually set by owner agencies based on their previous experience with RAP performance.

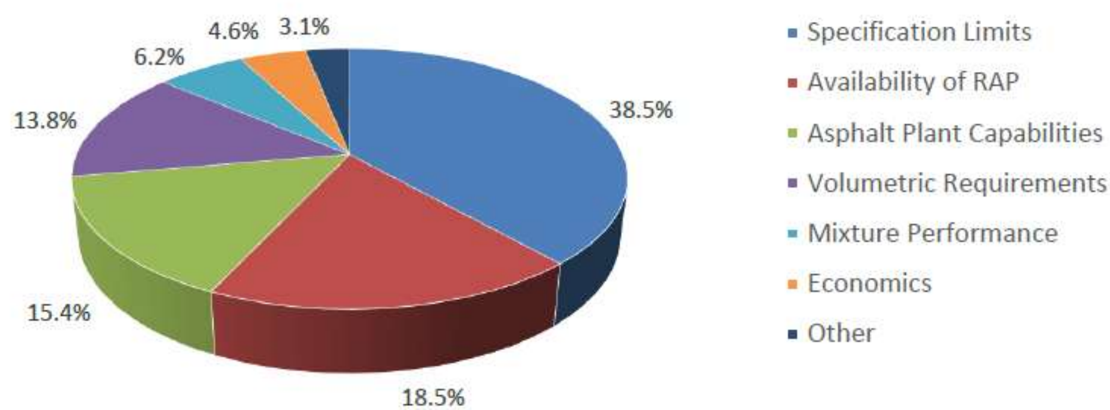


Figure 2. Road Blocks Behind Using More RAP (Adapted from NAPA, 2017)

During its service life, asphalt pavements are subjected to aging mainly due to sun, ultraviolet radiations, and oxygen. This aging process results in the stiffening of the material. Several studies have reported a successful use of RAP with a satisfying performance. However, the performance of pavements with RAP in harsh hot climate is yet to be studied. Arizona is one example that experience hot climate. Figure 3 shows the use of RAP in the US between 2013 and 2017. As the figure shows, Arizona (at the State level) doesn't use more than 15% of RAP in its asphalt mixtures. Thus, the performance of using higher RAP contents in hot climate areas is yet to be studied, especially at the level of public works. This thesis focuses on studying the performance of RAP mixtures, with higher RAP content, for the City of Phoenix, Arizona.

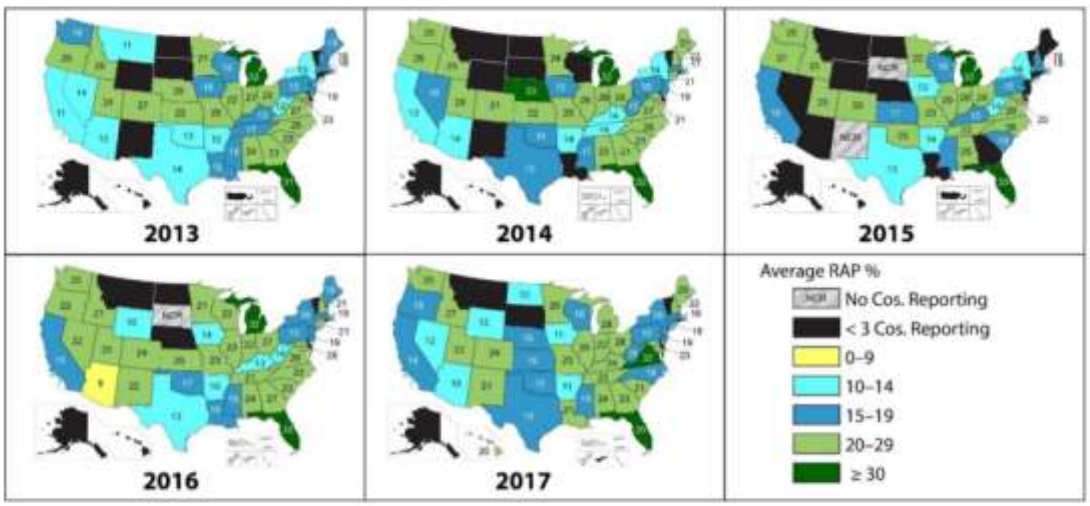


Figure 3. RAP Usage in the US Between 2013 And 2017 (Adapted from NAPA, 2017)

1.2- Study Objective

The objective of the study presented herein is to evaluate the laboratory and field performance of asphalt mixtures containing different percentage of RAP for the City of Phoenix, Arizona.

1.3- Scope of Work

Although many researchers have studied the performance of RAP mixtures, the performance of these mixtures in hot climate areas with plant produced mixtures-in the absence of RAP size control- is yet to be studied. This study will cover the work done in the literature with a focus on RAP in hot climate areas. In cooperation with the City of Phoenix, three road sections with different RAP percentages (0%, 15%, and 25%) used in an asphalt base layer were constructed in Phoenix, Arizona. A PG 70-10 was used for both the control and 15% RAP mixtures per Maricopa Association of Governments (MAG) specification. For the 25% RAP mixture, a drop of one binder grade was used (PG 64-16) per the Maricopa Association of Governments (MAG) specifications. The laboratory testing program included assessment of mixture stiffness through the Dynamic Modulus test, mixture resistance to each of (i) rutting (through Flow Number test), (ii) Fatigue (through Uniaxial Fatigue test), and (iii) Moisture Damage (through Tensile Strength Ratio). In addition, the crack initiation and propagation properties of the three mixtures were studied through the Indirect Tension Test (IDT) and C* Fracture test, respectively. Extraction and recovery of the asphalt binder were performed on the sampled material and the following tests were conducted using the Dynamic Shear Rheometer (DSR): (i) Complex Modulus, (ii) Multiple Stress Creep and Recovery (MSCR), and (iii) Performance Grading (PG). Field cores from the test sections were extracted and tested for their indirect tensile strength properties. The experimental plan is shown in Figure 4.

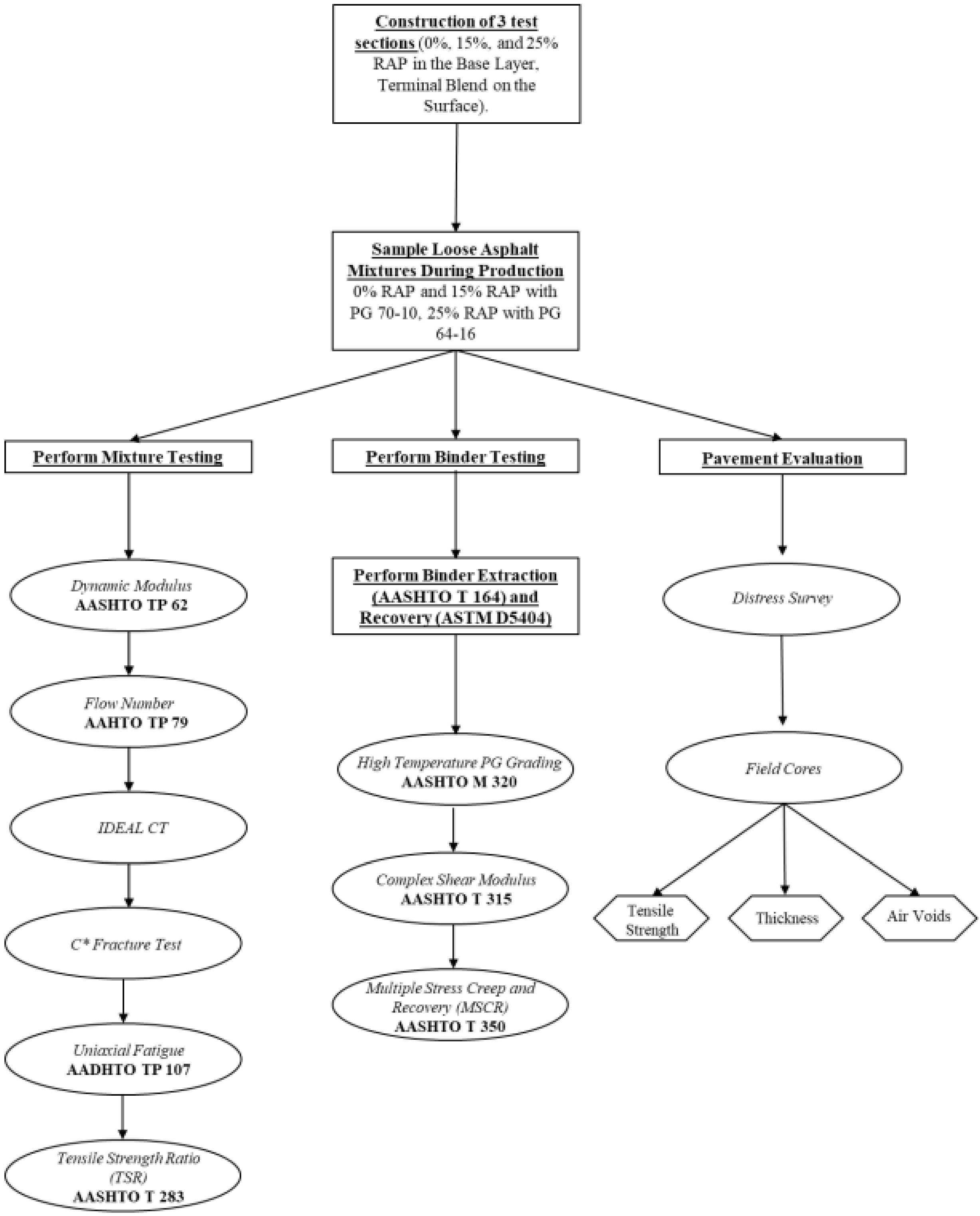


Figure 4. Experimental Plan

1.4- Thesis Organization

This thesis is divided into seven chapters. Chapter 1 gives the introduction, some background about RAP research, and identifies the objective and scope of this work. Chapter 2 provides a summary of the literature review with a focus on using RAP in Arizona. Chapter 3 documents the road test sections construction, and some information about the material used in this study. Chapter 4 presents the mixture level testing and analysis. Chapter 5 includes the binder level testing and analysis. Chapters 6 reports the field cores testing results and analysis. Finally, Chapter 7 provides a summary and conclusions of the study.

CHAPTER 2 LITERATURE REVIEW

2.1- RAP Background

At the end of its service life, asphalt pavement materials still have a value and can be used to construct new asphalt pavements. Reclaimed Asphalt Pavement (RAP), which is basically obtained from old asphalt, can be mixed with different percentages of virgin aggregates and binder to produce a new asphalt.

Serious interest in using RAP in the US started in 1970s when the nation experienced an oil embargo leading to very expensive oil products. Before that time, the cost of recycling asphalt was higher than using virgin materials due to old equipment. After 1970s, serious attention about the feasibility of using RAP has started, in which agencies started incorporating RAP in their mixtures. Among these agencies, some of them witnessed positive benefits and others experienced different problems mainly related to cracking. Regardless of these failures, many agencies persisted on the importance of using RAP in their mixtures, and after more than two decades of trial and error, best practices were identified, and a better performance was obtained.

There are generally five different methods of recycling. These five methods can either be used alone or in conjunction with each other on a certain pavement section (ARRA, 2015). These methods are:

- Hot Recycling
- Hot In-Place Recycling (HIR)
- Cold In-Place Recycling (CIR)
- Cold Central Plant Recycling (CCPR)
- Full Depth Reclamation (FDR)

2.1.1- Hot Recycling

Hot Recycling is a method of recycling in which RAP is combined with virgin aggregates and binder at a central plant. This RAP is usually a result of milling/removing of an old asphalt pavement that has been transported and stockpiled at the plant. Figure 5 is an example of such millings stockpiled at an asphalt plant. Then, these millings will be processed and stockpiled again, to make it ready to be incorporated in the newly produced mixtures. Figure 6 shows a processed RAP stockpile. This method utilizes the heat-transfer approach to soften the RAP binder to allow proper blending with the virgin binder. If the RAP binder is too stiff, it might not blend well and might be prone to cracking. This may lead to some adjustments in the RAP content or the amount of virgin aggregate and binder. Once the recycled mix has been produced, it can be transported to the site, placed, and compacted just as any regular asphalt.

Figure 5. Unprocessed Milled RAP

Figure 6. Processed RAP Stockpile

2.1.2- Hot In-Place Recycling (HIR)

During this method, asphalt is completely recycled on site. Usually, the treatment depth of an HIR is between 20 to 50 mm. During an HIR, asphalt is heated and softened so that it can be scarified or milled to the required depth. Then, the scarified material is mixed and placed and compacted using a conventional HMA paving equipment. During mixing, virgin aggregates, asphalt binder, or recycling agents can be added based on the need. Figure 7 describes the HIR process.

Figure 7. HIR Process (Adapted from Gallagher Asphalt Corporation, by Zeller Marketing and Design)

2.1.3- Cold In-Place Recycling

Cold recycling is a rehabilitation technique in which the deteriorated pavement materials are used in place without the application of heat. The RAP in this method is obtained by milling or crushing the in-place pavement. Virgin aggregates, asphalt binder, and recycling agents can be added to the RAP before laying it down and compacting it. CIR is suitable for a low volume roads that are not close to a central plant. Figure 8 shows an example of a CIR process.

Figure 8. CIR Process (Adapted from Asphalt Paving Systems)

2.1.4- Cold Central Plant Recycling (CCPR)

During CCPR, material is removed from the existing pavements and transported to a central plant. This material can be processed (screened or crushed) and then used again in the construction of new pavements. Similar to CIR, CCPR relies on the use of emulsion or foamed asphalt as a binding agent. Once the material and the agent are mixed, it can be transported to the project site, laid down, and compacted.

2.1.5- Full Depth Reclamation (FDR)

During FDR, the full asphalt pavement layer and portion of the underlying materials (base, subbase, or subgrade) is pulverized and mixed properly to provide an upgraded base material. Similar to CIR, the process is performed in the absence of heat. The FDR process is summarized in the following steps: reclamation of the existing pavement materials, adding virgin materials if required, proper mixing, initial laying down of the mix, compaction, then final shaping followed by an application of an asphalt surface or wearing course. This method produces a granular pavement layer which might be ready for direct use, have additional granular materials on top of it, or can be improved by adding stabilizing additives. Figure 9 shows and example of FDR project.

Figure 9. FDR Process (Adapted from SUIT-KOTE CORPORATION)

Among the recycling methods presented above, Hot plant recycling is the most common. In this process, mixtures containing RAP are produced and moved to the constructed site, before being laid down and compacted. However, in the mixing process, some sort of blending will occur between the virgin asphalt binder, and the aged asphalt binder on the RAP aggregates. The degree of blending will have a significant effect on the performance. The highly aged asphalt binder also plays an important role in the performance. Many researchers have found a successful performance of RAP, while others reported some failures. Yet, research on highly aged RAP in an extreme weather is yet to be studied. This chapter represents the state-of-the-art work in RAP research in the United States with a focus on Arizona.

2.2- RAP Asphalt Mixtures Performance Testing

Performing mixture testing on RAP is necessary to predict the performance especially when high RAP contents exist. Researchers have performed many studies to evaluate the effect of replacing RAP (with different contents) on the mechanical properties of the mix.

A study done by Shah et al (2007) investigated the effect of adding 3 different contents of RAP (15, 25, and 40%) on the stiffness and low temperature properties of the mix. The Indirect Tensile Strength (IDT) test was performed at three different temperatures (0, -10, and -20°C) and the strength values at -10℃ were used to calculate the critical cracking temperature. A PG 64-22 binder was used with the three RAP mixtures in addition to the control mix, another two mixtures were prepared by adding PG 58-28 to the RAP mixtures with both contents 25% and 40%.

The Dynamic Modulus test results indicated that adding 15% RAP on the mix significantly increase the stiffness values, whereas adding 25% RAP didn't have any significant effect. The high RAP content (40%) addition increases the stiffness significantly at warmer temperatures. However, increasing the RAP content from 15% to 25%, 15% to 40%, and from 25% to 40% significantly increased the stiffness.

The critical cracking temperature (Tc) indicated that mixture with 40% RAP has the highest cracking temperature, followed by 15% RAP, 25% RAP, and then control. The 25% RAP mix had a surprising critical cracking temperature as it was expected to show a higher one than the 15% RAP. Adding a softer binder to the mix had an improvement on the low temperature cracking potential of the 25% and 40% RAP mixtures by decreasing the Tc value compared to PG 64-22.

Shu et al (2008) evaluated the fatigue characteristics of HMA mixtures containing different RAP contents (0, 10, 20, and 30%). Both IDT and Beam Fatigue tests were conducted to evaluate the cracking potential of the 4 mixtures. The results indicated that mixtures with higher RAP contents had higher indirect tensile strength (ITS), lower toughness index, and lower strain at peak load. Conducting the Resilient Modulus test on the IDT specimens showed that increasing RAP content will lead to an increase in the stiffness. The beam fatigue test results analyzed with the plateau analysis method indicated that mixtures with higher RAP contents experience more damage that would result in shorter fatigue life. Although these results contradict the load cycles results, yet, the authors believed that the plateau method is more reasonable.

Loria et al (2011) conducted a field and laboratory study to investigate the effect of adding two RAP contents (15% and 50%) on moisture resistance and thermal cracking resistance of the asphalt mix. Two binders were used with the mixture that incorporates 50% RAP, PG 58-28, and PG 52-34. Materials were sampled from the field during construction and a laboratory fabricated samples were also prepared with the same virgin materials to compare both the field and laboratory results.

The moisture damage assessment was conducted by evaluating the measured tensile strength of unconditioned samples, in addition to samples conditioned with one freeze-thaw cycles, and samples conditioned with three freeze-thaw cycles. The results indicated that RAP increased the tensile strength of unconditioned and both one and three cycle conditioned samples. The results were consistent between the field and laboratory samples.

The dynamic modulus test was performed on unconditioned specimens, and specimens subjected to one and three freeze-thaw cycles. The results indicated that at a given freeze-thaw cycle, RAP mixtures had higher stiffness compared to the control one. This stiffness increased with increasing RAP content.

The thermal cracking resistance of the mixtures was evaluated using the Thermal Stress Restrained Specimen Test (TSRST) after multiple freeze-thaw cycles. The results showed that the 50% RAP without a grade change field mixture yielded a greater fracture temperature than both 0% and 15% RAP mixtures at unconditioned and conditioned specimens. However, the use of a softer binder resulted in a similar fracture temperature to that of the control mix.

A study by Apeagyei et al (2011) evaluated the rutting resistance of plant produced asphalt mixtures with different RAP contents. The dynamic modulus and flow number tests were performed to evaluate the stiffness and permanent deformation properties of the mixtures. 19 mixtures were evaluated in the study in which 8 were surface mixtures with Nominal Maximum Aggregate Size (NMAS) of 9.5 mm, another 8 were base mixtures with NMAS of 12.5 mm, and the remaining 3 are Stone Matrix Asphalt (SMA) with NMAS of 12.5 mm. In this study, a PG 70-22 binder was used for the mixtures with RAP content less than 20%, whereas mixtures with RAP content of more than 20% were prepared using PG 64-22.

The dynamic modulus testing results showed that stiffness has increased with the addition of 10% and 15% RAP, however, mixtures with 25% RAP content showed stiffness values similar to that of the control. The authors interpretation of these results is the softer binder that was used with the 25% RAP mixtures.

The flow number test results showed that incorporating 10% and 15% of RAP in the mix will lead to a significant increase in the flow number values compared to that of the 25% RAP with softer binder.

City of Phoenix 2017 Study

Similar to the work in this study, the City of Phoenix Public Works in conjunction with the Resource Innovation and Solutions Network (RISN) program at Julie Ann Wrigley Global Institute of Sustainability, Arizona State University (ASU), conducted a 2017 limited laboratory study to evaluate the viability of using RAP in future pavement maintenance and rehabilitation projects. The study also included a survey of current practices by local and national agencies. Overall, public works agencies in Arizona have been slow in adopting the use of RAP. The survey conducted on the current use of RAP is shown in Table 1.

Other uses of RAP in the table below were identified as backfills, dust control, dirt road stabilization and shoulders, among others.

The study reported RAP asphalt contents between 3.70% and 6.26%. The recovered binder Performance Grading (PG) results showed very stiff characteristics and as high as PG 130+26. Gradation of extracted aggregates from RAP were within specification limits of common mixtures. The mixture designs were conducted based on City of Phoenix

Table 1. Summary of Practices from Other Agencies – City of Phoenix 2017 Study (Arredondo, 2018)

Agency	Surface	Non-Surface	Unbound Base	Other
City of Phoenix			X*	X
Arizona Department of Transportation (ADOT)	X	X	X	X
Maricopa Association of Governments (MAG)		X	X*	X
Pima Association of Governments (PAG)	X	X	X	
Maricopa County Dept. of Transportation (MCDOT)		X	X*	X
East Valley Asphalt Committee (EVAC)		X		X
Apache Junction			X	X
Mesa		X	X	X
Queen Creek			X	X
Las Vegas (Nevada)	X	X	X	X
Nevada Department of Transportation (NDOT)	X	X	X	X
Texas Department of Transportation (TxDOT)	X	X	X	X
New Mexico Department of Transportation (NMDOT)	X	X	X	X
California Department of Transportation (Caltrans)	X	X	X	X

*Conditional

specifications for gyratory compaction and followed the Superpave methodology. The procedure to incorporate RAP was customized based on national and local practices.

Dynamic modulus and flow number test results showed no statistical difference between the RAP mixtures and control. The TSR testing showed that all mixtures performed well and above the specified minimum limit of 75% required by the City specifications.

The study indicated that the 15% RAP contents are feasible to use and will not affect greatly nor negatively the pavement performance based on the preliminary laboratory performance testing done at ASU.

Arredondo (2017) performed and expanded the City of Phoenix 2017 study as part of his master's thesis at ASU. He used two asphalt binders: PG 70-10 and PG 64-16 and four different RAP contents: 10%, 15%, 25% (using PG 70-10), and 25% content with the softer PG64-16 binder; this is in addition to a control mix (0% RAP).

Laboratory test results showed slightly higher modulus as RAP content increased. For TSR testing, all mixtures performed well and showed some improvement for the RAP mixtures.

CHAPTER 3 MATERIALS AND SECTIONS CONSTRUCTION

3.1- Pavement Structure

In this project, pavement designs that are typically used by the CoP were used for the test sections, except RAP was used in the base layer. These sections were constructed using a mixture with a Nominal Maximum Aggregate Size (NMAS) of ¾ inches in the base layer, and a Terminal Blend (TR) mixture with NMAS of ½ inch was used in the surface. The TR mix includes some polymer and rubber. Section 1 was a control, where Section 2 had a RAP replacement of 15 percent in the base layer, and Section 3 had a 25 percent RAP replacement in the base layer. Figure 10 shows a schematic of the three sections.

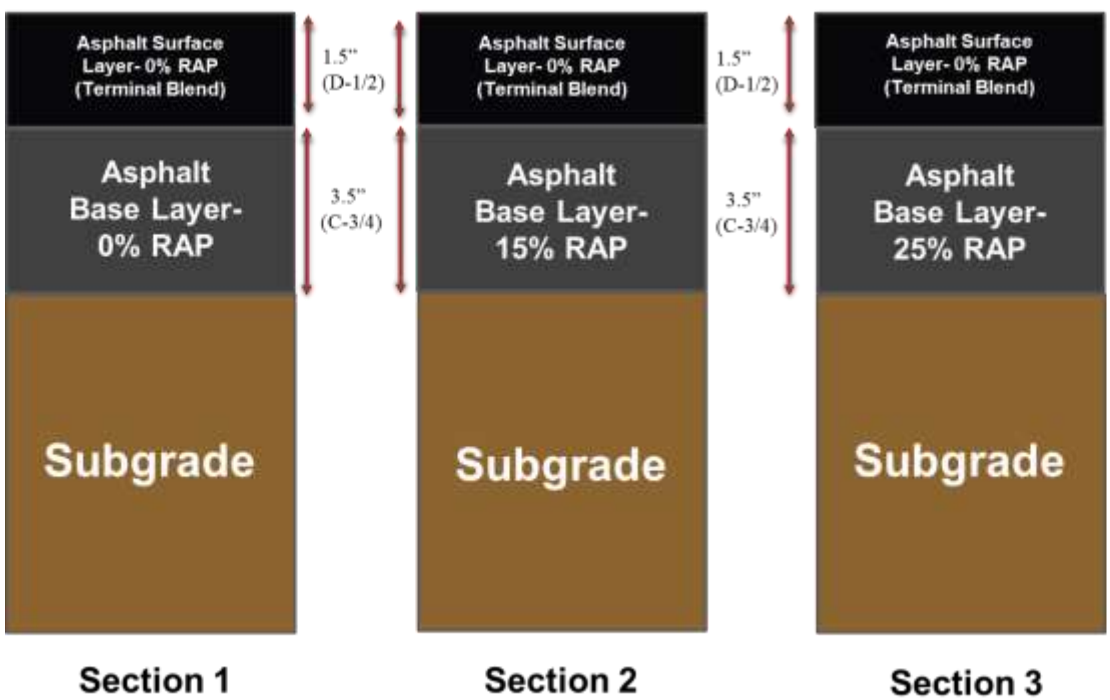


Figure 10. Pavement Structure of the Three Sections

3.2- Material Selection

The materials used in this project are the most widely used aggregates and binders in Phoenix. The RAP incorporated in sections 2 and 3 mixtures are a result of millings that are processed and stockpiled in the plant. Below are the properties of the materials selected, in addition to the mixture properties.

3.2.1- Aggregates

The aggregates used in this study are constantly used by contractors in the Phoenix Area. The base layer mixtures have an NMAS of ¾ inches, whereas the surface TR mix has an NMAS of ½ inch. Table 2 shows the properties of the virgin aggregates used in the three base mixtures. Figure 11 shows the gradation of the 3 base mixtures.

Table 2. Virgin Aggregate Properties

	Coarse Aggregates	Fine Aggregates	Combination (without Admixture)	Combination (with Admixture)	Specifications
Bulk OD Specific Gravity	2.672	2.635	2.654	2.647	2.35-2.85
SSD Specific Gravity	2.704	2.664	2.685	2.677	
Apparent Specific Gravity	2.761	2,714	2.738	2.729	
Absorption (%)	1.207	1.112	1.159	1.141	0.00-2.50
Effective Specific Gravity (Gse)				2.682	
Sand Equivalent		64			50 Min
Uncompacted Voids		48.1			45 Min
%1 or more fractured face	96				85 Min
%2 or more fractured face	90				80 Min
Los Angeles Abrasion					
% Loss @100 Rev-Grading B	4				9 Max
% Loss @500 Rev-Grading B	17				40 Max
% Clayclumps and Friable Particles	0.2	0.3			

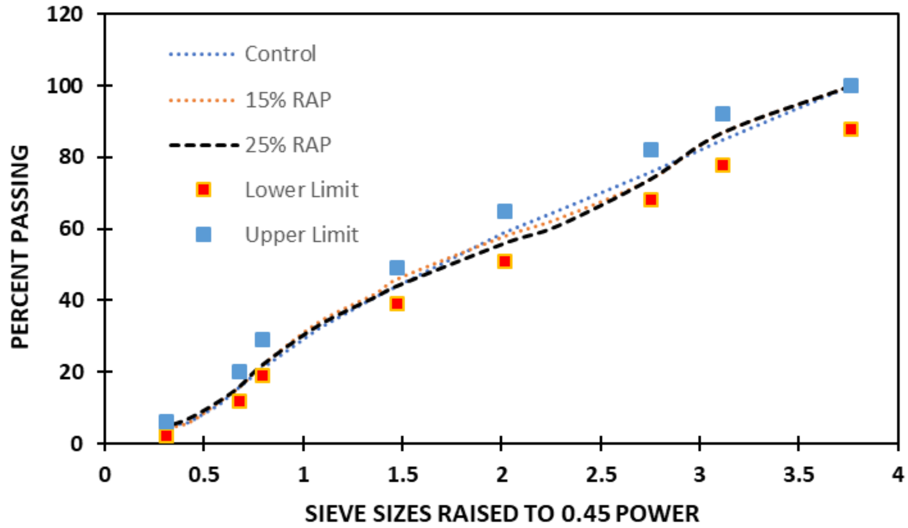


Figure 11. Aggregate Gradation of the Three Base Mixtures

The properties of RAP aggregates were measured and reported in Table 3.

Table 3. RAP Aggregate Properties

	RAP	Specifications
Bulk OD Specific Gravity	2.543	2.35-2.85
SSD Specific Gravity	2.573	
Absorption (%)	1.159	0.00-2.50
Effective Specific Gravity (Gse)	2.574	
Los Angeles Abrasion		
%1 or more fractured face	5	9 Max
%2 or more fractured face	21	40 Max

3.2.2- Binder Properties

The asphalt binders used in mixtures production in this study are a Superpave performance-graded binder, PG 70-10 for mixtures with 0% and 15% RAP, and PG 64-16 for the 25% RAP mixture. These binders were provided by Western Refining located in Phoenix, Arizona. The binder used for the surface mix is PG 76-22 TR+. This binder was provided by HollyFrontier located in Phoenix, Arizona as well. Tables 4 and 5 show the properties of the PG 70-10 and PG 64-16 binder respectively.

Table 4. PG 70-10 Properties

	Test	Test Temperature	Test Result	Specification
Tests on Original Binder	Flash Point, T48		>230 C	Min. 230 C
	Apparent Viscosity, AASHTO T316	135 °C	0.565 Pa-s	Max. 3 Pa-s
		175 °C	0.101 Pa-s	
	Dynamic Shear, T315, G*/sin δ	70 °C	1.19 kPa	Min. 1.00 kPa
Tests on Residue from RTFO	Mass Change		-0.143	Max 1.0
	Dynamic Shear, T315, G*/sin δ	70 °C	3.05 kPa	Min. 2.20 kPa
Tests in Residue from PAV	PAV Aging Temperature	110 °C		
	Dynamic Shear, T315, G*sin δ	34 °C	3840 kPa	Max. 5000 kPa
	Creep Stiffness, T313	0°C	93.0 Mpa	Max. 300 Mpa
	m-value, T313	0°C	0.312	Min. 0.300

Table 5. PG 64-16 Properties

	Test	Test Temperature	Test Result	Specification
Tests on Original Binder	Flash Point, T48		>230 C	Min. 230 C
	Apparent Viscosity, AASHTO T316	135 °C	0.428 Pa-s	Max. 3 Pa-s
		175 °C	0.082 Pa-S	
	Dynamic Shear, T315, G*/sin δ	64 °C	1.62 kPa	Min. 1.00 kPa
Tests on Residue from RTFO	Mass Change		-0.106 weight %	Max 1.0
	Dynamic Shear, T315, G*/sin δ	64 °C	3.85 kPa	Min. 2.20 kPa
Tests in Residue from PAV	PAV Aging Temperature	100 °C		
	Dynamic Shear, T315, G*sin δ	28 °C	3790 kPa	Max. 5000 kPa
	Creep Stiffness, T313	-6°C	117.0 Mpa	Max. 300 Mpa
	m-value, T313	-6°C	0.335	Min. 0.300

3.3- Mix Design Methods

The Marshall mix design method was used to design the asphalt mixtures used in this study. The Maricopa Association of Governments (MAG) guidelines were followed during the mix design. MAG specification requires a drop in one PG grade when RAP content of 15% or higher is used. Thus, in the current mix design, PG 64-16 was used for the 25% RAP mix instead of PG 70-10. The mixtures were designed with 75 blows on each side. Table 6 shows the volumetric properties of the three base mixtures used in this study. More information in the mix design calculations are provided in APPENDIX A.

Table 6. Volumetric Properties

	0% RAP (Control)	15% RAP	25% RAP
Total Binder Content	5	5	5
Marshall Bulk Density (pcf)	148	148.7	149.2
Max. Theoretical Specific Gravity	2.478	2.481	2.486
Max. Theoretical Specific Density (pcf)	154.6	154.8	155.1
Stability	5010	5390	5210
Marshall Flow (in)	11	10	11
% Air Voids	4.3	3.9	3.8
% VMA	14.5	14.5	14.2
% Air Voids Filled	70.5	72.7	72.8
% Eff Asphalt Total Mix	4.39	4.52	4.41
Film Thickness (micro)	9	9	9
Dust/Bitumen Ratio	1.1	1	1.1

3.4- Project Description

The test sections were built on 15^{th} Avenue from Roeser Road to Broadway Road. The total project length is around 2685 feet divided equally between the three sections. Figure 12 shows the as-constructed sections layout. These test sections were constructed in December 2018.

Figure 12. As-Constructed Map of the Sections

3.5- Sections Construction

Road Sections were constructed following City of Phoenix specifications. Loose asphalt mixtures were sampled from the plant. Trucks were stopped randomly before going out to the site and metal buckets were used to sample the asphalt mixtures directly from the truck. These buckets were transported to the ASU pavement laboratory and the buckets were processed by splitting into bags of uniform gradations as much as possible. These bags were stored at a controlled temperature conditions to prevent any potential aging. The bags after that were used to prepare samples and start the testing process (Figure 13).

Figure 13. Sections Construction and Material Sampling

CHAPTER 4 TESTING AND ANALYSIS

4.1- Introduction

The goal of performing mixture laboratory testing is to measure and compare the mechanical properties of each mixture that reflect the performance in the field. These properties range from characterizing material stiffness, permanent deformation, crack initiation properties, crack propagation properties, fatigue cracking resistance, and moisture damage. In this research, the Dynamic Modulus test (E*) was performed to characterize the stiffness properties, the Flow Number test (FN) to evaluate the permanent deformation properties (which indicates the rutting performance in the field), the IDEAL CT test to evaluate the crack initiation properties, C* fracture test to determine the crack propagation properties, uniaxial fatigue test to investigate the fatigue cracking potential of the mix, and the Tensile Strength Ratio (TSR) which is based on testing the sample in indirect tension mode before and after conditioning to evaluate the moisture resistance.

4.2- Mixture Testing

4.2.1- Dynamic modulus

Stiffness is one of the important parameters that characterize HMA. This parameter defines the stress-strain relationship of the material, which can give a good indication on the performance. Stiffness varies depending on the type of asphalt binder used, air voids, asphalt binder content, aggregate gradation and definitely temperature. The dynamic modulus of asphalt is a fundamental property that is determined by testing asphalt in its linear viscoelastic range. This parameter is important in the analysis of pavement response under traffic loading and different climatic condition. It is one of the main inputs to the AASHTO Pavement Mechanistic Empirical (ME) design software, level 1 analysis.

The test measures the strain response of the asphalt to determine its stiffness under a continuous sinusoidal loading. This test also measures the phase angel of the material, which is basically the lag between the stress and its corresponding strain. This phase angel reflects the viscous properties of the material.

For a linear viscoelastic material, the parameter that defines the stress-strain relationship is a complex number called "Complex Modulus", which is symbolized by E*. The absolute value of this complex number is the dynamic modulus value, which is basically the ratio of peak stress to the peak strain. The dynamic modulus is defined using Equation 1 below:

$$|E*\ (\omega)| = \sqrt{\left(\frac{\sigma_0}{\varepsilon_0} cos\, \phi\right)^2 + \left(\frac{\sigma_0}{\varepsilon_0} sin\, \phi\right)^2} = \frac{\sigma_0}{\varepsilon_0} \qquad (1)$$

Where:

E* = Complex modulus or dynamic modulus

Φ = Phase angle

σ_0 = peak stress amplitude (applied load/sample cross area)

ε_0 = peak amplitude of recoverable axial strain

The Dynamic Modulus protocol (AASHTO TP62-03) was developed at Arizona State University and consists of applying a repeated axial cyclic load at different frequencies and different temperatures. The protocol recommends conducting the test at five temperatures (-10, 4.4, 21.1, 37.7, and 54.4°C) and six frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz) to develop the full master curve based on the Time-Temperature superposition principle.

The Dynamic Modulus test was conducted using IPC Global Universal Testing Machine (UTM) shown in Figure 14. The environmental chamber act to keep the specimen at the required testing temperature. The low temperature (-10°C) was not considered in this study since pavements in Phoenix don't experience this temperature.

Figure 14. UTM Machine for Dynamic Modulus Testing

Samples of each mixture were compacted using a Superpave Gyratory Compactor (SGC) then cored and cut to arrive at the recommended specimen size of 100 mm in diameter and 150 mm in height. The air voids content was then determined and verified to be in the range of 6.5 ± 0.5%. Specimens with air voids outside this range were discarded. LVDTs were used to measure the strain caused by the load applied form the actuator.

Specimens were placed in the environmental chamber for 8 hours before performing the test at the first temperature (4°C), and then for 5 hours between each temperature. The testing temperature order was from the lowest till the highest. At each temperature, six frequencies were tested. These frequencies are 0.1, 0.5, 1, 5, 10, and 25 Hz. The highest frequency was tested first followed by the others in the descending order. Three replicates were tested for each mix, and the coefficient of variation (CoV) was calculated and verified to be below the maximum allowable value.

Once the test is done, the E* master curves were constructed using equations 2 to 4 below. The dynamic modulus for each mix were plotted conforming the isothermal curves. Then, using the time-temperature superposition principle, the data were shifted to arrive to the final master curve for each mix. These master curves are constructed by shifting the isothermal curves horizontally using a shift factor a(t). The curves were shifted to a reference temperature of 70 F (21.1°C).

$$log\,|\,E^*| = \alpha + \frac{\beta}{1+e^{\delta+\gamma\, log(f_r)}} \qquad (2)$$

$$Log(at) = aT^2 + bT + c \qquad (3)$$

$$log(\,f_r) = log(\,f\,) + log(\,a(T)) \qquad (4)$$

Where

|E*| = dynamic modulus, psi

f = loading frequency at the test temperature, Hz

f_r = reduced frequency at the reference temperature, Hz

α, β, δ, γ = regression coefficients

a(T) = temperature shift factor

4.2.2- Flow Number (FN)

The flow number test was recommended during the NCHRP 9-19 project as a simple performance test to indicate the rutting potential of asphalt mixtures. The flow number results have been showing good correlations with field performance. This test indicates the stage where shear deformation starts, which strongly represents the start of permanent deformation in the field. The test procedure is outlined in AASHTO TP79.

The flow number test is conducted by applying a uniaxial compressive load, with a 0.1 seconds haversine pulse and a 0.9 seconds rest period. The test is done at a constant and specific temperature, usually close to the effective temperature at the studied location. The cumulative strain graph has a three stage as shown in Figure 15. The first section (stage one) represents the deformation that occurs during asphalt compaction and initial traffic loading. The second section (secondary stage) reflects the majority of the shear deformation that occurs in the asphalt during its service life. The third section (tertiary stage) describes the point in which the maximum limit of the shear deformation has been crossed and rutting begins. The flow number value is basically the cycle number where the tertiary stage begins.

Similar to dynamic modulus, samples of 100 mm in diameter and 150 mm in height were prepared for FN testing. The Air voids were measured and validated to be within 6.5 +_ 0.5%. The selected testing temperature was 50°C, which is the recommended effective temperature for Phoenix. Before testing, the sample was conditioned inside the environmental chamber for 5 hours, in which the temperature stabilizes at 50°C after this period. The test was conducted using IPC Global Universal Testing Machine (UTM) shown in Figure 16.

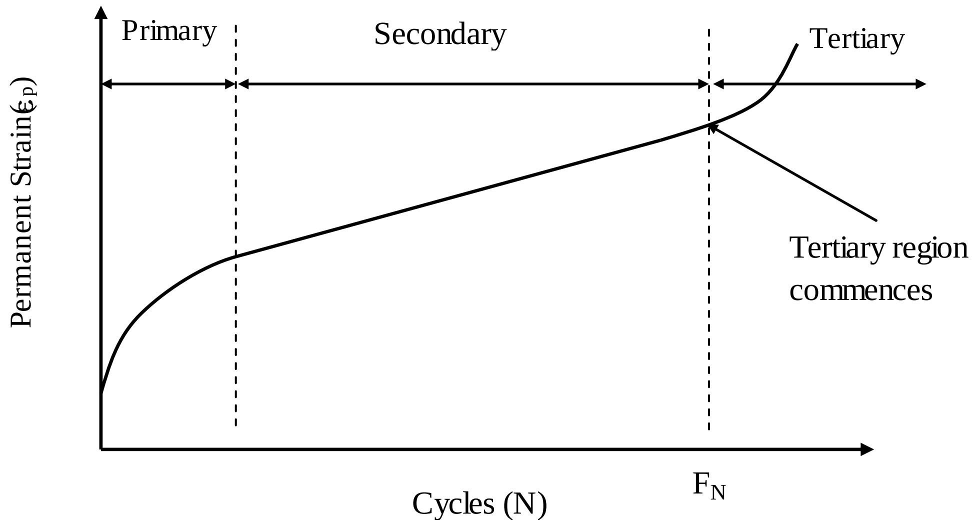


Figure 15. Accumulated Strain Zones

Figure 16. UTM Machine Used for Flow Number Testing

The Francken model (equation 5) was used to model the permanent strain curve. The parameters a, b, c, and d are determined using the nonlinear regression analysis.

To determine the flow number value (i.e inflection point), the second derivative (equation 7) is set to zero.

$$\varepsilon_p(N) = a \cdot N^b + c(e^{d \cdot N} - 1) \qquad (5)$$

$$\frac{\partial \varepsilon p}{\partial N} = abN^{b-1} + cde^{dN} \qquad (6)$$

$$\frac{\partial^2 \varepsilon_p}{\partial N^2} = ab(b-1)N^{b-2} + cd^2 e^{dN} \qquad (7)$$

Where:

$\varepsilon_p(N)$ = Permanent strain at N cycles

N = Number of cycles

a, b, c, d = Regression coefficients

4.2.3 IDEAL CT Test

The indirect tensile cracking test is performed to determine the cracking potential of asphalt mixtures at intermediate temperatures. This test is performed on disk specimens obtained from the Super Pave Gyratory Compactor (SGC) specimens. The disks used in this research were 100 mm in diameter and 62 mm in thickness.

The test was conducted at 25°C intermediate temperature at a loading rate of 50 mm/min. This high loading rate allows the test to be performed in less than 1 minute. The specimens were conditioned in an environmental chamber for around 5 hours at the testing temperature before conducting the test.

The output of this test is a typical load-displacement curve as shown in Figure 17. The slope at the point corresponding to 75% of the maximum load is determined and considered as a post peak behavior. Zhou et al. (2017) have determined that this point is typically the inflection point of the post peak behavior and can identify the brittle or ductile material

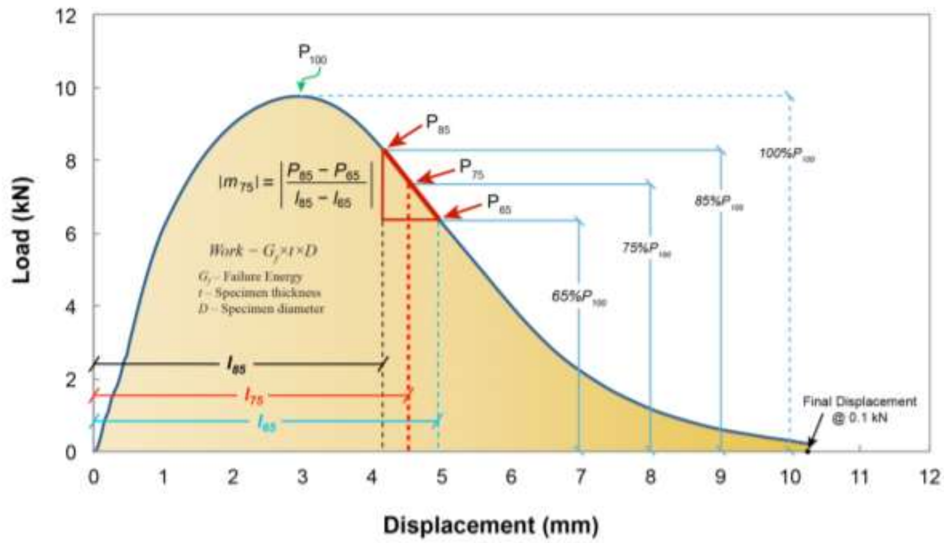


Figure 17. Typical Load-Displacement Curve for IDEAL CT Analysis (Adapted from Zhou et al. 2017)

behavior. Based on all these parameters, the CTI index is calculated using Equation 9. As it can be seen, the higher the fracture energy, the higher the work needed to fracture the material, thus the higher the CTI. From the other side, the lower the slope, the better ductility or post peak behavior, the higher the CTI. Thus, higher CTI values correspond to better cracking resistance.

$$CTI = \frac{t}{62} \times \frac{I75}{D} \times \frac{Gf}{m75} \times 10^{\wedge}6 \qquad (9)$$

Where:

CTI = Cracking Tolerance Index

Gf = failure energy (Joules/m2), Gf = Wf/Dxt, where Wf is the area below the load displacement curve

m75 = absolute value of the post-peak slope m75 (N/m)

I75 = displacement at 75 percent the peak load after the peak (mm)

D = specimen diameter (mm)

t = specimen thickness (mm)

4.2.4- C* Fracture Test

Having measured the energy required for the crack to start, it is important to determine the rate of propagation of this crack inside the asphalt layer. To do so, the C* fracture test which was developed by Stempihar and Kaloush (2013) was used. This test applies load to a notched disk specimen cut from a gyratory compactor as shown in Figure 18. A small cut is initiated in the disk since the test measures the crack propagation only and not the initiation. The specimen dimensions is shown in Figure 19. Figure 20 shows the test setup.

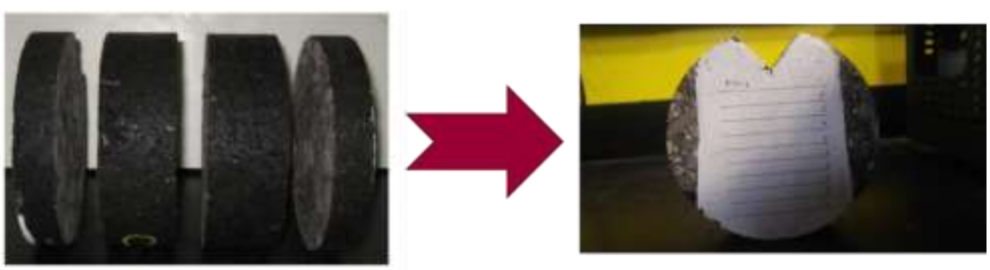


Figure 18. C* Sample Preparation

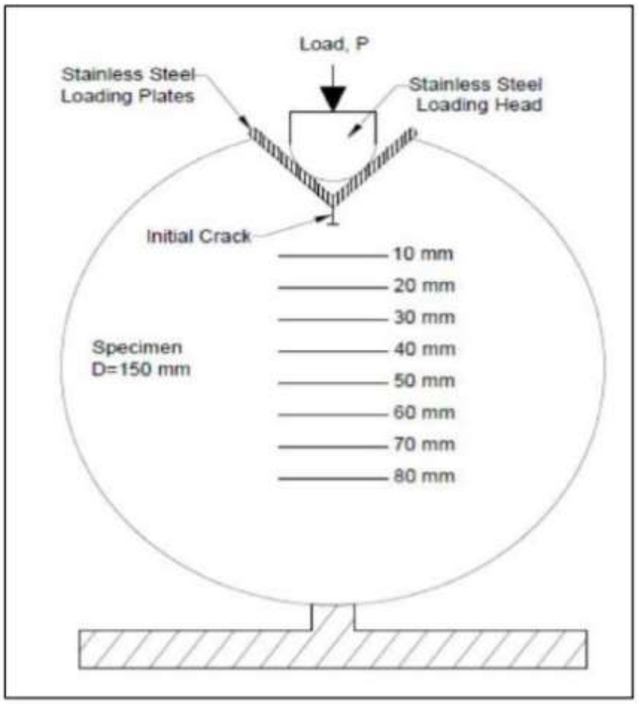


Figure 19. C* Specimen Geometry (Stempihar, 2013)

Figure 20. Typical C* Fracture Test Setup

The initiation and propagation of the crack inside the asphalt material in governed by the principles of fracture mechanics. The local stress distribution in this material is strengthened by the available surface notches. The crack starts to propagate when the stored energy is enough for new crack surface. When the strain energy release rate becomes equal to the fracture toughness, the crack growth take place under steady state conditions. Majidzadeh (1970) research was one of the earlies in applying the fracture mechanics to asphalt concrete. After that, Abulshafi (1992) applied the C*-line integral method to predict the fatigue life of pavements using crack initiation, crack propagation, and failure. He concluded that it is required to conduct two different tests, the first one is to evaluate the crack initiation properties and the second one to reflect on the crack propagation properties using notched specimen subjected to repeated loading. Later Abdulshafi and Majidzadeh used notched disk specimens to utilize the J-integral concept to the fracture and fatigue of asphalt pavements. A recent research by Stempihar (2013) developed a procedure for the C* Fracture Test (CFT). Stempihar and Kaloush (2017) provided the technical details on performing the test including the specimen geometry, selecting test temperature, and the analysis procedure to arrive to the results.

Landes and Begley (1976) were the first to apply the C* parameter to fracture mechanics to describe the stresses and stains surrounding the crack tip in metals at high temperatures. In a viscous material, C* can be defined as the energy rate line integral that describes the stress and strain rate field surrounding the crack tip. The C* can be measured experimentally due to the relationship between the J-integral and C* parameter. J can be defined as the energy difference between two specimens subjected to the same load yet have different crack length. Thus, C* can be calculated as power or energy rate difference between two specimens, under same loading, with incrementally different crack length. Mathematically, C* can be expressed by Equation 10 below.

$$C^* = \left(-\frac{1}{b}\right)\left(\frac{dU^*}{dl}\right) \qquad (10)$$

Where

U* = Power or energy rate for a given load P

b = Specimen thickness

The rate of work done (U*) is defined as the area under the P* vs displacement curve. It is calculated using Equation 11 below:

$$U^* = \int_0^u P\,du \qquad (11)$$

4.2.5- Uniaxial Fatigue Test

The uniaxial fatigue test was conducted to evaluate the effect of adding RAP on the fatigue life of the asphalt mix. The test was conducted at 18°C by subjecting a cylindrical specimen of 150 mm height and 75 mm diameter to sinusoidal displacement. Figure 21 shows the test setup. The failure criteria used in this test is the drop-in phase angle.

Figure 21. Uniaxial Fatigue Test Setup

The test was conducted at four strain levels, which were estimated such that the sample will fail in less than 10,000 cycles, between 10,000 and 50,000 cycles, between 50,000 and 100,000 cycles, and greater than 100,000 cycles. The Simplified Viscoelastic Continuum Damage (S-VECD) model was used to analyze the test results. The result of this analysis is the damage characteristic curve (C vs. S). The power function shown in Equation 12 was used to fit the curves.

$$C = 1 - C_{11}S^{C_{12}} \qquad (12)$$

Although the C vs. S is a good indication of the performance and can indicate the level of damage sustained before failure, yet, it doesn’t indicate directly the fatigue performance. In order to predict the number of cycles needed for fatigue failure at different strain levels, Equation 13 was used.

$$N_{failure} = \frac{(f)(2^{3\alpha})S_{failure}^{\alpha-\alpha C_{12}+1}}{(\alpha-\alpha C_{12}+1)(C_{11}C_{12})^{\alpha}\left[(\beta+1)(\varepsilon_{0.pp})(|E*|_{LVE})\right]^{2\alpha}K_1} \quad (13)$$

Where:

$N_{failure}$ = predicted cycles to failure,

f = frequency of loading,

$|E^*|$ = dynamic modulus at the frequency and temperature of loading simulated,

α = viscoelastic damage rate (characterized from the dynamic modulus mastercurve),

β = load form factor, taken as 0 in this work to simulate reversed sinusoidal loading,

$\varepsilon_{0.pp}$ = the peak-to-peak strain magnitude for the simulated loading history,

K_1 = loading shape factor, and

$S_{failure}$ = damage level at failure (defined from the experimental results).

4.2.6- Tensile Strength Ratio (TSR)

Moisture damage is one of the major distresses of asphalt pavements. It is due to the loss of adhesion between the aggregate and binder in the presence of water. This loss of bond separates the aggregate and binder and causes stripping.

TSR is a performance test that indicates the resistance of the mix to moisture damage. The test protocol is described in AASHTO T283. The gyratory compacted specimens of 150 mm in diameter and 180 mm in height were prepared for each one of the mixes (0% RAP, 15% RAP, and 25% RAP). After cooling, the samples were cored to a diameter of 100 mm. then, two samples of 62 mm thickness were cut from each sample, conforming six samples (disks) for each mixture. The air voids were determined for each disk. The disks from each mixture were divided into two subsets: unconditioned subset and condition subset. The unconditioned subset was stored at room temperature, and the conditioned subset was partially vacuum-saturated, by applying a partial pressure of 26 in Hg for a short time (5 to 10 minutes). After that the specimen was kept submerged in water for another 5 minutes, and the saturation level was measured using Equation 12 below. The sample was considered ready for freeze-thaw conditioning when the saturation level is between 70% and 80%.

$$S = \frac{(B-A)}{V} \cdot 100 \quad (12)$$

Where,

A = Weight of dry specimen in air (gm)

B = Weight of saturated surface dry specimen after partial vacuum saturation (gm)

V = Volume of air voids

The saturated set is conditioned first at -16°C for at least 16 hours (Figure 22), and then in hot water bath at 60°C for 24 hours (Figure 23). Then, both conditioned and unconditioned subsets are placed in a water bath of temperature 25°C (after wrapping the disks with plastic wrap to keep the unconditioned subset dry). After that, the IDT is performed (Figure 24) on both the conditioned and unconditioned samples and the ratio of the tensile strength of the conditioned set to that of unconditioned set is determined and defined as TSR. The Tensile Strength (T) is determined using the equation 8 below.

$$T = \frac{P \cdot 2000}{\pi \cdot D \cdot t} \qquad (8)$$

Where:

P = Maximum load, in N

D = diameter of sample, in mm

t = thickness of sample, in mm

Figure 22. Specimens During the Freeze Cycle

Figure 23. Specimens During the Thaw Cycle

Figure 24. Specimen During IDT Testing

4.3- Results

4.3.1- Dynamic Modulus Test results

The master curves based on the dynamic moduli of each mix were obtained. The average dynamic modulus master curves for each mix are shown in Figure 25. As it can be seen, adding 15% on the RAP mix didn't not have a stiffening effect when compared to the control mix. Adding 25% RAP on the mix while dropping one binder grade (PG 64-16) resulted in almost similar stiffness to the control and 15% RAP mixture.

To clarify the differences in the modulus values, the dynamic modulus values at each temperature and each frequency were plotted in Figure 26. It can be noted from the figures that as the frequency decreases, the value of the dynamic modulus decreases, as the material is experiencing slower loading. From the other side, as the temperature increases, the value of the dynamic modulus decreases, due to binder softening at higher temperature. In all cases, the dynamic modulus values are comparable.

Having a comparable stiffness at the different frequencies and temperatures indicate that adding 15% RAP and 25% RAP (with softer binder) will not have an impact on the cracking properties of the mix, yet, this will be thoroughly investigated in the cracking testing and evaluation.

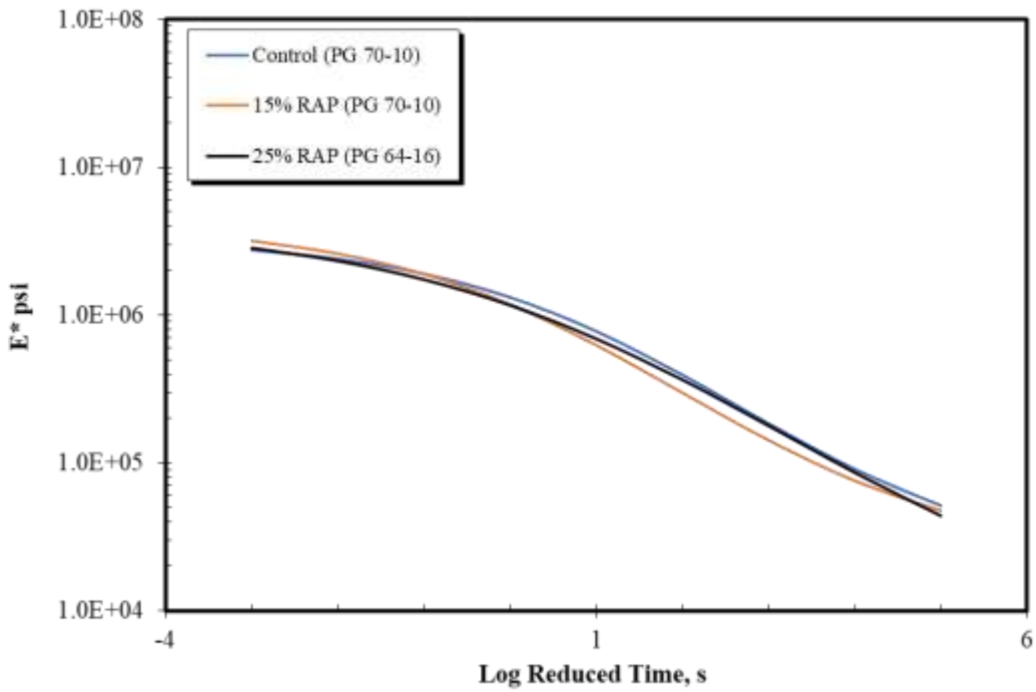


Figure 25. E* Master Curves of the 3 Mixtures

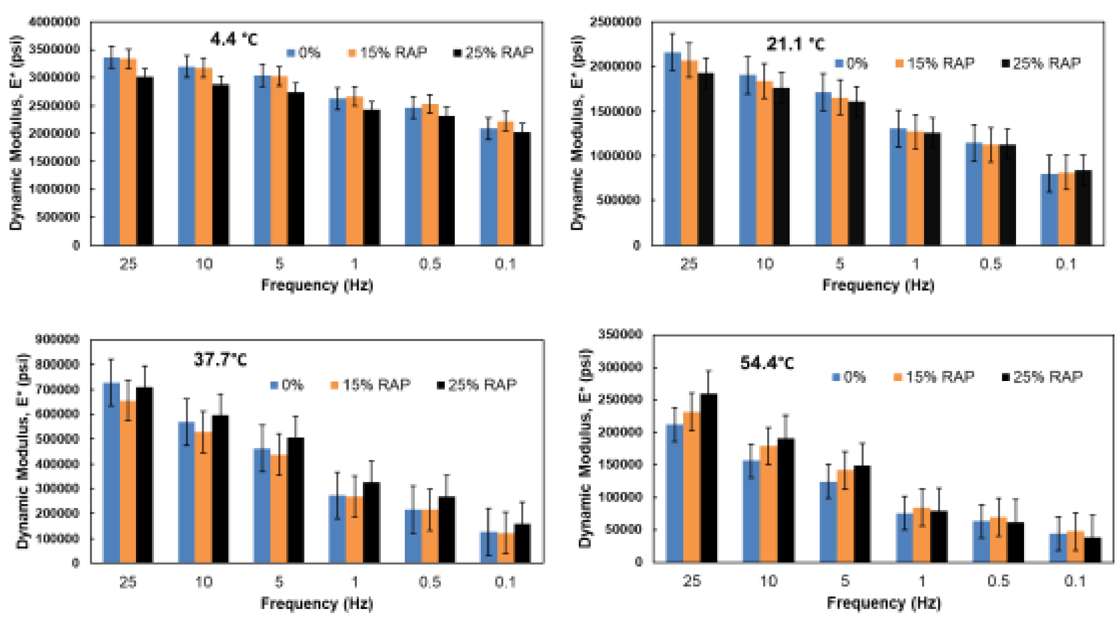


Figure 26. Dynamic Modulus Values at Each Temperature and Frequency

The ANOVA analysis was conducted on the results at all tested temperatures and frequencies. The results are presented in Table 7. The results indicated that generally there is no statistical difference between the modulus values, except at 37.8°C in which there are some differences at the frequencies of 1, 0.5, and 0.1 Hz.

Table 7. ANOVA of Dynamic Modulus Results

Frequency (Hz)	Temperature (°C)			
	4.4	21.1	37.8	54.4
25	NS	NS	NS	NS
10	NS	NS	NS	NS
5	NS	NS	NS	NS
1	NS	NS	S	NS
0.5	NS	NS	S	NS
0.1	NS	NS	S	S

NS= Not Statistically Significant S= Statistically Significant

The t-test (with one and two tails) was conducted to compare each two mixtures at a time. The results are presented in Tables 8 and 9. The results also assure that there are no differences in the modulus values at most combinations of frequency and temperatures, except at 37.7 °C where some differences are reported. These tests are based on the null hypothesis (Ho) which compares the group mean values to see if they are statistically equal or not, so the null hypothesis can be rejected (R) or if there is no statistical difference, the hypothesis cannot be rejected (CNR).

Table 8. t-Test (One Tail) of Dynamic Modulus Results

Freq (Hz)	t-Test comparing:	Temperature (°C)			
		4.4	21.1	37.7	54.4
25	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	R	CNR	CNR
	15% to 25%	CNR	CNR	CNR	CNR
10	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	CNR	CNR	CNR
	15% to 25%	CNR	CNR	R	CNR
5	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	CNR	CNR	CNR
	15% to 25%	CNR	CNR	R	CNR
1	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	CNR	R	CNR
	15% to 25%	CNR	CNR	R	CNR
0.5	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	CNR	R	CNR
	15% to 25%	CNR	CNR	R	CNR
0.1	0% to 15%	R	CNR	R	CNR
	0% to 25%	CNR	CNR	R	R
	15% to 25%	CNR	CNR	R	CNR

R= Reject H_0 CNR= Cannot reject H_0

Table 9. t-Test (Two Tail) of Dynamic Modulus Results

Freq (Hz)	t-Test comparing:	Temperature (°C)			
		4.4	21.1	37.7	54.4
25	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	R	CNR	CNR
	15% to 25%	CNR	CNR	CNR	CNR
10	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	CNR	CNR	CNR
	15% to 25%	CNR	CNR	CNR	CNR
5	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	CNR	CNR	CNR
	15% to 25%	CNR	CNR	R	CNR
1	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	CNR	CNR	CNR
	15% to 25%	CNR	CNR	R	CNR
0.5	0% to 15%	CNR	CNR	CNR	CNR
	0% to 25%	CNR	CNR	CNR	CNR
	15% to 25%	CNR	CNR	R	CNR
0.1	0% to 15%	CNR	CNR	R	CNR
	0% to 25%	CNR	CNR	R	R
	15% to 25%	CNR	CNR	CNR	CNR

R= Reject H_0 CNR= Cannot reject H_0

4.3.2- Flow Number Test Results

The Flow Number (FN) test results were in agreement with most studies found in literature, where there is an expected improvement in the rutting resistance of the asphalt mix when RAP is incorporated. The change in the accumulated strain percentage with the increased number of loading cycles is shown in Figure 27. The graph shows that with the increase in RAP content, the number of cycles to reach a certain strain percentage get higher, which indicates the increase in mixture resistance to rutting. It is also noted that the stiffening effect of the 25% RAP has dominated the softening effect of the PG 64-16 binder.

To clarify the results, the average FN value of each mix were compared in Figure 28. The addition of 15% RAP had a stiffening effect to the mix that lead to a better resistance to rutting failure, as the 15% RAP mix failed at around 1400 cycles. Moreover, the addition of 25% RAP improved the rutting performance, in which the 25% RAP mixture had the best rutting resistance with failing cycle around 1863. The aged binder in the RAP has contributed to the stiffening of the final asphalt mix which lead to a better rutting resistance.

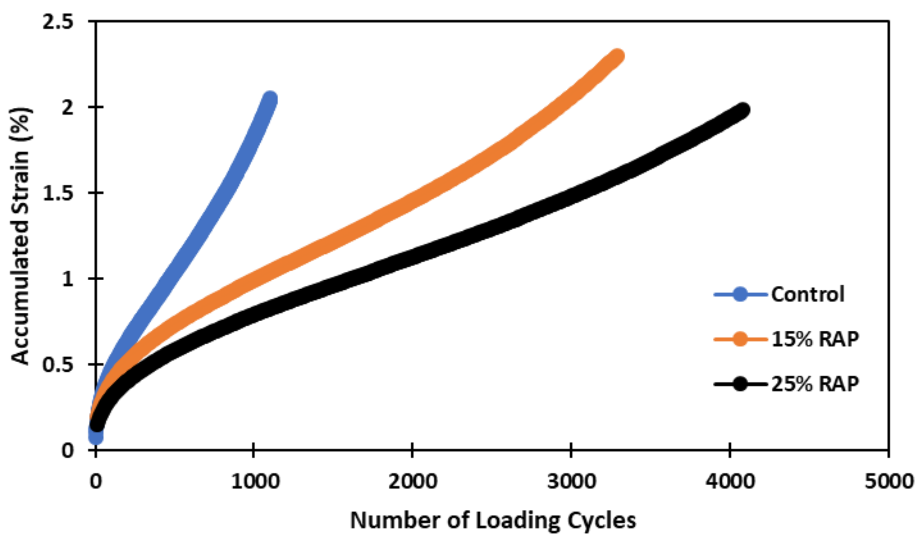


Figure 27. Accumulated Strain Curves of the 3 Mixtures

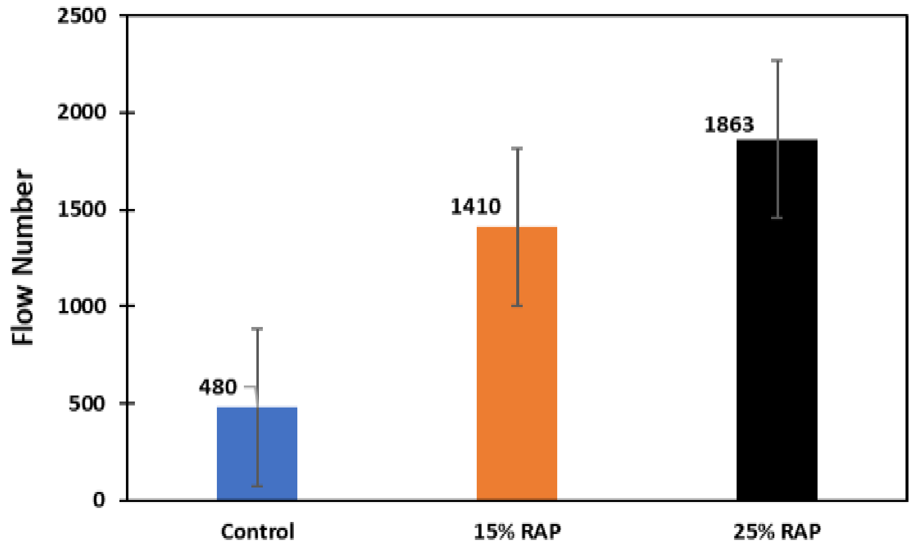


Figure 28. Number of Cycles Till Rutting Failure

The statistical analysis presented in Table 10 showed that there is statistical significance in the difference between the three flow number values. The t-test results showed that adding 15% RAP will significantly improve the rutting potential of the mix and adding more RAP (25%) will significantly improve it better.

Table 10. Flow Number Statistical Analysis

Mixture	Flow Number (Cycles)					α = 0.05			t-Test comparing:
	Repl. 1	Repl. 2	Repl. 3	Average	CV (%)	ANOVA	t-Test one-tail	t-Test two-tail	
0% RAP	**533**	**509**	**397**	480	15.1	S	R	CNR	0% to 15%
15% RAP	**1047**	**1519**	**1663**	1410	22.9		R	R	0% to 25%
25% RAP	**1535**	**1967**	**2087**	1863	15.6		R	R	15% to 25%

NS= Not Statistically Significant; S= Statistically Significant; R= Reject H_0; CNR= Cannot reject H_0

4.3.3- IDEAL CT Test

The IDEAL CT test has been proven to be well correlated to cracking potential in the field (Zhou et al. 2017). The CTI Index was also found to be sensitive to the presence of RAP contents. The test analysis provides us with 3 important parameters: (i) maximum tensile strength, which is determined from the maximum load attained before failure, (ii) Fracture energy which is basically the area under the load-displacement curve, and it represents the energy needed to cause the fracture, and (iii) CTI index which is a cracking index that indicates the cracking potential of the mix. The higher the CTI value, the better resistance to cracking.

The effect of adding RAP on the maximum tensile strength is shown in Figure 29. As expected, the addition of 15% RAP to the mix yielded higher tensile strength, due to the stiffening effect of the RAP. Moreover, the addition of 25% RAP with its corresponding stiffening effect yielded a higher tensile strength. These results agree with the work that have been reported in the literature.

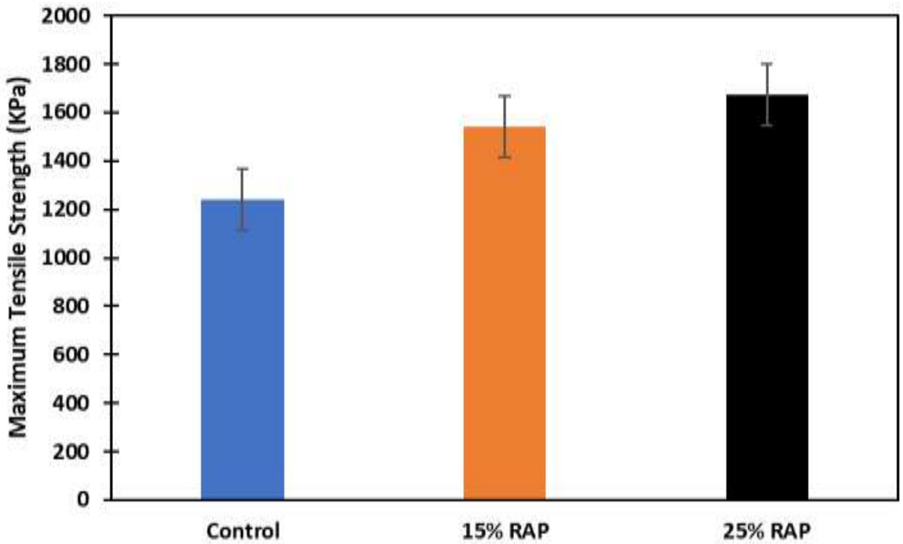


Figure 29. Maximum Tensile Strength of the Three Mixtures

When it comes to fracture energy, the work required to fracture the sample doesn't only depend on the maximum load to fail it, but also on the post-peak behavior. The average area below the load-displacement curve of each mix was calculated and presented in Figure 30. As it can be seen from the figure, the addition of 15% RAP yielded a slight increase in the fracture energy, and further increase in the RAP content to 25% yielded even a higher value.

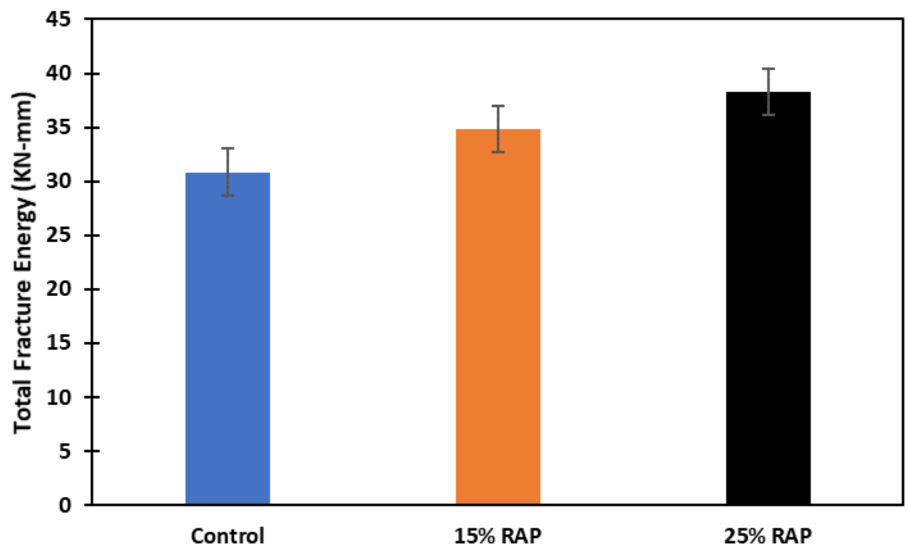


Figure 30. Fracture Energy of the Three Mixtures

The CTI was calculated based on Equation 9 presented earlier. The higher CTI index reflects a better resistance to cracking. The CTI calculation procedure includes values of both fracture energy and post-peak behavior (slope at inflection point). Thus, this index reflects both properties. Since these two properties describe the cracking behavior of the material, the index was found to be well correlated to field cracking. The CTI values are presented in Figure 31. As expected, the addition of 15% RAP increased the cracking potential, and adding more RAP yielded to a lower cracking resistance, as it can be concluded from the decrease in CTI values.

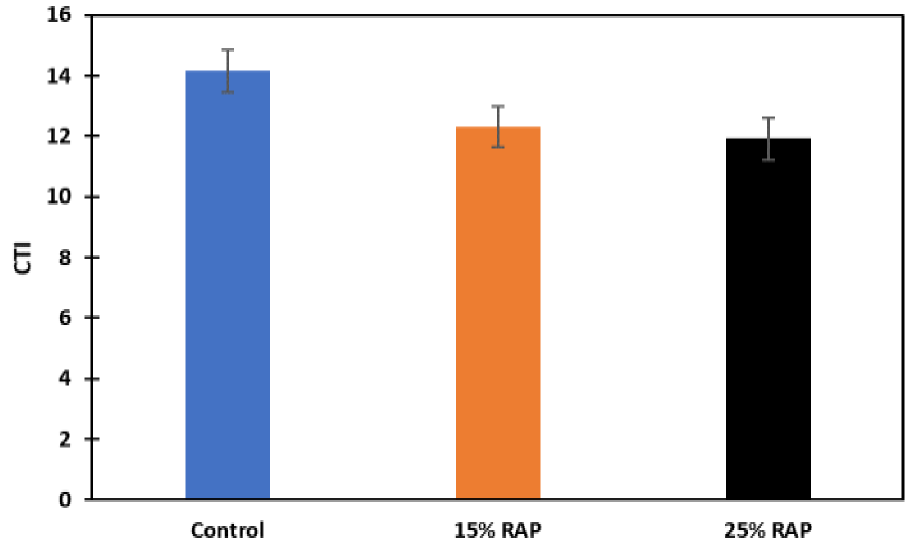


Figure 31. CTI Values of the Three Mixtures

The statistical analysis presented in Table 11 indicates that adding RAP in both percentages didn't have any effect on the tensile strength, fracture energy, and CTI values, which means that RAP didn't affect the cracking potential of the mix.

Table 11. IDEAL CT Results Statistical Analysis

Measured Parameter	Mixture					α = 0.05			t-Test comparing:
		Repl. 1	Repl. 2	Average	CV (%)	ANOVA	t-Test one-tail	t-Test two-tail	
St	0	1303.7	1221.2	1262.5	4.6	NS	CNR	CNR	0% to 15%
	15%	1552.8	1585.1	1568.9	1.5		CNR	CNR	0% to 25%
	25%	1609.8	1746.6	1678.2	5.8		CNR	CNR	15% to 25%
Wf	0	32.5	29.2	30.8	7.7	NS	CNR	CNR	0% to 15%
	15%	30.3	32.2	31.2	4.4		CNR	CNR	0% to 25%
	25%	35.2	37.0	36.1	3.6		R	R	15% to 25%
CTI	0	13.1	15.2	14.2	10.7	NS	R	R	0% to 15%
	15%	7.2	8.7	7.9	13.1		CNR	CNR	0% to 25%
	25%	11.4	7.8	9.6	26.5		CNR	CNR	15% to 25%

NS= Not Statistically Significant; S= Statistically Significant; R= Reject H_0; CNR= Cannot reject H_0

4.3.4- C* Fracture Test

When the cracks propagate through the asphalt layer and reach the surface, moisture finds its way to the base and subbase materials, which weakens its properties and leads to more distresses. Thus, it is important to characterize the rate of crack propagation inside the asphalt layer. The slower the propagation rate, the longer pavement life. The C* versus the crack growth rate (a*) are plotted in Figure 32. The higher the slope the more energy needed to propagate the crack. As it can be seen from Figure 32, the 15% RAP mix has a better crack propagation property than both the control and the 25% RAP. The 25% RAP mix has the worst crack propagation properties, yet, it is not far from the control. One of the potential reasons behind having the best crack propagation properties in the 15% RAP in the higher VMA value of this mix.

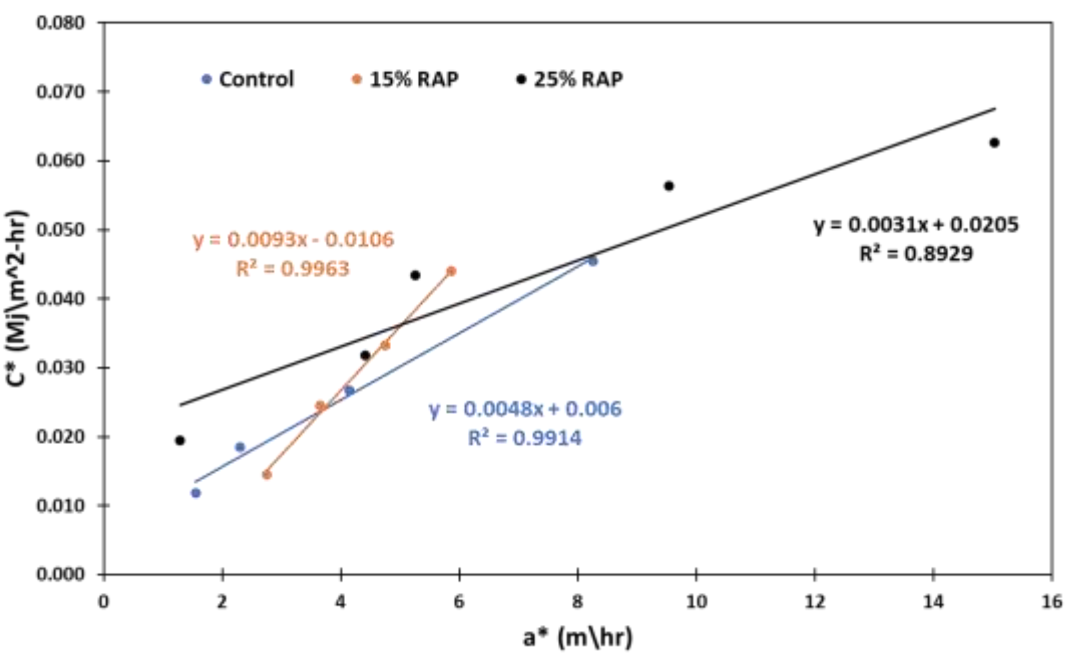


Figure 32. C* Test Results

4.3.5- Uniaxial Fatigue

The fatigue test was conducted at an intermediate temperature of 18°C and following AASHTO TP107 procedure. The outputs of this test are the damage characteristic curve (C vs. S) which reflects the material integrity changes with damage, and the number of loading cycles till fatigue failure for different strain levels, which reflects the fatigue life of the mix. The damage characteristic curves of the three mixtures are presented in Figure 33. As expected, the control mixture sustained more damage before failure, while the 15% RAP and 25% RAP mixtures sustained less damage.

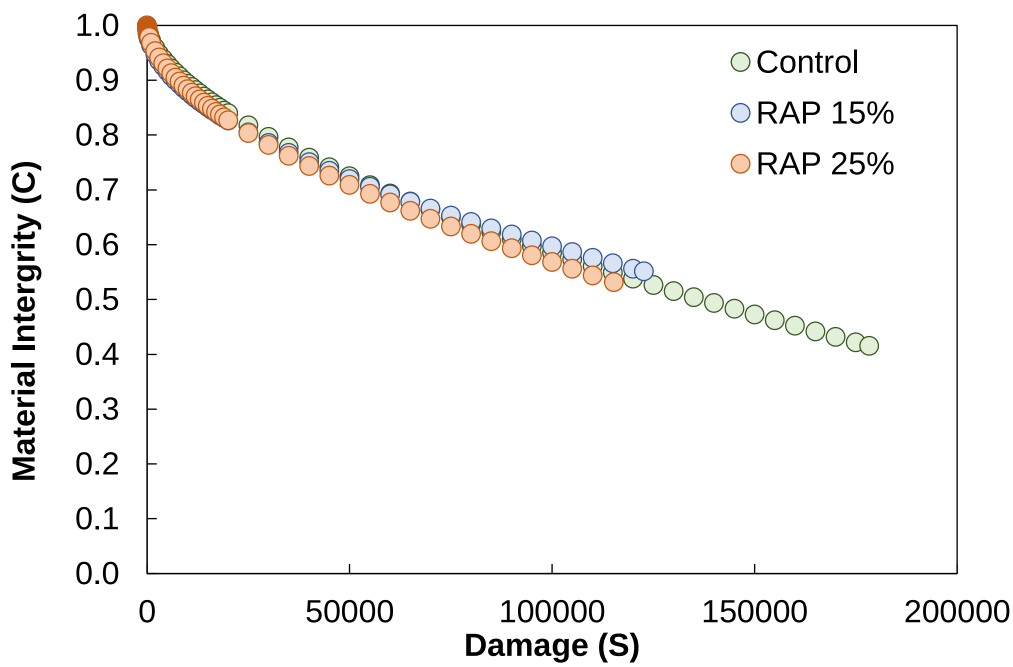


Figure 33. Damage Characteristic Curves of the Three Mixtures

These curves are not enough to tell the full story, thus the number of cycles till fatigue failure were determined for each mix and presented in Figure 34. As it can be seen from the figure, the three curves almost overlap on top of each other. Thus, for a certain strain level, the number of cycles required to cause fatigue failure is almost identical, yielding to the fact that adding 15% and 25% (with softer binder) RAP contents will not have a significant effect on the fatigue life of the mixtures.

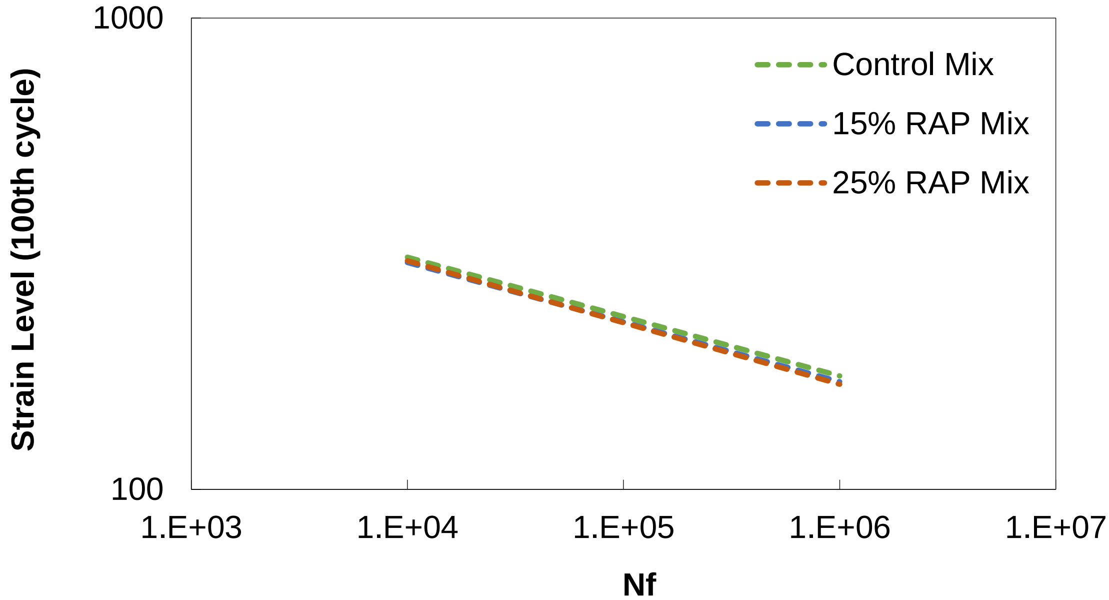


Figure 34. Fatigue Life Curves of the Three Mixtures

4.3.6- Tensile Strength Ratio Test (TSR) Results

Moisture damage is a result of loss of adhesion between the binder and aggregate in the presence of moisture. The TSR method was conducted in the three mixtures to evaluate the change in the indirect tensile strength after moisture conditioning. The TSR results are presented in Figure 35. As it can be seen, adding 15% and 25% RAP to the mixture didn't have any significant effect on the moisture damage resistance, as the TSR values are comparable. Moreover, all the mixtures passed both City of Phoenix specifications of TSR value above 75%, and the recommendations based on the literature of TSR value above

80%. It is worth to note that hydrated lime was used as antistripping agent in the three mixtures, which improved the moisture resistance properties.

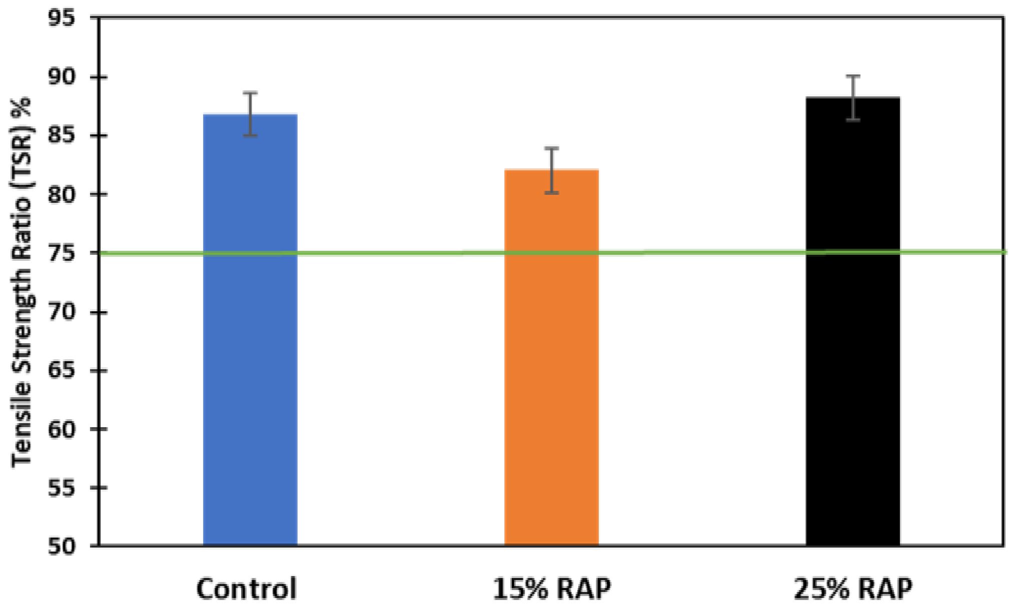


Figure 35. TSR Results of the 3 Mixtures

The statistical analysis shown in Table 12 indicated that there is not statistically significant difference between the three percentages, which means that adding RAP didn't affect the moisture resistance of the mix.

Table 12. TSR Statistical Analysis

Mixture	Tensile Strength (kPa)					α = 0.05			t-Test comparing:
	Repl. 1	Repl. 2	Repl. 3	Average	CV (%)	ANOVA	t-Test one-tail	t-Test two-tail	
0% RAP	84	90	86	86.8	3.6	NS	CNR	CNR	0% RAP-15% RAP
15% RAP	78	88	79	82.1	7.1		CNR	CNR	0% RAP-25% RAP
25% RAP	85	96	83	88.2	8.1		R	R	15% RAP-25% RAP

NS= Not Statistically Significant; S= Statistically Significant; R= Reject H_0; CNR= Cannot reject H_0

CHAPTER 5 BINDER LEVEL TESTING

The mixture testing performed and described in earlier chapters reflects the changes in the mechanical properties of the asphalt mix while adding two different percentages of RAP. Yet, there are two different factors that need to be considered before jumping to conclusions: (i) degree of binder blending and (ii) role of the variable RAP gradation of the properties of the mix. In order to eliminate or minimize the effect of these two variables, it is required to remove these components from the story, which means conducting testing at the binder level. Although binder testing will eliminate the effect of RAP gradation in the analysis yet will not completely solve the degree of blending issue. When testing at the mixture level, the aged RAP binder will not completely blend with the virgin binder, which will affect the properties of the final mix. Yet, the binder level testing might give a better indication on the properties of the aged-virgin binder composite, although it can’t be assumed fully blended.

5.1- Binder Extraction and Recovery

During the mixing process, RAP is mixed with virgin aggregates and virgin binder at high temperature. The aged RAP binder affects the properties of the total binder in the mix, yet the extent of this effect is dependent on the degree of blending. Figure 36 below explains the mixing process and how the final binder might be affected.

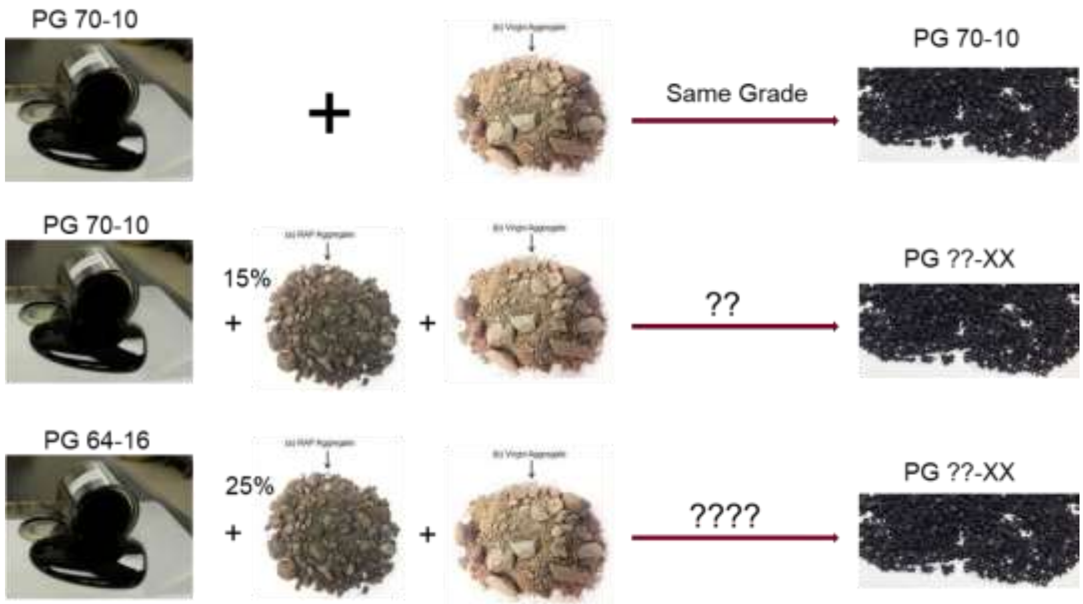


Figure 36. Binder Grade Changes After RAP Replacement

In the control mix (0% RAP) case, the PG 70-10 virgin binder was mixed with virgin aggregates, yielding to the final asphalt mix. Since no RAP was introduced in this mixture, the binder properties will not change and the final binder in the mix will have the same PG. However, in the other two mixtures, the properties of the final binder will change. In the case of the 15% RAP mix, a PG 70-10 virgin binder was added to virgin aggregate and RAP of 15% content. Some of the aged binder in this mix will blend with the virgin binder and might affect its properties. Thus, the properties of the binder in the final mix can't be assumed unchanged. Similarly, in the 25% RAP mix case, the PG 64-16 virgin binder will blend with some of the RAP binder (25% content) and the properties of the binder in the final mix will change. Thus, in order to determine the properties of these binders, extraction and recovery of the binder were performed.

The extraction process was carried using the centrifuge method, according to AASHTO T 164 "*Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)".* The loose asphalt mixture was placed in the centrifuge bowl (Figure 37) and then Trichlorethylene (TCE) solvent was added to remove the asphalt from the aggregates. The asphalt was kept immersed in the TCE for 1 hour to give some time for the TCE to remove the binder. After that the centrifuge machine was used to remove all the binder and TCE from the bowl.

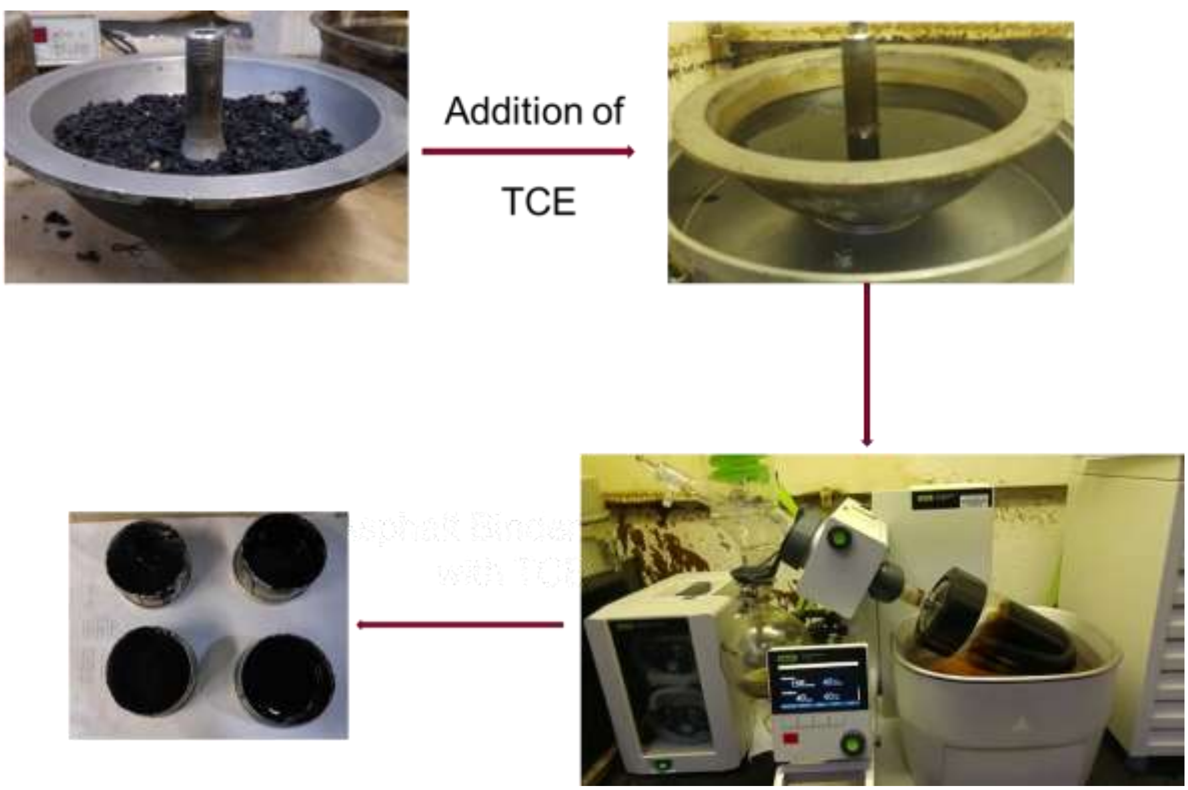


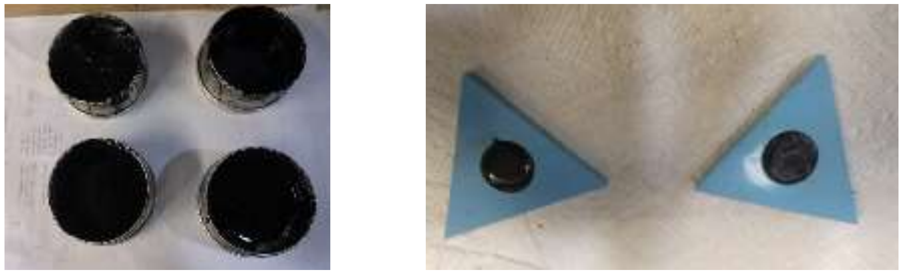
Figure 37. Extraction and Recovery Processes

The extraction process output is binder mixed with TCE. However, in order to determine the properties of the binder, the TCE has to be removed, as the TCE affects the properties of the binder. For this purpose, the RotoVap equipment (Figure 38-a) was used. In this process, the solution of TCE and asphalt was distilled by partially immersing the rotating distillation flask of the rotary evaporator in a heated oil bath while the solution is subjected to a partial vacuum and a flow of nitrogen gas to prevent binder oxidation. The recovered asphalt can then be subjected to testing as required. The process was done according to ASTM D5404 standard *"Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator".* Figure 38-b shows the binder in the flask that is immersed in a hot oil bath during the recovery process.

(a) (b)

Figure 38. Binder Recovery using RotoVap (a) Equipment and (b) During Flask Immersion in the Hot Oil Bath

After that, the binder was removed from the flask and poured into metal cans for DSR testing (Figure 39).



(a) (b)

Figure 39. Recovered Binder Poured Into: (a) Metal Cans Then (b) DSR Specimen Molds

5.2- Binder Level Testing

5.2.1- High Temperature PG Grading

Having extracted and recovered the binder from the three mixtures, the high temperature PG grading was conducted to evaluate the stiffening effect of the RAP binder, on the binder of the final mix. The PG grading was performed based on AASHTO M320, in which the recovered binders were considered short term aged since it is a plant mixture and it was already mixed before sampling. The AASHTO M320 high temperature PG grading RTFO criteria is presented in Equation 14:

$$\frac{G*}{Sin\,\delta} \geq 2.2\,kPa \qquad (14)$$

A 25 mm diameter plate geometry was used for this test, since the binder testing will take place at high temperature. The procedure of preparing the binder specimen is presented in Figure 40. The tested was set to start at 64°C for both the control and 15% RAP mixture, since the virgin binder was PG 70-10. For the 25% RAP mix, the test was set to start at 58°C, since the virgin binder was PG 64-16. The shear modulus and the phase angel were determined at each temperature, until Equation 14 was satisfied, the failing temperature was determined, and the test was completed.

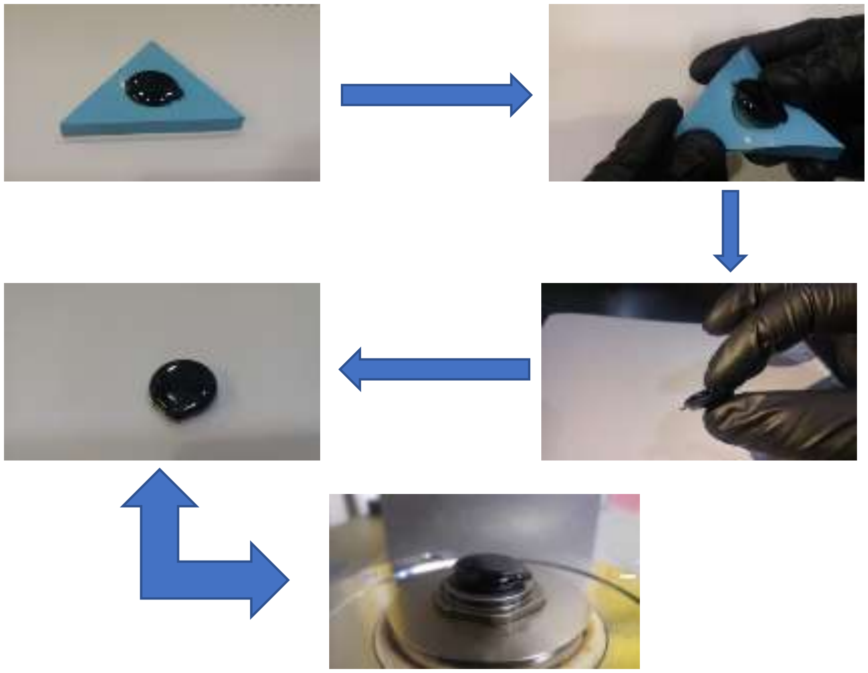


Figure 40. DSR Sample Preparation

5.2.2- Time-Temperature Sweep test (Complex Shear Modulus)

To determine the stiffening effect that the RAP binder induces in the blended binder, the complex shear modulus was performed on the extracted and recovered binders. The test was conducted at five different temperatures (10, 20, 30, 40, and 54°C) and at nine different frequencies ranging from 30 Hz to 0.1 Hz. The test allows the evaluation of the binder stiffness at different loading rates and different temperatures. Similar to the dynamic modulus, the time-temperature superposition principle was used to shift the isothermal curves into a final master curve. The CAM model presented in Equation 15 was used to perform the shifting. The WLF equation presented in Equation 16 was used to model the shift factor.

$$|G^*| = \frac{10^g}{\left(1+\left(\frac{\omega_c}{\omega_R}\right)^k\right)^{\frac{m_e}{k}}} \qquad (15)$$

$$log a_T = \frac{C_1(T - T_R)}{C_2 + T - T_R} \qquad (16)$$

Where:

|G*| = the dynamic shear modulus (Pa)

10g = binder glassy modulus (Pa) (determined through optimization)

Ω c = crossover frequency (rad/s)

me and k = fitting coefficients

T = test temperature (° C)

TR = reference temperature (C)

C1 and C2 = time-temperature shift factor function fitting coefficients.

5.2.3- Multiple Stress Creep and Recovery (MSCR)

MSCR tests were performed on the three recovered binders. The test temperature was maintained at 64°C for all the binders, and creep and recovery parameters were

Figure 41. MSCR Test Setup

determined. The test setup is shown in Figure 41. The two test parameters determined from the MSCR tests are the percentage recovery (R), and the nonrecoverable compliance (Jnr). The MSCR test is done by subjecting the binder to repeated cycles of shear creep and recovery. MSCR tests characterize the viscoelastic properties based on the amount of strains incurred and recovered during the creep and recovery cycles respectively. Repeated cycles of 1 s creep loading and 9 s recovery periods are used to measure the strains incurred by the binders. The test is performed at two separate stress levels of 0.1 and 3.2 kPa to simulate the linear and nonlinear viscoelastic regions respectively. Jnr measures the non-recoverable strains of the binder with respect to the stress at which the deformation occurs, thus it is desired to minimize it. R measures the recovery of the asphalts observed during the rest period of the MSCR test as a ratio of the recovered strain to the original strain at the beginning of each creep and recovery cycle. A higher R indicates more elastic binder with lower accumulated strains in each loading cycle. Equations 17 and 18 were used to determine the creep and recovery parameters (AASHT T350).

$$Jnr = \frac{Average\ Non\ Recoverable\ Strain}{Average\ Stress} \quad (17)$$

$$Percentage\ Recovery = \frac{Recovered\ Strain}{Total\ Strain} * 100 \quad (18)$$

5.3- Results

5.3.1- PG Grading Results

The PG grading results are shown in Figure 42. The testing was performed on the binder recovered from the control mix just to ensure that the extraction, recovery, and testing procedures were properly done. The resulted PG was expected with a high temperature PG grading of 70. This because there is no RAP in the control mix so there was no stiffening effect. The test stopped at 71 °C after the failure criteria was met. The testing on the binder recovered from the 15% RAP mix showed that the addition of 15% RAP had a slight stiffening effect, in which the binder failed at 74°C, yet, the high temperature PG grading didn’t change. For the 25% RAP binder, which was initially with high temperature PG grade of 64, the addition of 25% RAP yielded to an increase from 64 to 76. The test was completed at a temperature of 80°C, which means the binder was close to be graded as 82. The reason behind this is the very stiff RAP binder, which was shown to have a high temperature PG of 108 (Figure 43).

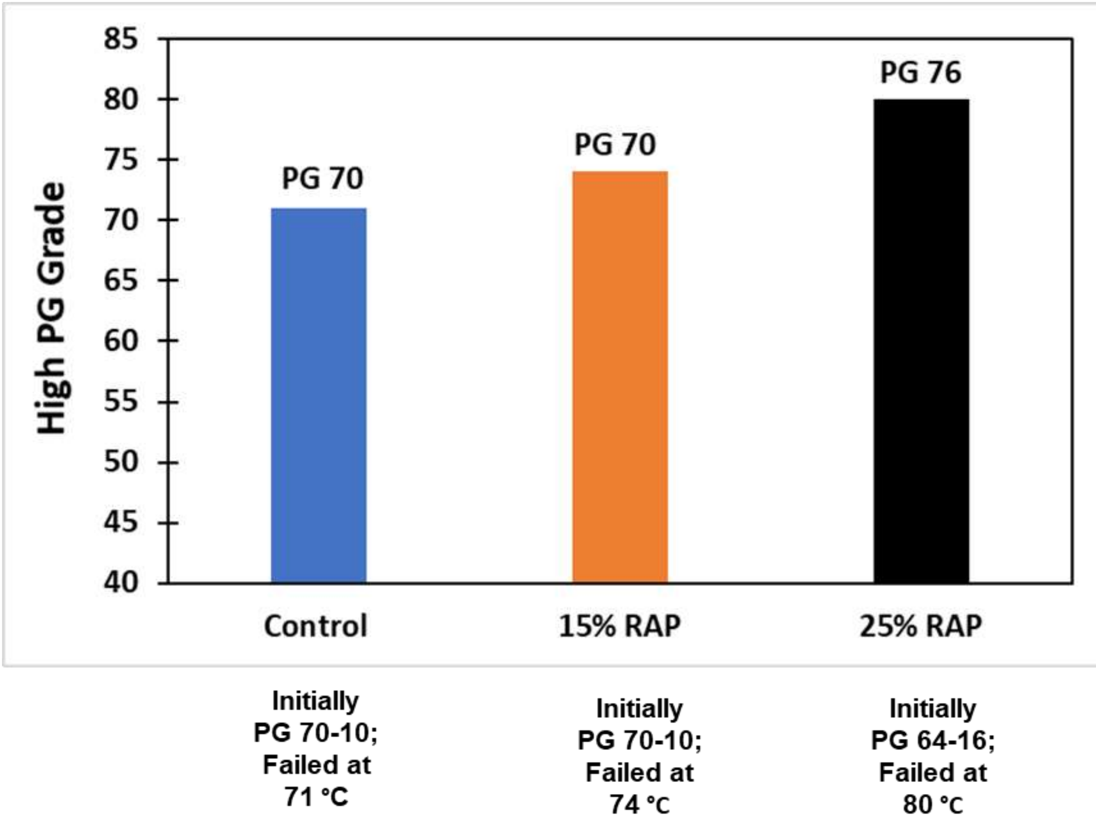


Figure 42. PG Results

Figure 43. Aged RAP Binder PG

5.3.2- Complex Shear Modulus (G*)

The complex shear modulus test was conducted on the three recovered binder, to evaluate the stiffness at different loading rates and different frequencies. The master curves for the three binders are shown in Figure 44. As the figure illustrates, the addition of 15% RAP to the mix doesn't have a significant stiffening effect on the binder, in which the two master curves corresponding to the control binder and 15% RAP binder are very close. this is also in agreement with the PG grading results. For the 25% RAP binder, the stiffening effect of the highly aged RAP is clearly shown, in which the master curve is above the two other binders at all combinations of temperature and frequencies. This result is in contrast with the mixture dynamic modulus results due to the blending that occurred while extracting and recovering the binder.

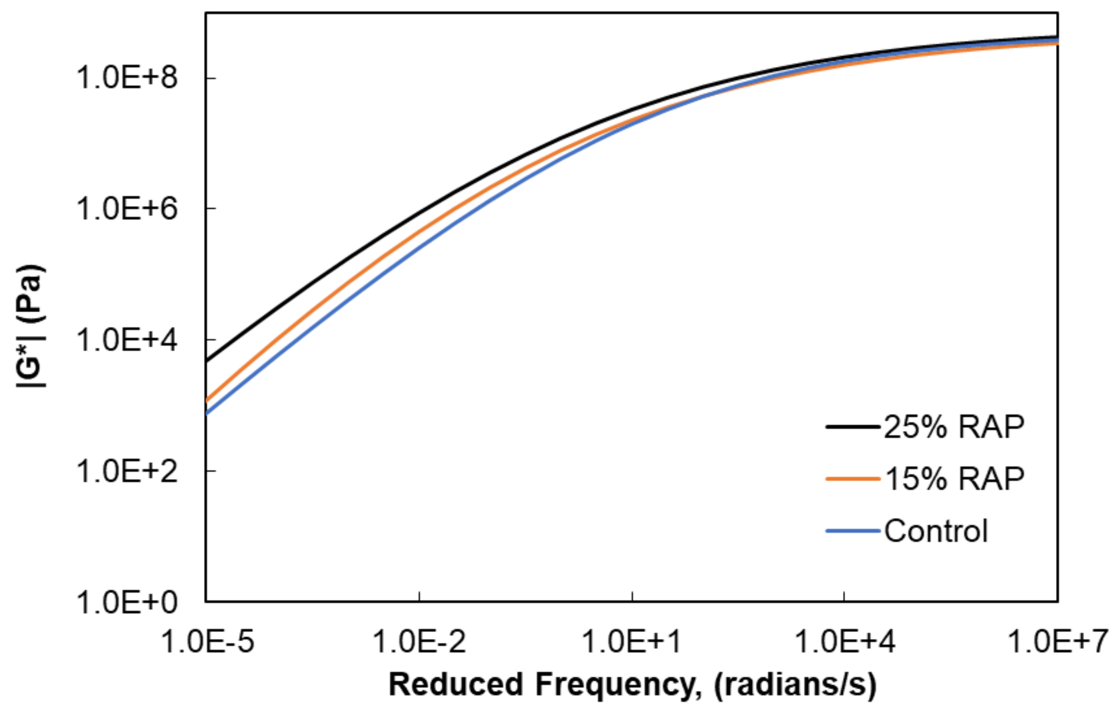


Figure 44. Complex Shear Modulus Master Curves of the Three Recovered Binders

5.3.3- Multiple Stress Creep and Recovery (MSCR)

The MSCR test gives a clear idea on the recovery properties of binders outside the linear viscoelastic range, which is typically the range where damage and deformation start happening in the field. Figures 45 and 46 show the Jnr and recovery percentage for the 3 binders, respectively. As expected, the addition of 15% RAP decreases the Jnr values and increase the recovery values, and these changes are due to the increase in the elastic components inside the binder caused by the addition of aged RAP binder. Similarly, the addition of 25% RAP yields a lower Jnr and higher recovery, due to the availability of more elastic binder.

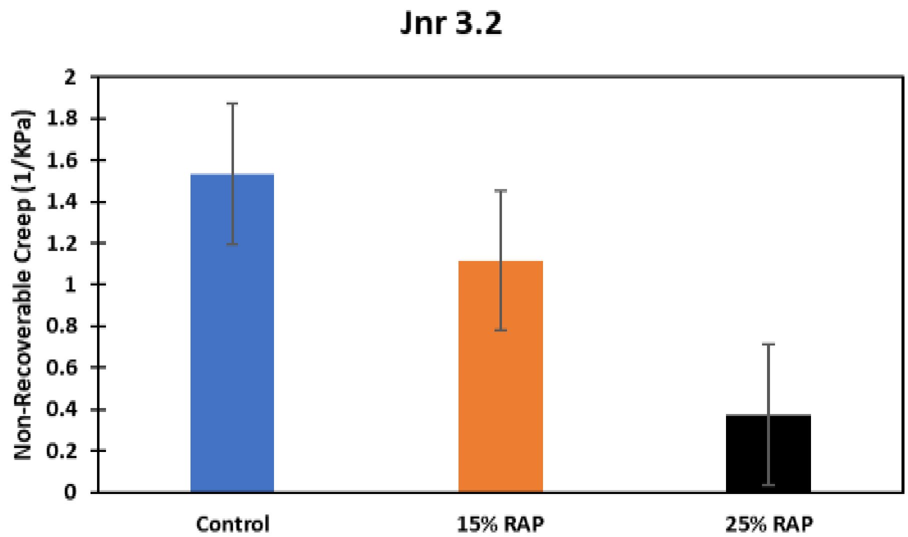


Figure 45. Jnr Values of the Three Recovered Binders

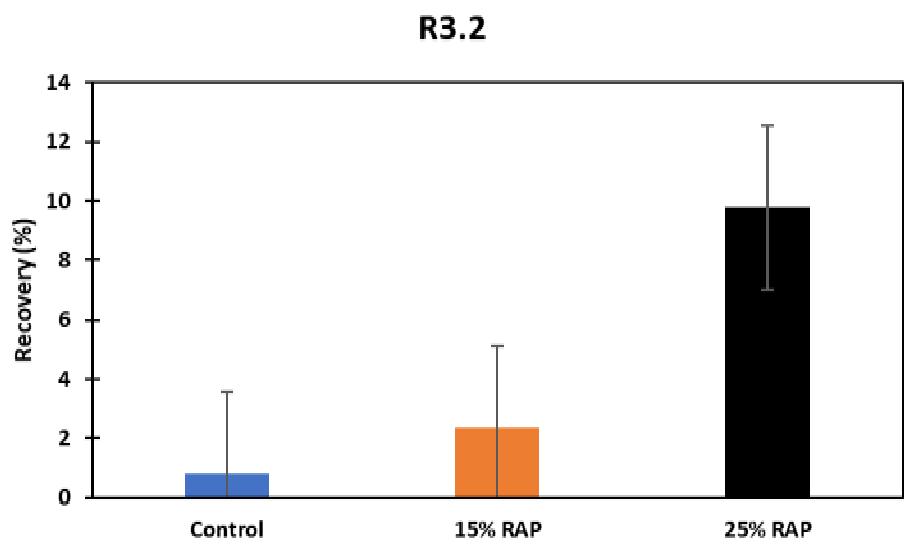


Figure 46. Recovery Values of the Three Recovered Binders

CHAPTER 6 Field Evaluation

Having constructed three different sections to evaluate the field performance of the mixtures containing two different percentages (15% and 25%) in the field, it is very important to keep monitoring the performance of these 3 sections. To do so, surface evaluation (distress survey) was conducted on April 24, 2018 to evaluate the distresses in each section. Moreover, 5 cores were taken from each section to measure the thicknesses and air voids, and at the same time perform the Indirect Tensile Strength (IDT) test to compare the field results to that of the laboratory one.

6.1- Surface Evaluation

A field visit was conducted on April 24, 2019 to evaluate the field performance of the three sections. At the time of the visit the road has been subjected to light traffic for a period of 142 days and considerable rain over the winter months. As expected, the three test sections showed no distresses at this time as shown in Figure 47. The road is still relatively newly constructed, and distresses need more time to develop. In addition, the test sections are also protected with the surface mix (terminal blend), that is, the RAP mixtures are placed below this layer. Future field monitoring over the next few years needs to be continued to monitor the field performance of the RAP base layers.

Figure 47. Surface Evaluation of the Three Sections

6.2- Field Cores

Five cores were taken from each test section to determine the air voids and thicknesses of the layers. Figures 48 to 50 show the five cores taken from each section. One core from each of the 15 percent RAP and 25 percent RAP sections fell apart during coring, so obviously no measurements were taken for these samples.

Figure 48. Cores Taken from the Control Section

Figure 49. Cores Taken from 15% RAP Section

Figure 50. Cores Taken from 25% RAP Section

For each core, four different thickness measurements were taken, and the average was reported. The cores were cut using a cutting saw blade to arrive at a thickness of 62 mm that was determined suitable for testing. In the case where the core thickness did not allow to reach this value, the thickness closest to 62 mm was chosen. The air voids were measured for each core and reported. The IDT test was performed. Figure 51 shows the thicknesses, air voids, and tensile strengths for each core. As it can be seen from the Figure, the results were variable for all these properties across the sections.

The average thicknesses, air voids, and tensile strengths for the cores from each test section were calculated and presented in Figure 52. The control and 15 percent RAP sections had similar air voids, whereas the 25 percent RAP section had a lower air void content. As far as thicknesses, the control section had the least average thickness followed by the 15 percent RAP section. The 25 percent RAP section had the highest thickness. While the variation in the air voids and thicknesses will affect the performance, it is noted that these test sections were placed on a small residential street that had variable subbase conditions and elevations. Therefore, the comparison between the three sections in terms of these properties may not be best represented. However, the 25 percent RAP showed the highest tensile strength followed by the 15 percent RAP section and then the control section. This result is in general agreement with the laboratory test results.

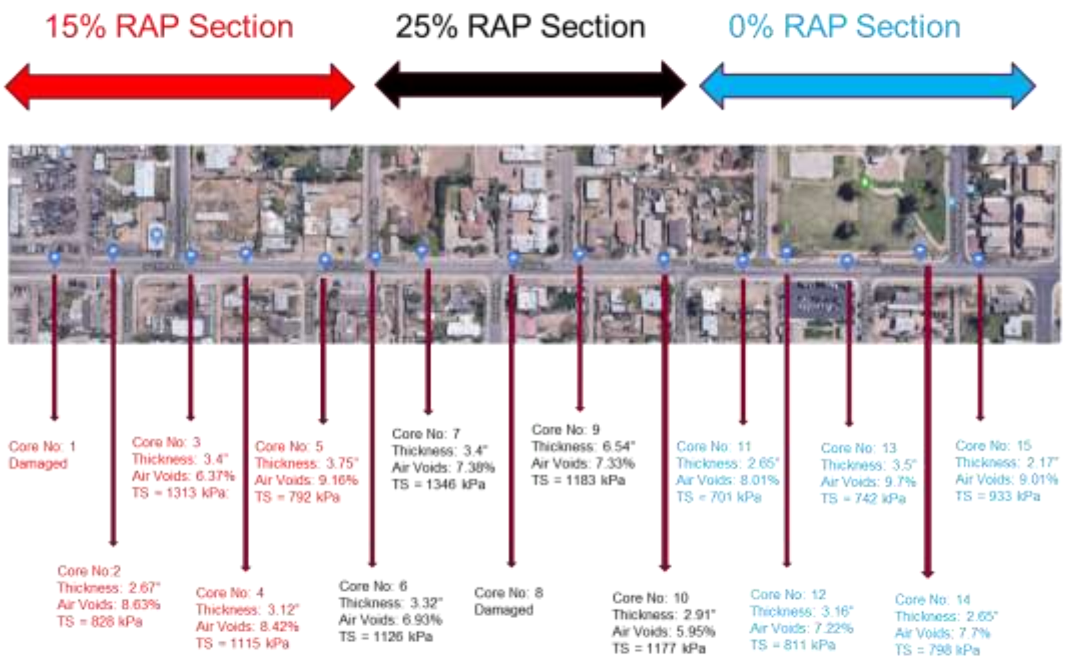


Figure 51. Field Cores Properties

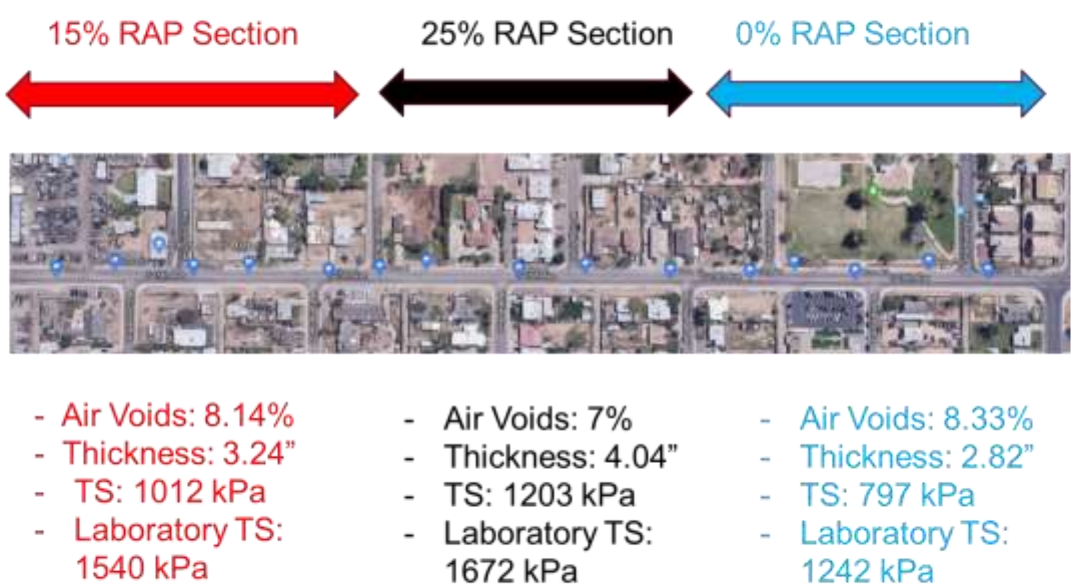


Figure 52. Average Cores Properties for Each Section

Figure 53 shows the air voids values for each core; the red bar being the generally targeted air voids of 6.5%. It is noted that all the laboratory specimens were compacted to this air void level. As shown in Figure 53, many cores deviated from the target air voids level in the 15 percent RAP and control sections. The air voids level in the 25 percent RAP section appeared to be comparable to the target. In general, this difference in the air voids may affect the rutting and fatigue performance in the test sections, thus it will be equally important to consider these variations when comparing the performance in the future.

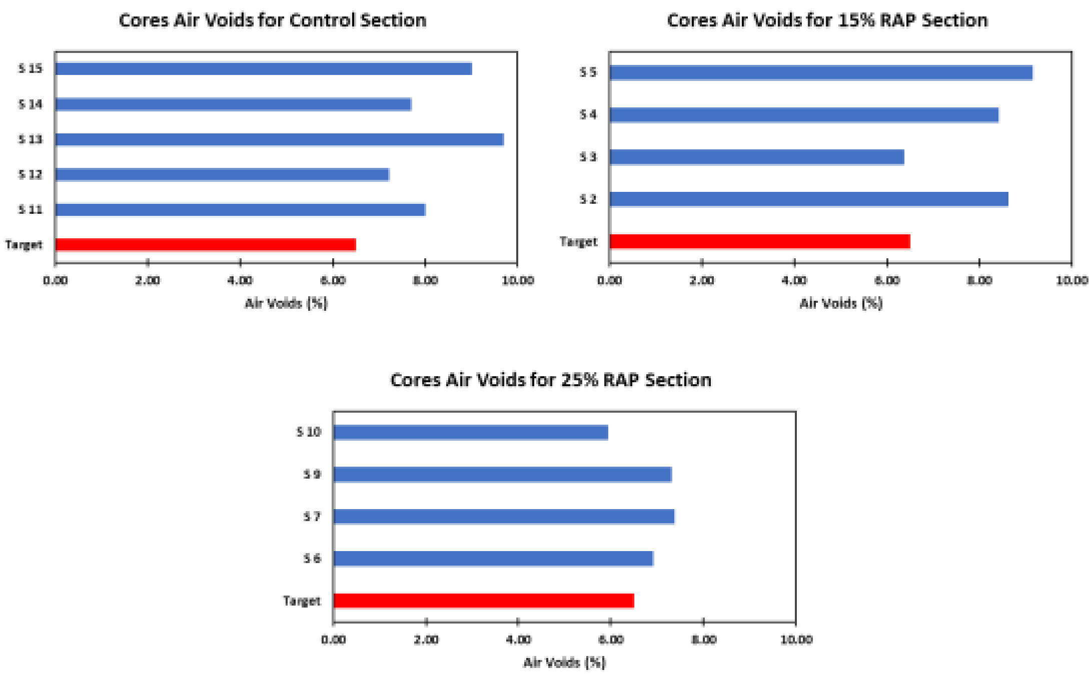


Figure 53. Air Voids Analysis of the Field Cores

Figure 54 shows a detailed thickness analysis for the three sections. The red bar in each graph is the target pavement design thickness of 3.5 inches. Again, it is noted that the core thicknesses in each section were variable, mostly lower than the target but in few cases higher. As mentioned earlier, this variation in thickness may lead to a difference in performance especially when the driven distress is structural, such as fatigue cracking. This will also make the field performance comparison between the three sections inaccurate, in which fatigue might be due to structural failure governed by the low thickness and not necessarily the addition of RAP. This variation needs to be considered for such comparison.

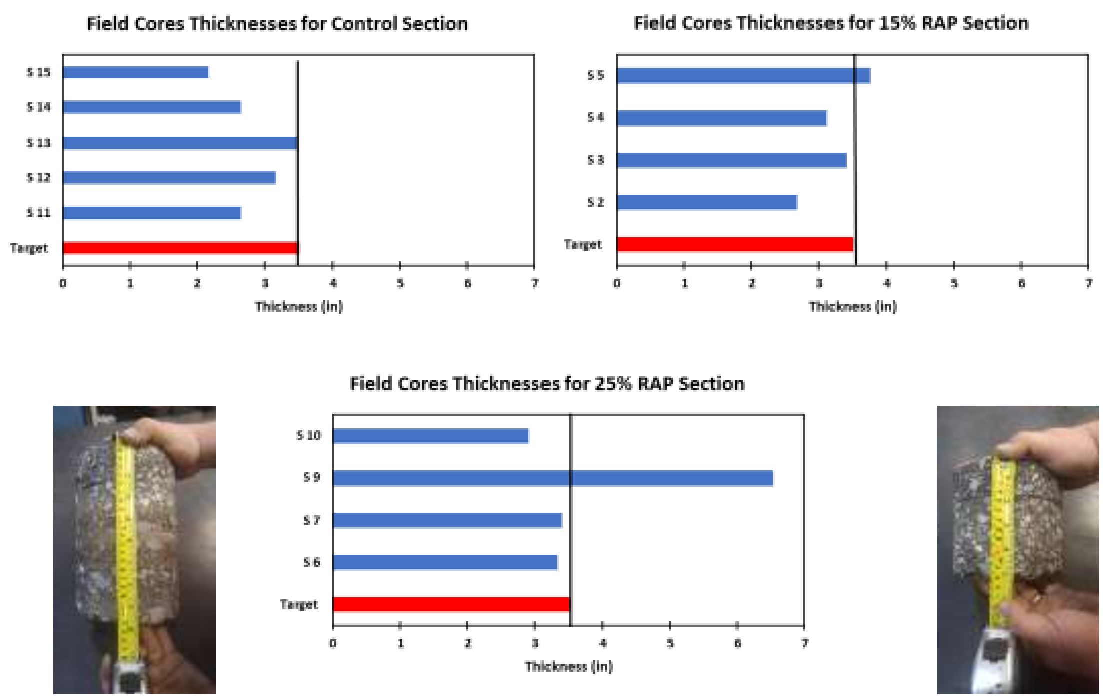


Figure 54. Field Cores Thickness Analysis

Figure 55 shows a detailed representation of the tensile strength values of the field cores. The red bar indicates the laboratory measured value of the tensile strength. As it can be seen, all field cores had a lower tensile strength, which is expected because of the higher air voids. The tensile strength also showed higher variability and deviation from the laboratory measured values. It is understandable that this was a local street constructed with minimum field tests; however, this emphasizes the fact that better quality control testing needs to be enforced in future projects.

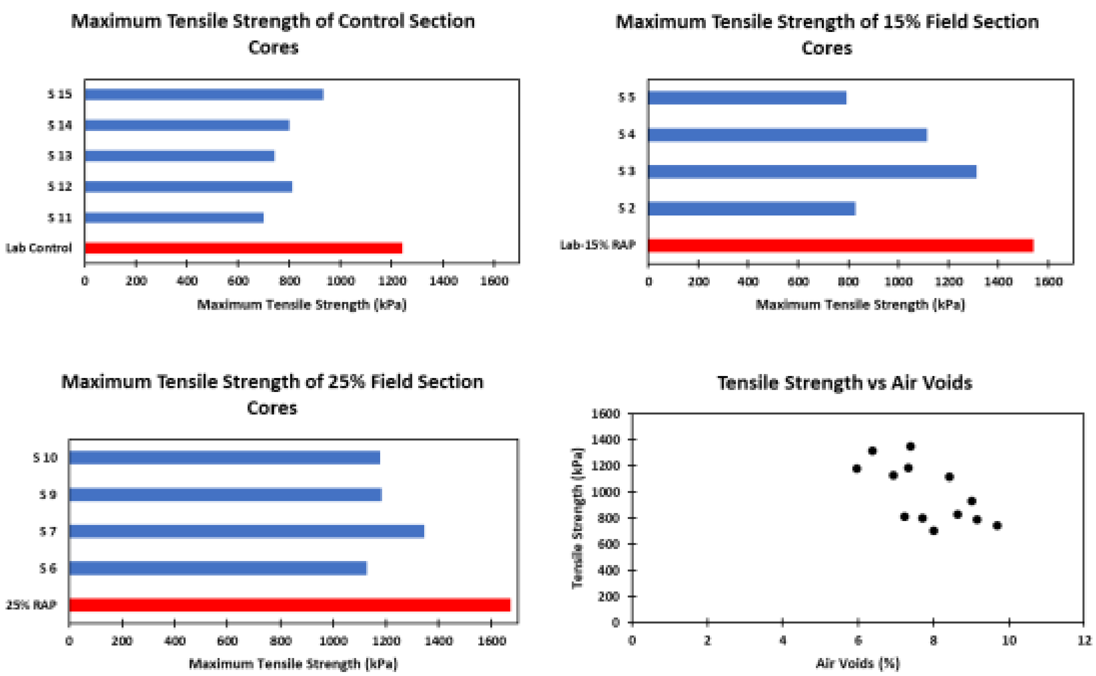


Figure 55. Tensile Strength Analysis of the Field Cores

Although the laboratory testing showed similar characteristics when 15 and 25 percent RAP were included in the mixtures, there is incompatibility between laboratory studies and field performance. This inconsistency gap needs to be better controlled and considered in future evaluation of the sections.

CHAPTER 7 Summary, Conclusions, and Recommendations

Asphalt concrete recycling can potentially save public works agencies money and energy. In this research, the effect of adding 15% and 25% RAP on the mix was studied through constructing field sections and through performing laboratory testing. The following conclusions can be drawn from this study:

- Incorporating 15% RAP into HMA will not affect the stiffness of the mix, given that the same binder grading is kept.
- The addition of 25% RAP into HMA required dropping one binder grade down at each temperature. In this study, PG 64-16 was used instead of PG 70-10 when 25% RAP was added.
- The dynamic modulus of an HMA doesn't change significantly when 25% RAP is added and when binder grade is lowered.
- Incorporating 15% and 25% (with softer binder) RAP will improve the rutting resistance of the mixtures.
- Mixtures with the aforementioned RAP contents have similar crack initiation properties as the control mixture.
- The crack propagation properties of the mixtures will be affected when 25% RAP is added, yet still comparable to the control. The addition of 15% RAP had a positive effect on the crack propagation properties of the mix.
- The fatigue life of the mixtures studied in this research wasn't affected with the incorporation of the used two RAP contents.

- The addition of RAP into HMA at both contents doesn't affect the mixture resistance to moisture damage.
- Performance Grading of the extracted and recovered binders indicated that the addition of 15% RAP will not affect the grading of the final binder, whereas the addition of 25% RAP will increase the grade of the binder. This was explained by the high temperature PG of the RAP itself in which it exceeded 100.
- The complex shear modulus testing indicated that the addition of 25% RAP binders will affect the stiffness of the final binder at the different temperatures and frequencies tested, yet the addition of the 15% RAP didn't yield any stiffening effect.
- Binder recovered from 15% RAP mixtures and 25% RAP mixtures showed better recovery behavior and less non-recoverable strain values when the MSCR test was performed. This is a result of the additional elastic component that the aged RAP binder adds to the binder.
- The surface evaluation performed to date showed no difference in the performance between the three test sections. However, the road sections are newly constructed, and more time should be given to investigate the long-term durability of the test sections.
- The testing performed on the field cores indicated that there were variability issues in thicknesses and air voids between the three sections and within each test section. These differences may lead to widen the gap between the laboratory test results and field performance. These issues should be carefully taken into consideration in future follow up projects and performance monitoring, and a

good Quality Control and Quality Assurance (QC/QA) program need to be enforced on all future projects.

Based on this study's results, it is recommended that the City of Phoenix consider the immediate implementation of using 15 percent RAP in their asphalt mixtures while keeping the same binder grade; it is also recommended that the City consider additional test sections incorporating 25 percent RAP while dropping one PG grade at both temperature ends.
In addition, it is recommended to move on to the next stage of this collaborative research effort between the City of Phoenix and ASU. This phase would investigate the effect of using RAP in the Terminal Blend mixture which was used as a surface layer in this study. Surface layer replacement comprises the majority of the road maintenance repaving work done by the City of Phoenix. Incorporating RAP into the mix design for the surface layer will greatly expand the use of RAP, decreasing the environmental footprint (GHG) of their road maintenance operations. Finally, a continued laboratory testing program over the next few years is recommended to build historical records and supports findings from this study.

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APPENDIX A
MIXTURE DESIGN

SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

MARSHALL MIX DESIGN - 75 BLOW

SUPPLIER: Southwest Asphalt - PLANT NO.: 4
PROJECT: 2018 Annual Mix Design El Mirage
LOCATION: Various
MIX DESIGNATION: COP C- ¾" Marshall Asphalt Concrete
LAB NO: 4903

DATE: 01/23/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
AGENCY: COP
PLANT NO.: 4
COMMODITY CODE: 432CH & 432DH

COMPOSITE GRADATION

Material I.D.	*Material Source*	*% Used*
Blend Sand	Fisher Sand and Gravel New River	27.0
Crusher Fines	Fisher Sand and Gravel New River	23.9
3/8 Inch Agg.	Fisher Sand and Gravel New River	9.0
#8 Agg.	Fisher Sand and Gravel New River	8.0
3/4 Inch Agg.	Fisher Sand and Gravel New River	31.0
Hydrated Lime	Lhoist North America	1.1

Sieve US/mm	*w/o Admix % Passing*	*w/Admix % Passing*	*City of Phoenix Mix Design Target*	*Production Limits*
1½" / 37.5	100	100		
1" / 25	100	100	100	
3/4" / 19	100	100	95	88 - 100
1/2" / 12.5	85	85	85	78 - 92
3/8" / 9.5	75	76	75	68 - 82
1/4" / 6.3	64	65		
#4 / 4.75	58	59	58	51 - 65
#8 / 2.36	43	44	44	39 - 49
#10 / 2.00	40	41		
#16 / 1.18	31	32		
#30 / .600	20	21	24	19 - 29
#40 / .425	15	16		
#50 / .300	10	11		
#100 / .150	5	6		
#200 / .075	3.7	4.7	4.0	2.0 - 6.0

ADDITIONAL DATA

Asphalt Binder Source:	Western
Asphalt Binder Grade:	PG 70-10
Asphalt Binder Secific Gravity:	1.021
Mineral Admix Type:	Hydrated Lime
Mineral Admix Specific Gravity:	2.20
Recommended Lab Mixing Temperature:	319°F to 330°F
Recommended Lab Compaction Temperature:	299°F to 307°F
Actual Lab Mixing Temperature Used:	324.5°F
Actual Lab Compaction Temperature Used:	303°F

DESIGN DATA	432CH	&	432DH
Traffic Loading	Hi Vol		Lo Vol
Total Binder Content (%)	5.0		5.5
Marshall Bulk Density (pcf)	148.0		149.1
Max. Theoretical Specific Gravity	2.478		2.459
Max. Theoretical Specific Density (pcf)	154.6		153.4
Stability	5,010		4,860
Marshall Flow (in.)	11		12
% Air Voids	4.3		2.8
% VMA	14.5		14.3
% Air Voids Filled	70.5		80.1
% Eff Asphalt Total Mix	4.39		4.89
Film Thickness (µ)	9		10
Dust/Bitumen Ratio	1.1		1.0

AGGREGATE PROPERTIES

Aggregate Property	*Coarse Aggr.*	*Fine Aggr.*	*Comb. w/o Adm*	*Comb. w/ Admix*	*Spec.*
Bulk OD Specific Gravity	2.667	2.615	2.640	2.634	2.35-2.85
SSD Specific Gravity	2.696	2.646	2.670	2.664	
Apparent Specific Gravity	2.749	2.698	2.722	2.715	
Absorption (%)	1.117	1.175	1.147	1.132	0.00-2.50
Effective Specific Gravity (Gse)				2.679	
Sand Equivalent		73			55 Min
Plasticity Index		NP			NP
% 1 or More Fractured Face	94				92 Min
% 2 or More Fractured Face	89				85 Min
Uncompacted Voids		46.0			45 Min
Los Angeles Abrasion					
% Loss @ 100 Rev - Grading B	3				9 Max
% Loss @ 500 Rev - Grading B	17				40 Max
% Flat & Elongated (5:1 Ratio)	1.7				10 Max
% Soundness Loss (NaSO4)	1	1			
% Claylumps & Friable Particles	0.2	0.3			

Registered Professional Engineer (Civil)
CERTIFICATE NO. 60483
JUAN LOPEZ
DATE SIGNED 1-23-18
ARIZONA U.S.A.
Exp 9-30-18

Registered Professional Engineer (Civil)
CERTIFICATE 47822
MICHAEL W. MOEHN
Date Signed 1-23-18
ARIZONA, U.S.A.
Expires 3-31-20

SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

75 BLOW MARSHALL MIX DESIGN - WITH RAP

SUPPLIER: Southwest Asphalt - PLANT NO.: 4
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
AGENCY: COP
COMMODITY CODE: 432GH

COMPOSITE GRADATION

Material I.D.	Material Source	% Used
Blend Sand	MR Tanner ElMirage	20.0
Crusher Fines	MR Tanner ElMirage	8.9
Washed CF	MR Tanner ElMirage	12.0
3/8 Inch Agg.	MR Tanner ElMirage	11.0
3/4 Inch Agg.	MR Tanner ElMirage	32.0
RAP	MR Tanner ElMirage	15.0
Hydrated Lime	Lhoist North America	1.1

Sieve US/mm	w/o Admix % Passing	w/Admix % Passing	Specification Limits	Production Limits
1½" / 37.5	100	100		
1" / 25	100	100	100	
3/4" / 19	100	100	95	88 - 100
1/2" / 12.5	87	87	85	78 - 92
3/8" / 9.5	74	74	75	68 - 82
1/4" / 6.3	62	63		
#4 / 4.75	57	58	58	51 - 65
#8 / 2.36	45	46	44	39 - 49
#10 / 2.00	42	42		
#16 / 1.18	33	34		
#30 / .600	21	22	24	19 - 29
#40 / .425	15	16		12 - 20
#50 / .300	11	12		
#100 / .150	5	6		
#200 / .075	3.5	4.5	4.0	2.0 - 6.0

ADDITIONAL DATA

Virgin Asphalt Binder Source:	Western
Virgin Asphalt Binder Grade:	PG 70-10
Virgin Asphalt Specific Gravity:	1.024
Mineral Admix Type:	Hydrated Lime
Mineral Admix Source:	Lhoist North America
Mineral Admix Specific Gravity:	2.20
Recommended Lab Mixing Temperature:	317°F to 328°F
Recommended Lab Compaction Temperature:	297°F to 305°F
Actual Lab Mixing Temperature Used:	322.5°F
Actual Lab Compaction Temperature Used:	301°F
Percent Virgin Aggergate***:	83.9
Percent RAP Aggergate***:	14.8
RAP Percent Binder:	3.96
RAP Binder Specific Gravity:	1.050 @ 77°F
Percent RAP Binder **:	11.6
Percent Virgin Binder (100-%RAP Binder)**:	88.4

RECOMMENDED TOTAL BINDER CONTENT (%)*:	**5.00**
ADDED VIRGIN BINDER CONTENT (%)*:	**4.41**
CONTRIBUTED RAP BINDER CONTENT (%)*:	**0.59**

*-by weight of total mix, **-by Weight of total binder, ***-by weight of total aggr.

DESIGN DATA

					Criteria
Total Binder Content (%)	4.5	**5.0**	5.5	6.0	
Marshall Bulk Density (pcf)	147.8	**148.7**	149.6	150.2	
Marshall Stability (lb)	5,430	**5,390**	5,340	5,260	
Marshall Flow (in.)	9	**10**	13	15	
% Air Voids	5.2	**3.9**	2.6	1.5	
% VMA	14.5	**14.5**	14.4	14.5	
% Air Voids Filled	64.0	**72.7**	81.8	89.7	
% Eff Asphalt Total Mix	4.02	**4.52**	5.03	5.53	
Film Thickness (μ)	8	**9**	10	11	
Dust/Bitumen Ratio	1.1	**1.0**	0.9	0.8	

Max Theoretical Sp. Gr. / Dens.	2.481 /	154.8	pcf @	5.0%	
% Asphalt Abs. on Dry Agg	0.50				0.0-1.0

TSR - ASTM D4867

Set ID	Dry PSI	Wet PSI	Retained Strength	Percent Asphalt	Percent Admix
Number 1	164	152	93	5.0	1.10
Specification	100 Min		65 Min		

AGGREGATE PROPERTIES

Virgin Aggregates	Coarse Aggr.	Fine Aggr.	Comb. w/o Adm	Comb. w/ Admix	Spec.
Bulk OD Specific Gravity	2.672	2.635	2.654	2.647	2.35-2.85
SSD Specific Gravity	2.704	2.664	2.685	2.677	
Apparent Specific Gravity	2.761	2.714	2.738	2.729	
Absorption (%)	1.207	1.112	1.159	1.141	0.00-2.50
Effective Specific Gravity (Gse)				2.682	
Sand Equivalent		64			50 Min
Uncompacted Voids		48.1			45 Min
% 1 or More Fractured Face	96				85 Min
% 2 or More Fractured Face	90				80 Min
Los Angeles Abrasion					
% Loss @ 100 Rev - Grading B	4				9 Max
% Loss @ 500 Rev - Grading B	17				40 Max
% Claylumps & Friable Particles	0.2	0.3			

RAP Aggregates	RAP				
Bulk OD Specific Gravity	2.543				2.35-2.85
SSD Specific Gravity	2.573				
Absorption (%)	1.159				0.00-2.50
Effective Specific Gravity (Gser)	2.574				
Los Angeles Abrasion					
% Loss @ 100 Rev - Grading B	5				9 Max
% Loss @ 100 Rev - Grading B	21				40 Max

Combined Virgin & RAP Aggregate				w/ Admix	Spec.
Bulk OD Specific Gravity				2.631	
SSD Specific Gravity				2.661	
Apparent Specific Gravity				2.713	
Absorption (%)				1.159	
Effective Specific Gravity (Gse)				2.682	
% 1 or More Fractured Face				97	85 Min
% 2 or More Fractured Face				92	80 Min

SOUTHWEST Asphalt

A DIVISION OF FISHER SAND & GRAVEL CO.

COMPOSITE #1 - VIRGIN & RAP AGGREGATES

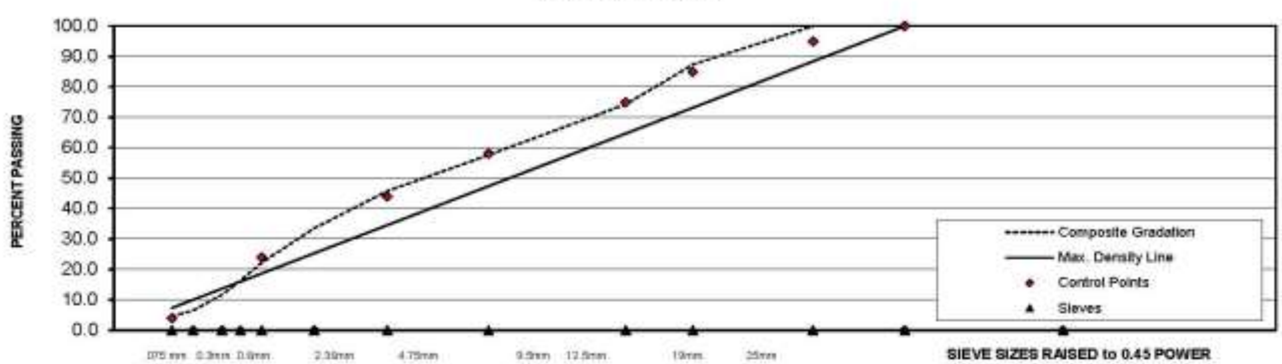
SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH
AGENCY: MAG/EVAC

	ORIGINAL GRADATION - % PASSING											COMPOSITE % PASS		GRADATION SPECS with ADMIX	
	MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	MAT'L 8	MAT'L 9	MAT'L 10		without ADMIX	with ADMIX		
MAT'L NAME	Blend Sand	Crusher Fines	Washed CF	3/8 inch Agg.	3/4 inch Agg.				RAP		Hydrated Lime				
LAB NO.											N/A				
% USED	20.0	8.9	12.0	11.0	32.0				15.0		1.1				
SIEVE															SIEVE
1½"	100.0	100.0	100.0	100.0	100.0				100.0		100.0	100.0	100.0		1½"
1"	100.0	100.0	100.0	100.0	100.0				100.0		100.0	100.0	100.0	100	1"
3/4"	100.0	100.0	100.0	100.0	100.0				100.0		100.0	100.0	100.0	95 - 95	3/4"
1/2"	100.0	100.0	100.0	100.0	63.2				94.4		100.0	87.2	87.4	85 - 85	1/2"
3/8"	100.0	100.0	100.0	100.0	26.0				86.4		100.0	74.0	74.3	75 - 75	3/8"
1/4"	100.0	100.0	100.0	74.1	3.9				74.6		100.0	62.2	62.6		1/4"
#4	100.0	100.0	96.6	46.7	2.8				66.4		100.0	57.1	57.6	58 - 58	#4
#8	88.3	82.0	83.8	12.4	2.2				50.8		100.0	45.2	45.8	44 - 44	#8
#10	83.3	72.9	75.4	10.2	2.1				47.6		100.0	41.6	42.2		#10
#16	68.4	52.8	56.8	6.9	1.9				39.4		100.0	32.8	33.6		#16
#30	40.5	35.4	36.8	5.1	1.7				29.0		100.0	21.4	22.2	24 - 24	#30
#40	24.8	28.2	26.8	4.6	1.6				23.4		100.0	15.4	16.3		#40
#50	12.9	22.4	18.4	4.2	1.5				19.2		100.0	10.7	11.7		#50
#100	2.4	14.3	7.2	3.4	1.3				13.0		100.0	5.4	6.4		#100
#200	0.8	10.9	2.4	2.6	0.9				9.4		100.0	3.5	4.5	4.0 - 4.0	#200

MAT'L 1 =	Blend Sand	MR Tanner ElMirage
MAT'L 2 =	Crusher Fines	MR Tanner ElMirage
MAT'L 3 =	Washed CF	MR Tanner ElMirage
MAT'L 4 =	3/8 inch Agg.	MR Tanner ElMirage
MAT'L 5 =	3/4 inch Agg.	MR Tanner ElMirage
MAT'L 6 =		
MAT'L 7 =		
MAT'L 8 =		
MAT'L 9 =	RAP	MR Tanner ElMirage
MAT'L 10 =		

COMPOSITE GRADATION



SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

COMPOSITE #2 - VIRGIN AGGREGATE GRADATION

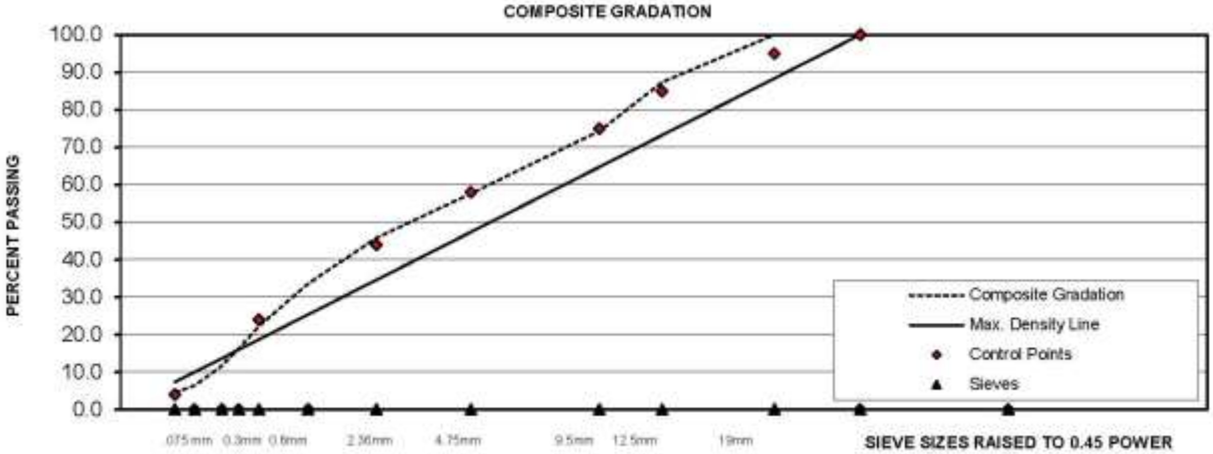
SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

DATE: 10-12-2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH
AGENCY: MAG/EVAC

	ORIGINAL GRADATION - % PASSING								COMPOSITE % PASS		
	MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	MAT'L 8			
MAT'L NAME	Blend Sand	Crusher Fines	Washed CF	3/8 Inch Agg.	3/4 Inch Agg.						
LAB NO.									without	with	
ADJ. BIN %'s	**23.8**	**10.6**	**14.3**	**13.1**	**38.1**				ADMIX	ADMIX	
ORIG. BIN %'s	20	8.9	12	11	32						
SIEVE											SIEVE
1½"	100.0	100.0	100.0	100.0	100.0				100.0	100.0	1½"
1"	100.0	100.0	100.0	100.0	100.0				100.0	100.0	1"
3/4"	100.0	100.0	100.0	100.0	100.0				100.0	100.0	3/4"
1/2"	100.0	100.0	100.0	100.0	63.2				86.0	86.1	1/2"
3/8"	100.0	100.0	100.0	100.0	26.0				71.8	72.1	3/8"
1/4"	100.0	100.0	100.0	74.1	3.9				60.0	60.5	1/4"
#4	100.0	100.0	96.6	46.7	2.8				55.5	56.1	#4
#8	88.3	82.0	83.8	12.4	2.2				44.2	44.9	#8
#10	83.3	72.9	75.4	10.2	2.1				40.5	41.3	#10
#16	68.4	52.8	56.8	6.9	1.9				31.6	32.5	#16
#30	40.5	35.4	36.8	5.1	1.7				20.0	21.0	#30
#40	24.8	28.2	26.8	4.6	1.6				13.9	15.1	#40
#50	12.9	22.4	18.4	4.2	1.5				9.2	10.4	#50
#100	2.4	14.3	7.2	3.4	1.3				4.1	5.3	#100
#200	0.8	10.9	2.4	2.6	0.9				2.4	3.6	#200

MATERIAL 1 = Blend Sand — MR Tanner ElMirage
MATERIAL 2 = Crusher Fines — MR Tanner ElMirage
MATERIAL 3 = Washed CF — MR Tanner ElMirage
MATERIAL 4 = 3/8 Inch Agg. — MR Tanner ElMirage
MATERIAL 5 = 3/4 Inch Agg. — MR Tanner ElMirage
MATERIAL 6 =
MATERIAL 7 =
MATERIAL 8 =

COMPOSITE GRADATION



A DIVISION OF FISHER SAND & GRAVEL CO.

COMPOSITE GRADATION #3 - VIRGIN AGGREGATE WITH DRY SCREENED RAP

SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

DATE: 10-12-2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH
AGENCY: MAG/EVAC

	ORIGINAL GRADATION - % PASSING										
	MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	MAT'L 8	MAT'L 9	MAT'L 10	
MAT'L NAME	Blend Sand	Crusher Fines	Washed CF	3/8 Inch Agg.	3/4 Inch Agg.				RAP		
LAB NO.											
% USED	20	8.9	12	11	32				15.6		
SIEVE											SIEVE
1½"	100.0	100.0	100.0	100.0	100.0				100.0		1½"
1"	100.0	100.0	100.0	100.0	100.0				100.0		1"
3/4"	100.0	100.0	100.0	100.0	100.0				100.0		3/4"
1/2"	100.0	100.0	100.0	100.0	63.2				94.1		1/2"
3/8"	100.0	100.0	100.0	100.0	26.0				85.7		3/8"
1/4"	100.0	100.0	100.0	74.1	3.9				70.8		1/4"
#4	100.0	100.0	96.6	46.7	2.8				61.5		#4
#8	88.3	82.0	83.8	12.4	2.2				42.2		#8

MAT'L 1 =	Blend Sand	MR Tanner ElMirage
MAT'L 2 =	Crusher Fines	MR Tanner ElMirage
MAT'L 3 =	Washed CF	MR Tanner ElMirage
MAT'L 4 =	3/8 Inch Agg.	MR Tanner ElMirage
MAT'L 5 =	3/4 Inch Agg.	MR Tanner ElMirage
MAT'L 6 =		
MAT'L 7 =		
MAT'L 8 =		
MAT'L 9 =	RAP	MR Tanner ElMirage
MAT'L 10 =		

A DIVISION OF FISHER SAND & GRAVEL CO.

MARSHALL MIX DESIGN DATA - 75 BLOW

SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207

MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
COMMODITY CODE: 432GH

LAB NO: ASU 15%
Plant 4

PERCENT ASPHALT	SPECIMEN NO.	SSD WEIGHT	H20 WEIGHT	AIR WEIGHT	SPECIFIC GRAVITY	UNIT WEIGHT	HEIGHT (in.)	STABILITY (LBS. / NEWTONS)		FACTOR	CORRECTED STABILITY	FLOW (0.01 in.)
4.5	1	1184.6	685.3	1183.2	2.370	147.9	2.501	5410	24062	1.00	5410	9
	2	1185.3	684.3	1184.1	2.363	147.5	2.510	5450	24240	0.99	5400	9
	3	1183.2	684.7	1182.5	2.372	148.0	2.503	5490	24418	1.00	5490	9
	AVG				2.368	147.8					5430	9
5.0	1	1190.2	691.9	1189.4	2.387	148.9	2.492	5310	23618	1.01	5360	10
	2	1191.9	692.7	1190.6	2.385	148.8	2.485	5350	23796	1.01	5400	10
	3	1191.0	690.2	1190.3	2.377	148.3	2.471	5300	23573	1.02	5410	11
	AVG				2.383	148.7					5390	10
5.5	1	1196.3	699.8	1195.5	2.408	150.3	2.468	5250	23351	1.02	5360	12
	2	1199.5	698.7	1198.2	2.393	149.3	2.475	5200	23128	1.02	5300	14
	3	1195.7	696.6	1194.6	2.394	149.4	2.459	5190	23084	1.03	5350	12
	AVG				2.398	149.6					5340	13
6.0	1	1201.9	703.1	1201.2	2.408	150.3	2.438	5100	22684	1.04	5300	15
	2	1201.0	702.1	1200.3	2.406	150.1	2.429	5050	22461	1.05	5300	15
	3	1202.1	703.4	1201.6	2.409	150.4	2.445	4980	22150	1.04	5180	14
	AVG				2.408	150.2					5260	15

Southwest Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

MIX DESIGN VOID CALCULATIONS

SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH
AGENCY: MAG/EVAC

ASPHALT GRADE: PG 70-10
ASPHALT SUPPLIER: Western

ADMIX TYPE: Hydrated Lime
ADMIX SUPPLIER: Lhoist North America

AGGREGATE SPECIFIC GRAVITY DATA

MATERIAL % USED	VIRGIN-CA 43.0	VIRGIN-FA 40.9	COMB VIRG AGGR	ADMIX 1.1	COMB VIRG W/ ADMIX	RAP 14.8		COMB SP GR
BULK OD	2.672	2.635	2.654	2.200	2.647	2.543		2.631
SSD	2.704	2.664	2.685	2.200	2.677	2.573		2.661
APPARENT	2.761	2.714	2.738	2.200	2.729	2.620		2.713
ABSORPTION	1.207	1.112	1.159	N/A	1.141	1.159		1.159

MAXIMUM THEORETICAL SPECIFIC GRAVITY OF BITUMINOUS MIXTURES - AASHTO T 209 w/ ADMIX

SAMPLE I.D.	SAMPLE WT. (DRY)	FLASK + H_2O	SAMPLE + FLASK+ H2O	SAMPLE WT (S.S.D.)	SAMPLE VOLUME	MAXIMUM SP. GR	MAXIMUM DENSITY
1	1060.4	3322.4	3950.3	1061.5	433.6	2.446	152.6
2	1064.8	3347.5	3978.3	1065.8	435.0	2.448	152.7
3	1064.9	3335.3	3964.5	1065.8	436.6	2.439	152.2
AVERAGE	1063.4	3190.1				2.444	152.5

PHYSICAL PROPERTIES

MAX SP GR	MAX DENSITY	PERCENT ASPHALT	ASPHALT SP GR	EFFECTIVE SP GR	ASPHALT ABSORP.	ADMIX SP GR
2.444	152.5	6.0	1.0240	2.682	0.501	2.20

VOLUMETRIC CALCULATIONS

PERCENT ASPHALT	MIX SP GR	MIX UNIT WT (pcf)	MAXIMUM SP GR	% ASPH ABSORPT	EFFCTIVE % AC	VMA	EFF VOIDS	STABILITY (lb.)	FLOW (in.)	VOIDS FILLED	DUST/BIT RATIO
4.5	2.368	147.8	2.499	0.501	4.021	14.544	5.242	5430	9	64.0	1.12
5.0	2.383	148.7	2.481	0.501	4.524	14.471	3.944	5390	10	72.7	1.00
5.5	2.398	149.6	2.462	0.501	5.026	14.384	2.613	5340	13	81.8	0.90
6.0	2.408	150.2	2.444	0.501	5.529	14.486	1.486	5260	15	89.7	0.82
5.0	**2.383**	**148.7**	**2.481**	**0.501**	**4.524**	**14.471**	**3.944**	**5390**	**10**	**72.7**	**1.0**

SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

RESISTANCE OF COMPACTED BITUMINOUS MIXTURE TO MOISTURE INDUCED DAMAGE - ASTM D 4867

SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LOCATION: Various
LAB NO: ASU 15%
COMPACTION METHOD: MARSHALL - 28 BLOWS

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH
COMMODITY CODE: 432GH
PERCENT BINDER: 5.0

SPECIMEN NO.		1	4	5	2	3	6
DIAMETER (in)		4.00	4.00	4.00	4.00	4.00	4.00
THICKNESS (in)		2.56	2.57	2.57	2.57	2.58	2.57
AIR WEIGHT (g)		1194.2	1191.7	1189.1	1193.7	1193.8	1190.3
SSD WEIGHT (g)		1195.7	1193.1	1192.9	1196.8	1198.2	1193.8
H2O WEIGHT (g)		677.8	675.3	678.5	678.4	679.2	679.3
VOLUME (cc)		517.9	517.8	514.4	518.4	519.0	514.5
BULK SPECIFIC GRAVITY		2.306	2.301	2.312	2.303	2.300	2.314
MAX. SPECIFIC GRAVITY		2.481	2.481	2.481	2.481	2.481	2.481
% AIR VOIDS		7.1	7.2	6.8	7.2	7.3	6.7
VOLUME AIR VOIDS (cc)		36.5	37.4	35.1	37.2	37.8	34.7
LOAD (lbs)		2612	2698	2610	N/A	N/A	N/A
SATURATED	45	SECONDS @	25	INCHES Hg			
H2O WEIGHT (g)		N/A	N/A	N/A	702.5	701.5	701.1
SSD WEIGHT (g)		N/A	N/A	N/A	1222.1	1221.8	1216.7
VOLUME (cc)		N/A	N/A	N/A	519.6	520.3	515.6
VOLUME ABS. H2O (cc)		N/A	N/A	N/A	28.4	28.0	26.4
% SATURATION		N/A	N/A	N/A	76.3	74.1	76.1
% SWELL		N/A	N/A	N/A	0.2	0.3	0.2
CONDITIONED 24 hr in 60° C WATER							
SSD WEIGHT (g)		N/A	N/A	N/A	1229.3	1228.6	1222.1
H2O WEIGHT (g)		N/A	N/A	N/A	706.3	707.1	705.1
VOLUME (cc)		N/A	N/A	N/A	523.0	521.5	517.0
VOLUME ABS. H2O (cc)		N/A	N/A	N/A	35.6	34.8	31.8
% SATURATION		N/A	N/A	N/A	95.7	92.1	91.7
% SWELL		N/A	N/A	N/A	0.9	0.5	0.5
LOAD (lbs)		N/A	N/A	N/A	2426	2471	2459
DRY STRENGTH (psi)		162.2	167.2	161.9	N/A	N/A	N/A
WET STRENGTH (psi)		N/A	N/A	N/A	150.4	152.5	152.2
AVERAGE DRY STRENGTH (psi) =					**163.8**		
AVERAGE WET STRENGTH (psi) =					**151.7**		
AVERAGE TSR (%) =					**93**		

REMARKS:
VISUAL MOISTURE DAMAGE: NOT APPRECIABLE
CRACK/BREAK AGGREGATE: MINIMAL

A DIVISION OF FISHER SAND & GRAVEL CO.

RAP TEST DATA

SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH
AGENCY: MAG/EVAC

AVG RAP %AC & GRAD

	RAP -	
SIEVE SIZE	PERCENT PASSING	PERCENT PASSING
1¼"	100.00	
1"	100.00	
3/4"	100.00	
1/2"	94.40	
3/8"	86.40	
1/4"	74.60	
#4	66.40	
#8	50.80	
#10	47.60	
#16	39.40	
#30	29.00	
#40	23.40	
#50	19.20	
#100	13.00	
#200	9.40	
% AC	3.96	

DRY SCREENED RAP GRADATION

	RAP			
SIEVE SIZE	WEIGHT RETAINED	PERCENT PASSING	WEIGHT RETAINED	PERCENT PASSING
1½"		100.0		
1"		100.0		
3/4"		100.0		
1/2"	1588	94.1		
3/8"	2253	85.7		
1/4"	4002	70.8		
#4	2495	61.5		
#8	5170	42.2		
- #8	11318	0.0		
TOTAL	26826			

PERCENT OF TOTAL BINDER CONTRIBUTED BY RAP

11.6%

LOS ANGELES ABRASION - AASHTO T 96

NUMBER REVS.	*INITIAL WEIGHT*	*FINAL WEIGHT*	*PERCENT LOSS*
100	5000.0	4740.2	5
500	5000.0	3960.3	21

ESTIMATED RAP AGGREGATE PROPERTIES

MATERIAL PROPERTY	RAP *TEST VALUE*	*TEST VALUE*
RAP BINDER SP GR	1.050	N/A
EFFECTIVE SP GR	2.574	N/A
RAP AGGREGATE ASPHALT ABSORP	0.500	N/A
BULK O.D. SP. GR.	2.543	N/A
RAP AGGREGATE WATER ABSORP	1.159	N/A

MAXIMUM THEORETICAL SPECIFIC GRAVITY OF BITUMINOUS MIXTURES - Ariz 417

RAP -

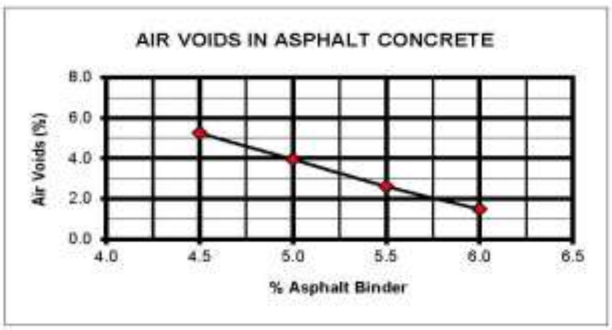
NO.	*SAMPLE WT. (DRY)*	*FLASK + H2O*	*SAMPLE + FLASK +H2O*	*SAMPLE WT. (S.S.D.)*	*SAMPLE VOLUME*	*MAXIMUM SP. GR.*	*MAXIMUM DENSITY*
1	1008.1	3322.7	3920.3	1010.5	412.9	2.442	152.4
2	1012.7	3347.8	3945.0	1014.2	417.0	2.429	151.5
3	1009.9	3335.7	3932.6	1012.0	415.1	2.433	151.8
AVG	*1010.2*	*3030.7*			*415.0*	*2.434*	*151.9*

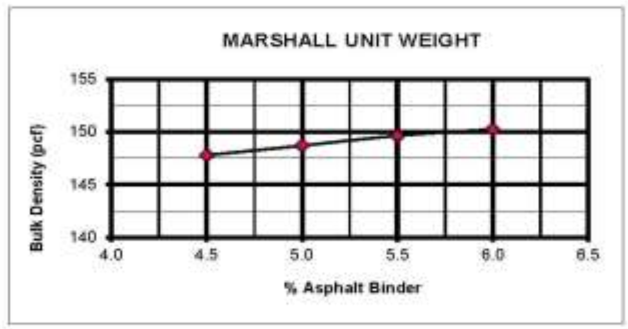
SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

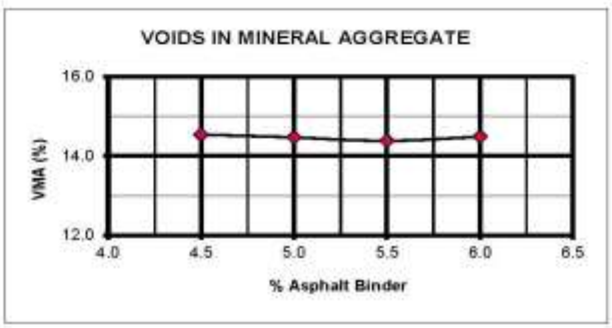
TEST PROPERTY CURVES - ASPHALT PAVING DESIGN

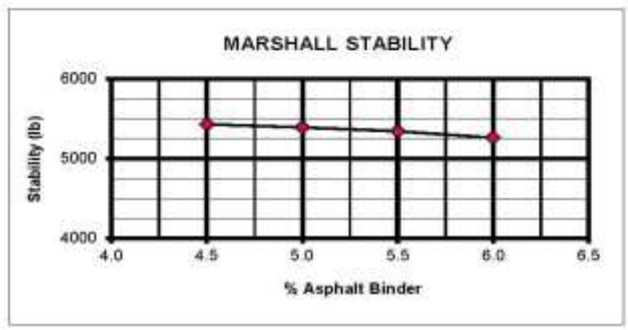
SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

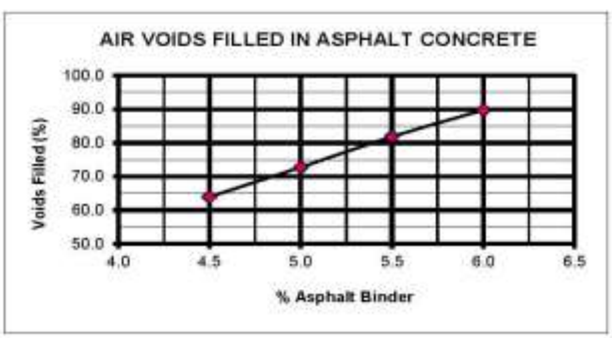
DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH
AGENCY: MAG/EVAC

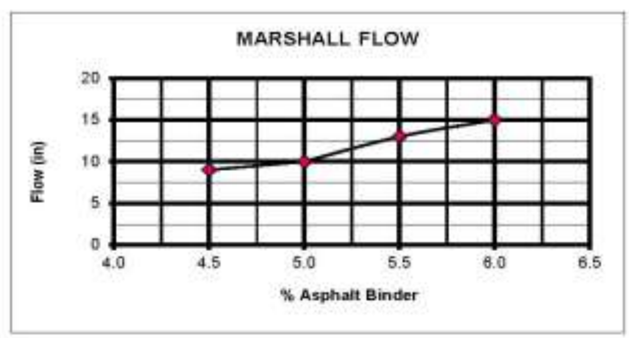












SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

VIRGIN AGGREGATE TEST DATA

SUPPLIER: Southwest Asphalt
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH
AGENCY: MAG/EVAC

AGGREGATE SPECIFIC GRAVITIES - AI MS-2/SP2

	COMBINED		MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	MAT'L 8	MAT'L 9	MAT'L 10
MAT'L	COARSE AGGR.	FINE AGGR.	Blend Sand	Crusher Fines	Washed CF	3/8 Inch Agg.	3/4 Inch Agg				RAP	
AIR WT			493.8	496.2	496.5	3408.5	3248.2					
H2O WT			972.8	982.1	981.3	2172.0	2072.5					
SSD WT			500.0	502.3	500.4	3456.7	3285.1					
CALIB WT			662.1	667.0	667.1							
BULK O.D. SP. GR.	2.672	2.635	2.609	2.651	2.667	2.653	2.679					
S.S.D. SP. GR.	2.704	2.664	2.641	2.683	2.688	2.691	2.709					
APPARENT SP. GR.	2.761	2.714	2.697	2.740	2.724	2.757	2.763					
% ABSORPTION	1.207	1.112	1.256	1.229	0.785	1.414	1.136					

SAND EQUIVALENT - AASHTO T 176

READING	SAMPLE # 1	SAMPLE # 2	SAMPLE # 3	AVERAGE
SAND	3.0	3.0	3.0	
CLAY	4.9	4.6	4.9	
S.E.	62	66	62	64

UNCOMPACTED VOIDS - AASHTO T 304

TRIAL NUMBER	SAMPLE WEIGHT	MEASURE VOLUME	PERCENT UNCOMPACTED VOIDS
1	137.5		
2	137.2		
AVG	137.35	100.4	48.1

% OF FRACTURED AGGREGATE PARTICLES - Az 212

	TOTAL SAMPLE WT.	WT. CRUSHED	% CRUSHED FACES
1 or more	963.2	928.9	96
2 or more	963.2	870.8	90

LOS ANGELES ABRASION - AASHTO T 96

NUMBER REVS	INITIAL WEIGHT	FINAL WEIGHT	PERCENT LOSS
100	5009.1	4823.9	4
500	5009.1	4151.2	17

COMBINED VIRGIN/RAP AGGREGATES
% OF FRACTURED AGGREGATE PARTICLES - Az 212

	TOTAL SAMPLE WT.	WT. CRUSHED	% CRUSHED FACES
1 or more	986.2	960.2	97
2 or more	986.2	910.3	92

COMBINED VIRGIN AND RAP AGGREGATES
FLAT AND ELONGATED PARTICLES - ASTM D4791; 5:1 Ratio

SIEVE US/mm	TOTAL SAMPLE WEIGHT	WEIGHT OF FLAT & ELONG. PARTICLES (g)	% FLAT AND ELONG.	WEIGHTED AVERAGE (%)
3/4" / 19	0.0	0.0	0.0	
1/2" / 12.5	889.2	4.5	0.5	
3/8" / 9.5	610.5	2.9	0.5	2.0
1/4" / 6.3	240.6	10.5	4.4	
#4 / 4.75	95.3	4.0	4.2	

SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

SUPPLEMENTAL AGGREGATE TESTING

SUPPLIER: Southwest Asphalt PLANT NO.: 4
PROJECT: ASU 15% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 15% RAP
LAB NO: ASU 15%

DATE: 10/12/2018
PROJ. SOLICITATION NO.: N/A
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GH

SODIUM SULFATE SOUNDNESS - ASTM C 88

COARSE FRACTION SIEVE SIZE	GRADING OF ORIGINAL SAMPLE	ORIGINAL SAMPLE WEIGHT	WEIGHT OF TEST FRACTION BT, g	WEIGHT OF TEST FRACTION AT, g	PERCENT PASSING SIEVE, AT	WEIGHTED PERCENT LOSS
37.5mm to 25mm	0.0	5.0	5.0		100.0	0.0
25mm to 19mm						
19mm to 12.5mm	60.7	670.1	999.4	994.6	0.5	0.3
12.5mm to 9.5mm		329.3				
9.5mm to 4.75mm	39.3	301.6	301.6	295.8	1.9	0.7
TOTALS	100.0					1

FINE FRACTI(Seive Size	GRADING OF ORIGINAL SAMPLE	WEIGHT OF TEST FRACTION BT, g	WEIGHT OF TEST FRACTION AT, g	PERCENT PASSING SIEVE, AT	WEIGHTED PERCENT LOSS
#4 to #8	20.9	100.00	98.6	1.4	0.3
#8 to #16	21.7	100.00	99.0	1.0	0.2
#16 to #30	20.1	100.00	98.9	1.1	0.2
#30 to #50	18.6	100.00	98.2	1.8	0.3
Totals	100.0				1

QUALITATIVE EXAMINATION OF COARSE SIZES									
SIEVE SIZE	NUMBER OF PARTICLES BEFORE TEST	SPLITTING		CRUMBLING		CRACKING		FLAKING	
		No.	Percent	No.	Percent	No.	Percent	No.	Percent
19-37.5mm			-		-		-		-

CLAY LUMPS AND FRIABLE PARTICLES - ASTM C 142

SIEVE SIZE	GRADING OF ORIGINAL SAMPLE	WEIGHT OF TEST FRACTION BEFORE TEST, g	WEIGHT OF TEST FRACTION AFTER TEST, g	PERCENT LOSS	WEIGHTED PERCENT LOSS
FINE AGGREGATE					
1.18mm (No. 16) to 4.75mm	N/A	102.60	102.30	0.3	**0.3**
			FINE AGGREGATE FRACTION		**0.3**
COARSE AGGREGATE					
4.75mm to 9.5mm	39.3	1062.3	1060.2	0.2	0.1
9.5mm to 19mm	60.7	2836.4	2830.1	0.2	0.1
19mm to 37.5mm	0.0	0.0	0.0	0.0	0.0
			COARSE AGGREGATE FRACTION		**0.2**

SOUTHWEST Asphalt

A DIVISION OF FISHER SAND & GRAVEL CO.

75 BLOW MARSHALL MIX DESIGN - WITH RAP

SUPPLIER: Southwest Asphalt - PLANT NO.: 4
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
AGENCY: COP
COMMODITY CODE: 432GK

COMPOSITE GRADATION

Material I.D.	*Material Source*	*% Used*
Blend Sand	MR Tanner ElMirage	20.0
Crusher Fines	MR Tanner ElMirage	3.0
Washed CF	MR Tanner ElMirage	10.0
3/8 Inch Agg.	MR Tanner ElMirage	9.9
3/4 Inch Agg.	MR Tanner ElMirage	31.0
RAP	MR Tanner ElMirage	25.0
Hydrated Lime	Lhoist North America	1.1

Sieve US/mm	*w/o Admix % Passing*	*w/Admix % Passing*	*Specification Limits*	*Production Limits*
1½" / 37.5	100	100		
1" / 25	100	100	100	
3/4" / 19	100	100	95	88 - 100
1/2" / 12.5	87	87	85	78 - 92
3/8" / 9.5	73	74	75	68 - 82
1/4" / 6.3	61	61		
#4 / 4.75	55	56	58	51 - 65
#8 / 2.36	44	44	44	39 - 49
#10 / 2.00	40	41		
#16 / 1.18	32	33		
#30 / .600	21	22	24	19 - 29
#40 / .425	15	16		12 - 20
#50 / .300	11	12		
#100 / .150	6	7		
#200 / .075	3.7	4.7	4.0	2.0 - 6.0

ADDITIONAL DATA

Virgin Asphalt Binder Source:	Western
Virgin Asphalt Binder Grade:	PG 64-16
Virgin Asphalt Specific Gravity:	1.022
Mineral Admix Type:	Hydrated Lime
Mineral Admix Source:	Lhoist North America
Mineral Admix Specific Gravity:	2.20
Recommended Lab Mixing Temperature:	307°F to 317°F
Recommended Lab Compaction Temperature:	287°F to 295°F
Actual Lab Mixing Temperature Used:	312°F
Actual Lab Compaction Temperature Used:	291°F
Percent Virgin Aggergate***:	73.9
Percent RAP Aggergate***:	24.7
RAP Percent Binder:	3.96
RAP Binder Specific Gravity:	1.050 @ 77°F
Percent RAP Binder **:	19.4
Percent Virgin Binder (100-%RAP Binder)**:	80.6

RECOMMENDED TOTAL BINDER CONTENT (%)*:	5.00
ADDED VIRGIN BINDER CONTENT (%)*:	4.01
CONTRIBUTED RAP BINDER CONTENT (%)*:	0.99

*-by weight of total mix, **-by Weight of total binder, ***-by weight of total aggr.

DESIGN DATA

					Criteria
Total Binder Content (%)	4.5	**5.0**	5.5	6.0	
Marshall Bulk Density (pcf)	148.1	**149.2**	150.1	150.7	
Marshall Stability (lb)	5,330	**5,210**	5,100	5,040	
Marshall Flow (in.)	10	**11**	14	15	
% Air Voids	5.3	**3.8**	2.5	1.4	
% VMA	14.3	**14.2**	14.1	14.2	
% Air Voids Filled	63.3	**72.8**	82.2	90.4	
% Eff Asphalt Total Mix	3.91	**4.41**	4.91	5.42	
Film Thickness (µ)	8	**9**	10	11	
Dust/Bitumen Ratio	1.2	**1.1**	1.0	0.9	
Max Theoretical Sp. Gr. / Dens.	2.486 /	155.1	pcf @	5.0%	
% Asphalt Abs. on Dry Agg	0.62				0.0-1.0

TSR - ASTM D4867

Set ID	*Dry PSI*	*Wet PSI*	*Retained Strength*	*Percent Asphalt*	*Percent Admix*
Number 1	160	150	93	5.0	1.10
Specification	100 Min		65 Min		

AGGREGATE PROPERTIES

Virgin Aggregates	*Coarse Aggr.*	*Fine Aggr.*	*Comb. w/o Adm*	*Comb. w/ Admix*	*Spec.*
Bulk OD Specific Gravity	2.673	2.630	2.653	2.645	2.35-2.85
SSD Specific Gravity	2.705	2.659	2.684	2.676	
Apparent Specific Gravity	2.761	2.709	2.738	2.728	
Absorption (%)	1.203	1.111	1.160	1.140	0.00-2.50
Effective Specific Gravity (Gse)				2.689	
Sand Equivalent		69			50 Min
Uncompacted Voids		47.6			45 Min
% 1 or More Fractured Face	96				85 Min
% 2 or More Fractured Face	90				80 Min
Los Angeles Abrasion					
% Loss @ 100 Rev - Grading B	4				9 Max
% Loss @ 500 Rev - Grading B	17				40 Max
% Claylumps & Friable Particles	0.2	0.3			

RAP Aggregates	*RAP*				
Bulk OD Specific Gravity	2.543				2.35-2.85
SSD Specific Gravity	2.573				
Absorption (%)	1.160				0.00-2.50
Effective Specific Gravity (Gser)	2.574				
Los Angeles Abrasion					
% Loss @ 100 Rev - Grading B	5				9 Max
% Loss @ 100 Rev - Grading B	21				40 Max

Combined Virgin & RAP Aggregate				*w/ Admix*	*Spec.*
Bulk OD Specific Gravity				2.619	
SSD Specific Gravity				2.649	
Apparent Specific Gravity				2.700	
Absorption (%)				1.160	
Effective Specific Gravity (Gse)				2.689	
% 1 or More Fractured Face				99	85 Min
% 2 or More Fractured Face				96	80 Min

A DIVISION OF FISHER SAND & GRAVEL CO.

COMPOSITE #1 - VIRGIN & RAP AGGREGATES

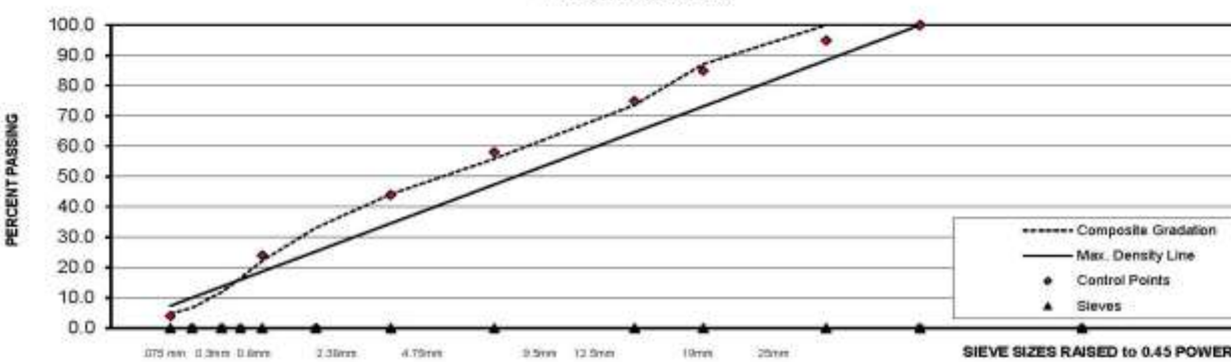
SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
AGENCY: MAG/EVAC

	ORIGINAL GRADATION - % PASSING											COMPOSITE % PASS		GRADATION SPECS with ADMIX	
	MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	MAT'L 8	MAT'L 9	MAT'L 10					
MAT'L NAME	Blend Sand	Crusher Fines	Washed CF	3/8 Inch Agg.	3/4 Inch Agg.				RAP		Hydrated Lime				
LAB NO.											N/A	without ADMIX	with ADMIX		
% USED	20.0	3.0	10.0	9.9	31.0				25.0		1.1				
SIEVE															SIEVE
1½"	100.0	100.0	100.0	100.0	100.0				100.0		100.0	100.0	100.0		1½"
1"	100.0	100.0	100.0	100.0	100.0				100.0		100.0	100.0	100.0	100	1"
3/4"	100.0	100.0	100.0	100.0	100.0				100.0		100.0	100.0	100.0	95 - 95	3/4"
1/2"	100.0	100.0	100.0	100.0	63.2				94.4		100.0	87.0	87.2	85 - 85	1/2"
3/8"	100.0	100.0	100.0	100.0	26.0				86.4		100.0	73.4	73.7	75 - 75	3/8"
1/4"	100.0	100.0	100.0	74.1	3.9				74.6		100.0	60.9	61.3		1/4"
#4	100.0	100.0	96.6	46.7	2.8				66.4		100.0	55.4	55.9	58 - 58	#4
#8	88.3	82.0	83.8	12.4	2.2				50.8		100.0	43.6	44.2	44 - 44	#8
#10	83.3	72.9	75.4	10.2	2.1				47.6		100.0	40.4	41.0		#10
#16	68.4	52.8	56.8	6.9	1.9				39.4		100.0	32.4	33.1		#16
#30	40.5	35.4	36.8	5.1	1.7				29.0		100.0	21.4	22.2	24 - 24	#30
#40	24.8	28.2	26.8	4.6	1.6				23.4		100.0	15.5	16.4		#40
#50	12.9	22.4	18.4	4.2	1.5				19.2		100.0	10.9	11.9		#50
#100	2.4	14.3	7.2	3.4	1.3				13.0		100.0	5.7	6.7		#100
#200	0.8	10.9	2.4	2.6	0.9				9.4		100.0	3.7	4.7	4.0 - 4.0	#200

MAT'L 1 = Blend Sand — MR Tanner ElMirage
MAT'L 2 = Crusher Fines — MR Tanner ElMirage
MAT'L 3 = Washed CF — MR Tanner ElMirage
MAT'L 4 = 3/8 Inch Agg. — MR Tanner ElMirage
MAT'L 5 = 3/4 Inch Agg. — MR Tanner ElMirage
MAT'L 6 =
MAT'L 7 =
MAT'L 8 =
MAT'L 9 = RAP — MR Tanner ElMirage
MAT'L 10 =

COMPOSITE GRADATION



SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

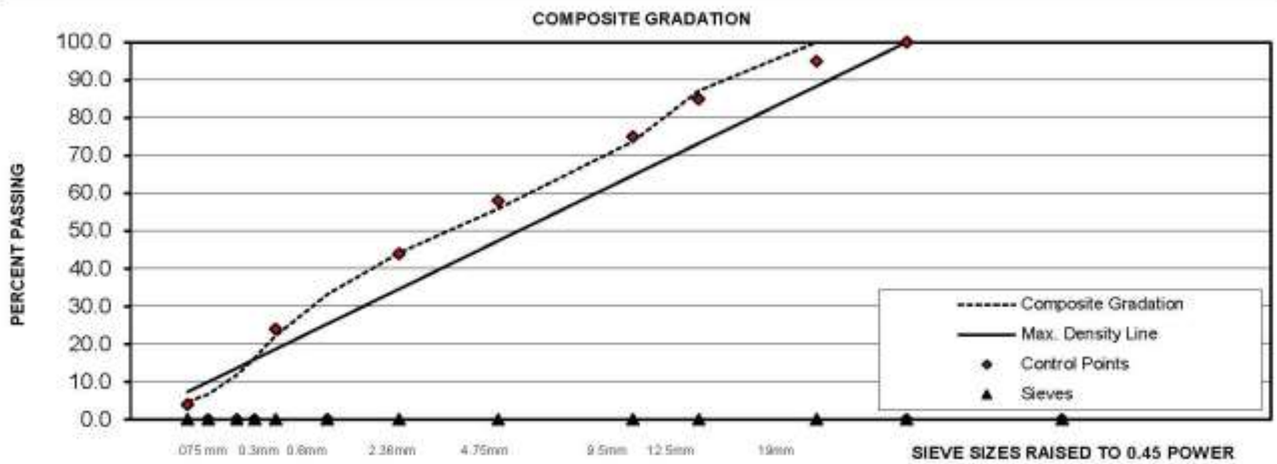
COMPOSITE #2 - VIRGIN AGGREGATE GRADATION

SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

DATE: 10-12-2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
AGENCY: MAG/EVAC

	ORIGINAL GRADATION - % PASSING								COMPOSITE % PASS		
	MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	MAT'L 8	without ADMIX	with ADMIX	
MAT'L NAME LAB NO.	Blend Sand	Crusher Fines	Washed CF	3/8 Inch Agg.	3/4 Inch Agg.						
ADJ. BIN %'s	**27.1**	**4.1**	**13.5**	**13.4**	**41.9**						
ORIG. BIN %'s	20	3	10	9.9	31						
SIEVE											SIEVE
1½"	100.0	100.0	100.0	100.0	100.0				100.0	100.0	1½"
1"	100.0	100.0	100.0	100.0	100.0				100.0	100.0	1"
3/4"	100.0	100.0	100.0	100.0	100.0				100.0	100.0	3/4"
1/2"	100.0	100.0	100.0	100.0	63.2				84.6	84.8	1/2"
3/8"	100.0	100.0	100.0	100.0	26.0				69.0	69.4	3/8"
1/4"	100.0	100.0	100.0	74.1	3.9				56.2	56.9	1/4"
#4	100.0	100.0	96.6	46.7	2.8				51.6	52.4	#4
#8	88.3	82.0	83.8	12.4	2.2				41.1	42.0	#8
#10	83.3	72.9	75.4	10.2	2.1				37.9	38.9	#10
#16	68.4	52.8	56.8	6.9	1.9				30.0	31.1	#16
#30	40.5	35.4	36.8	5.1	1.7				18.8	20.0	#30
#40	24.8	28.2	26.8	4.6	1.6				12.8	14.0	#40
#50	12.9	22.4	18.4	4.2	1.5				8.1	9.4	#50
#100	2.4	14.3	7.2	3.4	1.3				3.2	4.6	#100
#200	0.8	10.9	2.4	2.6	0.9				1.7	3.2	#200

MATERIAL 1 =	Blend Sand	MR Tanner ElMirage
MATERIAL 2 =	Crusher Fines	MR Tanner ElMirage
MATERIAL 3 =	Washed CF	MR Tanner ElMirage
MATERIAL 4 =	3/8 Inch Agg.	MR Tanner ElMirage
MATERIAL 5 =	3/4 Inch Agg.	MR Tanner ElMirage
MATERIAL 6 =		
MATERIAL 7 =		
MATERIAL 8 =		



A DIVISION OF FISHER SAND & GRAVEL CO.

COMPOSITE GRADATION #3 - VIRGIN AGGREGATE WITH DRY SCREENED RAP

SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

DATE: 10-12-2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
AGENCY: MAG/EVAC

	ORIGINAL GRADATION - % PASSING										
	MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	MAT'L 8	MAT'L 9	MAT'L 10	
MAT'L NAME	Blend Sand	Crusher Fines	Washed CF	3/8 Inch Agg.	3/4 Inch Agg.				RAP		
LAB NO.											
% USED	20	3	10	9.9	31				26.0		
SIEVE											SIEVE
1½"	100.0	100.0	100.0	100.0	100.0				100.0		1½"
1"	100.0	100.0	100.0	100.0	100.0				100.0		1"
3/4"	100.0	100.0	100.0	100.0	100.0				100.0		3/4"
1/2"	100.0	100.0	100.0	100.0	63.2				94.1		1/2"
3/8"	100.0	100.0	100.0	100.0	26.0				85.7		3/8"
1/4"	100.0	100.0	100.0	74.1	3.9				70.8		1/4"
#4	100.0	100.0	96.6	46.7	2.8				61.5		#4
#8	88.3	82.0	83.8	12.4	2.2				42.2		#8

MAT'L 1 =	Blend Sand	MR Tanner ElMirage
MAT'L 2 =	Crusher Fines	MR Tanner ElMirage
MAT'L 3 =	Washed CF	MR Tanner ElMirage
MAT'L 4 =	3/8 Inch Agg.	MR Tanner ElMirage
MAT'L 5 =	3/4 Inch Agg.	MR Tanner ElMirage
MAT'L 6 =		
MAT'L 7 =		
MAT'L 8 =		
MAT'L 9 =	RAP	MR Tanner ElMirage
MAT'L 10 =		

SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

MARSHALL MIX DESIGN DATA - 75 BLOW

SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207

MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
COMMODITY CODE: 432GK

LAB NO: ASU 25%
Plant 4

PERCENT ASPHALT	SPECIMEN NO.	SSD WEIGHT	H20 WEIGHT	AIR WEIGHT	SPECIFIC GRAVITY	UNIT WEIGHT	HEIGHT (in.)	STABILITY (LBS. / NEWTONS)		FACTOR	CORRECTED STABILITY	FLOW (0.01 in.)
4.5	1	1186.5	687.1	1185.0	2.373	148.1	2.480	5310	23618	1.01	5360	10
	2	1187.5	687.2	1186.1	2.371	147.9	2.491	5300	23573	1.01	5350	10
	3	1186.4	687.4	1185.2	2.375	148.2	2.498	5280	23484	1.00	5280	9
	AVG				2.373	148.1					5330	10
5.0	1	1191.9	693.4	1190.9	2.389	149.1	2.485	5120	22773	1.01	5170	11
	2	1192.1	693.5	1190.8	2.388	149.0	2.470	5200	23128	1.02	5300	10
	3	1195.0	696.5	1193.2	2.394	149.4	2.490	5110	22728	1.01	5160	11
	AVG				2.390	149.2					5210	11
5.5	1	1197.1	699.4	1196.0	2.403	150.0	2.454	5010	22283	1.03	5160	13
	2	1197.0	700.4	1195.9	2.408	150.3	2.471	5000	22239	1.02	5100	14
	3	1198.6	700.8	1197.3	2.405	150.1	2.468	4950	22017	1.02	5050	14
	AVG				2.405	150.1					5100	14
6.0	1	1202.9	705.6	1202.1	2.417	150.8	2.451	4860	21616	1.03	5010	16
	2	1202.0	704.2	1201.0	2.413	150.5	2.443	4800	21349	1.04	4990	15
	3	1200.9	704.5	1200.1	2.418	150.9	2.461	4980	22150	1.03	5130	15
	AVG				2.416	150.7					5040	15

SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

MIX DESIGN VOID CALCULATIONS

SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

ASPHALT GRADE: PG 64-16
ASPHALT SUPPLIER: Western

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
AGENCY: MAG/EVAC

ADMIX TYPE: Hydrated Lime
ADMIX SUPPLIER: Lhoist North America

AGGREGATE SPECIFIC GRAVITY DATA

MATERIAL	VIRGIN-CA	VIRGIN-FA	COMB VIRG	ADMIX	COMB VIRG	RAP		COMB
% USED	40.9	33.0	AGGR.	1.1	W/ ADMIX	24.7		SP GR
BULK OD	2.673	2.630	2.653	2.200	2.645	2.543		2.619
SSD	2.705	2.659	2.684	2.200	2.676	2.573		2.649
APPARENT	2.761	2.709	2.738	2.200	2.728	2.620		2.700
ABSORPTION	1.203	1.111	1.160	N/A	1.140	1.160		1.160

MAXIMUM THEORETICAL SPECIFIC GRAVITY OF BITUMINOUS MIXTURES - AASHTO T 209 w/ ADMIX

SAMPLE I.D.	SAMPLE WT. (DRY)	FLASK + H_2O	SAMPLE + FLASK+ H2O	SAMPLE WT. (S.S.D.)	SAMPLE VOLUME	MAXIMUM SP. GR.	MAXIMUM DENSITY
1	1064.6	3322.4	3953.5	1065.7	434.6	2.450	152.9
2	1064.1	3347.5	3977.5	1065.1	435.1	2.446	152.6
3	1062.8	3335.3	3965.5	1063.7	433.5	2.452	153.0
AVERAGE	1063.8	3191.5				2.449	152.8

PHYSICAL PROPERTIES

MAX SP GR	MAX DENSITY	PERCENT ASPHALT	ASPHALT SP GR	EFFECTIVE SP GR	ASPHALT ABSORP	ADMIX SP GR
2.449	152.8	6.0	1.0220	2.689	0.620	2.20

VOLUMETRIC CALCULATIONS

PERCENT ASPHALT	MIX SP GR	MIX UNIT WT (pcf)	MAXIMUM SP GR	% ASPH ABSORPT	EFFCTIVE % AC	VMA	EFF VOIDS	STABILITY (lb.)	FLOW (in.)	VOIDS FILLED	DUST/BIT RATIO
4.5	2.373	148.1	2.505	0.620	3.908	14.337	5.264	5330	10	63.3	1.21
5.0	2.390	149.2	2.486	0.620	4.411	14.162	3.847	5210	11	72.8	1.07
5.5	2.405	150.1	2.467	0.620	4.914	14.071	2.506	5100	14	82.2	0.96
6.0	2.416	150.7	2.449	0.620	5.417	14.158	1.354	5040	15	90.4	0.87
5.0	**2.390**	**149.2**	**2.486**	**0.620**	**4.411**	**14.162**	**3.847**	**5210**	**11**	**72.8**	**1.1**

A DIVISION OF FISHER SAND & GRAVEL CO.

RAP TEST DATA

SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
AGENCY: MAG/EVAC

AVG RAP %AC & GRAD

SIEVE SIZE	RAP - PERCENT PASSING	PERCENT PASSING
1½"	100.00	
1"	100.00	
3/4"	100.00	
1/2"	94.40	
3/8"	86.40	
1/4"	74.60	
#4	66.40	
#8	50.80	
#10	47.60	
#16	39.40	
#30	29.00	
#40	23.40	
#50	19.20	
#100	13.00	
#200	9.40	
%AC	3.96	

DRY SCREENED RAP GRADATION

SIEVE SIZE	RAP WEIGHT RETAINED	RAP PERCENT PASSING	WEIGHT RETAINED	PERCENT PASSING
1½"		100.0		
1"		100.0		
3/4"		100.0		
1/2"	1588	94.1		
3/8"	2253	85.7		
1/4"	4002	70.8		
#4	2495	61.5		
#8	5170	42.2		
- #8	11318	0.0		
TOTAL	26826			

PERCENT OF TOTAL BINDER CONTRIBUTED BY RAP

19.4%

LOS ANGELES ABRASION - AASHTO T 96

NUMBER REVS.	INITIAL WEIGHT	FINAL WEIGHT	PERCENT LOSS
100	5000.0	4740.2	5
500	5000.0	3960.3	21

ESTIMATED RAP AGGREGATE PROPERTIES

MATERIAL PROPERTY	RAP TEST VALUE	TEST VALUE
RAP BINDER SP GR	1.050	N/A
EFFECTIVE SP GR	2.574	N/A
RAP AGGREGATE ASPHALT ABSORP	0.500	N/A
BULK O.D. SP. GR.	2.543	N/A
RAP AGGREGATE WATER ABSORP	1.160	N/A

MAXIMUM THEORETICAL SPECIFIC GRAVITY OF BITUMINOUS MIXTURES - Ariz 417

RAP -

NO.	SAMPLE WT. (DRY)		FLASK + H2O	SAMPLE + FLASK +H2O	SAMPLE WT. (S.S.D.)	SAMPLE VOLUME	MAXIMUM SP. GR.	MAXIMUM DENSITY
1	1008.1		3322.7	3920.3	1010.5	412.9	2.442	152.4
2	1012.7		3347.8	3945.0	1014.2	417.0	2.429	151.5
3	1009.9		3335.7	3932.6	1012.0	415.1	2.433	151.8
AVG	1010.2	3030.7				415.0	2.434	151.9

SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

RESISTANCE OF COMPACTED BITUMINOUS MIXTURE TO MOISTURE INDUCED DAMAGE - ASTM D 4867

SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LOCATION: Various
LAB NO: ASU 25%
COMPACTION METHOD: MARSHALL - 30 BLOWS

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
COMMODITY CODE: 432GK
PERCENT BINDER: 5.0

SPECIMEN NO.		1	2	5	3	4	6
DIAMETER (in)		4.00	4.00	4.00	4.00	4.00	4.00
THICKNESS (in)		2.58	2.58	2.56	2.57	2.58	2.58
AIR WEIGHT (g)		1191.8	1192.8	1193.0	1193.0	1190.8	1187.1
SSD WEIGHT (g)		1194.5	1195.4	1195.5	1196.0	1194.7	1190.5
H2O WEIGHT (g)		679.6	681.8	680.2	680.2	681.7	677.4
VOLUME (cc)		514.9	513.6	515.3	515.8	513.0	513.1
BULK SPECIFIC GRAVITY		2.315	2.322	2.315	2.313	2.321	2.314
MAX. SPECIFIC GRAVITY		2.486	2.486	2.486	2.486	2.486	2.486
% AIR VOIDS		6.9	6.6	6.9	7.0	6.6	6.9
VOLUME AIR VOIDS (cc)		35.5	33.8	35.4	35.9	34.0	35.6
LOAD (lbs)		2650	2510	2610	N/A	N/A	N/A
SATURATED	45	SECONDS @	25	INCHES Hg			
H2O WEIGHT (g)		N/A	N/A	N/A	702.3	701.1	700.0
SSD WEIGHT (g)		N/A	N/A	N/A	1220.0	1217.1	1214.5
VOLUME (cc)		N/A	N/A	N/A	517.7	516.0	514.5
VOLUME ABS. H2O (cc)		N/A	N/A	N/A	27.0	26.3	27.4
% SATURATION		N/A	N/A	N/A	75.2	77.4	77.0
% SWELL		N/A	N/A	N/A	0.4	0.6	0.3
CONDITIONED 24 hr in 60° C WATER							
SSD WEIGHT (g)		N/A	N/A	N/A	1226.3	1223.2	1220.2
H2O WEIGHT (g)		N/A	N/A	N/A	706.3	705.2	704.3
VOLUME (cc)		N/A	N/A	N/A	520.0	518.0	515.9
VOLUME ABS. H2O (cc)		N/A	N/A	N/A	33.3	32.4	33.1
% SATURATION		N/A	N/A	N/A	92.8	95.4	93.1
% SWELL		N/A	N/A	N/A	0.8	1.0	0.5
LOAD (lbs)		N/A	N/A	N/A	2390	2410	2458
DRY STRENGTH (psi)		163.5	154.9	162.4	N/A	N/A	N/A
WET STRENGTH (psi)		N/A	N/A	N/A	147.6	148.7	152.8
AVERAGE DRY STRENGTH (psi) =					160.3		
AVERAGE WET STRENGTH (psi) =					149.7		
AVERAGE TSR (%) =					93		

REMARKS:
VISUAL MOISTURE DAMAGE: NOT APPRECIABLE
CRACK/BREAK AGGREGATE: MINIMAL

SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

RESISTANCE OF COMPACTED BITUMINOUS MIXTURE TO MOISTURE INDUCED DAMAGE - ASTM D 4867

SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LOCATION: Various
LAB NO: ASU 25%
COMPACTION METHOD: MARSHALL - 30 BLOWS

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
COMMODITY CODE: 432GK
PERCENT BINDER: 5.0

SPECIMEN NO.		1	2	5	3	4	6
DIAMETER (in)		4.00	4.00	4.00	4.00	4.00	4.00
THICKNESS (in)		2.58	2.58	2.56	2.57	2.58	2.56
AIR WEIGHT (g)		1191.8	1192.8	1193.0	1193.0	1190.8	1187.1
SSD WEIGHT (g)		1194.5	1195.4	1195.5	1196.0	1194.7	1190.5
H2O WEIGHT (g)		679.6	681.8	680.2	680.2	681.7	677.4
VOLUME (cc)		514.9	513.6	515.3	515.8	513.0	513.1
BULK SPECIFIC GRAVITY		2.315	2.322	2.315	2.313	2.321	2.314
MAX. SPECIFIC GRAVITY		2.486	2.486	2.486	2.486	2.486	2.486
% AIR VOIDS		6.9	6.6	6.9	7.0	6.6	6.9
VOLUME AIR VOIDS (cc)		35.5	33.8	35.4	35.9	34.0	35.6
LOAD (lbs)		2650	2510	2610	N/A	N/A	N/A
SATURATED	45	SECONDS @	25	INCHES Hg			
H2O WEIGHT (g)		N/A	N/A	N/A	702.3	701.1	700.0
SSD WEIGHT (g)		N/A	N/A	N/A	1220.0	1217.1	1214.5
VOLUME (cc)		N/A	N/A	N/A	517.7	516.0	514.5
VOLUME ABS. H2O (cc)		N/A	N/A	N/A	27.0	26.3	27.4
% SATURATION		N/A	N/A	N/A	75.2	77.4	77.0
% SWELL		N/A	N/A	N/A	0.4	0.6	0.3
CONDITIONED 24 hr in 60° C WATER							
SSD WEIGHT (g)		N/A	N/A	N/A	1226.3	1223.2	1220.2
H2O WEIGHT (g)		N/A	N/A	N/A	706.3	705.2	704.3
VOLUME (cc)		N/A	N/A	N/A	520.0	518.0	515.9
VOLUME ABS. H2O (cc)		N/A	N/A	N/A	33.3	32.4	33.1
% SATURATION		N/A	N/A	N/A	92.8	95.4	93.1
% SWELL		N/A	N/A	N/A	0.8	1.0	0.5
LOAD (lbs)		N/A	N/A	N/A	2390	2410	2458
DRY STRENGTH (psi)		163.5	154.9	162.4	N/A	N/A	N/A
WET STRENGTH (psi)		N/A	N/A	N/A	147.8	148.7	152.6
AVERAGE DRY STRENGTH (psi) =					**160.3**		
AVERAGE WET STRENGTH (psi) =					**149.7**		
AVERAGE TSR (%) =					**93**		

REMARKS:

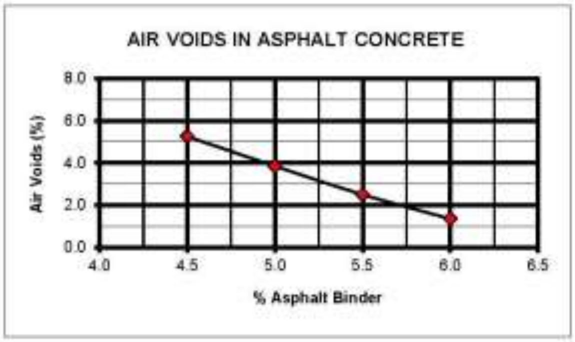
VISUAL MOISTURE DAMAGE: NOT APPRECIABLE
CRACK/BREAK AGGREGATE: MINIMAL

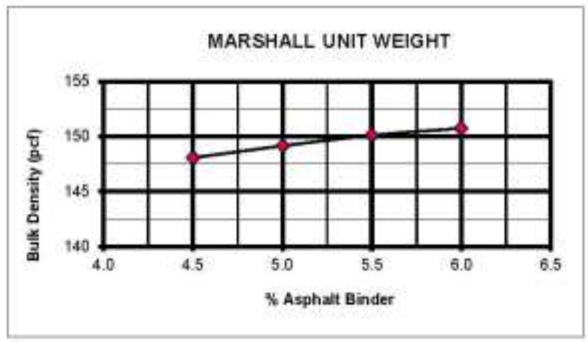
A DIVISION OF FISHER SAND & GRAVEL CO.

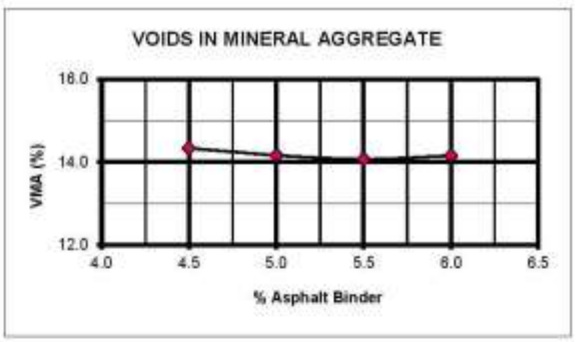
TEST PROPERTY CURVES - ASPHALT PAVING DESIGN

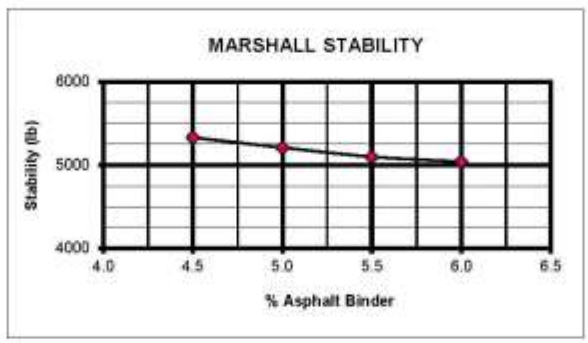
SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

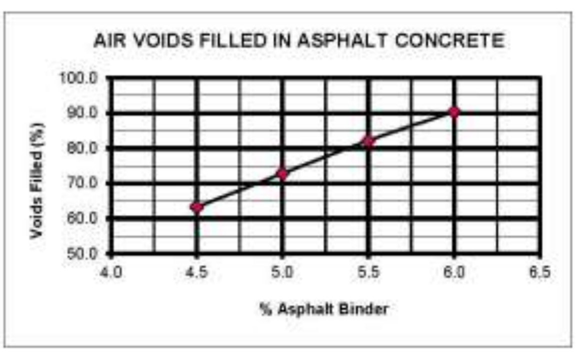
DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
AGENCY: MAG/EVAC

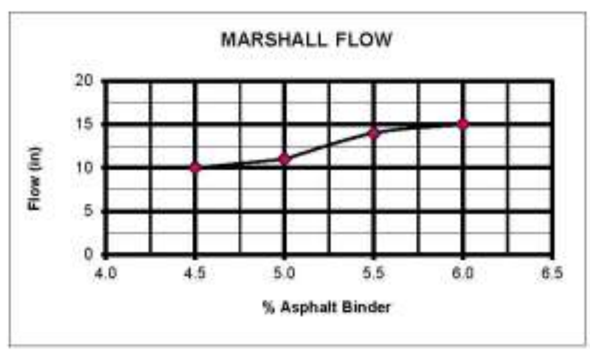












SOUTHWEST Asphalt
A DIVISION OF FISHER SAND & GRAVEL CO.

VIRGIN AGGREGATE TEST DATA

SUPPLIER: Southwest Asphalt
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

DATE: 10/12/2018
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK
AGENCY: MAG/EVAC

AGGREGATE SPECIFIC GRAVITIES - AI MS-2/SP2

	COMBINED		MAT'L 1	MAT'L 2	MAT'L 3	MAT'L 4	MAT'L 5	MAT'L 6	MAT'L 7	MAT'L 8	MAT'L 9	MAT'L 10
MAT'L	COARSE AGGR.	FINE AGGR.	Blend Sand	Crusher Fines	Washed CF	3/8 Inch Agg.	3/4 Inch Agg.				RAP	
AIR WT			493.8	496.2	496.5	3408.5	3248.2					
H2O WT			972.8	982.1	981.3	2172.0	2072.5					
SSD WT			500.0	502.3	500.4	3456.7	3285.1					
CALIB WT			662.1	667.0	667.1							
BULK O.D. SP. GR.	2.673	2.630	2.609	2.651	2.667	2.653	2.679					
S.S.D. SP. GR.	2.705	2.659	2.641	2.683	2.688	2.691	2.709					
APPARENT SP. GR.	2.761	2.709	2.697	2.740	2.724	2.757	2.763					
% ABSORPTION	1.203	1.111	1.256	1.229	0.785	1.414	1.136					

SAND EQUIVALENT - AASHTO T 176

READING	SAMPLE # 1	SAMPLE # 2	SAMPLE # 3	AVERAGE
SAND	3.1	3.0	3.0	
CLAY	4.5	4.4	4.5	
S.E.	69	69	67	69

UNCOMPACTED VOIDS - AASHTO T 304

TRIAL NUMBER	SAMPLE WEIGHT	MEASURE VOLUME	PERCENT UNCOMPACTED VOIDS
1	138.2		
2	138.4		
AVG.	138.30	100.4	47.6

% OF FRACTURED AGGREGATE PARTICLES - Az 212

	TOTAL SAMPLE WT.	WT. CRUSHED	% CRUSHED FACES
1 or more	982.3	947.3	96
2 or more	982.3	888.1	90

LOS ANGELES ABRASION - AASHTO T 96

NUMBER REVS.	INITIAL WEIGHT	FINAL WEIGHT	PERCENT LOSS
100	5009.1	4823.9	4
500	5009.1	4151.2	17

COMBINED VIRGIN/RAP AGGREGATES
% OF FRACTURED AGGREGATE PARTICLES - Az 212

	TOTAL SAMPLE WT.	WT. CRUSHED	% CRUSHED FACES
1 or more	965.3	957.3	99
2 or more	965.3	928.6	96

COMBINED VIRGIN AND RAP AGGREGATES
FLAT AND ELONGATED PARTICLES - ASTM D4791; 5:1 Ratio

SIEVE US/mm	TOTAL SAMPLE WEIGHT	WEIGHT OF FLAT & ELONG. PARTICLES (g)	% FLAT AND ELONG.	WEIGHTED AVERAGE (%)
3/4" / 19	0.0	0.0	0.0	
1/2" / 12.5	889.2	4.5	0.5	
3/8" / 9.5	610.5	2.9	0.5	2.0
1/4" / 6.3	240.6	10.5	4.4	
#4 / 4.75	95.3	4.0	4.2	

A DIVISION OF FISHER SAND & GRAVEL CO.

SUPPLEMENTAL AGGREGATE TESTING

SUPPLIER: Southwest Asphalt PLANT NO.: 4
PROJECT: ASU 25% RAP COP High Volume
LOCATION: Various
MIX DESIGNATION: COP C-3/4" Marshall Asphalt Concrete 25% RAP
LAB NO: ASU 25%

DATE: 10/12/2018
PROJ. SOLICITATION NO.: N/A
PROJECT NO: N/A
SWA PROJECT NO: 18-207
COMMODITY CODE: 432GK

SODIUM SULFATE SOUNDNESS - ASTM C 88

COARSE FRACTION SIEVE SIZE	GRADING OF ORIGINAL SAMPLE	ORIGINAL SAMPLE WEIGHT	WEIGHT OF TEST FRACTION BT, g	WEIGHT OF TEST FRACTION AT, g	PERCENT PASSING SIEVE, AT	WEIGHTED PERCENT LOSS
37.5mm to 25mm	0.0	5.0	5.0		100.0	0.0
25mm to 19mm						
19mm to 12.5mm	59.7	670.1	999.4	994.6	0.5	0.3
12.5mm to 9.5mm		329.3				
9.5mm to 4.75mm	40.3	301.6	301.6	295.8	1.9	0.8
TOTALS	100.0					1

FINE FRACTI(Seive Size	GRADING OF ORIGINAL SAMPLE	WEIGHT OF TEST FRACTION BT, g	WEIGHT OF TEST FRACTION AT, g	PERCENT PASSING SIEVE, AT	WEIGHTED PERCENT LOSS
#4 to #8	21.3	100.00	98.6	1.4	0.3
#8 to #16	20.2	100.00	99.0	1.0	0.2
#16 to #30	20.0	100.00	98.9	1.1	0.2
#30 to #50	18.9	100.00	98.2	1.8	0.3
Totals	100.0				1

QUALITATIVE EXAMINATION OF COARSE SIZES									
SIEVE SIZE	NUMBER OF PARTICLES BEFORE TEST	SPLITTING		CRUMBLING		CRACKING		FLAKING	
		No.	Percent	No.	Percent	No.	Percent	No.	Percent
19-37.5mm			-		-		-		-

CLAY LUMPS AND FRIABLE PARTICLES - ASTM C 142

SIEVE SIZE	GRADING OF ORIGINAL SAMPLE	WEIGHT OF TEST FRACTION BEFORE TEST, g	WEIGHT OF TEST FRACTION AFTER TEST, g	PERCENT LOSS	WEIGHTED PERCENT LOSS
FINE AGGREGATE 1.18mm (No. 16) to 4.75mm	N/A	102.60	102.30	0.3	**0.3**
				FINE AGGREGATE FRACTION	**0.3**
COARSE AGGREGATE					
4.75mm to 9.5mm	40.3	1062.3	1060.2	0.2	0.1
9.5mm to 19mm	59.7	2836.4	2830.1	0.2	0.1
19mm to 37.5mm	0.0	0.0	0.0	0.0	0.0
				COARSE AGGREGATE FRACTION	**0.2**

APPENDIX B
MIXTURE TESTING RESULTS

Dynamic Modulus Results

Control (0% RAP)

Table 13. Dynamic Modulus Data of Control Mix Tested Replicates

Temp (°C)	Freq (Hz)	Dynamic Modulus, |E*|					
		Repl. 1 (ksi)	Repl. 2 (ksi)	Repl. 3 (ksi)	Aver. (ksi)	Std. Dev.	Coeff. Of Var. (%)
4.4	25	3334	3310	3449	3364	74	2
	10	3165	3134	3292	3197	84	3
	5	3016	2978	3119	3038	73	2
	1	2639	2572	2676	2629	52	2
	0.5	2478	2419	2510	2469	46	2
	0.1	2111	2038	2126	2092	47	2
21.1	25	2123	2223	2127	2158	57	3
	10	1901	1967	1840	1903	64	3
	5	1724	1765	1654	1714	56	3
	1	1335	1374	1215	1308	83	6
	0.5	1177	1201	1060	1146	75	7
	0.1	847	842	714	801	76	9
37.8	25	733	790	657	727	67	9
	10	572	623	512	569	55	10
	5	467	508	413	463	48	10
	1	288	297	237	274	33	12
	0.5	228	235	186	216	26	12
	0.1	132	132	114	126	10	8
54.4	25	213	235	188	212	23	11
	10	159	167	143	156	12	8
	5	129	131	113	125	10	8
	1	76	77	72	75	3	3
	0.5	63	63	63	63	0	0
	0.1	42	45	45	44	1	3

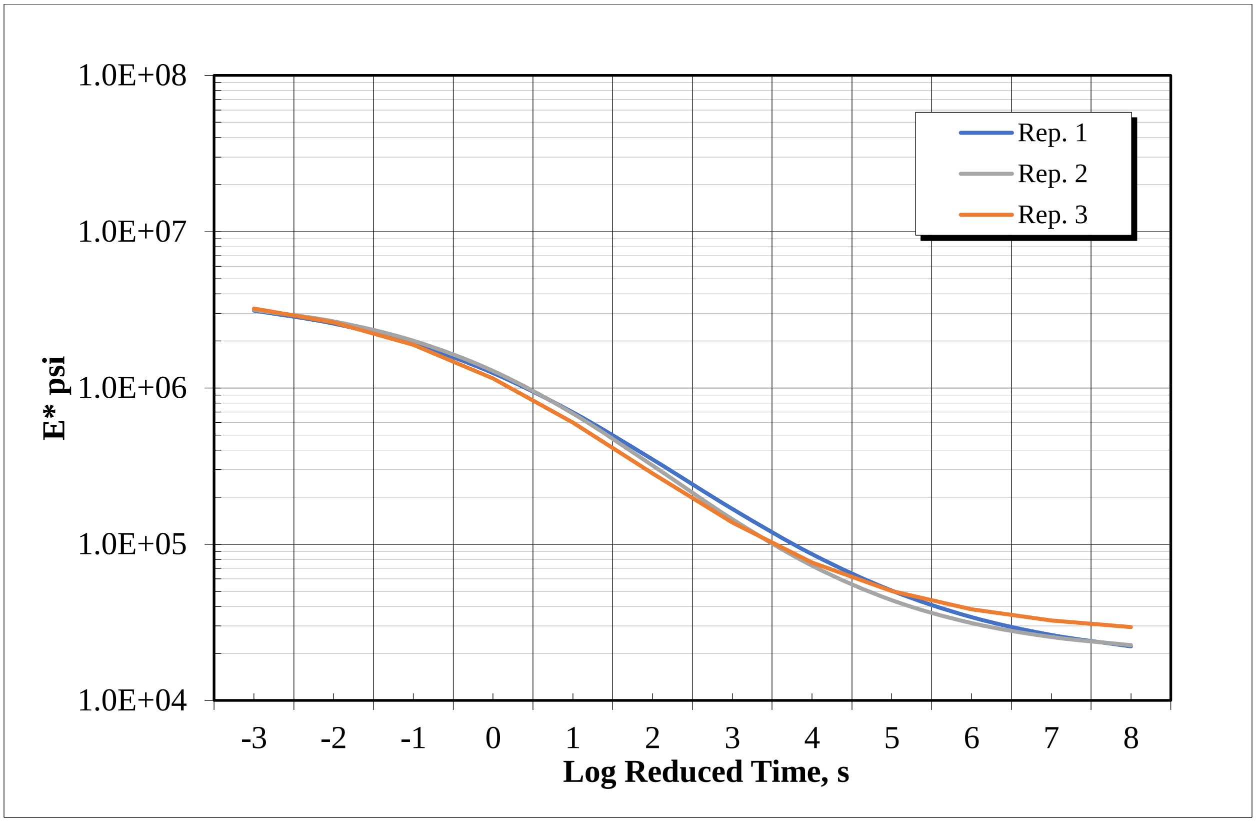


Figure 56. Dynamic Modulus Replicates Master Curves of the Control Mix

Dynamic Modulus Results

15% RAP

Table 14. Dynamic Modulus Data of 15% RAP Mix Tested Replicates

Temp (°C)	Freq (Hz)	Dynamic Modulus, |E*|				
		Repl. 1 (ksi)	Repl. 2 (ksi)	Aver. (ksi)	Std. Dev.	Coeff. Of Var. (%)
4.4	25	3360	3308	3334	37	1
	10	3184	3162	3173	16	1
	5	3083	2966	3025	83	3
	1	2742	2598	2670	102	4
	0.5	2604	2459	2532	103	4
	0.1	2278	2163	2221	81	4
21.1	25	2222	1913	2068	218	11
	10	1961	1708	1835	179	10
	5	1775	1533	1654	171	10
	1	1379	1166	1272	151	12
	0.5	1214	1038	1126	124	11
	0.1	866	762	814	73	9
37.8	25	674	637	655	27	4
	10	541	517	529	17	3
	5	446	430	438	12	3
	1	270	266	268	3	1
	0.5	216	216	216	0	0
	0.1	122	123	123	0	0
54.4	25	210	252	231	30	13
	10	161	196	179	25	14
	5	128	155	141	19	13
	1	76	92	84	11	13
	0.5	63	75	69	9	13
	0.1	43	52	47	7	14

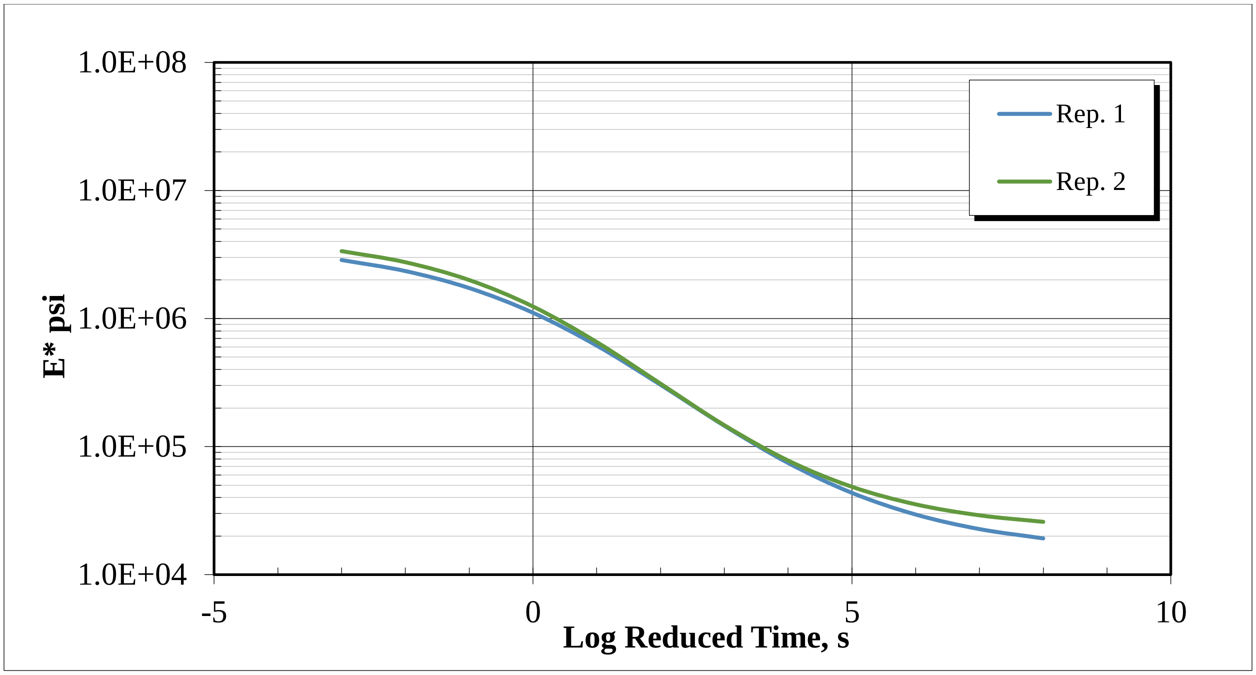


Figure 57. Dynamic Modulus Replicates Master Curves of the 15% RAP Mix

Dynamic Modulus Results

25% RAP

Table 15. Dynamic Modulus Data of 25% RAP Mix Tested Replicates

Temp (°C)	Freq (Hz)	Dynamic Modulus, |E*|				
		Repl. 1 (ksi)	Repl. 2 (ksi)	Repl. 3 (ksi)	Aver. (ksi)	Std. Dev.	Coeff. Of Var. (%)
4.4	25	2850	3330	2847	3009	278	9.2
	10	2725	3176	2721	2874	262	9.1
	5	2601	3019	2623	2748	235	8.6
	1	2313	2686	2290	2430	222	9.2
	0.5	2211	2553	2194	2319	203	8.7
	0.1	1926	2233	1939	2033	173	8.5
21.1	25	1855	2016	1897	1923	84	4.3
	10	1664	1845	1790	1767	93	5.2
	5	1511	1655	1666	1611	86	5.4
	1	1179	1311	1288	1259	71	5.6
	0.5	1063	1178	1150	1130	60	5.3
	0.1	786	866	873	842	48	5.7
37.8	25	709	714	707	710	3	0.5
	10	600	595	595	597	3	0.5
	5	510	502	502	505	4	0.9
	1	332	332	316	327	9	2.8
	0.5	272	270	260	267	6	2.3
	0.1	167	159	156	161	6	3.6
54.4	25	262	253	264	259	6	2.3
	10	187	183	203	191	11	5.7
	5	146	141	158	148	8	5.7
	1	78	77	83	79	3	4.1
	0.5	61	59	65	62	3	4.8
	0.1	37	37	38	37	0	1.2

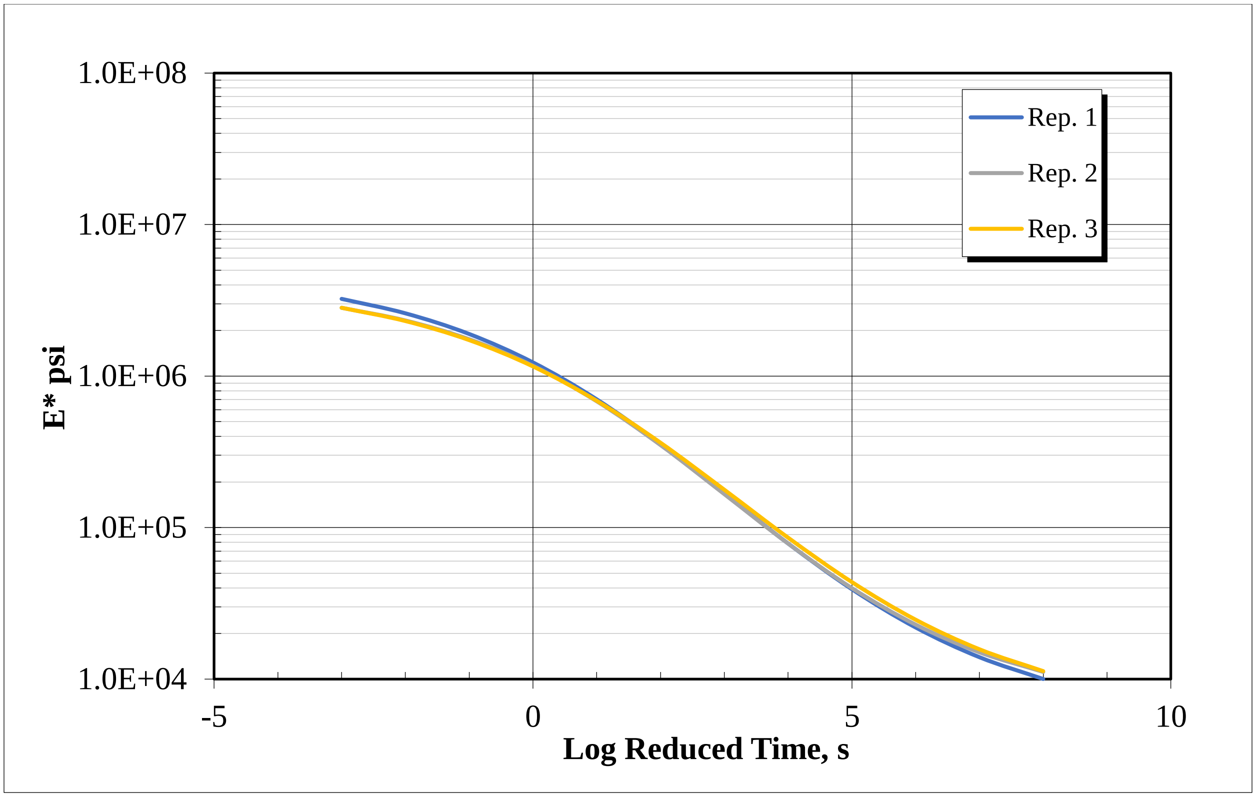


Figure 58. Dynamic Modulus Replicates Master Curves of the 25% RAP Mix

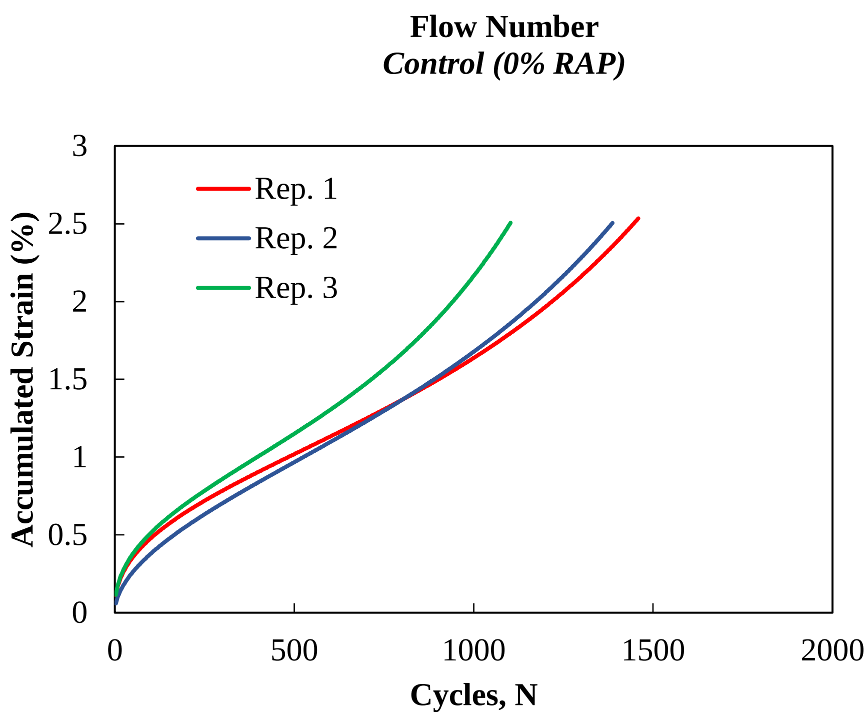


Figure 59. Accumulated Strain Versus Number of Cycles for All Replicates of the Control (0% RAP) mix

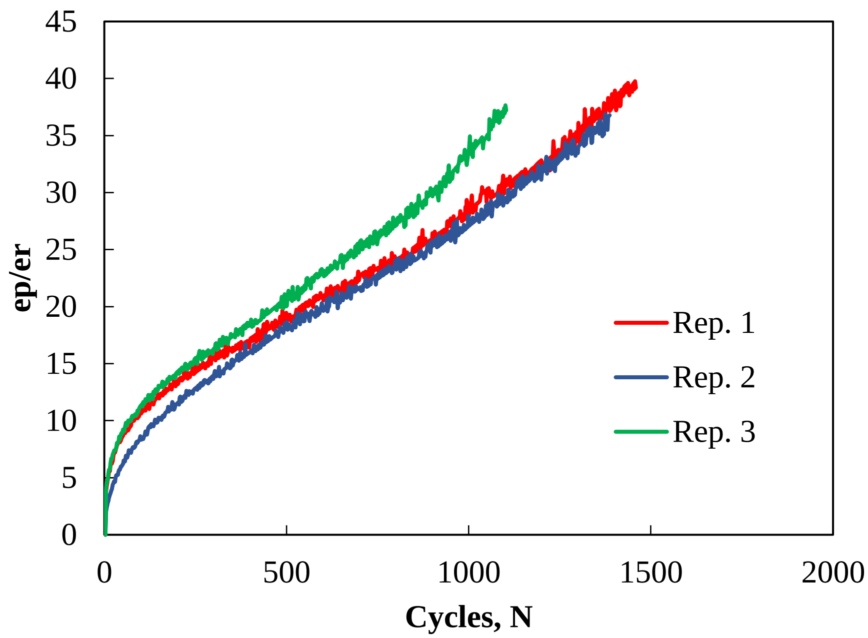


Figure 60. Permanent and Recoverable Strain Ratio for Number of Cycles for all Replicates of the Control (0% RAP) Mix

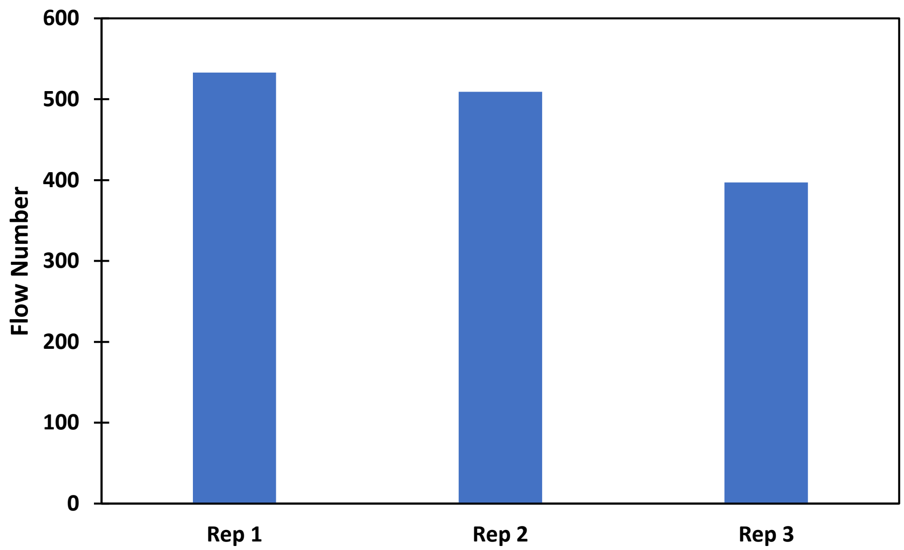


Figure 61. Flow Number Values for the Three Replicates of the Control Mix

15% RAP

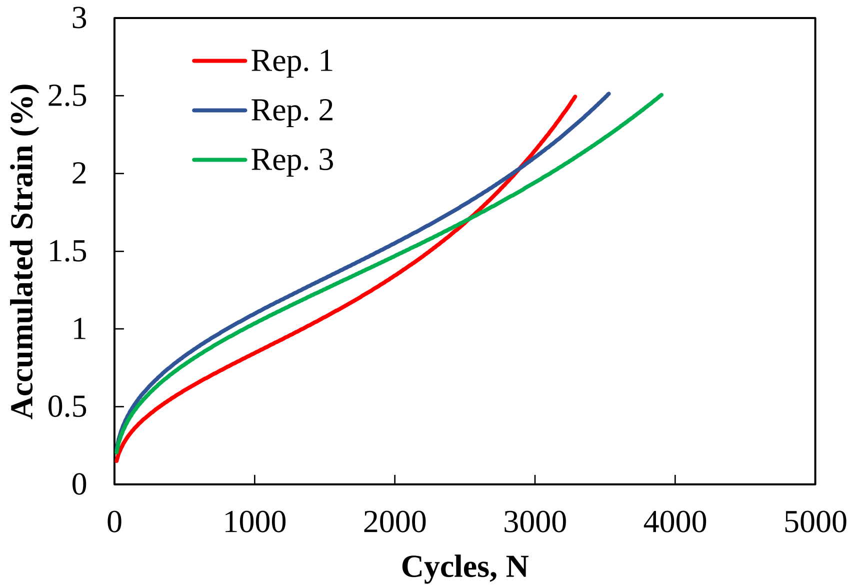


Figure 62. Accumulated Strain Versus Number of Cycles for all Replicates of the 15% RAP Mix

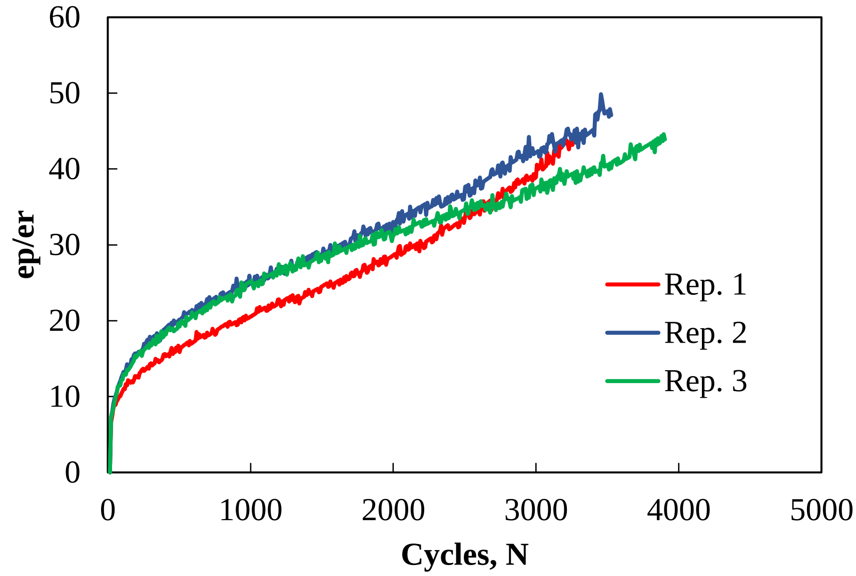


Figure 63. Permanent and Recoverable Strain Ratio for Number of Cycles for All Replicates of the 15% RAP Mix

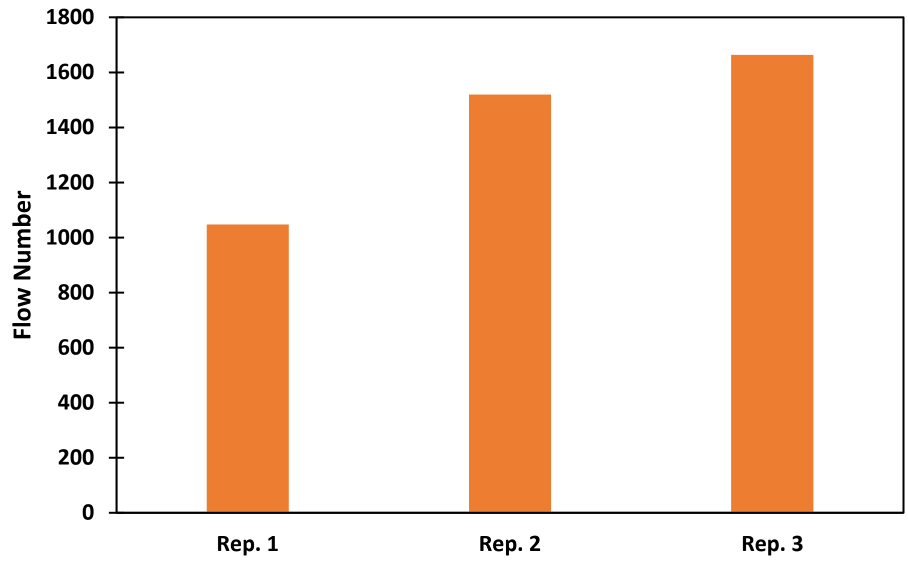


Figure 64. Flow Number Values of 3 Replicates of the 15% RAP Mix

25% RAP

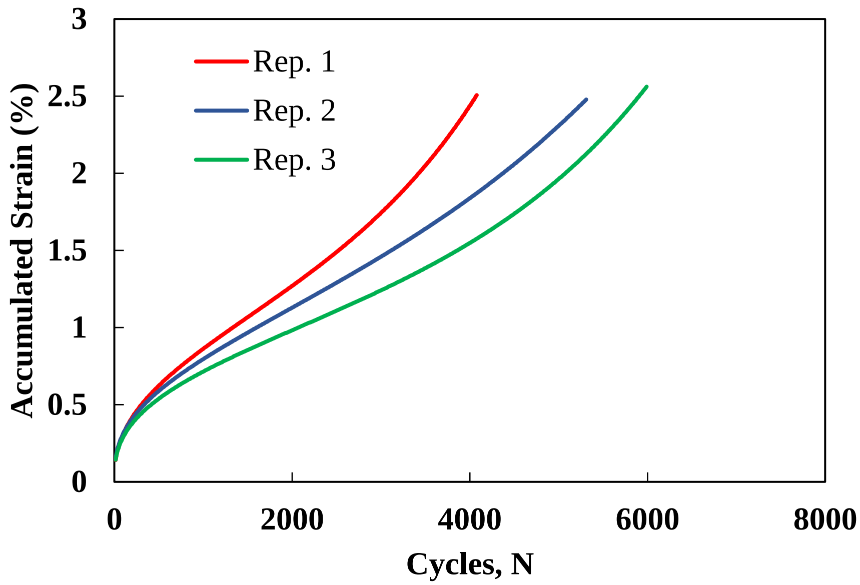


Figure 65. Accumulated Strain Versus Number of Cycles for all Replicates of the 25% RAP Mix

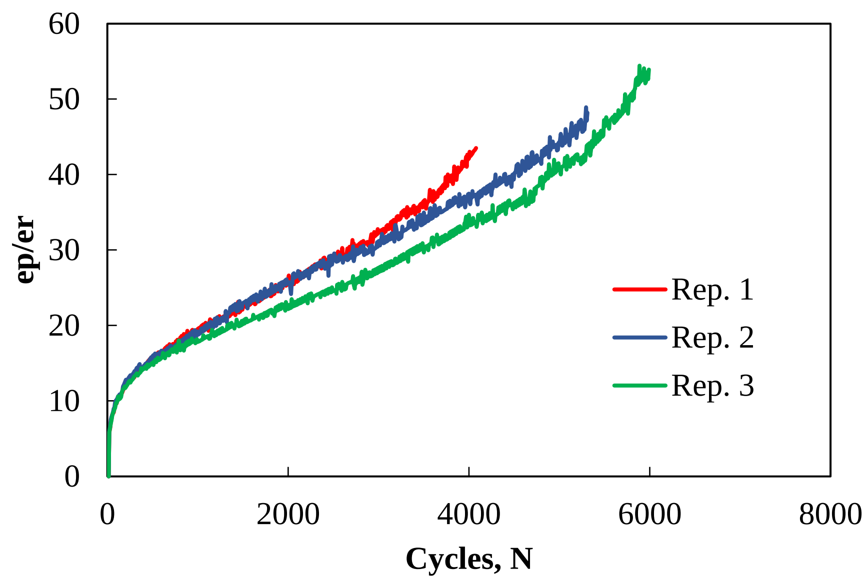


Figure 66. Permanent and Recoverable Strain Ratio for Number of Cycles for All Replicates of the 25% RAP Mix

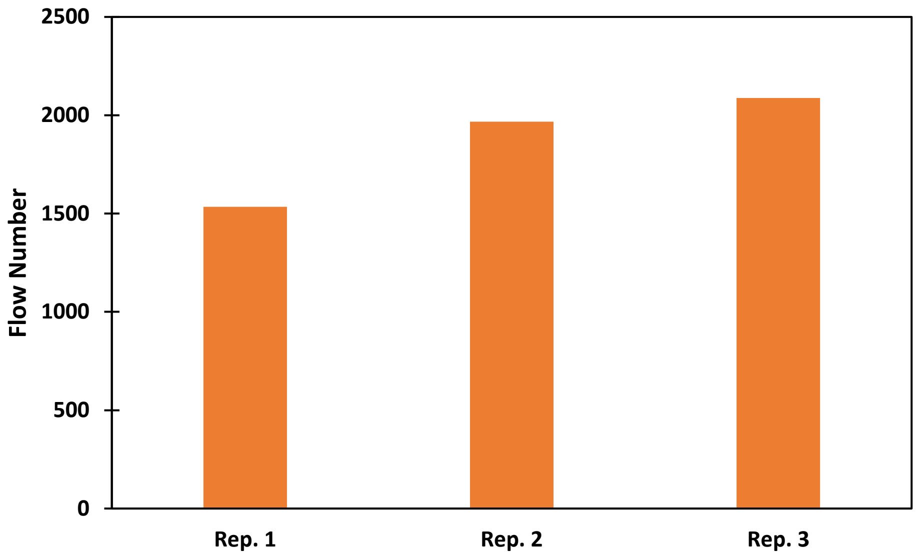


Figure 67. Flow Number Values of 3 Replicates of the 25% RAP Mix

IDEAL CT
Load-Displacement Curves

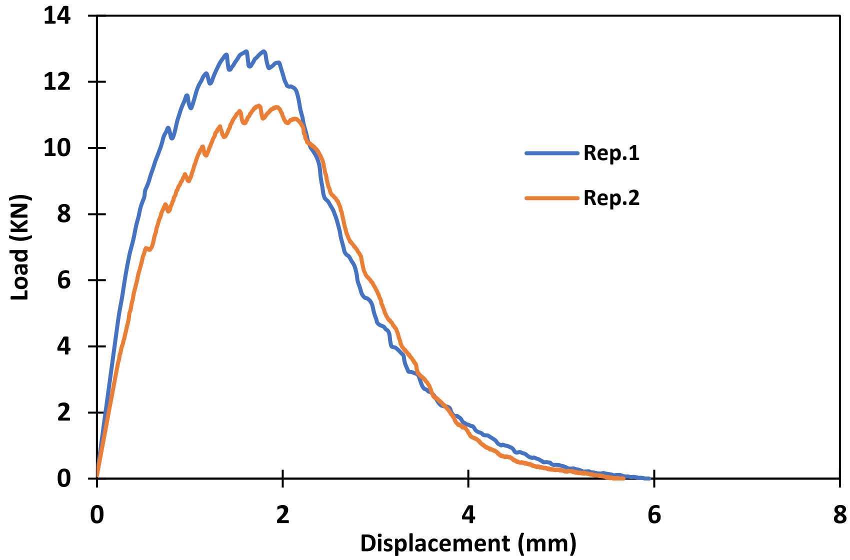


Figure 68. Load-Displacement Curve of 2 Replicates of the Control Mix

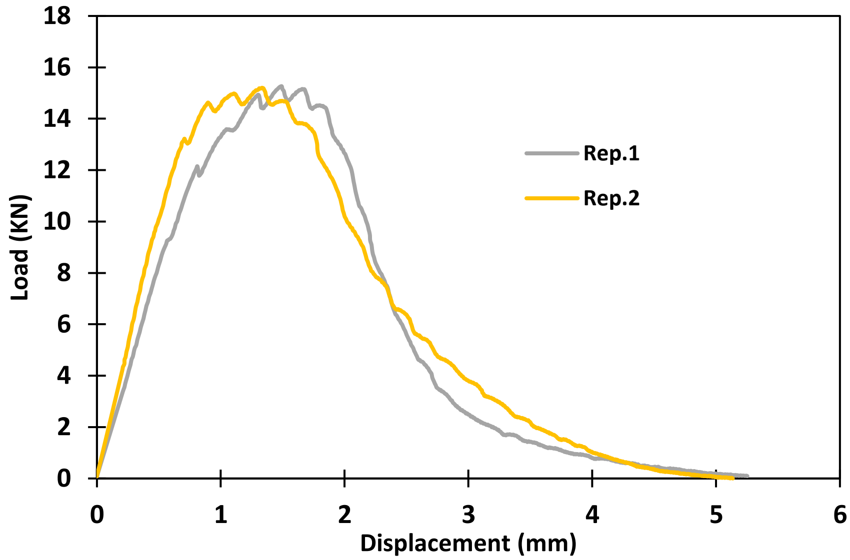


Figure 69. Load-Displacement Curve of 2 Replicates of the 15% RAP Mix

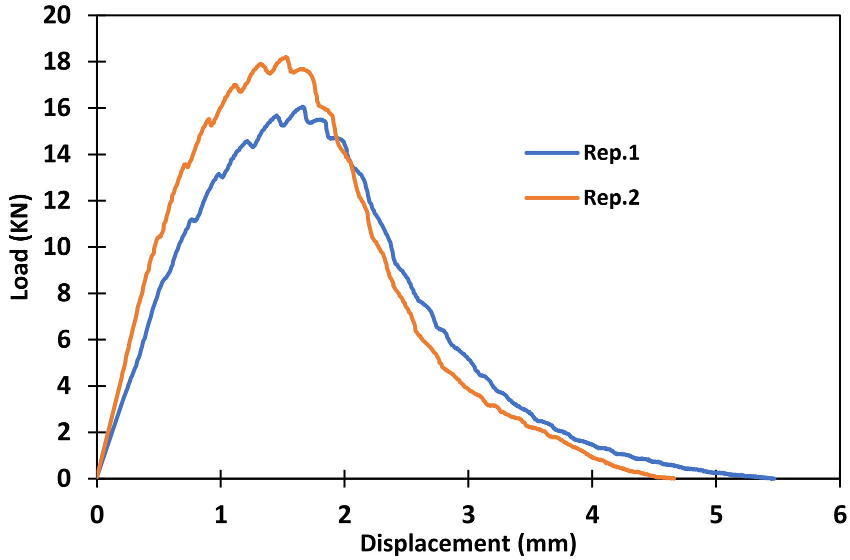


Figure 70. Load-Displacement Curve of 2 Replicates of the 25% RAP Mix

Indirect Tensile Strength

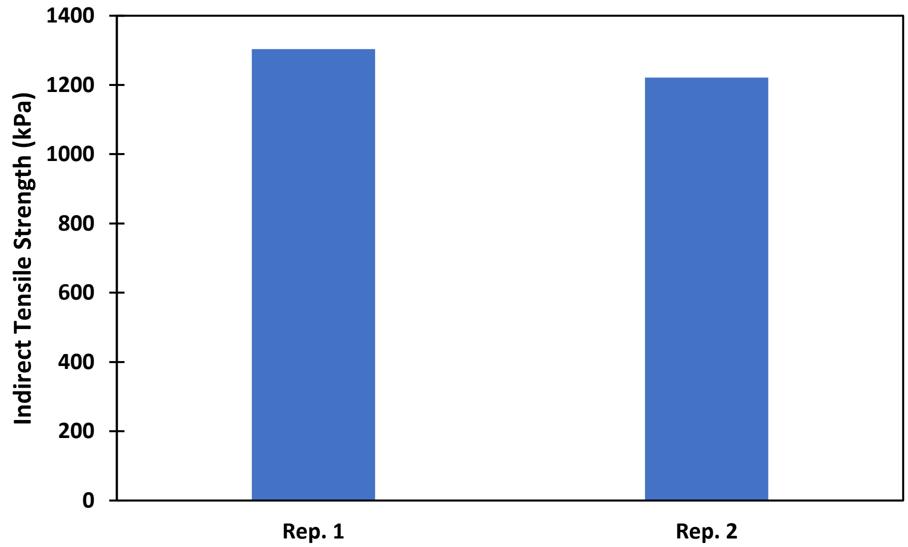


Figure 71. Indirect Tensile Strength Values of 2 Replicates of the Control Mix

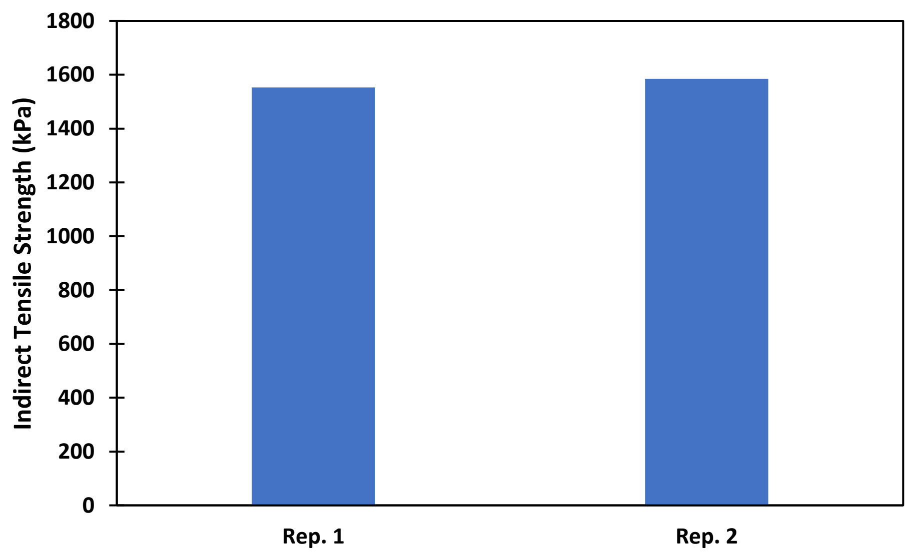


Figure 72. Indirect Tensile Strength Values of 2 Replicates of the 15% RAP Mix

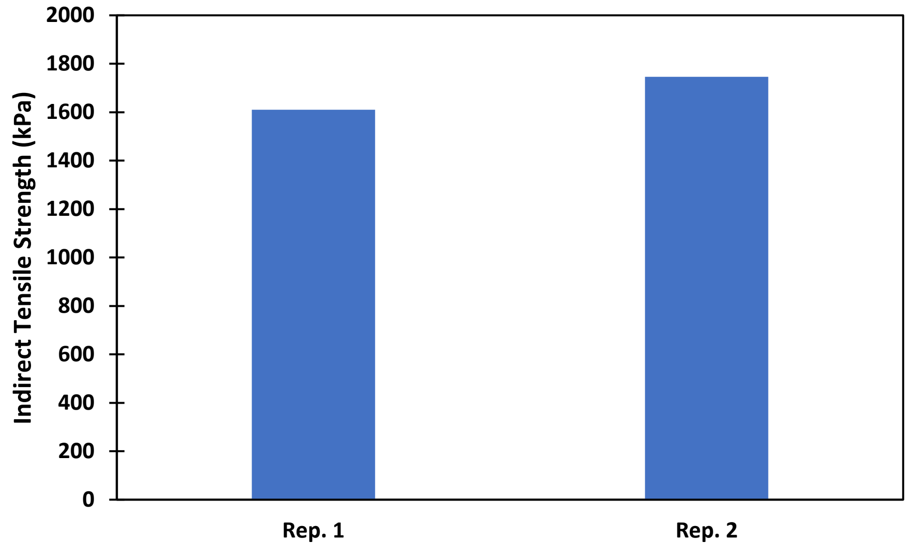


Figure 73. Indirect Tensile Strength Values of 2 Replicates of the 25% RAP Mix

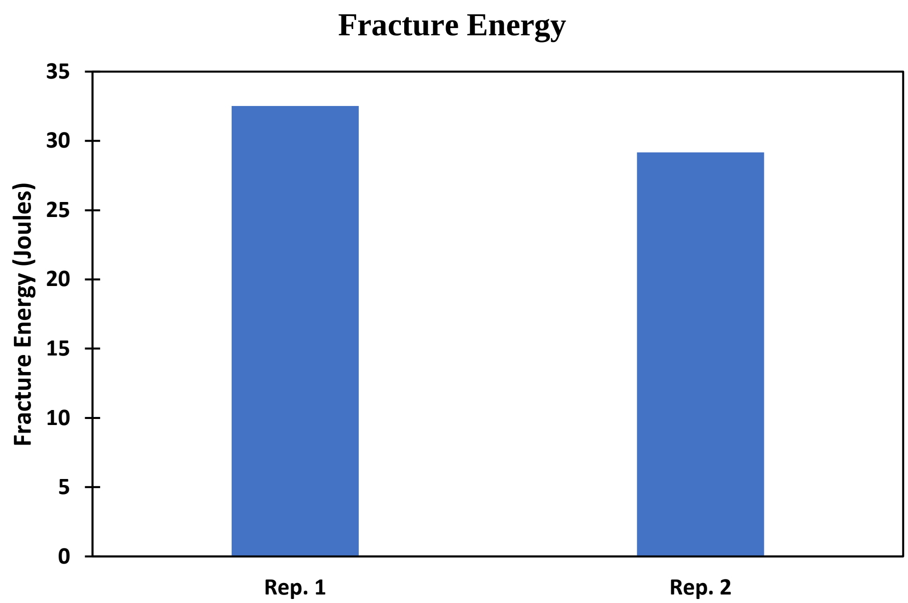


Figure 74. Fracture Energy Values of 2 Replicates of the Control Mix

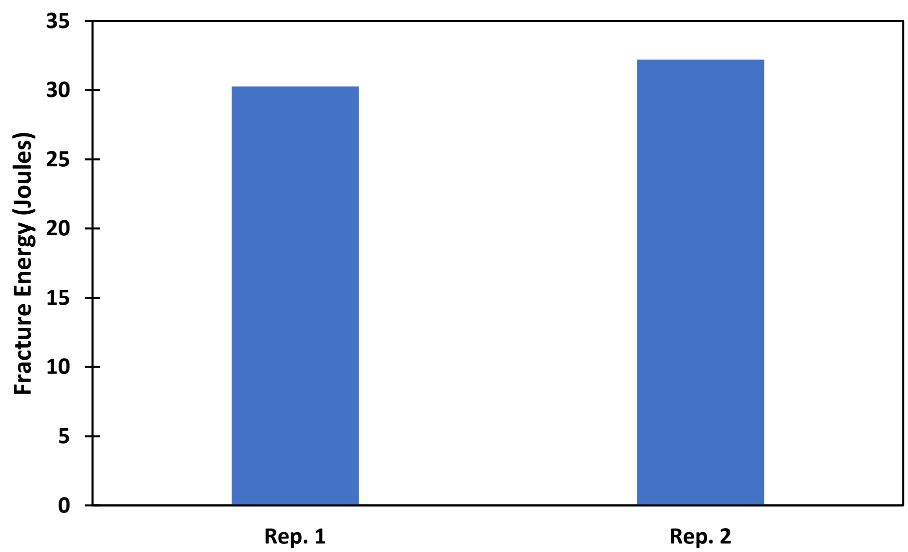


Figure 75. Fracture Energy Values of 2 Replicates of the 15% RAP Mix

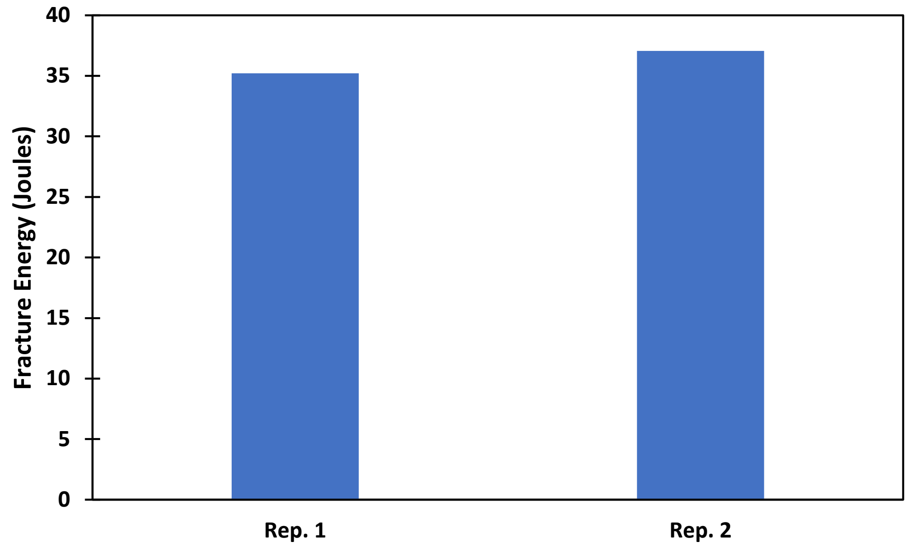


Figure 76. Fracture Energy Values of 2 Replicates of the 25% RAP Mix

Cracking Tolerance Index (CTI)

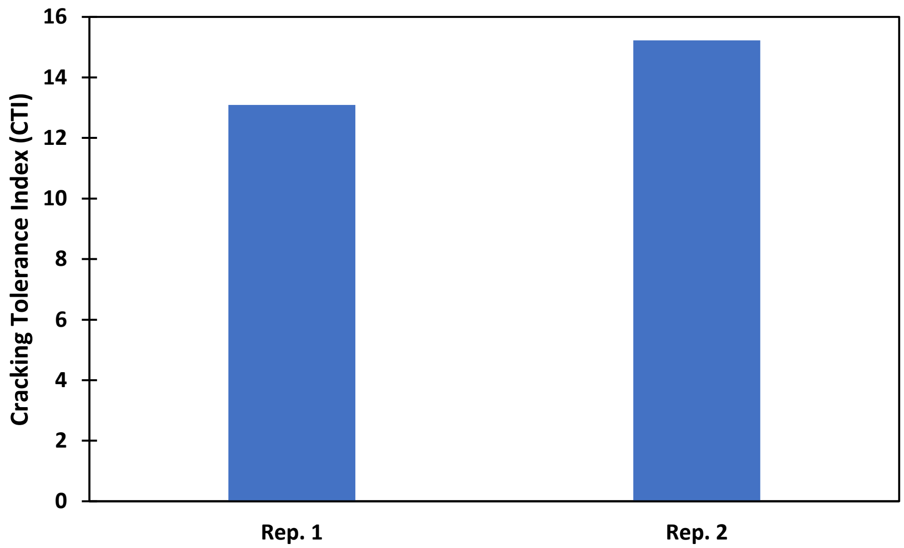


Figure 77. CTI Values of 2 Replicates of the Control Mix

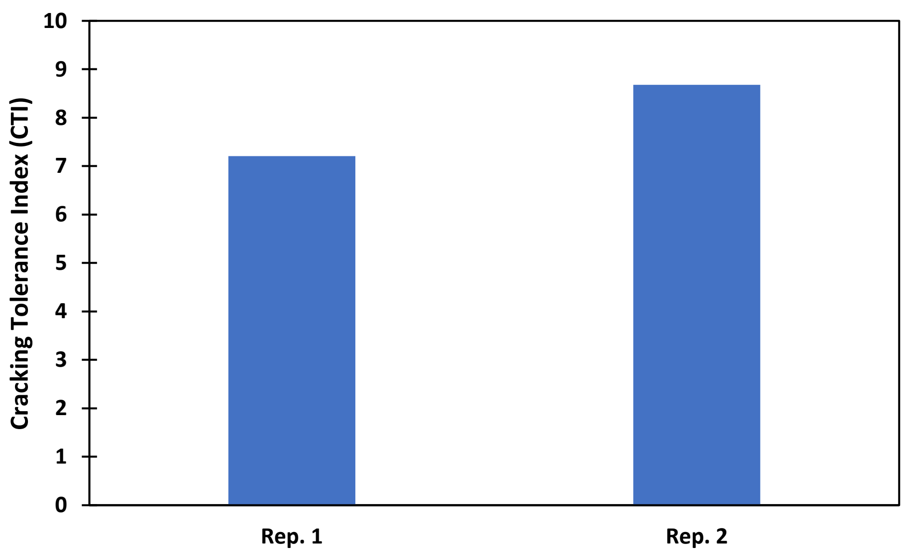


Figure 78. CTI Values of 2 Replicates of the 15% RAP Mix

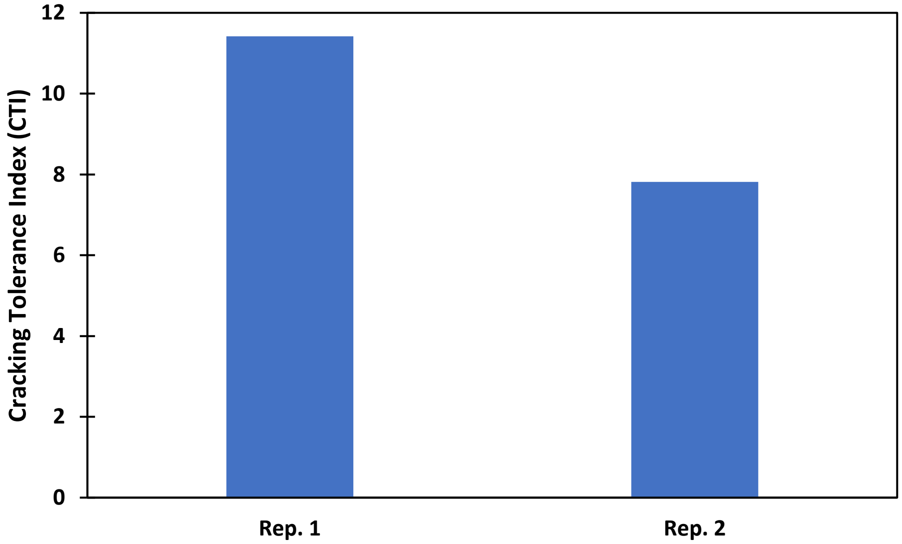


Figure 79. CTI Values of 2 Replicates of the 25% RAP Mix

C* Fracture Test

Control (0% RAP)

Table 16. Summary of C* Fracture Test Analysis for the Control Mix

Sample ID:	AV	Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
C9-1	6.73	51.50	0.15	
Crack Length, a (mm)	Time T, (Min)	Force (KN)	Force per Unit Thickness P* (N/mm)	Crack Growth Rate, a* (m/hr)
10.00	9.47	7.28	141.27	1.55
20.00	9.98	6.24	121.12	
30.00	10.60	4.19	81.30	
40.00	10.97	3.02	58.55	
50.00	11.17	2.38	46.28	
60.00	11.28	2.05	39.76	
70.00	11.83	1.18	22.93	
80.00	12.50	0.69	13.39	
			R^2 =	0.95
Sample ID:	AV	Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
C9-2	6.69	52.00	0.23	
10.00	4.80	7.87	151.42	2.30
20.00	5.90	6.81	130.93	
30.00	6.67	4.36	83.92	
40.00	6.80	3.81	73.24	
50.00	6.90	3.65	70.19	
60.00	7.10	3.07	58.98	
70.00	7.25	2.75	52.94	
80.00	7.60	2.22	42.67	
			R^2 =	0.90
Sample ID:	AV	Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
C12-1	7.14	50.80	0.30	
10.00	4.53	9.98	196.38	4.14
20.00	4.77	8.96	176.32	
30.00	4.87	8.11	159.62	
40.00	4.93	7.68	151.15	
50.00	5.03	6.29	123.87	
60.00	5.12	4.96	97.56	

70.00	**5.23**	**2.87**	**56.47**	
80.00	**5.65**	**1.10**	**21.69**	
			R^2 =	**0.88**
Sample ID:	**AV**	**Average Thickness, b (mm):**	**Displacement Rate, Δ* (mm/min) :**	
C14-1	**6.65**	**51.90**	**0.38**	
10.00	**3.23**	**10.40**	**200.40**	**2.42**
20.00	**3.37**	**9.99**	**192.40**	
30.00	**3.63**	**8.33**	**160.47**	
40.00	**3.75**	**7.46**	**143.83**	
50.00	**4.07**	**4.65**	**89.67**	
60.00	**4.27**	**3.42**	**65.98**	
70.00	**4.62**	**1.73**	**33.40**	
80.00	**4.83**	**1.33**	**25.64**	
			R^2 =	**0.99**
Sample ID:	**AV**	**Average Thickness, b (mm):**	**Displacement Rate, Δ* (mm/min) :**	
C17-2	**6.30**	**50.70**	**0.42**	
10.00	**2.45**	**8.68**	**171.13**	**8.25**
20.00	**2.58**	**6.31**	**124.36**	
30.00	**2.63**	**4.97**	**97.93**	
40.00	**2.67**	**4.02**	**79.27**	
50.00	**2.72**	**3.29**	**64.95**	
60.00	**2.85**	**2.10**	**41.35**	
70.00	**2.90**	**1.76**	**34.73**	
80.00	**3.00**	**1.49**	**29.31**	
			R^2 =	**0.96**

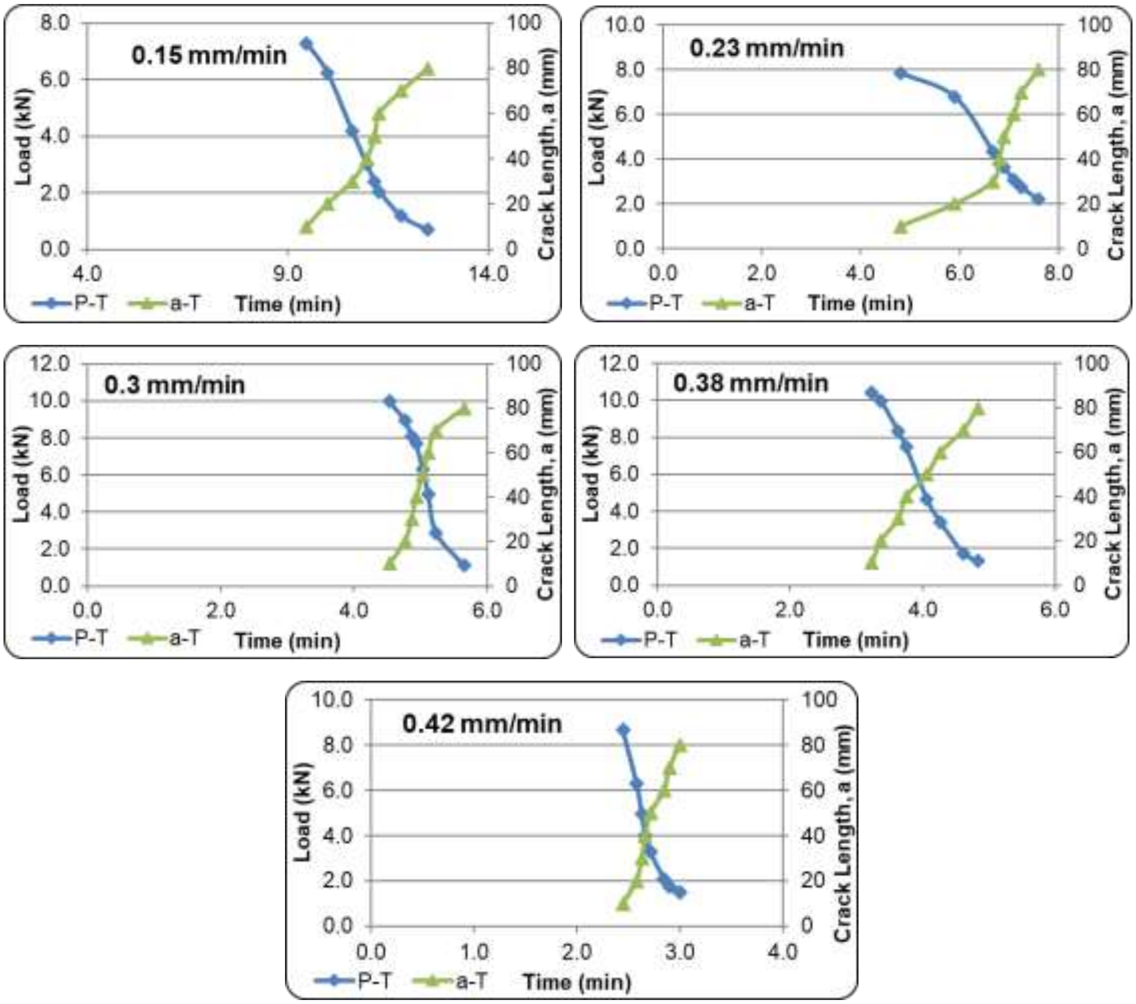


Figure 80. Load and Crack Length as Function of Time for Each Displacement Rate for the Control Mix

15% RAP

Table 17. Summary of C* Fracture Test Analysis for the 15% RAP Mix

Sample ID:	AV	Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
R2-1	6.59	55.00	0.15	
Crack Length, a (mm)	Time T, (Min)	Force (KN)	Force per Unit Thickness P* (N/mm)	Crack Growth Rate, a* (m/hr)
10.00	7.67	11.16	202.92	2.76
20.00	8.40	9.18	166.85	
30.00	8.57	8.42	153.09	
40.00	8.75	6.75	122.79	
50.00	8.90	5.64	102.60	
60.00	9.12	4.41	80.23	
70.00	9.30	3.77	68.47	
80.00	9.75	2.70	49.16	
			R^2 =	0.97
Sample ID:	AV	Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
R3-2	5.93	53.50	0.23	
10.00	4.45	9.03	168.85	3.65
20.00	4.55	8.90	166.39	
30.00	5.00	6.23	116.42	
40.00	5.13	4.50	84.08	
50.00	5.18	4.06	75.87	
60.00	5.30	2.66	49.74	
70.00	5.47	1.67	31.15	
80.00	5.58	1.32	24.59	
			R^2 =	0.91
Sample ID:	AV	Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
R3-1	7.01	53.50	0.30	
10.00	5.33	8.79	164.28	4.75
20.00	5.45	7.83	146.32	
30.00	5.60	5.57	104.16	
40.00	5.65	4.90	91.50	
50.00	5.70	4.12	77.01	
60.00	5.82	3.05	57.10	
70.00	5.90	2.61	48.83	
80.00	6.25	1.52	28.41	

			R^2 =	0.90
Sample ID:	**AV**	**Average Thickness, b (mm):**	**Displacement Rate, Δ* (mm/min) :**	
R13-1	6.83	53.70	0.38	
10.00	3.23	12.30	229.08	5.86
20.00	3.42	11.49	213.91	
30.00	3.62	9.38	174.58	
40.00	3.70	7.63	142.02	
50.00	3.73	6.43	119.74	
60.00	3.77	5.29	98.43	
70.00	3.82	4.03	75.13	
80.00	4.10	1.57	29.27	
			R^2 =	0.88
Sample ID:	**AV**	**Average Thickness, b (mm):**	**Displacement Rate, Δ* (mm/min) :**	
R2-2	6.35	49.30	0.42	
10.00	2.72	3.85	78.18	56.37
20.00	2.73	3.30	66.85	
30.00	2.75	2.94	59.74	
40.00	2.75	2.94	59.74	
50.00	2.77	2.67	54.16	
60.00	2.77	2.67	54.16	
70.00	2.78	2.36	47.91	
80.00	2.80	2.08	42.28	
			R^2 =	0.95

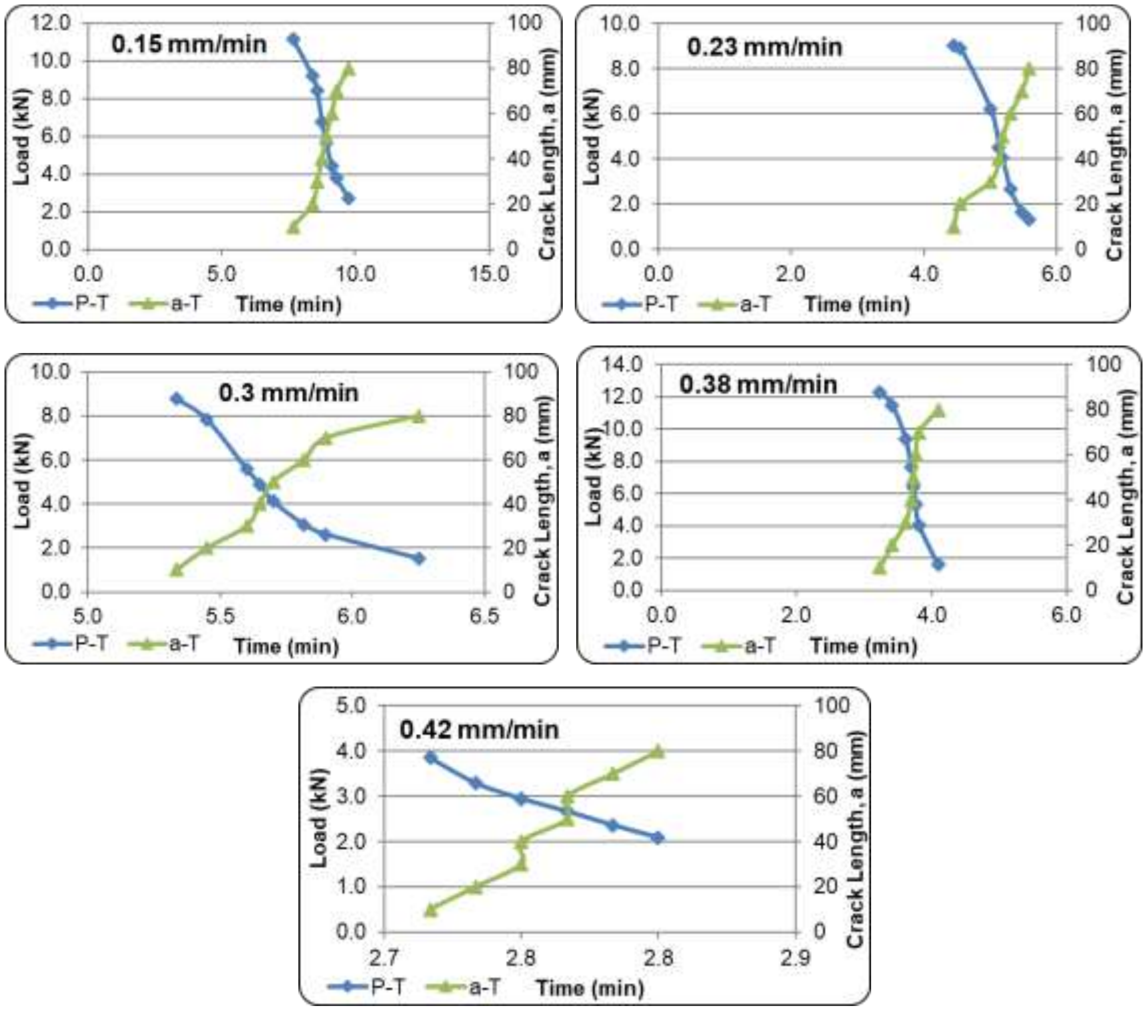


Figure 81. Load and Crack Length as Function of Time for Each Displacement Rate for the 15% RAP Mix

25% RAP

Table 18. Summary of C* Fracture Test Analysis for the 25% RAP Mix

Sample ID:		Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
H8-1		49.90	0.15	
Crack Length, a (mm)	Time T, (Min)	Force (KN)	Force per Unit Thickness P* (N/mm)	Crack Growth Rate, a* (m/hr)
10.00	7.42	9.34	187.27	1.29
20.00	7.75	9.07	181.82	
30.00	8.17	8.27	165.74	
40.00	8.58	6.21	124.52	
50.00	9.28	3.35	67.09	
60.00	9.65	2.65	53.09	
70.00	10.07	2.10	42.02	
80.00	10.42	1.78	35.59	
			R^2 =	0.99
Sample ID:		Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
H4-1		50.50	0.23	
10.00	4.38	9.00	178.15	4.41
20.00	4.80	8.62	170.60	
30.00	4.97	8.10	160.45	
40.00	5.07	7.36	145.76	
50.00	5.25	4.28	84.73	
60.00	5.32	3.22	63.76	
70.00	5.40	2.53	50.10	
80.00	5.67	1.55	30.64	
			R^2 =	0.98
Sample ID:		Average Thickness, b (mm):	Displacement Rate, Δ* (mm/min) :	
H4-2		51.10	0.30	
10.00	3.23	9.91	193.98	5.26
20.00	3.35	9.72	190.16	
30.00	3.50	8.77	171.64	
40.00	3.60	7.44	145.60	
50.00	3.68	5.93	116.04	
60.00	3.75	4.66	91.20	
70.00	3.88	2.58	50.41	
80.00	4.08	1.58	31.00	

			R^2 =	0.98
Sample ID:		**Average Thickness, b (mm):**	**Displacement Rate, Δ* (mm/min) :**	
H19-1		**51.10**	**0.38**	
10.00	**3.02**	**10.65**	**208.37**	**9.54**
20.00	**3.08**	**9.96**	**194.87**	
30.00	**3.13**	**9.07**	**177.43**	
40.00	**3.17**	**8.59**	**168.18**	
50.00	**3.22**	**7.23**	**141.54**	
60.00	**3.30**	**4.36**	**85.28**	
70.00	**3.40**	**2.66**	**51.96**	
80.00	**3.43**	**2.37**	**46.28**	
			R^2 =	**0.97**
Sample ID:		**Average Thickness, b (mm):**	**Displacement Rate, Δ* (mm/min) :**	
H8-2		**49.49**	**0.42**	
10.00	**2.83**	**11.03**	**222.80**	**15.03**
20.00	**2.87**	**9.07**	**183.21**	
30.00	**2.88**	**7.76**	**156.88**	
40.00	**2.90**	**6.62**	**133.81**	
50.00	**2.93**	**4.67**	**94.41**	
60.00	**2.95**	**3.99**	**80.53**	
70.00	**2.97**	**3.77**	**76.22**	
80.00	**3.10**	**2.37**	**47.85**	
			R^2 =	**0.82**

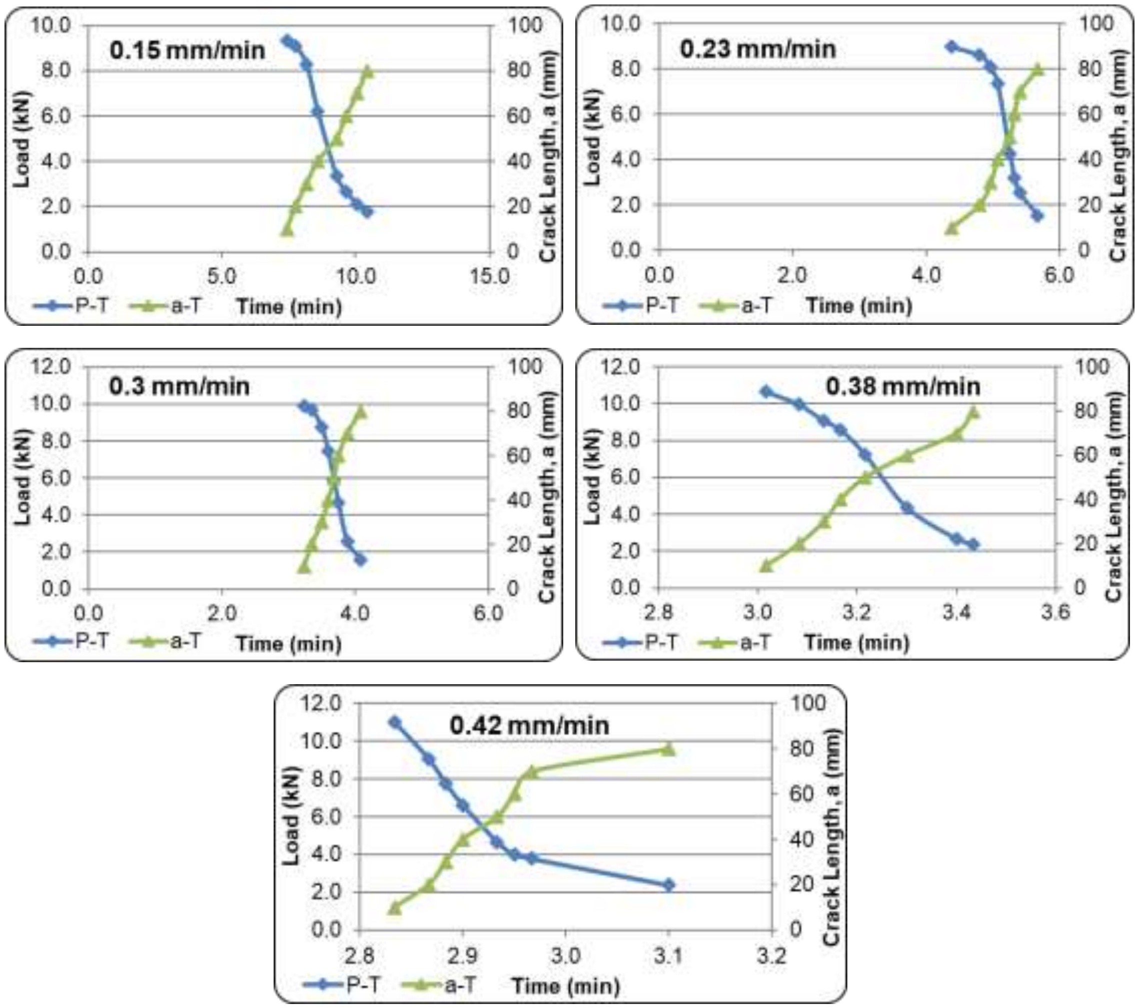


Figure 82. Load and Crack Length as Function of Time for Each Displacement Rate the 25% RAP mix

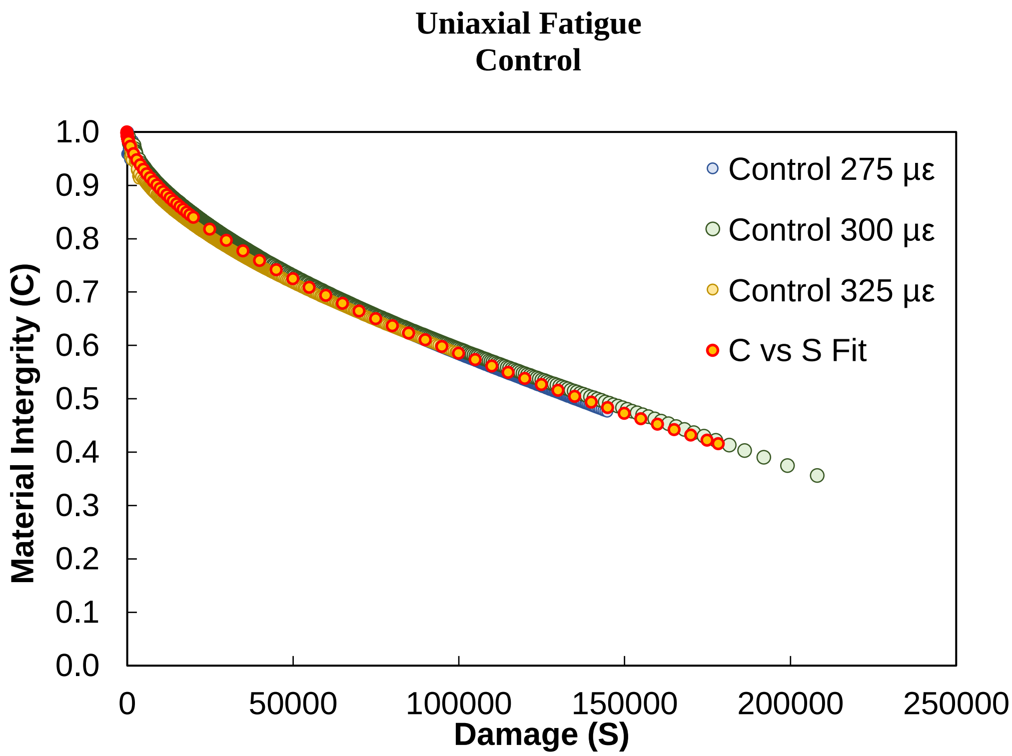


Figure 83. Damage-Characteristic Curves of the Control Mix

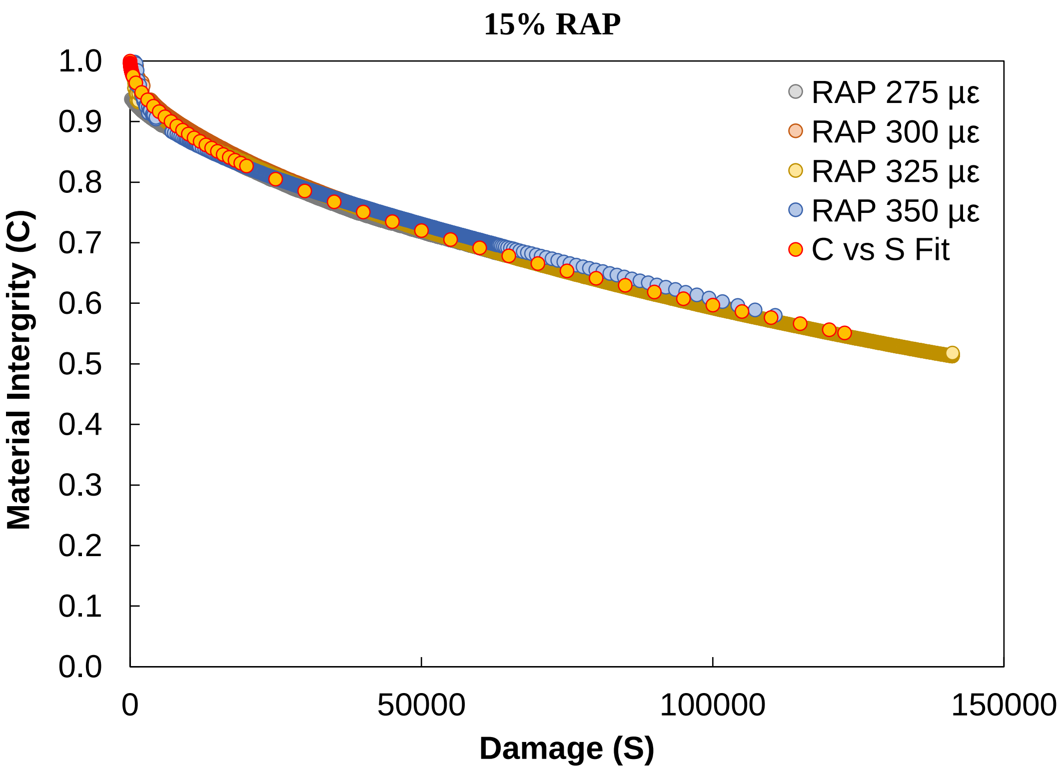


Figure 84. Damage Characteristic Curves of the 15% RAP Mix

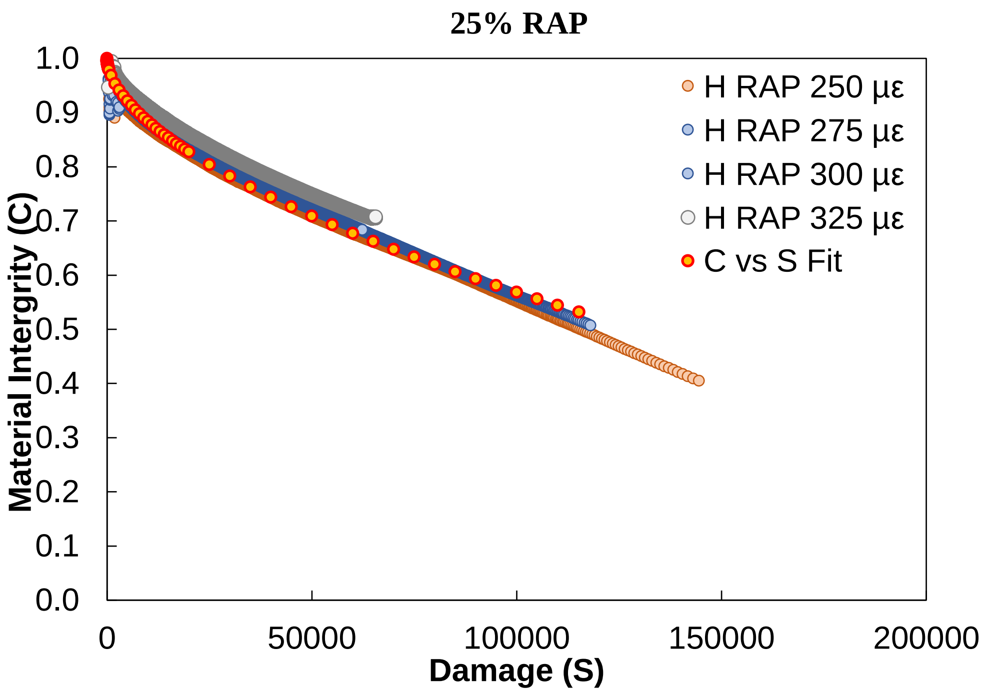


Figure 85. Damage Characteristic Curves of the 25% RAP Mix

Tensile Strength Ratio

Table 19. TSR Control Mix Disks Air Voids

	Air Voids (%)		
Dry Set	Disk 1	Disk 2	Disk 3
	7.43	6.22	7.70
Average	7.11		
Wet Set	Disk 1	Disk 2	Disk 3
	6.65	7.28	7.34
Average	7.09		

Table 20. TSR 15% RAP Mix Disks Air Voids

	Air Voids (%)		
Dry Set	Disk 1	Disk 2	Disk 3
	6.33	6.91	6.22
Average	6.48		
Wet Set	Disk 1	Disk 2	Disk 3
	6.01	6.14	7.51
Average	6.56		

Table 21. TSR 25% RAP Mix Disks Air Voids

	Air Voids		
Dry Set	Disk 1	Disk 2	Disk 3
	6.45	5.60	6.56
Average	6.21		
Wet Set	Disk 1	Disk 2	Disk 3
	7.08	6.10	6.14
Average	6.44		

Table 22. Tensile Strength Calculations of the Unconditioned Specimens

Disk	P (Maximum Load, KN)	P (Maximum Load, N)	t (thickness, mm)	D (Diameter, mm)	St (kPa)
Control-1	12.92	12921	63.48	99.40	1304
Control-2	10.97	10965	58.39	99.54	1201
Control-3	11.28	11283	59.03	99.64	1221
15% RAP-1	15.26	15262	62.75	99.72	1553
15% RAP-2	15.20	15204	61.30	99.62	1585
15% RAP-3	14.52	14524	62.48	99.78	1483
25% RAP-1	16.06	16056	63.65	99.76	1610
25% RAP-2	18.20	18204	66.53	99.74	1747
25% RAP-3	16.34	16336	62.88	99.56	1661

Table 23. Tensile Strength Calculations of the Conditioned Specimens

Disk	P (Maximum Load, KN)	P (Maximum Load, N)	t (thickness, mm)	D (Diameter, mm)	St (kPa)
Control-1	11.46	11463	66.46	100.20	1096
Control-2	10.79	10785	63.15	100.39	1083
Control-3	10.70	10700	64.31	100.61	1053
15% RAP-1	12.53	12530	65.31	100.56	1215
15% RAP-2	13.92	13919	62.93	100.08	1407
15% RAP-3	11.72	11720	63.27	100.43	1174
25% RAP-1	13.86	13860	64.25	100.12	1372
25% RAP-2	14.13	14130	65.14	100.03	1380
25% RAP-3	17.30	17295	65.41	100.02	1683

APPENDIX C
BINDER TESTING DATA

Performance Grading

Control

Table 24. Complex Shear Modulus Values for the First Replicate of the Recovered Control Binder

Temperature	Complex Shear Modulus	Phase Shift Angle	|G*|/sin(delta)
[°C]	[kPa]	[°]	[kPa]
64 °C	6.17	83.30	6.21
70 °C	2.64	85.28	2.65
76 °C	1.19	86.81	1.19

Table 25. Complex Shear Modulus Values for the Second Replicate of the Recovered Control Binder

Temperature	Complex Shear Modulus	Phase Shift Angle	|G*|/sin(delta)
[°C]	[kPa]	[°]	[kPa]
64 °C	5.91	83.34	5.95
70 °C	2.56	85.22	2.56
76 °C	1.17	86.65	1.17

15% RAP

Table 26. Complex Shear Modulus Values for the first Replicate of the Recovered 15% RAP binder

Temperature	Complex Shear Modulus	Phase Shift Angle	|G*|/sin(delta)
[°C]	[kPa]	[°]	[kPa]
64 °C	7.51	81.51	7.60
70 °C	3.31	83.82	3.33
76 °C	1.50	85.69	1.51

Table 27. Complex Shear Modulus Values for the Second Replicate of the Recovered 15% RAP Binder

Temperature	Complex Shear Modulus	Phase Shift Angle	|G*|/sin(delta)
[°C]	[kPa]	[°]	[kPa]
64 °C	8.83635	81.139	8.9429
70 °C	3.81	83.5335	3.83435
76 °C	1.7168	85.4555	1.7222

25% RAP

Table 28. Complex Shear Modulus Values for the First Replicate of the Recovered 25% RAP Binder

Temperature	Complex Shear Modulus	Phase Shift Angle	|G*|/sin(delta)
[°C]	[kPa]	[°]	[kPa]
64 °C	19.94	77.67	20.41
70 °C	8.41	80.68	8.52
76 °C	3.69	83.21	3.72
82 °C	1.68	85.24	1.68

Table 29. Complex Shear Modulus Values for the Second Replicate of the Recovered 25% RAP Binder

Temperature	Complex Shear Modulus	Phase Shift Angle	|G*|/sin(delta)
[°C]	[kPa]	[°]	[kPa]
64 °C	20.46	77.58	20.95
70 °C	8.60	80.63	8.71
76 °C	3.77	83.16	3.80
82 °C	1.71	85.22	1.72

Time-Temperature Sweep Test

Control

Table 30. Time-Temperature Sweep Test Data for the First Replicate of the Recovered Control Binder

Temperature	Frequency	|G*|	Phase Angle
(°C)	(rad/sec)	Pa	(°)
10.00	188.51	1.02E+08	26.48
10.00	87.96	8.09E+07	28.45
10.00	40.84	6.30E+07	30.41
10.00	18.85	4.82E+07	32.44
10.00	8.80	3.64E+07	34.57
10.00	4.08	2.69E+07	36.86
10.00	1.88	1.95E+07	39.35
10.00	0.88	1.39E+07	41.96
10.00	0.63	1.20E+07	43.15
20.00	188.51	3.90E+07	35.73
20.00	87.96	2.85E+07	37.99
20.00	40.84	2.05E+07	40.33
20.00	18.85	1.43E+07	42.83
20.00	8.80	9.88E+06	45.43
20.00	4.08	6.64E+06	48.15
20.00	1.88	4.35E+06	51.05
20.00	0.88	2.79E+06	53.95
20.00	0.63	2.28E+06	55.31
30.00	188.51	1.14E+07	47.19
30.00	87.96	7.58E+06	49.49
30.00	40.84	4.92E+06	52.13
30.00	18.85	3.11E+06	54.83
30.00	8.80	1.93E+06	57.57
30.00	4.08	1.17E+06	60.27
30.00	1.88	6.86E+05	62.94
30.00	0.88	3.98E+05	65.45
30.00	0.63	3.11E+05	66.53
40.00	188.51	2.84E+06	58.56
40.00	87.96	1.68E+06	60.81
40.00	40.84	9.83E+05	63.28
40.00	18.85	5.62E+05	65.76
40.00	8.80	3.18E+05	68.05

40.00	4.08	1.75E+05	70.17
40.00	1.88	94987	72.35
40.00	0.88	51477	74.44
40.00	0.63	38989	75.38
54.00	188.51	4.31E+05	81.97
54.00	87.96	2.02E+05	76.84
54.00	40.84	1.06E+05	76.24
54.00	18.85	54959	77.31
54.00	8.80	28398	78.54
54.00	4.08	14394	80.28
54.00	1.88	7155.2	81.81
54.00	0.88	3535	83.4
54.00	0.63	2566.4	84.49

Table 31. CAM Model Fit Coefficients for the First Replicate of the Recovered Control Binder

Master Curve Coefficients	Value
g	8.672335
w_c	0.657043
k	0.176193
m_e	1.135667
C1	-20.5309
C2	150.9084
Tr	15
Error^2	0.019

Table 32. Time-Temperature Sweep Test Data for the Second Replicate of the Recovered Control Binder

Temperature	Frequency	|G*|	Phase Angle
(°C)	(rad/sec)	Pa	(°)
10.00	188.51	9.89E+07	26.22
10.00	87.96	7.85E+07	28.14
10.00	40.84	6.13E+07	30.08
10.00	18.85	4.70E+07	32.08
10.00	8.80	3.56E+07	34.18
10.00	4.08	2.64E+07	36.43
10.00	1.88	1.92E+07	38.86
10.00	0.88	1.38E+07	41.39
10.00	0.63	1.19E+07	42.53
20.00	188.51	3.81E+07	35.36
20.00	87.96	2.80E+07	37.55
20.00	40.84	2.01E+07	39.84
20.00	18.85	1.42E+07	42.3
20.00	8.80	9.82E+06	44.85
20.00	4.08	6.64E+06	47.53
20.00	1.88	4.36E+06	50.39
20.00	0.88	2.82E+06	53.28
20.00	0.63	2.31E+06	54.56
30.00	188.51	1.12E+07	46.42
30.00	87.96	7.49E+06	48.85
30.00	40.84	4.88E+06	51.5
30.00	18.85	3.10E+06	54.19
30.00	8.80	1.93E+06	56.89
30.00	4.08	1.18E+06	59.58
30.00	1.88	6.97E+05	62.16
30.00	0.88	4.07E+05	64.65
30.00	0.63	3.19E+05	65.7
40.00	188.51	2.82E+06	60.12
40.00	87.96	1.70E+06	60.93
40.00	40.84	1.01E+06	62.9
40.00	18.85	5.80E+05	65.19
40.00	8.80	3.31E+05	67.35
40.00	4.08	1.85E+05	69.49
40.00	1.88	1.01E+05	71.59
40.00	0.88	54176	73.68
40.00	0.63	40852	74.54

54.00	188.51	4.44E+05	77.17
54.00	87.96	2.09E+05	74.55
54.00	40.84	1.11E+05	74.9
54.00	18.85	57353	76.51
54.00	8.80	29885	77.9
54.00	4.08	15248	79.68
54.00	1.88	7615.3	81.43
54.00	0.88	3787.4	83.12
54.00	0.63	2788.3	83.47

Table 33. CAM Model fit Coefficients for the Second Replicate of the Recovered Control Binder

Master Curve Coefficients	Value
g	8.668545
w_c	0.543276
k	0.172887
m_e	1.138744
C1	-20.451
C2	149.9168
Tr	15
Error^2	0.018

15% RAP

Table 34. Time-Temperature Sweep Test Data for the First Replicate of the Recovered 15% RAP Binder

Temperature	Frequency	|G*|	Phase Angle
(°C)	(rad/sec)	Pa	(°)
10.00	188.51	1.02E+08	25.42
10.00	87.96	8.15E+07	27.2
10.00	40.84	6.42E+07	28.98
10.00	18.85	4.97E+07	30.83
10.00	8.80	3.81E+07	32.76
10.00	4.08	2.86E+07	34.83
10.00	1.88	2.11E+07	37.09
10.00	0.88	1.54E+07	39.45
10.00	0.63	1.34E+07	40.53
20.00	188.51	4.05E+07	34.05
20.00	87.96	3.01E+07	36.05
20.00	40.84	2.20E+07	38.15
20.00	18.85	1.57E+07	40.42
20.00	8.80	1.11E+07	42.8
20.00	4.08	7.62E+06	45.32
20.00	1.88	5.11E+06	48.02
20.00	0.88	3.36E+06	50.79
20.00	0.63	2.78E+06	52.03
30.00	188.51	1.25E+07	44.39
30.00	87.96	8.50E+06	46.63
30.00	40.84	5.65E+06	49.11
30.00	18.85	3.67E+06	51.69
30.00	8.80	2.34E+06	54.26
30.00	4.08	1.46E+06	56.89
30.00	1.88	8.83E+05	59.51
30.00	0.88	5.27E+05	62.03
30.00	0.63	4.18E+05	63.08
40.00	188.51	3.39E+06	54.58
40.00	87.96	2.05E+06	57.15
40.00	40.84	1.24E+06	59.73
40.00	18.85	7.30E+05	62.24
40.00	8.80	4.26E+05	64.57
40.00	4.08	2.43E+05	66.78
40.00	1.88	1.36E+05	68.97

40.00	0.88	75336	71.17
40.00	0.63	57704	72.11
54.00	188.51	5.52E+05	67.66
54.00	87.96	2.74E+05	68.86
54.00	40.84	1.46E+05	71.12
54.00	18.85	77326	73.46
54.00	8.80	41087	75.35
54.00	4.08	21501	77.37
54.00	1.88	10971	79.53
54.00	0.88	5535	81.54
54.00	0.63	4086.4	82.26

Table 35. CAM Model Fit Coefficients for the First Replicate of the ecovered 15% RAP bBinder

Master Curve Coefficients	Value
g	8.693401858
w_c	0.281543219
k	0.164511574
m_e	1.147011886
C1	-20.8620743
C2	152.6909087
Tr	15
Error^2	0.016

Table 36. Time-Temperature Sweep Test Data for the Second Replicate of the Recovered 15% RAP Binder

Temperature	Frequency	|G*|	Phase Angle
(°C)	(rad/sec)	Pa	(°)
10.00	188.51	1.01E+08	25.26
10.00	87.96	8.07E+07	27.06
10.00	40.84	6.36E+07	28.86
10.00	18.85	4.94E+07	30.71
10.00	8.80	3.78E+07	32.64
10.00	4.08	2.85E+07	34.73
10.00	1.88	2.10E+07	37
10.00	0.88	1.53E+07	39.4
10.00	0.63	1.33E+07	40.43
20.00	188.51	4.00E+07	33.84
20.00	87.96	2.97E+07	35.93
20.00	40.84	2.17E+07	38.06
20.00	18.85	1.55E+07	40.34
20.00	8.80	1.09E+07	42.72
20.00	4.08	7.52E+06	45.25
20.00	1.88	5.05E+06	47.94
20.00	0.88	3.32E+06	50.7
20.00	0.63	2.75E+06	51.98
30.00	188.51	1.23E+07	44.35
30.00	87.96	8.39E+06	46.61
30.00	40.84	5.58E+06	49.08
30.00	18.85	3.62E+06	51.67
30.00	8.80	2.31E+06	54.25
30.00	4.08	1.44E+06	56.89
30.00	1.88	8.72E+05	59.5
30.00	0.88	5.21E+05	62
30.00	0.63	4.13E+05	63.16
40.00	188.51	3.27E+06	55.92
40.00	87.96	2.00E+06	57.69
40.00	40.84	1.21E+06	59.96
40.00	18.85	7.13E+05	62.37
40.00	8.80	4.16E+05	64.66
40.00	4.08	2.36E+05	66.85
40.00	1.88	1.31E+05	69.06
40.00	0.88	73461	71.16
40.00	0.63	56188	72.08

54.00	188.51	5.23E+05	75.8
54.00	87.96	2.59E+05	72.56
54.00	40.84	1.40E+05	73
54.00	18.85	74164	74.28
54.00	8.80	39439	75.69
54.00	4.08	20461	77.47
54.00	1.88	10456	79.69
54.00	0.88	5273.6	81.43
54.00	0.63	3868.8	82.27

Table 37. CAM Model Fit Coefficients for the Second Replicate of the Recovered 15% RAP Binder

Master Curve Coefficients	Value
g	8.718435
$\mathbf{w_c}$	6.866539
k	0.193494
$\mathbf{m_e}$	0.934299
C1	-60.6298
C2	520.6429
Tr	15
Error^2	0.085

25% RAP

Table 38. Time-Temperature Sweep Test Data for the First Replicate of the Recovered 25% RAP Binder

Temperature	Frequency	|G*|	Phase Angle	log(|G*|)
(°C)	(rad/sec)	Pa	(°)	
10.00	188.51	126145000.00	22.22	8.10
10.00	87.96	103667000.00	23.74	8.02
10.00	40.84	84169500.00	25.24	7.93
10.00	18.85	67416500.00	26.78	7.83
10.00	8.80	53481000.00	28.37	7.73
10.00	4.08	41809500.00	30.08	7.62
10.00	1.88	32166000.00	31.95	7.51
10.00	0.88	24476000.00	33.91	7.39
10.00	0.63	21672500.00	34.83	7.34
20.00	188.51	54662500.00	29.63	7.74
20.00	87.96	42171500.00	31.34	7.63
20.00	40.84	32054000.00	33.10	7.51
20.00	18.85	23961000.00	34.97	7.38
20.00	8.80	17706500.00	36.93	7.25
20.00	4.08	12841500.00	39.03	7.11
20.00	1.88	9118050.00	41.32	6.96
20.00	0.88	6381650.00	43.72	6.80
20.00	0.63	5419500.00	44.81	6.73
30.00	188.51	19088500.00	38.90	7.28
30.00	87.96	13620500.00	40.82	7.13
30.00	40.84	9543500.00	43.00	6.98
30.00	18.85	6538300.00	45.27	6.82
30.00	8.80	4417050.00	47.64	6.65
30.00	4.08	2906000.00	50.09	6.46
30.00	1.88	1874600.00	52.65	6.27
30.00	0.88	1186950.00	55.20	6.07
30.00	0.63	963555.00	56.43	5.98
40.00	188.51	5588700.00	49.87	6.75
40.00	87.96	3618750.00	51.74	6.56
40.00	40.84	2308200.00	54.02	6.36
40.00	18.85	1435300.00	56.49	6.16
40.00	8.80	879975.00	58.90	5.94
40.00	4.08	523905.00	61.32	5.72
40.00	1.88	305500.00	63.72	5.49

40.00	0.88	175835.00	66.04	5.25
40.00	0.63	137340.00	67.02	5.14
54.00	188.51	931900.00	68.30	5.97
54.00	87.96	514045.00	66.81	5.71
54.00	40.84	292085.00	67.59	5.47
54.00	18.85	162020.00	69.40	5.21
54.00	8.80	89274.00	71.29	4.95
54.00	4.08	48579.00	73.21	4.69
54.00	1.88	25679.00	75.38	4.41
54.00	0.88	13430.50	77.45	4.13
54.00	0.63	10116.45	78.40	4.01

Table 39. CAM Model Fit Coefficients for the First Replicate of the Recovered 25% RAP Binder

Master Curve Coefficients	Value
g	8.77148
w_c	1.412556
k	0.173865
m_e	0.932517
C1	-70.0536
C2	582.9776
Tr	15
Error^2	0.063

Table 40. Time-Temperature Sweep Test Data for the Second Replicate of the Recovered 25% RAP Binder

Temperature	Frequency	|G*|	Phase Angle
(°C)	(rad/sec)	Pa	(°)
10.00	188.51	1.19E+08	22.51
10.00	87.96	9.76E+07	24.08
10.00	40.84	7.90E+07	25.64
10.00	18.85	6.31E+07	27.24
10.00	8.80	4.98E+07	28.9
10.00	4.08	3.88E+07	30.72
10.00	1.88	2.97E+07	32.65
10.00	0.88	2.25E+07	34.72
10.00	0.63	1.99E+07	35.76
20.00	188.51	5.20E+07	29.97
20.00	87.96	4.00E+07	31.76
20.00	40.84	3.03E+07	33.62
20.00	18.85	2.25E+07	35.61
20.00	8.80	1.65E+07	37.7
20.00	4.08	1.19E+07	39.95
20.00	1.88	8.38E+06	42.41
20.00	0.88	5.81E+06	44.98
20.00	0.63	4.91E+06	46.16
30.00	188.51	1.80E+07	39.34
30.00	87.96	1.28E+07	41.35
30.00	40.84	8.93E+06	43.64
30.00	18.85	6.08E+06	46
30.00	8.80	4.08E+06	48.47
30.00	4.08	2.67E+06	51.03
30.00	1.88	1.70E+06	53.68
30.00	0.88	1.07E+06	56.29
30.00	0.63	8.65E+05	57.56
40.00	188.51	5.33E+06	49.94
40.00	87.96	3.44E+06	51.85
40.00	40.84	2.20E+06	54.17
40.00	18.85	1.36E+06	56.66
40.00	8.80	8.35E+05	59.08
40.00	4.08	4.96E+05	61.46
40.00	1.88	2.89E+05	63.87
40.00	0.88	1.66E+05	66.14
40.00	0.63	1.30E+05	67.09

54.00	188.51	9.21E+05	65.81
54.00	87.96	5.00E+05	65.82
54.00	40.84	2.83E+05	67.14
54.00	18.85	1.57E+05	69.17
54.00	8.80	86359	71.16
54.00	4.08	47052	73.13
54.00	1.88	24846	75.3
54.00	0.88	13015	77.38
54.00	0.63	9820.9	78.29

Table 41. CAM Model Fit Coefficients for the Second Replicate of the Recovered 25% RAP Binder

Master Curve Coefficients	Value
g	8.717987
w_c	0.052769
k	0.153074
m_e	1.161679
C1	-23.4054
C2	169.243
Tr	15
Error^2	0.011

Multiple Stress Creep and Recovery

Control

Table 42. MSCR Test Results for the First Replicate of the Recovered Control Binder

Parameter	Value
R0.1	5.02
R3.2	0.78
Jnr 0.1	1.40
Jnr 3.2	1.54

Table 43. MSCR Test Results for the Second Replicate of the Recovered Control Binder

Parameter	Value
R0.1	4.89
R3.2	0.79
Jnr 0.1	1.39
Jnr 3.2	1.53

15% RAP

Table 44. MSCR Test Results for the First Replicate of the Recovered 15% RAP Binder

Parameter	Value
R0.1	8.63
R3.2	2.08
Jnr 0.1	1.07
Jnr 3.2	1.21

Table 45. MSCR test Results for the Second Replicate of the Recovered 15% RAP Binder

Parameter	Value
R0.1	9.36
R3.2	2.63
Jnr 0.1	0.91

Jnr 3.2	1.02

25% RAP

Table 46. MSCR Test Results for the First Replicate of the Recovered 25% RAP Binder

Parameter	Value
R0.1	17.29
R3.2	9.61
Jnr 0.1	0.34
Jnr 3.2	0.38

Table 47. MSCR Test Results for the Second Replicate of the Recovered 25% RAP Binder

Parameter	Value
R0.1	16.85
R3.2	9.96
Jnr 0.1	0.34
Jnr 3.2	0.36