Feasibility of Using Recycled Asphalt Pavements (RAP) in Hot Mix Asphalt for the City of Phoenix, Arizona

by

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ABSTRACT

Asphalt concrete is the most recycled material in the United States and its reclamation allows the positive reuse of the constituent aggregates and asphalt binder, contributing to the long-term sustainability of the transportation infrastructure; decreasing costs, and the total energy and greenhouse emissions embodied into new materials and infrastructure. Although the national trends in Reclaimed Asphalt Pavements (RAP) usage are encouraging, the environmental conditions in Phoenix, Arizona are extreme and needs further consideration.

The objective of this research study was to evaluate the viability of using RAP in future pavement maintenance and rehabilitation projects for the City. Agencies in the State of Arizona have been slow adopting the use of RAP as a regular practice. While the potential benefits are great, there is some concern on the impact to long-term pavement performance.

RAP millings were sampled from the city's stockpiles; processed RAP and virgin materials were provided by a local plant. Two asphalt binders were used: PG 70-10 and PG 64-16. RAP variability was evaluated by aggregate gradations; extracted and recovered binder was tested for properties and grading.

A mixture design procedure based on the City's specifications was defined to establish trial blends. RAP incorporation was based on national and local practices. Four different RAP contents were studied 10%, 15%, 25%, and 25% content with a softer binder, in addition to a control mix (0% RAP).

Performance tests included: dynamic modulus to evaluate stiffness; Flow Number, to assess susceptibility for permanent deformation (rutting); and Tensile Strength Ratio as a measure of susceptibility to moisture damage.

Binder testing showed very stiff recovered asphalts and variable contents with a reasonable variability on aggregate gradations. Performance test results showed slightly higher modulus as RAP content increases, showing a slight improvement related to rutting as well. For moisture damage potential, all mixtures performed well showing improvement for RAP mixtures in most cases.

Statistical analysis showed that 0%, 10%, 15% and 25% with softer binder do not present significant statistical difference among mixtures, indicating that moderate RAP contents are feasible to use within the City paving operations and will not affect greatly nor negatively the pavement performance.

DEDICATION

This thesis is dedicated to my wife, Paola Zabala, for her impulse, emotional support in all the stages and courage; to my children Natalia and Adrian, for their patience and sacrifice. Without their love, support and inspiration I would not be here.

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TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

CHAPTER Page

CHAPTER Page

LIST OF TABLES

Table Page

Table Page

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

1. Introduction

1.1. Background

Asphalt concrete is the most recycled material in the United States [1]. The reclamation of asphalt concrete for positive reuse of the constituent aggregates and asphalt binder begins with salvaging, pulverizing, or milling old asphalt pavements or retaining and stockpiling new mixture residual from plant start-up, shutdown, or rejection lots [2] [3]. According to the Asphalt Recycling an Reclaiming Association, hot recycling process is the most widely used asphalt recycling method in the world and consists of combining reclaimed asphalt pavements (RAP) with virgin aggregates and binder in a central plant to produce a recycled asphalt mixture. Many agencies use reclaimed asphalt pavements into newly constructed and rehabilitated roads because they view it as a key component to an overall approach of improving the long-term sustainability of transportation infrastructure. In addition to reducing the economic cost of new infrastructure, the positive reuse of RAP reduces demands for natural, non-renewable resources and thus reduces the need to manufacture, extract, and transport raw materials thereby reducing the total energy and greenhouse gas emissions embodied into new infrastructure.

While the potential for positive benefits is great, recycling old pavements into new ones carries some concern on the impact to long-term performance of the roads. Shorter lifespans for pavements incorporating RAP could negate any short term initial benefits that are derived from its use. These concerns are not insurmountable, and according to a survey conducted by the National Asphalt Paving Association (NAPA) using 214 companies/branches (1,119 plants) from 48 states, the percentage of producers using RAP has increased from 96 percent in 2009 to 99 percent in 2015. RAP usage during 2015 is estimated to have reduced the need for 3.7 million tons (21 million barrels) of asphalt binder and nearly 70.5 million tons of aggregate [2]. Nationally, the average estimated percent RAP used in all mixes has increased from 15.6 percent in 2009 to 20.4 percent in 2014. As agencies and companies are becoming more confident reaching acceptable performance with these type of mixes, many have increased the maximum allowed RAP contents and limits now range from between 30% and 50% [3]. The Asphalt Pavement Alliance reports that close to 100 million tons of RAP are generated annually in the US and about 95% (95 million tons) are being reused/recycled [4]. In 2015, NAPA estimated that more than 74.2 million tons of RAP were used in new pavements, saving taxpayers more than $2.6 billion, compared to the cost of raw materials [2]. The asphalt and aggregate components of an asphalt mix represent the greatest proportion of the cost of pavement construction [5]. The combined saving of asphalt binder and aggregate by using RAP in asphalt mixes purportedly keeps pavement construction costs low and allows owners to achieve greater roadway maintenance and construction activities within limited budgets [2].

According to NAPA, the use of recycled materials in asphalt pavements saves about 50 million cubic yards of landfill space each year [1].

Although the national trends in RAP usage are encouraging, the conditions in Phoenix, Arizona are extreme and therefore more careful study of this issue is warranted. The asphalt binder used in Phoenix has a naturally higher modulus to account for the high temperatures within the City, and these high temperatures can also promote even greater stiffening and embrittlement than other places in the country. The research presented in this study investigates the City of Phoenix RAP materials stream and develops procedures that permit the most advantageous use of RAP into the City's roadway building, rehabilitation, and maintenance activities.

The City of Phoenix Public Works in conjunction with the Resource Innovation and Solutions Network (RISN) program at Global Sustainability Solutions Services, part of the Rob and Melani Walton Sustainability Solutions Initiatives at the Julie Ann Wrigley Global Institute of Sustainability at Arizona State University (ASU), proposed a project to conduct research on the reuse of Reclaimed Asphalt Pavements (RAP) in the City's pavement rehabilitation programs. The project would evaluate the viability of using RAP in future pavement maintenance and rehabilitation projects; adding another potential important piece to City's already growing program of becoming a sustainability leader in the region. An eight-month study was defined for the project, where Public Works provided the funding and RAP material; the Engineering Materials Laboratory of the City of Phoenix provided the liaison between the project and the City; RISN was responsible for project management. Research, sampling, and testing was performed by ASU's School of Sustainable Engineering and the Built Environment. The research project is presented in this thesis.

1.2. Study Objective

The main objective of this study is to provide a technical criterion on the viability of reclaimed asphalt as a source material that can be diverted from the landfill to future construction and maintenance pavement projects within the City of Phoenix. To achieve this goal, the study focuses on evaluating the properties of RAP, the extracted and recovered binders to assess material variability, and also on performance testing and comparison of the properties of asphalt mixtures including different percentages of RAP.

1.3. Scope of Work

The scope of work included literature review on available practices involving RAP; sample identification; development of mix design procedure including RAP gradations, binder content and characterization (from extraction and recovery of RAP binder), and recommendation of RAP % in the mix; it also included performance-based testing on design trial blends to evaluate mixtures for optimum properties.

Based on the City's specifications the study was limited to one asphalt binder PG 70-10, but an additional effort was conducted to evaluate a higher RAP content of 25% using a softer binder PG 64-16. Lower RAP contents were preferred by the City (0%, 10%, and 15%) and for research purposes and additional mix with a higher RAP content was evaluated with both binders (25%).

RAP material variability study was limited to one storage location owned by the City. For mix design and performance testing, virgin aggregates and RAP were limited to one source (Southwest Asphalt plant from El Mirage), which is one of the City's approved hot mix asphalt providers. Only one filler type was used (lime). Binder characterization and mix design was defined under Superpave methodology, following the City's specifications. Mixture performance testing was limited to dynamic modulus, to evaluate the stiffness of the material; flow number, to evaluate the potential for permanent deformation; and tensile strength ratio determined by the indirect tensile test, to evaluate the susceptibility of moisture damage.

1.4. Report Organization

This report is divided into six chapters. Chapter 1 provides the background, research objective and scope of work. Chapter 2 summarizes the literature review on RAP and the results of a survey on current practices from local agencies that support the current study. Chapter 3 provides information about the material sampling process, study location, RAP and binder characterization and grading. Chapter 4 presents information about the material and the mix design process. Chapter 5 presents the results and analysis of the performance testing. Chapter 6 presents the summary of conclusions and recommendations of the present study. The Appendixes present all the complementary information that support the calculations, procedures and outputs.

2. Literature Review

2.1. RAP Background

The use of Reclaimed Asphalt Pavements (RAP) involves reprocessing RAP aggregates and binder along with new materials to yield asphalt mixtures that meet general specifications [6]. The asphalt and aggregate components of an asphalt mix represent the greatest proportion of the cost of pavement construction [5].

The Asphalt Recycling and Reclaiming Association categorizes recycling techniques in five broad classifications: Hot Recycling, Cold Planning or Milling, Hot In-place Recycling, Cold Recycling, and Full Depth Reclamation [4]. All the information presented in this document is dedicated to Hot Recycling, which is the conventional and most common process [7] where RAP is combined with virgin aggregates and binder (and/or recycling agents) in a plant to produce Hot Mix Asphalt (HMA). Heat transfer method is used to soften the RAP material to permit blending with the virgin aggregates and the new asphalt binder. In this method batch or drum mix plants can be used and might need some special modifications to work properly [4]. One of the primary distinguishing feature of this process is that RAP can be stockpiled and reserved as any other aggregate, being able to be crushed, screened, and stockpiled to be used when required.

While the view of RAP as a potentially valuable commodity is not new (the earliest notions of its use date to 1915), the current state of the art and practice with this material has been largely shaped by efforts since the early 1970's when the oil embargo first led to extremely high asphalt prices [3]. After this event and through the 1980's, asphalt mixture specifications with RAP advanced significantly and many agencies (including the City of Phoenix) rushed to incorporate the materials into their practices [3]. Agency experiences were mixed with some showing positive benefits and others experiencing high profile failures, moratoriums, and ultimate abandoning of the technology. However, many agencies persisted and after more than 20 years of trial and error, best practices were identified and a more consistent performance has been observed [[5], [8]-9]. Although the potential benefits of RAP few state agencies currently use more than 25% RAP (high RAP) [9]. ADOT allows 15 to 20% (surface courses) and 25 percent (intermediate or base courses) of some new pavements to be made up of reclaimed material [10].

Even though many different means of recycling asphalt concrete mixtures exist, the most common use of RAP in asphalt concrete mixtures is hot-central plant recycling [7]. In this process, an existing roadway is first milled using heavy equipment. The millings are transported to a centralized facility (such as an asphalt concrete plant) where they are first stored (Figure 2-1) and then processed (Figure 2-2) [11] [4]. Depending on the nature of the millings this processing may involve inventorying the relevant characteristics (amount of asphalt binder in the RAP, modulus and viscosity of the RAP asphalt binder, sizes of aggregate, and other mass/volume characteristics relevant to mixture engineering), crushing and/or separation of the RAP based on the size of the particles, and stockpiling [9] [11]. Processed materials are stockpiled at the central facilities and then fed into the plant’s mixing drum, along with new aggregate and fresh asphalt binder at predetermined rates [12]. During the mixing process, the asphalt binder that is on the RAP materials will partially or entirely re-liquefy and blend with the new asphalt and new aggregates. Engineers account for this full or partial blending when determining the proportions of RAP, new aggregate, and new asphalt to be used with the mixture. If the asphalt binder in the RAP is too stiff or brittle it may not mix well and/or be prone to cracking. Engineers consider this possibility and may adjust the quantity of RAP in the mixture or the amount of new, more flexible asphalt binder in the system, or may add chemical modifiers to facilitate better blending [12] [13]. These decisions are made well in advance of project construction and involve several steps of analytical and experimental evaluation of the available materials. Once the mixture design process is complete and the mixture is produced, the materials are transported and constructed like any asphalt concrete mixture.

Figure 2-1 RAP stockpile before processing

Figure 2-2 RAP processed millings (Southwest Asphalt Plant)

Once placed, engineers and roadway managers are principally concerned with how the mixtures that incorporate RAP perform. There are some general perceptions regarding RAP mixtures [9]:

- Rutting and other forms of permanent deformation decreases with the use of RAP or higher RAP contents because this material increases the overall mixture stiffness;
- Cracking potential (traffic related or reflective) increases, depending on the mixture location in the pavement structure because the mixture becomes more brittle;
- Thermal cracking potential increases because of the higher mixture stiffness.

Objective research shows that while the physical mechanisms that create these perceptions do exist, these performance perceptions are not always accurate [9] [3] [14]. Many of these differences between perception and real-world performance can be related to local practices, specific material streams, variability in either practices or materials, and applications where RAP mixtures are used. Despite these concerns, national, regional, and state research to consolidate best practices have led many state agencies to increase the maximum allowable RAP contents in asphalt mixes [15] [9] [13]. However, few if any of these states experience the extreme conditions encountered in Phoenix [13].

2.2. RAP Properties

RAP can be obtained from salvaged, pulverized, broken or demolished old asphalt pavements, milling of existing pavement wearing courses, and fresh mixtures residual from plant start-up, shutdown, or rejected mixtures [9] [16], and can be used as an aggregate substitute and/or as an aggregate and asphalt binder replacement, that can be incorporated in granular bases/subbases, stabilized bases and wearing courses. After its service period, the properties of the mixture have changed, then to be reused in new mixtures it is important to determine its actual properties.

2.2.1. Asphalt

Usually for low RAP contents (10 – 20%) it is not necessary to do extraction, recovery, and testing of RAP binder properties, since the presence of the old, hardened RAP binder is not enough to change the final binder properties. For higher contents, old binder will have an important effect and determination of its properties will be needed [17].

Asphalt content is most frequently determined using the ignition oven method (AASHTO T308), or centrifuge and/or reflux solvent extraction (AASHTO T164). For the first, a correction factor may be necessary to account for non-asphalt material that also burns off or degrade and at the end of the procedure no binder is left. The second allows binder recovery for testing but requires the use of solvent (Trichloroethylene or npropyl bromide, toluene, methylene chloride, ethanol) to dissolve and remove the asphalt from the recycled materials, with the disadvantage of safety and environmental hazard [9].

Asphalt is extracted and recovered by either the Abson (AASHTO T170) method, where the solvent is boiled off and condensed back into liquid, leaving the binder behind [17]; or by the Rotavapor (ASTM D5404) method, where the chemicals mentioned before are used to dissolve the asphalt binder, then filtered to remove the fine particles, and finally is distilled to remove out the solvent [9]. Modified SHRP procedure (AASHTO TP2 modified) is a third method which result in less severe change to the binder properties and uses an extraction cylinder that rotates to mix the solvent with the mixture, which is then vacuumed, filtered, and extracted.

When higher RAP contents are to be used, blending charts must be constructed to evaluate the final blended binder grade. The extracted and recovered asphalt is used to determine its properties and performance grading (critical temperatures). The high critical high PG temperature is determined using the dynamic shear rheometer (DSR) (AASHTO T315) and to evaluate the binder properties at high, intermediate, and low temperatures by finding the shear modulus (G*) as well as the G*/sinδ parameter. The low critical PG temperature is determined using the bending beam rheometer (BBR) (AASHTO T313), using measurements of stiffness (s) and a rate of change in stiffness called m-value. Studies showed that G* increase with increasing RAP. RAP seems to have more influence on the upper and intermediate critical asphalt temperatures than the low, the upper critical temperature increases about twice as much as the lower critical temperature

[9]. Superpave system developed two types of binder aging tests: Short-term aging of binder is simulated by the rolling thin film oven (RTFO) (AASHTO T240) procedure and long-term aging by the pressure aging vessel (PAV) (AASTHO R28) procedure. DSR is performed on the original unaged (as-recovered) asphalt binder, and on the RTFO and PAV aged portion. BBR is performed on the aged RTFO and PAV binder [9].

Many studies showed that the use of RAP result in stiffer asphalt binders with a consequent improved rutting resistance and lower low temperature cracking resistance [18].

Specific gravity of the asphalt binder is typically assumed to be between 1.01 and 1.035 or the virgin asphalt specific gravity is used for the recycled material asphalt [9].

2.2.2. Aggregates

Aggregate consensus properties (coarse and fine aggregate angularity; flat and elongated particles; and clay content) and source properties (Toughness, Soundness, and Deleterious materials) are only occasionally determined, since most of the time the used RAP was subjected to these criteria when it was manufactured. Usually those properties are verified when more than about 30% fine RAP aggregate is used [9]. Consensus properties must be verified from the complete mixture gradation (virgin + RAP aggregates) [17].

Sand equivalent is usually waived since changes in aggregate properties after the extraction methods can influence the results [9].

Gradation of extracted RAP aggregates is the most frequently and routinely determined aggregate property and is made after the asphalt is removed either by ignition oven or solvent extraction. Ignition oven can cause some damage to the aggregate and gradations could be finer than those obtained with solvent extraction, also affecting the values of the specific gravity, showing higher values for the ignition oven samples [9]. Gradation is performed according to the standards: Mechanical Analysis of Extracted Aggregate (AASHTO T30) or Sieve Analysis of Fine and Coarse Aggregates (AASHTO T27) [17].

There is no specific method for determining specific gravity of RAP aggregate that could suit all materials across the US and local research must be made to adjust asphalt contents for mix designs [11]. Specific gravity of the aggregates is typically calculated using measured theoretical maximum specific gravity of the recycled material (prior to removing the asphalt), although, few agencies directly measure the fine and coarse aggregate specific gravity after either ignition oven or solvent extraction [9]. The extraction process can affect the specific gravity. One approach is to use the effective specific gravity of the RAP instead of the bulk specific gravity but is not recommendable because lead to error. A second approach consists in calculate bulk specific gravity based on the maximum theoretical specific gravity and assume a value for the absorption of the RAP aggregate, where success will be based on how well this last value was assumed [17].

2.2.3. RAP

RAP Moisture is eliminated during mix design in the laboratory when the material is heated up to reach the adequate mixing temperature. In the field, moisture must be evaluated constantly as with virgin aggregates to do the timely corrections [17].

2.3. Asphalt Mixture Design with RAP

Different design guides for RAP asphalt mixtures have been developed, only Superpave approach is included in the present review. The concepts cited here are the outcome of NCHRP Project 9-12 and from the current national practices.

2.3.1. Total asphalt content (TAC)

Total asphalt content is based on the virgin asphalt binder content and the RAP useful binder content within the mixture (contribution from 0% to 100%), where 0% or 100% is assuming that all or none ("black rock") of the RAP binder is useful for the mix, respectively. The real contribution is difficult to determine and some States assume certain values (e.g., 70 to 85%), defined as the asphalt availability factor from 0 to 1 (F_{RAP}). The total asphalt content is determined using the following expression:

$$\text{Total AC} = F_{RAP}\,(\text{RAP AC})\,(\text{RAP\% in the mix}) + \text{Virgin AC}$$

Recent research show that RAP mixtures performance is closely related to the percentage of virgin binder in the mix, and its amount can be controlled by the minimum Asphalt Binder Ratio (ABR), which is the ratio between the virgin asphalt content (%) and the total asphalt content (%). Some states specify limits for this value (e.g., 70%) and is function of the type of RAP, location in the pavement structure and virgin asphalt grade. In a similar way, some uses the maximum Recycled Binder Ratio (RBR), which is the ratio between the RAP asphalt content contribution and the total asphalt content, to limit the recycled asphalt in the mixture McDaniel et. al. conducted a study and found that most of time, RAP binder contribution is significant [9].

2.3.2. Virgin asphalt grade selection and RAP content

The virgin asphalt binder grade must be selected so that combined with the RAP binder, the final properties meet the specifications. Usually when low RAP contents are used (<15%) no change in the virgin binder grade is required. For RAP contents between 15 to 25% one binder grade is dropped, and for higher contents extraction, recovering and testing is required. The time and cost regarding this action discourage agencies from using more than 24% [9].

AASHTO M 323 Standard Specification allow the use of RAP and binder replacement in Superpave Volumetric Mix Design. The standard specifies a three-tier system. Binder grade selection might be adjusted according to the specification's guidelines (Table 2 of M323) which is shown in the table below [12].

Table 2-1 Binder Selection Guidelines for Reclaimed Asphalt Pavement (RAP) Mixtures

Recommended Virgin Asphalt Binder Grade	**RAP Percentage**
No change in binder selection	<15%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	15-25%
Follow recommendations from blending charts	>25%

NCHRP Project 9-12 conducted by R. McDaniel et. al. [13], performed three different studies: black rock, binder effects, and mixture effects; with three different binders from Florida, Connecticut and Arizona. In the black rock study, RAP practices were compared with two extreme cases: "black rock" case, where only RAP aggregate was blended with virgin binder and aggregates, assuming RAP contribution only as aggregate; and the "total blending" case, where RAP extracted and virgin binders were physically blended before blending with aggregates, assuming a total contribution from

RAP binder. The finding was that a low RAP contents (10%) there was no significant difference among all blending cases. At high RAP contents (40%), there were differences leading to conclude that RAP binder should be considered, confirming the three-tier system. The binder effect study concluded that linear blending equations are suitable to develop blending charts to determine RAP content and virgin binder grade. The mixture effects study it was concluded that higher RAP contents increase the mixture stiffness, supporting the concept that softer binder should be used with high RAP contents.

Based on those studies, a new three-tiered system was proposed, concluding that stiffer binders, as the ones from Arizona, have a greater effect on the blended asphalt binder grade, the higher the high grade of RAP binder, the smaller that the RAP percentage is allowed to use without applying a blending chart. The proposed three-tier system guidelines are shown in the table below.

Table 2-2 Binder Selection Guidelines for RAP Mixtures

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

Some agencies limit the percentage of RAP (usually less than 15%) so blending charts and additional testing is no longer required (low RAP). When RAP content is between 15% and 25%, some states follow the general recommendation of selecting one grade softer binder. In other cases, extracting, recovering, and testing is required in order to measure the recycled material properties to build blending charts [9].

ADOT specifies that when less than or equal to 15% RAP binder is used by weight of the total binder in the mix, no testing is required on the RAP binder properties during the mix design process. When more than 15% RAP binder is used, it must be extracted, recovered, and tested during the mix design process. Depending on the results of these tests, the grade of virgin binder supplied to the project may need to be different than the grade specified in the bid documents. A different virgin binder grade may be required to ensure the blend of virgin and RAP binder meets the grade specified in the bid documents. However, a change of only one virgin PG binder grade (6^{o}C on either or both the high and low temperatures) will be allowed from the specified for conventional mixtures [19].

2.3.3. Mix design

Virgin and RAP mixtures must meet the same specifications and the most common design method for both is Superpave® mix design [5]. The amount of RAP that can be used and other material-related limits may be different between Superpave and Marshall design because of the differing specification limits, like Superpave usually requires lower fines contents [17].

Superpave mix design process is basically the same as the conventional mix with a few differences to account for RAP inclusion. McDaniel and Anderson [17] detailed the differences as follows:

- RAP aggregate is treated like another stockpile for blending and weighing but must be heated gently to avoid changing the RAP binder properties.
- The RAP aggregate specific gravity must be estimated.
- The weight of the binder in the RAP must be accounted for when batching aggregate.
- The total asphalt content is reduced to compensate for the binder provided by the RAP.
- A change in virgin binder grade may be needed depending on the amount of RAP, desired final binder grade, and RAP binder grade.

Laboratory practices vary significantly and there are no standard procedures for drying, preparing, batching, sequence of material addition, preheating times, laboratory temperatures, mixing, compaction, and some of them seem no to replicate the conditions of typical plants [9].

Gradation requirements must be met by the final blend of virgin and RAP aggregates and the must pass between the control points and avoid the restricted zone, based on the 0.45 gradation power chart. Consensus properties must be met by the final aggregate blend as well. Additionally, the final aggregate and asphalt blend must meet the required volumetric properties (i.e., VMA, VFA, dust proportion, etc.) at 4% air voids [17].

Many agencies have developed own equations to calculate batch weights [9]. RAP is treated as any other aggregate stockpile. It is important to account for the weight of the binder present in the RAP when batching RAP aggregate, so the weight of RAP must be increased and the amount of added binder must decrease. Normally, the procedure consists on fractionating each aggregate stockpile into various sizes and then recombine them in the proper proportions, giving better control of the gradation [17]. Superpave method recommends that for aggregate gradations, at least three trial blends be evaluated [17]. To determine the optimum asphalt binder content, typical mix design use from three to five different asphalt contents applied on the final aggregate gradation [9].

RAP must be heated to be workable with the virgin aggregates and short periods are preferred and better, even though it must be thoroughly heated. Longer heating times have shown to change the RAP properties. There is no consensus in preheating time nor temperature, some agencies do not preheat recycled materials, others do with low temperatures than those required for virgin materials and some also combine and heat virgin and recycled materials together [9].

Short-term aging time and temperature is variable from 1.5, 4 and 15 ±3 hours, being 2 hours the typical value and from 60°C to 168°C (140°F to 335°F) [9].

Compacting N_{design} values for dense mixtures vary from 65 for most agencies to different number of gyrations based on traffic levels or positions in the pavement structure. Marshall mix designs are still used [9].

Volumetric properties as air voids, voids in aggregates and dust-to-asphalt ratio can be difficult to meet specially when percentage of RAP is above 25%. There is no a single trend about volumetric properties, many studies have reported contradictory results as decreases in air voids, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA) with increasing RAP percentages. Differences are most likely a function of factors such as gradations, effective asphalt content, additives, rather than simply the RAP percentage content [9].

ADOT specifies that before gradation and RAP binder content, the material must be dried at 140^{o}F. Higher temperatures are not recommended since it could soften the binder causing the RAP to break. Shaking time for sieving is limited to 5 minutes and ±15 seconds to avoid further breakdown. A correction factor for the RAP binder content is required for each stockpile. The correction factor is determined from the difference of the average binder contents obtained from the ignition furnace and the solvent extraction [19].

2.4. Performance testing

RAP sampling, testing and analysis are very important to manage the material and for assessing uniformity, especially when RAP contents increase [11]. Different methods and criteria for performance laboratory assessment are used among agencies, and there are no consistent practices for testing and evaluating asphalt mixes containing RAP.

Rutting resistance is evaluated most frequently either by Asphalt Pavement Analyzer or Hamburg loaded wheel. Less frequently and mainly for research purposes, mixture stiffness is evaluated either by resilient or dynamic modulus testing. Traffic-related, thermal, and reflective cracking potential can be evaluated by many test methods depending on the cracking type: bending beam fatigue, disc-shaped compact tension, indirect tension, overlay tester, repeated direct tension, semi-circular bend, simplified viscoelastic continuum damage, thermal stress restrained stress and uniaxial thermal stress and strain [9]. Rutting potential can also be evaluated by flow number test and moisture susceptibility by the tensile strength ratio test based on the indirect tension test.

Increasing RAP percentages can increase stiffness and tensile strength and decrease rutting potential. It also will increase the low temperature cracking potential. For intermediate temperatures, results showed mixed results. Care must be applied in the use of most rejuvenators, since they decrease stiffness, thereby increasing rutting potential and lowering critical low temperatures [9].

Higher RAP content mixtures tend to look dry and some agencies report having difficulties with dry mixes during construction and also presenting signs of early distresses, thus they found a way to counteract those effects by reducing the compacting levels and/or increasing the virgin asphalt percentage. Even though there is no standard definition of dry [9].

2.5. Testing Methods

2.5.1. *Dynamic Modulus*

One important parameter of HMA mixtures is stiffness and can be defined as a performance parameter that describes Hot Mix Asphalt stress – strain relationship, characterized by elastic or resilient modulus. Stiffness is sensitive to asphalt binder type, aggregate type, air void content and temperature. Asphalt concrete behaves as a Linear Viscoelastic material and creep, relaxation and temperature and rate/frequency of loading dependence are very useful parameters to predict pavement response. The dynamic modulus is a fundamental material property and conforms the linear viscoelastic testing of asphalt concrete. This parameter is fundamental to the analysis of pavement response to traffic loading and is a required input for higher design levels in the latest AASHTO Pavement ME Design software.

The test measures the recoverable strain and permanent deformation of the specimen under a continuous sinusoidal loading. The applied load varies and is usually applied in a haversine wave, which is the inverted cosine offset by half its amplitude. This test can also be able to measure the phase angle, which is defined as the interval between the peak applied stress and the peak resultant strain, which provides insight into viscous properties of the material. For linear viscoelastic materials, where stress – strain ratio is independent of the loading stress applied, this relationship is defined by a complex number called "complex modulus", that was defined by Witczak as E* [20]. The absolute value of the complex modulus, |E*|, is the resultant dynamic modulus, which is mathematically defined as the peak of maximum dynamic stress (σ_0) divided by the peak recoverable axial strain (ε_0). The complex modulus is defined below:

$$\left|E^*(\omega)\right| = \sqrt{\left(\frac{\sigma_0}{\varepsilon_0}\cos\phi\right)^2 + \left(\frac{\sigma_0}{\varepsilon_0}\sin\phi\right)^2} = \frac{\sigma_0}{\varepsilon_0} \qquad (2.1)$$

Where:

E* = Complex modulus or dynamic modulus

Φ = Phase angle (angle by which ε_0 lags behind σ_0)

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

ε_0 = peak amplitude of recoverable axial strain, either measured with strain gauges or calculated from displacements measured with linear variable displacement transducers (LVDTs)

As result of the Dynamic modulus test, the complex modulus for different frequencies and temperatures can be plotted conforming isothermal curves founded on the sigmoidal model. Based on those, master curves can be constructed for any data obtained from frequency sweeps, and the individual isothermal curves can be horizontally shifted (time – temperature superposition) to create a continuous curve based on a reference temperature by the so-called Shift Factor (a(t)). The amount of horizontal shift is called "time - temperature shift factor" and varies by temperature. The selection of the reference temperature is arbitrary but very important to properly use the curve.

The latest Dynamic Modulus test protocol was developed in Arizona State University under AASHTO TP62-03 and basically consists in applying a repeated axial cyclic load of fixed magnitude and cycle duration at different frequencies to a test specimen over a relatively short period. This test is carried out at up to five temperatures 14, 40, 70, 100, and 130°F (-10, 4.4, 21.1, 37.8, and 54.4°C), and up to six frequencies 25, 10, 5, 1, 0.5, 0.1 Hz for the development of master curves that are used in material characterization and performance analysis [20]. Dynamic modulus test correlates reasonably well with rutting measurements from pavements in service.

2.5.2. *Flow Number*

NCHRP Project 9-19, as described in the NCHRP 465 report, recommends the Flow Number (FN) test as a simple performance test for the evaluation of rutting in asphalt mixtures [21]. The FN test results have shown good correlation with rutting under various traffic levels on pavements. A significant parameter for the evaluation of rutting in the field is shear deformation in asphalt mixtures, and this value can be identified by the Flow Number test. This value is obtained from the Repeated Load Permanent Deformation (RLPD) lab test as outlined in AASHTO TP79 [22].

The flow number represents a measure of rutting potential and can be determined by applying a uniaxial compressive load, using a 0.1s haversine pulse with a 0.9 s of rest period, to a compacted lab specimen. The test is conducted by exposing the specimen to the repeated compressive load at a specific temperature, determined by the effective temperature of the location where the asphalt is to be placed. The number of cycles of the applied load is plotted against the cumulative permanent deformation (strain percent) and yields a graph with three distinct sections, a primary section that describes the shear deformation accumulated during compaction and initial traffic loads, a secondary section that mimics the behavior of the asphalt over the majority of the life span of a pavement, and a tertiary section that describes the point at which the threshold of shear deformation is overcome and rutting begins. The flow number is the cycle number that corresponds to the point where tertiary flow begins.

The test for flow number also yields more valuable information about an asphalt mix like the resilient modulus, which is a measure of the material strength and is often used similarly to Young’s modulus; the amount of resilient strain, which is the amount of recoverable axial strain experienced by the material during the rest period of the loading process, yielding to the elasticity of the sample and corresponds to the field performance of the asphalt. The permanent and recoverable strains measured from the flow number provide the strain ratio parameter, which gives an overall view of how the material will behave, taking into account the two ways that the material experiences. A higher strain ratio will show less recoverability, which can indicate more rutting potential in the field. The test for flow number is a valuable tool in simple performance testing of asphalt materials as it provides a great deal of information about the strength and performance of a complex material.

The methodology to determine the flow number is outlined in the NCHRP 9-19 report. The Francken model is used to determine the FN or tertiary flow. Nonlinear regression analysis is used to fit the model to the test data.

$$\varepsilon_p(N) = a \cdot N^b + c(e^{d \cdot N} - 1) \qquad (2.2)$$

Where:

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

N = Number of cycles

a, b, c, d = Regression coefficients

The intercept, a, represents the permanent strain at N = 1, and the slope, b, represents the rate of change in permanent strain as a function of the change in loading cycles (log(N)). An alternative form of the model used to characterize the permanent strain per load repetition (ε_{pn}) can be expressed by:

$$\frac{\partial \varepsilon_p}{\partial N} = \varepsilon_{pn} = \frac{\partial (aN^b)}{\partial N} \qquad (2.3)$$

$$\varepsilon_{pn} = abN^{(b-1)} \qquad (2.4)$$

Equation (2.2) is the model used to describe the behavior of deformation of the material under a certain number of cycles of the haversine applied load, giving the strain for each cycle of load. The first derivative of the permanent strain function will provide the slope of the tangent line to the function at some point N and shows whether a function is increasing or decreasing and by what rate the change is occurring. Zero slope indicates a local maximum or minimum is defined at that point or that a turning point was defined. A positive derivative signifies the function is increasing, and a negative derivative signifies the function is decreasing. The following equation show the first derivative of the strain model:

$$\frac{\partial \varepsilon p}{\partial N} = abN^{b-1} + cde^{dN} \quad (2.5)$$

The second derivate of the strain function shows where the Flow Number (inflection point) is given. If the second derivative is positive, it means that the first derivative is increasing, and that the slope of the tangent line to the function is increasing as N increases. Thus, the second derivative of the strain function will tell when N is a local maximum or minimum. The second derivative is shown in the following equation:

$$\frac{\partial^2 \varepsilon_p}{\partial N^2} = ab(b-1)N^{b-2} + cd^2e^{dN} \quad (2.6)$$

2.5.3. *Tensile Strength Ratio*

Moisture susceptibility is the primary cause for distress in HMA pavements. HMA mixtures may be considered susceptible to moisture if the internal asphalt binder-to-aggregate bond weakens in the presence of water and this results in stripping. Moisture damage is mainly due to moisture interaction between binder and aggregate [23]. This loss of bonding separates binder from aggregate causing stripping.

Tensile strength ratio is a performance test for analyzing the moisture damage potential of the HMA mix. The test also known as the modified Lottman test basically compares the indirect tensile strength test results of two samples, one dry and the other subjected to water/freeze/thaw cycle. This test is evaluated by performing ASTM D4867 or AASHTO T-283 test. City of Phoenix specifications indicate to use ASTM D4867 [24]. In this test, two sets of samples are tested for tensile strength test. One set is conditioned and other set is unconditioned. The average air voids in both sets should be about the same. The test method is intended to evaluate the effects of saturation and accelerated water conditioning with an optional freeze-thaw cycle of compacted HMA [25]. The strength loss is measured due to the conditioning of the sample. If the ratio of strengths for condition and unconditioned sample is less than 80% (75% for City of Phoenix specifications), the sample is moisture susceptible [26].

The stripping can be controlled by several methods. It may be reduced by selecting low porosity aggregates, controlling air void content, pre-treating aggregates and adding anti strip additives like chemicals and lime [23].

2.6. Stockpiling and Processing Practices

Material variability is one of the main concerns that avoid the increase in RAP usage, since the material can come from different sources and circumstances. Old pavement constituent materials, asphalt binder used, RAP aggregate gradations, dust content, and asphalt content vary because of the types of equipment used to crush and/or mill the old pavement, processing practices, pavement milling depths, asphalt layer thickness and the types of mixtures in each layer milled (dense-graded, open-graded, etc.). The maintenance history of the milled pavement is also a source of variability, since there might be a number of resurfaced coatings, patches, crack seals or previous seal coat applications.

Variability can be minimized by separating different materials and sources in different stockpiles, keeping track of the source, mix type, aggregate properties, asphalt content and applying suitable equipment and trained personnel to manage RAP stockpiles [9]. Typically, material properties such as asphalt content, gradation, specific gravity, and binder characteristics are very consistent when milled RAP comes from a single project and if the amount of material is significant, the best practice is to stockpile separately and minimize additional processing to avoid the increase of fine content (P_{200}) [11].

Fractionating RAP into two, or at most three sizes can help minimize material variability when higher percentages of RAP are used. Finer RAP fractions tend to have higher asphalt contents than coarser fractions but can also have high percentages of minus 0.075-mm material that can limit the percentage of RAP that can be used (i.e., specification limits on dust-to-asphalt ratio) [9].

ADOT specifies that when more than 15% RAP aggregate is used, by weight of the total aggregate in the mix, RAP must be processed into uniform coarse and fine stockpiles meeting the gradation requirements of the specifications, and such that there will be a minimum amount of fines [19].

Adequate stockpiling and processing techniques allow material from multiple sources to became very consistent. Inventory analysis helps in process decisions. Suitable stockpile practices are: layered stockpiling to minimize variations, avoid equipment over the stockpiles to minimize compaction and avoid pushing material over the edges to minimize segregation [11].

When higher RAP percentage is used, additional quality control testing must be conducted to manage RAP variability [9].

RAP scalping sieve sizes are typically 19 mm (3/4 in.), 12.5 mm (1/2 in.) and 14.3 mm (9/16 in.) and fractionating sieve sizes for coarse and fine RAP include 4.75 mm (No. 4), 9.5 mm (3⁄8 in.) and 2.36 mm (No. 8) [9].

Moisture control is one major concern that influence production rates and drying costs. Moisture sources could be from the rain, water used for processing, anti-sticking, dust control, etc. The equipment features, age and type of the plant, control the capability to remove moisture in the recycled materials. The type of RAP and the percentage that can be added to the mix is directly related to the ability of the plant to remove the moisture [9].

Sometimes when using more than 25% RAP, moisture reducing efforts include increasing plant temperatures, slowing down the production rates. Therefore, some useful plant modifications to increase the percentage of RAP used is the addition of an independent drying and preheating system [9].

Conical shaped stockpiles or covering can minimize moisture from the rain and snow, and also heating from the sun. Stockpiles should be placed over paved slope surfaces to drain water. Stockpiles must have height limitations to reduce potential of self-consolidation and heavy equipment over the stockpiles should be avoided since they can compact the material. Even though moisture contents could be minimized by covering the stockpiles, many agencies and contractors do not require the practice neither use it [9].

Quality control at the asphalt plant during production and placement involves using the ignition oven to control asphalt content, and washed aggregates gradations. Aggregate specific gravity is mostly determined using the theoretical maximum specific gravity from the RAP stockpile sample [9].

2.7. Pavement Performance

Literature shows that most states have increased the maximum allowable RAP contents in asphalt mixes, since best practices are followed and the confidence in the technique and the performance results is increasing. Ohio and Florida are two states with the lead in high RAP contents [3].

Agencies performance perceptions can be summarized in the following: Rutting decreases with the use of RAP or higher RAP contents because this material increase the overall mixture stiffness; Cracking potential (traffic related or reflective) increases, depending on the mixture location in the pavement structure; Thermal cracking potential increases due to higher mixture stiffness [9].

The National Center for Asphalt Technology (NCAT) documented about high RAP content experiments, where sections with 20% and 45% were constructed and evaluated. High RAP sections used different grades of binder ranging from PG 52-28 to PG 76-22 and after five years of heavy traffic, sections showed less than 5 mm of rutting. Raveling was consistent with binder grades where softer binders showed better performance. Low severity cracking was evident in all sections, presenting less with lower RAP content and stiffer binders. Despite of that IRI was not affected. The conclusion of these experiments was to use softer virgin binder grade for High RAP contents (>25%) and for low to moderate RAP content mixes (<25%) use the standard binder grade. An experiment conducted by the Mississippi DOT with 50% RAP and polymer-modified PG 76-22 binder showed less rutting and fatigue cracking than the control section and despite of the increased stiffness, the mixture showed equivalent cracking performance compared to the virgin mix test section [3]. NCAT test track determined that decreasing the upper PG temperature, reduce the impact of high RAP percentages on traffic-related cracking without a detrimental effect on rutting [9].

A survey based on the Long-Term Performance Pavements (LTPP) Study, with sections all over United States and Canada, reported similar performance between virgin pavement sections and sections with up to 30% RAP [5]. Literature also reported that after 5 and 10 years, mixes containing up to 30% RAP had comparable performance as the control sections (no RAP) almost half of the time, where no RAP sections performed better than RAP sections almost 30% of the time and inversely 20% of the time [9].

Hong et al. also investigated the LTPP-specific pavement studies test sections in Texas with 35% RAP. The performance monitoring period in Texas covered 16 years from 1991 to 2007, the high RAP sections were compared to virgin sections and the performance indicators included transverse cracking, rut depth, and ride quality (IRI). Overall, both types of sections had satisfactory performance over the period. Compared with the virgin pavement sections, high RAP sections had higher cracking amounts, less rut depth, and similar ride quality change over time. Based on this analysis it was concluded that pavements with 35% RAP, if designed properly, can perform well and as satisfactorily as a virgin pavement during a normal pavement life span [14].

In a similar study, the California Department of Transportation (Caltrans) performed a comparative analysis of 47 RAP sections and 7 other different treatments (located within a reasonable distance on the same route) in 3 different environmental zones. Caltrans allowed up to 15% RAP to be substituted for virgin aggregate. Comparisons were made for the following indices: in situ structural capacity, distress condition, roughness condition, and construction consistency. The long-term performance of RAP was found and expected to be comparable to the other treatments based on deterioration models [27].

Literature also reported that performance is closely related to construction difficulties since projects reporting related issues such as visible deleterious materials, oversized RAP, dry looking mixtures, low asphalt contents and mixture segregation showed early pavement distresses; the percentage of virgin asphalt in the mix; variations in the upper PG temperature reduced traffic related cracking without inducing rutting resistance [9].

Load-related longitudinal cracking can be reduced by applying a virgin asphalt with a reduced upper PG temperature [9]. Federal Highway Administration emphasizes that there are profuse technical studies that endorse that suitable specified and produced recycled HMA with RAP have an equivalent quality and structural performance, compared with conventional mixes, showing slowly rates of aging and more resistance to water, with comparable behavior to rutting, raveling, weathering and fatigue cracking [7].

2.8. Economics

The cost of raw materials had a fast growth over the past decade having a sensible impact on highway construction, affecting the capacity of transportation agencies to maintain their existing pavement system. In order to counteract this effect, many agencies increase the use of recycled materials in their pavements, being RAP the preferred alternative. This election is also chosen to be consistent with the impulse of using more sustainable construction practices in transportation infrastructure [3].

RAP can replace expensive virgin aggregates and asphalt binders, giving the most economical advantages in asphalt mixtures. Usage is optional and its use will depend on material availability, plant site, production capabilities and economic considerations [5].

Stabilization of unit prices is one important benefit that Agencies using RAP can accomplish even if cost of raw materials is constantly increasing. When RAP supply is sufficient, contractors can be more competitive, compensating the higher prices of virgin materials. The same road maintenance budget is more effective and have greater impact on users, by having more and high level-maintained roads translated to the reduce in expenses of taxpayers [3].

Material cost savings evaluated from the amount of virgin material saved by RAP replacement are shown in the literature. Using 20% to 50% RAP can save 20% to 50% when materials and construction costs were considered, representing savings about 1% of mixture cost for every 1% of RAP used (Kandhal and Mallick, 1997). Savings of 7% to 8% for 10% RAP, 15% for 20% RAP and 20% to 22% for 30% RAP (Vukosavlievic, 2006). 20% RAP can save about $42 million worth of asphalt per year (Ontario Hot Mix Producers Association, 2007). [9]

Agencies with a strong RAP history found that contractors involved in pavement rehabilitation are more cost-effective when the reclaimed material is considered within the cost of milling, allowing them to control and manage RAP qualities better, when the material becomes their property.

Higher RAP contents usage is currently being evaluated by many state transportation departments and contractors in a way that high quality material, well-performance pavement and economical savings could still be achieved. Some concerns are that contractor costs could increase because higher plant temperatures are needed to transfer heat from virgin to recycled materials, entailing the risk of increased wear and damage of the plant, shortening maintenance periods, damage to asphalt mix properties and out-of-specification mixture temperatures, and may finally offset the initial savings from the recycled material use [9].

RAP management based on data, inventory, disciplined processing, uniformity and quality, will maximize the return on materials, equipment and personnel investment [11].

According to the Arizona Department of Transportation (ADOT), 12% of asphalt mixtures were produced with RAP in the Phoenix area between 2010-2016, using 15% RAP. RAP binder savings are approximately $3 to $5 per ton of asphalt mixture, and about $1 to $3 per ton of aggregate depending on the amount of RAP used and the location of the source of virgin aggregate. ADOT estimates approximately $3.9 million dollars savings during the first year allowing RAP, and over $55 million since 2009 [28].

2.9. Area Practices

Research on available specifications and a survey of RAP usage on local Agencies were conducted (Survey questions presented on Appendix A). Overall, the State of Arizona and its municipality and county agencies, have been slow to adopt the use of RAP as regular practice. However, many agencies within the State have specifications in place and/or practices for using RAP materials. Practices of nearby agencies and organizations with respect to RAP usage are summarized in Table 2-3 and more detailed descriptions for certain select groups are shown below.

Table 2-3. Summary of Practices from Other Agencies

Agency	RAP Usage				Specifications
	Asphalt Concrete		Unbound Base	Other	
	Surface	Non-Surface			
City of Phoenix	No	No	Conditional	Dust control Dirt street stabilization	2015 City of Phoenix Supplement to 2015 MAG Uniform Standard Specifications [29]
City of Tucson	No	Yes	Yes	Dust control Shoulders Dirt roads	2014 PAG Standard Specifications [30]
Arizona Dept. of Trans. (ADOT)	Yes	Yes	Yes	Miscellaneous asphaltic concrete	ADOT's Policy and Procedure Directive No.20 for the use of RAP in asphaltic concrete [19]
Maricopa Assoc. of Gov. (MAG)	Yes	Yes	Yes	Shoulders Dirt roads	2017 Revision to the 2015 MAG Uniform Standard Specifications [31]
Pima Assoc. of Gov. (PAG)	Yes	Yes	Yes	----	2014 PAG Standard Specifications [30]
Maricopa Co. Dept. of Trans. (MCDOT)	No	Yes	Conditional	Shoulders Dirt roads	2017 Maricopa County DOT Supplement to the MAG Uniform Standard Specifications [32]
Pima Co. Dept. of Trans. (PCDOT)	Yes	Yes	Yes	Shoulders Dirt roads	2014 PAG Standard Specifications [30]
East Valley Asphalt Comm.	No	Yes	No	Structural backfill Dust control Dirt roads	2014 EVAC Hot Asphalt Mix Criteria [33]

Agency	RAP Usage				Specifications
	Asphalt Concrete		Unbound Base	Other	
	Surface	Non-Surface			
Apache Junction	No	No	Yes	Dirt road stabilization Shoulders on rural roads and urban arterials	No specifications
Mesa	No	Yes	Yes	Shoulders Backfills	2016 Amendments to MAG Uniform Standard Specifications [34] and EVAC [33]
Scottsdale	No	---	---	Dust control Dirt street stabilization Not for backfills	2015 City of Scottsdale Supplement to 2015 MAG Uniform Standard Specifications [35] and EVAC [33]
Chandler	---	---	---	Dust proofing	2016 Supplement to MAG Uniform Standard Specifications [36] and EVAC [33]
Gilbert	No	No	No	No	2015 Town of Gilbert Supplement to 2015 MAG Uniform Standard Specifications [37] and EVAC [33]
Queen Creek	No	No	Yes	Shoulders Dust control Dirt road stabilization	2017 Revision to the 2015 MAG Uniform Standard Specifications [31] and EVAC [33]

Agency	RAP Usage				Specifications
	Asphalt Concrete		Unbound Base	Other	
	Surface	Non-Surface			
Las Vegas (Nevada)	Yes	Yes	Yes	Structure granular backfill	Uniform Standard Specifications of RTCSNV [38]
Nevada Dept. of Trans. (NDOT)	Yes	Yes	Yes	Shouldering	2014 Nevada DOT Standard Specifications for Road and Bridge Construction [39]
Texas Dept. of Trans. (TXDOT)	Yes	Yes	Yes	Subgrade stabilization	2014 Texas DOT Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges [40]
New Mexico Dept. of Trans. (NMDOT)	Yes	Yes	Yes	Not for backfills	2014 New Mexico DOT Standard Specifications for Highway and Bridge Construction [41]
California Dept. of Trans. (Caltrans)	Yes	Yes	Yes	Shoulder backing	2015 California State Transportation Agency, Department of Transportation, Caltrans, 2015 [42]

- City of Phoenix

RAP usage in the City of Phoenix is largely based on the City's supplement to the 2015 Maricopa Association of Governments (MAG) Standard Specification [29]. Reclaimed asphalt pavement (RAP) is not allowed to be used in Asphalt Concrete and its use in other type of fill requires prior approval of the Engineer. RAP is not allowed to be used as base material without approval from the City of Phoenix Laboratory. Based on anecdotical information, the main use of RAP is for road dust control and dirt street stabilization.

- Arizona Department of Transportation (ADOT)

The Arizona DOT started to include RAP in their specifications for Hot Mix Asphalt (HMA) mixtures after August of 2009 without any restriction on the source of the material. The specifications were developed based on different project experiences and needs, and because experience showed engineering value. After 2009, approximately two-thirds of the HMA placed included RAP and now it is even more common. Projects in the Phoenix region use the least amount of RAP (12%) compared to 33% in Tucson and Prescott and 22% in Flagstaff [28].

Currently RAP is allowed in HMA, miscellaneous asphalt concrete, and aggregate bases. A maximum of 20% RAP aggregate or binder by weight of total mix is allowed in the surface (upper 2 in.) and a maximum of 25% is permitted in lower lifts (below 2 in.). Based on ADOT's information, 15% RAP was the common RAP aggregate and RAP binder content considered in most of their projects (63%), about 31% include 20% RAP aggregate and binder and one project used almost 25% RAP binder [28]. For the RAP, 100% of the material must pass the 1 1/4 in. sieve. In case that more than 15% RAP aggregate is used, it must be fractionated into coarse and fine stockpiles at the 3/8 in. and 3/4 in. sieves. When the RAP asphalt cement will constitute more than 15% of the total binder, it must be extracted, recovered, and tested [19].

According to ADOT, 12% of all tons of asphalt concrete were produced with RAP in the Phoenix area between 2010-2016, using 15% RAP. RAP binder savings are approximately $3 to $5 per ton of hot mix asphalt (HMA) and about $1 to $3 per ton of aggregate depending on the amount of RAP used and the location of the source of virgin aggregate. ADOT estimates approximately $3.9 million dollars savings during the first year allowing RAP and over $55 million since 2009 [28].

- Maricopa Association of Governments (MAG)

The 2017 Revision to the 2015 Edition of Uniform Standard Specifications and Details for Public Works Construction of MAG [31] states that RAP can be used as aggregate if it complies with the respective specifications regarding aggregates in general. The specifications also allow 100% RAP usage as base material and up to 30% contribution when used in base and intermediate asphalt courses. In surface courses RAP should be limited to 20% as aggregate and binder contribution. The specification for asphalt concrete also emphasize that if 15% RAP binder is used, the added virgin binder should meet the requirements for PG 70-10 binder and when higher RAP contents are used, the added virgin binder should be dropped one grade to a PG 64-16, unless testing indicates that the final blend meets the requirements for PG 70-10. The general requirement is that 100% of RAP must pass the 1 1/2 in. sieve.

- Pima Association of Governments (PAG)

As the Tucson area Metropolitan Planning Organization, PAG does not own, operate, or maintain any roadway assets and its role in relation to pavements has been focused on facilitating the collection and analysis of region wide pavement condition data (S. Sanford, personal communication, February 23, 2017). This Association does produce standards for the Pima area governments, and the last revision of the 2014 of the Standard Specifications and Details for Public Improvements, allows the use of RAP in asphaltic concrete and in aggregate base courses [30] limiting its content to 15% of the total weight of aggregate in the mix and by not more than 50% by weight or by volume of the blended material respectively.

- Maricopa County Department of Transportation (MCDOT)

Maricopa County DOT reported that RAP implementation on pavement structure layers is not common practice and that when this alternative is needed, MAG Specifications are followed (J. Shi, personal communication, February 27, 2017). This Agency has a recent supplement to the MAG Specifications published on January of 2017 where is emphasized the use of RAP for base materials only for roads that are classified as minor collector or local roads. In the case of asphalt concrete bases or intermediate courses of arterial streets, RAP aggregate or binder contribution shall not exceed 20%. For collector streets, the contribution is limited up to 30%. The use of RAP in the surface courses in not allowed for any roadway classifications [32]. The Agency conveyed that RAP material is frequently used in shoulders and on dirt roads, mostly for dust suppression and dirt control.

- East Valley Asphalt Committee (EVAC)

This committee comprised of members from the Cities of Chandler, Mesa, Scottsdale, Tempe and the Towns of Gilbert and Queen Creek, was developed to standardize hot asphalt mix design criteria for the cities in Eastern Maricopa County considering the materials available and practices followed in these areas. In 2014, the Committee referenced the MAG Uniform Standard Specifications and an Asphalt Concrete Specification was standardized, highlighting that recycled asphalt mixes were not part of their approved list, giving the option to each agency to study and approve this type of mixes as appropriate [33].

Based on anecdotical information, RAP is not currently allowed because there is the perception that the variability of the material, could give inconsistent and variable results. Based on their experiences, the costs of including RAP into the mixes are closer to those for virgin materials, making the idea of incorporating one more ingredient into the mix, less attractive. However, strict adherence to EVAC guidelines is not required and some cities in eastern Maricopa county have elected to use RAP in specific applications. Some contractors and cities have RAP stockpiles that are being used mostly used for shoulders, sidewalks, dust suppression and for alleyways and personal driveways. Some examples include:

City of Mesa - Currently the stockpiled millings are crushed for various purposes and are offered to the contractors for use in backfills, shoulders and as aggregate base courses. There are also pilot projects to use crushed RAP to replace aggregate in fracture aggregate surface treatments. The City is not currently using RAP in asphalt mixtures and their concerns are based on variability of the stockpiles and binder, as well as performance of pavements. At present, the City follows MAG and EVAC specifications and do not have specific and detailed standards about RAP usage, although there is interest in implement RAP as part as their residential street maintenance program.

City of Chandler – Has used screened and processed RAP with an asphalt emulsion for dust proofing in low traffic areas. RAP is also used for alleyways reconstruction.

City of Apache Junction – Uses RAP as dust stabilizer and to restore shoulders on rural roads and urban arterials. After appropriate processing, RAP is also used as a base material. At present, the City has not yet used RAP for any paving or maintenance operations. The main concerns are rounded in performance of pavements and detailed specifications about RAP usage were not developed yet.

Town of Queen Creek – Supporting Maricopa County's clean air initiative, Running Out of Air, this Town has used RAP for dust control and to stabilize unpaved shoulders and roads. The City pavements are relatively new and consequently the use of the material in surface or intermediate courses was not needed so far.

- Pima County Department of Transportation (PCDOT)

Pima County DOT follows the 2014 PAG Standard Specifications for Public Improvements, and the last revision allows the use of RAP in asphaltic concrete and in aggregate base courses [30] limiting its content to 15% of the total weight of aggregate in the asphalt concrete mixture and by not more than 50% by weight or by volume on unbound or aggregate base courses.

Pima County DOT reported that RAP implementation on surface courses is not the preferred practice, since there is the belief that to prolong the service life and retard the maintenance of pavements, new binder should be used. Even tough, the use of low RAP contents up to 15% are used with the additional benefits of avoiding further binder testing and simplify mixture design. RAP is commonly used in 1 in. mixture leveling (base) courses and in 1/2" mixture surface courses, except when terminal blend plus polymers are used. It is also allowed for shoulders, dirt control and in some minor fills (J. Norton, personal communication, May 8, 2017).

- City of Tucson

City of Tucson reported that RAP usage on pavement structure layers is not a common practice, even though RAP is permitted. RAP is allowed as aggregate for unbound base courses. In the case of asphalt concrete bases or intermediate courses, RAP contribution shall not exceed 15%. The use of RAP in the surface courses in not allowed. The Agency conveyed that RAP material is frequently used in shoulders, alleyways, dust control and on dirt roads by their maintenance unit. (L. Peterson, personal communication, September 15, 2017).

- Nevada Department of Transportation (NDOT) and the City of Las Vegas

The 2014 Nevada DOT Standard Specifications for Road and Bridge Construction [39] defines that 100% of RAP should pass the 1/2 in. sieve, allowing RAP for shouldering or base and to replace 5 to 15% by mass of the total aggregate for dense-graded bituminous pavement (plant-mix bituminous surface).

The City of Las Vegas, with similar climatic conditions as Phoenix, is under the authority of Clark County DOT which follows the specifications of the Regional Transportation Commission of Southern Nevada (RTCSNV). The last approved revision of the Uniform Standard Specifications of RTCSNV [38] states that 100% of RAP should pass the 1 1/2 in. sieve and allows contractors to substitute conventional base course or surface course mixtures with mixtures containing up to 15% RAP. Mixtures with more than 15% RAP could be allowed if the resultant mixture meets the specified mix criteria (PG 76-22 or PG 64-22). As aggregate base material, RAP is permitted up to 30% and it can be used as structure granular backfill also.

- Texas Department of Transportation (TxDOT)

The 2014 Texas DOT Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges [40] (least specifications) defines that the 100% of RAP should pass the 2-in. sieve, allowing its incorporation in different types of materials based on the percentage by weight, the maximum ratio of recycled binder to total binder and in function of fractionated or unfractionated material. When it is fractionated, a minimum of one coarse and one fine stockpile must be placed and are divided at the 3/8 in. or 1/2 in. screen. RAP is not permitted for thin overlay mixes and for retaining walls backfill, but it is accepted for base courses (maximum to 20%), non-surface asphalt treatments (maximum to 20% of unfractionated RAP or 30% fractionated and 40% maximum binder ratio), dense graded HMA, and Superpave mixtures. TXDOT also allows unfractionated RAP in the surface, intermediate and base courses (up to 10%) and fractionated RAP (maximum 20% in the surface, 25% - 30% in the intermediate and 30%

- 40% in the base). Only the coarse portion of RAP is allowed for permeable friction courses and stone matrix asphalt up to 10% and 15% - 20% respectively.

- New Mexico Department of Transportation (NMDOT)

The 2014 New Mexico DOT Standard Specifications for Highway and Bridge Construction [41] specifies that 100% processed RAP should pass the 1 1/2 in. sieve, allowing RAP in the base course (maximum 50%), in miscellaneous paving (up to 35%), in Superpave HMA (no changes in asphalt binder required if a maximum of 15% by weight is used) and in warm mix asphalt (WMA). For quantities greater than 15% to 25% the asphalt grade should be lowered by one grade or the grade must be verified by extracting, recovering, and testing the RAP asphalt. For quantities greater than 25% to 35% only the last option can be applied. No more than 35% of RAP is allowed and it cannot be allowed as select backfill material. For HMA mixes containing more than 15%, adequate stockpile management is required as well as fractionation into a minimum of two stockpiles.

- California Department of Transportation (Caltrans)

2015 California State Transportation Agency, Department of Transportation, Caltrans, 2015 [42] specifications define that 100% processed RAP should pass the 1 ½" sieve and allow RAP in shoulder backing, aggregate subbases and bases, and lean concrete bases. In Hot Mix Asphalt mixtures, the maximum allowed binder replacement is 25% in the upper 0.2 foot, exclusive of the Open Graded Friction Course and 40% below. For binder replacement, less than or equal to 25% of the optimum binder content is permitted. RAP can be conformed from multiple sources, but all the material must be thoroughly blended before fractionating. If RAP aggregate substitution is less or equal to 15%, fractionation is not required. If substitution is greater than 15%, RAP must be fractionated into coarse and fine fractions by 3/8” sieve. In Asphalt Treated Permeable Bases RAP is not allowed.

3. RAP Stockpile Sampling and Characterization

3.1. Introduction

To study the feasibility for the City of Phoenix to use reclaimed asphalt pavements (RAP) on future maintenance and rehabilitation operations, the nature of the available materials needs to be evaluated. The relevant characteristics of RAP include the aggregate gradation, asphalt binder content, rheology of the RAP binder, and the manufactured properties of the RAP aggregates.

In the case of the City of Phoenix, millings that come from repairs and rehabilitation works are stockpiled in the Closed Del Rio Landfill (1150 E. Elwood Street) and at the North Service Center (138 E. Union Hills Drive). Although some general guidelines are in place, there is no strategy in place that links the storage location to the type of millings taken, which creates a very heterogenous source of recovered material. For example, any given location in the storage yard may contain paving materials from different streets or projects, plant waste, small milling projects, rejected asphalt mixes, rubbles from demolition of roads or parking lots, materials from different pavements and service periods, surface treatments, overlays, etc.

The variability of RAP material is one of the main concerns when it comes to implementing this alternative, both when making and designing the mixtures, as well as when evaluating the performance of pavements, discouraging the use of higher RAP contents. Phase I of the project includes the evaluation of variability and/or consistency of the stockpiled City of Phoenix RAP material resources. The goal of characterizing the variability/consistency in these materials is course to provide a complete analysis of the location, availability, and composition for future use in maintenance and rehabilitation operations.

The present chapter describes the assessment of the RAP material from the Del Rio Landfill. Evaluation consists of comparisons of the visual appearance of the RAP materials across the stockpile, the gradation and asphalt content of the RAP, the gradation of the aggregate within the RAP, and performance grading of the recovered asphalt. Note that in this chapter units are presented in the form that is common for the test and parameter being described. Where no common units exist, United States customary units are used.

3.2. RAP Sampling

To analyze the consistency and variability of the available RAP material and to evaluate its properties, a series of experiments were conducted on the RAP, the extracted aggregates, and the extracted asphalt binder. The purpose of the procedure was to evaluate RAP gradations, and to characterize the recovered asphalt binders, as well as the gradation and features of the extracted aggregates from different samples.

3.2.1. General Description of the Study Location

The study location for assessing the City of Phoenix RAP stockpiles was the closed Del Rio Landfill at 1150 East Elwood Street. The area immerses inside Del Rio Area boundaries, that includes land between 7th Avenue and 16th Street, from the Salt River south to Broadway Road, located within the South Mountain Village.

The Closed Del Rio Landfill is under the management of the Public Works Department of the City of Phoenix, which currently owns the site, being one of the two locations where the City stores the asphalt millings. The Streets Department manages the piles and uses a portion of this landfill to store the millings.

The location has an approximate area of 93 acres, classified as zone type A-2 which correspond to Industrial area. About 73 acres of the site were used previously for municipal solid waste operations. The site is located very close to downtown Phoenix and is interconnected by the local transportation system with access to interstate 17 and to Sky Harbor Airport.

A photograph of the overall stockpile condition is shown in Figure 3-1 and a close-up of a typical location is shown in Figure 3-2. From this close-up image, it can be seen a variety of particle sizes, material pieces, and the presence of deleterious materials like road paint residue. To address and reduce the impact of these heterogeneities, agencies generally follow a set of stockpile management practices, which was discussed briefly in Chapter 2.

Figure 3-1 General view of a single RAP stockpile

Figure 3-2 Typical unprocessed millings of RAP material (card in lower left corner is approximately 3 inches long and 2 inches wide)

The relief of the area is practically flat and is located very close to the river bank. Approximately 9 acres (41.000 square yards) of the landfill are currently occupied by RAP material coming from different roads and projects within the City of Phoenix area. The material is concentrated in a main large stockpile of approximately 10 feet height (3 meters), with some smaller piles of material surrounding it. Figure 3-3 shows an aerial view of the landfill. Photo records show that RAP stockpiles are in this site from the early 90’s and based on the information provided by the landfill management, asphalt pavement millings are stockpiled and sporadically used for dust control on unpaved roads.

Figure 3-3 General sight of the stockpile site in Del Rio Landfill

Based on the shape of the overall stockpile it appears that new material is deposited on the top of the stockpile and is also removed from the top when needed (see Figure 3-4), leaving the old material laying in the lower layers and being compacted by self-weight and by machinery operations. The material in the lower layers is very consolidated and appreciably stiff. The surface shows a consolidated and stiff crust as well. The top of the pile is topped by smaller discharges of material made by dump trucks.

Figure 3-4 Small piles of RAP millings over the top of the main RAP stockpile

Figure 3-5 Areas for RAP volume estimation of the main stockpile

The following shows an estimation of the available RAP material in the landfill, taking into consideration only the main stockpile. Figure 3-5 Areas for RAP volume estimation of the main stockpile Figure 3-5 shows an approximate area of 115.000 ft2 within the white polygon and an area of approximately 38.000 ft2 delimited by the yellow polygon, which is approximately the sector with constant height of about 10 feet. The rest of the area inside of the white polygon after subtracting the previous one (77.000 ft2), is the sector where the relief goes from the level of natural soil up to 10 feet, with an average height of 5 feet. The final approximate volume of RAP material is 765.000 ft3 (28.300 yd3), which considering an average RAP unit weight of 130 lb./ft3 (typical values range between 120 and 140 lb./ft3) gives a total of 99.45x106 lb. of RAP.

To have a rough view of the amount of the material stockpiled, if we consider 15% RAP usage for a base course of 12 ft. wide and 6 inches thickness, with an asphalt concrete density of 145 lb./ ft3, the stockpiled RAP could be used for approximately 144 miles.

3.2.2. Sampling Operations

To have an overall look of the site, a first reconnaissance visit was carried out on February 27th, 2017, in this opportunity one sample of about 198 lb. (90 kg) was taken. Due to the consolidated material, it was difficult to sample the material with a shovel and the sampling was reduced to collect loose material from the segregated sides of the stockpile. For labeling purposes, this sample was called S-6.

To have a more representative sample from the core of the stockpile, machine excavation was needed. Machinery use was requested but there were difficulties to provide this equipment on site. Based on this, it was decided to sample material from the non-consolidated stockpiles at the surface.

The first sampling activity was done on March 17th of 2017. Five samples of about 132 lb. (60 kg) each were taken randomly from different locations of the pile. The location of the samples is shown in Figure 3-6. Collection of representative RAP material samples from each of the randomly selected locations was conducted using Arizona Department of Transportation method ARIZ 105f [43]. In short, this method involves first removing the top 6 inches (150 mm) of material from the surface and with the use of a square pointed shovel, taking random samples from the stockpile. For each location, the material was shoveled into cloth bags, labeled, and then transported to Arizona State University (ASU) for further testing. Once at ASU, samples were reduced to a representative and appropriate quantity for extraction/recovery, gradation, and specific gravity testing using AASHTO T 248 [44].

Figure 3-6 RAP stockpile sampling locations

3.2.3. Sampling Locations

A total of six locations were sampled from the Del Rio landfill (designated as S-1 through S-6) and another sample was taken from the Southwest Asphalt plant from El Mirage in the Glendale area (designated as SW-1). This plant is one of the approved asphalt mix providers for the City of Phoenix. The present section describes these RAP sources, the conditions when sampled, and their visual appearance.

Stockpile Sample S-1

A basic overview of location one reveals small piles of material containing generally small agglomerates of millings less than 1 1/4-inch in size. Visual inspection also finds considerable fines and dust and a few random pieces of larger sizes. The color of the material fluctuates within the range of brown tones, where the lack of black tones could possible denote a very old material with high dust contents (Figure 3-7).

Figure 3-7 Detail of RAP sample S-1

Stockpile Sample S-2

As seen in Figure 3-8, small piles of material characterize the location showing less presence of fines than the previous stockpile and with apparently coarser particles. After the removal of the surface material, the coloration ranges between brown and black tones, denoting higher presence of binder.

Figure 3-8 Detail of RAP sample S-2

Stockpile Sample S-3

The material in this location show a mix of larger agglomerations between 1 inch and 3 inches and up to 12 inches, apparent coarser particles and some fines (see Figure 3-9). The coloration ranges mostly between grey and black tones, denoting higher presence of binder.

Figure 3-9 Detail of RAP sample S-3.

Stockpile Sample S-4

Figure 3-10 shows the condition of sampling location four. Visual inspection shows less apparent coarser particles. The coloration ranges between brown and black tones, and the consolidation of the material denotes a higher presence of binder.

Figure 3-10 Detail of RAP sample S-4

Stockpile Sample S-5

Location 5 is outside the main stockpile and forms part of a smaller pile along the side of the road on the northern side of the main stockpile. In general, the material is made up of small agglomerations of millings and shows fines and dust. The color of the material fluctuates within the range of brown tones, where the lack of black tones could possible denote a very old material with high dust contents.

Figure 3-11 Detail of RAP sample S-5

Stockpile Sample S-6

Location 6 is situated along the northeast edge of the stockpile and comes from the lateral edge of the stockpile. The sample was taken from the loose accumulated side material at the bottom of the slope. In general, it presents a high content of fines and dust. The color fluctuates within the range of brown tones, almost appearing as soil. Possibly the material is made up by segregated and erode particles subjected to sun, wind, and rain, showing less binder content. Figure 3-12 shows the described features.

Figure 3-12 Detail of RAP sample S-6

Southwest Asphalt Plant RAP stockpiles SW-1

While the study of variability was conducted, it was defined that the mix design should be accomplished with the available material that more likely could be incorporated into the City of Phoenix projects. Considering that Southwest Asphalt is one of the City Materials Laboratory approved plants, one additional RAP sample was obtained from the plant's processed RAP stockpile for testing. RAP material and virgin aggregates for mix design and specimen testing were sampled from the El Mirage Southwest Asphalt plant.

The plant has one large stockpile of asphalt pavement millings which is continuously processed to incorporate low percentages of RAP (up to 15%) into mixes where it is allowed by the specifications (e.g., for the Arizona Department of Transportation). The RAP millings stockpile is showed on Figure 3-13 and there can be noted large agglomerations and different size milling pieces, as well as difference in coloration, denoting different types of materials and binder contents.

RAP samples for mix design and for variability studies were sampled from the final processed crushed material pile. Figure 3-14 shows the processed RAP material stockpile where RAP is accumulated prior to feed the conveyor. Following good practice guidelines, Figure 3-15 shows the randomly sampling process from a representative smaller pile that was taken with the front loader machine.

Figure 3-13 Stockpile of RAP millings from Southwest Asphalt of El Mirage Plant

Figure 3-14 Stockpile of processed RAP from Southwest Asphalt plant from El Mirage

Figure 3-15 Sampling of RAP processed material

3.3. Test Methods

3.3.1. RAP Millings and Extracted Aggregate

Typical characterization tests were conducted on the RAP millings and the extracted aggregate from these millings. Tests included determining the dry and washed gradation (AASHTO T27 [45] and T11 [46]) and the specific gravity of fine and coarse extracted aggregates (AASHTO T84 [40] and AASHTO T85 [48]). Tests were conducted according to the standard protocols with any necessary equipment calibration completed prior to testing. Before testing the RAP millings, samples were reduced and sampled according to AASHTO T248 [37]. Since only a limited amount of extracted aggregate were available, the material could not be sampled after extraction. Instead appropriate sampling protocols were enacted on the RAP millings prior to extraction. Washed sieve analysis was also conducted on the aggregates. In these cases, the aggregates were washed till they were free from dust and were oven heated at 230°F (110°C) overnight. The oven dried aggregates were sieved and the dust content of the samples were determined. Unless specifically referred to as washed sieve analysis, gradation results reported in this report should be interpreted as the non-washed (i.e., dry) sieve analysis.

The limitation on the amount of extracted aggregate had an impact on the specific gravity test. The standard requires a minimum of 4.4 lb. (2 kg) for coarse aggregate and 2.2 lb. (1 kg) for fine aggregate, but the extracted material available was only 1.98 lb. (0.9 kg) of coarse and 3.97 lb. (1.8 kg) of fine aggregates. The tests were conducted under the premise that if inconsistent results were obtained, these tests would be rejected. The final results were accepted as valid, since the values for coarse aggregates are typical and within the range of the specifications (2.35 – 2.85) as will be seen later in this document.

3.3.2. Binder Extraction and Recovery

Extraction and recovery of aggregates and asphalt binder from selected reduced samples of RAP material was conducted according to the Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA) (AASHTO T164 [49]/ ASTM D2172) and the Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator (ASTM D5404 [50]). Testing was conducted by the AMEC Foster Wheeler laboratory in Phoenix, Arizona.

The method used for the extraction of the asphalt binder (Test Method A) uses a centrifuge extractor (Soiltest) and a chemical solvent (Reagent grade trichloroethylene) to remove the asphalt binder from the aggregate. A loose RAP sample is weighed and then the solvent is added to dissolve the asphalt binder. The material plus the solvent are then placed inside the centrifuge apparatus to separate the aggregate from the asphalt binder/solvent. The asphalt binder mass is calculated by subtracting the mass of the extracted aggregate from the original mass of the sample. Then, the asphalt binder content is calculated by dividing the calculated binder mass by the total original mass of the sample. Once the aggregate is separated from the asphalt binder, the binder recovery can be performed by removing the solvent from the asphalt by using a rotavapor (Buchi RotaVapor). The equipment has a vacuum controller that helps to keep a steady vacuum within the system, allowing removal of the solvent at a very low temperature. This low temperature process is important because of the ability to remove the solvent without significant changes in the chemical properties of the asphalt. Although it was not verified in the current study, AMEC Foster Wheeler regularly checks for the presence of residual solvent in the extracted binder and so there is a high level of confidence that solvent was not present in the extractant.

Five extraction and recovery runs were completed for the different stockpiles. Samples of stockpiles S-1, S-3, S-4, and S-5, and samples from the Southwest Asphalt plant (SW-1) were processed for characterization of RAP material and variability study. On average, 3000 grams of millings were tested at a time yielding between 2762 and 2897 grams of aggregate and 125 and 180 grams of asphalt binder.

3.3.3. Binder Testing

The extracted asphalt binder was tested according to the standard Superpave performance grading protocols. These protocols involve a suite of tests and instruments for both testing and conditioning the asphalt. In this study, the entire suite of tests was conducted. Prior to all testing, the asphalt binder was conditioned to simulate different aging levels.

- Penetration

This test measures the binder consistency at 77°F (25°C) by releasing a standard needle with a total mass of 100 grams which is placed on the surface and allowed to penetrate the binder for 5 seconds. The penetration depth with a precision of 0.1 mm is recorded as the penetration value indicating the softness of the binder. Testing was conducted following ASTM D5 [51].

- Rolling Thin-Film Oven (RTFO)

The test is used to simulate short term asphalt binder aging and create materials for physical property evaluation and long-term aging simulation. Testing was performed following AASHTO T240 [52]. Samples are exposed to high temperatures and blowing air to simulate manufacturing and placement aging. The process starts with unaged asphalt binder samples in poured into cylindrical glass bottles and placed in a rotating carriage within an oven. The carriage rotates while the binder is subjected to a temperature of 325°F (163°C) and to an air jet for 85 minutes to speed up the aging process.

- Pressure Aging Vessel (PAV)

The PAV equipment is used to simulate long term aging of asphalt binder. The test exposes asphalt that to heat and pressure. The PAV conditioning was carried out in accordance with AASTHO R28 [53]. This procedure starts with RTFO aged asphalt binder samples, which are poured evenly onto stainless steel pans and then placed into an autoclave for 20 hours at 194, 212 or 230°F (90, 100 or 110°C) and pressurized to 305 psi (2.10 MPa). For desert climates, the aging temperature for PG 70-XX and above is specified as 230°F (110°C). The residue of this test is used to estimate the physical or chemical properties of the binders. In the present study, it was used to conduct the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR) tests.

- Dynamic Shear Rheometer (DSR)

For rheological characterization, the dynamic shear rheometer (DSR) was used to measure the dynamic modulus, $|G^*|$, and phase angle, δ, of the asphalt at both high temperatures (above 234°F (112°C)) and at intermediate temperatures (between approximately 153 and 180°F (67 and 82°C). The dynamic shear modulus (|G*|) indicates the total resistance of the sample to deformation when repeatedly sheared. The phase angle (δ) is the interval between the applied shear stress and the resulting shear strain, where a larger phase angle (δ) means a more viscous material (0° = pure elastic, 90° = pure viscous).

Testing was conducted according to the guidelines and procedures of AASHTO T315 [54]. Testing was conducted at a fixed temperature and with sinusoidal loading at 10 rad/s. A parallel plate geometry was used for both high temperature (25 mm diameter) and intermediate temperature testing (8 mm diameter). The test is used for characterization of the viscous and elastic behavior of asphalt binders in the range from medium to high temperatures. High temperature DSR tests were conducted on the as-extracted asphalt (representing the condition of the material at the mixing stage) and asphalt that had been oxidized in the RTFO (high temperatures) and the RTFO+PAV (intermediate temperatures). using the method described in AASHTO T240 [52]. Intermediate temperature DSR testing and BBR testing was conducted on the asphalt binder that was subjected to RTFO conditioning and then long-term aging simulation using the Pressure Aging Vessel, PAV.

- Bending Beam Rheometer (BBR)

The BBR test was used to evaluate the asphalt binder's ability to resist low temperature cracking based on the measure of low temperature stiffness and relaxation properties. This test is used to determine the asphalt binder's low temperature PG grade. The test uses a small PAV aged binder beam that is simply supported and immersed in a cold liquid bath with controlled temperature, a constant load of 980 ± 50 MN is applied to the center of the beam and its deflection is measured versus time. While the beam creeps, the deflection at the midpoint is monitored for 8, 15, 30, 60, 120 and 240 seconds. The measured deflection and the beam properties helps to calculate the binder stiffness, and the grade of asphalt binder load induced stresses relaxation can also be measured. The creep stiffness (S) and the slope of the logarithms of the stiffness vs. time curve (m-value) is related to the low-temperature thermal cracking performance of pavement mixtures.

The method followed was the same as the one specified in AASHTO T313 [55]. The only exception from the standard method was that the temperatures were generally between 54 and 75°F (12 and 24 °C) owing to the high overall stiffness of the asphalt. In AASHTO T313 a fixed level center point load is applied to a beam of asphalt (6.25 x 12.5 x 12.5 mm), while a linear variable displacement measures the overall deflection of the beam. From the known applied force and the measured displacement, the beam stiffness, S, and log-log slope of the deflection, m, are calculated and reported at 60 seconds.

- Performance Grading

Once all testing was completed the performance grade of the asphalt binder was determined according to the method given in AASHTO M320 [56]. The tables given in this standard do not include grades as extreme as the ones that make-up the extracted binder. However, the same basic approach and grading guidelines were extrapolated to produce the PG grade of the extracted binder. While not part of the standard, this process is consistent with engineering practice in determining the grade of RAP extracted asphalts.

3.3.4. Superpave Binder Grading

The properties of the extracted and recovered asphalt binders are reported in terms of the equivalent binder grade (AASHTO M320 [56]). For these specifications, the grade limits on the physical properties remain constant and what defines the performance grade is the temperature at which the properties are achieved. The highest standard and commercial temperature in the standard is 82°C and is expected to be used for slow or standing loads in very hot climates, therefore higher temperatures will mean high stiff binders. However, the concept of the standard specification can be extended to higher temperatures. The experiments used in determining the grade are the same ones described in the previous point (DSR and BBR on as extracted and laboratory aged asphalt binder). Table 3-1 lists the tests, aging conditions, and grade limits that establish the threshold temperatures. These temperatures are rounded to the appropriate standard, 6°C temperature and both the continuous grade and the standard grade are reported.

Table 3-1 Summary of AASHTO M320 Parameters and Limits

Aging Level	Test	AASHTO Standard	Parameter	Limit
As Extracted	DSR (25 mm plate)	T315	$\|G^*\|/\sin\delta$	≥1 kPa
RTFO	DSR (25 mm plate)	T315	$\|G^*\|/\sin\delta$	≥2.2 kPa
PAV	DSR (8 mm plate)	T315	$\|G^*\|\sin\delta$	≤5000 kPa
	BBR	T313	S	≤300 MPa
	BBR	T313	m	≥0.3

Note that in the standard specification tests are completed on unaged, RTFO aged, and PAV aged residues. For the case of the extracted and recovered asphalt the same aging conditions were applied. In this case the as extracted asphalt represented the unaged condition.

3.4. Results on RAP Millings

3.4.1. Gradation of Del Rio Landfill Samples

The gradations of RAP stockpiles were determined to convey the state and to check the consistency of these stockpiles, in order to understand the nature of the millings (i.e., were there large agglomerations, were they very dusty, etc.). Prior to testing the as-sampled stockpile materials were first homogenized and reduced to obtain test samples consistent with AASHTO T 248 [44] (5000 g). To compare the gradations of the RAP stockpiles, six gradation control points were considered and the reduced samples were sieved using the following standard sieves: 1 in (25 mm), 3/4 in (19 mm), 1/2 in (12.5 mm), No.8 (2.36 mm), No. 40 (0.425 mm) and No. 200 (0.075 mm), following AASHTO T27 [45]. Final gradations were plotted using the 0.45 power gradation chart. The results of this sieving are summarized in Table 3-2 and Figure 3-16 below. A photograph of the condition of the stockpiles after sieving is shown in Figure 3-17.

Table 3-2 Gradation Comparison of Del Rio Landfill RAP Millings Stockpiles (as-received)

Sieve Size (std.)	Sieve Size (mm)	Sieve Size$^{0.45}$ (mm)	% Passing			
			S-1	S-3	S-4	S-5
1 in.	25.40	4.26	95	96	96	97
3/4 in.	19.05	3.76	90	89	90	92
1/2 in.	12.50	3.12	77	77	76	81
#8	2.38	1.48	28	35	20	32
#40	0.42	0.68	9.1	10	5.1	9.5
#200	0.075	0.31	1.6	1.1	0.6	1.2

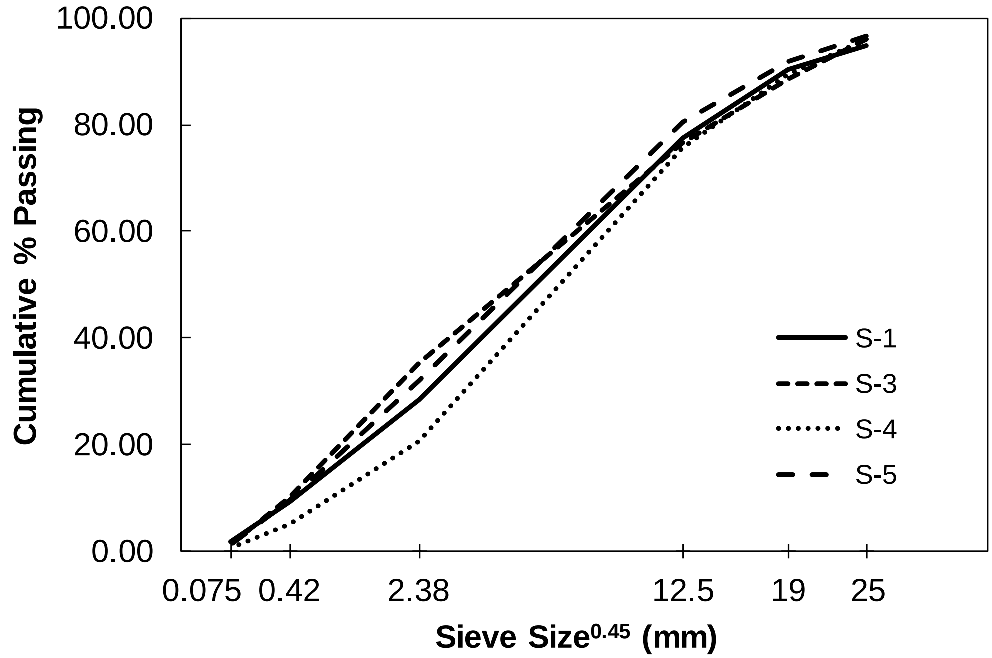

Figure 3-16 Gradation plots from Del Rio landfill RAP millings (as-received) samples

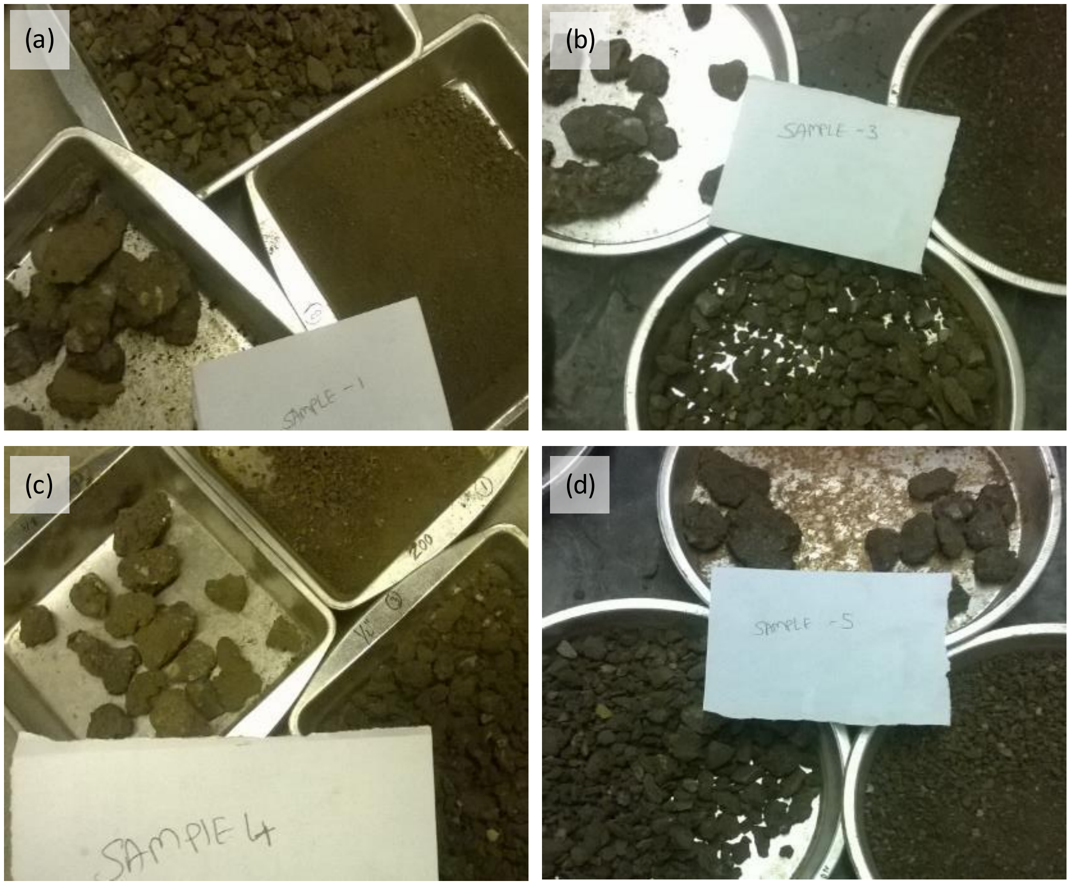

Figure 3-17 Different size particles present in different RAP samples; (a) S-1, (b) S-3, (c) S-4, and (d) S-5

The gradation comparison between stockpiles shows consistency except for sample 4, which is somewhat coarser than the other blends. All samples have 3-5% by weight retained on the 1 in. sieve and between 5-7% for the 3/4 in. sieve. The reason for this situation, is that the RAP of the sampled stockpile is not processed or crushed, and in many cases the particles are an agglomeration of smaller particles (see Figure 3-18).

Figure 3-18 RAP aggregates retained on the 1 in. size sieve; (a) comparison of RAP aggregates retained on 1 in. size sieve for different samples, (b) S-5, (c) S-3, (d) S-1, and (e) S-4

A washed sieve analysis was also conducted on each of the stockpiles to estimate the percentage of dust present. Table 3-3 provides a summary of the washed sieve analysis and it was found that each of the stockpiles present approximately between 2.3 and 2.7% dust. Part of this material could be dust from the environment, since the material is in the open.

Table 3-3 Results of Washed Sieve Analysis of Del Rio Landfill RAP Samples

Sieve Size (Std.)	Sieve Size (mm)	Sieve $Size^{0.45}$ (mm)	% Passing			
			S-1	S-3	S-4	S-5
1in.	25.40	4.26	95	96	96	97
3/4 in.	19.05	3.76	90	88	90	92
1/2 in.	12.50	3.12	77	76	76	80
3/8 in.	9.50	2.75	66	67	63	68
#8	2.38	1.48	27	34	20	31
#40	0.42	0.68	7	8	3	7
#200	0.075	0.31	2.62	2.65	2.29	2.62

3.4.2. Gradation of Southwest Asphalt Sample

The RAP sample from Southwest Asphalt was also evaluated using AASHTO T27 [45] and the results are shown in Table 3-4. and shown in comparison to the Del Rio landfill samples in Figure 3-19. A photograph showing the condition of the RAP stockpile from Southwest Asphalt is shown in Figure 3-20.

Table 3-4 RAP Stockpile Gradation from Southwest Asphalt Plant

Sieve Size (Std.)	Sieve Size (mm)	Sieve $Size^{0.45}$	SW-1
1 in.	25.40	4.26	100
3/4 in.	19.05	3.76	100
1/2 in.	12.50	3.12	89
3/8 in.	9.50	2.75	77
#8	2.38	1.48	28
#40	0.42	0.68	7
#200	0.075	0.31	0.7

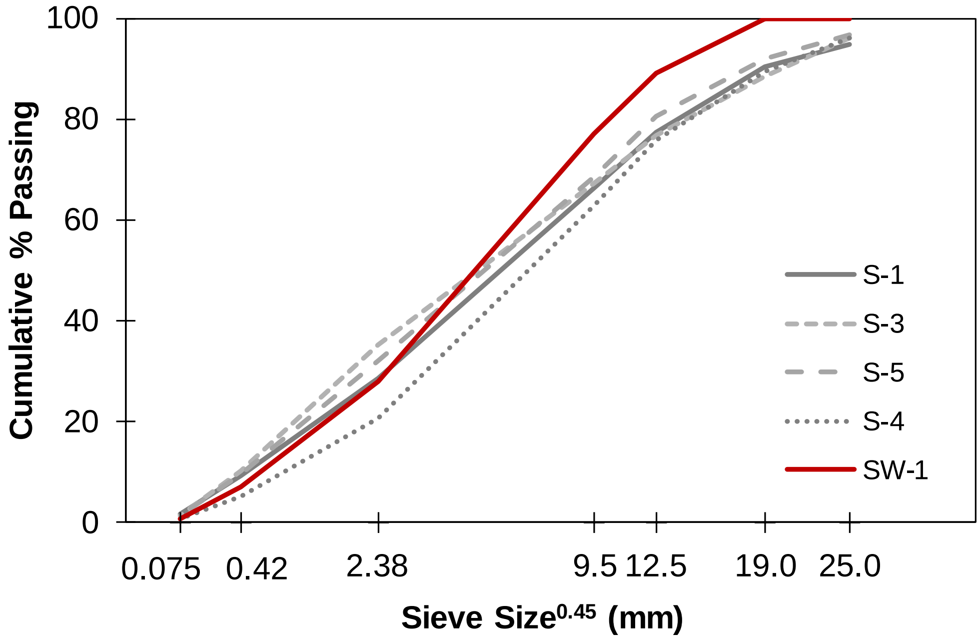

Figure 3-19 Comparison of RAP gradation between as-received Southwest Asphalt plant and Del Rio Landfill millings

From the comparison, the Southwest Asphalt RAP has less coarse particles than the other materials. The processing conducted at Southwest Asphalt has broken down many of the larger agglomerations. It is also noted that the fine particles are less than most of the landfill materials.

Del Rio Landfill RAP millings stockpiles could have more dust from the environment since they are sitting in the stockpile for long periods being subjected to wind and dust accumulation. Processed RAP from the plant shows a better graded gradation since the material is sieved and is the product of a controlled process.

Figure 3-20 shows a representation of the processed RAP, showing a well graded material with larger particles about 1/2 in. and imperceptible dust presence.

Figure 3-20 Processed RAP from Southwest Asphalt plant.

The basic procedure of Southwest Asphalt plant to process RAP consists on stockpiling the RAP millings in the central plant after the ripping/crushing/milling operation; when needed, and to produce a homogeneous product, RAP is blended with a front end loader; then the millings are crushed basically with a jaw crusher to downsize the top stone size to be adequate for the HMA being produced; after that a mobile stacker is used to send the processed material into the new stockpile; when required the material is transported from the RAP processed stockpile by a front loader, and is downloaded into the feed hopper; finally the material is placed on the conveyor belt to feed the mixing plant (Figure 3-21).

Figure 3-21 Southwest Asphalt plant RAP processing.

3.5. Results on Extracted Aggregate

3.5.1. Visual Inspection

There are certain aggregate characteristics that will affect the performance of hot mix asphalt such as coarse and fine aggregate angularity, flat and elongated particles, and clay content. These properties, also called consensus properties, are important since they will determine the degree of internal friction and rutting resistance, or the tendency to break during construction and service, or the ability of the material to bond properly.

There are different test methods to evaluate the aforementioned characteristics and are usually a requirement in the specifications for virgin materials. For RAP evaluation, it is assumed that these characteristics are already met, since the old material was subjected to certain specifications when they were manufactured. Although these tests were not performed in the present study, a visual inspection was conducted to see if the main criteria were met and to evaluate the aggregate for a future application in RAP mixes.

Figure 3-22(a) shows the extracted material from S-1 of the Del Rio Landfill. It can be seen that it presents a considerable amount of fines and round coarse aggregate with some fractured faces. There is not noticeable presence of elongated particles and only a few flat particles. Figure 3-22(b) correspond to the material from S-3, which shows the same basic characteristics (considerable of fines and round coarse aggregates and no observed flat and elongated particles. Figure 3-23 displays the material after sieving separated by their different sizes. As in the previous cases it is noted a higher presence of fines.

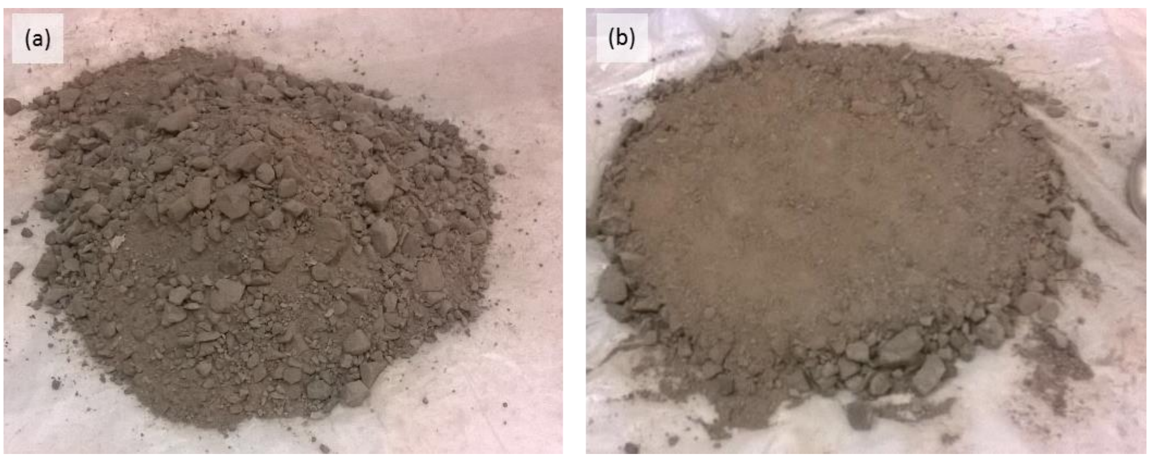

Figure 3-22 Extracted aggregates from Del Rio landfill; (a) S-1 and (b) S-3

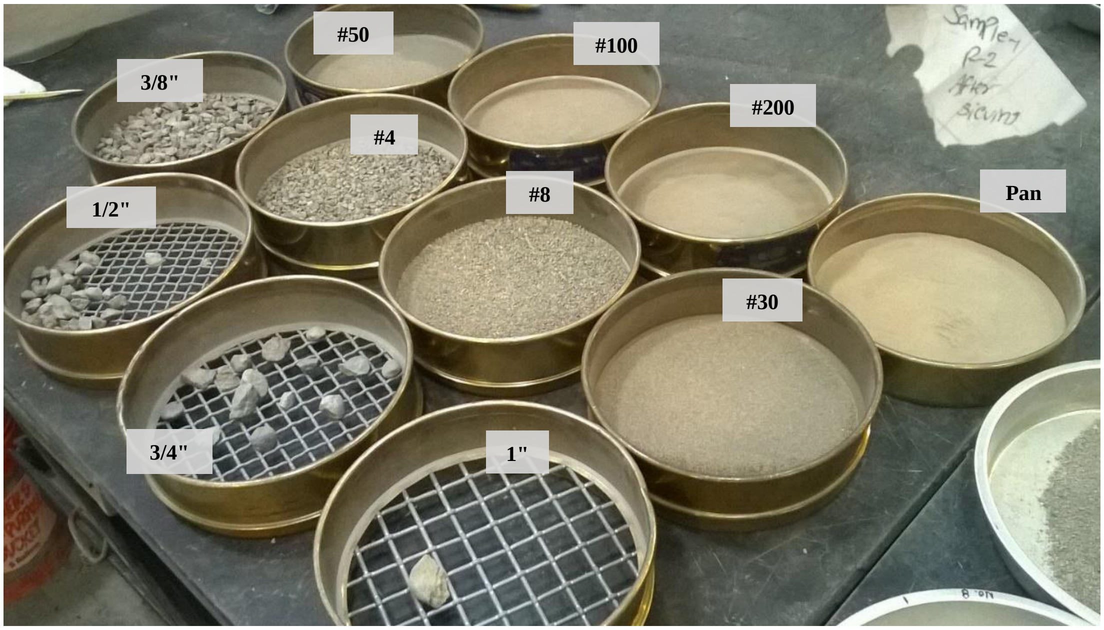

Figure 3-23 Extracted aggregates from Sample-1 of Del Rio landfill

A similar visual overview of the Southwest Asphalt RAP materials is shown in Figure 3-24. Comparing the visual characteristics of this sample to the Del Rio landfill samples, a more angular coarse aggregate structure and a smaller amount of fines is observed. Like the Del Rio materials, the Southwest Asphalt RAP samples do not show the presence of flat or elongated particles.

Figure 3-24 Extracted aggregates from Southwest Asphalt plant.

3.5.2. Extracted Aggregates Gradation

The extracted aggregates were reduced to a 1500 grams samples and dry sieve analysis was conducted using standard AASHTO T30 [57]. Washed sieve analysis was also performed to determine the dust content following AASHTO T11 [46]. Dry gradations were compared with the City specification limits for total mixture aggregate gradations for 1/2 and 3/4 in. mix specifications. The results of dry and wet sieve analysis are reported in Table 3-5 and Table 3-6 respectively. City specifications are shown in Table 3-7. Figure 3-25 and Figure 3-26 show the comparisons.

Table 3-5 Dry Sieve Analysis Results of Extracted Aggregate from Del Rio Landfill and Southwest Asphalt Plant Samples

Sieve Size (Std.)	Sieve Size (mm)	Sieve Size$^{0.45}$ (mm)	% Passing				
			S-1	S-3	S-4	S-5	SW-1
1 in.	25.40	4.26	100	100	100	100	100
3/4 in.	19.05	3.76	99	99	100	100	100
1/2 in.	12.50	3.12	93	92	96	98	91
3/8 in.	9.50	2.75	86	86	89	92	77
#8	2.38	1.48	50	58	52	51	36
#40	0.42	0.68	22	22	22	22	14
#200	0.075	0.31	6.2	5.1	5.8	7.4	3.9

Table 3-6 Washed Sieve Analysis Results of Del Rio Landfill and Southwest Asphalt Samples and Comparison with City of Phoenix 1/2 in. Mix Gradation

Sieve Size (Std.)	Sieve Size (mm)	Sieve Size$^{0.45}$ (mm)	% Passing				
			S-1	S-3	S-4	S-5	SW-1
1 in.	25.40	4.26	100	100	100	100	100
3/4 in.	19.05	3.76	99	99	100	100	100
1/2 in.	12.50	3.12	93	92	96	98	90
3/8 in.	9.50	2.75	85	85	88	91	76
#8	2.38	1.48	46	56	48	46	32
#40	0.42	0.68	16	17	16	15	9
#200	0.075	0.31	7.3	7.3	7.1	9.0	5.6

Table 3-7 City of Phoenix Aggregate Gradation Specifications for 1/2 and 3/4 in. Mixes

Sieve Size (Std.)	Sieve Size (mm)	Sieve Size$^{0.45}$ (mm)	1/2"		3/4"	
			Upper Limit	Lower Limit	Upper Limit	Lower Limit
1 in.	25.40	4.26	100	100	100	100
3/4 in.	19.05	3.76	100	100	100	90
1/2 in.	12.50	3.12	100	90	89	43
3/8 in.	9.50	2.75	89	53	---	---
#8	2.38	1.48	40	29	36	24
#40	0.42	0.68	20	3	18	3
#200	0.075	0.31	7.5	2.0	6.5	2.0

The dry sieve analysis in Table 3-5 confirms the visual inspection with respect to the quantity of fines in the Del Rio landfill samples and the relatively smaller quantity of fines in the Southwest Asphalt Samples. The reason for the increased fines content in the Del Rio landfill samples could be related to the origin of the RAP itself. It is known that Del Rio samples contain City of Phoenix mixtures, but the sources of Southwest Asphalt material could be broader. It may also be due to mechanical degradation of aggregates due to milling and crushing [58]. Another cause of increasing fines could be the long exposure periods of the stockpiled material to the environment due to wind and dust, while SW material is in a more constant use.

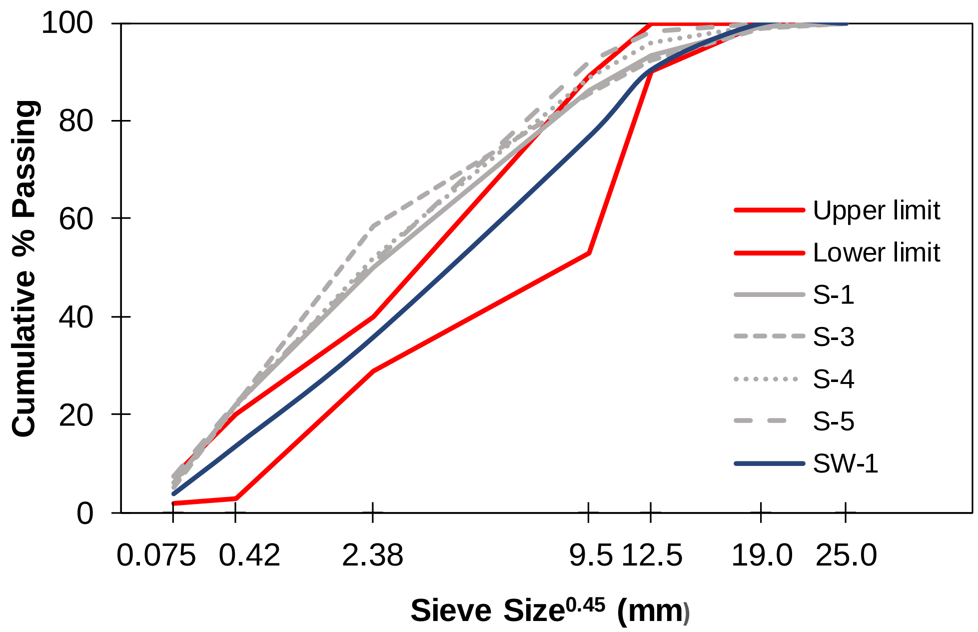

Figure 3-25 Comparison gradation plot of extracted aggregate with City of Phoenix 1/2 in. mix specifications

It can be noticed from the figure, that since SW material is already processed (crushed and sieved), it fits within City gradation specifications. Even though City limits are set for the final aggregate blend of the mixture, this gives an idea that processed material will fit better in the final gradation for a 1/2 in. mixture.

The next figure shows the comparison of the extracted aggregate gradations with the 3/4 in. mix City limits. It can be noticed that extracted SW processed RAP material is very close to the upper limit but still fit within the specifications, while the rest of the samples are way off the limits. This reaffirms the concept of pre-processing RAP before its incorporation into the mix.

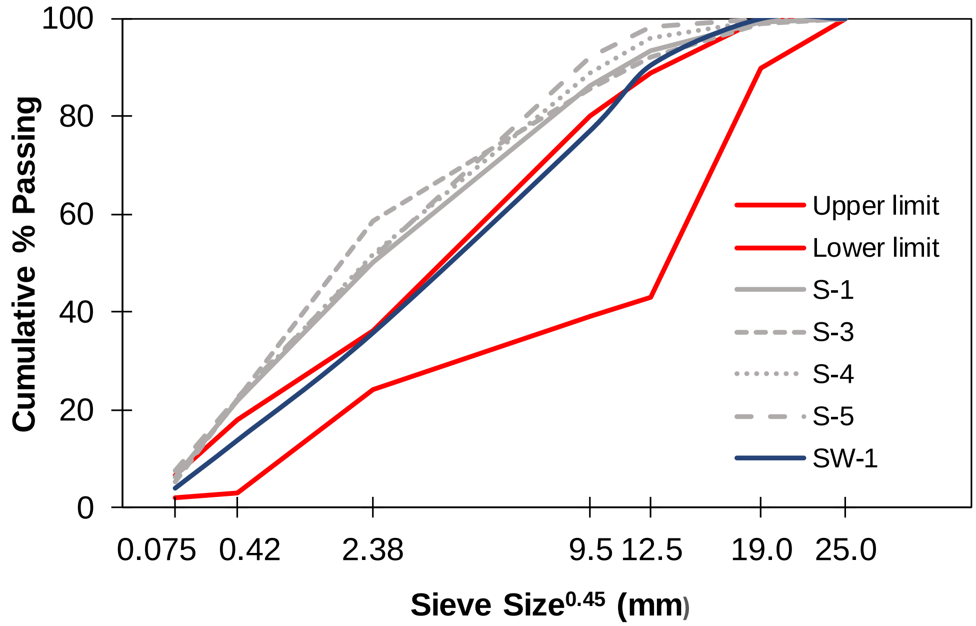

Figure 3-26 Comparison gradation plot of extracted aggregate with City of Phoenix 3/4 in. mix specifications

3.5.3. Specific Gravity

The extracted aggregates were tested for specific gravity. Table 3-8 and Table 3-9 show the specific gravities of coarse and fine aggregates respectively, determined for the different Del Rio Landfill and for Southwest Asphalt plant samples.

Table 3-8 Specific Gravity of Coarse Extracted Aggregates

	S-1	S-3	S-4	S-5	SW-1
G_{sb} (Dry)	2.63	2.71	2.64	2.62	2.60
G_{sb} (SSD)	2.66	2.74	2.66	2.64	2.63
G_{sb} (Apparent)	2.71	2.80	2.70	2.68	2.69
Absorption %	1.12	1.13	0.85	0.84	1.29

Table 3-9 Specific Gravity of Fine Extracted Aggregates

	S-1	S-3	S-4	S-5	SW-1
G_{sb} (Dry)	2.62	2.65	2.63	2.62	2.60
G_{sb} (SSD)	2.66	2.69	2.66	2.65	2.64
G_{sb} (Apparent)	2.71	2.76	2.70	2.70	2.72
Absorption %	1.24	1.49	1.03	1.22	1.62

Based on the specific gravity results for either coarse and fine aggregates, Southwest Asphalt plant sample shows lower values. This could represent a lighter or porous material and this can also be noticed on the higher absorption percentage. Nonetheless, all values are similar and represent low absorption.

Specific gravity values of coarse and fine aggregates comply with the specifications for the City of Phoenix [31], that states a minimum apparent specific gravity of 2.50 and a combined Bulk Specific Gravity between the range of 2.35 to 2.85.

3.6. Results on Extracted and Recovered Asphalt Binders

3.6.1. Asphalt Content

Table 3-10 shows the asphalt contents found for the different recovered binders. The results show that stockpile samples S-3 and S-4 have higher asphalt contents (5.25% and 6.26% respectively) and samples S-1 and S-5 show similar asphalt contents of 4.88% and 4.83%. The results from the extraction confirm the characteristics described on the visual inspection, where the locations that presented brown tones, have less asphalt (locations S-1 and S-5) and those that presented grey-black or brown-black tones, have higher binder contents (locations S-3 and S-4).

The amount of recovered asphalt from each stockpile after extraction and recovery process was 182.7 grams from sample S-1; 201.9 grams from sample S-3; 224.1 grams from sample S-4; and 176.1 grams from sample S-5. As reference, each content was obtained from about 3500 grams of RAP. The amounts of extracted asphalt binders were the minimum necessary to conduct the characterization testing.

For the RAP sample of Southwest Asphalt plant, two extractions and recovery processes were conducted. Each extraction was done based on 3000 grams of RAP making a total of 6000 grams of RAP. After the process 180.2 grams of asphalt binder were obtained and the two extractions reported asphalt contents of 3.70% and 3.93%, giving an average of 3.82%.

Table 3-10 Recovered Binder Asphalt Contents

Sample	Asphalt content (%)
S-1	4.88
S-3	5.25
S-4	6.26
S-5	4.83
SW-1	3.82

Southwest Asphalt sample (SW-1) presents the least binder content close to 3.8%.

3.6.2. Handling of Extracted and Recovered Binders

Each of the extracted and recovered binders of the different RAP stockpiles exhibited high viscosity at normal handling temperatures. This characteristic was noted while binder testing was conducted, since the manipulation of the binders presented some difficulty at the time of heating, manipulating, or pouring the binder into the various molds that were used for RTFO, PAV, DSR, and BBR testing. To prepare the extracted binders for testing, the samples were divided into different containers heating up to 383°F (195°C). Even though the temperature was high, the binders showed a rapid stiffening while being poured outside the oven. This behavior can be seen from Figure 3-27 to Figure 3-30.

Figure 3-27 shows the extracted binder poured into RTFO bottles where the binder became stiff in a very short time precluding further actions to distribute the binder over the bottles inner surface. It must be noted that during the RTFO aging, because of the testing temperature, the binder spread over the bottle inner surface as normal. Figure 3-28 displays a similar condition after extracting the binder from the RTFO bottles and pouring into PAV pans, after the test due to high temperature, the binder melted again. The consistency of the hardened binders was like glass and was easily broken by hand. Figure 3-29 shows a BBR beam with glassy appearance where trimming was very difficult to perform since the overfilled material was very brittle and the trimming operations generated splinters breaking the surface of the beam. Figure 3-30 displays very brittle BBR beams broken at the time of demolding. Extreme care was taken to avoid these types of failures and none of the tests with reported values experienced these types of failure. Nevertheless, the tendency to behave in such a brittle fashion could have led to some inadvertent impact on the tests.

Figure 3-27 Extracted binder poured into RTFO bottles prior to aging.

Figure 3-28 Extracted binder poured into PAV pans prior to aging.

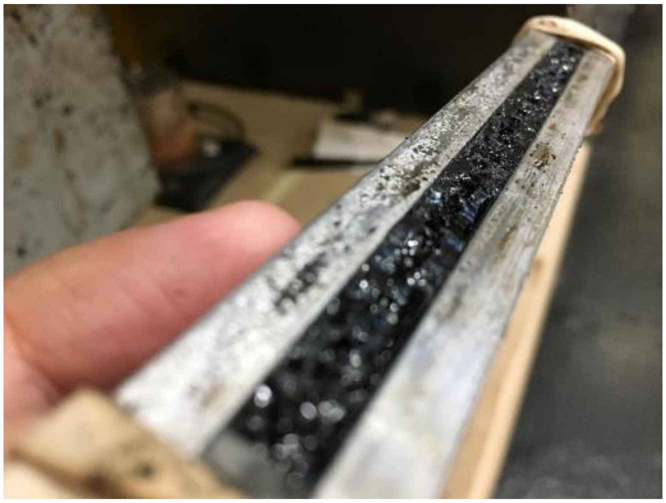

Figure 3-29 Glassy appearance of a BBR beam.

Figure 3-30 Brittle broken BBR beams at the time of demolding.

3.6.3. Extracted Binder Characterization Results

To characterize the recovered asphalt binder for all samples, DSR and BBR tests were conducted. DSR testing was performed for different temperatures in the intermediate and high range, and those temperature values were different in most of the samples. BBR test was performed at low temperatures at 12, 18 and 24°C. Because of the variable results obtained for each sample and to normalize them to appreciate the differences between binders better, the grade limits on the physical properties were kept constant and the temperature at which the properties are achieved are reported. The testing results for all replicates are detailed in Appendix B.

The experiments used to characterize the recovered binders are the same ones described in 3.3.3, and the parameters considered for testing are described in previous point 3.3.4. The tests were conducted on As Extracted and laboratory aged asphalt binders.

Figure 3-31 shows the temperatures were As Extracted and RTFO aged samples meet the specifications, corresponding to the high range of temperatures.

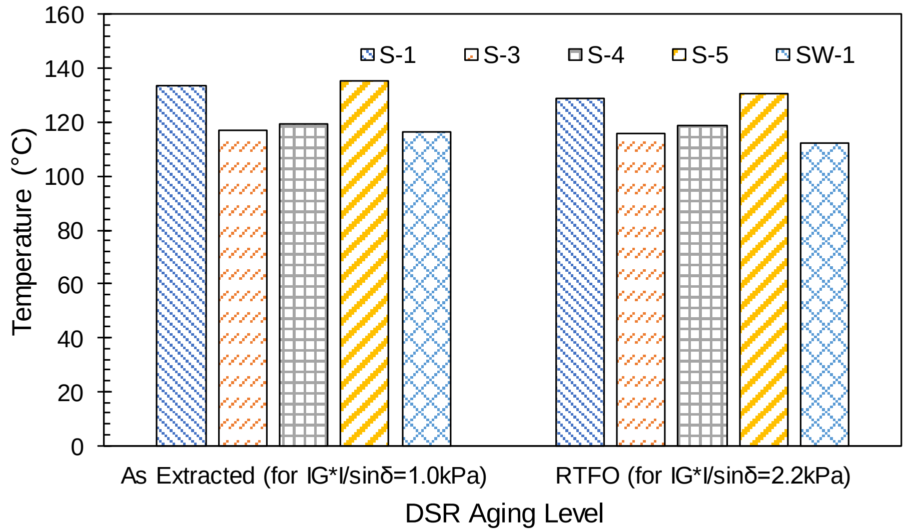

Figure 3-31 DSR Temperatures of all samples were As Extracted and RTFO aged samples meet specifications

Figure 3-32 shows the temperatures were PAV aged samples meet the specifications, corresponding to the intermediate range of temperatures.

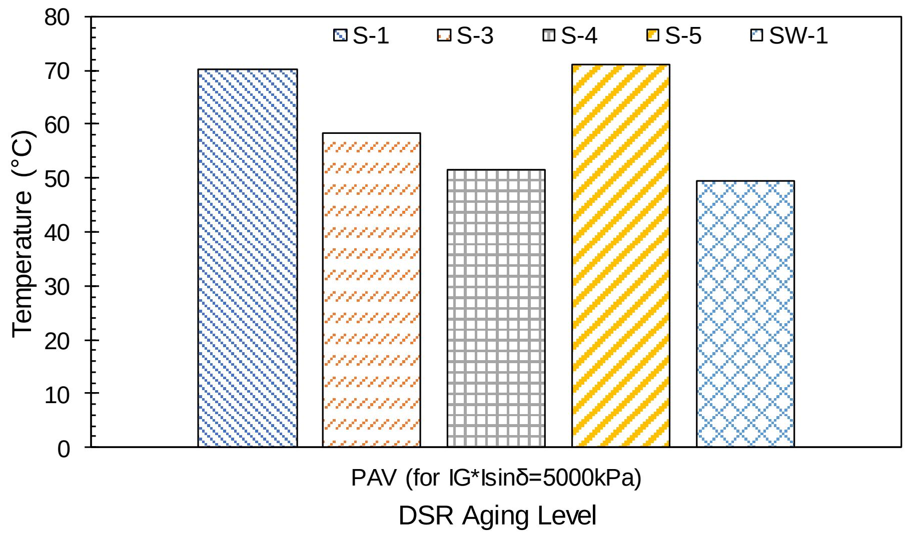

Figure 3-32 DSR Temperatures of all samples were PAV aged samples meet specifications

Figure 3-33 shows the temperatures were PAV aged samples meet the specifications, corresponding to the low range of temperatures.

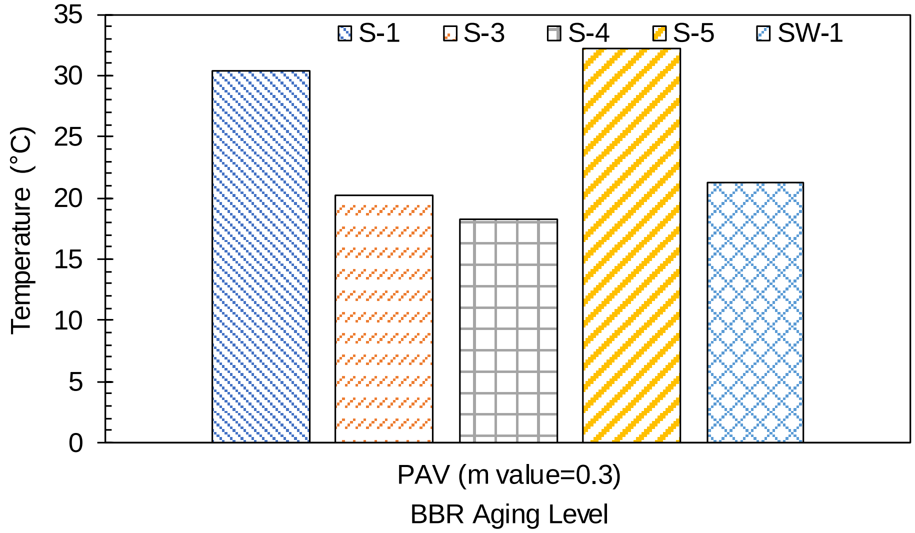

Figure 3-33 BBR Temperatures of all samples were PAV aged samples meet specifications

- Stockpile S-1

DSR testing on As Extracted and RTFO binder samples met the specification parameters for higher temperatures in a range from 124 to 130°C denoting a very stiff binder. BBR was tested at a maximum temperature of 24°C and the binder still failed to pass the specification. Higher temperatures were not able to be tested because of the equipment limitations, forcing to extrapolate the values for PG grading. In this case the lower temperature grade was extrapolated.

- Stockpile S-3

DSR testing on As Extracted and RTFO binder samples met the specification parameters for higher temperatures in a range from 112 to 118°C denoting a stiff binder, although less stiff than S-1. BBR test passed temperatures between 18 and 24°C.

- Stockpile S-4

DSR testing on As Extracted and RTFO binder samples met the specification parameters for higher temperatures in a range from 118 to 124°C denoting similar behavior as sample S-3. BBR passing temperatures are between 18 and 24°C, consistent with the previous sample.

- Stockpile S-5

DSR testing on As Extracted and RTFO binder samples met the specification parameters for higher temperatures in a range from 130 to 136°C denoting the highest stiffer binder from all samples. There was noticed a slight difference in the aging level between the original and the RTFO aged binder, showing that old aged binders are less prone to the effect of aging and present high intermediate temperatures also. The effect of stiffening on the aged binder can also be noticed on the BBR results, where as well as in the first sample, the binder does not pass the specifications leading to extrapolation of the lower temperature values for PG grading.

- Southwest Asphalt Plant SW-1

DSR testing on As Extracted and RTFO binder samples met the specification parameters for higher temperatures in a range from 112 to 118°C denoting a less stiff binder, similar to S-3. BBR passing temperatures are between 18 and 24°C.

3.6.4. Performance Grading of Extracted and Recovered Binder

Based on the results of the characterization tests, the temperatures that comply with the parameter limits given in Table 3-1 were estimated by interpolation or extrapolation. The BBR equipment, which results will dictate the low temperature of the binder, only allows testing from -40°C (-40°F) to +25°C (77°F) and samples for stockpile

1 and 5 required higher temperatures to pass the test. Due to this limitation, the values for low temperatures were extrapolated based on the results obtained for +18°C (64°F) and +24°C (75°F) testing temperatures. It must be noted that the grading procedure states that the final low temperature grade will be 10°C (50°F) less than the temperature found in the test.

The true (continuous) and the standard PG grades were defined for each binder sample. The results are shown in Table 3-11.

Table 3-11 Performance Grade of the Extracted and Recovered Binders

Sample name	Threshold Temperatures[a]			Extracted PG Grade	
	HT	IT	LT	Continuous	Standard
S-1	128.6	70.2	20.4[b]	128.6 + 20.4	124 + 26
S-3	115.7	58.4	10.2	115.7 + 10.2	112 + 14
S-4	119.0	51.5	8.2	119.0 + 8.2	118 + 14
S-5	130.8	71.2	22.3[b]	130.8 + 22.3	130 + 26
SW-1	112.5	49.4	11.3	112.5 + 11.3	112 + 14

[a] HT = temperature based on As Extracted and RTFO T315 results,
IT = temperature based on PAV T315 results,
LT = temperature based on T313 results
[b] Value extrapolated based on the results at 18 and 24°C

The standard grade is defined by the minimum standard temperatures that satisfy the grading criteria for the calculated temperature and are defined every 6°C. The intermediate temperatures showed in Table 3-11 are for control purposes. In all cases the true intermediate temperatures are less than the standard intermediate temperatures, which means compliance with the grading criteria parameters, since as the intermediate temperature increases the value of G*sinδ decreases dropping the values to less than 5000 kPa, complying with the grading criteria.

A comparison of the true and the standard temperatures found for the samples are shown in the following figures.

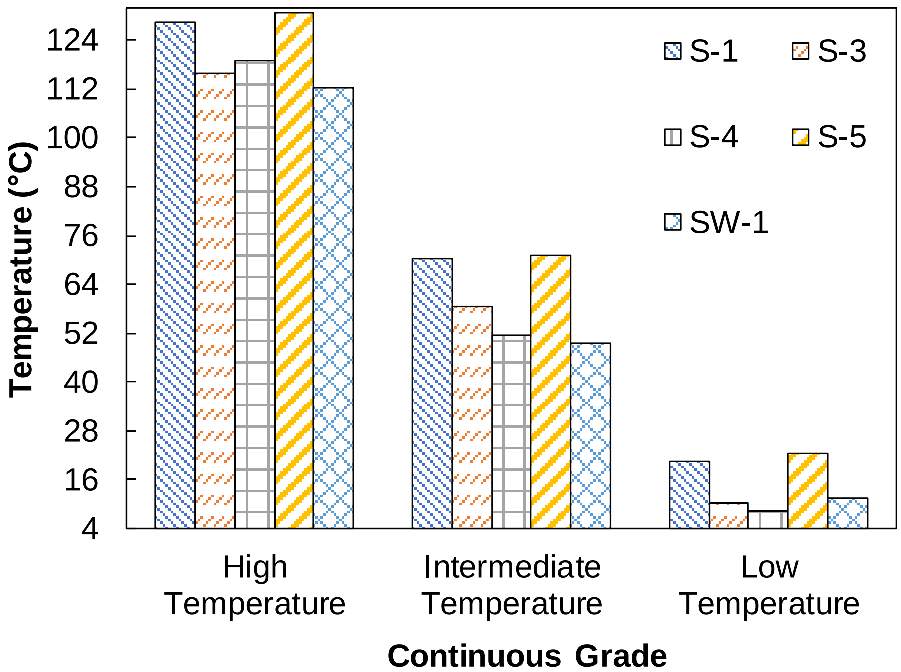

Figure 3-34 Samples high, intermediate, and low temperature comparison based on continuous grade

The continuous or true grade indicates the real temperatures where a certain binder complies with the specifications, where the temperatures are mainly related to the air temperature. Figure 3-34 shows the difference between the true range of temperatures where the sampled and extracted binders stand. Superpave Performance Grading (PG grade) is based on the concept that asphalt properties should be related to the climatic and aging conditions under the material will be used. Therefore, in warmer climates, stiffer binders (higher temperature range) will be needed and that is why PG 70-10 virgin binder is specified for new paving projects in the City. Higher temperature ranges mean stiffer but more brittle binders.

Based on the above, it was found that the five extracted binders are very stiff (high temperature ≥ 112°C, and low temperature ≥ +8°C). This statement correlates with the observed difficulty in handling the binders during the laboratory preparation and testing, where the binders required higher temperatures to be workable and tend to harden very fast when cooling. Binders from stockpiles 1 and 5 are the stiffer ones, and Southwest Asphalt sample presents the minor stiffness from all samples.

There is not a correlation between RAP binder content and RAP binder stiffness, these two variables are independent. Higher binder contents in this study are in samples S-3 and S-4.

It is difficult to state average RAP recovered binder grades based on the literature since it will depend on many variables as original binder, aging conditions, type of mixture, etc. As a reference, a study on RAP binder effects conducted in California [59] found continuous grades about 89.0°C and – 6.4°C for the high and low temperatures. Comparing the values found in the study to those in California, it can show very stiff aged binders in Arizona due to the climate conditions and the original binders used.

Based on the aforementioned, local RAP binders are very stiff and high RAP contents should be investigated, since increasing the RAP contribution will also contribute to the hardening effects of the final blends.

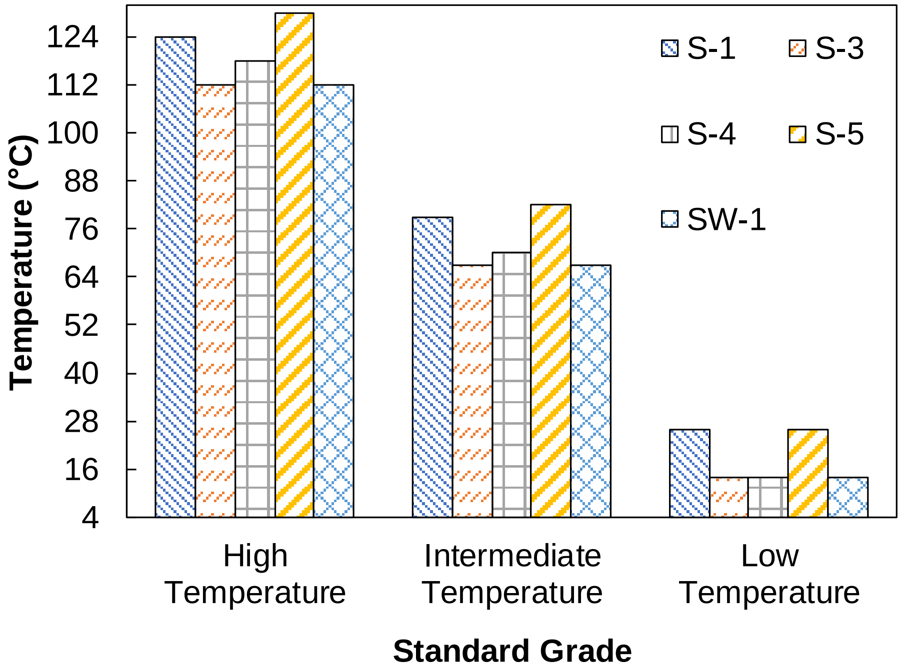

Figure 3-35 Stockpile high, intermediate, and low temperature comparison based on standard grade

Figure 3-35 shows the standardized high, intermediate, and low temperatures for all samples. Southwest Asphalt SW-1 and Stockpile S-3 have the same and lowest standard grades.

3.6.5. Blended Performance Grade

Literature states that tests for the blending of virgin and recovered binders are not required for low RAP contents. Additionally, due to extracted binder material limitations, blending tests were not allowed in this study. Nevertheless, in order to evaluate the possible outcome of the binder blends, the final blended grade was predicted.

For the analysis below, the two City of Phoenix specified binders were used, PG 70-10 and PG 64-16. The following tables show the resultant PG grade of the blend of each recovered binder and the two approved virgin binders. To estimate the final PG grade of the blended binder, blending chart equations from NCHRP Report 452 linear approach were used [60].

The following equation shows the relationship between the temperatures of RAP, virgin, and blended binder, based on RAP percentage for high, intermediate, and low critical temperatures. This equation is a rearranged version of Method A (Blending at a known RAP Percentage) from NCHRP Report 452. For this estimation, four different RAP contents are considered (5%, 10%, 15%, and 20%). It is assumed a total asphalt content of the final blended mix of 5.2% and Table 3-12 also shows the RAP binder contribution and the binder replacement based on that assumption.

$$T_{Blend} = \%RAP\left(T_{RAP} - T_{Virgin}\right) + T_{Virgin} \tag{3.1}$$

Where:

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

T_{Blend} = critical temperature of the blended asphalt binder

%RAP = percentage of RAP expressed as a decimal (i.e., 0.15 for 15%)

T_{RAP} = critical temperature of recovered RAP binder

The following relationships show how to calculate the RAP binder contribution, the binder replaced by RAP and the virgin binder to be added.

$$RAP_{BC} = \%RAP \times RAP_{B} \tag{3.2}$$

$$Mix_{BR} = \frac{RAP_{BC}}{Mix_{B}} \times 100 \tag{3.3}$$

$$Virgin_{B} = Mix_{B} - RAP_{BC} \tag{3.4}$$

Where:

RAP_{BC} = RAP binder contribution, %,

$\%RAP$ = Percentage of RAP expressed as a decimal (i.e., 0.15 for 15%)

RAP_B = RAP binder content, %,

Mix_{BR} = Mix binder replaced, %,

Mix_B = Mix binder content, %, and

$Virgin_B$ = Virgin binder content, %.

Table 3-12 Performance Grade of the Blended Mixtures of Virgin PG 70 - 10 and RAP Binder

Stockpile	RAP in mix (%)	Extracted binder				Mix asphalt content (%)	Virgin binder (%)	RAP binder contribution (%)	Binder replaced (%)	Virgin binder			Blended binder			
		Asphalt Content (%)	Continuous grade							Binder grade			Continuous grade			Standard grade
			HT (°C)	IT (°C)	LT (°C)					HT (°C)	IT (°C)	LT (°C)	HT (°C)	IT (°C)	LT (°C)	
S - 1	5	4.88	128.6	70.2	20.4	5.2	4.96	0.24	4.7	70	34	-10	72.9	35.8	-8.5	PG 70-4
	10						4.71	0.49	9.4				75.9	37.6	-7.0	PG 70-4
	15						4.47	0.73	14.1				78.8	39.4	-5.4	PG 76-4
	20						4.22	0.98	18.8				81.7	41.2	-3.9	PG 76+2
S - 3	5	5.25	115.7	58.4	10.2	5.2	4.94	0.26	5.0	70	34	-10	72.3	35.2	-9.0	PG 70-4
	10						4.68	0.53	10.1				74.6	36.4	-8.0	PG 70-4
	15						4.41	0.79	15.1				76.9	37.7	-7.0	PG 76-4
	20						4.15	1.05	20.2				79.1	38.9	-6.0	PG 76-4
S - 4	5	6.26	119.0	51.5	8.2	5.2	4.89	0.31	6.0	70	34	-10	72.5	34.9	-9.1	PG 70-4
	10						4.57	0.63	12.0				74.9	35.8	-8.2	PG 70-4
	15						4.26	0.94	18.1				77.4	36.6	-7.3	PG 76-4
	20						3.95	1.25	24.1				79.8	37.5	-6.4	PG 76-4
S - 5	5	4.83	130.8	71.2	22.3	5.2	4.96	0.24	4.6	70	34	-10	73.0	35.9	-8.4	PG 70-4
	10						4.72	0.48	9.3				76.1	37.7	-6.8	PG 76-4
	15						4.48	0.72	13.9				79.1	39.6	-5.2	PG 76-4
	20						4.23	0.97	18.6				82.2	41.4	-3.5	PG 82+2
SW-1	5	3.82	112.5	49.4	11.3	5.2	5.01	0.19	3.7	70	34	-10	72.1	34.8	-8.9	PG 70-4
	10						4.82	0.38	7.3				74.3	35.5	-7.9	PG 70-4
	15						4.63	0.57	11.0				76.4	36.3	-6.8	PG 76-4
	20						4.44	0.76	14.7				78.5	37.1	-5.7	PG 76-4

HT = High temperature (°C), IT = Intermediate temperature (°C), LT = Low temperature (°C)

Table 3-13 Performance Grade of the Blended Mixtures of Virgin PG 64 - 16 and RAP Binder

Stockpile	RAP in mix (%)	Extracted binder				Mix asphalt content (%)	Virgin binder (%)	RAP binder contribution (%)	Binder replaced (%)	Virgin binder			Blended binder			
		Asphalt Content (%)	Continuous grade							Binder grade			Continuous grade			
			HT (°C)	IT (°C)	LT (°C)					HT (°C)	IT (°C)	LT (°C)	HT (°C)	IT (°C)	LT (°C)	Standard Grade
S - 1	5	4.88	128.6	70.2	20.4	5.2	4.96	0.24	4.7	64	28	-16	67.2	30.1	-14.2	PG 64-10
	10						4.71	0.49	9.4				70.5	32.2	-12.4	PG 70-10
	15						4.47	0.73	14.1				73.7	34.3	-10.5	PG 70-10
	20						4.22	0.98	18.8				76.9	36.4	-8.7	PG 76-4
S - 3	5	5.25	115.7	58.4	10.2	5.2	4.94	0.26	5.0	64	28	-16	66.6	29.5	-14.7	PG 64-10
	10						4.68	0.53	10.1				69.2	31.0	-13.4	PG 64-10
	15						4.41	0.79	15.1				71.8	32.6	-12.1	PG 70-10
	20						4.15	1.05	20.2				74.3	34.1	-10.8	PG 70-10
S - 4	5	6.26	119	51.5	8.2	5.2	4.89	0.31	6.0	64	28	-16	66.8	29.2	-14.8	PG 64-10
	10						4.57	0.63	12.0				69.5	30.4	-13.6	PG 64-10
	15						4.26	0.94	18.1				72.3	31.5	-12.4	PG 70-10
	20						3.95	1.25	24.1				75.0	32.7	-11.2	PG 70-10
S - 5	5	4.83	130.8	71.2	22.3	5.2	4.96	0.24	4.6	64	28	-16	67.3	30.2	-14.1	PG 64-10
	10						4.72	0.48	9.3				70.7	32.3	-12.2	PG 70-10
	15						4.48	0.72	13.9				74.0	34.5	-10.3	PG 70-10
	20						4.23	0.97	18.6				77.4	36.6	-8.3	PG 76-4
SW-1	5	3.82	112.5	49.4	11.3	5.2	5.01	0.19	3.7	64	28	-16	66.4	29.1	-14.6	PG 64-10
	10						4.82	0.38	7.3				68.9	30.1	-13.3	PG 64-10
	15						4.63	0.57	11.0				71.3	31.2	-11.9	PG 70-10
	20						4.44	0.76	14.7				73.7	32.3	-10.5	PG 70-10

HT = High temperature (°C), IT = Intermediate temperature (°C), LT = Low temperature (°C)

From Table 3-12 and Table 3-13 it can be observed that for the lowest RAP content of 5%, all the blended binders keep the higher temperatures of the virgin binders (70 and 64 respectively), but there is a change of one grade on the low temperatures from -10 to -4 and from -16 to -10 respectively.

For 10% RAP, it can be noted that for four of five stockpiles, the blended binder goes from 70-10 to 70-4. Only the stiffer binder of all five stockpiles (sample S-5) the high temperature increases one grade to 76-4. For the virgin binder 64-16, the two stiffer binders (samples S-1 and S-5) increase one whole grade in both boundaries from 64-16 to 70-10, and for the less stiff binders it goes from 64-16 to 64-10, changing only the low temperature limit.

In the case of 15% RAP, for all stockpiles the final blended binders increase one grade on the high and low temperature sides (stiffer blended binder) from 70-10 to 76-4 and from 64-16 to 70-10.

For 20% the results are the same as for 15% in the case of the softer aged binders (stockpile samples S-3, S-4 and SW1), but for the stiffer binders (stockpile samples S-1 and S-5) the blended binder grade increases two grades up to 82+2 for the 70-10 and up to 76-4 for the 64-16.

3.7. Statistical Measures

The consistency of the RAP stockpiles can be evaluated by monitoring the coefficient of variability (CV) of multiple samples from the stockpile [9]. Also, the standard deviation statistic is a basic measure of variability [15]. Average values, standard deviations, and coefficients of variance were determined for asphalt content and aggregate gradations for dry and washed conditions.

NCHRP Report 752 on improved practices for HMA with RAP [15], summarizes guidelines on analysis of RAP variability and are presented in the following table.

Table 3-14 Variability Guidelines for RAP Stockpiles

RAP Property	Maximum Std. Dev. (%)
Asphalt content	0.5
% Passing 2.36 mm Median Sieve (No.8)	5.0
% Passing 0.075 mm Sieve (No.200)	1.5
Bulk Specific Gravity (provisional)	0.03

Table 3-15 shows the statistic measures comparing two cases: only the landfill samples and all samples including Southwest Asphalt. In both cases the standard deviation exceeds the maximum stated previously, showing slight variability within the landfill samples and high variability compared to the processed RAP.

Table 3-15 Statistic Measures for Asphalt Binder Content

Sample	Asphalt content (%)	
	Del Rio Landfill	Del Rio Landfill + SW Plant
S-1	4.88	4.88
S-3	5.25	5.25
S-4	6.26	6.26
S-5	4.83	4.83
SW-1	---	3.82
Maximum (%)	6.26	6.26
Average (%)	5.31	5.01
Minimum (%)	4.83	3.82
Standard Deviation (%)	**0.58**	**0.79**

Table 3-16 presents the values of the specific gravities for coarse aggregates, were in all cases the standard deviation is greater than the guideline limits showing considerable variability between the results, probably indicating that aggregates come from different sources.

Table 3-16 Specific Gravity of Coarse Extracted Aggregates

	Average	Minimum	Maximum	Std. Dev. (%)	CV (%)
G_{sb} (Dry)	2.640	2.600	2.710	0.04	1.58
G_{sb} (SSD)	2.666	2.630	2.740	0.04	1.63
G_{sb} (Apparent)	2.716	2.680	2.800	0.05	1.78
Absorption %	1.0	0.8	1.3	0.20	18.69

In the case of fine extracted aggregates, the following table shows compliance with the limit meaning less variability in the finer side.

Table 3-17 Specific Gravity of Fine Extracted Aggregates

	Average	Minimum	Maximum	Std. Dev. (%)	CV (%)
G_{sb} (Dry)	2.624	2.600	2.650	0.02	0.69
G_{sb} (SSD)	2.660	2.640	2.690	0.02	0.70
G_{sb} (Apparent)	2.718	2.700	2.760	0.02	0.92
Absorption %	1.3	1.0	1.6	0.23	17.74

Table 3-18 and Table 3-19 show the statistical measures of RAP milling gradations and extracted aggregates gradations, considering two cases: only samples from the Del Rio Landfill to evaluate the variability of the stockpile; and all samples including Southwest Asphalt plant to evaluate the effect of processed RAP.

Statistic measures on RAP millings (As Recovered) are presented only for information purposes and the extracted aggregates statistic measures are used to evaluate variability. From this, it can be noticed that the landfill material presents moderate and acceptable variability considering all size sieves including the passing No.200.

Comparing landfill with the processed RAP from Southwest Asphalt plant, variability shows an increase falling out of the maximum in the guidelines. Specially between 3/8 in. and No.8 sizes (median sieve).

Table 3-18 Statistical Measures of RAP Millings Gradation from Del Rio Landfill and Southwest Asphalt Plant Samples

Sieve size	Average		Maximum and Minimum				Landfill + SW Plant				Landfill only			
	Dry	Washed	Dry		Washed		Dry	Washed	Dry	Washed	Dry	Washed	Dry	Washed
	Average cumulative % passing		Maximum % Passing	Minimum % Passing	Maximum % Passing	Minimum % Passing	Standard Deviation (%)		Coeff. of Variation (%)		Standard Deviation (%)		Coeff. of Variation (%)	
1 in	97	97	100	95	100	95	2.0	2.0	2.0	2.0	0.7	0.7	0.8	0.8
3/4 in.	92	92	100	89	100	88	4.6	4.6	5.0	5.0	1.5	1.4	1.7	1.6
1/2 in.	80	80	89	76	89	76	5.6	5.6	7.0	7.1	2.1	2.1	2.7	2.7
3/8 in.	68	68	77	63	76	63	5.2	5.2	7.5	7.6	2.4	2.4	3.7	3.6
#4	44	44	48	37	48	37	4.4	4.4	10.0	10.1	4.9	4.8	11.1	11.2
#8	29	28	35	20	34	20	5.5	5.5	19.1	19.7	6.4	6.3	21.9	22.5
#30	11	10	13	7	12	6	2.8	2.6	25.9	27.4	3.1	2.9	27.2	29.2
#50	5	4	7	3	6	3	1.5	1.3	28.2	31.0	1.5	1.3	26.4	29.6
#100	2	1	3	2	1	1	0.7	0.3	28.8	25.5	0.7	0.3	26.5	24.8
#200	1	0	2	1	0	0	0.4	0.0	41.3	---	0.4	0.0	38.2	---

Table 3-19 Statistical Measures of Extracted Aggregates Gradation from Del Rio Landfill and Southwest Asphalt Plant Samples

Sieve size	Average		Maximum and Minimum				Landfill + SW Plant				Landfill only			
	Dry	Washed	Dry		Washed		Dry	Washed	Dry	Washed	Dry	Washed	Dry	Washed
	Average cumulative % passing		Maximum % Passing	Minimum % Passing	Maximum % Passing	Minimum % Passing	Standard Deviation (%)		Coeff. of Variation (%)		Standard Deviation (%)		Coeff. of Variation (%)	
1 in	100	100	100	100	100	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3/4 in.	100	100	100	99	100	99	0.4	0.5	0.4	0.5	0.4	0.5	0.4	0.5
1/2 in.	94	94	98	91	98	90	3.1	3.2	3.3	3.4	2.7	2.8	2.9	2.9
3/8 in.	86	85	92	77	91	76	5.6	5.8	6.5	6.8	3.0	3.0	3.4	3.5
#4	66	63	72	51	69	49	8.3	8.4	12.7	13.4	2.4	2.4	3.4	3.6
#8	49	46	58	36	56	32	8.4	8.5	16.9	18.6	3.8	4.5	7.3	9.1
#30	26	21	29	18	25	13	4.6	4.3	17.9	20.8	1.0	1.8	3.5	7.9
#40	20	15	22	14	17	9	3.8	3.2	18.5	21.4	0.3	0.8	1.3	4.7
#50	16	10	18	11	11	6	3.1	2.3	19.3	22.4	0.8	0.1	4.8	1.1
#100	10	4	12	7	5	2	2.0	1.0	21.0	25.6	1.2	0.4	11.9	8.8
#200	6	0	7	4	0	0	1.3	0.0	23.2	---	1.0	0.0	16.0	---

The overall results show that binder content of RAP is a characteristic that must be adequately controlled in order to have uniform HMA mixes with RAP, since the variability is considerable. In the other hand, aggregate gradation showed acceptable variability confirming what was found in the literature, that since aggregates were previously controlled during original mixture manufacture, recovered gradations usually falls with acceptable limits.

Landfill samples showed pretty good consistency about the gradation of the aggregates, but stockpile management must be improved in order to reduce standard deviations in the binder content.

It is worth to be noted that sampling practices can have a significant effect on variability results.

Comparing the results of all samples showed that the processed RAP has an expected effect on the aggregate variability, especially in the middle size range of the particles.

4. Mix Design Procedure

4.1. Introduction

Hot mix recycling is basically the process where reclaimed asphalt pavement materials are combined with virgin aggregates and asphalt binder to produce hot mix asphalt mixtures. To ensure an adequate performance, mixtures must be designed properly and similar properties as conventional mixes can be accomplished.

One of the main tasks in the scope of this project is to develop a customized mix design procedure to be followed for the preliminary laboratory evaluation of asphalt mixtures containing RAP. The present chapter describes the steps considered in the procedure and presents the results obtained for the evaluated mixtures. Mix design was developed based on the current national practices and following basically the Superpave mixture design method, which integrates the project climate and design traffic. Fundamentally, it involves two main steps: a) material selection and evaluation, to determine the properties of the component materials, and b) the mix design properly, to combine the materials and determine the type and percentage of asphalt binder [61].

Superpave mix design method including RAP is almost the same as for virgin mixtures with some differences that include the following [17]:

- For blending and weighing RAP aggregate is treated like another stockpile but must be heated moderately to avoid changing the binder properties.
- RAP aggregate specific gravity must be estimated.
- RAP binder weight must be accounted for, when batching aggregates.

- The total asphalt content must be reduced to compensate the contribution of the RAP binder.
- Depending on the RAP content, a change in virgin binder grade may be needed to accomplish final binder grade and stiffness.

The specific steps followed by the RAP mix design procedure are:

1) Selection of materials:
   - Sampling. Obtain representative field samples of the virgin and recycled materials.
   - Determine RAP composition and properties.
   - Determine proper amounts of virgin aggregates to be added.
   - Select type, grade, and amount of virgin asphalt binder.
2) Selection of design aggregate structure:
   - Mixing, compaction, evaluation and selection of trial blends.
3) Selection of design asphalt binder content:
   - Compaction.
   - Mixture properties.
   - Selection of optimum binder content.
4) Mix design verification of the design criteria.

Superpave method is based on asphalt binder performance specification, where the performance grade of the binder (PG grade) is designed to improve the HMA pavement performance at three temperatures: High temperature during summer, to minimize rutting (DSR factor $G^*/\sin\delta$); service intermediate temperature to minimize fatigue cracking (DSR factor G*sinδ); and low temperature during winter, to minimize low temperature cracking (BBR maximum creep stiffness S and m-value). PG grading system specifies two numbers representing high and low service temperatures prevailing at the project site. The method also involves volumetric mix design and the use of the Superpave gyratory compactor (SGC) [61].

For mix design criteria, the parameters stablished in Section 710 (Asphalt Concrete) of the 2015 City of Phoenix Supplement to MAG Uniform Standard Specifications for "Gyratory Mix Design Criteria" were used [29]. That specification follows the requirements of the Asphalt Institute SP-2 Manual for new HMA mixtures. Mix design procedure including RAP is detailed in the sections below and is based on the recommended procedure by NCHRP Report 452 [17]. Subsequently, summaries of the different evaluated mixtures made are also presented.

4.2. Selection of Materials

4.2.1. *Sampling*

Representative samples from different locations of the RAP stockpiles must be obtained. General practices recommend 10 samples per mix design. Segregation should be minimized and the minimum recommended sample size should be 11 lb. (5 kg). At least, half of the sample will be used for characterization and the other half for mix design. In the present project, for research purposes, a total of 7 samples of about 132 lb. (60 kg) were taken. Sampling standards and the procedure followed is described in 3.

4.2.2. *RAP Properties Determination and Evaluation*

RAP material needs to be evaluated because aging and oxidation might change significantly the material properties, including binder loss of the lighter fractions, increase in asphaltenes and viscosity, and loss of ductility; as well as changes in aggregate gradations due to degradation by traffic loads and the environment [61]. The following describes the main steps:

1) Extraction of RAP binder and determination of binder content (Pb) following the extraction process described in point 3.3.2 of 3. If testing of RAP binder properties is anticipated extraction and recovery will be needed.
2) Determination of RAP aggregate gradation following the extraction process described in 3.3.2 and testing from point 3.3.1 of 3.
3) Determination of RAP consensus properties. This step is recommended but optional since these properties must be complied by the final aggregate mix (virgin + RAP), and because usually RAP aggregates met specifications when originally manufactured. Consensus Properties include coarse and fine aggregate angularity (to ensure high degree of internal friction, high shear strength and rutting resistance); flat and elongated particles (limited to ensure no aggregate breakage during handling, construction, and service); and clay content (limited to ensure enhancement of the adhesive bond between binder and aggregate) [62].
4) Estimation of the desired RAP content following AASHTO M323 three-tier system [12] (see Table 4-1). Test RAP binder properties as outlined in point 3.3.3 3, if required.

Table 4-1 Binder Selection Guidelines for Reclaimed Asphalt Pavement (RAP) Mixtures

Recommended Virgin Asphalt Binder Grade	RAP Percentage
No change in binder selection	<15%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	15-25%
Follow recommendations from blending charts	>25%

5) Measurement of the maximum theoretical specific gravity (Gmm) of the RAP according to AASHTO T209 [63].

6) Estimation of RAP aggregate specific gravity using the effective specific gravity (Gse) or calculate the bulk specific gravity (Gmb) based on assumed asphalt absorption. (See 4.6).

4.2.3. *Select Virgin Asphalt Binder*

Superpave approach uses performance graded binders (PG binders), where the desired virgin binder grade is selected based on the climate and the traffic level for the specific project where the mix will be used. The selection of the virgin binder follows the next steps:

1) Determination of project weather conditions using weather database. City of Phoenix specifications dictates the use of PG 64-16 or PG 70-10, unless otherwise specified.

2) Binder adjustment. If required, binder grade can be adjusted based on desired RAP content (see Table 4-1).

3) Determination of temperature and viscosity relationship for lab mixing and compaction temperature ranges based on virgin binder grade. Follow testing for binder apparent viscosity, AASHTO T316 [64].

4.2.4. *Selection of Virgin Aggregates*

This is an important step since the design aggregate structure will ensure the development of a strong stone skeleton to improve rutting resistance and allow sufficient void space to develop mixture durability. Therefore, the properties of the material must be verified:

1) Measurement of consensus properties (recommended, but optional (see 4.2.2, 3)).
    a. Combined gradation. Superpave uses the 0.45 power gradation chart with gradation control limits and a restricted zone to develop a design aggregate structure. The chart shows the cumulative particle size distribution of an aggregate blend. The restricted zone is used to avoid mixtures that have a significant proportion of fine sand relative to the total sand, and to avoid gradations that follow the maximum density line. This line represents the maximum density gradation where the aggregate particles fit together in their densest possible arrangement [62]. Superpave recommends to avoid the restricted zone but it is not a requirement, and there are discrepancies in the general practice regarding this point.
    b. Coarse and fine aggregate angularity.
    c. Flat and elongated particles.

d. Clay content.

2) Determination of source properties as toughness (resistance to abrasion measured by LA abrasion test); soundness (resistance to in-service weathering measured by sodium or magnesium sulfate test); and deleterious materials (contaminant materials measured by clay lumps and friable particles test). Measurement of specific gravities.

4.3. Selection of Design Aggregate Structure

1) Establishment of Trial Blends. Based on the gradations from the virgin and RAP aggregates, the combination must meet the desired specification requirements. The amount of both type of aggregates in the blend would be expressed as percentages. The total blend must pass between the control points and is recommended to avoid the restricted zone (see 4.2.4, 1)). To define the trial blends the next guidelines can be followed:

   a. Select trial percentage(s) of the RAP aggregate. The decision will be based on specification limits, economics, aggregate gradations and consensus properties, plant type and capacity, and binder properties. The present procedure contemplates the use up to 15% RAP.

   b. At least three blends must be developed.

   c. Evaluate combined aggregate consensus and source properties. The combined aggregate bulk and apparent specific gravities will be based on the estimated RAP aggregate specific gravity (see 4.6).

2) Compaction of Trial Blend Specimens

d. Estimation of trial asphalt binder content:

- Superpave method. Based on assumed initial values to fill the equations below:

$$Gse = Gsb + AbsorptionFactor(Gsa - Gsb) \tag{4.1}$$

$$V_{ba} = \frac{P_s(1-V_a)}{\left(\frac{P_b}{G_b} + \frac{P_s}{Gse}\right)} \cdot \left(\frac{1}{Gsb} - \frac{1}{Gse}\right) \tag{4.2}$$

$$V_{be} = 0.081 - 0.02931(\ln S_n) \tag{4.3}$$

$$W_s = \frac{P_s(1-V_a)}{\left(\frac{P_b}{G_b} + \frac{P_s}{Gse}\right)} \tag{4.4}$$

$$P_{bi} = \left[\frac{G_b(V_{be}+V_{ba})}{(G_b(V_{be}+V_{ba}))+W_s}\right] \cdot 100\% \tag{4.5}$$

Where:

Gse = effective specific gravity of the combined aggregate

Gsb = bulk specific gravity of the combined aggregate

Gsa = apparent specific gravity of the combined aggregate

G_b = binder specific gravity

V_{ba} = volume of absorbed binder

V_{be} = volume of effective binder

P_b = assumed total binder content (%)

P_s = assumed aggregate content (P_s=100-P_b) (%)

P_{bi} = estimated initial trial binder content (% by weight of total mix)

V_a = volume of design air voids

S_n = nominal maximum sieve size of the largest aggregate in the aggregate trial blend

W_s = mass of the aggregate

Absorption Factor = 0.8 (typical)

- Experience/Engineering judgment method.

e. Decrease amount of binder added to account for RAP binder content.

f. Establishment of trial blend specimens. The same as for virgin HMA. Batch weights are calculated for the gyratory specimens and for Gmm. To provide the proper specimen height gyratory specimens needs approximately between 4600 and 4700 g and Gmm needs about 2000 g per replicate.

g. Determination of number of gyrations based on design traffic level. $N_{initial}$ (initial number of gyrations used as a measure of mixture compactability during construction), N_{design} (design number of gyrations to produce a sample with same density as expected in the field), and N_{max} (number of gyrations required to produce lab density that should never be exceeded in the field). City of Phoenix

(CoP) specifications [29] defines number of gyrations based on two design traffic classes:

Table 4-2 Number of gyrations based on traffic level (extracted from Section 710 of CoP Specifications)

Number of gyrations	Low Traffic	High Traffic
$N_{initial}$	7	8
N_{design}	75	100
N_{max}	115	160

h. Based on AASHTO Provisional Standards low traffic is defined when estimated 20-year design traffic loading is between 0.3 to < 10 million of ESALs and high traffic between 10 to <30 million of ESALs.

i. Batching of trial blend specimens. When batching the RAP aggregate, it is important to remember that part of the RAP weight is binder. Decrease the weight of new binder added by the weight of RAP binder.

j. Mixing of virgin aggregates, RAP, admixture and virgin binder must be mixed together for 90 to 120 seconds at the required lab mixing temperature ±5°F. Mechanical mixing is required.

k. Aging of trial blends. Each sample is heated to the anticipated mixing temperature and aged for 2 hours (for mix design) or for 4 hours (testing sample preparation. Trial blends must be stirred each hour in both cases. RAP heating temperature, time and lab handling procedure is detailed in section 4.7). Mixing and compaction temperatures are selected according to the asphalt binder properties and viscosity level.

l. Compaction of specimens and generation of densification tables. The Superpave gyratory compactor (SGC) is used to make the compacted specimens, simulating the actual field compaction and particle orientation following AASHTO TP4 [65]. Two replicates for each trial blend are made, compacted, and bulked. Mix design specimen dimensions are 6-in. (150 mm) in diameter and around 4.5-in. (115 mm) in height. For testing sample preparation height is about 7-in. (180 mm). Compaction pressure is typically 87 psi (600 kPa). Sample inclination at 1.25°. Rotation at 30 revolutions per minute.

m. Determination of mixture properties (Gmm and Gmb). Usual procedures performed for virgin HMA mixtures. Theoretical maximum specific gravity, Gmm, following ASTM D2041 [66] or AASHTO T209 [63], and Bulk Specific Gravity, Gmb, following AASHTO T166 [67].

3) Evaluation of Trial Blends

a. Determination of %Gmm @ $N_{initial}$ and N_{design} as usual. Values are obtained from the information generated by the SGC software. 4% is the target air voids for mix design.

b. Determination of % Air Voids and % VMA. The VMA calculation will be based on the Gsb as determined in Step 4.3, 1) above.
c. Estimation of asphalt binder content to achieve 4 percent air voids.
d. Estimation of mix properties at estimated asphalt binder content as usual (VFA, absorbed asphalt).
e. Determination of dust-to-asphalt ratio as usual.
f. Comparison of mixture properties to specification criteria as usual.

4) Selection of the most promising design aggregate structure for further analysis.

4.4. Selection of Design Asphalt Binder Content

1) Compaction of Design Aggregate Structure Specimens at Multiple Binder Contents to determine the optimum asphalt binder content.
    a. Batching of design aggregate structure specimens. RAP binder weight must be accounted in the batching process, and the amount of new binder added must be reduced by the weight of the binder provided by the RAP.
    b. Compaction of specimens and generation of densification tables as in previous steps. Two replicates specimens should be compacted at each binder content.
2) Determination of Mixture Properties versus Asphalt Binder Content by graphics as usual.
    a. Determine %Gmm @ $N_{initial}$ and N_{design}.
    b. Determine volumetric properties.

c. Determine dust-to-asphalt ratio.

d. Graph mixture properties versus asphalt binder content.

3) Selection of Design Asphalt Binder Content.

a. Determine asphalt binder content at 4 percent air voids.

b. Determine mixture properties at selected asphalt binder contents.

c. Compare mixture properties to criteria.

4.5. Mix Design Verification

1) Verification of specifications design criteria based on the mix requirements and maximum nominal size of the mixture. Verification of %Gmm @ N_{max}, N_{design} and N_{ini}. The following table shows the required densities following AASHTO Provisional Standards, 2001 Interim Edition.

Table 4-3 Required Densities for N_{max}, N_{design} and $N_{initial}$ (extracted from AASHTO, 2001)

20-yr traffic loading (in millions of ESALs)	Required Density (as a percentage of Theoretical maximum density (TMD))		
	$N_{initial}$	N_{design}	N_{max}
<0.3	≤ 91.5	96.0	≤ 98.0
0.3 to <3	≤ 90.5		
3 to <10	≤ 89.0		
10 to <30			
≥30			

2) Evaluation of the final aggregate blend at the design asphalt binder content for moisture sensitivity using ASTM D4867 [24] or AASHTO T283 [25]. Specimens are compacted between a 6 to 8 air void range. Basically, one subset of three specimens are considered as control specimens (dry condition), and other subset of three specimen is conditioned subjected to a partial vacuum saturation, and to

an optional freeze cycle, followed by a 24-hour thaw cycle at 140°F (60°C). All specimens are tested by the Indirect Tensile Strength (IDT) test. Moisture susceptibility is determined as a ratio between the average tensile strengths of the conditioned subset to the control subset, known as the Tensile Strength Ratio (TSR). TSR must comply at least with the specification minimum percent.

4.6. RAP Specific Gravity

RAP aggregate bulk specific gravity (Gsb) cannot be measured directly, hence it is necessary to estimate it. In order to do the estimation, the next procedure can be followed:

1) The RAP effective specific gravity is calculated based on the RAP maximum specific gravity, which can be determined by conducting AASHTO T209 [63].
    a. The asphalt binder content of RAP can be determined by extraction or ignition process.
    b. The binder specific gravity can be assumed. Based on the Arizona Department of Transportation (ADOT) specifications [16], when >15% RAP binder is used the value must be determined from the tested specific gravity of the recovered and tested RAP binder. When ≤15% RAP binder is used, an estimated specific gravity of 1.050 is used for the RAP binder.
    c. The effective specific gravity is then calculated:

$$Gse = \frac{100 - P_b}{\frac{100}{Gmm} - \frac{P_b}{G_b}} \quad (4.6)$$

Where:

Gse = effective specific gravity of aggregate

Gmm = RAP theoretical maximum specific gravity

P_b = RAP binder content

G_b = specific gravity of RAP binder

2) Absorption of the RAP aggregate is assumed based on past experience with the same virgin aggregates. ADOT's specification states that this value is normally estimated to be 0.50%. An exception is made when the RAP binder content is less than 1.0%, in which case the value is estimated to be one-half of the binder content of the RAP material.

3) Bulk specific gravity can be estimated using the next equation:

$$Gsb = \frac{Gse}{\left(\frac{P_{ba} \cdot G_{se}}{100 \cdot G_b}\right) + 1} \tag{4.7}$$

Where:

Gse = effective specific gravity of aggregate

Gsb = bulk specific gravity of aggregate

P_{ba} = absorbed binder, percent by weight Gsb of aggregate

G_b = specific gravity of RAP binder

4) Finally, with the previous result, the value of the combined aggregate bulk specific gravity can be determined:

$$Gsb = \frac{P_1 + P_2 + \cdots + P_N}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \cdots + \frac{P_N}{G_N}} \tag{4.8}$$

Where:

Gsb = bulk specific gravity of the total aggregate

$P_{1,..N}$ = individual percentages by mass of virgin aggregate and RAP

$G_{1,...N}$ = individual bulk specific gravities of virgin aggregate and RAP

4.7. Handling virgin materials and RAP in the laboratory

Mixing and compaction temperatures must be determined using a viscosity versus temperature plot, corresponding with the binder viscosities of 0.17±0.02 Pa-s and 0.28±0.03 Pa-s respectively (viscosity range not valid for modified asphalt binders). For mixes containing ≤ 15% RAP binder, the mixing and compaction temperatures must be determined based on the virgin binder used [16]. For mixes containing >15% RAP binder, the laboratory temperatures must be determined based on the viscosity-temperature plot developed for the blended binder.

Virgin aggregate must be heated in an oven set approximately between 50 to 59°F (10 to 15°C) higher than the determined mixing temperature. About 2 to 4 hours are required for the aggregate to reach the mixing temperature [62], and the usual practice is to heat up aggregates overnight.

Asphalt binder is also heated to the desired mixing temperature. The time required will be dependent on the amount of binder heated and the heating method. Containers with 300 to 500 g usually take about two hours to reach the mixing temperature with a forced draft oven.

RAP material must be heated to make it workable and to mix with the virgin materials. Heating procedure in this case must be done with care, since RAP has adhered binder. Even though is necessary that RAP is thoroughly heated, heating time should be the minimum required. High temperatures and long heating periods have been shown changes in the RAP properties. Literature shows that there is not a standard procedure for heating RAP, and even worse, practices around the country are varied presenting a variety of temperatures, heating times and procedures. In order to clarify the best way to handle RAP in the lab for mix design, a heating experiment was conducted and is detailed in the following paragraphs.

After mixing, mix design mixtures are short term aged in a draft oven at the mixing compaction for two hours. Testing specimen mixtures are short term aged for four hours at 275°F (135°C).

4.7.1. *RAP Heating Experiment*

To mix RAP with virgin aggregates and binder, RAP must reach the mixing temperature to blend adequately with the rest of the materials. If it is too cold, RAP binder will not be able to be combined with the new binder. And if it is overheated, either by high temperatures or excessive time, RAP binder properties and characteristics could be changed. Therefore, the objective is to be in the range of mixing temperature enough time to soften the binder and allow blending, without affecting the aged RAP binder.

To find an appropriate way to heat RAP for mix design and specimen preparation, a small experiment was conducted were a RAP sample was heated in the oven at the mixing temperature, and the material temperature was monitored to see the evolution of temperature versus time. A detailed description of this experiment is described in Appendix C.

Based on the results of the experiment, it was decided to heat RAP for 60 minutes at the mixing temperature before mixing. To do so, an ADOT's practice was followed, which consist in placing RAP over the virgin aggregate within a crater formed in the surface, to avoid that RAP material touches the metal pan. In that way heat is mostly transferred from the virgin aggregates without further affection to the aged RAP binder.

4.8. City of Phoenix Gyratory Mix Design Criteria

Section 710 for Asphalt Concrete of the 2015 City of Phoenix Supplement to the 2015 Edition Maricopa Association of Governments Uniform Standard Specifications for Public Works Construction [29], gives the mix design criteria for mixes under Superpave gyratory compaction. The following table is extracted from the specification and show all the required parameters:

Table 4-4 Gyratory Mix Design Criteria (extracted from Table 710-3 of Section 710 of CoP Specifications)

Criteria	Requirements			Designated Test Method
	3/8" Mix	1/2" Mix	3/4" Mix	
Voids in Mineral Aggregate (VMA): %, Min.	15.0	14.0	13.0	AI SP-2
Effective Voids: %, Range	4.0 +/- 0.2	4.0 +/- 0.2	4.0 +/- 0.2	AI SP-2
Absorbed Asphalt: %, range*	0 – 1.0	0 – 1.0	0 – 1.0	AI SP-2
Dust to Eff. Asphalt Ratio, Range**	0.6 – 1.4	0.6 – 1.4	0.6 – 1.4	AI SP-2
Tensile Strength Ratio: %, Min.	75	75	75	ASTM D4867
Dry Tensile Strength: psi, Min.	75	75	75	ASTM D4867
Mineral Aggregate Grading Limits				**AASHTO T27**
Sieve Size		**3/8-inch Mix**	**1/2-inch Mix**	**3/4-inch Mix**
1 inch				100
3/4 inch			100	90 – 100
1/2 inch		100	90 – 100	43 – 89
3/8 inch		90 – 100	53 – 89	-
No.8		32 – 47	29 – 40	24 – 36

No.40	2 – 24	3 – 20	3 – 18
No.200	2.0 – 8.0	2.0 – 7.5	2.0 – 6.5
Number of Gyrations	**Low Traffic**		**High Traffic**
N_{ini}	7		8
N_{des}	75		100
N_{max}	115		160

*Unless otherwise approved by the Engineer.
**The ratio of the mix design composite gradation target for the No.200 sieve, including admixture, to the effective asphalt content shall be within the indicated range.

Material:

- Asphalt: PG 64-16 or PG 70-10 (unless otherwise specified in the special provisions).
- Aggregate: Coarse and fine aggregates limited by No.4 sieve. Blending sand can be natural or crushed fines.
- Combined aggregates: at least 85% of the aggregate retained on No.8 shall have at least one rough, angular surface produced by crushing.
- With/without mineral filler and Anti-Stripping agent: Mineral filler conform to AASHTO M-17. Dry hydrated lime (ASTM C1097) or Portland cement or other.

4.9. Project Mix Designs

4.9.1. *Mix Requirements*

In consensus with the City of Phoenix, it was defined to evaluate three different mixtures, a control mix (0% RAP), and two low RAP mixtures with 10% and 15% RAP. City of Phoenix gyratory design criteria was used to control all the designs. The designs were prepared for a 3/4-inch (19 mm) mix to be used as either a surface course or as an asphalt base layer for local roads with low traffic. Virgin aggregates and processed RAP from Southwest Asphalt plant from El Mirage were used, as well as PG 70-10 Virgin binder from Western Refining from their Phoenix terminal. The mix design procedure described before was followed, and the details are presented in the following sections.

To complement the project findings and as an additional objective of the present thesis, supplementary mixes were performed to evaluate the effect of mid to high RAP contents, and 25% RAP mixes were decided to be analyzed. In this case, the goal was to evaluate the effect of using a stiffer binder as the City's allowed PG 70-10 and also to follow the AASHTO recommendations of reducing one grade binder when the amount of RAP is in the second tier (between 15% and 25%). For this purpose, a Softer Binder (designated as SB in the rest of the text) PG 64-16 was used, also following the City's specifications. The mixture data and the performance test results for the 25% RAP with a PG 70-10 binder were extracted from the thesis work of Phani Sasank Kaligotla, titled: "Performance Evaluation of Reclaimed Asphalt Pavement Mixtures Modified with Organosilane Additives" [68], since this mixture was performed using the same materials and procedures described in the present thesis.

4.9.2. *RAP Properties Determination and Evaluation*

Even though, for mixtures containing < 15% RAP, recovery and testing of RAP binder is not required, binder testing was conducted for research purposes. The procedure and results are reported in 3.

1) RAP Binder content (Pb): 3.81%
2) Extracted RAP aggregate gradation process is detailed in 3. The following figure shows the gradation. Nominal maximum aggregate size 3/4 inch.

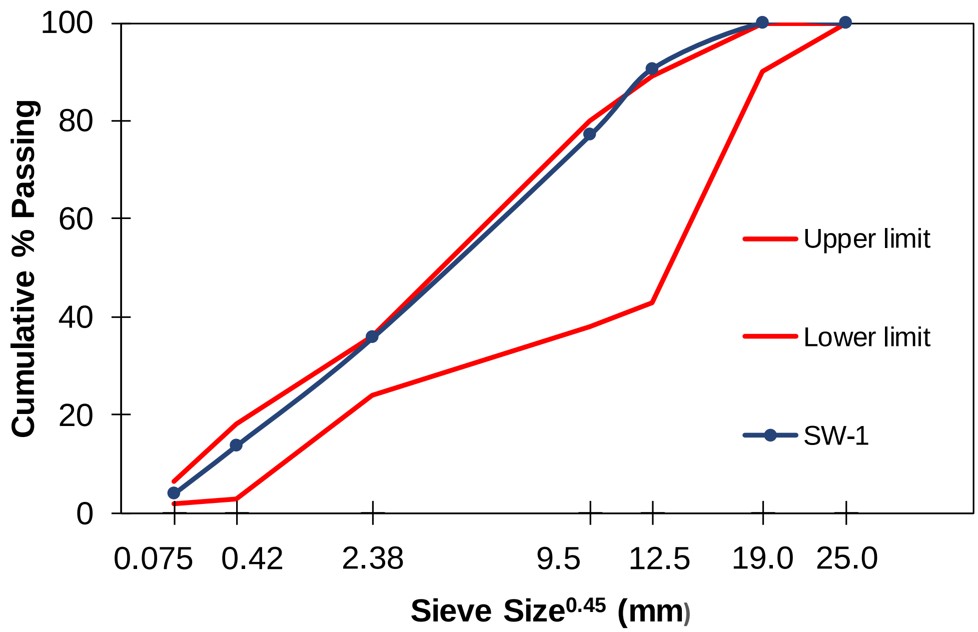

Figure 4-1 Extracted RAP aggregate gradation and 3/4 in. mix specifications (Southwest Asphalt Plant).

3) RAP consensus properties: Southwest Asphalt laboratory constantly verifies their material properties and those were adopted for the project.
4) RAP content: 10%, 15% and 25%.
5) RAP Maximum theoretical specific gravity (Gmm), RAP aggregate specific gravity, effective specific gravity (Gse) based on assumed asphalt absorption.

Table 4-5 RAP Specific Gravity

RAP Gmm Replicate-1	2.549
RAP Gmm Replicate-2	2.559
Average RAP Gmm	2.554
RAP binder content (%)	3.81
Assumed binder Spec. Gravity	1.05
Assumed binder absorption (%)	0.5
Gse (RAP)	2.707
Gsb (RAP)	2.673
Water absorption	1.302
Gssdb (RAP)	2.708
Gsa (RAP)	2.769

4.9.3. *Selection of Virgin Asphalt Binder*

1) City of Phoenix specifications dictates the use of PG 64-16 or PG 70-10. PG 70-10 was used for control (0%), 10%, 15% and 25% RAP. An additional 25% RAP mix was performed with a PG 64-16 as a Softer Binder (SB).
2) For 10% and 15% RAP, no binder adjustment was made since RAP contents fall in the first tier (see Table 4-1). Even though for RAP contents <15% binder testing is not required, Chapter 3 shows the testing conducted on the recovered binders for research purposes. RAP binder is equivalent to a PG 112+14.
3) Virgin binder specific gravities are:

PG 70-10 Binder specific gravity:	1.0244 @ 60°F
	1.0184 @ 77°F
PG 64-16 Binder specific gravity:	1.0183 @ 60°F
	1.0123 @ 77°F

4) Mixing and compaction temperature. Western Refining provided temperature ranges:

For PG 70-10:	
Mixing temperature range:	315 – 326°F (157 – 163°C)
Compaction temperature range:	296 – 304°F (147 – 151°C)
For PG 64-16:	
Mixing temperature range:	303 – 314°F (151 – 157°C)
Compaction temperature range:	283 – 291°F (139 – 144°C)

The higher range limit was used for mixing to ensure proper heating of the RAP material (326°F (163°C) and 314°F (157°C) respectively). Compaction was conducted at the average range (300°F (149°C) and 287°F (142°C) respectively for both binders).

4.9.4. *Selection of Virgin Aggregates*

Virgin aggregates from Southwest Asphalt plant from M.R. Tanner El Mirage Pit were sampled to perform the mix designs. The materials were designated as 3/4 in. aggregate, 3/8 in. aggregate, crusher fines (CF) and blend sand (BS). Type N hydrated lime from Lhoist North America was used as mineral admixture.

1) Consensus and source properties. Southwest Asphalt laboratory constantly verifies their material properties and those were adopted for the project.

Gradation:

Table 4-6 Virgin aggregates gradations

Sieve Sizes	Percent Passing			
	3/4"	3/8"	CF	BS
1 in.	100	100	100	100
3/4 in.	100	100	100	100
1/2 in.	62	100	100	100
3/8 in.	25	100	100	100
1/4 in.	3	65	100	100
#4	5	33	100	100
#8	2	5	74	88
#16	2	4	50	67
#30	3	3	35	39
#40	2	4	29	24
#50	4	3	25	13
#100	1	2	18	5
#200	1.0	2.4	12.4	3.1

Specific gravities:

Table 4-7 Virgin aggregates specific gravities

Material % used	**3/4"**	**3/8"**	**CF**	**BS**
Bulk OD (Gsb)	2.659	2.620	2.645	2.610
SSD (Gssdb)	2.689	2.661	2.677	2.648
Apparent (Gsa)	2.741	2.733	2.732	2.714
Absorption (%)	1.13	1.57	1.19	1.46

4.10. Selection of Design Aggregate Structure

Establishment of Trial Blends. For the present case and under research perspective, an exception to the normal procedure previously described was made. An initial aggregate gradation was assumed, based on the Type C-3/4" Marshall asphalt concrete of City of Phoenix specifications, considered as any random trial blend to be verified by mix design. At the end of the process, the chosen trial gradation satisfied the Superpave mix design criteria. City of Phoenix Gyratory Mix Design Criteria has slight adjustments compared to Superpave guidelines. It specifies slight coarser gradations specially for No. 8 sieve, where, as can be seen in Figure 4-3, the chosen and verified aggregate gradation exceeds the limits for that sieve. The gradation of the available material stockpiles and the final virgin aggregate blend is shown in the table below.

Table 4-8 Final Blending of Virgin Aggregates for Mix Design

Sieve Sizes	Cum % Passing						
	3/4"	3/8"	CF	BS	Admix	Blend	
	% Used						
	38	12	16.8	33.2	1.1	w/o admix	w/admix
1 in.	100	100	100	100	100	100	100
3/4 in.	100	100	100	100	100	100	100
1/2 in.	62	100	100	100	100	86	86
3/8 in.	25	100	100	100	100	72	72
1/4 in.	3	65	100	100	100	59	59
#4	5	33	100	100	100	56	56
#8	2	5	74	88	100	43	43
#16	2	4	50	67	100	32	32
#30	3	3	35	39	100	20	21
#40	2	4	29	24	100	14	15
#50	4	3	25	13	100	10	11
#100	1	2	18	5	100	5	6
#200	1.0	2.4	12.4	3.1	100.0	3.8	4.8

Figure 4-2 shows the gradation of the final aggregate blend using the 0.45 power gradation chart, presenting the Superpave limits and restriction zone for a 3/4 in. mix.

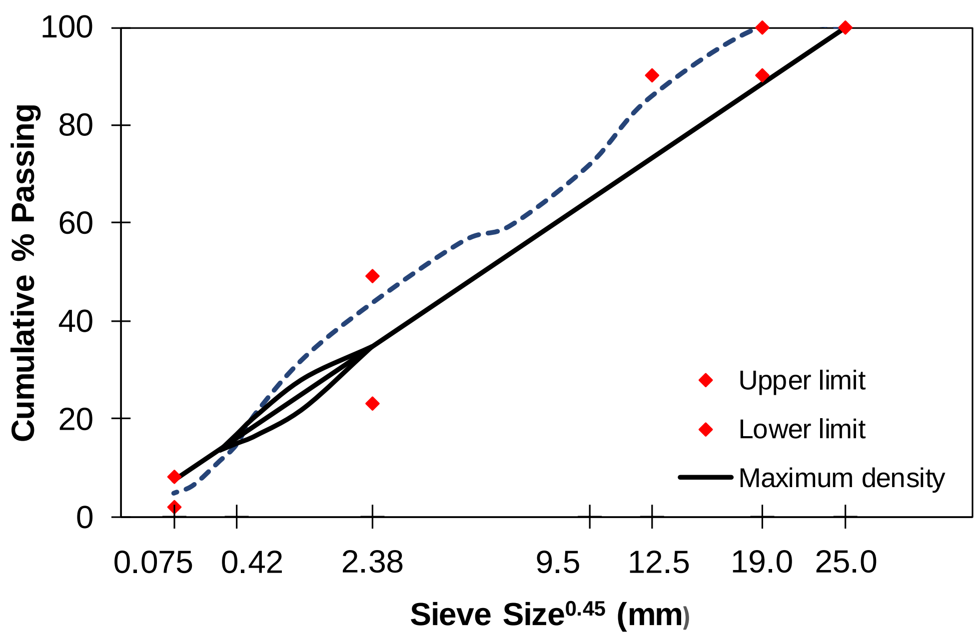

Figure 4-2 Final aggregate gradation for mix design and 3/4 in. Superpave specifications

The following figure shows the gradation comparing to City of Phoenix gradation criteria. As explained before, the gradation is slightly off the limits for sieve No. 8.

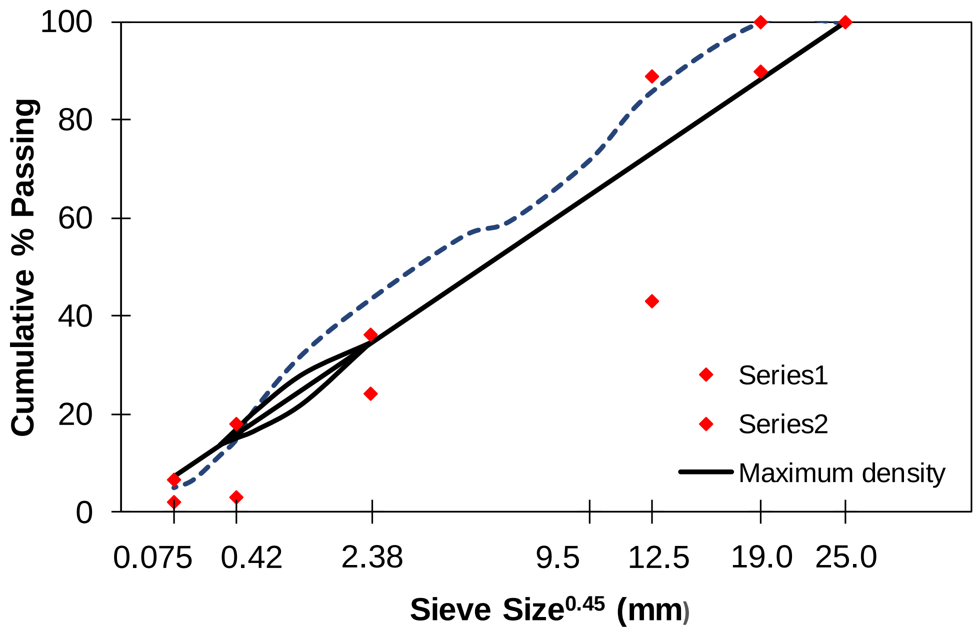

Figure 4-3 Final aggregate gradation for mix design and 3/4 in. City of Phoenix specifications

Regarding RAP gradation for the research project, in order to have a better control on the mixture, RAP was substituted for each individual size by the amount selected for each RAP content (10%, 15% and 25%). Table 4-9, Table 4-10, Table 4-11 and Table 4-12 show the specific gravities for the combined materials for all four mixes. Coarse aggregate (CA) and fine aggregate (FA) are combined from the material stockpiles.

Table 4-9 Combined Specific Gravities for Control Mix (0% RAP)

Material	3/4"	3/8"	CF	BS	CA	FA	Comb. Agg.	Admix	Comb. Agg w/Admix
% used	38	12	16.8	33.2	50	50		1.1	
Bulk OD (Gsb)	2.659	2.620	2.645	2.610	2.650	2.622	2.636	2.2	2.630
SSD (Gssdb)	2.689	2.661	2.677	2.648	2.682	2.658	2.670	2.2	2.664
Apparent (Gsa)	2.741	2.733	2.732	2.714	2.739	2.720	2.730	2.2	2.722
Absorption (%)	1.13	1.57	1.19	1.46	1.211	1.357	1.280	0.9	1.274

Table 4-10 Combined Specific Gravities for 10% RAP

Material	**CA**	**FA**	**Comb. Agg.**	**Admix**	**Comb. Agg w/Admix**	**RAP**	**Comb. Virgin +RAP+Admix**
% used	**50**	**50**	**90**	**1.0**		**10**	
Bulk OD (Gsb)	2.650	2.622	2.636	2.2	2.630	2.673	2.634
SSD (Gssdb)	2.682	2.658	2.670	2.2	2.664	2.708	2.668
Apparent (Gsa)	2.739	2.720	2.730	2.2	2.723	2.769	2.727
Absorption (%)	1.236	1.369	1.302	0	1.289	1.302	1.289

Table 4-11 Combined Specific Gravities for 15% RAP

Material	**CA**	**FA**	**Comb. Agg.**	**Admix**	**Comb. Agg w/Admix**	**RAP**	**Comb. Virgin +RAP+Admix**
% used	**50**	**50**	**85**	**1.1**		**15**	
Bulk OD (Gsb)	2.650	2.622	2.636	2.2	2.630	2.673	2.635
SSD (Gssdb)	2.682	2.658	2.670	2.2	2.664	2.708	2.669
Apparent (Gsa)	2.739	2.720	2.730	2.2	2.722	2.769	2.728
Absorption (%)	1.236	1.369	1.302	0	1.288	1.302	1.288

Table 4-12 Combined Specific Gravities for 25% RAP

Material	**CA**	**FA**	**Comb. Agg.**	**Admix**	**Comb. Agg w/Admix**	**RAP**	**Comb. Virgin +RAP+Admix**
% used	**50**	**50**	**85**	**1.1**		**25**	
Bulk OD (Gsb)	2.650	2.622	2.636	2.2	2.630	2.673	2.639
SSD (Gssdb)	2.682	2.658	2.670	2.2	2.664	2.708	2.673
Apparent (Gsa)	2.739	2.720	2.730	2.2	2.722	2.769	2.732
Absorption (%)	1.236	1.369	1.302	0	1.288	1.302	1.288

4.11. Selection of Design Asphalt Binder Content

1) Three different binder contents were chosen for each mix to determine the optimum asphalt binder content.

Table 4-13 Selection of Asphalt Binder Contents for Mix Design

Mix	**% Binder 1**	**% Binder 2**	**% Binder 3**
0% RAP	4.5	5.0	5.5
10% RAP	5.0	5.5	6.0
15% RAP	5.0	5.5	6.0
25% RAP	5.0	5.5	6.0

2) Batching of trial blend specimens. RAP binder weight correspondent to 3.81% was accounted in the batching process, the amount of new binder added was reduced by the weight of the binder provided by the RAP. The aggregate batching weights are shown in Appendix D – Mix Design.
3) For compaction of specimens considering low traffic (estimated 20-year design traffic loading between 0.3 to < 10 million of ESALs), the number of gyrations is: $N_{initial}$ = 7, N_{design} = 75, and N_{max} = 115.
4) Mechanical mixing of virgin aggregates, RAP, admixture and virgin binder was performed for 90 seconds at the mixing temperature depending on the binder.
5) Mixtures were short aged for 2 hours at the mixing temperature depending on the binder 326°F (163°C) and 314°F (157°C) for PG 70-10 and PG 64-16 respectively (for mix design) and for 4 hours at 275°F (135°C) for testing specimen preparation. Mixtures were stirred every hour. RAP was heated 1-hour prior mixing at the mixing temperature.
6) Compaction of specimens and generation of densification tables. Two replicates for each trial blend were made, compacted, and bulked. Tables and values are presented in Appendix D.
7) Determination of mixture properties (Gmm and Gmb). Values presented in Appendix D.
8) Evaluation of Trial Blends, determination of Mixture Properties versus Asphalt Binder Content, %Gmm @ $N_{initial}$ and N_{design}, volumetric properties, dust-to-asphalt ratio are presented in Appendix D.

9) Determination of mixture properties at selected asphalt binder contents are presented on Appendix D. Table 4-14 summarizes the final blends comparing the mixtures properties to criteria.

4.12. Mix Design Verification

1) The following table shows the verification of the mix designs with the specifications and design criteria.
2) Evaluation of moisture sensitivity by the Tensile Strength Ratio (TSR) is detailed in Chapter 5.

Table 4-14 Mix Design Summary (0%, 10% and 15% RAP)

Mix Property	Criteria 3/4" Mix	0%	10%	15%	Specifications
Asphalt Binder (%)		5.02	5.17	5.37	
Air Voids (%)	4.0+/-0.2	4.00	4.00	4.00	
VMA (%)	13 min.	14.76	14.05	13.45	Pass
VFA (%)	65 - 78	72.59	71.63	70.33	Pass
Absorbed Asphalt (%)	0 - 1.0	0.40	0.32	0.30	Pass
Dust Proportion	0.6 - 1.4	1.03	0.99	0.94	Pass
%Gmm@N_{ini} = 7	less than 90.5	89.42	89.33	89.34	Pass
%Gmm@N_{max} = 115	less than 98	97.01	96.94	96.94	Pass
Eff. Asphalt content (%)		4.64	4.87	5.08	
P0.075		4.80	4.80	4.80	
Total Binder (%)		5.02	5.17	5.37	(by weight of total mix)
Added Virgin Binder (%)		5.02	4.80	4.82	(by weight of total mix)
Contributed RAP Binder (%)		0.00	0.37	0.55	(by weight of total mix)
Gmm		2.458	2.452	2.445	
Gsb		2.629	2.634	2.635	

Table 4-15 Mix Design Summary (0%, 25% and 25% SB RAP)

Mix Property	Criteria 3/4" Mix	0%	25% (*)	25% SB	Specifications
Asphalt Binder (%)		5.02	5.75	5.02	
Air Voids (%)	4.0+/-0.2	4.00	4.00	4.00	
VMA (%)	13 min.	14.76	15.10	14.68	Pass
VFA (%)	65 - 78	72.59	74.79	72.76	Pass
Absorbed Asphalt (%)	0 - 1.0	0.40	0.25	0.25	Pass
Dust Proportion	0.6 - 1.4	1.03	0.87	1.02	Pass
%Gmm@N_{ini} = 7	less than 90.5	89.42	88.76	88.64	Pass
%Gmm@N_{max} = 115	less than 98	97.01	97.02	97.02	Pass
Eff. Asphalt content (%)		4.64	5.52	4.79	
P0.075		4.80	4.80	4.90	
Total Binder (%)		5.02	5.75	5.02	(by weight of total mix)
Added Virgin Binder (%)		5.02	4.80	4.07	(by weight of total mix)
Contributed RAP Binder (%)		0.00	0.95	0.95	(by weight of total mix)
Gmm		2.458	2.476	2.456	
Gsb		2.629	2.639	2.639	

(*) Information extracted from Kaligotla, P.S.

VMA and VFA show decrement as RAP percentage increases for low RAP contents (10% and 15%) compared to control mix, and for 25% there is an increase in the values, being less for the mix with the softer binder. According to the literature, studies report contradictions to this matter; some reporting increments and others decrements when increasing percentages of recycled materials or when using different types of RAP. In addition, addressing this as a function of other factors as gradations, effective asphalt content, additives, rather than only for the use of higher RAP contents [9]. The optimum binder content increased as RAP content was increased when using the same binder. For the softer binder, the asphalt content decreased to a similar value as the control mix.

One aspect that is worth mentioning the fact that general practice recommends fractionating RAP to have a better control of the gradation and asphalt content in the stockpile [9]. Fractionation is the act of processing and separating RAP into at least two sizes, typically coarse and fine fractions [5] using, for example, the 4.75 mm (No.4) sieve, so RAP can be analyzed as two separate fractions. This is because the asphalt content of finer RAP particles is generally higher than the coarse RAP, and therefore fractionation will also help in the control of the RAP asphalt content and minimization of dust content [9].

For the present study and to have a better control of the mixtures in the laboratory, instead of replacing the virgin aggregates by just to fractions of the RAP, the substitution was conducted for each sieve size. For the binder content calculations and the laboratory materials proportioning, the overall RAP binder content was only considered and could have affected the real final binder content of the mixes. However, the determination of the binder content for each RAP size is very costly and not practical. This can be one reason explaining the increasing amount of total binder content as RAP percentage increases.

Even though there is a believe that fractionation is required to improve the consistency of RAP, data gathered by NCAT from contractors across the country showed that fractionated RAP stockpiles were no more consistent than processed unfractionated stockpiles [5].

5. Laboratory Testing and Evaluation

5.1. Introduction

Performance tests relate laboratory mix design to field performance. A series of mix performance tests were conducted on the specimens made with the different mix designs described in 4. This included the dynamic modulus (E*) as a fundamental property of the material related to mixture stiffness, the Flow Number test (FN) for the evaluation of permanent deformation (rutting) potential, and moisture damage susceptibility was evaluated using the Tensile Strength Ratio (TSR) test, which is based on the Indirect Tension Test (IDT).

To get a better picture of the relationship between laboratory and field performance, a powerful tool for assessment are performance models. These are algorithms that can predict pavement performance based on laboratory test results. The latest mechanical-empirical pavement design method has these models as a fundamental part of its methodology.

The present Chapter describes the three fundamental laboratory performance tests conducted on the control (0%RAP), 10%, 15% and 25% RAP mixes; and present the main results and conclusions.

5.2. Mixture Performance Tests

5.2.1. Dynamic Modulus

Dynamic modulus tests were conducted using a IPC Global universal testing machine, which is shown in Table 2-3. The conditioning chamber keeps the samples within the test temperature ranges. LVDTs are used to measure the strains and an actuator loads the sample. Mix design samples were compacted in a Superpave gyratory compactor (SGC) to dimensions of 150 mm in diameter and 180 mm height. Once cooled, the compacted samples were cut and cored to yield specimens 100 mm in diameter by 150 mm height. The air void content was then determined and verified to be within a range of 6 ± 0.5 %. Specimens outside the range were discarded.

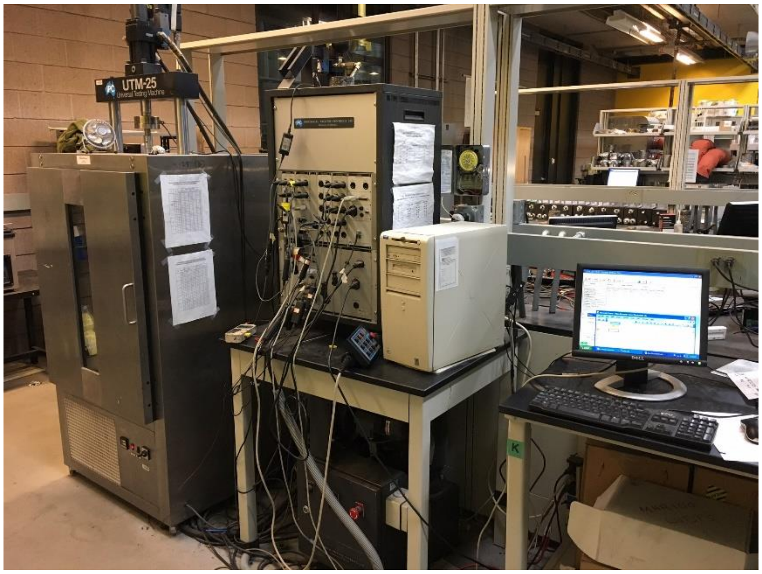

Figure 5-1 Universal testing machine to perform Dynamic Complex Modulus

LVDT mounting buttons were glued onto each specimen in 120° intervals around the specimens. Instrumentation to support LVDTs were attached to the specimens. Specimens were placed in the environmental chamber and conditioned at the desired test temperature for 8 hours. Five test temperatures were used, starting with the lowest temperature. Testing temperatures were 14, 40, 70, 100, and 130°F (-10, 4.4, 21.1, 37.8, and 54.4°C). At each test temperature, the specimens were tested at six frequencies: 0.1, 0.5, 1, 5, 10, and 25 Hz. For each test temperature, the highest frequency was tested first, and the lowest frequency was tested last. A confining pressure of 20 psi was used during testing at all temperatures and frequencies. Three replicate specimens were prepared and tested for each mix (0%, 10% and 15% RAP). To ensure data quality, the maximum coefficient of variation (CV%) between replicates was verified. If the results for a set exceeded that limit, additional specimens were prepared and tested.

Based on the results obtained by the test from the frequency sweeps, and for the average of the three replicates, the complex modulus for each mix was plotted conforming isothermal curves. The time and reduced time, and shifting factors were calculated. The predicted Dynamic modulus were calculated and the fitting coefficients were estimated. The Master curves were constructed horizontally shifting the individual isothermal curves (time – temperature superposition) by the Shift Factor (a(t)). The reference temperature was 70°F (21.1°C). The master curves were plotted, based on the sigmoidal function that is shown below. The master curves for all three mixes and the fitted coefficients are shown in Appendix 6.

$$\log|E^*| = \alpha + \frac{\beta}{1 + e^{\delta + \gamma \log(f_r)}} \qquad (5.1)$$

$$\mathrm{Log}(at) = aT^2 + bT + c \qquad (5.2)$$

$$\log(f_r) = \log(f) + \log(a(T)) \qquad (5.3)$$

Where

|E*|	= dynamic modulus, psi
f	= loading frequency at the test temperature, Hz
fr	= reduced frequency at the reference temperature, Hz
α, β, δ, γ	= regression coefficients
a(T)	= temperature shift factor

Log(at) = Shifting equation

5.2.2. Flow Number

The preparation and fabrication of the test specimens is the same as for dynamic modulus. Figure 5-2 shows the equipment setup to run Flow Number test that can be performed in the universal testing machine. The conditioning chamber keeps the samples within the test temperature. LVDTs are used to measure the strains and an actuator loads the sample. Three samples for each mix were compacted to a nominal 6%±0.5% air void content, to have comparable specimens with the dynamic modulus samples. Specimens were tested for flow number at the suggested effective temperature for the City of Phoenix of 122°F (50°C).

Prior to testing, specimens were conditioned inside the environmental chamber for 7 hours until the testing temperature was stable. The deviator stress was 58 psi (400 kPa). The flow number is determined by the point at which the specimen exhibits tertiary flow, which is shear deformation at constant volume. The test procedure destroys the samples. During testing it was noticed that the equipment was not able to maintain a constant temperature fluctuating about six degrees (three degrees C) from 120 to 126°F (49 to 52°C). Insulation of the environmental chamber was increased, and there was an improvement in the temperature range, nevertheless, some FN values were obtained within the range described.

Figure 5-2 Universal testing machine to perform Flow Number Test

5.2.3. Tensile Strength Ratio

TSR test was selected because it is the most common moisture damage susceptibility test in the country and is part of the current Superpave mix design method and a requirement of City of Phoenix specifications. By gyratory compaction, three samples of 6 in. (150 mm) in diameter and 7.2 in. (180 mm) in height were produced for each mix design (0, 10 and 15% RAP). After cooling, the samples were cut and cored to a size of 4 in. (100 mm) in diameter and 6 in. (150 mm) in height. Two specimens of 4 in. (100 mm) in diameter and about 2.5 in. (64 mm) thick were cut from each sample, conforming a total of 6 specimens per mix design. To maintain consistency with the rest of the tests, specimens were compacted to 6±0.5% air void content.

Air voids were determined for each specimen (6 samples from each mix) and divided into two subsets of three. The subsets were formed in a way that the average void content of all three specimens were similar to the other subset. One subset was selected as "unconditioned" and the other as "conditioned". The first subset corresponds to the control set (dry condition) and the second to the saturated set (water, freeze and thaw). Freeze-thaw cycle is an optional step in the standard, but in the present case, it was decided to be followed, because this not only help evaluate asphalts performing in cold climate, but rather also accelerates damage in the samples simulating various years of service.

The dry samples were stored at room temperature the conditioned set of specimens were vacuum saturated to between 55 and 80 percent with a partial vacuum pressure of about 350-450 mmHg (47-60 kPa) for about 10 minutes in most cases.

Bulk specific gravity was determined and the specimens were wrapped and stored in plastic bags. After that, conditioned specimens were subjected to one freeze-thaw cycle at −0.4±3.6°F (−18± 2.0°C) for 16 h in the freezer. Later, the samples were immersed in a water bath at 140±1.8°F (60±1.0°C) for 24 hours. Both conditioned and unconditioned specimens were conditioned to 77±1.8°F (25±0.5°C) water bath prior to testing.

After conditioning, specimens were loaded diametrically at a rate of 2 in./min (50 mm/min) in the IDT machine. The maximum compressive force was recorded and then the indirect tensile strength and tensile strength ratios were calculated. The ratio of the average tensile strengths of the conditioned specimens to the average tensile strengths of the unconditioned specimens is the tensile strength ratio (TSR). TSR values were evaluated to comply with at least 75% from City of Phoenix specifications.

After saturating, the degree of saturation S is calculated as follows:

$$S = \frac{(B - A)}{V} \cdot 100 \qquad (5.4)$$

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

If saturation is greater than 80% the samples are damaged and should be discarded and if are less than 55%, they have to be saturated more time or with higher pressure. The following equation shows the calculation of the tensile strength, T, in kPa.

$$T = \frac{P \cdot 2000}{\pi \cdot D \cdot t} \qquad (5.5)$$

Where:

P = Maximum load in N

D = diameter of sample

t = thickness of sample

5.3. Test Results

The most relevant test results from dynamic modulus, flow number and tensile strength ratio are presented in this section, and to evaluate whether the differences in the values obtained for the different tests and for the different mixes represent a noticeable mix improvement or in the contrary, a potential performance weakness; statistical analysis was conducted.

All results were subjected to an Analysis of Variance (ANOVA) to determine if there are statistically significant differences between the means of the three mixes. Also, t-test with one and two tails were conducted, to compare results between two mixes at a time (control vs. 10%, control vs. 15% and 10% vs. 15%), to evaluate whether the test parameter is greater or less than a critical value at 95% confidence level, and to test if two means were significantly different from each other with 90% confidence level, respectively. 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).

A two-tailed test is used when it is tested for the possibility of a relationship in both directions, regardless of the direction of the relationship that is hypothesized. In the present case, the hypothesis that both means are equal is tested, and the result will show if that null hypothesis (Ho = 0) is rejected or not, regardless if the values of one RAP content are significantly greater than or less than the other. The mean is considered significantly different if the test statistic is in the top 2.5% or bottom 2.5% of its probability distribution (two tails of the distribution of the test statistic), resulting in a p-value less than the alpha (0.05) [69].

A one-tail test allots all of alpha to test the statistical significance in the one direction of interest, where that 0.05 is in one tail of the distribution of the test statistic. In this case, the possibility of the relationship in one direction is tested, disregarding the possibility of the other direction. In the present case, the null hypothesis is that the means are equal, and depending on the chosen tail, it will test either if the mean is significantly greater than the other or if it is significantly less than the other, but not both. Depending on the chosen tail, the mean will be greater than or less than the other if the test statistic is in the top 5% or in the bottom 5% of its probability distribution, resulting in a p-value less than 0.05. The one-tail test provides more power to detect an effect in one direction by not testing the effect in the other direction, but the option should be taken carefully depending if the consequences of missing an effect in the other direction is negligible or not [69].

The following sections show the relevant results and tables with the statistical measurement evaluation. Partial results can be found in Appendix D.

5.3.1. Dynamic Modulus

A master curve based on the dynamic moduli determined for the different testing temperatures and frequencies from each sample for all three mixes tested was plotted. The following graph shows the average master curve of each mix for comparison.

Dynamic modulus testing, showed that RAP mixtures tend to present slightly higher modulus as the RAP content increases for most of the temperatures, especially at the higher side. This can be seen in the following figure where the modulus is plotted against reduced time.

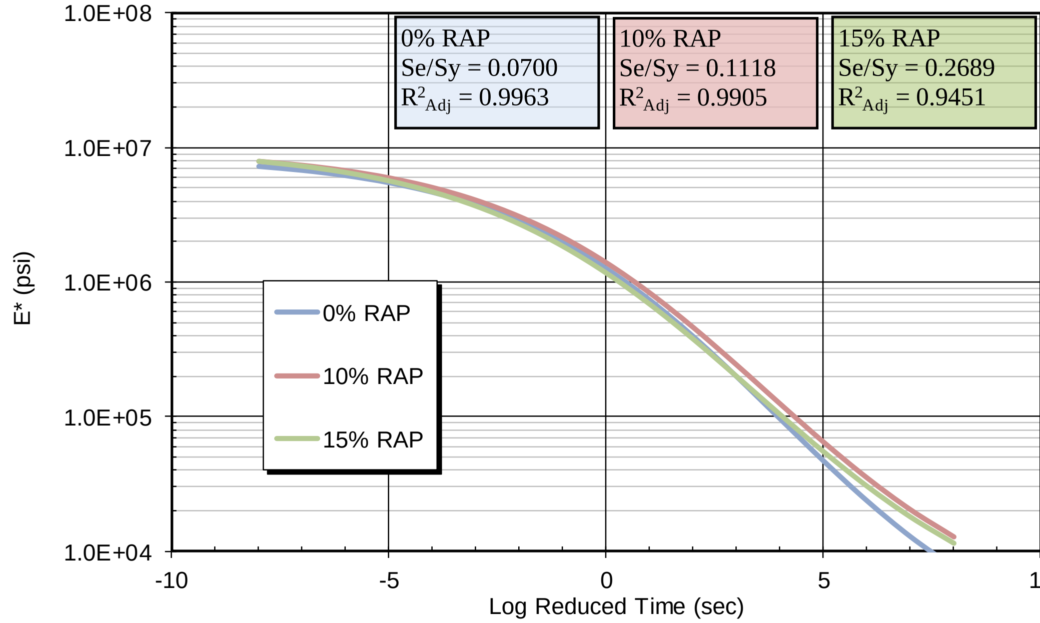

Figure 5-3 Average master curve comparison between mixes (control, 10% and 15% RAP)

To clarify the differences in dynamic modulus for the different RAP contents and frequencies, the values were rearranged and are presented in the figures below. It can be noted from the figures that as frequency decreases, the modulus also decreases, as well as temperatures go warmer. In all cases, the RAP mixes show a slight increase in stiffness, with the particularity that for the lowest temperature (14°F (-10°C)) and for the mid temperature (70°F (21.1°C)), 10% RAP shows higher modules than 15% RAP.

Increase in stiffness is related to better performance under rutting potential. Lower frequencies are related to low traffic speeds and vice versa. Therefore, increase in stiffness could represent less rutting potential in intersections and local roads. Higher frequencies are related to higher speeds as collectors or higher capacity roads and highways. Hence, RAP mixtures could denote better performance for rutting but could also signify more brittle mixture, susceptible to fatigue or thermal cracking.

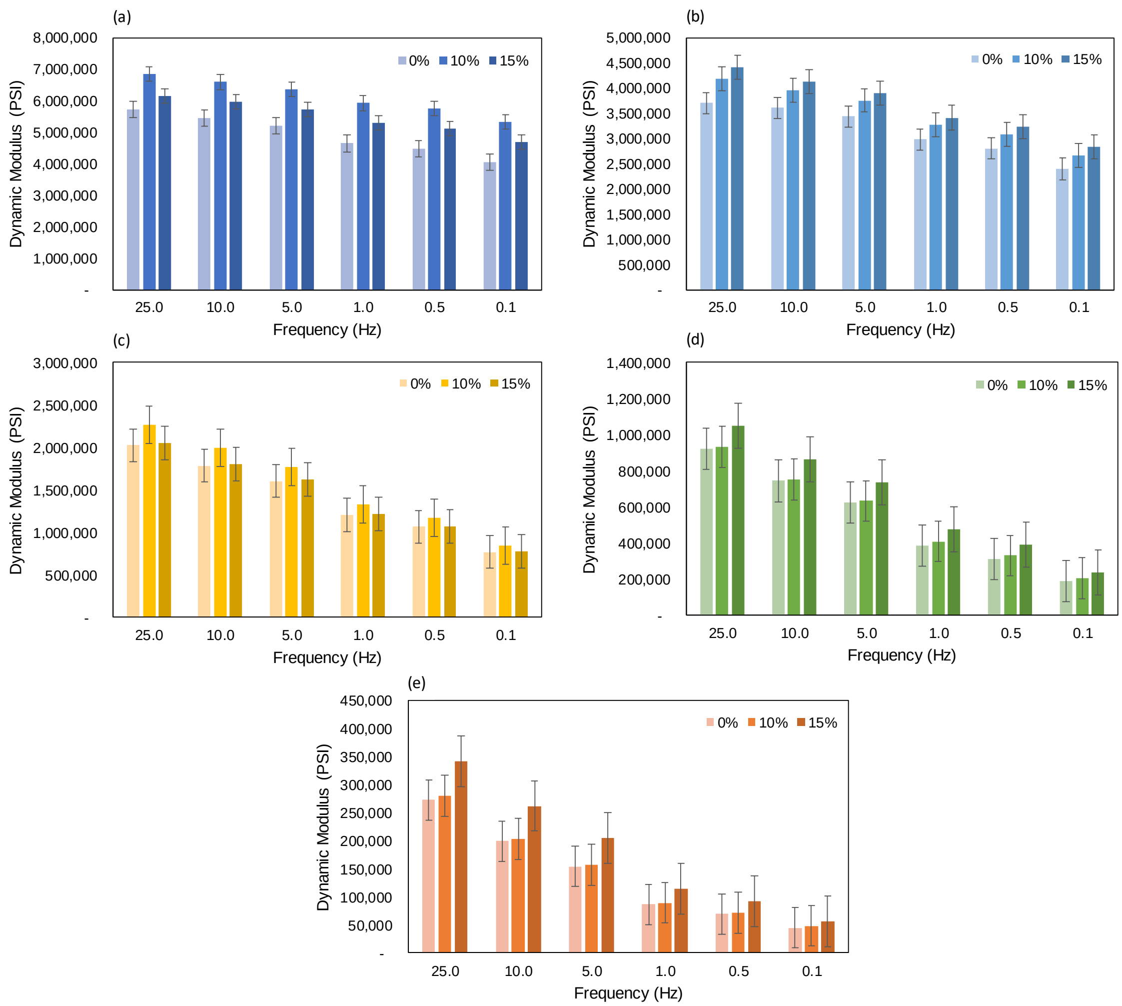

Figure 5-4 Dynamic Modulus for different temperatures and frequencies (control, 10% and 15% RAP); (a) for 14°F (-10.0°C), (b) for 40°F (4.4°C) , (c) for 70°F (21.1°C) , (d) for 100°F (37.8°C) , (e) for 130°F (54.4°C)

Table 5-1 ANOVA of Dynamic Modulus results

Frequency (Hz)	Temperatures (°C)				
	-10	**4.4**	**21.1**	**37.8**	**54.4**
25	NS	NS	NS	NS	NS
10	NS	NS	NS	NS	NS
5	NS	NS	NS	NS	NS
1	NS	NS	NS	NS	NS
0.5	NS	NS	NS	NS	NS
0.1	NS	NS	NS	NS	NS

NS= Not Statistically Significant S= Statistically Significant

Table 5-2 t-Test (one tail) of Dynamic Modulus results

Frequency (Hz)	Mix	Temperatures (°C)				
		-10	**4.4**	**21.1**	**37.8**	**54.4**
25	10% RAP	CNR	CNR	CNR	CNR	CNR
	15% RAP	CNR	CNR	CNR	CNR	CNR
10	10% RAP	CNR	CNR	CNR	CNR	CNR
	15% RAP	CNR	CNR	CNR	CNR	CNR
5	10% RAP	CNR	CNR	CNR	CNR	CNR
	15% RAP	CNR	CNR	CNR	CNR	CNR
1	10% RAP	CNR	CNR	CNR	CNR	CNR
	15% RAP	CNR	CNR	CNR	R	CNR
0.5	10% RAP	CNR	CNR	CNR	CNR	CNR
	15% RAP	CNR	CNR	CNR	R	CNR
0.1	10% RAP	CNR	CNR	CNR	CNR	CNR
	15% RAP	CNR	CNR	CNR	R	CNR

R= Reject H_0 CNR= Cannot reject H_0

Table 5-3 t-Test (two tail) of Dynamic Modulus results

Frequency (Hz)	Mix	Temperatures (°C)				
		-10	**4.4**	**21.1**	**37.8**	**54.4**
25	0% to 10%	CNR	CNR	CNR	CNR	CNR
	0% to 15%	CNR	CNR	CNR	CNR	CNR
	10% to 15%	CNR	CNR	CNR	CNR	CNR
10	0% to 10%	CNR	CNR	CNR	CNR	CNR
	0% to 15%	CNR	CNR	CNR	CNR	CNR
	10% to 15%	CNR	CNR	CNR	CNR	CNR
5	0% to 10%	CNR	CNR	CNR	CNR	CNR
	0% to 15%	CNR	CNR	CNR	CNR	CNR
	10% to 15%	CNR	CNR	CNR	CNR	CNR
1	0% to 10%	CNR	CNR	CNR	CNR	CNR
	0% to 15%	CNR	CNR	CNR	CNR	CNR
	10% to 15%	CNR	CNR	CNR	CNR	CNR
0.5	0% to 10%	CNR	CNR	CNR	CNR	CNR
	0% to 15%	CNR	CNR	CNR	R	CNR
	10% to 15%	CNR	CNR	CNR	CNR	CNR
0.1	0% to 10%	CNR	CNR	CNR	CNR	CNR
	0% to 15%	CNR	CNR	CNR	R	CNR
	10% to 15%	CNR	CNR	CNR	CNR	CNR

R= Reject H_0 CNR= Cannot reject H_0

As it can be seen in the tables above, there is not a significant statistical difference between RAP and control mixes about dynamic modulus, even though there is a slight increase in the modules of the RAP mixes, as RAP contribution increases. The comparison between control mix with 10% and 15% RAP shows difference only for three values at the lowest frequencies for 37.8°C (100°F), denoting some stiffening of the 15% RAP for high temperatures.

5.3.2. Flow Number

Flow number results showed an expected trend, since the addition of higher RAP contents will increase in certain magnitude the stiffness of the overall mix. Figure 5-5 shows the percentage of accumulated strain versus the number of cycles attained during the test for all specimens of the three mixtures. As RAP contents increase, the number of cycles to reach a certain level of accumulated strain is also higher.

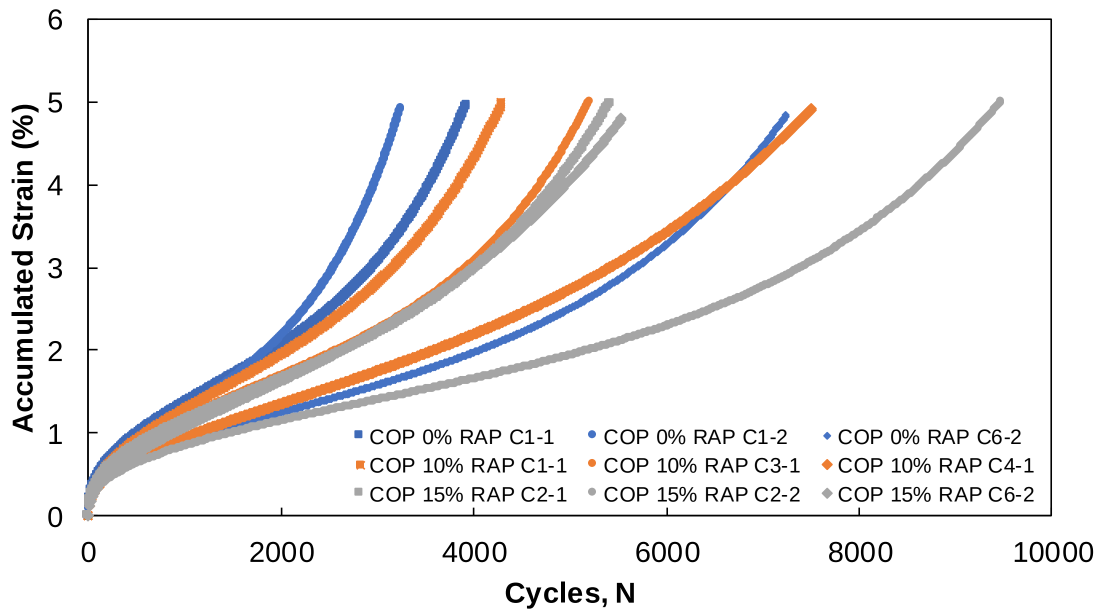

Figure 5-5 Accumulated strain during Flow Number test (Cycles) for different RAP contents

The following table summarizes the results of Flow Number tests for all replicates and the final averages for each mix. The ratio between the permanent strain (εp) and the resilient strain (εr) is used in the Mechanical-Empirical pavement design guide to predict rutting. The FN results show a slight increase in the permanent strain for RAP mixtures, that is also showed in the permanent-resilient strain relationship. This confirms the fact that RAP mixtures turn less elastic having higher level of permanent strains compared to the recoverable strains.

Table 5-4 Summary of Results from Flow Number Tests

Mix	Specimen ID	Flow Number (Cycles)	Resilient Modulus at Failure (psi)	Axial Permanent Strain at Failure εp (%)	Axial Resilient Strain at Failure εr (%)	εp/εr	εp/εr at 5% εp
0% RAP	0% RAP C1-1	1311	107331	1.564	0.053	29.5	84.80
	0% RAP C1-2	959	118489	1.201	0.05	25.0	89.45
	0% RAP C6-2	2087	142484	1.277	0.04	32.7	106.36
Average		**1452**	**122768**	**1.347**	**0.05**	**29.1**	**93.5**
Standard Deviation		577	17963	0.191	0.007	4	11
Coefficient of Variation		39.7%	14.6%	14.2%	15.2%	13.3%	12.1%
10% RAP	10% RAP C1-1	1351	120799	1.525	0.047	32.4	81.98
	10% RAP C3-1	1759	138871	1.544	0.04	37.7	102.18
	10% RAP C4-1	2087	137724	1.375	0.04	33.5	200.32
Average		**1732**	**132464**	**1.481**	**0.04**	**34.5**	**128.2**
Standard Deviation		369	10119	0.093	0.003	3	63
Coefficient of Variation		21.3%	7.6%	6.2%	8.1%	8.0%	49.4%
15% RAP	15% RAP C2-1	1679	118984	1.473	0.047	31.3	80.61
	15% RAP C2-2	3023	130438	1.391	0.04	32.3	97.94
	15% RAP C6-2	1615	113713	1.425	0.05	28.5	78.19
Average		**2106**	**121045**	**1.430**	**0.05**	**30.7**	**85.6**
Standard Deviation		795	8551	0.041	0.004	2	11
Coefficient of Variation		37.8%	7.1%	2.9%	7.5%	6.5%	12.6%

More detailed results for each mixture are presented in Appendix E.

To clarify the outcome, the average flow number for each mix was compared and is presented in Figure 5-6. From the rutting potential point of view, flow number test results show that RAP mixtures present a slight improvement, since they are stiffer because of the presence of the aged binder, providing better performance against rutting development.

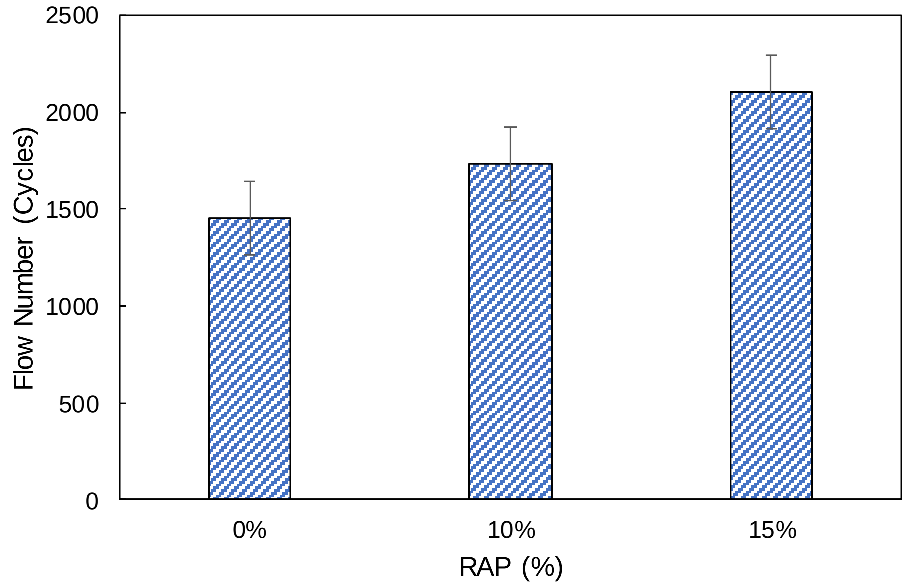

Figure 5-6 Flow Number (Cycles) for different RAP contents

Statistical analysis of the flow number test results was conducted to evaluate whether the mixes containing RAP yield results similar to the virgin control mix. Literature and experience indicates that, in most cases, mixes containing RAP perform equal or better than, mixes without RAP in terms of permanent deformation. The table below, shows the results of ANOVA and t-test.

Table 5-5 Summary of ANOVA and t-Test of Flow Number Results

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%	1311	959	2087	1452	39.7	NS	CNR	CNR	0% to 10%
10%	1351	1759	2087	1732	21.3		CNR	CNR	0% to 15%
15%	1679	3023	1615	2106	37.8		CNR	CNR	10% to 15%

ANOVA: NS= Not Statistically Significant S= Statistically Significant

t-TEST: R= Reject H_0 CNR= Cannot reject H_0

Statistical analysis of Flow Number results does not show statistical difference between the mixes.

5.3.3. Tensile Strength Ratio

An important step in the testing process is to divide specimens into dry and conditioned subsets that have similar average air void contents. The following table shows the final subset specimen setting.

Table 5-6 Specimen Air Voids of Conditioned and Unconditioned Subsets for 0%, 10% and 15% RAP

	Air voids (%)					
RAP	**0%**		**10%**		**15%**	
Sample/set	Dry	Wet	Dry	Wet	Dry	Wet
1	6.715	6.544	6.684	6.761	6.471	6.466
2	6.222	6.311	6.654	6.522	6.504	6.664
3	6.111	6.122	6.119	6.031	6.241	6.105
Average	6.350	6.326	6.485	6.438	6.405	6.412
Difference	0.024		0.047		0.006	
Average	6.338		6.462		6.408	

Average	Std. Dev.	CV%
6.403	0.058209	0.9

Based on the difference of the final air voids for condition and unconditioned subsets and on the coefficient of variance, the specimens have acceptable differences to process the test. Test results for each specimen are presented in Appendix E.

As shown in Figure 5-7, unconditioned samples presented higher tensile strength than the moisture conditioned ones as expected. Conditioned samples showed increase in the tensile strength as RAP content increases, but this trend is not followed for the dry condition, where 10% RAP shows a slight decrease compared to control. This might be attributed to the variability of RAP mixtures and the overall process itself, were air voids, aggregate distribution, etc. plays an important role. Although, 10% RAP shows the least difference between dry and moisture tensile strength.

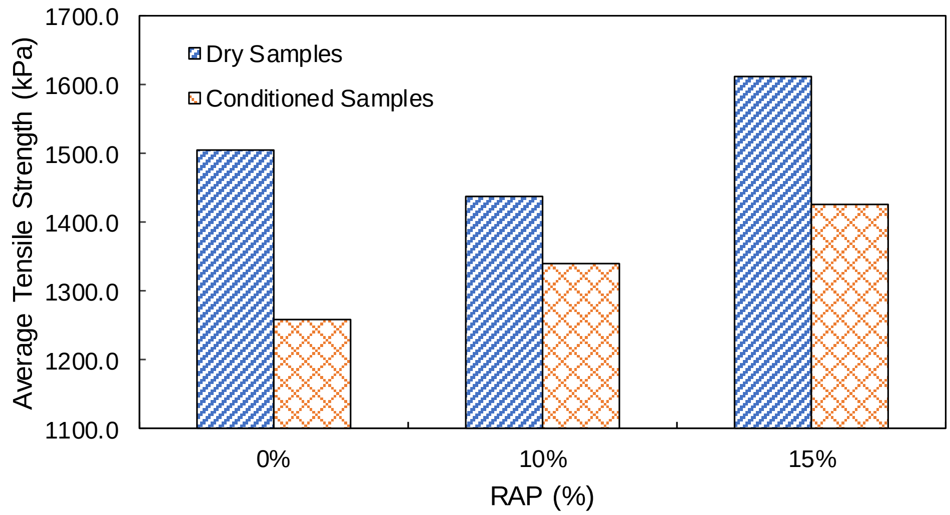

Figure 5-7 Tensile Strength (kPa) for dry and conditions specimens at different RAP contents

Figure 5-8 shows the final TSR values and it can be noticed that all mixes present values higher than the specified minimum limit of 75% (City of Phoenix specifications). RAP mixes presented an improvement against moisture susceptibility, probably due to better binder coating of RAP aggregates. Due to the small difference between conditioned versus unconditioned tensile strength, 10% RAP shows the higher TSR value.

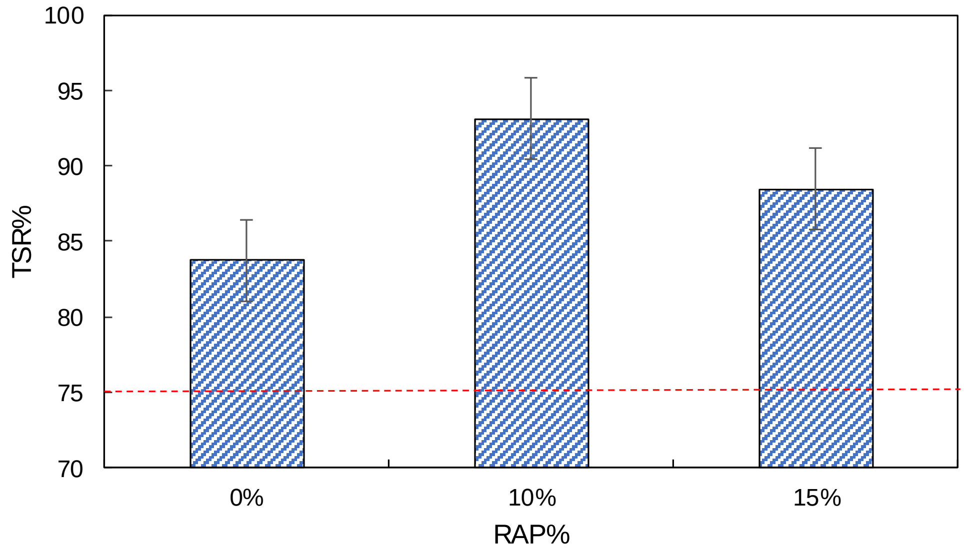

Figure 5-8 Tensile Strength Ratio (%) for different RAP contents

For moisture susceptibility evaluation, TSR test showed a slight improvement between RAP mixes compared to control mix. ANOVA and t-test showed no statistical difference between the tensile strength of the three mixtures.

Table 5-7 ANOVA and t-Test of Tensile Strength results

Condition	Mix	Tensile Strength (kPa)					α = 0.05			t-Test comparing:
		Repl. 1	Repl. 2	Repl. 3	Avg.	CV (%)	ANOVA	t-Test one-tail	t-Test two-tail	
Dry	0%	1561	1516	1437	1504	4.2	NS	CNR	CNR	0% to 10%
	10%	1514	1364	1438	1439	5.2		CNR	CNR	0% to 15%
	15%	1495	1664	1680	1613	6.4		CNR	CNR	10% to 15%
Wet/ Freeze/ thaw	0%	1219	1286	1274	1260	2.8	NS	CNR	CNR	0% to 10%
	10%	1270	1316	1432	1339	6.2		CNR	CNR	0% to 15%
	15%	1506	1279	1496	1427	9.0		CNR	CNR	10% to 15%

ANOVA: NS= Not Statistically Significant S= Statistically Significant
t-TEST: R= Reject H_0 CNR= Cannot reject H_0

5.4. Effect of Binder Grade Reduction on 25% RAP Mix

The evaluation of the effect of the reduction of one grade binder using a mid-RAP content of 25% is presented in this separate section for more clarity.

5.4.1. Dynamic Modulus

The individual replicates and average master curves for 25% RAP SB mixture are presented in Appendix E. The following figure shows a comparison between control and 25% RAP with a stiffer and a softer binder. It can be noticed that 25% RAP with a PG 70-10 binder shows a higher stiffness as expected, presenting its higher values, the correspondent to the cold temperatures, close to the ones for the control mix. On the contrary, for the 25% RAP with a PG 64-16 (Softer Binder), the dynamic modulus is less than the control mix, showing a slight similarity on the values for high temperatures. The stiffness brought by the aged RAP binder for 25% is decreased considerably by the inclusion of one grade softer binder. In this case, the apparent positive effect on the increase in stiffness by the 25% mix and stiffer binder could lead to a less resistance to fatigue and thermal cracking due to brittleness.

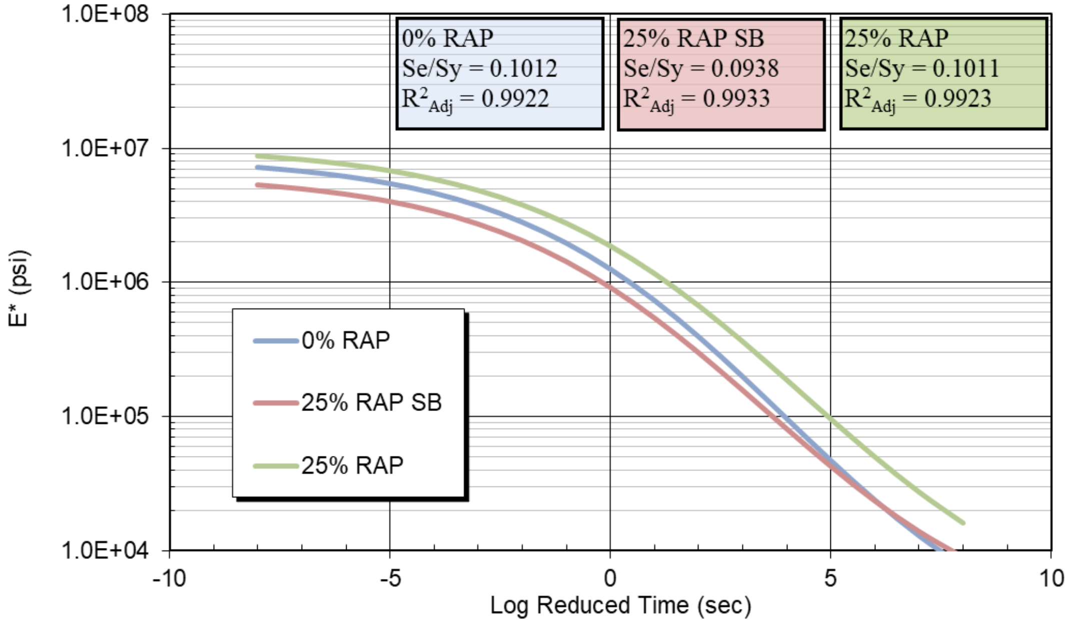

Figure 5-9 Average master curve comparison between mixes (control, 25% and 25% SB RAP)

The following figure shows the dynamic modulus comparison for each temperature and frequency, being evident the considerable difference between both 25% RAP mixes.

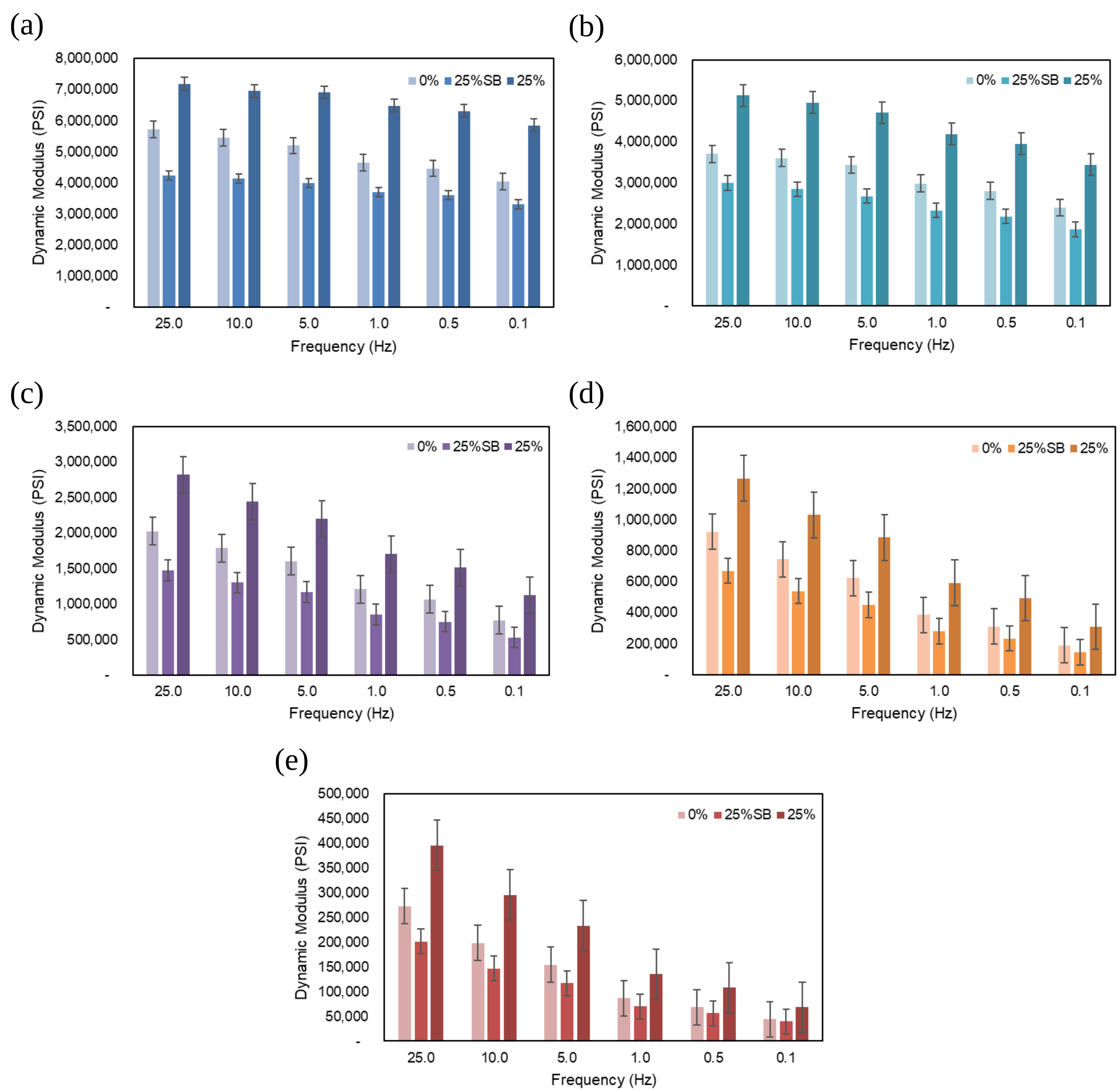

Figure 5-10 Dynamic modulus for different temperatures and frequencies (control, 25% and 25% SB RAP); (a) for 14°F (-10.0°C), (b) for 40°F (4.4°C) , (c) for 70°F (21.1°C) , (d) for 100°F (37.8°C) , (e) for 130°F (54.4°C)

Statistical analysis was conducted in order to evaluate if there is a consistent difference between the mixes. Table 5-8shows the analysis of variance conducted over the control, 25% and 25% SB RAP mixes, comparing the three mixes at the same time. As can be seen on the results there is a significant statistical difference between them for most of the temperatures and the frequencies.

Table 5-8 ANOVA of Dynamic Modulus (0%, 25% and 25% SB RAP)

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

NS= Not Statistically Significant S= Statistically Significant

ANOVA results show that essentially the three mixes are statistically different or at least some values in one or more mixes are different from each other. Results show similar values only for 4.4°C and for mid to high frequencies (from 1 to 25 Hz). To differentiate between them, one and two tailed t-test were conducted to evaluate and compare the three mixes one by one.

The following table shows the results of the test of hypothesis for one-tail t-test where it can be seen that the important statistical difference is given when the 25% RAP and the 25% RAP with softer binder (SB) are compared, resulting in rejection of the hypothesis (R). When comparing the control mix with 25% RAP, it can be noticed that in general the values for colder temperatures (-10°C and 4.4°C) are statistically similar, being different in the case of mid to high temperatures (21.1°C, 37.8C and 54.4°C), especially for low frequencies (0.1, 0.5 and 1 Hz). When control and 25% RAP SB are compared, it can be noted that as the previous case, both mixtures have statistical similar values for colder temperatures (-10°C and 4.4°C) and in this case also for the higher temperature (54.4°C). 37.8°C temperature shows mixed criteria and there is considerable difference for the mid temperature of 21.1°C.

Table 5-9 t-Test (One-Tail) of Dynamic Modulus for 0%, 25% and 25% SB

Frequency (Hz)	Mix Comparison	Temperatures (°C)				
		-10	**4.4**	**21.1**	**37.8**	**54.4**
25	0%-25% SB	CNR	CNR	R	CNR	CNR
	0%-25%	CNR	CNR	R	CNR	R
	25% SB -25%	R	R	R	R	R
10	0%-25% SB	CNR	CNR	R	CNR	CNR
	0%-25%	CNR	CNR	R	CNR	R
	25% SB -25%	R	R	R	R	R
5	0%-25% SB	CNR	CNR	R	R	CNR
	0%-25%	CNR	CNR	R	CNR	R
	25% SB -25%	R	R	R	R	R
1	0%-25% SB	CNR	CNR	R	R	CNR
	0%-25%	CNR	CNR	R	R	R
	25% SB -25%	R	R	R	R	R
0.5	0%-25% SB	CNR	CNR	R	R	CNR
	0%-25%	CNR	CNR	R	R	R
	25% SB -25%	R	R	R	R	R
0.1	0%-25% SB	CNR	CNR	R	R	CNR
	0%-25%	CNR	CNR	R	R	R
	25% SB -25%	R	R	R	R	CNR

R= Reject H_0 CNR= Cannot reject H_0

Two-tails t-test analysis is shown in Table 5-10, and from this comparison it can be concluded that control and 25% SB mixtures present greater similarity, showing statistical difference only in three values for 21.1°C and for higher frequencies (5, 10 and 25 Hz). Comparing control and 25% RAP show many statistical similarities as well, but also showing higher hypothesis rejections than the previous case. The comparison between 25% RAP and 25% RAP SB shows even less similarities. Based on this analysis it can be concluded that when using 25% RAP and bumping down the binder in one grade from PG 70-10 to PG 64-16 gives a consistently different sorter mixture. In this case, control mix stiffness falls within the range of both 25% RAP mixes, being similar to both of them in certain way, but showing higher similarity to the 25% RAP with softer binder mix. This outcome fits within the basic criteria proposed in the tiered binder selection guideline AASHTO M 323, that recommends to use a softer binder grade when using RAP between 15 and 25%.

Table 5-10 t-Test (Two-Tail) of Dynamic Modulus for 0%, 25% and 25% SB

Frequency (Hz)	**Mix Comparison**	**Temperatures (°C)**				
		-10	**4.4**	**21.1**	**37.8**	**54.4**
25	0%-25% SB	CNR	CNR	R	CNR	CNR
	0%-25%	CNR	CNR	R	CNR	CNR
	25% SB -25%	CNR	CNR	R	R	R
10	0%-25% SB	CNR	CNR	R	CNR	CNR
	0%-25%	CNR	CNR	R	CNR	CNR
	25% SB -25%	CNR	CNR	R	R	R
5	0%-25% SB	CNR	CNR	R	CNR	CNR
	0%-25%	CNR	CNR	R	CNR	CNR
	25% SB -25%	CNR	CNR	R	R	R
1	0%-25% SB	CNR	CNR	CNR	CNR	CNR
	0%-25%	CNR	CNR	R	R	CNR
	25% SB -25%	CNR	CNR	R	R	CNR
0.5	0%-25% SB	CNR	CNR	CNR	CNR	CNR
	0%-25%	CNR	CNR	CNR	R	CNR
	25% SB -25%	CNR	R	R	R	CNR
0.1	0%-25% SB	CNR	CNR	CNR	CNR	CNR
	0%-25%	CNR	CNR	CNR	R	CNR
	25% SB -25%	CNR	R	R	R	CNR

R= Reject H_0 CNR= Cannot reject H_0

- Variability of test results

In regards of the precision and variability of the dynamic modulus results, the literature shows that the coefficient of variance (CV%) is a better indicator of the variability rather than the standard deviation. On the contrary, in the case of phase angle the standard deviation gives a better approach. In order to evaluate the test results obtained for the present study, a repeatability analysis must be conducted to assimilate the results as a single-operator precision and is the maximum acceptable range between replicate test results in a single laboratory. Based on AASHTO TP 79 [22] and NCHRP Report 702 [70], the precision limit is determined by multiplying the repeatability CV with the appropriate factor dependent on the number of test results, which is dependent on the nominal maximum aggregate size (NMAS) and the average E* values of the mix. On the other hand, Bennert and Williams (2009) developed general precision statements that are not a function of any mix variables, determining a CV of 13.03% with a multiplying factor of 2√2 for two replicate samples. Other studies showed an acceptable value of 15% for the CV and about 2.3° for the standard deviation of the phase angle.

The following table shows the average E* for the different mixes in relation to the testing temperatures and how they compare to the precision values of AASHTO TP 79 for a NMAS of 3/4 inches (19 mm). Based on these values only the CV for the control mix (0%) and 4.4°C is off the limits. If the overall CV allowable value of 15% and the standard deviation of 2.3° are considered, it can be noticed that the mixture with higher variability correspond to the control mix, where most of the values are above 15%, except for 21.1°C. There are also very few values from 10%, 15% and 25% that are very close to 15%. From this analysis, there is an apparent improvement in the mix structure when RAP is incorporated, that shows less variability between the results of the different replicates. All the values of dynamic modulus, phase angle, coefficients of variance and standard deviations for the different replicates and for the different mixtures are presented in Appendix E.

Table 5-11 Statistical Measures for Dynamic Modulus results

RAP %	Statistical measures	Temperature (°C)				
		-10.0	**4.4**	**21.1**	**37.8**	**54.4**
0%	Avg.|E*| (Mpa)	33926	21767	9720	3655	948
	%CV	20.5	**38.2**	3.2	18.4	26.6
	Sr%	22.0	22.0	26.0	31.0	45.0
	Avg.φ	8.3	9.1	20.6	29.7	31.6
	φ Std. Dev.	2.0	1.4	1.6	1.3	1.2
	Sr°	2.6	2.6	3.0	3.6	5.1
10%	Avg.|E*| (Mpa)	42287	24048	10772	3750	974
	%CV	16.2	5.4	6.8	4.9	14.5
	Sr%	22.0	22.0	22.0	31.0	45.0
	Avg.φ	7.3	9.2	21.1	28.8	34.3
	φ Std. Dev.	1.2	0.5	1.2	1.2	1.0
	Sr°	2.6	2.6	2.6	3.6	5.1
15%	Avg.|E*| (Mpa)	37857	25181	9831	4315	1228
	%CV	3.8	15.9	11.7	10.8	6.8
	Sr%	22.0	22.0	26.0	31.0	38.0
	Avg.φ	6.9	10.2	20.5	26.7	32.4
	φ Std. Dev.	2.0	1.9	1.9	1.0	1.8
	Sr°	2.6	2.6	3.0	3.6	4.3
25%	Avg.|E*| (Mpa)	45606	30334	13558	5268	1421
	%CV	13.4	11.2	12.5	6.2	16.6
	Sr%	22.0	22.0	22.0	26.0	38.0
	Avg.φ	4.2	8.0	18.5	26.1	31.7
	φ Std. Dev.	1.2	0.4	1.1	0.5	1.2
	Sr°	2.6	2.6	2.6	3.0	4.3
25% SB	Avg.|E*| (Mpa)	26416	17127	6987	2670	725
	%CV	12.7	12.4	11.7	14.5	12.7
	Sr%	22.0	22.0	26.0	31.0	45.0
	Avg.φ	6.3	10.0	20.5	29.0	32.1
	φ Std. Dev.	1.8	1.2	2.2	2.2	1.5
	Sr°	2.6	2.6	3.0	3.6	5.1

Sr% = Repeatability coefficient of variation for E*(%)
Sr° = Repeatability standard deviation for phase angle (°)

5.4.2. Flow Number

Flow number results ratify the behavior observed in the dynamic modulus test, where the high modulus mix (25% RAP) showed a very high number of cycles to failure.

As expected, the softer mix (25% SB RAP) presented values less than control mix. The table below shows the results for all the replicates and the averages per mix and also statistical information.

Table 5-12 Summary of Results from Flow Number Tests (0%, 25% and 25% SB)

Mix	Specimen ID	Flow Number (Cycles)	Resilient Modulus at Failure (psi)	Axial Permanent Strain at Failure εp (%)	Axial Resilient Strain at Failure εr (%)	εp/εr	εp/εr at 5% εp
0% RAP	0% RAP C1-1	1311	107331	1.564	0.053	29.5	84.80
	0% RAP C1-2	959	118489	1.201	0.05	25.0	89.45
	0% RAP C6-2	2087	142484	1.277	0.04	32.7	106.36
Average		**1452**	**122768**	**1.347**	**0.05**	**29.1**	**93.5**
Standard Deviation		577	17963	0.191	0.007	4	11
Coefficient of Variation		39.7%	14.6%	14.2%	15.2%	13.3%	12.1%
25% SB RAP	25% RAP R1-4	987	94767	1.422	0.06	23.7	58.14
	25% RAP R1-6	1031	102923	1.103	0.06	20.1	57.45
	25% RAP R2-4	1035	92892	1.397	0.06	22.9	61.47
Average		**1018**	**96861**	**1.307**	**0.06**	**22.2**	**59.0**
Standard Deviation		27	5333	0.177	0.003	2	2
Coefficient of Variation		2.6%	5.5%	13.6%	5.5%	8.6%	3.6%
25% RAP (*)	R25-1	3599	147014	1.136	0.038	29.9	60.65
	R25-2	5663	148819	1.258	0.04	33.1	0.00
	R25-3	7039	152031	1.158	0.04	31.3	92.88
Average		**5434**	**149288**	**1.184**	**0.04**	**31.4**	**51.2**
Standard Deviation		1731	2541	0.065	0.001	2	47
Coefficient of Variation		31.9%	1.7%	5.5%	1.5%	5.1%	92.1%

(*) Data extracted from Kaligotla, P.S. [68]

Detailed results are presented in Appendix E.

The final flow number results for the three mixes are presented in the following figure. As it can be seen, the value for 25% RAP is very high with respect to the rest of the mixes. To evaluate how different are the three mixes an analysis of variance and one-tailed and two-tailed t-tests were conducted. The results are shown in Table 5-13.

As well as dynamic modulus, a similar situation is given for flow number, a statistical difference is identified when comparing the three mixes due to one or more than one mix which is giving the spread. To be more precise the t-test conducted showed that the significant difference is given when control is compared to 25% RAP and when 25% is compared with 25% SB.

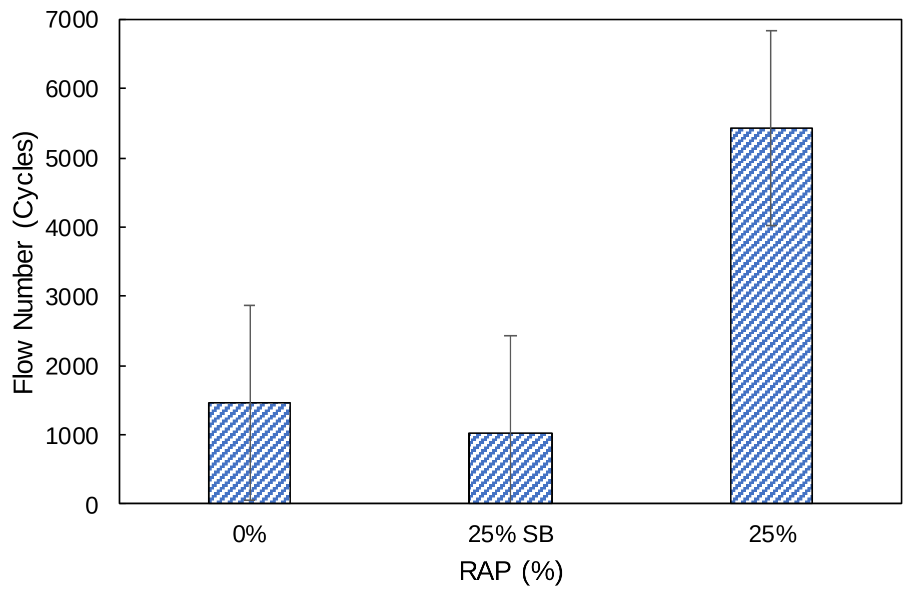

Figure 5-11 Flow Number (cycles) for 0%, 25% and 25% SB RAP

Table 5-13 Summary of ANOVA and t-Test for Flow Number (0%, 25% and 25% SB)

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%	1311	959	2087	1452	39.7	S	CNR	CNR	0%-25% SB
25% SB	987	1031	1035	1018	2.6		R	R	0%-25%
25%	3599	5663	7039	5434	31.9		R	R	25% SB-25%

ANOVA: NS= Not Statistically Significant S= Statistically Significant

t-TEST: R= Reject H_0 CNR= Cannot reject H_0

To evaluate the flow number results from 25% SB, a comparison with the rest of the low RAP content mixes was done. Table 5-14 show the results where it can be noticed that the 25% SB mix has no significant statistical difference with the rest of the mixes.

Table 5-14 Summary of ANOVA and t-Test for Flow Number (0%, 10%, 15% and 25% SB)

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%	1311	959	2087	1452	39.7	NS	CNR	CNR	0%-10%
10%	1351	1759	2087	1732	21.3		CNR	CNR	0%-15%
15%	1679	3023	1615	2106	37.8		CNR	CNR	10%-15%
25% SB	987	1031	1035	1018	2.6		CNR	CNR	0%-25% SB
							R	CNR	10%-25% SB
							CNR	CNR	15%-25% SB

ANOVA: NS= Not Statistically Significant S= Statistically Significant

t-TEST: R= Reject H_0 CNR= Cannot reject H_0

- Variability of test results

According to the recommendations stated for flow number in AASHTO TP 79, a single-operator precision or a single laboratory repeatability precision must be followed. The coefficient of variation for unconfined flow number tests is a function of the nominal maximum aggregate size (NMAS), which corresponds to 3/4 inches (19 mm). The CV for the flow number of the different mixtures are shown in Table 5-4 and Table 5-12. The recommended maximum coefficient of variation is 58.5%. All the flow number results for all the mixes evaluated are below this value showing an adequate repeatability and variability.

5.4.3. Tensile Strength Ratio

Tensile Strength Ratio test requires that the average of air voids from the conditioned and unconditioned subsets be similar. The table below shows the air voids from the different samples compared.

Table 5-15 TSR Replicate Air Voids for 0%, 25% and 25% SB

RAP	0%		25% SB		25%	
Sample/set	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
1	6.715	6.544	6.862	6.970	6.012	6.398
2	6.222	6.311	6.670	6.636	6.393	5.922
3	6.111	6.122	6.015	5.958	5.645	5.699
Average	**6.350**	**6.326**	**6.516**	**6.521**	**6.017**	**6.006**
Difference	0.024		0.005		0.010	
Average	6.338		6.519		6.011	

Average	Std. Dev.	CV%
6.289	0.230	3.7

The target air voids for this test as well as for the rest of the mixes tested in this study is 6.5 ±0.5%, therefore all the samples are within the range. The results of the test for each specimen are presented in detail in Appendix E.

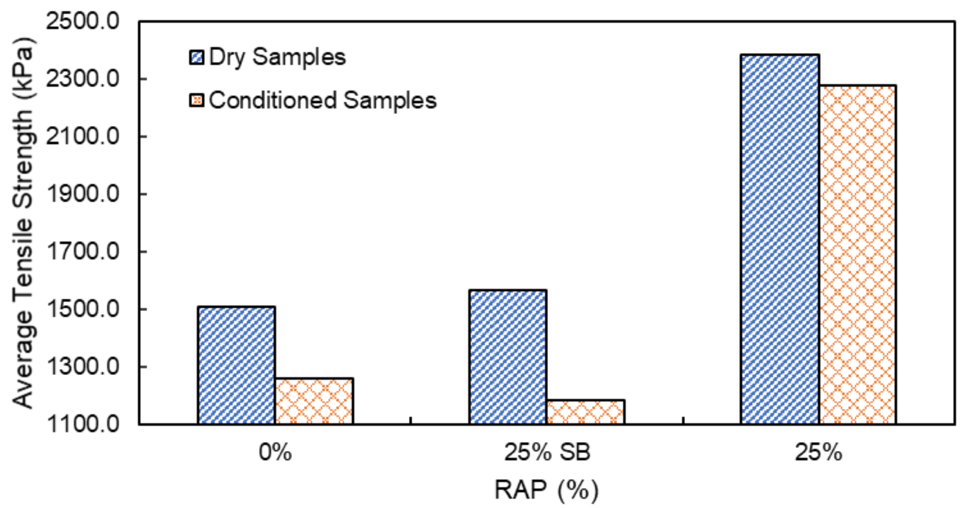

Figure 5-12 Tensile Strength (kPa) for conditioned and unconditioned specimens for 0%, 25% and 25% SB RAP

From Figure 5-12 it can be observed that the presence of RAP in the mix improves the average tensile strength showing a slight improvement for cracking. This effect is even more noticeable when there is the combination of a higher RAP content with more aged and stiff binder and also a stiffer virgin binder. On the contrary, for the conditioned scenario in this case, that trend is not followed for all cases. The 25% RAP and softer binder mix shows the least conditioned tensile strength, affecting the final TSR value.

The figure below shows a comparison within the three mixes and the specification limit from the City of Phoenix. There can be observed that the mix with the PG 64-16 binder passes the specification just by 1%, over the limit.

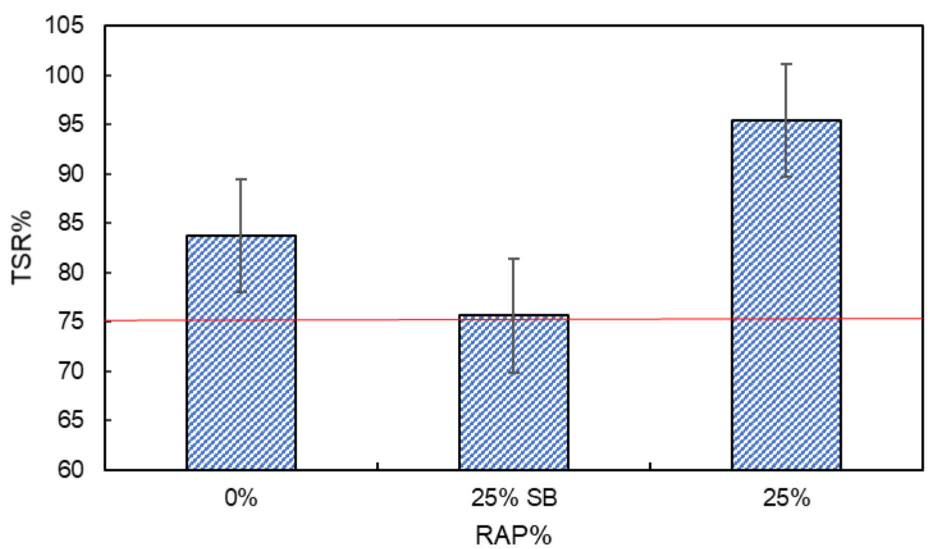

Figure 5-13 Tensile Strength (kPa) for conditioned and unconditioned specimens for 0%, 25% and 25% SB RAP

Table 5-16 ANOVA and t-Test of Tensile Strength for 0%, 25% and 25% SB RAP

Condition	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	
Dry	0%	1561.1	1516.0	1437.3	1504.8	4.2	S	CNR	CNR	0%-25% SB
	25% SB	1568.5	1584.0	1541.2	1564.6	1.4		R	R	0%-25%
	25%	2294.1	2423.2	2433.3	2383.5	3.3		R	R	25% SB-25%
Conditioned	0%	1219.7	1286.3	1274.4	1260.1	2.8	S	CNR	CNR	0%-25% SB
	25% SB	1299.2	1073.5	1176.6	1183.1	9.6		R	R	0%-25%
	25%	2225.9	2279.4	2319.0	2274.8	2.1		R	R	25% SB-25%

ANOVA: NS= Not Statistically Significant S= Statistically Significant

t-TEST: R= Reject H_0 CNR= Cannot reject H_0

Similar as when comparing previous performance testing, there is a significant statistical difference within the three mixes, nevertheless again control and 25% SB mix are the most alike. In this particular case that effect could be biased, and an analysis of the possible causes is detailed below:

- RAP heating time during the mixing process, as RAP amount increases it could be possible to require more time to reach the mixing temperature and to facilitate the old and virgin binder to blend. This effect could have more influence since a softer virgin binder was used and added to the fact that it requires a lower mixing temperature (in the experiment 157°C was reached to mix a PG 64-16 binder and 163°C was used for PG70-10).
- Controlled experiments using 20% of screened RAP subjected to staged extraction and recovery showed that a small portion of aged asphalt in RAP actually participated in the remixing process, where other portions formed a stiff coating around RAP aggregates, performing basically as

"composite black rock" [70]. A softer binder could not adhere well to the already covered RAP aggregates, that also have more presence in the mix due to the RAP content.

- Studies showed that RAP mixes at different emulsion contents indicate that increasing emulsion content significantly improved the moisture susceptibility, attributing this effect possibly to the fact that there is a better coating of RAP aggregates at higher emulsion content and reduction in the infusion of moisture between aggregate surface and binder coating which can improve the adhesion between aggregate and asphalt binder [71]. In the present research the 25% RAP SB mix showed the same binder content as the control mix (5.02%), showing a reduction compared to 25% which has almost 5.8%.
- The lowest conditioned strength values for 25% RAP SB correspond to the higher air voids of all sets. Higher air voids could be a possible reason why the overall average tensile strength of the wet samples is lower than the control mix, since they let the intrusion of a higher volume of water, subjected to the freeze-thaw cycle.
- A study that evaluated moisture damage potential using TSR and fracture resistance performance of HMA and WMA containing different percentages of RAP (0%, 10, 20, 30 and 40%) and using one binder (VG30, PEN 60-70), showed that addition of RAP increased TSR values of the mix indicating that RAP may help in enhancing moisture damage

potential of a mix. HMA-RAP mixes had higher values compared with WMA-RAP mixes, that being more prone to moisture damage. In this study HMA-RAP mixes had higher TSR values than control mix (88%) up to addition of 30% RAP, however the value was less (83%) than the control mix for higher RAP contents (40% RAP), even though it still satisfies the minimum requirements of the specification. It has to be noted that TSR values were decreasing for RAP contents higher than 20%. For mixes with 10%, 20% and 30% RAP, the TSR values were 95%, 95% and 91% respectively. The study points that such drop-off in TSR value could be possible due to significant change in volumetric properties such as drop-off in optimum binder content for higher RAP contents, asserting that further investigation is needed to make conclusive remarks regarding this fact. This study also points that such trend indicates that higher RAP content (>20%) may result in a poor mix as far as moisture damage potential is concerned, and careful attention should be given for designing high RAP content mixes [72].

5.5. Rodezno's Rutting Prediction Model

To complement the results obtained by the performance testing, a pavement performance prediction model for rutting was used to evaluate the mixes under study.

The rutting estimation was performed by the prediction model proposed by Rodezno and Kaloush [74]. The pavement structure considered for the calibration and development of the model consists of a subgrade with a resilient modulus of 20,000 psi, and a crushed stone subbase with a modulus of 40,000 psi and 10 inches in thickness.

The model is based on the input of the Flow Number test and relates this value with traffic and layer thickness as input variables. The model was developed with almost 1500 asphalt pavement sections for different climatic locations and traffic levels and had very good statistical accuracy. The final model form is presented in the next equation:

$$R = 0.0038 \cdot FN^{-0.242} \times ESALs^{0.485} \times h^{-1.021} \tag{5.6}$$

Where:

R = rutting in inches

FN = flow number in cycles

ESAL = Equivalent Single Axle Load in millions

H = Pavement layer thickness in inches

The pavement structure considered for this evaluation consist of an asphalt concrete surface course with 3 inches thickness, as recommended per the minimum required thickness for collector streets by the City's specifications. In terms of traffic volume, the parameters correspond to local roads with low traffic with a 20-year traffic loading between 0.3 to <3 million of ESALs.

The following table shows the predicted rutting values.

Table 5-17 Predicted Rutting by Rodezno's Model

Mixture	FN	ESALs	Pavement Thickness (in)	Rutting	
				(in)	(mm)
0%	1452	3,000,000	3	0.29	7.5
10%	1732			0.28	7.2
15%	2106			0.27	6.8
25% SB	1018			0.32	8.1
25%	5434			0.21	5.4

As expected, the stiffer mix has the least rutting depth (25% RAP) and the one with the softer binder, even though having 25% RAP in the mix shows the largest rutting. Despite of this, when comparing 0.32 in (8.1 mm) for 25% SB and 0.29 in (7.5 mm) for control, the difference between those two is just 0.03 in (0.6 mm), showing a similar performance. Results show a slight improvement as RAP increases, but with no appreciable difference between mixtures. The results predicted by the model show reasonable rutting values, following the expected trend of displaying less rutting as the material stiffness increase. It is worth to note that the model can capture the minimal variations of the flow number as the RAP contents increase as low as from control to 10% or to 15%. One of the advantages of this model is that it can predict rutting based only on the flow number cycles for the mix disregarding the direct influence of other variables.

6. Summary, Conclusions and Recommendations

Asphalt concrete is the most recycled material in the United States and its reclamation allows the positive reuse of the constituent aggregates and asphalt binder, contributing to the long-term sustainability of the transportation infrastructure. The percent of RAP used in the country has increased considerably as agencies are becoming more confident reaching acceptable pavement performance. Although the national trends are encouraging, the environmental conditions in Phoenix are extreme and needs further consideration. There are concerns about RAP usage will result in higher mixture stiffness that could be more susceptible to cracking and failure, even though stiffer mixtures also provide better performance related to rutting. Variability of RAP materials stored from different projects within the same stockpiles is also a concern. The effects described are increased when higher percentages are considered, which also complicates the complete understanding of the physio-chemical interactions between the RAP and the virgin binder in the mixtures. Consequently, the percentage and effect of using RAP on the long-term pavement performance must be evaluated and quantified for each local agency.

The objective of this research study was to evaluate some of the RAP sources available to the City of Phoenix to have a better understanding of the variability of the material and its characteristics, and also conduct a preliminary laboratory performance study to evaluate the viability of using RAP for the City's pavement operations. Three RAP contents were studied 10%, 15% and 25% compared to a control mix (0%), using two different binders, PG 70-10 for all RAP contents and PG 64-16 for the highest RAP content of 25%. Virgin material and RAP were provided by a local approved asphalt plant. Laboratory testing included simulated short and long-term aging (RTFO and PAV), and high-mid and low temperature characterization testing (DSR and BBR). Mix performance testing included Dynamic Modulus, Flow Number and Tensile Strength Ratio.

The conclusions and recommendations of this study are detailed below:

- While there has been substantial research on the use of RAP nationally, the literature on specific use in climates and conditions of the Southwest, like those in Phoenix, are limited. The different origins and conditions of millings in this location necessitate insightful studies and adequate stockpile management to have a better understanding of the material as the aged binder.
- A cautious approach to the adoption of RAP is not unique to Phoenix, and many agencies within the state have been similarly reticent to adopt this technique. Most local city agencies are not currently using RAP in surface asphalt courses but are currently using RAP for dust control and stabilization of roads, shoulders, backfills and as unbound bases.
- ADOT has reported an overall increased use of RAP in asphalt pavements with allowable percentages of up to 20% in surface layers. Even with this, increased usage adoption in the Phoenix area has been slower than elsewhere. ADOT experience shows an increasing use of RAP within the asphalt concrete produced, with 15% RAP as the average usage, estimating approximately $3.9 million dollars savings during the first year allowing RAP and over $55 million since 2009.

- Based on subjective information from nearby agencies, the general perception is that RAP use is avoided because: variability of the material, costs of incorporating RAP are closer to virgin mixes making RAP less attractive, will require more or early maintenance, and concerning about long-term pavement performance.
- **Sampling process.** Based on the sampling process and the testing conducted on the RAP, extracted aggregates and binder, it can be concluded that there is certain variability in RAP material that can be addressed by appropriate stockpile management procedures.
- **Recovered binders.** Recovered binders from RAP showed high stiffness after testing, greater than the average values observed in the literature, denoting very stiff binders within the City stockpiles. This effect is attributed to the use of stiffer binders due to the specified climatic requirements and the aging process under those extreme climatic conditions. Binder content is variable and should be monitored frequently as part of the stockpile management.
- Based on the final binder blending theoretical approach proposed in NCHRP studies, RAP contents up to 10% does not affect the resultant blended binder grade and no further testing is required. Also, that approach showed PG grading change by one grade when 15% RAP is used, alerting that higher RAP contents can affect the final binder blend in a higher degree, therefore, further testing must be conducted to evaluate the resultant binder blending and stiffening effect. Even though the stiffening effect is a fact, the present study

showed that for 15% RAP, the stiffness is increased but there is not a significant statistical difference compared to control mix.

- Statistical measures of consistency of the RAP stockpiles showed that binder content must be adequately controlled to have uniform HMA mixtures with RAP, since binder variability is considerable.
- On the other hand, RAP and extracted aggregate gradations presented reasonable variability between samples.
- **RAP variability.** This acceptable variability can be supported by the fact that most RAP come from mixes that were previously approved and the aggregates were tested to be used in the old virgin mixtures, where those materials usually falls within standard or specified gradations. Study results showed higher variability in the coarse fraction of RAP for both, gradation and specific gravity. Landfill samples showed pretty good consistency about the gradation of the aggregates, but stockpile management must be improved in order to reduce standard deviations in the binder content. Recovered aggregate gradations should be also constantly monitored as part of the quality control and quality assurance process.
- **Superpave mix design.** Superpave mix design process including RAP is the same as for virgin mixtures with some exceptions that include the following: RAP aggregate is treated as another stockpile for batching and blending but must be heated carefully to avoid changing the binder properties. Heating one hour at the mixing temperature prior to mixing resulted adequate; RAP

aggregate specific gravity must be estimated based on the RAP maximum specific gravity, assuming the binder specific gravity; RAP binder weight must be accounted when batching aggregates, binder content can be determined by ignition oven or solvent extraction; the total asphalt content must be reduced to compensate for the binder provided by the RAP; and a change in the binder grade may be needed depending on the RAP content and expected final binder grade, the study showed that up to 15% RAP original binder can be used. RAP properties needed for mix design include RAP aggregate properties, gradation and asphalt content. Consensus properties should be verified on the final aggregate blend.

- **Lab mixing temperature.** It is recommended that the laboratory mixing temperature should be on the higher side of the range to ensure proper blending or RAP material with virgin aggregates and binder.
- **Performance tests.** Three performance tests were conducted on laboratory prepared samples to identify material properties: dynamic modulus test (E*) for stiffness of the material and behavior under various traffic loadings and temperatures; the Flow Number (FN) test, to measure the susceptibility of the asphalt mixture for permanent deformation or rutting; and the Tensile Strength Ratio (TSR) as a measure of moisture damage, which also provides the cracking potential through the Indirect Tension test (IDT).
- **Dynamic modulus.** Testing showed that RAP mixtures tend to present slightly higher modulus (increase in stiffness) as the RAP content increases

for most of the temperatures, especially at the higher temperature side, when comparing mixes with the same binder.

- **Flow Number.** Testing for rutting potential showed that RAP mixtures had a slight improvement in mixture performance (same binder). The results are rational in that the RAP mixtures are slightly stiffer (aged binder) and would be expected to provide equal or better performance against rutting development.
- **Tensile Strength Ratio**. Testing for moisture damage potential, showed that for the same virgin binder, all mixtures performed well showing TSR values higher than the specified minimum limit of 75% required by city specifications. RAP mixtures presented an improvement in TSR values, meaning less susceptible to moisture damage, probably due to better binder coating of RAP aggregates.
- When a softer binder (PG 64-16) was used, even though a higher RAP content was used (25%), all testing results regarding dynamic modulus, flow number cycles, tensile strength and TSR values dropped compared to the control mix and hence to the low RAP contents, showing a clear softening effect due to one grade binder decrease.
- To evaluate the rutting potential of the RAP mixtures, Rodezno’s rutting prediction model was used. The results showed that as RAP contents increase, slightly less rutting depth is expected.

- Statistical analysis showed that between the three mixes (control 0%, 10% and 15% RAP), there is not statistical difference in their properties or performance.
- **25% RAP with stiffer binder (PG 70-10).** Statistical analysis showed that for 25% RAP and stiffer binder (PG 70-10), there is a statistical difference compared to the rest of the mixes, especially when compared to the same amount of RAP and a softer binder.
- **25% RAP with softer binder (PG 64-16).** Statistical analysis also showed that even though 25% RAP with a softer binder presented lower values in all the performance tests considered, there is no statistical difference when compared to control mix, confirming the practice recommended on AASHTO M 323 of the tiered binder selection guideline.
- **Low RAP contents.** The implementation of low RAP contents (10% and 15%) has no negative effect on the material properties or pavement performance, considering the test conducted.
- Results from performance tests showed that AASHTO tiered recommendations are useful. 15% RAP content was developed with the same PG 70-10 binder and the results showed no significant difference in the performance between all mixes.
- This study was based on information formed through literature review, experiences of other agencies, and preliminary laboratory performance testing done at ASU.

- **Final conclusion and recommendation.** The results were promising in that asphalt mixtures utilizing RAP up to 15% would perform equal to the standard mixtures.
- Based on this initial outcome, it is recommended to do an expanded research and testing study to evaluate RAP performance in a field test section. Furthermore, an expanded laboratory testing program on plant produced mixtures will provide an additional important mixture performance related to cracking (thermal and fatigue). A field implementation study will also help identify issues related to plant production, quality control, paving practices, and pavement performance.
- Based upon the results of this study, it is believed that the use of RAP at moderate percentages within the city of Phoenix maintenance operations can lead to greater resource conservation, cost reduction and more environmentally friendly approach to paving.

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APPENDIX A

SURVEY INTERVIEW GUIDE

(time approximate = 20 min)

1. Does your agency/organization regularly or knowingly use RAP in your asphalt pavements?
2. If so, are there any specific projects in your jurisdiction that have used RAP recently? If so can you tell me where those are located and when they were placed?
3. If so, in which layers of pavement structure the usage of RAP is practiced? Why? Is RAP usage allowed in surface layers? Is it allowed in any type of road?
4. What is the maximum percentage of RAP that can be used in a project?
5. If RAP is used, do you have established practices to adjust the grade of the virgin binder? What is the factor to decide binder grade?
6. What is the important factor that need to be taken care of while designing/constructing RAP mix?
7. If you use RAP have you seen any systematic reduction in pavement performance that you attribute to the use of RAP, especially as it is related to high temperature? If so how do you attribute it to the RAP?
8. Are contractors familiar with RAP usage? Do they feel motivated to use it?
9. Do you have specific procedures for RAP stockpiling and managing?

APPENDIX B

RAP, EXTRACTED AGGREGATES AND BINDERS CHARACTERIZATION RESULTS

AVERAGE RAP AGGREGATE GRADATIONS

The following table shows the average aggregate RAP millings (As received) gradations from the different replicates tested:

Sieve size	Sample S-1		Sample S-3		Sample S-4		Sample S-5		Sample SW-1	
	Dry	Washed	Dry	Washed	Dry	Washed	Dry	Washed	Dry	Washed
	Average cumulative % passing									
1 in	95	95	96	96	96	96	97	97	100	100
3/4 in.	90	90	89	88	90	90	92	92	100	100
1/2 in.	77	77	77	76	76	76	81	80	89	89
3/8 in.	66	66	67	67	63	63	69	68	77	76
#4	43	42	48	48	37	37	46	46	47	46
#8	28	27	35	34	20	20	32	31	28	27
#30	12	10	13	12	7	6	13	12	9	8
#50	6	5	7	6	3	3	6	5	4	3
#100	3	1	3	1	2	1	3	1	2	1
#200	1.6	0.0	1.1	0.0	0.6	0.0	1.2	0.0	0.7	0.0

The following table shows the average RAP extracted aggregates gradations from the different replicates tested:

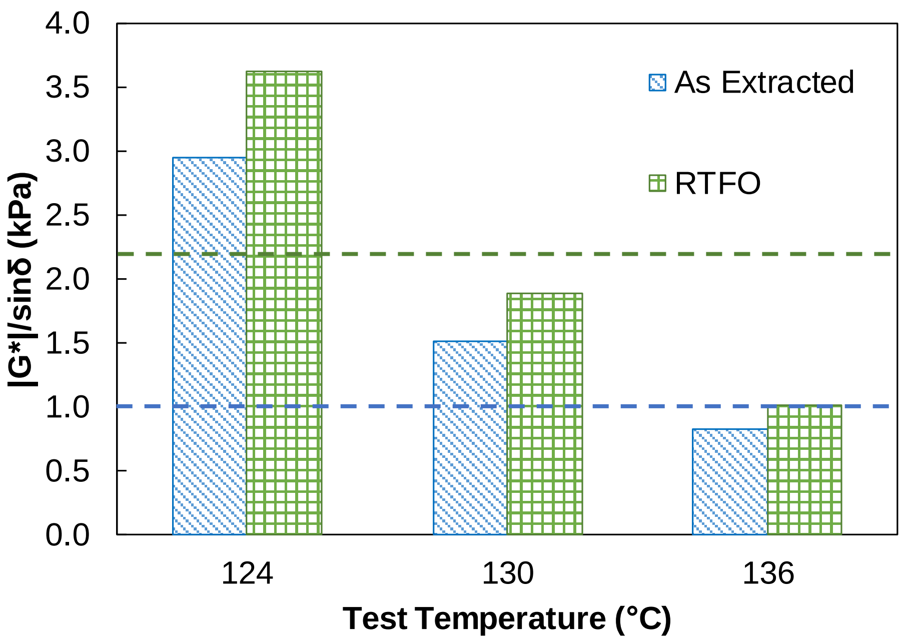
Sieve size	Sample S-1		Sample S-3		Sample S-4		Sample S-5		Sample SW-1	
	Dry	Washed	Dry	Washed	Dry	Washed	Dry	Washed	Dry	Washed
	Average cumulative % passing									
1 in	100	100	100	100	100	100	100	100	100	100
3/4 in.	99	99	99	99	100	100	100	100	100	100
1/2 in.	93	93	92	92	96	96	98	98	91	90
3/8 in.	86	85	86	85	89	88	92	91	77	76
#4	66	64	70	68	69	67	72	69	51	49
#8	50	46	58	56	52	48	51	46	36	32
#30	27	22	29	25	28	22	27	20	18	13
#40	22	16	22	17	22	16	22	15	14	9
#50	17	11	16	11	17	11	18	11	11	6
#100	11	4	9	4	10	4	12	5	7	2
#200	6.2	0.0	5.1	0.0	5.8	0.0	7.4	0.0	3.9	0.0

EXTRACTED BINDER CHARACTERIZATION RESULTS

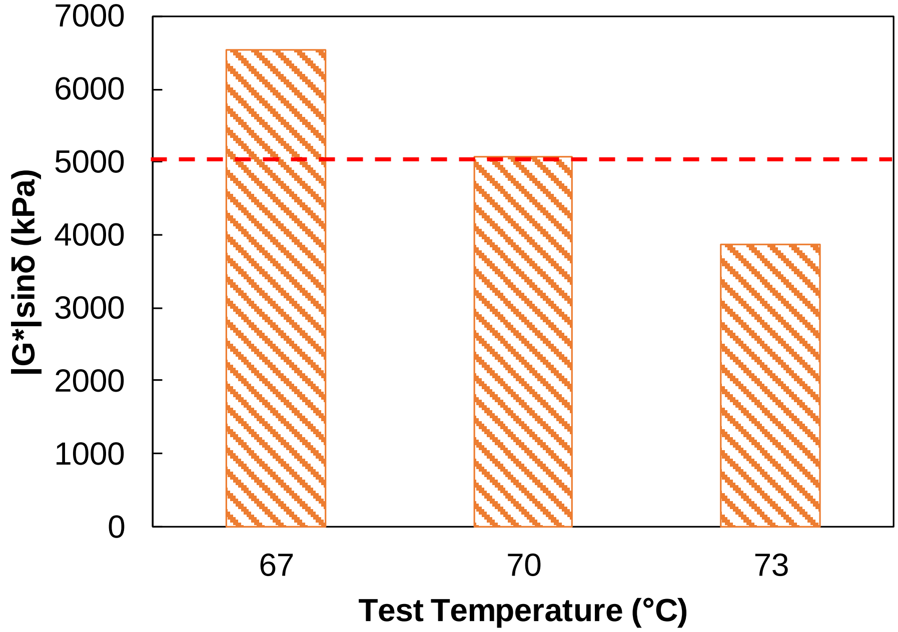
Stockpile S-1

High, Intermediate, and Low Temperature Testing on Sample S-1

AASHTO Test Method	Aging Level	Parameter	Temperature	Result	
T315 - 25mm	As Extracted	|G*|/sinδ	124	3.0	kPa
			130	1.5	kPa
			136	0.8	kPa
T315 - 25mm	RTFO	|G*|/sinδ	124	3.6	kPa
			130	1.9	kPa
			136	1.0	kPa
T315 - 8mm	PAV at 110°C	|G*|sinδ	67	6542	kPa
			70	5067	kPa
			73	3874	kPa
T313	PAV at 110°C	m	18	0.234	
		S		240	MPa
		m	24	0.266	
		S		149	MPa



(a)



(b)

Variation of |G*|/sinδ and |G*|sinδ with temperature and aging level; (a) for As Extracted and RTFO aged, and (b) for PAV aged.

BBR| (AASHTO T313) Testing Memo Sample S-1

BBR (AASHTO T313) Testing Memo							
PAV Temp (°C)	Temp (°C)	Test Data					
		Parameter	S-1	S-2	Avg.	CV	Notes
110	18	"m" Value	0.236	0.232	0.234	1.2087	
		S (MPa)	229	250	239.5	6.2001	
	24	"m" Value	0.269	0.263	0.266	1.595	passes
		S (MPa)	142	155	148.5	6.1902	

|G*| (AASHTO T315) Testing Memo Sample S-1

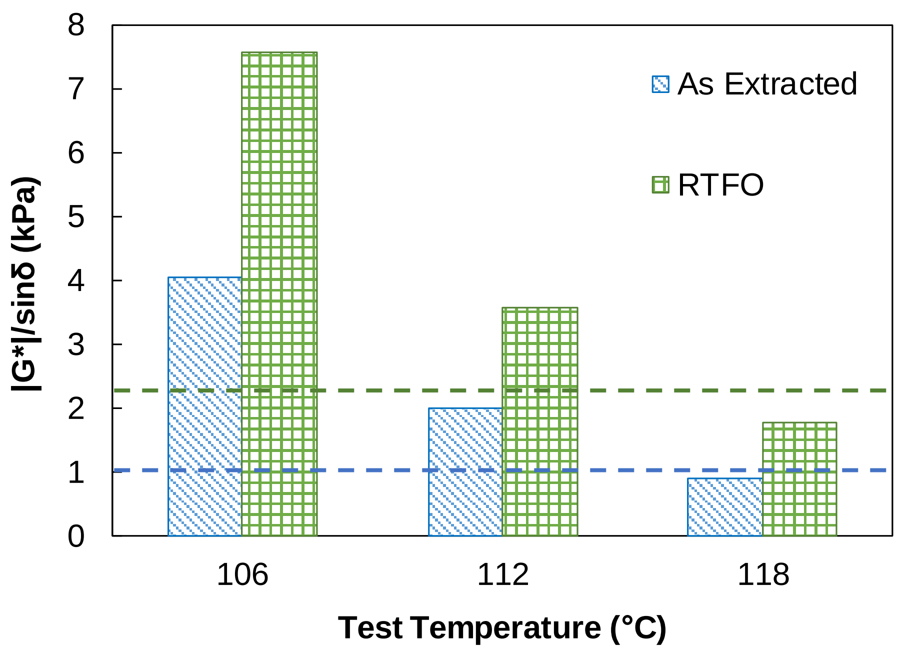
|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
124	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	2.932		2.932		
	$\delta_{orig.}$	82.85		82.85		
	$(G^*/\sin\delta)_{orig.}$	2.955		2.955		
	$\|G^*\|_{RTFO}$	3.592		3.592		
	δ_{RTFO}	81.92		81.92		
	$(G^*/\sin\delta)_{RTFO}$	3.628		3.628		
130	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	1.504		1.504		
	$\delta_{orig.}$	84.61		84.61		
	$(G^*/\sin\delta)_{orig.}$	1.511		1.511		
	$\|G^*\|_{RTFO}$	1.871		1.871		
	δ_{RTFO}	83.8		83.8		
	$(G^*/\sin\delta)_{RTFO}$	1.882		1.882		
136	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	0.823		0.823		
	$\delta_{orig.}$	85.76		85.76		
	$(G^*/\sin\delta)_{orig.}$	0.825		0.825		
	$\|G^*\|_{RTFO}$	1.007		1.007		
	δ_{RTFO}	85.23		85.23		
	$(G^*/\sin\delta)_{RTFO}$	1.01		1.01		
67	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	10813	10047	10430	5.1953	PAV Temp 110°C
	δ_{PAV}	38.6	39.11	38.855	0.9281	
	$(G^*\sin\delta)_{PAV}$	6745.9	6337.5	6541.7	4.4149	
70	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	8005.1	7426.4	7715.8	5.3036	PAV Temp 110°C
	δ_{PAV}	40.8	41.32	41.06	0.8955	
	$(G^*\sin\delta)_{PAV}$	5230.7	4903.4	5067	4.5678	
73	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	5856.4	5448.2	5652.3	5.1067	PAV Temp 110°C
	δ_{PAV}	43.05	43.51	43.28	0.7515	

	$(G^*\sin\delta)_{PAV}$	3997.8	3751	3874.4	4.5046	

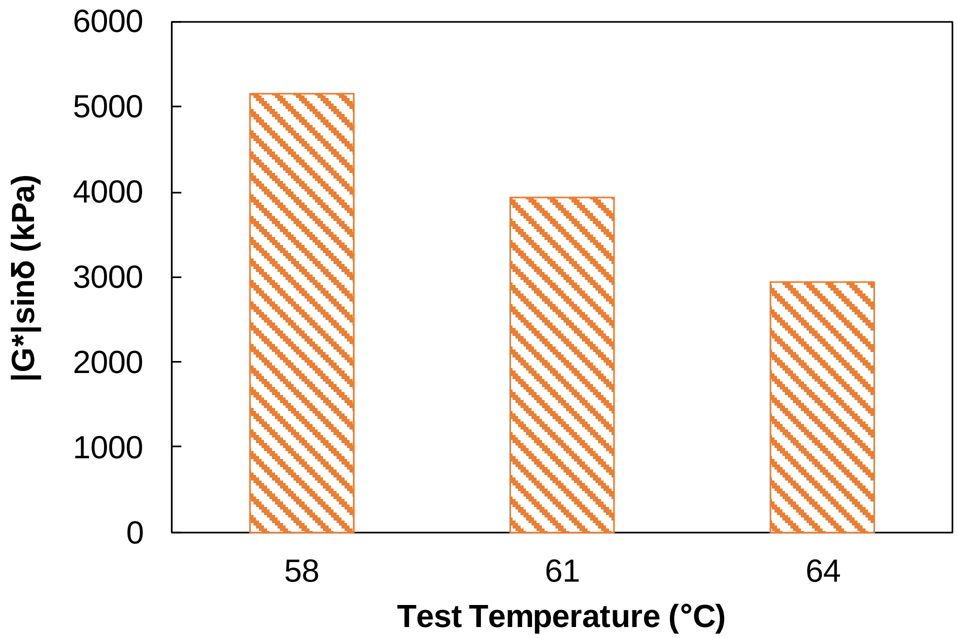
Stockpile S-3

High, Intermediate, and Low Temperature Testing on Sample S-3

AASHTO Test Method	Aging Level	Parameter	Temperature	Result	
T315 - 25mm	As Extracted	|G*|/sinδ	106	4.1	kPa
			112	2.0	kPa
			118	0.9	kPa
T315 - 25mm	RTFO	|G*|/sinδ	106	7.6	kPa
			112	3.6	kPa
			118	1.8	kPa
T315 - 8mm	PAV at 110°C	|G*|sinδ	58	5157	kPa
			61	3933	kPa
			64	2948	kPa
T313	PAV at 110°C	m	12	0.242	
		S		209	MPa
		m	18	0.28	
		S		110	MPa
		m	24	0.342	
		S		65	MPa



(a)



(b)

Variation of IG*I/sinδ and IG*Isinδ with temperature and aging level; (a) for As Extracted and RTFO aged, and (b) for PAV aged.

BBR| (AASHTO T313) Testing Memo Sample S-3

BBR (AASHTO T313) Testing Memo							
PAV Temp (°C)	Temp (°C)	Test Data					
110		Parameter	S-1	S-2	Avg.	CV	Notes
	12	"m" Value	0.239	0.245	0.242	1.7532	passes
		S (MPa)	201	217	209	5.4133	
	18	"m" Value	0.274	0.286	0.28	3.0305	
		S (MPa)	97.5	123	110.25	16.355	
	24	"m" Value	0.342	0.341	0.3415	0.2071	
		S (MPa)	61.4	68.1	64.75	7.3168	

|G*| (AASHTO T315) Testing Memo Sample S-3

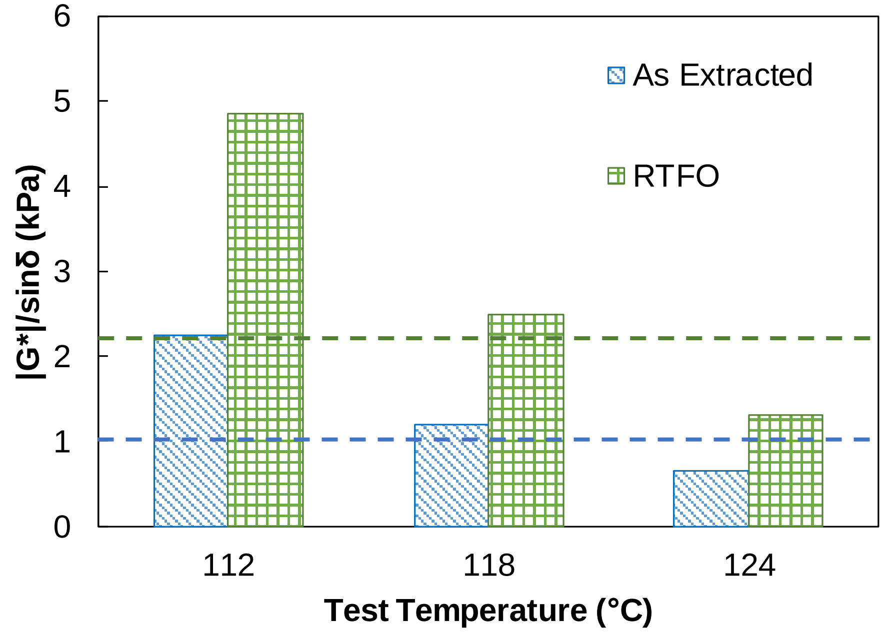
|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
106	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	4.01		4.01		
	$\delta_{orig.}$	81.63		81.63		
	$(G^*/\sin\delta)_{orig.}$	4.053		4.053		
	$\|G^*\|_{RTFO}$	7.46		7.46		
	δ_{RTFO}	80.28		80.28		
	$(G^*/\sin\delta)_{RTFO}$	7.569		7.569		
112	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	1.979		1.979		
	$\delta_{orig.}$	83.97		83.97		
	$(G^*/\sin\delta)_{orig.}$	1.99		1.99		
	$\|G^*\|_{RTFO}$	3.546		3.546		
	δ_{RTFO}	82.81		82.81		
	$(G^*/\sin\delta)_{RTFO}$	3.574		3.574		
118	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	0.895		0.895		
	$\delta_{orig.}$	86.55		86.55		
	$(G^*/\sin\delta)_{orig.}$	0.897		0.897		
	$\|G^*\|_{RTFO}$	1.757		1.757		
	δ_{RTFO}	84.94		84.94		
	$(G^*/\sin\delta)_{RTFO}$	1.764		1.764		
58	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	8393.3	7553.9	7973.6	7.4432	PAV Temp 110°C pass d2s
	δ_{PAV}	40.31	40.29	40.3	0.0351	
	$(G^*\sin\delta)_{PAV}$	5429.8	4884.8	5157.3	7.4722	
61	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	6111.6	5532.9	5822.2	7.0277	PAV Temp 110°C pass d2s
	δ_{PAV}	42.5	42.5	42.5	0	
	$(G^*\sin\delta)_{PAV}$	4128.9	3738	3933.4	7.0277	
64	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	4373	3996.1	4184.5	6.3691	PAV Temp 110°C pass d2s
	δ_{PAV}	44.84	44.72	44.78	0.1895	

|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
	Parameter	R-1	R-2	Avg.	CV	Notes
106	$\|G^*\|_{orig.}$	4.01		4.01		
	$\delta_{orig.}$	81.63		81.63		
	$(G^*/\sin\delta)_{orig.}$	4.053		4.053		
	$\|G^*\|_{RTFO}$	7.46		7.46		
	δ_{RTFO}	80.28		80.28		
	$(G^*/\sin\delta)_{RTFO}$	7.569		7.569		
	$(G^*\sin\delta)_{PAV}$	3083.5	2811.8	2947.6	6.518	

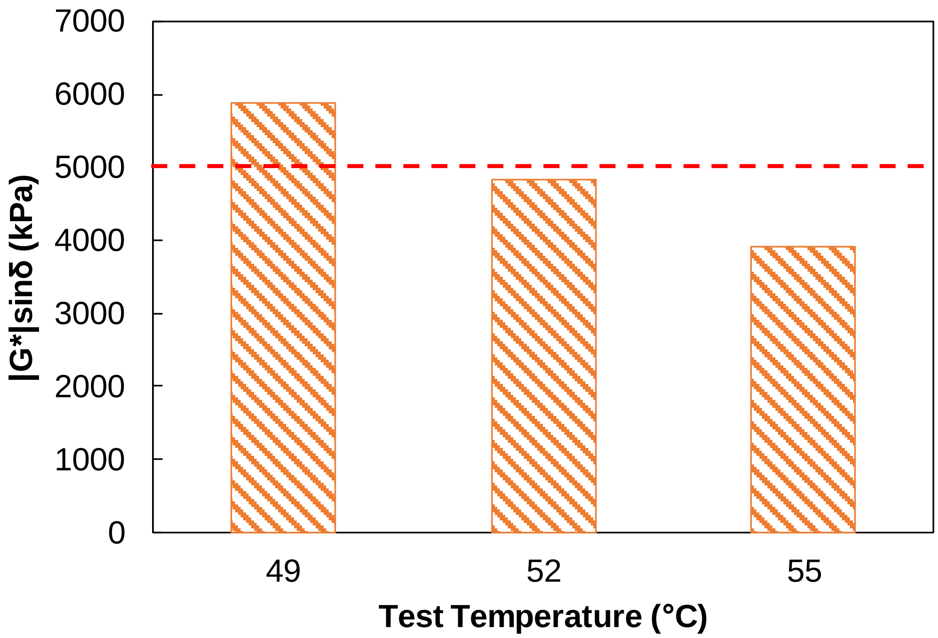
Stockpile S-4

High, Intermediate, and Low Temperature Testing on Sample S-4

AASHTO Test Method	Aging Level	Parameter	Temperature	Result	
T315 - 25mm	As Extracted	|G*|/sinδ	112	2.3	kPa
			118	1.2	kPa
			124	0.7	kPa
T315 - 25mm	RTFO	|G*|/sinδ	112	4.9	kPa
			118	2.5	kPa
			124	1.3	kPa
T315 - 8mm	PAV at 110°C	|G*|sinδ	49	5891	kPa
			52	4832	kPa
			55	3908	kPa
T313	PAV at 110°C	m	18	0.299	
		S		62	MPa
		m	24	0.338	
		S		35	MPa



(a)



(b)

Variation of |G*|/sinδ and |G*|sinδ with temperature and aging level; (a) for As Extracted and RTFO aged, and (b) for PAV aged.

BBR| (AASHTO T313) Testing Memo Sample S-4

BBR (AASHTO T313) Testing Memo							
PAV Temp (°C)	Temp (°C)	Test Data					
110		Parameter	S-1	S-2	Avg.	CV	Notes
	18	"m" Value	0.298	0.299	0.2985	0.2369	
		S (MPa)	58.5	64.7	61.6	7.117	
	24	"m" Value	0.337	0.339	0.338	0.4184	
		S (MPa)	33.4	36.6	35	6.465	

|G*| (AASHTO T315) Testing Memo Sample S-4

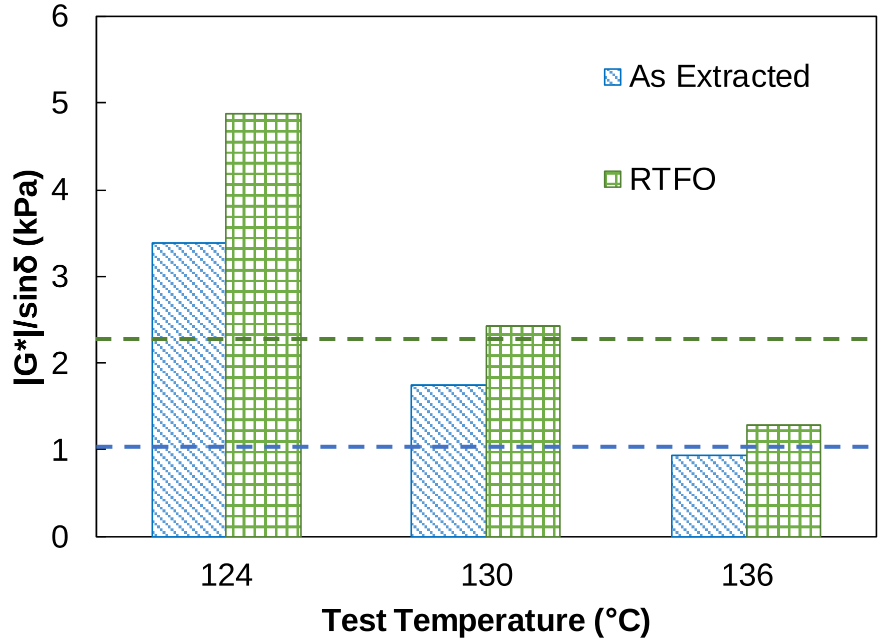
|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
112	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	2.213		2.213		
	$\delta_{orig.}$	79.04		79.04		
	$(G^*/\sin\delta)_{orig.}$	2.254		2.254		
	$\|G^*\|_{RTFO}$	4.69		4.69		
	δ_{RTFO}	74.99		74.99		
	$(G^*/\sin\delta)_{RTFO}$	4.856		4.856		
118	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	1.18		1.18		
	$\delta_{orig.}$	81.49		81.49		
	$(G^*/\sin\delta)_{orig.}$	1.193		1.193		
	$\|G^*\|_{RTFO}$	2.433		2.433		
	δ_{RTFO}	77.88		77.88		
	$(G^*/\sin\delta)_{RTFO}$	2.488		2.488		
124	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	0.654		0.654		
	$\delta_{orig.}$	83.58		83.58		
	$(G^*/\sin\delta)_{orig.}$	0.658		0.658		
	$\|G^*\|_{RTFO}$	1.292		1.292		
	δ_{RTFO}	80.47		80.47		
	$(G^*/\sin\delta)_{RTFO}$	1.31		1.31		
49	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	11838	11573	11706	1.599	PAV Temp 110°C
	δ_{PAV}	30.02	30.42	30.22	0.9359	

|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
112	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	2.213		2.213		
	$\delta_{orig.}$	79.04		79.04		
	$(G^*/\sin\delta)_{orig.}$	2.254		2.254		
	$\|G^*\|_{RTFO}$	4.69		4.69		
	δ_{RTFO}	74.99		74.99		
	$(G^*/\sin\delta)_{RTFO}$	4.856		4.856		
	$(G^*\sin\delta)_{PAV}$	5922.6	5860	5891.3	0.7515	
52	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	9275.1	9045.4	9160.2	1.7732	PAV Temp 110°C
	δ_{PAV}	31.63	32.05	31.84	0.9327	
	$(G^*\sin\delta)_{PAV}$	4864.2	4800	4832.1	0.9386	
55	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	7173.3	6965.6	7069.4	2.0775	PAV Temp 110°C
	δ_{PAV}	33.34	33.8	33.57	0.9689	
	$(G^*\sin\delta)_{PAV}$	3942.5	3874.9	3908.7	1.2222	

Stockpile S-5

High, Intermediate, and Low Temperature Testing on Sample S-5

AASHTO Test Method	Aging Level	Parameter	Temperature	Result	
T315 - 25mm	As Extracted	|G*|/sinδ	124	3.4	kPa
			130	1.7	kPa
			136	0.9	kPa
T315 - 25mm	RTFO	|G*|/sinδ	124	4.9	kPa
			130	2.4	kPa
			136	1.3	kPa
T315 - 8mm	PAV at 110°C	|G*|sinδ	67	7301	kPa
			70	5605	kPa
			73	4241	kPa
T313	PAV at 110°C	m	18	0.220	
		S		280	MPa
		m	24	0.254	
		S		185	MPa



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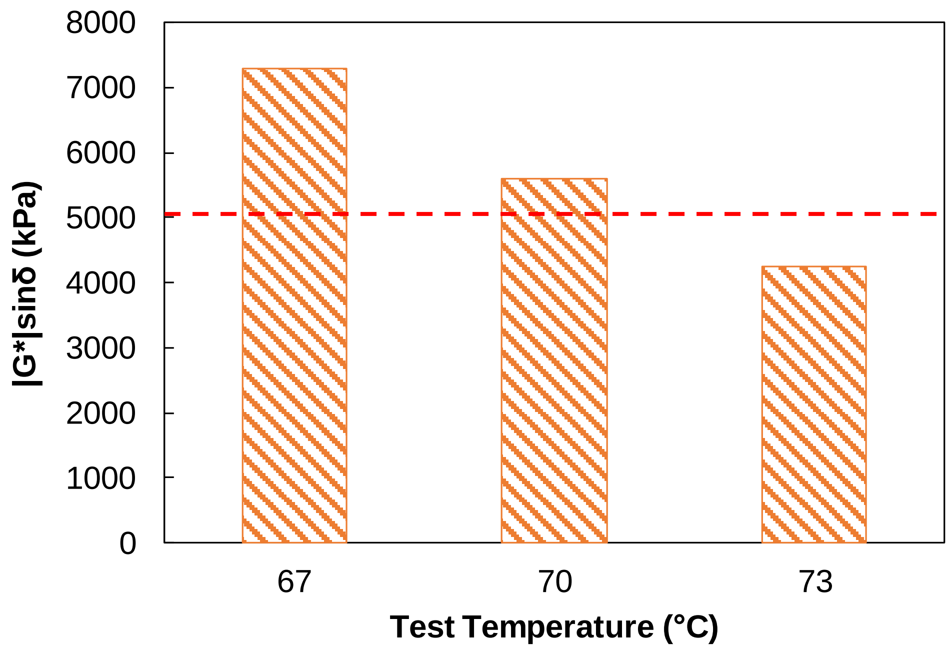


(b)

Variation of |G*|/sinδ and |G*|sinδ with temperature and aging level; (a) for As Extracted and RTFO aged, and (b) for PAV aged.

BBR| (AASHTO T313) Testing Memo Sample S-5

BBR (AASHTO T313) Testing Memo							
PAV Temp (°C)	Temp (°C)	Test Data					
110		Parameter	S-1	S-2	Avg.	CV	Notes
	18	"m" Value	0.225	0.215	0.22	3.2141	
		S (MPa)	295	265	280	7.5761	
	24	"m" Value	0.259	0.248	0.2535	3.0683	
		S (MPa)	196	173	184.5	8.8149	

|G*| (AASHTO T315) Testing Memo Sample S-5

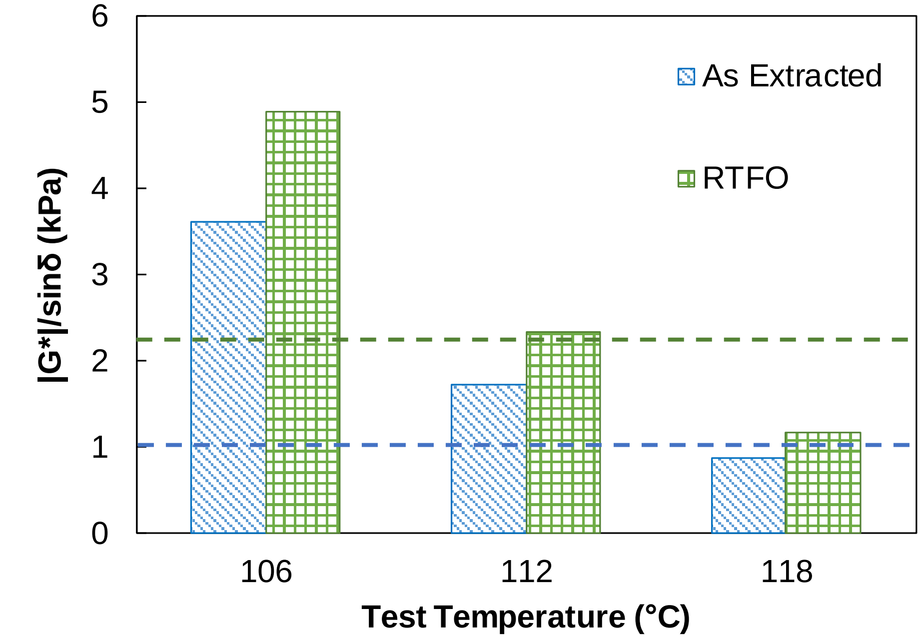
|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
124	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	3.367		3.367		
	$\delta_{orig.}$	82.98		82.98		
	$(G^*/\sin\delta)_{orig.}$	3.392		3.392		
	$\|G^*\|_{RTFO}$	4.825		4.825		
	δ_{RTFO}	81.73		81.73		
	$(G^*/\sin\delta)_{RTFO}$	4.876		4.876		
130	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	1.742		1.742		
	$\delta_{orig.}$	84.79		84.79		
	$(G^*/\sin\delta)_{orig.}$	1.749		1.749		
	$\|G^*\|_{RTFO}$	2.417		2.417		
	δ_{RTFO}	83.82		83.82		
	$(G^*/\sin\delta)_{RTFO}$	2.431		2.431		
136	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	0.932		0.932		
	$\delta_{orig.}$	86.17		86.17		
	$(G^*/\sin\delta)_{orig.}$	0.934		0.934		
	$\|G^*\|_{RTFO}$	1.272		1.272		
	δ_{RTFO}	85.43		85.43		
	$(G^*/\sin\delta)_{RTFO}$	1.276		1.276		
67	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	12271	11213	11742	6.3696	PAV Temp 110°C pass d2s
	δ_{PAV}	38.24	38.67	38.455	0.7907	

|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
124	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	3.367		3.367		
	$\delta_{orig.}$	82.98		82.98		
	$(G^*/\sin\delta)_{orig.}$	3.392		3.392		
	$\|G^*\|_{RTFO}$	4.825		4.825		
	δ_{RTFO}	81.73		81.73		
	$(G^*/\sin\delta)_{RTFO}$	4.876		4.876		
	$(G^*\sin\delta)_{PAV}$	7595	7006.2	7300.6	5.7026	
70	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	8945	8205.3	8575.2	6.1001	PAV Temp 110°C pass d2s
	δ_{PAV}	40.65	41	40.825	0.6062	
	$(G^*\sin\delta)_{PAV}$	5827.1	5383.1	5605.1	5.601	
73	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	6461.7	5934.7	6198.2	6.0128	PAV Temp 110°C pass d2s
	δ_{PAV}	43.02	43.34	43.18	0.524	
	$(G^*\sin\delta)_{PAV}$	4408.5	4073.1	4240.8	5.5927	

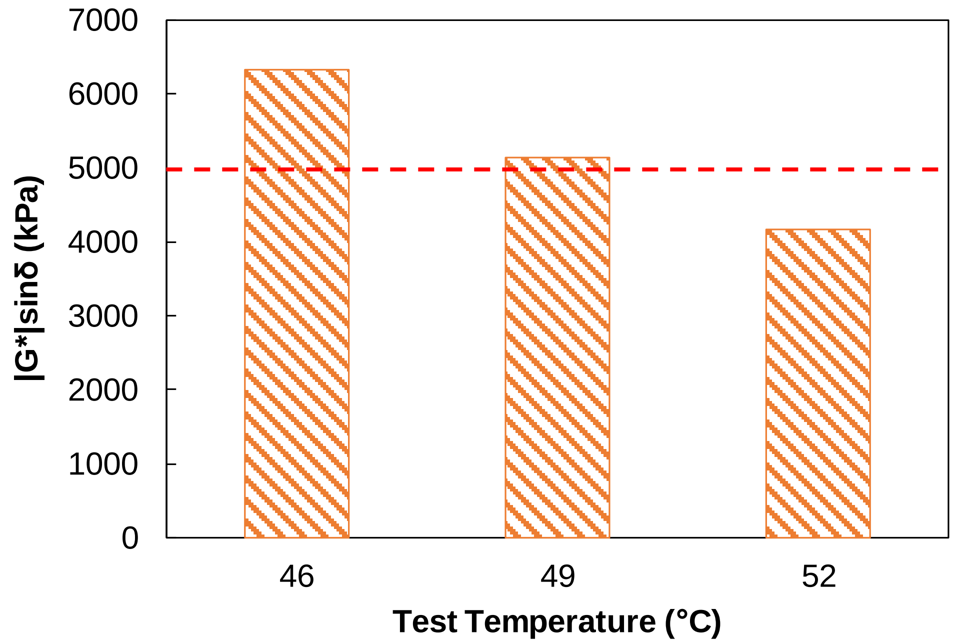
Southwest Asphalt Plant SW-1

High, Intermediate, and Low Temperature Testing on Sample SW-1

AASHTO Test Method	Aging Level	Parameter	Temperature	Result	
T315 - 25mm	As Extracted	$\|G^*\|/\sin\delta$	106	3.6	kPa
			112	1.7	kPa
			118	0.9	kPa
T315 - 25mm	RTFO	$\|G^*\|/\sin\delta$	106	4.9	kPa
			112	2.3	kPa
			118	1.2	kPa
T315 - 8mm	PAV at 110°C	$\|G^*\|\sin\delta$	46	6340	kPa
			49	5138	kPa
			52	4176	kPa
T313	PAV at 110°C	m	18	0.274	
		S		86	MPa
		m	24	0.321	
		S		48	MPa



(a)



(b)

Variation of |G*|/sinδ and |G*|sinδ with temperature and aging level; (a) for As Extracted and RTFO aged, and (b) for PAV aged.

BBR| (AASHTO T313) Testing Memo Sample SW-1

BBR (AASHTO T313) Testing Memo							
PAV Temp (°C)	Temp (°C)	Test Data					
		Parameter	S-1	S-2	Avg.	CV	Notes
110	18	"m" Value	0.275	0.273	0.274	0.5161	
		S (MPa)	87.1	84	85.55	2.5623	
	24	"m" Value	0.32	0.322	0.321	0.4406	
		S (MPa)	48.6	46.9	47.75	2.5174	

|G*| (AASHTO T315) Testing Memo Sample SW-1

|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
106	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	3.636	3.496	3.566	2.7761	As Extracted Pass d2s
	$\delta_{orig.}$	80.891	81.125	81.008	0.2043	
	$(G^*/\sin\delta)_{orig.}$	3.682	3.538	3.61	2.8206	
	$\|G^*\|_{RTFO}$	4.834	4.782	4.808	0.7648	
	δ_{RTFO}	79.581	79.579	79.58	0.0018	
	$(G^*/\sin\delta)_{RTFO}$	4.915	4.862	4.8885	0.7666	
112	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	1.734	1.67	1.702	2.6589	As Extracted Pass d2s
	$\delta_{orig.}$	83.361	83.472	83.417	0.0941	
	$(G^*/\sin\delta)_{orig.}$	1.746	1.681	1.7135	2.6823	
	$\|G^*\|_{RTFO}$	2.332	2.307	2.3195	0.7621	
	δ_{RTFO}	82.252	82.23	82.241	0.0189	
	$(G^*/\sin\delta)_{RTFO}$	2.353	2.328	2.3405	0.7553	
118	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	0.881	0.855	0.868	2.1181	
	$\delta_{orig.}$	85.33	85.386	85.358	0.0464	
	$(G^*/\sin\delta)_{orig.}$	0.884	0.858	0.871	2.1108	
	$\|G^*\|_{RTFO}$	1.166	1.156	1.161	0.609	
	δ_{RTFO}	84.463	84.406	84.435	0.0477	
	$(G^*/\sin\delta)_{RTFO}$	1.171	1.162	1.1665	0.5456	
46	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	12823	12971	12897	0.8164	PAV Temp 110°C
	δ_{PAV}	29.168	29.715	29.442	1.3137	

|G*| (AASHTO T315) Testing Memo						
Temp (°C)	Test Data					
106	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{orig.}$	3.636	3.496	3.566	2.7761	As Extracted Pass d2s
	$\delta_{orig.}$	80.891	81.125	81.008	0.2043	
	$(G^*/\sin\delta)_{orig.}$	3.682	3.538	3.61	2.8206	
	$\|G^*\|_{RTFO}$	4.834	4.782	4.808	0.7648	
	δ_{RTFO}	79.581	79.579	79.58	0.0018	
	$(G^*/\sin\delta)_{RTFO}$	4.915	4.862	4.8885	0.7666	
	$(G^*\sin\delta)_{PAV}$	6249.3	6429.7	6339.5	2.0123	
49	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	9511.1	10111	9811.1	4.3243	PAV Temp 110°C
	δ_{PAV}	31.658	31.506	31.582	0.3403	
	$(G^*\sin\delta)_{PAV}$	4991.9	5283.9	5137.9	4.0195	
52	Parameter	R-1	R-2	Avg.	CV	Notes
	$\|G^*\|_{PAV}$	7377.8	7789.2	7583.5	3.8364	PAV Temp 110°C
	δ_{PAV}	33.429	33.397	33.413	0.0677	
	$(G^*\sin\delta)_{PAV}$	4064.4	4287.5	4176	3.7766	

APPENDIX C

HANDLING RAP IN THE LABORATORY

One of the main objectives in the laboratory procedures is to know how to handle RAPs material in order to have a close representation of what is occurring in the field. Usually RAP aggregates in mixing plants are exposed to the environment and they are incorporated into the mixing process in a way that the material could reach the mixing temperature in a short period of time. Some plants combine RAP at the end of the aggregate heating drum and prior to mixing with the asphalt binder. The objective is to heat the material without affecting significative the RAP properties and characteristics.

Literature on national practices do not show a standard procedure or consensus between agencies about how to handle RAP in the lab, and temperatures and heating time intervals are variable. The following table shows a summary of the different methods used nationwide to heat RAP before mixing with virgin aggregate.

RAP heating times and temperatures

Heating time (hours)	Temperature °C (°F)
0.5	110 (230)
1	176 (350)
1.5	110 (230)
2	143 (290)
2	163 (325)
4	146 (295)
6	168 (335)
No RAP heating (mixed cold)	
All components mixed together before heating (virgin aggregate + RAP)	

To find the more suitable practice for the project a small experiment was conducted. Two cases were defined and evaluated and are detailed in the following section.

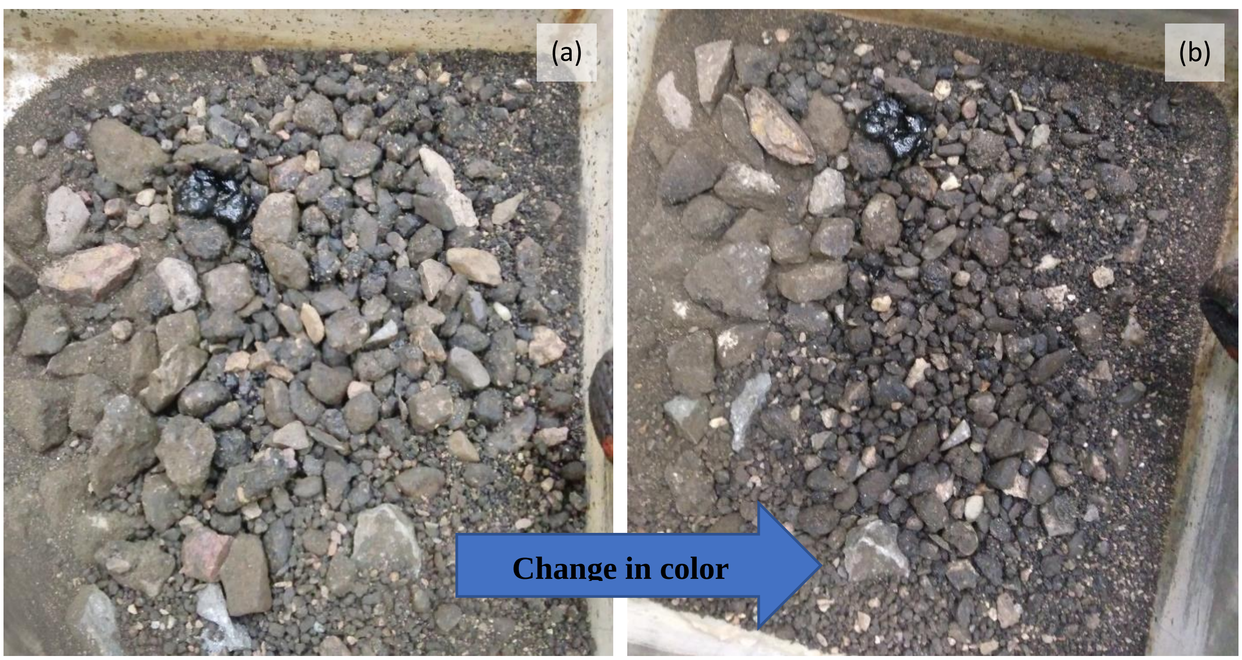
Heating of RAP aggregates before mixing

Case-1

In this case the RAP aggregates were placed at the center of the virgin aggregates in the oven at the mixing temperature (163°C) for an hour before mixing. After one hour, the binder in the RAP aggregate started to soften and the aggregates changed their color to black and glassy, indicating moderate softening of the binder from RAP aggregates.

Case-2

In this case the aggregates were heated separately at 110°C in a separate oven for 2 hours before mixing. The RAP aggregate after one hour of heating is shown in the following figure (a), and after two hours of heating is shown in indent (b). The RAP aggregates turned into a darker black. The RAP in case-1 showed more binder mobilized due to heating at high temperature and is darker in color.



RAP aggregates; (a) after one hour of heating, (b) after two hours of heating

In parallel, a brief survey was conducted to see what the local practices are, and it can be concluded that there is an agreement on following ADOT's specifications. ARIZ 833, Marshall Mix Design Method for Asphaltic Concrete with Reclaimed Asphalt Pavement (RAP) (An Arizona Method) is the specification currently in use and it basically states a procedure to heat RAP with the virgin aggregates until the material reaches the mixing temperature.

Based on this procedure, virgin aggregate plus admixture must be placed in a suitable pan and a shallow crater must be formed in the center of the aggregate, RAP should be placed in the crater avoiding that the RAP material touches the pan. All the aggregates are heated together. It is not clear how much time virgin aggregates and RAP must be heated.

Based on all results, it was decided to conduct a small experiment were a RAP sample was heated in the oven at the mixing temperature and the material temperature was monitored to see the evolution versus time. The practice related to RAP placing over the virgin aggregates recommended by ADOT was followed. In this case, virgin aggregates were heated for 5 hours prior the inclusion of the RAP. The material was placed to avoid contact between the material and the pan, this will ensure that RAP binder do not overheat and mobilize uneven. The Figure below shows the disposition of RAP material on the virgin aggregates. A thermocouple was installed to monitor the temperature change.

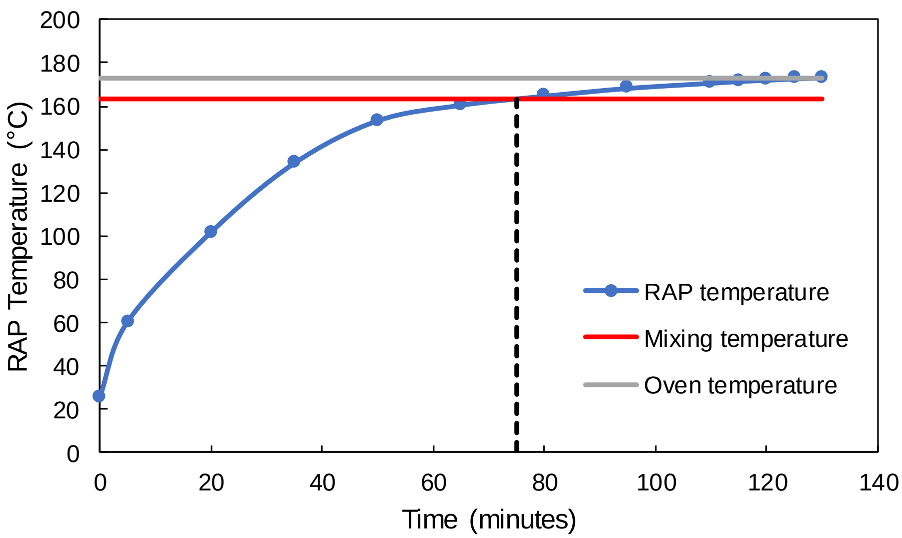
RAP sample in the oven with thermocouple.

RAP sample after heating.

The figure above shows how RAP looked like after the heating process, showing that the binder was mobilized by heat transfer from the virgin aggregate. The following table displays the results which are also plotted.

RAP heating temperature vs. time experiment

Hour	Minutes	Cumulative minutes	RAP temperature (°C)	Mixing temperature (°C)	Oven temperature (°C)
11:40	0	0	25	163	173
11:45	5	5	60	163	173
12:00	15	20	101.5	163	173
12:15	15	35	133.5	163	173
12:30	15	50	153.2	163	173
12:45	15	65	160.4	163	173
1:00	15	80	164.6	163	173
1:15	15	95	168.2	163	173
1:30	15	110	170.6	163	173
1:35	5	115	171.4	163	173
1:40	5	120	172	163	173
1:45	5	125	172.6	163	173
1:50	5	130	173	163	173



RAP aggregates; (a) after one hour of heating, (b) after two hours of heating

From the figure above, it can be concluded that the time needed for the RAP to reach the mixing temperature was 75 minutes approximately. Because that the maximum limit of the mixing temperature for the binder used was settled in the oven, it was decided to heat RAP for one hour before mixing at the highest mixing temperature of the range.

APPENDIX D

MIXTURE DESIGN

Control Mix 0% RAP

Maximum Specific Gravity of 0% RAP mix

Sample	Binder content (%)	Weight Container+Water (C)	Gmm
R-1	4.5	7595.5	2.477
R-2	4.5	7595.5	2.477
R-1	5.0	7595.5	2.458
R-2	5.0	7595.5	2.458
R-1	5.5	7595.5	2.440
R-2	5.5	7595.5	2.440

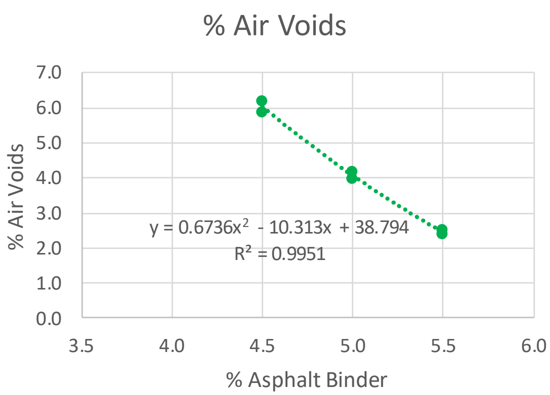
Bulk Specific Gravity of compacted paving mixture sample (Gmb) 0% RAP mix

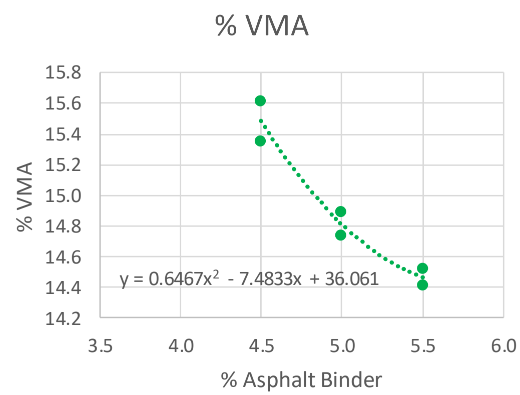
Specimen ID	Binder Content	Mass in Air (gm) A	Mass in Water (gm) C	Surface Dry Mass (gm) B	Sample Volume (cm3) (B-C)	Gmb (gm/cm3) A/(B-C)	Water Abs. (%) (B-A)/(B-C)*100	Gmb (Average)
1-COP-0%R-4.5%	4.5%	4689.1	2705.8	4703.9	1998.1	2.347	0.74	2.352
2-COP-0%R-4.5%	4.5%	4693.4	2718.8	4710.5	1991.7	2.356	0.86	
1-COP-0%R-5.0%	5.0%	4691.3	2725.1	4695.5	1970.4	2.381	0.21	2.383
2-COP-0%R-5.0%	5.0%	4689.4	2729.2	4695.2	1966.0	2.385	0.30	
1-COP-0%R-5.5%	5.5%	4688.8	2741.5	4692.3	1950.8	2.404	0.18	2.405
2-COP-0%R-5.5%	5.5%	4689.8	2743.1	4691.5	1948.4	2.407	0.09	

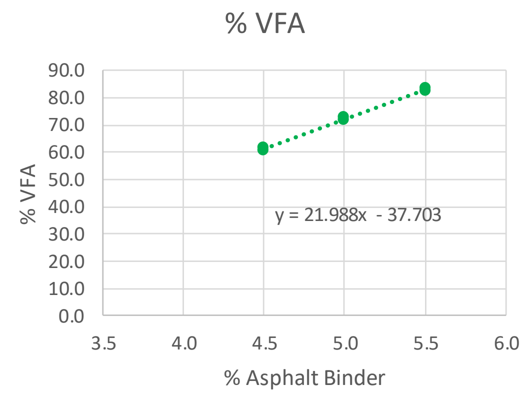
Densification Tables for 0% RAP mix

Sample	Pb	Mass	Heights at different N			Volume at different heights			Gmb (estimated)			Gmb (meas.)	Correct. factor
			Nini	Ndes	Nmax	Nini	Ndes	Nmax	ini	Des	max		
4.5%, Control	4.5	4691.0	123.90	115.53	114.40	2189.5	2041.6	2021.6	2.143	2.298	2.320	2.347	1.011
4.5%, Control	4.5	4694.0	124.88	115.55	114.30	2206.8	2041.9	2019.8	2.127	2.299	2.324	2.356	1.014
5%, control	5.0	4692.0	122.55	114.17	112.98	2165.6	2017.6	1996.5	2.167	2.326	2.350	2.381	1.013
5%, control	5.0	4691.0	122.24	113.83	112.64	2160.2	2011.5	1990.5	2.172	2.332	2.357	2.385	1.012
5.5%, control	5.5	4691.0	121.55	113.07	111.91	2148.0	1998.1	1977.6	2.184	2.348	2.372	2.404	1.013
5.5%, control	5.5	4691.0	120.74	112.44	111.26	2133.7	1987.0	1966.1	2.199	2.361	2.386	2.407	1.009

Sample	Pb	Gmb corrected			Gmm	%Gmm			% Air voids @Ndes	%VMA	%VFA
		Nini	Ndes	Nmax		Nini	Ndes	Nmax			
4.5%, Control	4.5	2.167	2.324	2.347	2.477	87.5	93.8	94.8	6.2	15.6	60.5
4.5%, Control	4.5	2.157	2.331	2.356	2.477	87.1	94.1	95.1	5.9	15.4	61.7
5%, control	5.0	2.195	2.356	2.381	2.458	89.3	95.8	96.9	4.2	14.9	72.1
5%, control	5.0	2.198	2.360	2.385	2.458	89.4	96.0	97.0	4.0	14.7	73.0
5.5%, control	5.5	2.213	2.379	2.404	2.440	90.7	97.5	98.5	2.5	14.5	82.7
5.5%, control	5.5	2.218	2.382	2.407	2.440	90.9	97.6	98.6	2.4	14.4	83.4







Mix design plots for 0%RAP.

0% RAP Mix Design

Mix Property	Criteria 3/4" Mix	0% RAP	Specifications
Asphalt Binder (%)		5.02	
Air Voids (%)	4.0+/-0.2	4.00	
VMA (%)	13 min.	14.76	Pass
VFA (%)	65 - 78	72.59	Pass
Absorbed Asphalt (%)	0 - 1.0	0.38	Pass
Dust Proportion	0.6 - 1.4	1.03	Pass
%Gmm@Nini = 7	less than 90.5	89.4	Pass
%Gmm@Nmax = 115	less than 98	97.0	Pass
Eff. Asphalt content (%)		4.66	
P0.075		4.8	

0% RAP Batching Weights for Optimum Binder Determination

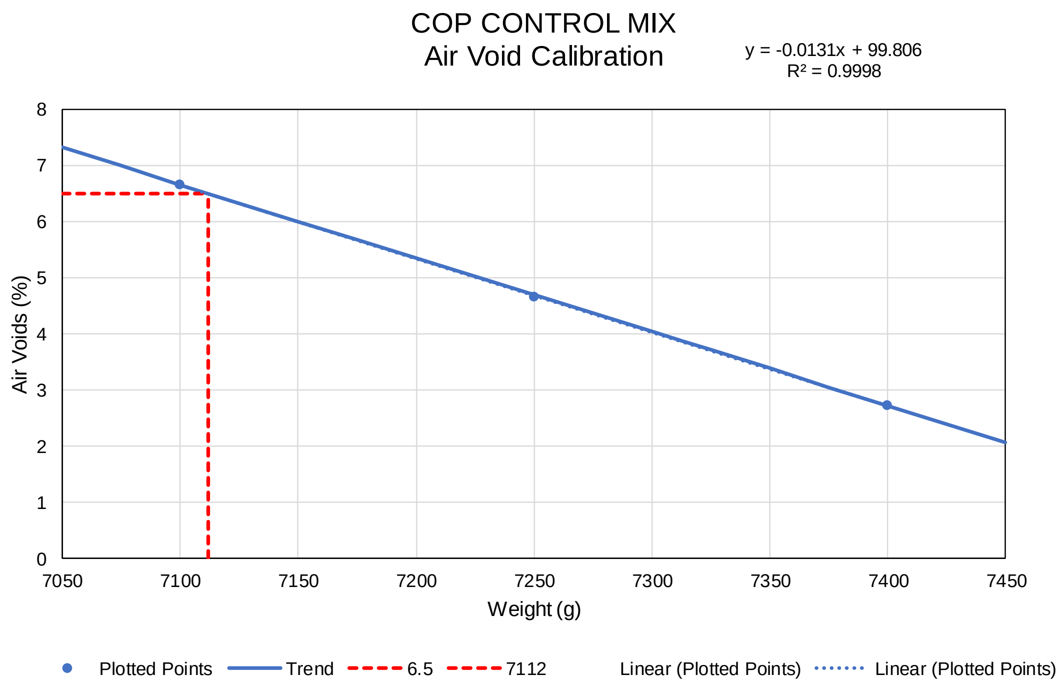
Control Mix							
Total mix weight				4750	4750	4750	7600
Binder weight				213.8	237.5	261.3	418.0
Aggregate weight				4536.3	4512.5	4488.8	7182.0
Binder percentage				4.5	5.0	5.5	5.5
Aggregate %				95.5	95	94.5	94.5
	Cum % Passing	Cum % Retained	% retained	weight			
1"	100	0	0	0.0	0.0	0.0	0.0
3/4"	100	0	0	0.0	0.0	0.0	0.0
1/2"	86	14	14	635.1	631.8	628.4	1005.5
3/8"	72	28	14	635.1	631.8	628.4	1005.5
1/4"	59	41	13	589.7	586.6	583.5	933.7
#4	56	44	3	136.1	135.4	134.7	215.5
#8	43	57	13	589.7	586.6	583.5	933.7
#16	32	68	11	499.0	496.4	493.8	790.0
#30	21	79	11	499.0	496.4	493.8	790.0
50	11	89	10	453.6	451.3	448.9	718.2
100	6	94	5	226.8	225.6	224.4	359.1
#200	4.8	95.2	1.2	54.4	54.2	53.9	86.2
Pan			3.7	167.8	167.0	166.1	265.7
Lime			1.1	49.9	49.6	49.4	79.0
Total			100	4536.3	4512.5	4488.8	7182.0

0% RAP Air Void Calibration

Control Mix 0%RAP			
Gmm	2.458		
	S1	S2	S3
	Cores		
Target Weight	7100	7250	7400
Dry Weight [A]	2785.5	2889.1	2933.1
Wet weight (C)	1578	1659.8	1708.6
SSD Weight (B)	2792	2892.4	2935.2
Gmb	2.294	2.344	2.391
% Absorbed	0.535	0.268	0.171
% Air Voids	6.653	4.642	2.716

Desired Air Voids (%)	7
Weight (g)	7074

Desired Air Voids (%)	6.5
Weight (g)	7112



Air void calibration plot for 0%RAP.

RAP Batching Weights for Testing Specimen Mixture

Required weight					7112	
Control Mix			0%	Total mix weight		7300
Binder percentage		5.02	Binder weight			366.5
Aggregate %		94.98	Aggregate weight			6933.5
Sieves US	Cum % Passing	Cum % Retained	% retained	weight		
1"	100	0	0	0.0		
3/4"	100	0	0	0.0		
1/2"	86	14	14	970.7		
3/8"	72	28	14	970.7		
1/4"	59	41	13	901.4		
#4	56	44	3	208.0		
#8	43	57	13	901.4		
#16	32	68	11	762.7		
#30	21	79	11	762.7		
50	11	89	10	693.4		
100	6	94	5	346.7		
#200	4.8	95.2	1.2	83.2		
Pan			3.7	256.5		
Lime			1.1	76.3		
			100	6933.5		

10% RAP Mix

Maximum Specific Gravity of 10% RAP mix

Sample	Binder content (%)	Weight Container+Water (C)	Gmm
R-1	4.5	7593.4	2.494
R-2	4.5	7593.4	2.490
R-1	5.0	7593.4	2.479
R-2	5.0	7593.4	2.484
R-1	5.5	7593.4	2.465
R-2	5.5	7593.4	2.451

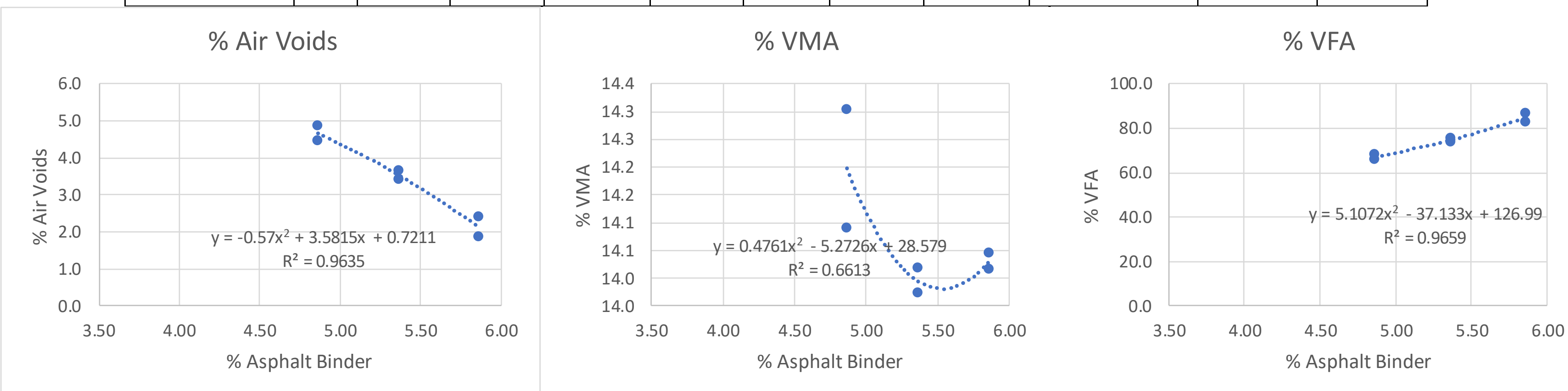
Bulk Specific Gravity of compacted paving mixture sample (Gmb) 10% RAP mix

Specimen ID	Binder Content	Mass in Air (gm) A	Mass in Water (gm) C	Surface Dry Mass (gm) B	Sample Volume (cm3) (B-C)	Gmb (gm/cm3) A/(B-C)	Water Abs. (%) (B-A)/(B-C)*100	Gmb (Average)
1-COP-10%R-4.5%	4.5%	4943.7	2886.7	4950.5	2063.8	2.395	0.33	2.398
2-COP-10%R-4.5%	4.5%	4919.7	2875.4	4924.6	2049.2	2.401	0.24	
1-COP-10%R-5.0%	5.0%	4946.2	2901.9	4948.2	2046.3	2.417	0.10	2.416
2-COP-10%R-5.0%	5.0%	4967.4	2914.1	4970.3	2056.2	2.416	0.14	
1-COP-10%R-5.5%	5.5%	4980.4	2926.7	4981.7	2055.0	2.424	0.06	2.424
2-COP-10%R-5.5%	5.5%	4997.8	2936.5	4998.7	2062.2	2.424	0.04	

Densification Tables for 10% RAP mix

Sample	Pb	Mass	Heights at different N			Volume at different heights			Gmb (estimated)			Gmb (meas.)	Correction factor
			N ini	N des	N max	N ini	N des	N max	ini	Des	max		
10%RAP -1	4.9	4943.7	128.82	119.51	118.37	2276.4	2111.9	2091.8	2.172	2.341	2.363	2.395	1.014
10%RAP -2	4.9	4919.7	126.83	118.14	117.04	2241.3	2087.7	2068.3	2.195	2.357	2.379	2.401	1.009
10%RAP -1	5.4	4946.2	126.60	118.13	117.01	2237.2	2087.5	2067.7	2.211	2.369	2.392	2.417	1.010
10%RAP -2	5.4	4967.4	127.62	118.61	117.49	2255.2	2096.0	2076.2	2.203	2.370	2.393	2.416	1.010
10%RAP -1	5.9	4980.4	126.59	118.04	117.17	2237.0	2085.9	2070.6	2.226	2.388	2.405	2.424	1.008
10%RAP -2	5.9	4997.8	126.79	118.46	117.55	2240.6	2093.4	2077.3	2.231	2.387	2.406	2.424	1.007

Sample	Pb	Gmb corrected			Gmm	%Gmm			% Air voids @Ndes	%VMA	%VFA
		N ini	N des	N max		N ini	N des	N max			
10%RAP -1	4.9	2.201	2.373	2.395	2.494	88.3	95.2	96.1	4.8	14.3	66.1
10%RAP -2	4.9	2.215	2.378	2.401	2.490	89.0	95.5	96.4	4.5	14.1	68.3
10%RAP -1	5.4	2.234	2.394	2.417	2.479	90.1	96.6	97.5	3.4	14.0	75.6
10%RAP -2	5.4	2.224	2.393	2.416	2.484	89.5	96.3	97.3	3.7	14.0	73.9
10%RAP -1	5.9	2.243	2.406	2.424	2.465	91.0	97.6	98.3	2.4	14.0	82.9
10%RAP -2	5.9	2.247	2.405	2.424	2.451	91.7	98.1	98.9	1.9	14.0	86.6



Mix design plots for 10%RAP.

10% RAP Mix Design

Mix Property	Criteria 3/4" Mix	10%RAP	Specifications
Asphalt Binder (%)		5.17	
Air Voids (%)	4.0+/-0.2	4.00	
VMA (%)	13 min.	14.05	Pass
VFA (%)	65 - 78	71.63	Pass
Absorbed Asphalt (%)	0 - 1.0	0.32	Pass
Dust Proportion	0.6 - 1.4	0.99	Pass
%Gmm@Nini = 7	less than 90.5	89.3	Pass
%Gmm@Nmax = 115	less than 98	96.9	Pass
Eff. Asphalt content (%)		4.87	
P0.075		4.8	
Total Binder Content (%)		5.17	(by weight of total mix)
Added Virgin Binder Content (%)		4.80	(by weight of total mix)
Contributed RAP Binder Content (%)		0.37	(by weight of total mix)

10% RAP Batching Weights for Optimum Binder Determination

%RAP			10		Total mix weight (g)			5000
Total Binder content (%)		5.4	Binder weight (g)					268.1
Total Aggregate content (%)		94.6	Aggregate+RAP Agg.+lime weight (g)					4731.9
			Aggregate+RAP Agg. weight (g)					4684.9
Admixture content (%)		1.00	Virgin aggregate weight (g)					4228.0
RAP binder content (%)		3.81	RAP Aggregate weight (g)					456.9
Virgin agg.+lime content (%)		90.35	RAP weight + binder (g)					**475.0**
			Lime weight (g)					47.0
			Virgin aggregate weight+lime (g)					**4275.0**
			RAP binder contribution weight (g)					18.1
			Virgin binder weight (g)					**250.0**
Sieve size	Cum % Passing	Cum % Ret.	% retained	weight	Virgin	RAP	RAP+binder	
1"	100	0	0	0.0	0.0	0.0	0.0	
3/4"	100	0	0	0.0	0.0	0.0	0.0	
1/2"	86	14	14	662.5	598.6	64.6	67.2	
3/8"	72	28	14	662.5	598.6	64.6	67.2	
1/4"	59	41	13	615.1	555.8	60.0	62.4	
#4	56	44	3	142.0	128.3	13.8	14.4	
#8	43	57	13	615.1	555.8	60.0	62.4	
#16	32	68	11	520.5	470.3	50.8	52.8	
#30	21	79	11	520.5	470.3	50.8	52.8	
50	11	89	10	473.2	427.5	46.1	48.0	
100	6	94	5	236.6	213.8	23.1	24.0	
#200	4.8	95.2	1.2	56.8	51.3	5.5	5.8	
Pan			3.70	175.1	158.2	17.1	17.8	
Lime			1.00	47.5	47.5		0.0	
			100	4727.3	4275.9	456.4	474.5	

%RAP			10	Total mix weight (g)				4980
Total Binder content (%)		4.9	Binder weight (g)					242.0
Total Aggregate content (%)		95.1	Aggregate+RAP Agg.+lime weight (g)					4738.0
			Aggregate+RAP Agg. weight (g)					4690.9
Admixture content (%)		1.00	Virgin aggregate weight (g)					4233.4
RAP binder content (%)		3.81	RAP Aggregate weight (g)					457.5
Virgin agg.+lime content (%)		90.35	RAP weight + binder (g)					**475.6**
			Lime weight (g)					47.1
			Virgin aggregate weight+lime (g)					**4280.5**
			RAP binder contribution weight (g)					18.1
			Virgin binder weight (g)					**223.9**
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+ binder	
1"	100	0	0	0.0	0.0	0.0	0.0	
3/4"	100	0	0	0.0	0.0	0.0	0.0	
1/2"	86	14	14	663.3	599.3	64.7	67.3	
3/8"	72	28	14	663.3	599.3	64.7	67.3	
1/4"	59	41	13	615.9	556.5	60.1	62.4	
#4	56	44	3	142.1	128.4	13.9	14.4	
#8	43	57	13	615.9	556.5	60.1	62.4	
#16	32	68	11	521.2	470.9	50.8	52.8	
#30	21	79	11	521.2	470.9	50.8	52.8	
50	11	89	10	473.8	428.1	46.2	48.0	
100	6	94	5	236.9	214.0	23.1	24.0	
#200	4.8	95.2	1.2	56.9	51.4	5.5	5.8	
Pan			3.70	175.3	158.4	17.1	17.8	
Lime			1.00	47.6	47.6		0.0	
			100	4733.4	4281.4	457.0	475.1	

%RAP	10	Total mix weight (g)	5025
Total Binder content (%)	5.9	Binder weight (g)	294.5
Total Aggregate content (%)	94.1	Aggregate+RAP Agg.+lime weight (g)	4730.5
		Aggregate+RAP Agg. weight (g)	4683.5
Admixture content (%)	1.00	Virgin aggregate weight (g)	4226.8
RAP binder content (%)	3.81	RAP Aggregate weight (g)	456.8
Virgin agg.+lime content (%)	90.35	RAP weight + binder (g)	**474.9**
		Lime weight (g)	47.0
		Virgin aggregate weight+lime (g)	**4273.8**
		RAP binder contribution weight (g)	18.1
		Virgin binder weight (g)	**276.4**

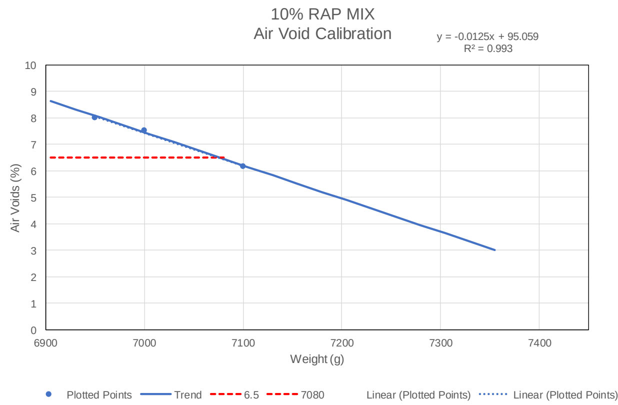
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+binder	
1"	100	0	0	0.0	0.0	0.0	0.0	
3/4"	100	0	0	0.0	0.0	0.0	0.0	
1/2"	86	14	14	662.3	598.4	64.6	67.1	
3/8"	72	28	14	662.3	598.4	64.6	67.1	
1/4"	59	41	13	615.0	555.7	60.0	62.4	
#4	56	44	3	141.9	128.2	13.8	14.4	
#8	43	57	13	615.0	555.7	60.0	62.4	
#16	32	68	11	520.4	470.2	50.7	52.8	
#30	21	79	11	520.4	470.2	50.7	52.8	
50	11	89	10	473.1	427.4	46.1	48.0	
100	6	94	5	236.5	213.7	23.1	24.0	
#200	4.8	95.2	1.2	56.8	51.3	5.5	5.8	
Pan			3.70	175.0	158.1	17.1	17.7	
Lime			1.00	47.5	47.5		0.0	
			100	4726.0	4274.7	456.3	474.4	

10% RAP Air Void Calibration

Air Voids	10% RAP		
Gmm	2.452		
	S1	S2	S3
	Cores		
Target Weight	6950	7100	7000
Dry Weight [A]	2741.6	2797.8	2771.6
Wet weight (C)	1533.4	1585.6	1556.5
SSD Weight (B)	2748.7	2801.4	2778.8
Gmb	2.256	2.301	2.268
% Absorbed	0.584	0.296	0.589
% Air Voids	8.002	6.155	7.528

Desired Air Voids (%)	7
Weight (g)	7036

Desired Air Voids (%)	6.5
Weight (g)	7076



Air void calibration plot for 10%RAP

10% RAP Batching Weights for Testing Specimen Mixture

						Required weight		7090
%RAP			10			Total mix weight (g)		7250
Binder percentage		5.17	Binder weight (g)					374.8
Aggregate %		94.83	Aggregate+RAP+lime weight (g)					6875.2
RAP binder content %		3.81	**Lime weight (g)**					**75.6**
Lime content %		1.1	Aggregate+RAP weight (g)					6799.5
			Virgin aggregate weight (g)					6119.6
			RAP weight (g)					680.0
			RAP +binder weight (g)					706.9
			RAP binder contribution weight (g)					26.9
			Virgin binder weight (g)					**347.9**
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+ bind	Lime
1"	100	0	0	0.0	**0.0**	0.0	**0.0**	
3/4"	100	0	0	0.0	**0.0**	0.0	**0.0**	
1/2"	86	14	14	962.5	**866.3**	96.3	**100.1**	
3/8"	72	28	14	962.5	**866.3**	96.3	**100.1**	
1/4"	59	41	13	893.8	**804.4**		**0.0**	
#4	56	44	3	206.3	**185.6**	110.0	**114.4**	
#8	43	57	13	893.8	**804.4**	89.4	**92.9**	
#16	32	68	11	756.3	**680.6**	75.6	**78.6**	
#30	21	79	11	756.3	**680.6**	75.6	**78.6**	
50	11	89	10	687.5	**618.8**	68.8	**71.5**	
100	6	94	5	343.8	**309.4**	34.4	**35.7**	
#200	4.8	95.2	1.2	82.5	**74.3**	8.3	**8.6**	
Pan			3.7	254.4	**228.9**	25.4	**26.4**	
Lime			1.1	75.6				75.6
			100	6875.2	**6119.6**	680.0	**706.9**	

15% RAP Mix

Maximum Specific Gravity of 15% RAP mix

Sample	Binder content (%)	Weight Sample (A)	Weight Sample+Water (B)	Weight Container+Water (C)	Gmm
R-1	4.5	2500.1	9090.4	7582.2	2.521
R-2	4.5	2500.1	9084.8	7582.2	2.506
R-1	5.0	2500.1	9085.8	7582.2	2.509
R-2	5.0	2500.2	9081.7	7582.2	2.498
R-1	5.5	2500.0	9070.5	7582.2	2.471
R-2	5.5	2500.0	9065.3	7582.2	2.458

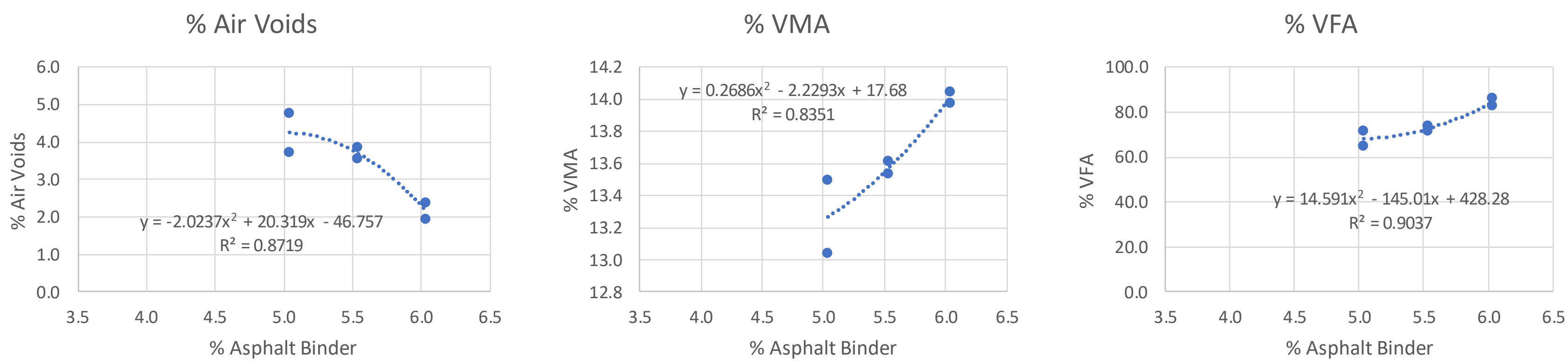
Bulk Specific Gravity of compacted paving mixture sample (Gmb) 15% RAP mix

Specimen ID	Binder Content	Mass in Air (gm) A	Mass in Water (gm) C	Surface Dry Mass (gm) B	Sample Volume (cm3) (B-C)	Gmb (gm/cm3) A/(B-C)	Water Abs. (%) (B-A)/(B-C)*100	Gmb (Average)
1-COP-15%R-4.5%	4.5%	4913.4	2888.8	4916.2	2027.4	2.423	0.14	2.430
2-COP-15%R-4.5%	4.5%	4937.0	2913.8	4940.7	2026.9	2.436	0.18	
1-COP-15%R-5.0%	5.0%	4953.9	2921.0	4955.4	2034.4	2.435	0.07	2.434
2-COP-15%R-5.0%	5.0%	4941.0	2911.2	4942.2	2031.0	2.433	0.06	
1-COP-15%R-5.5%	5.5%	4955.3	2917.8	4956.8	2039.0	2.430	0.07	2.430
2-COP-15%R-5.5%	5.5%	4956.6	2916.9	4957.4	2040.5	2.429	0.04	

Densification Tables for 15% RAP mix

Sample	Pb	Mass	Heights at different N			Volume at different heights			Gmb (estimated)			Gmb (meas.)	Correction factor
			N ini	N des	N max	N ini	N des	N max	ini	Des	max		
15%RAP -1	5.0	4913.4	128.82	119.51	118.37	2276.4	2111.9	2091.8	2.158	2.327	2.349	2.423	1.032
15%RAP -2	5.0	4937.0	126.83	118.14	117.04	2241.3	2087.7	2068.3	2.203	2.365	2.387	2.436	1.020
15%RAP -1	5.5	4953.9	126.60	118.13	117.01	2237.2	2087.5	2067.7	2.214	2.373	2.396	2.435	1.016
15%RAP -2	5.5	4941.0	127.62	118.61	117.49	2255.2	2096.0	2076.2	2.191	2.357	2.380	2.433	1.022
15%RAP -1	6.0	4955.3	126.59	118.04	117.17	2237.0	2085.9	2070.6	2.215	2.376	2.393	2.430	1.015
15%RAP -2	6.0	4956.6	126.79	118.46	117.55	2240.6	2093.4	2077.3	2.212	2.368	2.386	2.429	1.018

Sample	Pb	Gmb corrected			Gmm	%Gmm			% Air voids @Ndes	%VMA	%VFA
		N ini	N des	N max		N ini	N des	N max			
15%RAP -1	5.5	2.227	2.400	2.423	2.521	88.4	95.2	96.2	4.8	13.5	64.7
15%RAP -2	5.5	2.248	2.413	2.436	2.506	89.7	96.3	97.2	3.7	13.0	71.5
15%RAP -1	6.0	2.251	2.412	2.435	2.509	89.7	96.1	97.1	3.9	13.5	71.5
15%RAP -2	6.0	2.240	2.410	2.433	2.498	89.6	96.5	97.4	3.5	13.6	73.9
15%RAP -1	5.0	2.249	2.412	2.430	2.471	91.0	97.6	98.3	2.4	14.0	83.0
15%RAP -2	5.0	2.252	2.410	2.429	2.458	91.6	98.0	98.8	2.0	14.0	86.1



Mix design plots for 15%RAP.

15% RAP Mix Design

Mix Property	Criteria 3/4" Mix	15%RAP	Specifications
Asphalt Binder (%)		5.37	
Air Voids (%)	4.0+/-0.2	4.00	
VMA (%)	13 min.	13.45	Pass
VFA (%)	65 - 78	70.33	Pass
Absorbed Asphalt (%)	0 - 1.0	0.30	Pass
Dust Proportion	0.6 - 1.4	0.94	Pass
%Gmm@Nini = 7	less than 90.5	89.3	Pass
%Gmm@Nmax = 115	less than 98	96.9	Pass
Eff. Asphalt content (%)		5.08	
P0.075		4.8	
Total Binder Content (%)		5.37	(by weight of total mix)
Added Virgin Binder Content (%)		4.82	(by weight of total mix)
Contributed RAP Binder Content (%)		0.55	(by weight of total mix)

15% Air Voids Calibration RAP Batching Weights

			Required weight		6900			
%RAP			15	Total mix weight (g)				7050
Binder percentage		5.37	Binder weight (g)					378.6
Aggregate %		94.63	Aggregate+RAP+lime weight (g)					6671.4
RAP binder content %		3.81	**Lime weight (g)**					**73.4**
Lime content %		1.1	Aggregate+RAP weight (g)					6598.0
			Virgin aggregate weight (g)					5608.3
			RAP weight (g)					989.7
			RAP +binder weight (g)					1028.9
			RAP binder contribution weight (g)					39.2
			Virgin binder weight (g)					**339.4**
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+bind	Lime
1"	100	0	0	0.0	**0.0**	0.0	**0.0**	
3/4"	100	0	0	0.0	**0.0**	0.0	**0.0**	
1/2"	86	14	14	934.0	**793.9**	140.1	**145.6**	
3/8"	72	28	14	934.0	**793.9**	140.1	**145.6**	
1/4"	59	41	13	867.3	**737.2**		**0.0**	
#4	56	44	3	200.1	**170.1**	160.1	**166.5**	
#8	43	57	13	867.3	**737.2**	130.1	**135.2**	
#16	32	68	11	733.9	**623.8**	110.1	**114.4**	
#30	21	79	11	733.9	**623.8**	110.1	**114.4**	

50	11	89	10	667.1	**567.1**	100.1	**104.0**	
100	6	94	5	333.6	**283.5**	50.0	**52.0**	
#200	4.8	95.2	1.2	80.1	**68.0**	12.0	**12.5**	
Pan			3.7	246.8	**209.8**	37.0	**38.5**	
Lime			1.1	73.4				73.4
			100	6671.4	**5608.3**	989.7	**1028.9**	

Required weight				7050				
%RAP			15	Total mix weight (g)				7200
Binder percentage	5.37		Binder weight (g)					386.6
Aggregate %	94.63		Aggregate+RAP+lime weight (g)					6813.4
RAP binder content %	3.81		Lime weight (g)					74.9
Lime content %	1.1		Aggregate+RAP weight (g)					6738.4
			Virgin aggregate weight (g)					5727.7
			RAP weight (g)					1010.8
			RAP +binder weight (g)					1050.8
			RAP binder contribution weight (g)					40.0
			Virgin binder weight (g)					346.6
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+bind	Lime
1"	100	0	0	0.0	0.0	0.0	0.0	
3/4"	100	0	0	0.0	0.0	0.0	0.0	
1/2"	86	14	14	953.9	810.8	143.1	148.7	
3/8"	72	28	14	953.9	810.8	143.1	148.7	
1/4"	59	41	13	885.7	752.9		0.0	
#4	56	44	3	204.4	173.7	163.5	170.0	
#8	43	57	13	885.7	752.9	132.9	138.1	
#16	32	68	11	749.5	637.0	112.4	116.9	
#30	21	79	11	749.5	637.0	112.4	116.9	
50	11	89	10	681.3	579.1	102.2	106.2	
100	6	94	5	340.7	289.6	51.1	53.1	
#200	4.8	95.2	1.2	81.8	69.5	12.3	12.7	
Pan			3.7	252.1	214.3	37.8	39.3	
Lime			1.1	74.9				74.9
			100	6813.4	5727.7	1010.8	1050.8	

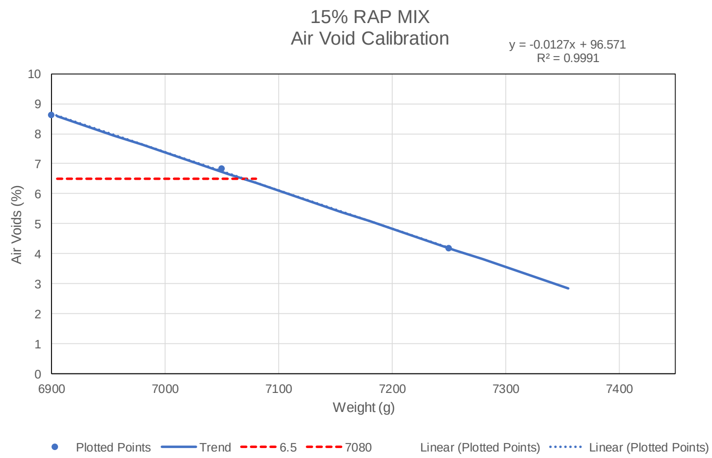
Required weight				7250				
%RAP			15	Total mix weight (g)				7400
Binder percentage		5.37	Binder weight (g)					397.4
Aggregate %		94.63	Aggregate+RAP+lime weight (g)					7002.6
RAP binder content %		3.81	**Lime weight (g)**					**77.0**
Lime content %		1.1	Aggregate+RAP weight (g)					6925.6
			Virgin aggregate weight (g)					5886.8
			RAP weight (g)					1038.8
			RAP +binder weight (g)					1080.0
			RAP binder contribution weight (g)					41.1
			Virgin binder weight (g)					**356.2**
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+bind	Lime
1"	100	0	0	0.0	**0.0**	0.0	**0.0**	
3/4"	100	0	0	0.0	**0.0**	0.0	**0.0**	
1/2"	86	14	14	980.4	**833.3**	147.1	**152.9**	
3/8"	72	28	14	980.4	**833.3**	147.1	**152.9**	
1/4"	59	41	13	910.3	**773.8**		**0.0**	
#4	56	44	3	210.1	**178.6**	168.1	**174.7**	
#8	43	57	13	910.3	**773.8**	136.6	**142.0**	
#16	32	68	11	770.3	**654.7**	115.5	**120.1**	
#30	21	79	11	770.3	**654.7**	115.5	**120.1**	
50	11	89	10	700.3	**595.2**	105.0	**109.2**	
100	6	94	5	350.1	**297.6**	52.5	**54.6**	
#200	4.8	95.2	1.2	84.0	**71.4**	12.6	**13.1**	
Pan			3.7	259.1	**220.2**	38.9	**40.4**	
Lime			1.1	77.0				77.0
			100	7002.6	**5886.8**	1038.8	**1080.0**	

15% RAP Air Void Calibration

Air Voids	15% RAP		
Gmm	2.445		
	S1	S2	S3
	Cores		
Target Weight	6900	7050	7250
Dry Weight [A]	2721.6	2781.2	2869.3
Wet weight (C)	1512.9	1566	1647.3
SSD Weight (B)	2730.9	2786.8	2871.8
Gmb	2.234	2.278	2.343

Desired Air Voids (%)	7
Weight (g)	7029

% Absorbed	0.764	0.459	0.204	Desired Air Voids (%)	6.5
% Air Voids	8.607	6.820	4.158	Weight (g)	7068



Air void calibration plot for 15%RAP.

15% RAP Batching Weights for Testing Specimen Mixture

Required weight						7080		
%RAP			15	Total mix weight (g)				7250
Binder percentage		5.37	Binder weight (g)					389.3
Aggregate %		94.63	Aggregate+RAP+lime weight (g)					6860.7
RAP binder content %		3.81	**Lime weight (g)**					**75.5**
Lime content %		1.1	Aggregate+RAP weight (g)					6785.2
			Virgin aggregate weight (g)					5767.4
			RAP weight (g)					1017.8
			RAP +binder weight (g)					1058.1
			RAP binder contribution weight (g)					40.3
			Virgin binder weight (g)					**349.0**
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+bind	Lime
1"	100	0	0	0.0	**0.0**	0.0	**0.0**	
3/4"	100	0	0	0.0	**0.0**	0.0	**0.0**	
1/2"	86	14	14	960.5	**816.4**	144.1	**149.8**	
3/8"	72	28	14	960.5	**816.4**	144.1	**149.8**	
1/4"	59	41	13	891.9	**758.1**		**0.0**	
#4	56	44	3	205.8	**174.9**	164.7	**171.2**	
#8	43	57	13	891.9	**758.1**	133.8	**139.1**	
#16	32	68	11	754.7	**641.5**	113.2	**117.7**	
#30	21	79	11	754.7	**641.5**	113.2	**117.7**	

50	11	89	10	686.1	**583.2**	102.9	**107.0**	
100	6	94	5	343.0	**291.6**	51.5	**53.5**	
#200	4.8	95.2	1.2	82.3	**70.0**	12.3	**12.8**	
Pan			3.7	253.8	**215.8**	38.1	**39.6**	
Lime			1.1	75.5				75.5
			100	6860.7	**5767.4**	1017.8	**1058.1**	

25% RAP Mix with Softer Binder (PG 64-16)

Maximum Specific Gravity of 25% RAP mix

Sample	Binder content (%)	Weight Sample (A)	Weight Sample+Water (B)	Weight Container+Water (C)	Gmm
R-1	5.0	2500.0	8969.6	7480.0	2.474
R-2	5.0	2546.8	8993.4	7480.0	2.464
R-1	5.5	2502.2	8964.0	7480.0	2.457
R-2	5.5	2545.0	8994.1	7480.0	2.469
R-1	6.0	2501.3	8959.5	7480.0	2.448
R-2	6.0	2575.7	9003.6	7480.0	2.448

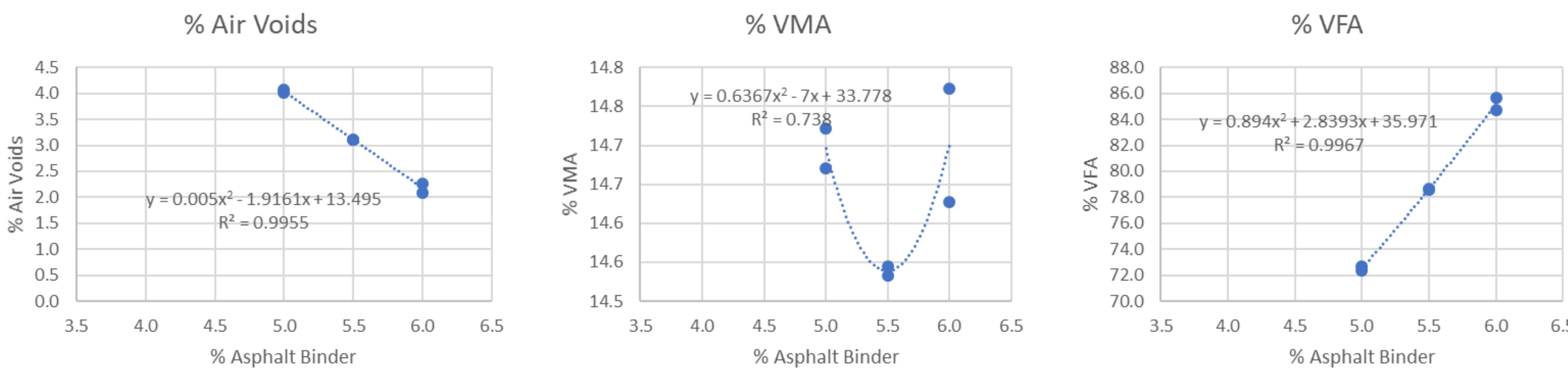
Bulk Specific Gravity of compacted paving mixture sample (Gmb) 25% RAP mix

Specimen ID	Binder Content	Mass in Air (gm) A	Mass in Water (gm) C	Surface Dry Mass (gm) B	Sample Volume (cm3) (B-C)	Gmb (gm/cm3) A/(B-C)	Water Abs. (%) (B-A)/(B-C)*100	Gmb (Average)
1-COP-25%R-5.0%	5.0%	4700.1	2748.0	4709.7	1961.7	2.396	0.49	2.395
2-COP-25%R-5.0%	5.0%	4701.2	2746.6	4710.6	1964.0	2.394	0.48	
1-COP-25%R-5.5%	5.5%	4699.9	2756.9	4706.3	1949.4	2.411	0.33	2.410
2-COP-25%R-5.5%	5.5%	4699.9	2753.3	4704.3	1951.0	2.409	0.23	
1-COP-25%R-6.0%	6.0%	4699.3	2750.7	4701.8	1951.1	2.409	0.13	2.414
2-COP-25%R-6.0%	6.0%	4699.3	2758.0	4701.0	1943.0	2.419	0.09	

Densification Tables for 25% RAP mix

Sample	Pb	Mass	Heights at different N			Volume at different heights			Gmb (estimated)			Gmb (meas.)	Correction factor
			N ini	N des	N max	N ini	N des	N max	ini	Des	max		
25%RAP -1	5.0	4700.1	123.07	113.57	112.41	2174.8	2006.9	1986.4	2.161	2.342	2.366	2.395	1.012
25%RAP -2	5.0	4701.2	123.26	113.85	112.62	2178.2	2011.9	1990.2	2.158	2.337	2.362	2.395	1.014
25%RAP -1	5.5	4699.9	122.38	113.06	111.97	2162.6	1997.9	1978.7	2.173	2.352	2.375	2.410	1.015
25%RAP -2	5.5	4699.9	121.58	112.61	111.51	2148.5	1990.0	1970.5	2.188	2.362	2.385	2.410	1.010
25%RAP -1	6.0	4699.3	121.39	112.26	111.48	2145.1	1983.8	1970.0	2.191	2.369	2.385	2.414	1.012
25%RAP -2	6.0	4699.3	121.09	112.20	111.23	2139.8	1982.7	1965.6	2.196	2.370	2.391	2.414	1.010

Sample	Pb	Gmb corrected			Gmm	%Gmm			% Air voids @Ndes	%VMA	%VFA
		N ini	N des	N max		N ini	N des	N max			
25%RAP -1	5.0	2.187	2.370	2.395	2.469	88.6	96.0	97.0	4.0	14.7	72.7
25%RAP -2	5.0	2.188	2.369	2.395	2.469	88.6	95.9	97.0	4.1	14.7	72.4
25%RAP -1	5.5	2.205	2.387	2.410	2.463	89.5	96.9	97.8	3.1	14.5	78.7
25%RAP -2	5.5	2.210	2.386	2.410	2.463	89.7	96.9	97.8	3.1	14.5	78.6
25%RAP -1	6.0	2.217	2.397	2.414	2.448	90.5	97.9	98.6	2.1	14.6	85.7
25%RAP -2	6.0	2.217	2.393	2.414	2.448	90.6	97.7	98.6	2.3	14.8	84.7



Mix design plots for 25%RAP.

25% RAP SB Mix Design

Mix Property	Criteria 3/4" Mix	15%RAP SB	Specifications
Asphalt Binder (%)		5.02	
Air Voids (%)	4.0+/-0.2	4.00	
VMA (%)	13 min.	14.68	Pass
VFA (%)	65 - 78	72.76	Pass
Absorbed Asphalt (%)	0 - 1.0	0.25	Pass
Dust Proportion	0.6 - 1.4	1.02	Pass
%Gmm@Nini = 7	less than 90.5	88.6	Pass
%Gmm@Nmax = 115	less than 98	97.0	Pass
Eff. Asphalt content (%)		4.79	
P0.075		4.9	
Total Binder Content (%)		5.02	(by weight of total mix)
Added Virgin Binder Content (%)		4.07	(by weight of total mix)
Contributed RAP Binder Content (%)		0.95	(by weight of total mix)

25% Air Voids Calibration RAP Batching Weights

%RAP			25	Total mix weight (g)				7490
Binder percentage		5.02		Binder weight (g)				376.0
Aggregate %		94.98		Aggregate+RAP+lime weight (g)				7114.0
RAP binder content %		3.81		**Lime weight (g)**				**78.3**
Lime content %		1.1		Aggregate+RAP weight (g)				7035.7
				Virgin aggregate weight (g)				5276.8
				RAP weight (g)				1758.9
				RAP +binder weight (g)				1828.6
				RAP binder contribution weight (g)				69.7
				Virgin binder weight (g)				**306.3**
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+ bind	Lime
1"	100	0	0	0.0	**0.0**	0.0	**0.0**	
3/4"	100	0	0	0.0	**0.0**	0.0	**0.0**	
1/2"	86	14	14	996.0	**747.0**	249.0	**258.9**	
3/8"	72	28	14	996.0	**747.0**	249.0	**258.9**	
1/4"	59	41	13	924.8	**693.6**		**0.0**	
#4	56	44	3	213.4	**160.1**	284.6	**295.8**	
#8	43	57	13	924.8	**693.6**	231.2	**240.4**	
#16	32	68	11	782.5	**586.9**	195.6	**203.4**	
#30	21	79	11	782.5	**586.9**	195.6	**203.4**	

50	11	89	10	711.4	**533.6**	177.9	**184.9**	
100	6	94	5	355.7	**266.8**	88.9	**92.4**	
#200	4.8	95.2	1.2	85.4	**64.0**	21.3	**22.2**	
Pan			3.7	263.2	**197.4**	65.8	**68.4**	
Lime			1.1	78.3				78.3
			100	7114.0	**5276.8**	1758.9	**1828.6**	

Required weight 7190

%RAP		25		Total mix weight (g)				7340
Binder percentage		5.02		Binder weight (g)				368.5
Aggregate %		94.98		Aggregate+RAP+lime weight (g)				6971.5
RAP binder content %		3.81		**Lime weight (g)**				**76.7**
Lime content %		1.1		Aggregate+RAP weight (g)				6894.8
				Virgin aggregate weight (g)				5171.1
				RAP weight (g)				1723.7
				RAP +binder weight (g)				1792.0
				RAP binder contribution weight (g)				68.3
				Virgin binder weight (g)				**300.2**
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+ bind	Lime
1"	100	0	0	0.0	**0.0**	0.0	**0.0**	
3/4"	100	0	0	0.0	**0.0**	0.0	**0.0**	
1/2"	86	14	14	976.0	**732.0**	244.0	**253.7**	
3/8"	72	28	14	976.0	**732.0**	244.0	**253.7**	
1/4"	59	41	13	906.3	**679.7**		**0.0**	
#4	56	44	3	209.1	**156.9**	278.9	**289.9**	
#8	43	57	13	906.3	**679.7**	226.6	**235.5**	
#16	32	68	11	766.9	**575.2**	191.7	**199.3**	
#30	21	79	11	766.9	**575.2**	191.7	**199.3**	
50	11	89	10	697.2	**522.9**	174.3	**181.2**	
100	6	94	5	348.6	**261.4**	87.1	**90.6**	
#200	4.8	95.2	1.2	83.7	**62.7**	20.9	**21.7**	
Pan			3.7	257.9	**193.5**	64.5	**67.0**	
Lime			1.1	76.7				76.7
			100	6971.5	**5171.1**	1723.7	**1792.0**	

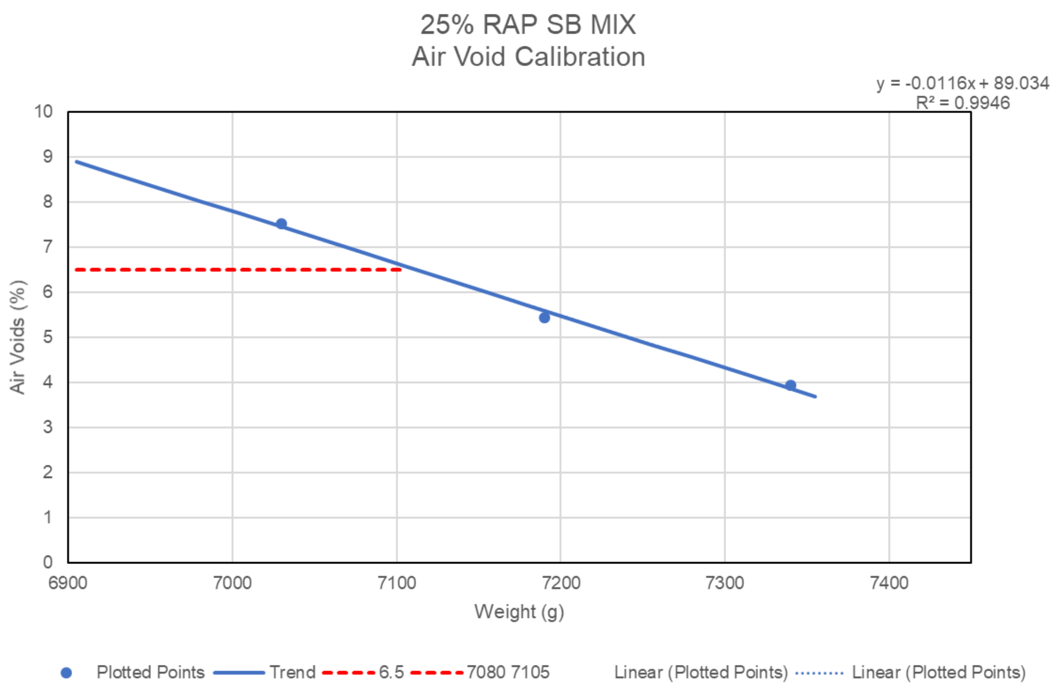
		Required weight			7030			
%RAP			25	Total mix weight (g)				7180
Binder percentage		5.02		Binder weight (g)				360.4
Aggregate %		94.98		Aggregate+RAP+lime weight (g)				6819.6
RAP binder content %		3.81		**Lime weight (g)**				**75.0**
Lime content %		1.1		Aggregate+RAP weight (g)				6744.5
				Virgin aggregate weight (g)				5058.4
				RAP weight (g)				1686.1
				RAP +binder weight (g)				1752.9
				RAP binder contribution weight (g)				66.8
				Virgin binder weight (g)				**293.6**
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+ bind	Lime
1"	100	0	0	0.0	**0.0**	0.0	**0.0**	
3/4"	100	0	0	0.0	**0.0**	0.0	**0.0**	
1/2"	86	14	14	954.7	**716.1**	238.7	**248.1**	
3/8"	72	28	14	954.7	**716.1**	238.7	**248.1**	
1/4"	59	41	13	886.5	**664.9**		**0.0**	
#4	56	44	3	204.6	**153.4**	272.8	**283.6**	
#8	43	57	13	886.5	**664.9**	221.6	**230.4**	
#16	32	68	11	750.2	**562.6**	187.5	**195.0**	
#30	21	79	11	750.2	**562.6**	187.5	**195.0**	
50	11	89	10	682.0	**511.5**	170.5	**177.2**	
100	6	94	5	341.0	**255.7**	85.2	**88.6**	
#200	4.8	95.2	1.2	81.8	**61.4**	20.5	**21.3**	
Pan			3.7	252.3	**189.2**	63.1	**65.6**	
Lime			1.1	75.0				75.0
			100	6819.6	**5058.4**	1686.1	**1752.9**	

25% RAP SB Air Void Calibration

Air Voids	25% RAP SB		
Gmm	2.456		
	S1	S2	S3
	Cores		
Target Weight	7340	7190	7030
Dry Weight [A]	2835	2803	2750.1
Wet weight (C)	1635.8	1600.4	1547.7
SSD Weight (B)	2837.6	2807.6	2758.8
Gmb	2.359	2.322	2.271
% Absorbed	0.216	0.381	0.718
% Air Voids	3.943	5.452	7.535

Desired Air Voids (%)	7
Weight (g)	7029

Desired Air Voids (%)	6.5
Weight (g)	7113



Air void calibration plot for 25%RAP.

25% RAP SB Batching Weights for Testing Specimen Mixture

Required weight		7110		
%RAP		25	Total mix weight (g)	7270
Binder percentage	5.02		Binder weight (g)	365.0
Aggregate %	94.98		Aggregate+RAP+lime weight (g)	6905.0
RAP binder content %	3.81		**Lime weight (g)**	**76.0**
Lime content %	1.1		Aggregate+RAP weight (g)	6829.1
			Virgin aggregate weight (g)	5121.8
			RAP weight (g)	1707.3
			RAP +binder weight (g)	1774.9
			RAP binder contribution weight (g)	67.6
			Virgin binder weight (g)	**297.3**

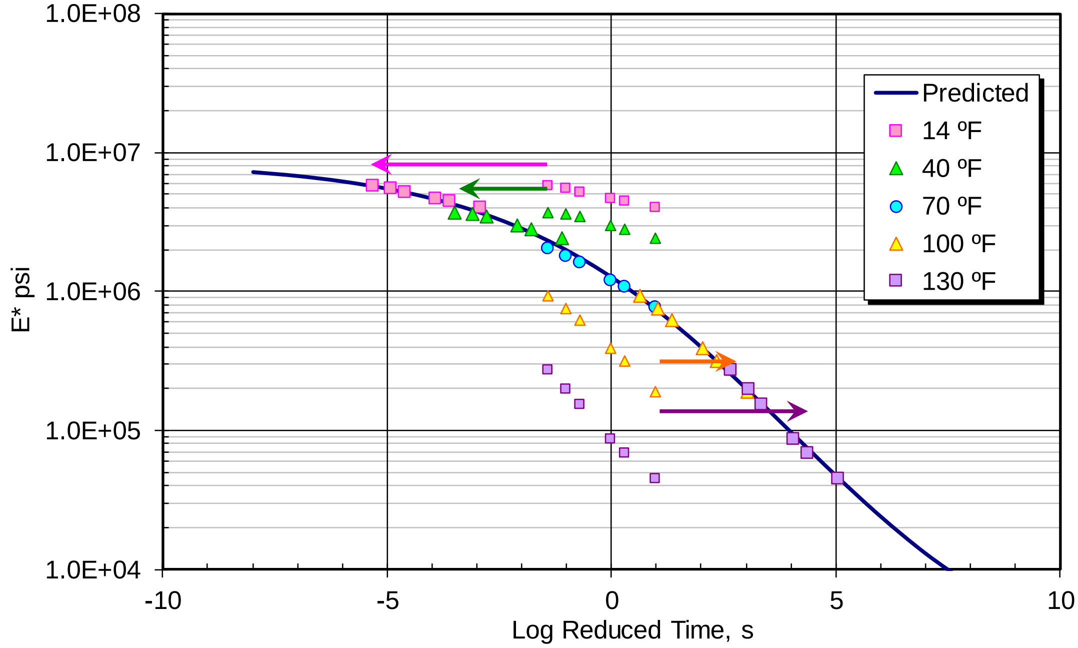
Sieve size	Cum % Passing	Cum % Retained	% retained	weight	Virgin	RAP	RAP+bind	Lime
1"	100	0	0	0.0	**0.0**	0.0	**0.0**	
3/4"	100	0	0	0.0	**0.0**	0.0	**0.0**	
1/2"	86	14	14	966.7	**725.0**	241.7	**251.2**	
3/8"	72	28	14	966.7	**725.0**	241.7	**251.2**	
1/4"	59	41	13	897.7	**673.2**		**0.0**	
#4	56	44	3	207.2	**155.4**	276.2	**287.1**	
#8	43	57	13	897.7	**673.2**	224.4	**233.3**	
#16	32	68	11	759.6	**569.7**	189.9	**197.4**	
#30	21	79	11	759.6	**569.7**	189.9	**197.4**	
#50	11	89	10	690.5	**517.9**	172.6	**179.5**	
#100	6	94	5	345.3	**258.9**	86.3	**89.7**	
#200	4.8	95.2	1.2	82.9	**62.1**	20.7	**21.5**	
Pan			3.7	255.5	**191.6**	63.9	**66.4**	
Lime			1.1	76.0				76.0
			100	6905.0	**5121.8**	1707.3	**1774.9**	

APPENDIX E

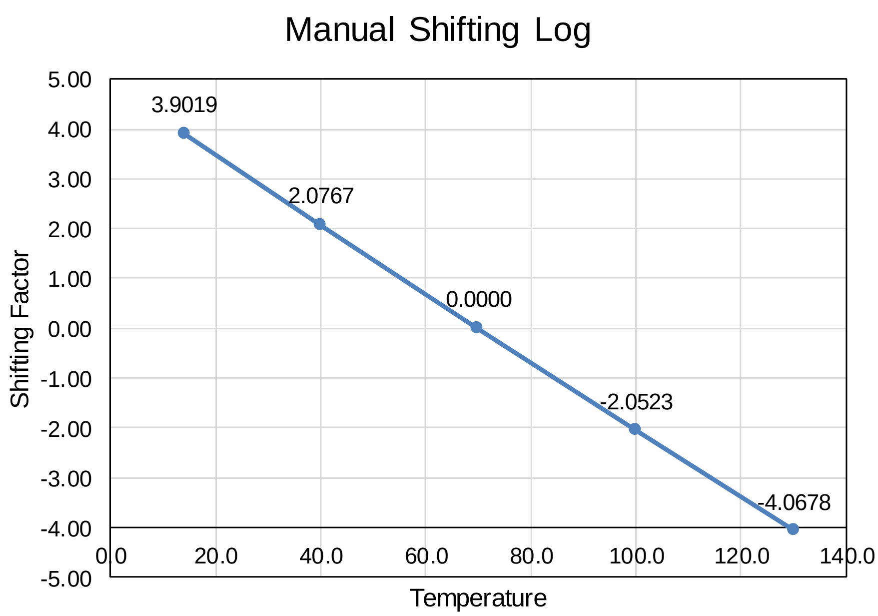
PERFORMANCE TEST RESULTS

DYNAMIC MODULUS (E*)

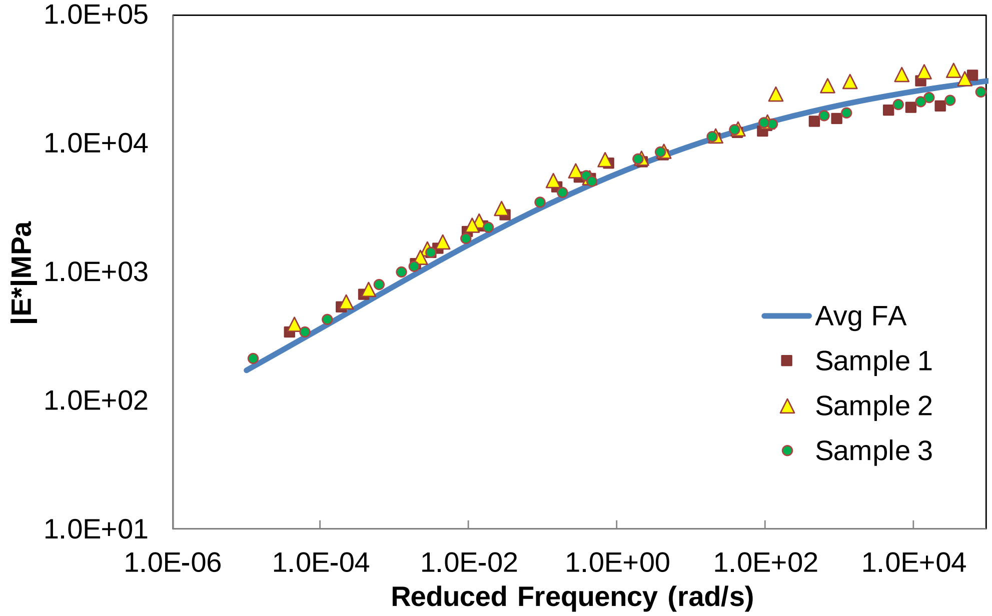
- Control Mix (0%RAP)



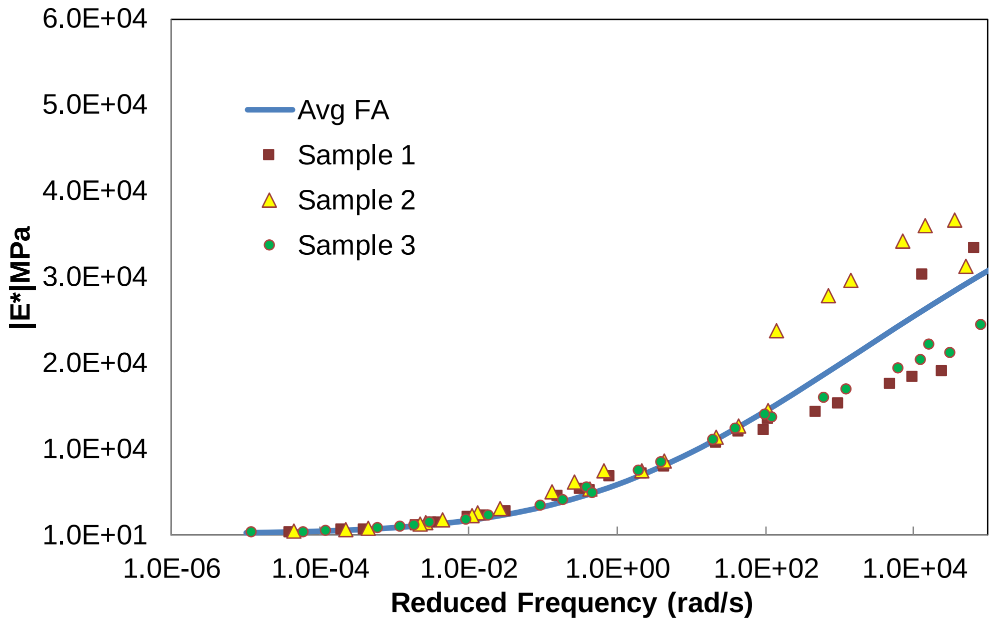
Master curve of control (0% RAP) mix based on reduced time.



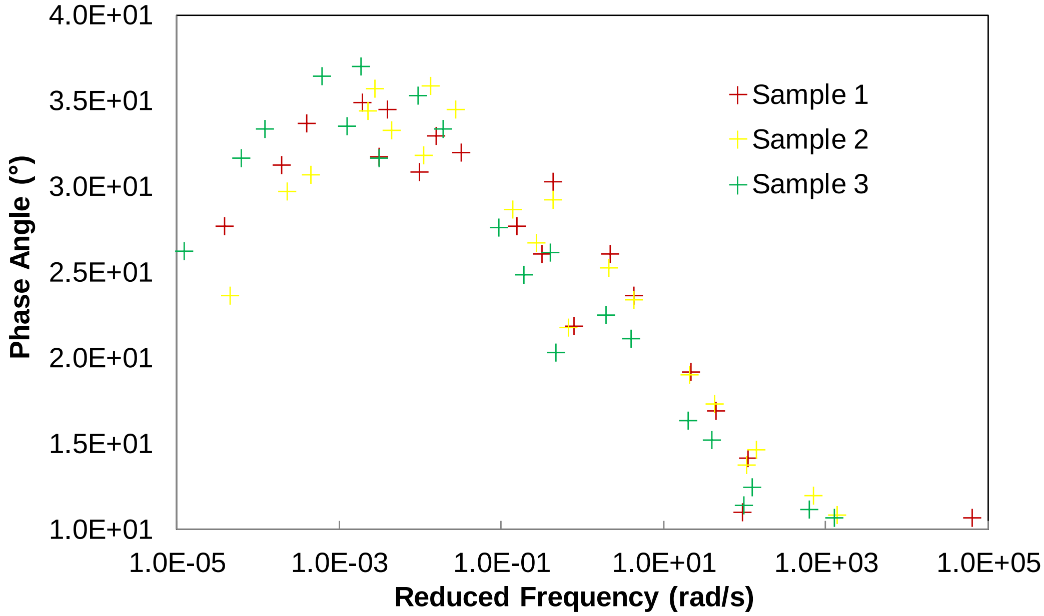
Master curve manual shifting log of control (0% RAP) mix.



Master curve of control (0% RAP) mix based on reduced frequency (log-log space).



Master curve of control (0% RAP) mix based on reduced frequency (semi-log space).



Phase angle vs. reduced frequency of control (0% RAP) mix (semi-log space).

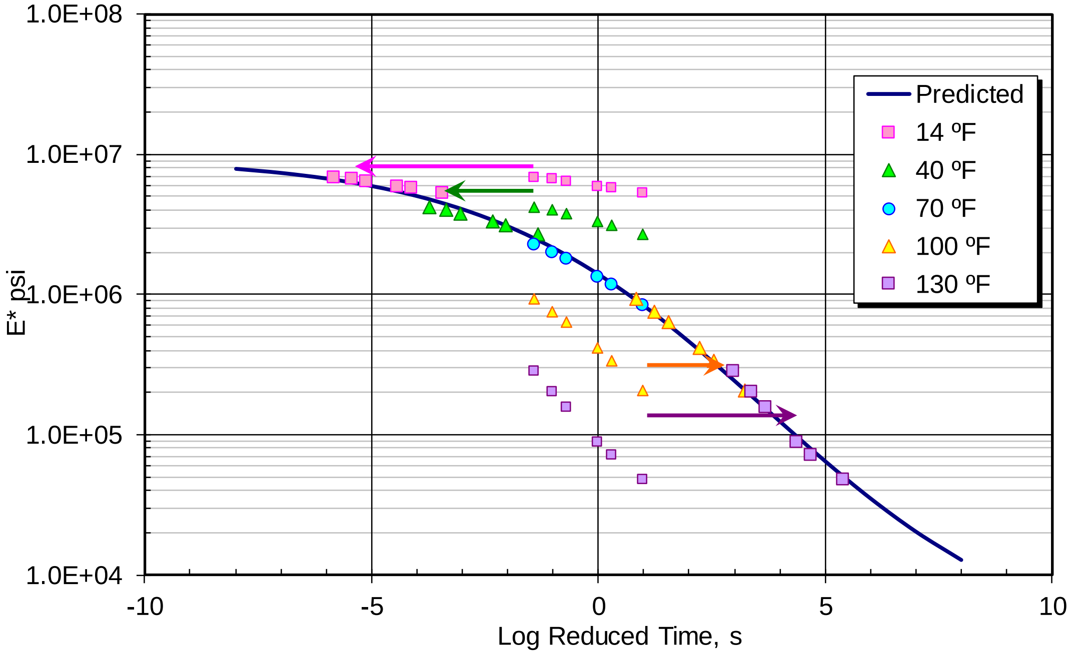
Master Curve Data of Control (0% RAP) Mix

E* Mpa	Specimen ID	Temp, ºF	Frequency Hz	E* ksi	E* psi	Log E* psi	Time, t s	Log Time s	Log Red Time, t_r	Pred Log E* psi	Pred E* psi	Error	Error^2
39442	Average	14 ºF	25	5721	5.72E+06	6.7574	0.04	-1.39794001	-5.2998	6.7567	5.71E+06	0.0007	0.0000
37586	Average	14	10	5451	5.45E+06	6.7365	0.1	-1	-4.9019	6.7331	5.41E+06	0.0034	0.0000
35860	Average	14	5	5201	5.20E+06	6.7161	0.2	-0.69897	-4.6008	6.7133	5.17E+06	0.0028	0.0000
32025	Average	14	1	4645	4.64E+06	6.6670	1	0	-3.9019	6.6601	4.57E+06	0.0069	0.0000
30776	Average	14	0.5	4464	4.46E+06	6.6497	2	0.301029996	-3.6008	6.6337	4.30E+06	0.0160	0.0003
27869	Average	14	0.1	4042	4.04E+06	6.6066	10	1	-2.9019	6.5635	3.66E+06	0.0431	0.0019
25554	Average	40 ºF	25	3706	3.71E+06	6.5689	0.04	-1.39794001	-3.4746	6.6220	4.19E+06	-0.0531	0.0028
24879	Average	40	10	3608	3.61E+06	6.5573	0.1	-1	-3.0767	6.5823	3.82E+06	-0.0250	0.0006
23705	Average	40	5	3438	3.44E+06	6.5363	0.2	-0.69897	-2.7757	6.5494	3.54E+06	-0.0131	0.0002
20588	Average	40	1	2986	2.99E+06	6.4751	1	0	-2.0767	6.4622	2.90E+06	0.0129	0.0002
19342	Average	40	0.5	2805	2.81E+06	6.4480	2	0.301029996	-1.7757	6.4197	2.63E+06	0.0282	0.0008
16534	Average	40	0.1	2398	2.40E+06	6.3799	10	1	-1.0767	6.3087	2.04E+06	0.0712	0.0051
13968	Average	70 ºF	25	2026	2.03E+06	6.3066	0.04	-1.39794001	-1.3979	6.3619	2.30E+06	-0.0553	0.0031
12312	Average	70	10	1786	1.79E+06	6.2518	0.1	-1	-1.0000	6.2954	1.97E+06	-0.0436	0.0019
11069	Average	70	5	1605	1.61E+06	6.2056	0.2	-0.69897	-0.6990	6.2410	1.74E+06	-0.0354	0.0013
8321	Average	70	1	1207	1.21E+06	6.0817	1	0	0.0000	6.1011	1.26E+06	-0.0195	0.0004
7341	Average	70	0.5	1065	1.06E+06	6.0272	2	0.301029996	0.3010	6.0349	1.08E+06	-0.0077	0.0001
5309	Average	70	0.1	770	7.70E+05	5.8865	10	1	1.0000	5.8675	7.37E+05	0.0190	0.0004
6368	Average	100 ºF	25	924	9.24E+05	5.9655	0.04	-1.39794001	0.6543	5.9526	8.97E+05	0.0129	0.0002
5134	Average	100	10	745	7.45E+05	5.8720	0.1	-1	1.0523	5.8543	7.15E+05	0.0177	0.0003
4305	Average	100	5	624	6.24E+05	5.7954	0.2	-0.69897	1.3533	5.7760	5.97E+05	0.0195	0.0004
2665	Average	100	1	387	3.87E+05	5.5872	1	0	2.0523	5.5825	3.82E+05	0.0047	0.0000
2154	Average	100	0.5	312	3.12E+05	5.4948	2	0.301029996	2.3533	5.4947	3.12E+05	0.0001	0.0000
1305	Average	100	0.1	189	1.89E+05	5.2771	10	1	3.0523	5.2830	1.92E+05	-0.0060	0.0000
1879	Average	130 ºF	25	273	2.73E+05	5.4354	0.04	-1.39794001	2.6699	5.4001	2.51E+05	0.0354	0.0013
1370	Average	130	10	199	1.99E+05	5.2982	0.1	-1	3.0678	5.2782	1.90E+05	0.0200	0.0004
1062	Average	130	5	154	1.54E+05	5.1877	0.2	-0.69897	3.3689	5.1845	1.53E+05	0.0032	0.0000
596	Average	130	1	86	8.65E+04	4.9370	1	0	4.0678	4.9644	9.21E+04	-0.0274	0.0008
474	Average	130	0.5	69	6.88E+04	4.8376	2	0.301029996	4.3689	4.8695	7.41E+04	-0.0320	0.0010
306	Average	130	0.1	44	4.43E+04	4.6467	10	1	5.0678	4.6526	4.49E+04	-0.0059	0.0000
											ΣE	-0.0061	0.0232

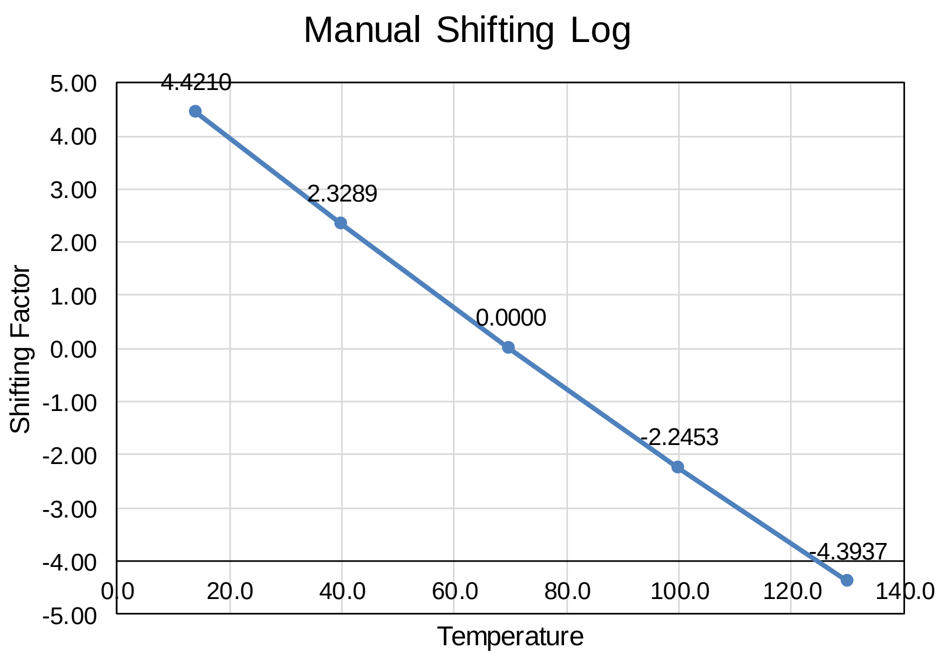
Dynamic Modulus and Phase Angle of Each Replicate of Control (0% RAP) Mix

Temp	Freq.	Dynamic Modulus, |E*| (Mpa)						Phase Angle, φ (Degree)					
(°C)	(Hz)	Sample 1	Sample 2	Sample 3	Avg. |E*|	St. Dev.	%CV	Sample 1	Sample 2	Sample 3	Avg.φ	St. Dev.	%CV
-9.8	25.0	40408.0	48622.0	29296.0	39442	9699	25	9.2	6.3	3.5	6.3	2.8	44
	10.0	39431.0	45184.0	28143.0	37586	8669	23	11.3	7.4	5.4	8.0	3.0	38
	5.0	37916.0	42228.0	27435.0	35860	7608	21	11.0	8.4	6.2	8.5	2.4	28
	1.0	34736.0	36071.0	25268.0	32025	5890	18	10.6	9.3	7.4	9.1	1.6	18
	0.5	33413.0	34532.0	24384.0	30776	5564	18	10.6	9.3	8.0	9.3	1.3	14
	0.1	30271.0	31201.0	22135.0	27869	4988	18	9.4	8.8	8.0	8.7	0.7	8
4.5	25.0	18950.0	36576.0	21135.0	25554	9608	38	3.9	7.5	5.7	5.7	1.8	31
	10.0	18374.0	35939.0	20325.0	24879	9628	39	6.5	8.0	7.8	7.4	0.8	11
	5.0	17508.0	34197.0	19409.0	23705	9136	39	6.9	9.2	8.8	8.3	1.2	14
	1.0	15264.0	29649.0	16851.0	20588	7887	38	8.9	10.8	10.6	10.1	1.1	11
	0.5	14313.0	27810.0	15902.0	19342	7377	38	8.9	11.9	11.1	10.6	1.6	15
	0.1	12245.0	23747.0	13609.0	16534	6284	38	10.9	14.6	12.4	12.6	1.9	15
21.2	25.0	13401.0	14490.0	14014.0	13968	546	4	14.1	13.8	11.3	13.1	1.5	12
	10.0	11929.0	12679.0	12328.0	12312	375	3	16.9	17.3	15.2	16.4	1.1	7
	5.0	10756.0	11354.0	11096.0	11069	300	3	19.2	19.0	16.3	18.2	1.6	9
	1.0	7944.0	8605.0	8414.0	8321	340	4	23.6	23.4	21.1	22.7	1.4	6
	0.5	7080.0	7488.0	7455.0	7341	227	3	26.1	25.2	22.5	24.6	1.9	8
	0.1	5175.0	5309.0	5443.0	5309	134	3	30.3	29.2	26.1	28.5	2.2	8
37.8	25.0	6817.0	7405.0	4882.0	6368	1320	21	21.9	21.8	20.3	21.3	0.9	4
	10.0	5262.0	6067.0	4074.0	5134	1003	20	26.1	26.7	24.8	25.9	1.0	4
	5.0	4473.0	5061.0	3380.0	4305	853	20	27.7	28.7	27.6	28.0	0.6	2
	1.0	2727.0	3085.0	2184.0	2665	454	17	32.0	34.5	33.4	33.3	1.3	4
	0.5	2220.0	2478.0	1765.0	2154	361	17	32.9	35.8	35.3	34.7	1.6	4
	0.1	1371.0	1483.0	1061.0	1305	219	17	31.7	35.7	37.0	34.8	2.8	8
54.0	25.0	1990.0	2280.0	1367.0	1879	467	25	30.9	31.8	31.6	31.4	0.5	2
	10.0	1475.0	1675.0	960.0	1370	369	27	34.5	33.3	33.5	33.8	0.6	2
	5.0	1141.0	1274.0	772.0	1062	260	24	34.9	34.5	36.5	35.3	1.1	3
	1.0	653.0	720.0	416.0	596	160	27	33.7	30.7	33.4	32.6	1.7	5
	0.5	513.0	580.0	330.0	474	129	27	31.2	29.7	31.6	30.8	1.0	3
	0.1	327.0	383.0	207.0	306	90	29	27.7	23.6	26.3	25.9	2.1	8

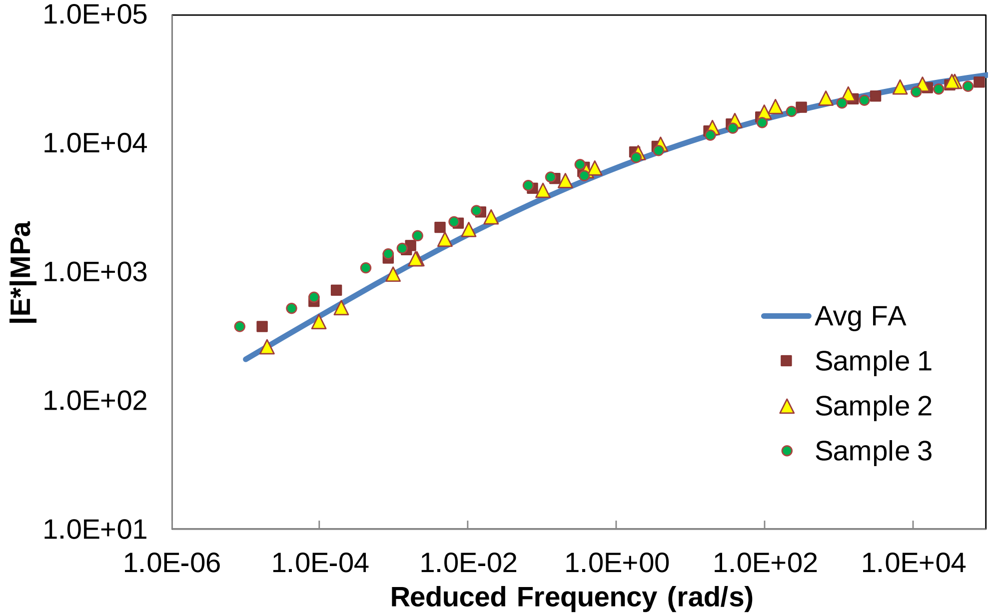
- 10% RAP Mix



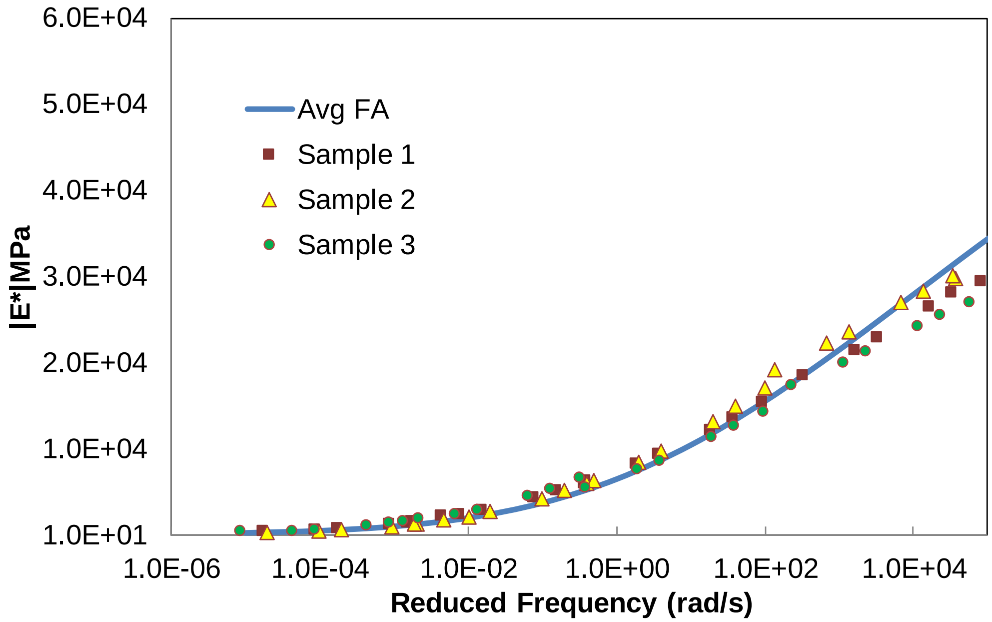
Master curve of 10% RAP mix based on reduced time



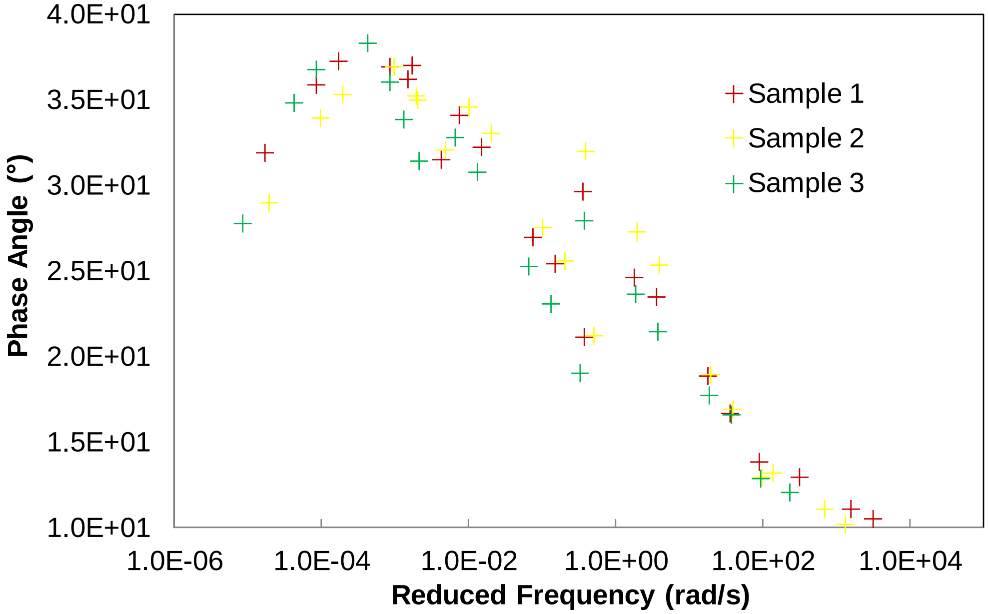
Master curve manual shifting log of 10% RAP mix.



Master curve of control 10% RAP mix based on reduced frequency (log-log space).



Master curve of control 10% RAP mix based on reduced frequency (semi-log space).



Phase angle vs. reduced frequency of 10% RAP mix (semi-log space).

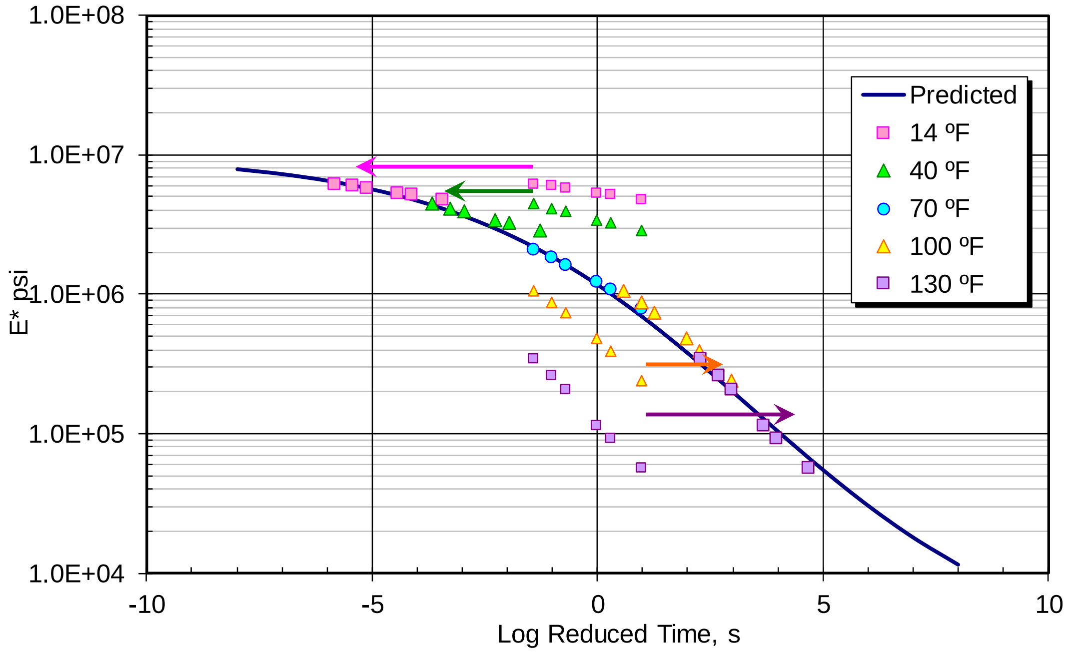
Master Curve Data of 10% RAP Mix

E* Mpa	Specimen ID	Temp, ºF	Frequency Hz	E* ksi	E* psi	Log E* psi	Time, t s	Log Time s	Log Red Time, t_r	Pred Log E* psi	Pred E* psi	Error	Error^2
47216	Average	14 ºF	25	6848	6.85E+06	6.8356	0.04	-1.39794	-5.8189	6.8212	6.62E+06	0.0144	0.0002
45450	Average	14	10	6592	6.59E+06	6.8190	0.1	-1	-5.4210	6.8005	6.32E+06	0.0185	0.0003
43880	Average	14	5	6364	6.36E+06	6.8038	0.2	-0.69897	-5.1200	6.7833	6.07E+06	0.0205	0.0004
40843	Average	14	1	5924	5.92E+06	6.7726	1	0	-4.4210	6.7369	5.46E+06	0.0357	0.0013
39607	Average	14	0.5	5745	5.74E+06	6.7593	2	0.30103	-4.1200	6.7139	5.18E+06	0.0453	0.0021
36726	Average	14	0.1	5327	5.33E+06	6.7265	10	1	-3.4210	6.6527	4.49E+06	0.0737	0.0054
28878	Average	40 ºF	25	4188	4.19E+06	6.6221	0.04	-1.39794	-3.7268	6.6809	4.80E+06	-0.0589	0.0035
27323	Average	40	10	3963	3.96E+06	6.5980	0.1	-1	-3.3289	6.6438	4.40E+06	-0.0457	0.0021
25904	Average	40	5	3757	3.76E+06	6.5748	0.2	-0.69897	-3.0279	6.6129	4.10E+06	-0.0381	0.0015
22606	Average	40	1	3279	3.28E+06	6.5157	1	0	-2.3289	6.5315	3.40E+06	-0.0158	0.0003
21249	Average	40	0.5	3082	3.08E+06	6.4888	2	0.30103	-2.0279	6.4919	3.10E+06	-0.0031	0.0000
18327	Average	40	0.1	2658	2.66E+06	6.4246	10	1	-1.3289	6.3886	2.45E+06	0.0360	0.0013
15613	Average	70 ºF	25	2265	2.26E+06	6.3550	0.04	-1.39794	-1.3979	6.3995	2.51E+06	-0.0445	0.0020
13738	Average	70	10	1992	1.99E+06	6.2994	0.1	-1	-1.0000	6.3341	2.16E+06	-0.0348	0.0012
12224	Average	70	5	1773	1.77E+06	6.2487	0.2	-0.69897	-0.6990	6.2810	1.91E+06	-0.0323	0.0010
9185	Average	70	1	1332	1.33E+06	6.1246	1	0	0.0000	6.1449	1.40E+06	-0.0203	0.0004
8083	Average	70	0.5	1172	1.17E+06	6.0691	2	0.30103	0.3010	6.0809	1.20E+06	-0.0118	0.0001
5789	Average	70	0.1	840	8.40E+05	5.9241	10	1	1.0000	5.9201	8.32E+05	0.0040	0.0000
6429	Average	100 ºF	25	932	9.32E+05	5.9696	0.04	-1.39794	0.8474	5.9566	9.05E+05	0.0130	0.0002
5187	Average	100	10	752	7.52E+05	5.8764	0.1	-1	1.2453	5.8599	7.24E+05	0.0165	0.0003
4368	Average	100	5	633	6.33E+05	5.8017	0.2	-0.69897	1.5464	5.7835	6.07E+05	0.0182	0.0003
2825	Average	100	1	410	4.10E+05	5.6125	1	0	2.2453	5.5969	3.95E+05	0.0156	0.0002
2285	Average	100	0.5	331	3.31E+05	5.5204	2	0.30103	2.5464	5.5133	3.26E+05	0.0071	0.0001
1408	Average	100	0.1	204	2.04E+05	5.3101	10	1	3.2453	5.3140	2.06E+05	-0.0039	0.0000
1928	Average	130 ºF	25	280	2.80E+05	5.4467	0.04	-1.39794	2.9958	5.3858	2.43E+05	0.0609	0.0037
1396	Average	130	10	202	2.02E+05	5.3064	0.1	-1	3.3937	5.2711	1.87E+05	0.0353	0.0012
1083	Average	130	5	157	1.57E+05	5.1960	0.2	-0.69897	3.6948	5.1838	1.53E+05	0.0122	0.0001
612	Average	130	1	89	8.88E+04	4.9485	1	0	4.3937	4.9820	9.59E+04	-0.0335	0.0011
492	Average	130	0.5	71	7.14E+04	4.8537	2	0.30103	4.6948	4.8964	7.88E+04	-0.0426	0.0018
331	Average	130	0.1	48	4.81E+04	4.6817	10	1	5.3937	4.7034	5.05E+04	-0.0217	0.0005
											ΣE	0.0198	0.0327

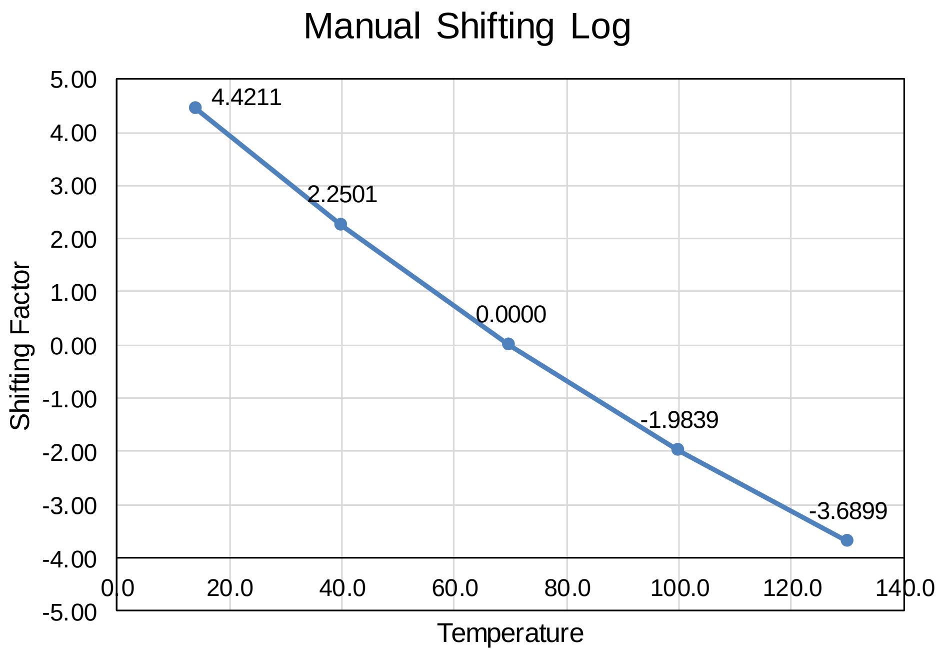
Dynamic Modulus and Phase Angle of Each Replicate of 10% RAP Mix

Temp. (°C)	Freq. (Hz)	Dynamic Modulus, |E*| (Mpa)						Phase Angle, φ (Degree)					
		Sample 1	Sample 2	Sample 3	Avg.|E*|	St. Dev.	%CV	Sample 1	Sample 2	Sample 3	Avg.φ	St. Dev.	%CV
-10	25.0	51070.0	38949.0	51630.0	47216	7165	15	5.4	9.5	8.3	7.7	2.1	27
	10.0	48606.0	37000.0	50744.0	45450	7396	16	5.4	8.5	6.3	6.7	1.6	23
	5.0	46826.0	35892.0	48923.0	43880	6997	16	6.3	8.0	6.3	6.9	1.0	15
	1.0	43509.0	33192.0	45828.0	40843	6727	16	6.9	8.7	7.2	7.6	0.9	12
	0.5	42089.0	32169.0	44564.0	39607	6560	17	6.6	8.5	6.4	7.1	1.2	16
	0.1	39017.0	29726.0	41435.0	36726	6182	17	7.7	8.3	7.7	7.9	0.4	5
4.67	25.0	29503.0	30064.0	27068.0	28878	1593	6	5.4	5.9	5.6	5.6	0.2	4
	10.0	28097.0	28326.0	25547.0	27323	1543	6	8.5	8.0	7.7	8.1	0.4	4
	5.0	26467.0	27003.0	24241.0	25904	1465	6	9.1	8.0	8.2	8.4	0.6	7
	1.0	22874.0	23619.0	21324.0	22606	1171	5	10.5	10.2	9.4	10.0	0.6	6
	0.5	21448.0	22235.0	20065.0	21249	1099	5	11.0	11.1	9.7	10.6	0.8	8
	0.1	18475.0	19199.0	17307.0	18327	955	5	12.9	13.2	12.0	12.7	0.6	5
21.33	25.0	15448.0	17138.0	14254.0	15613	1449	9	13.8	12.9	12.8	13.2	0.5	4
	10.0	13677.0	14860.0	12676.0	13738	1093	8	16.7	16.9	16.6	16.7	0.2	1
	5.0	12188.0	13103.0	11380.0	12224	862	7	18.9	18.9	17.7	18.5	0.7	4
	1.0	9329.0	9664.0	8563.0	9185	564	6	23.4	25.3	21.5	23.4	1.9	8
	0.5	8256.0	8381.0	7612.0	8083	413	5	24.6	27.3	23.6	25.2	1.9	8
	0.1	5920.0	6020.0	5426.0	5789	318	5	29.6	32.0	27.9	29.8	2.0	7
37.80	25.0	6296.0	6341.0	6651.0	6429	193	3	21.1	21.2	19.0	20.4	1.2	6
	10.0	5136.0	5124.0	5301.0	5187	99	2	25.4	25.6	23.1	24.7	1.4	6
	5.0	4353.0	4223.0	4527.0	4368	153	3	26.9	27.5	25.3	26.6	1.2	4
	1.0	2859.0	2661.0	2955.0	2825	150	5	32.2	33.0	30.8	32.0	1.1	4
	0.5	2333.0	2114.0	2409.0	2285	153	7	34.1	34.6	32.8	33.8	0.9	3
	0.1	1462.0	1260.0	1502.0	1408	130	9	36.2	35.0	33.9	35.0	1.2	3
54.30	25.0	2152.0	1763.0	1870.0	1928	201	10	31.5	32.1	31.4	31.7	0.3	1
	10.0	1580.0	1261.0	1347.0	1396	165	12	37.0	35.3	36.1	36.1	0.9	2
	5.0	1240.0	953.0	1055.0	1083	145	13	36.9	36.9	38.3	37.4	0.8	2
	1.0	699.0	517.0	621.0	612	91	15	37.3	35.3	36.8	36.4	1.0	3
	0.5	569.0	405.0	503.0	492	83	17	35.9	33.9	34.8	34.9	1.0	3
	0.1	369.0	256.0	369.0	331	65	20	31.9	29.0	27.8	29.5	2.1	7

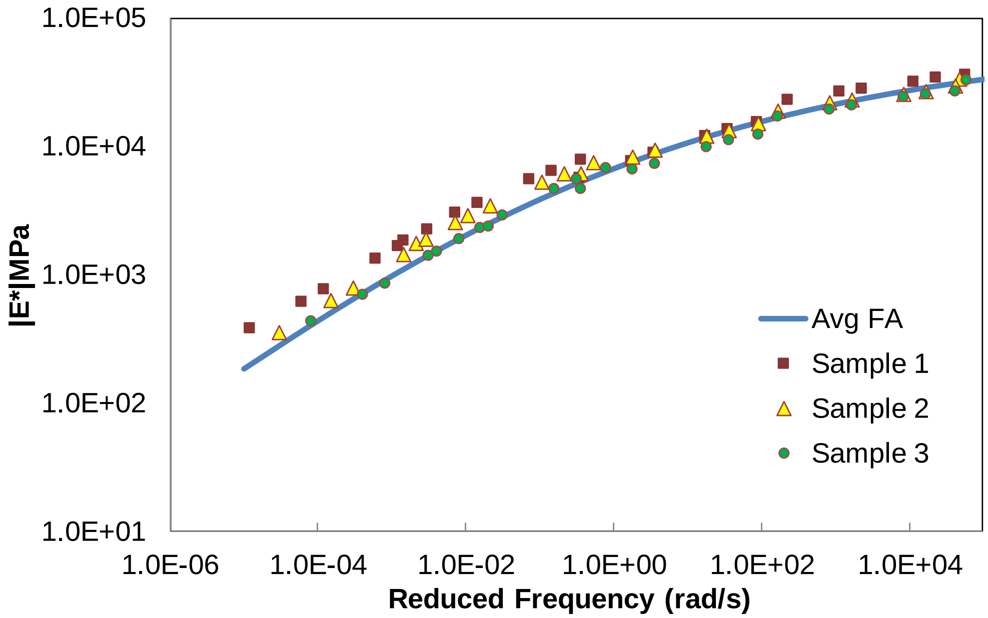
- 15% RAP Mix



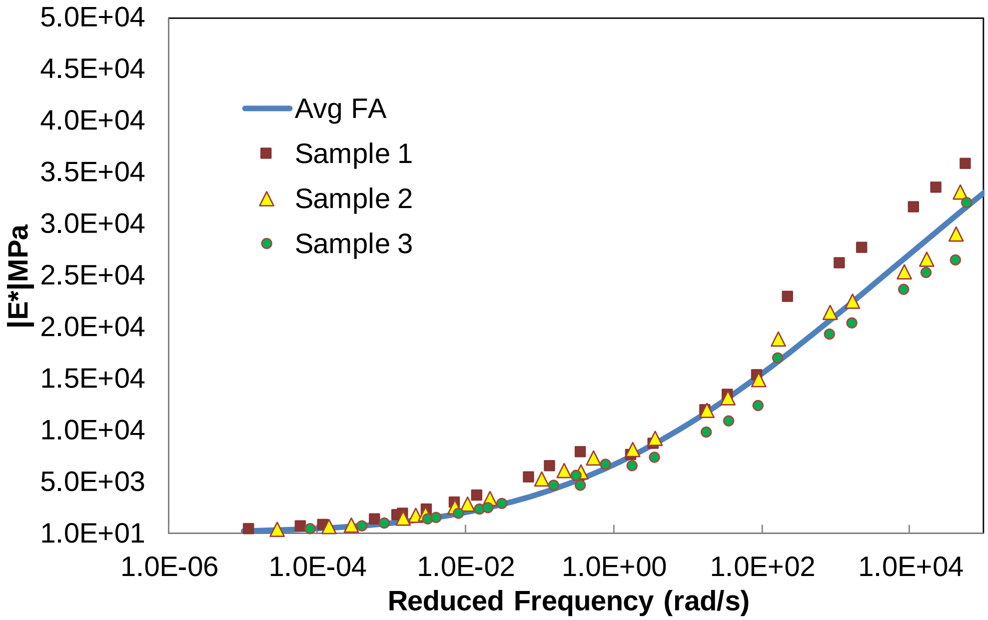
Master curve of 15% RAP mix based on reduced time.



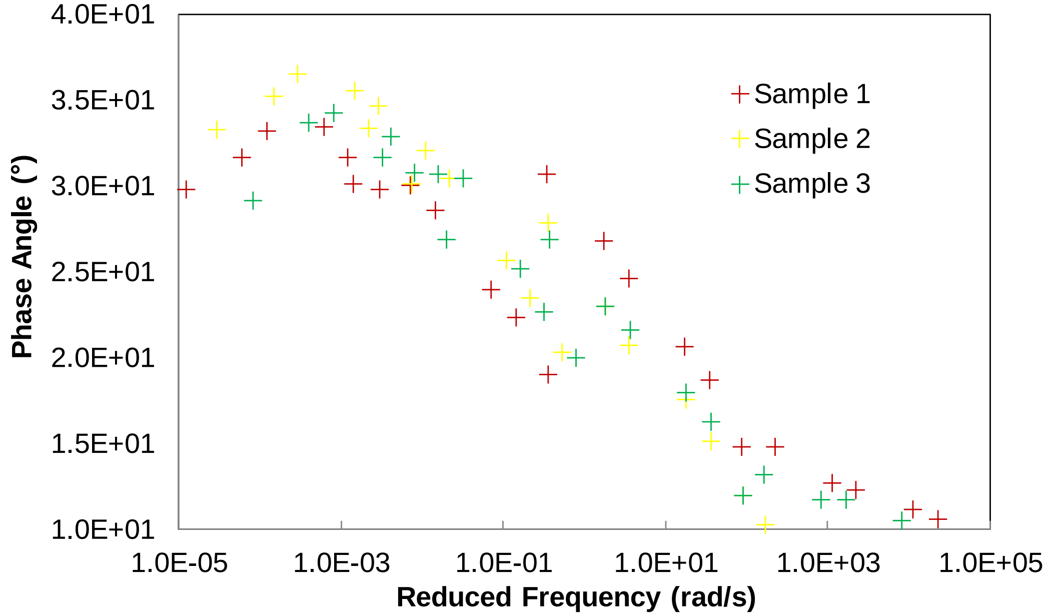
Master curve manual shifting log of 15% RAP mix.



Master curve of control 15% RAP mix based on reduced frequency (log-log space).



Master curve of control 15% RAP mix based on reduced frequency (semi-log space).



Phase angle vs. reduced frequency of 15% RAP mix (semi-log space).

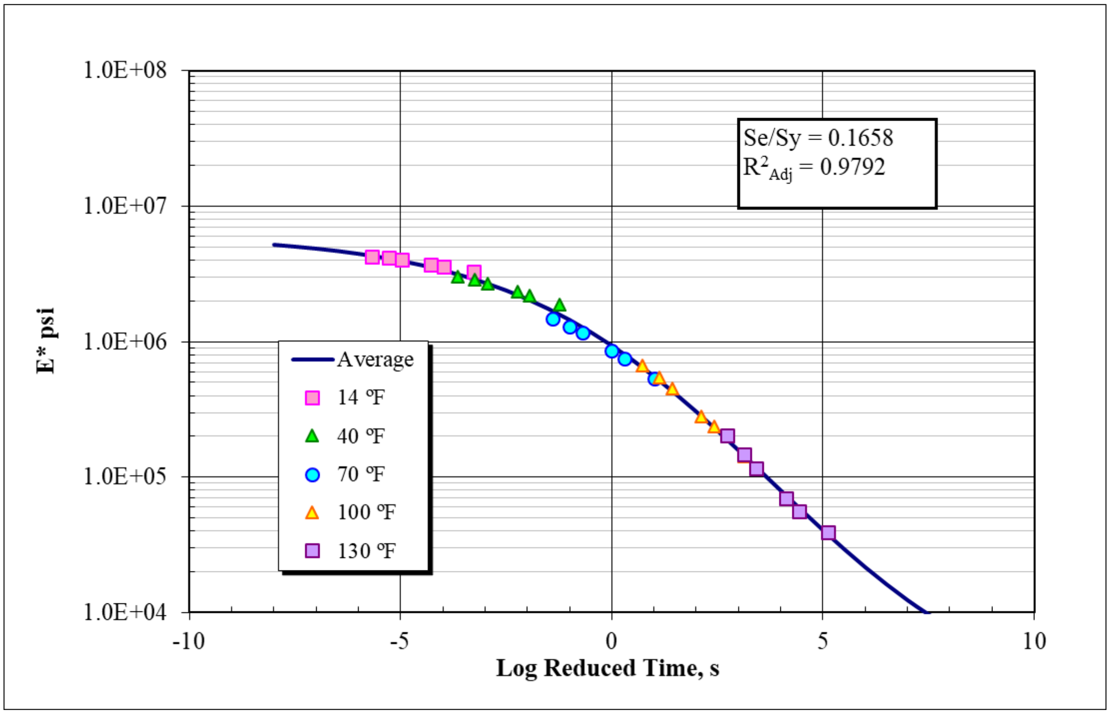
Master Curve Data of 15% RAP Mix

E* Mpa	Specimen ID	Temp, ºF	Frequency Hz	E* ksi	E* psi	Log E* psi	Time, t s	Log Time s	Log Red Time, t_r	Pred Log E* psi	Pred E* psi	Error	Error^2
42423	Average	14 ºF	25	6153	6.15E+06	6.7891	0.04	-1.39794	-5.8190	6.8072	6.42E+06	-0.0181	0.0003
41087	Average	14	10	5959	5.96E+06	6.7752	0.1	-1	-5.4211	6.7832	6.07E+06	-0.0080	0.0001
39520	Average	14	5	5732	5.73E+06	6.7583	0.2	-0.69897	-5.1200	6.7632	5.80E+06	-0.0049	0.0000
36462	Average	14	1	5288	5.29E+06	6.7233	1	0	-4.4211	6.7101	5.13E+06	0.0133	0.0002
35293	Average	14	0.5	5119	5.12E+06	6.7092	2	0.30103	-4.1200	6.6840	4.83E+06	0.0252	0.0006
32359	Average	14	0.1	4693	4.69E+06	6.6715	10	1	-3.4211	6.6151	4.12E+06	0.0563	0.0032
30413	Average	40 ºF	25	4411	4.41E+06	6.6445	0.04	-1.39794	-3.6480	6.6388	4.35E+06	0.0057	0.0000
28427	Average	40	10	4123	4.12E+06	6.6152	0.1	-1	-3.2501	6.5964	3.95E+06	0.0188	0.0004
26857	Average	40	5	3895	3.90E+06	6.5905	0.2	-0.69897	-2.9491	6.5615	3.64E+06	0.0291	0.0008
23528	Average	40	1	3412	3.41E+06	6.5331	1	0	-2.2501	6.4703	2.95E+06	0.0628	0.0039
22289	Average	40	0.5	3233	3.23E+06	6.5096	2	0.30103	-1.9491	6.4264	2.67E+06	0.0832	0.0069
19571	Average	40	0.1	2839	2.84E+06	6.4531	10	1	-1.2501	6.3131	2.06E+06	0.1400	0.0196
14173	Average	70 ºF	25	2056	2.06E+06	6.3129	0.04	-1.39794	-1.3979	6.3384	2.18E+06	-0.0255	0.0007
12461	Average	70	10	1807	1.81E+06	6.2570	0.1	-1	-1.0000	6.2687	1.86E+06	-0.0117	0.0001
11199	Average	70	5	1624	1.62E+06	6.2107	0.2	-0.69897	-0.6990	6.2123	1.63E+06	-0.0017	0.0000
8378	Average	70	1	1215	1.22E+06	6.0846	1	0	0.0000	6.0697	1.17E+06	0.0149	0.0002
7401	Average	70	0.5	1073	1.07E+06	6.0308	2	0.30103	0.3010	6.0033	1.01E+06	0.0274	0.0008
5373	Average	70	0.1	779	7.79E+05	5.8917	10	1	1.0000	5.8383	6.89E+05	0.0534	0.0029
7233	Average	100 ºF	25	1049	1.05E+06	6.0208	0.04	-1.39794	0.5859	5.9378	8.67E+05	0.0829	0.0069
5960	Average	100	10	864	8.64E+05	5.9367	0.1	-1	0.9839	5.8423	6.95E+05	0.0944	0.0089
5074	Average	100	5	736	7.36E+05	5.8668	0.2	-0.69897	1.2849	5.7670	5.85E+05	0.0998	0.0100
3280	Average	100	1	476	4.76E+05	5.6773	1	0	1.9839	5.5838	3.83E+05	0.0936	0.0088
2703	Average	100	0.5	392	3.92E+05	5.5933	2	0.30103	2.2849	5.5018	3.18E+05	0.0915	0.0084
1641	Average	100	0.1	238	2.38E+05	5.3767	10	1	2.9839	5.3068	2.03E+05	0.0699	0.0049
2351	Average	130 ºF	25	341	3.41E+05	5.5327	0.04	-1.39794	2.2919	5.4999	3.16E+05	0.0329	0.0011
1802	Average	130	10	261	2.61E+05	5.4173	0.1	-1	2.6899	5.3894	2.45E+05	0.0279	0.0008
1409	Average	130	5	204	2.04E+05	5.3103	0.2	-0.69897	2.9909	5.3048	2.02E+05	0.0055	0.0000
790	Average	130	1	115	1.15E+05	5.0589	1	0	3.6899	5.1067	1.28E+05	-0.0478	0.0023
632	Average	130	0.5	92	9.17E+04	4.9624	2	0.30103	3.9909	5.0216	1.05E+05	-0.0592	0.0035
386	Average	130	0.1	56	5.59E+04	4.7477	10	1	4.6899	4.8272	6.72E+04	-0.0796	0.0063
											ΣE	0.8720	0.1025

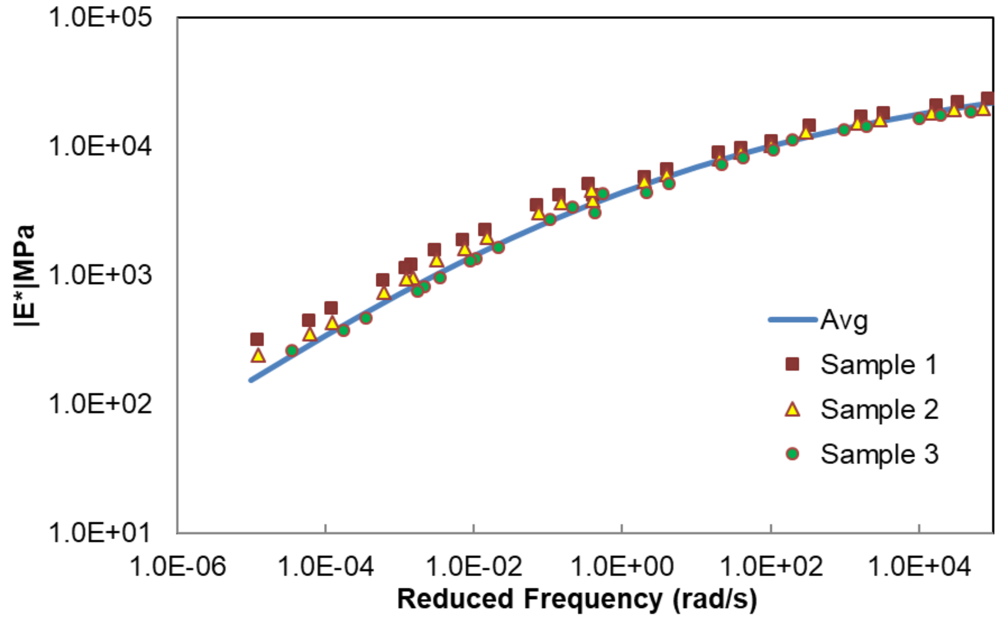
Dynamic Modulus and Phase Angle of Each Replicate of 15% RAP Mix

Temp. (°C)	Freq. (Hz)	Dynamic Modulus, |E*| (Mpa)						Phase Angle, φ (Degree)					
		Sample 1	Sample 2	Sample 3	Avg.|E*|	St. Dev.	%CV	Sample 1	Sample 2	Sample 3	Avg.φ	St. Dev.	%CV
-9.9	25.0	40214.0	40816.0	46239.0	42423	3318	8	2.6	3.4	7.3	4.4	2.5	56
	10.0	39358.0	40409.0	43494.0	41087	2150	5	5.3	4.5	8.5	6.1	2.1	35
	5.0	38225.0	39449.0	40885.0	39520	1331	3	6.7	4.8	9.0	6.8	2.1	31
	1.0	35594.0	36823.0	36969.0	36462	755	2	7.0	6.4	9.8	7.7	1.8	24
	0.5	34376.0	35958.0	35545.0	35293	821	2	7.5	6.6	10.1	8.1	1.8	22
	0.1	31859.0	33144.0	32073.0	32359	688	2	7.8	6.9	9.9	8.2	1.6	19
4.4	25.0	35847.0	28996.0	26395.0	30413	4883	16	8.4	5.6	9.1	7.7	1.9	24
	10.0	33527.0	26521.0	25234.0	28427	4463	16	10.6	7.0	8.4	8.7	1.8	21
	5.0	31628.0	25299.0	23645.0	26857	4213	16	11.2	7.3	10.5	9.6	2.1	21
	1.0	27727.0	22537.0	20321.0	23528	3801	16	12.3	9.1	11.7	11.0	1.7	16
	0.5	26204.0	21451.0	19213.0	22289	3570	16	12.7	9.4	11.7	11.2	1.7	15
	0.1	22935.0	18811.0	16968.0	19571	3055	16	14.8	10.2	13.1	12.7	2.3	18
21.6	25.0	15296.0	14917.0	12305.0	14173	1629	11	14.8	11.9	11.9	12.9	1.7	13
	10.0	13427.0	13090.0	10865.0	12461	1392	11	18.7	15.1	16.2	16.7	1.9	11
	5.0	11841.0	11976.0	9781.0	11199	1230	11	20.6	17.6	18.0	18.7	1.7	9
	1.0	8682.0	9185.0	7268.0	8378	994	12	24.6	20.7	21.6	22.3	2.0	9
	0.5	7593.0	8157.0	6453.0	7401	868	12	26.8	23.0	23.0	24.2	2.2	9
	0.1	5538.0	5967.0	4614.0	5373	691	13	30.7	27.8	26.8	28.4	2.0	7
38.0	25.0	7778.0	7309.0	6611.0	7233	587	8	19.0	20.3	19.9	19.7	0.7	3
	10.0	6414.0	6009.0	5456.0	5960	481	8	22.4	23.5	22.7	22.8	0.6	2
	5.0	5430.0	5205.0	4587.0	5074	437	9	23.9	25.6	25.2	24.9	0.9	4
	1.0	3572.0	3406.0	2861.0	3280	372	11	28.6	30.4	30.5	29.8	1.1	4
	0.5	2970.0	2848.0	2290.0	2703	363	13	30.0	32.0	30.7	30.9	1.0	3
	0.1	1835.0	1727.0	1362.0	1641	248	15	30.1	33.3	31.7	31.7	1.6	5
54.1	25.0	2214.0	2506.0	2333.0	2351	147	6	29.8	30.1	26.9	28.9	1.8	6
	10.0	1657.0	1871.0	1879.0	1802	126	7	31.6	34.7	30.8	32.4	2.0	6
	5.0	1315.0	1430.0	1481.0	1409	85	6	33.4	35.5	32.8	33.9	1.4	4
	1.0	752.0	781.0	836.0	790	43	5	33.2	36.5	34.3	34.7	1.7	5
	0.5	603.0	617.0	677.0	632	39	6	31.7	35.2	33.7	33.5	1.8	5
	0.1	378.0	351.0	428.0	386	39	10	29.8	33.3	29.2	30.8	2.2	7

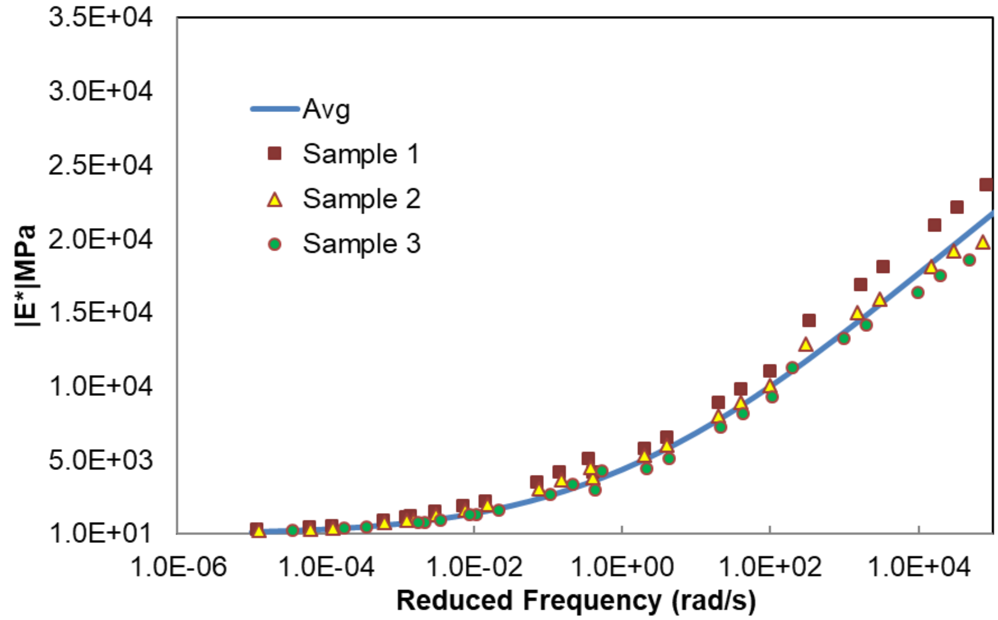
- 25% RAP SB Mix



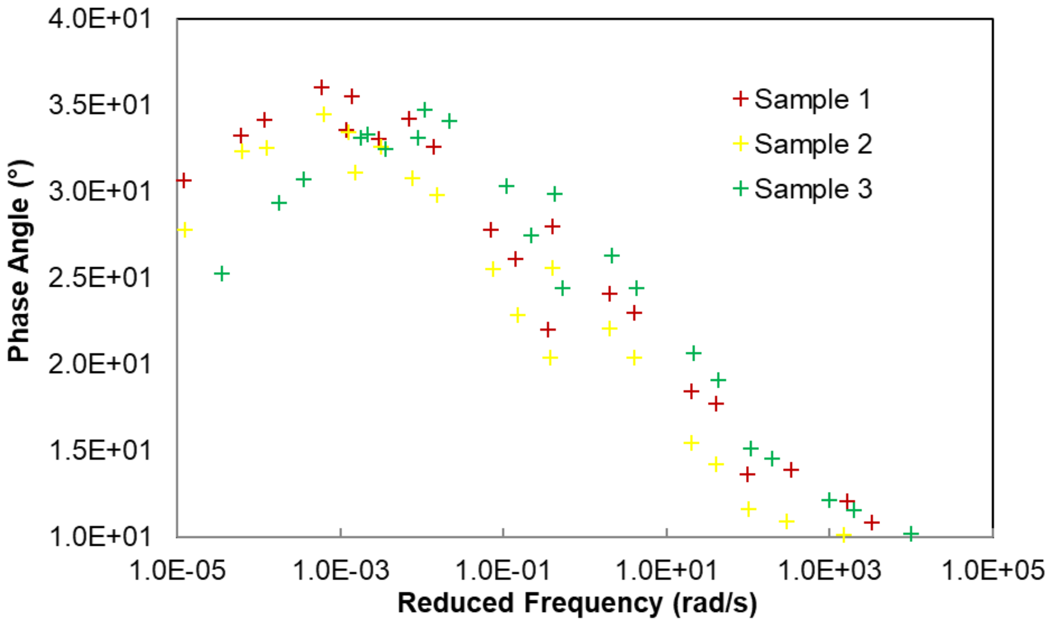
Master curve of 25% RAP SB based on reduced time



Master curve of 25% RAP SB based on reduced frequency (log-log space)



Master curve of 25% RAP SB based on reduced frequency (semi-log space)



Phase angle vs. reduced frequency of 25% RAP SB mix (semi-log space)

Master Curve Data of 25% RAP SB Mix

Specimen ID	Temp, ºF	Frequency Hz	E* ksi	E* psi	Log E* psi	Time, t s	Log Time s	Log Red Time, t_r	Pred Log E* psi	Pred E* psi	Error	Error^2
Average	14 ºF	25	4234	4.23E+06	6.6267	0.04	-1.39794	-5.5910	6.6563	4.53E+06	-0.0295	0.0009
Average	14	10	4136	4.14E+06	6.6166	0.1	-1	-5.1930	6.6328	4.29E+06	-0.0162	0.0003
Average	14	5	4001	4.00E+06	6.6022	0.2	-0.69897	-4.8920	6.6132	4.10E+06	-0.0110	0.0001
Average	14	1	3711	3.71E+06	6.5694	1	0	-4.1930	6.5608	3.64E+06	0.0087	0.0001
Average	14	0.5	3596	3.60E+06	6.5558	2	0.30103	-3.8920	6.5350	3.43E+06	0.0208	0.0004
Average	14	0.1	3311	3.31E+06	6.5200	10	1	-3.1930	6.4665	2.93E+06	0.0535	0.0029
Average	40 ºF	25	2999	3.00E+06	6.4769	0.04	-1.39794	-3.5954	6.5074	3.22E+06	-0.0305	0.0009
Average	40	10	2847	2.85E+06	6.4543	0.1	-1	-3.1975	6.4670	2.93E+06	-0.0126	0.0002
Average	40	5	2679	2.68E+06	6.4279	0.2	-0.69897	-2.8965	6.4335	2.71E+06	-0.0056	0.0000
Average	40	1	2329	2.33E+06	6.3672	1	0	-2.1975	6.3455	2.22E+06	0.0217	0.0005
Average	40	0.5	2185	2.18E+06	6.3394	2	0.30103	-1.8965	6.3030	2.01E+06	0.0364	0.0013
Average	40	0.1	1866	1.87E+06	6.2710	10	1	-1.1975	6.1923	1.56E+06	0.0787	0.0062
Average	70 ºF	25	1471	1.47E+06	6.1676	0.04	-1.39794	-1.3979	6.2258	1.68E+06	-0.0582	0.0034
Average	70	10	1301	1.30E+06	6.1142	0.1	-1	-1.0000	6.1580	1.44E+06	-0.0437	0.0019
Average	70	5	1169	1.17E+06	6.0677	0.2	-0.69897	-0.6990	6.1029	1.27E+06	-0.0352	0.0012
Average	70	1	857	8.57E+05	5.9328	1	0	0.0000	5.9624	9.17E+05	-0.0297	0.0009
Average	70	0.5	752	7.52E+05	5.8761	2	0.30103	0.3010	5.8965	7.88E+05	-0.0204	0.0004
Average	70	0.1	532	5.32E+05	5.7255	10	1	1.0000	5.7314	5.39E+05	-0.0058	0.0000
Average	100 ºF	25	672	6.72E+05	5.8271	0.04	-1.39794	0.6941	5.8057	6.39E+05	0.0214	0.0005
Average	100	10	540	5.40E+05	5.7327	0.1	-1	1.0920	5.7084	5.11E+05	0.0243	0.0006
Average	100	5	451	4.51E+05	5.6539	0.2	-0.69897	1.3931	5.6315	4.28E+05	0.0223	0.0005
Average	100	1	282	2.82E+05	5.4510	1	0	2.0920	5.4433	2.78E+05	0.0077	0.0001
Average	100	0.5	235	2.35E+05	5.3705	2	0.30103	2.3931	5.3587	2.28E+05	0.0117	0.0001
Average	100	0.1	143	1.43E+05	5.1565	10	1	3.0920	5.1565	1.43E+05	0.0000	0.0000
Average	130 ºF	25	201	2.01E+05	5.3042	0.04	-1.39794	2.6683	5.2799	1.91E+05	0.0242	0.0006
Average	130	10	147	1.47E+05	5.1671	0.1	-1	3.0662	5.1641	1.46E+05	0.0030	0.0000
Average	130	5	117	1.17E+05	5.0675	0.2	-0.69897	3.3672	5.0754	1.19E+05	-0.0080	0.0001
Average	130	1	70	6.99E+04	4.8445	1	0	4.0662	4.8686	7.39E+04	-0.0241	0.0006
Average	130	0.5	56	5.62E+04	4.7499	2	0.30103	4.3672	4.7801	6.03E+04	-0.0301	0.0009
Average	130	0.1	39	3.95E+04	4.5960	10	1	5.0662	4.5787	3.79E+04	0.0174	0.0003
										ΣE	-0.0089	0.0258

Dynamic Modulus and Phase Angle of Each Replicate of 25% SB RAP Mix

Temp. (°C)	Freq. (Hz)	Dynamic Modulus, |E*| (Mpa)						Phase Angle, φ (Degree)				
		Sample 1	Sample 2	Sample 3	Avg.|E*|	St. Dev.	%CV	Sample 1	Sample 2	Sample 3	Avg.φ	St. Dev.
-10.0	25.0	33064.0	27986.0	26526.0	29192	3432	12	2.6	5.3	5.0	4.3	1.5
	10.0	32454.0	27402.0	25689.0	28515	3517	12	4.9	3.9	7.9	5.6	2.1
	5.0	31405.0	26535.0	24815.0	27585	3418	12	5.6	4.7	8.1	6.1	1.8
	1.0	29246.0	24704.0	22801.0	25584	3311	13	6.4	5.6	8.9	7.0	1.7
	0.5	28390.0	23934.0	22048.0	24791	3257	13	6.8	5.4	8.8	7.0	1.7
	0.1	26262.0	22008.0	20217.0	22829	3105	14	7.6	6.1	9.7	7.8	1.8
4.6	25.0	23651.0	19785.0	18590.0	20675	2645	13	6.6	7.5	7.6	7.2	0.5
	10.0	22168.0	19218.0	17492.0	19626	2365	12	8.6	7.2	9.8	8.5	1.3
	5.0	20927.0	18100.0	16376.0	18468	2298	12	9.5	8.0	10.2	9.2	1.1
	1.0	18116.0	15912.0	14152.0	16060	1986	12	10.8	9.1	11.5	10.5	1.2
	0.5	16886.0	15010.0	13290.0	15062	1799	12	12.1	10.1	12.1	11.4	1.2
	0.1	14473.0	12887.0	11247.0	12869	1613	13	13.9	10.9	14.6	13.1	1.9
21.2	25.0	11043.0	10061.0	9321.0	10142	864	9	13.7	11.6	15.1	13.5	1.8
	10.0	9821.0	8926.0	8160.0	8969	831	9	17.7	14.2	19.1	17.0	2.5
	5.0	8899.0	8012.0	7262.0	8058	819	10	18.5	15.5	20.7	18.2	2.6
	1.0	6591.0	6001.0	5126.0	5906	737	12	23.0	20.4	24.4	22.6	2.0
	0.5	5837.0	5308.0	4405.0	5183	724	14	24.1	22.1	26.3	24.2	2.1
	0.1	4169.0	3807.0	3018.0	3665	589	16	28.0	25.6	29.9	27.8	2.2
37.8	25.0	5119.0	4531.0	4241.0	4630	447	10	22.0	20.4	24.4	22.3	2.0
	10.0	4169.0	3659.0	3349.0	3726	414	11	26.1	22.8	27.5	25.5	2.4
	5.0	3532.0	3076.0	2714.0	3107	410	13	27.8	25.5	30.3	27.9	2.4
	1.0	2244.0	1960.0	1639.0	1948	303	16	32.6	29.8	34.1	32.1	2.2
	0.5	1903.0	1614.0	1337.0	1618	283	17	34.2	30.8	34.7	33.2	2.2
	0.1	1202.0	957.0	807.0	989	199	20	35.5	31.1	33.3	33.3	2.2
54.5	25.0	1565.0	1308.0	1294.0	1389	153	11	33.1	32.6	33.1	32.9	0.3
	10.0	1149.0	938.0	952.0	1013	118	12	33.6	33.4	32.5	33.2	0.6
	5.0	925.0	742.0	749.0	805	104	13	36.0	34.5	33.1	34.5	1.5
	1.0	551.0	431.0	464.0	482	62	13	34.2	32.5	30.7	32.5	1.7
	0.5	442.0	349.0	372.0	388	48	12	33.2	32.3	29.4	31.6	2.0
	0.1	318.0	239.0	259.0	272	41	15	30.7	27.8	25.3	27.9	2.7

FLOW NUMBER (FN)

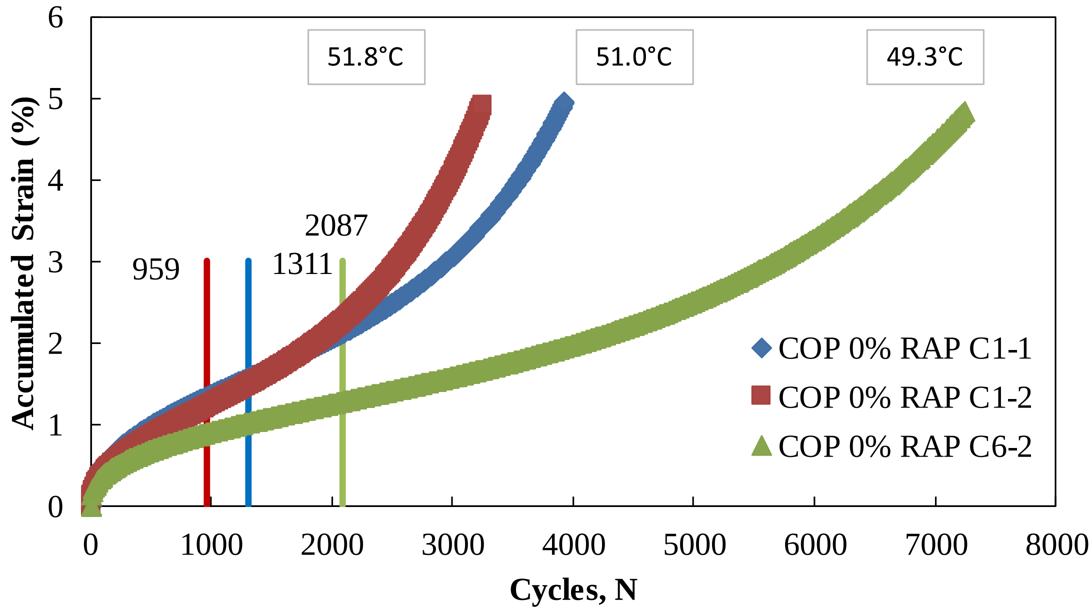
- Control Mix (0%RAP)

Flow Number Results for All Replicates of Control (0% RAP) Mix

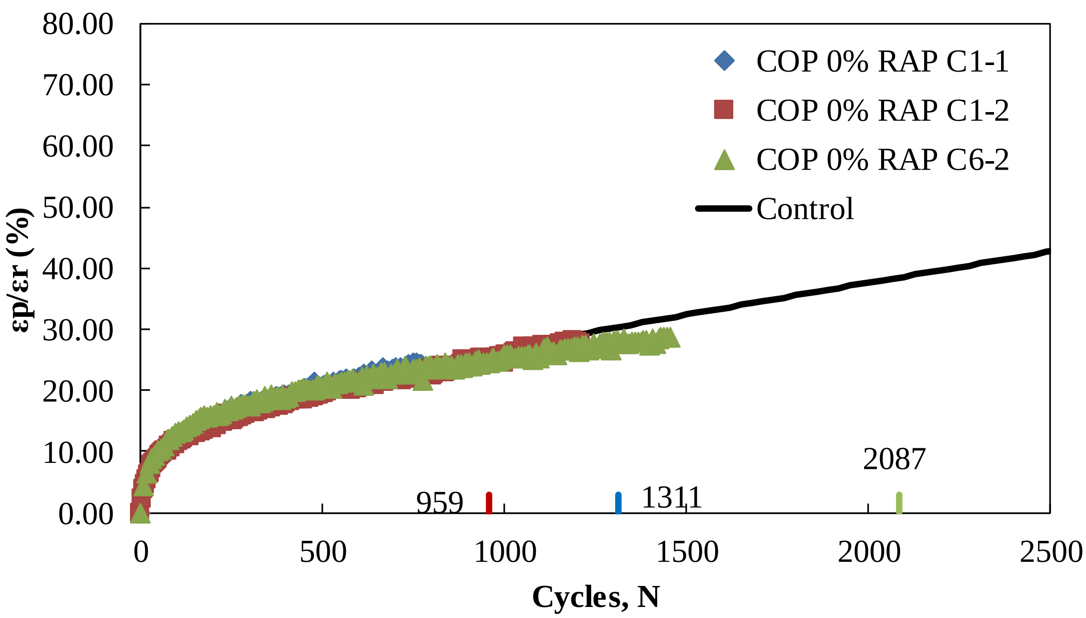
Mix	Specimen ID	Flow Number (Cycles)	Resilient Modulus at Failure (psi)	Axial Permanent Strain at Failure εp (%)	Axial Resilient Strain at Failure εr (%)	εp/εr	εp/εr at 5% εp
Control	COP 0% RAP C1-1	1311	107331	1.564	0.053	29.5	84.80
	COP 0% RAP C1-2	959	118489	1.201	0.05	25.0	89.45
	COP 0% RAP C6-2	2087	142484	1.277	0.04	32.7	106.36
Average		**1452**	**122768**	**1.347**	**0.05**	**29.1**	**93.5**
Standard Deviation		577	17963	0.191	0.007	4	11
Coefficient of Variation		39.7%	14.6%	14.2%	15.2%	13.3%	12.1%

Testing Temperatures of All Replicates of Control (0% RAP) Mix

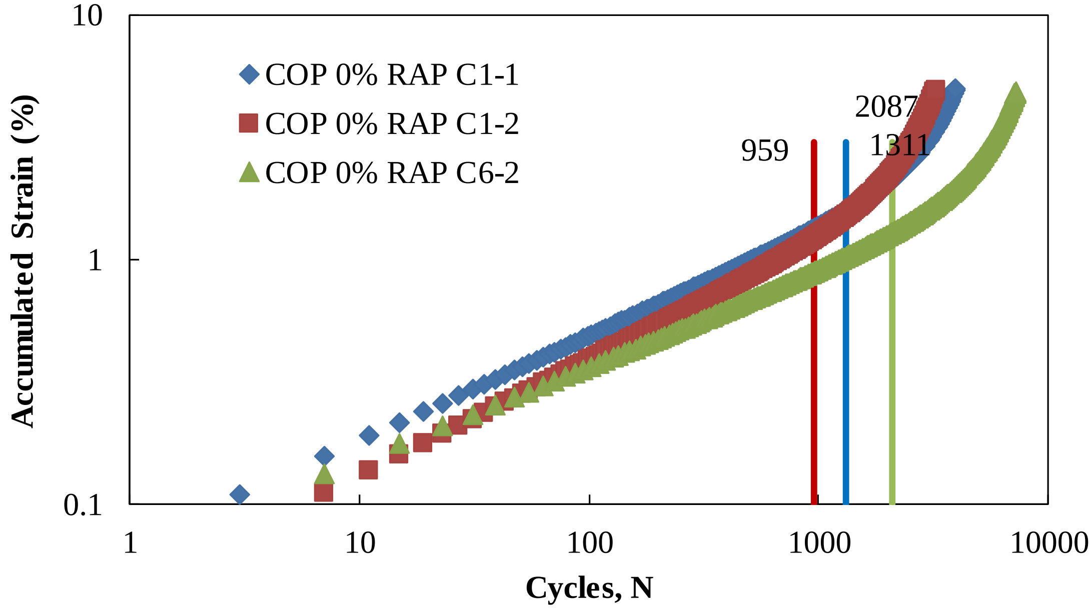
	Temperature			
	Average	S1	S2	S3
Temperature average	50.8	50.95	51.77	49.30
Minimum	49.14	50.87	50.85	49.14
Maximum	52.48	51.02	52.48	49.48
Difference	3.34	0.15	1.63	0.34
Thermocouple	50.6	50.7	51.5	49.5



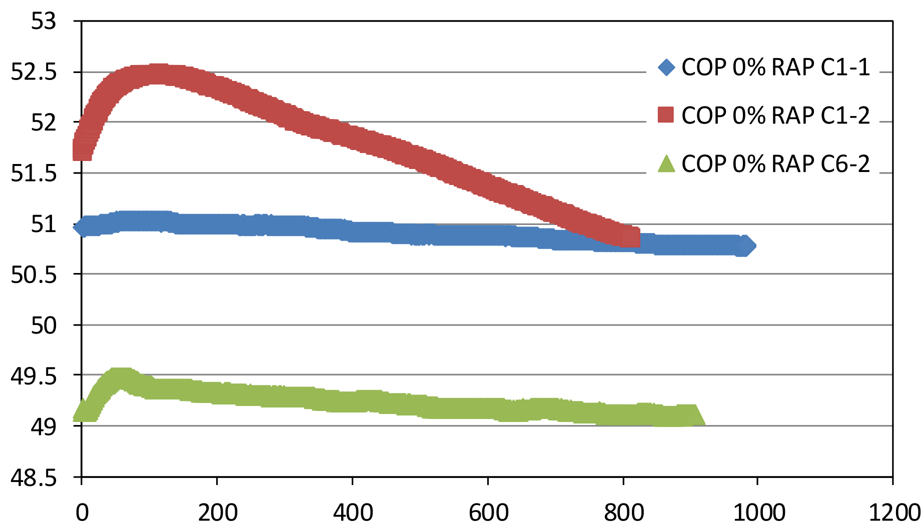
Accumulated strain versus number of cycles for all replicates of control (0% RAP) mix.



Permanent and recoverable strain ratio for number of cycles for all replicates of control (0% RAP) mix.



Accumulated strain versus number of cycles for all replicates of control (0% RAP) mix in log space.



Testing temperatures for all replicates of control (0% RAP) mix.

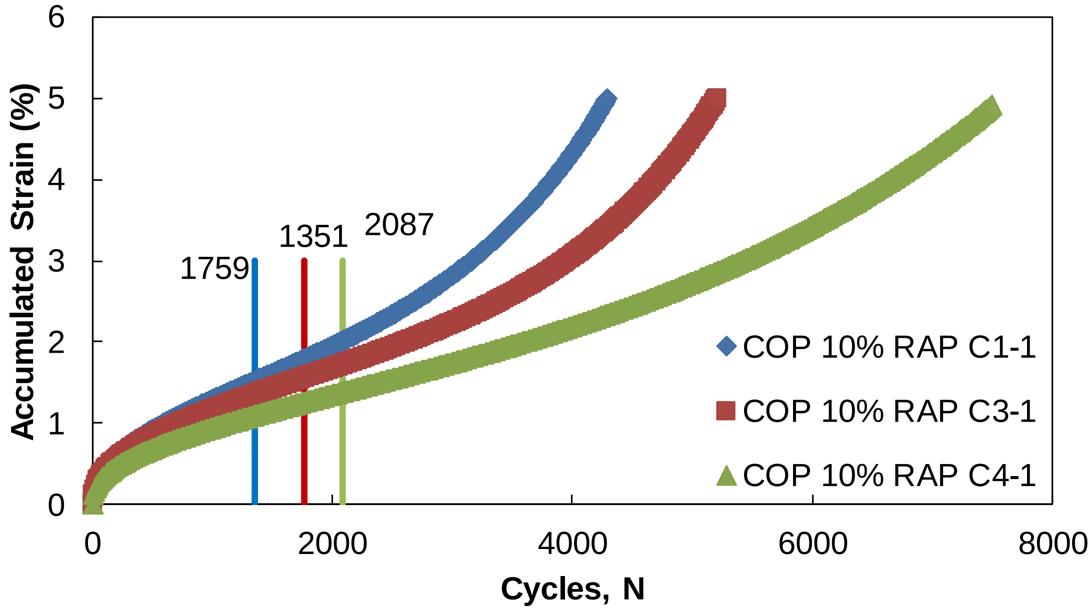
- 10% RAP Mix

Flow Number Results for All Replicates of 10% RAP Mix

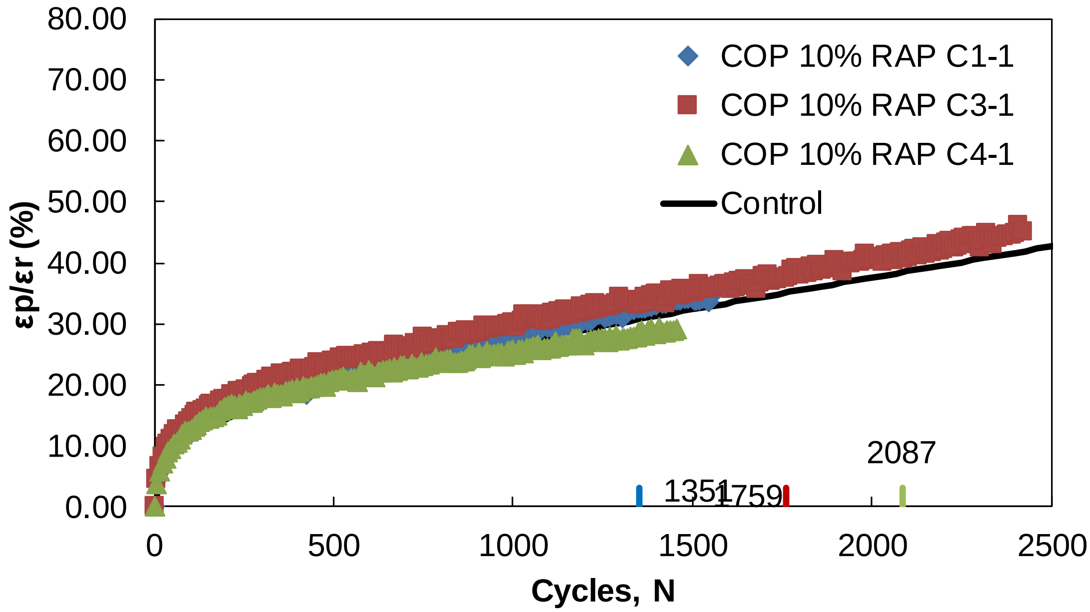
Mix	Specimen ID	Flow Number (Cycles)	Resilient Modulus at Failure (psi)	Axial Permanent Strain at Failure εp (%)	Axial Resilient Strain at Failure εr (%)	εp/εr	εp/εr at 5% εp
10%	COP 10% RAP C1-1	1351	120799	1.525	0.047	32.4	81.98
	COP 10% RAP C3-1	1759	138871	1.544	0.04	37.7	102.18
	COP 10% RAP C4-1	2087	137724	1.375	0.04	33.5	200.32
Average		**1732**	**132464**	**1.481**	**0.04**	**34.5**	**128.2**
Standard Deviation		369	10119	0.093	0.003	3	63
Coefficient of Variation		21.3%	7.6%	6.2%	8.1%	8.0%	49.4%

Testing Temperatures of All Replicates of 10% RAP Mix

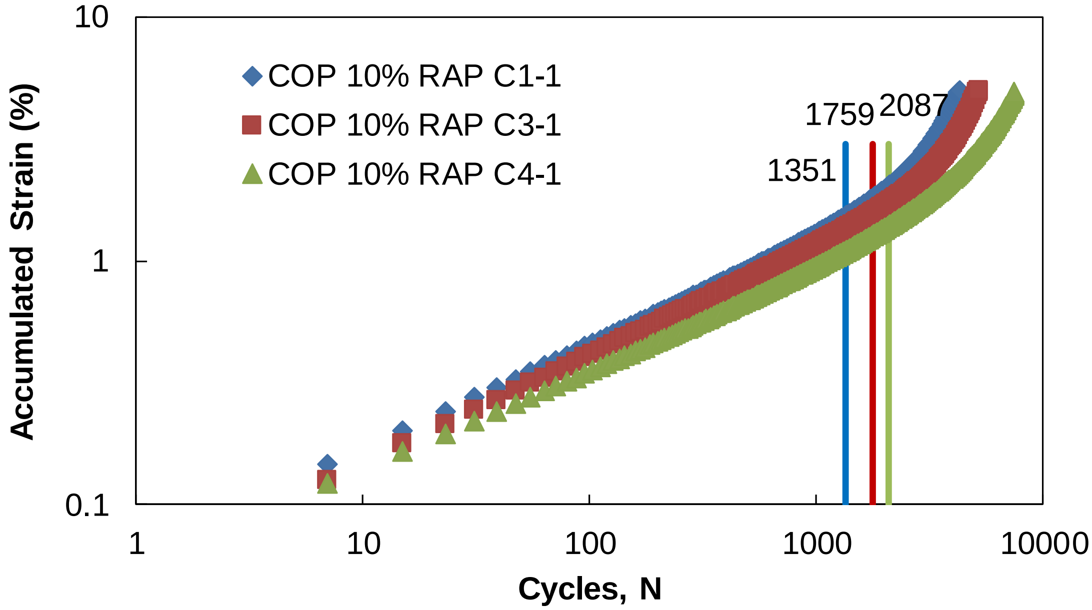
	Temperature			
	Average	S1	S2	S3
Temperature average	49.9	50.29	49.89	49.65
Minimum	49.61	50.07	49.77	49.58
Maximum	50.7	50.7	50.02	49.7
Difference	1.09	0.63	0.25	0.12
Thermocouple	50.2	50.5	50.0	50.0



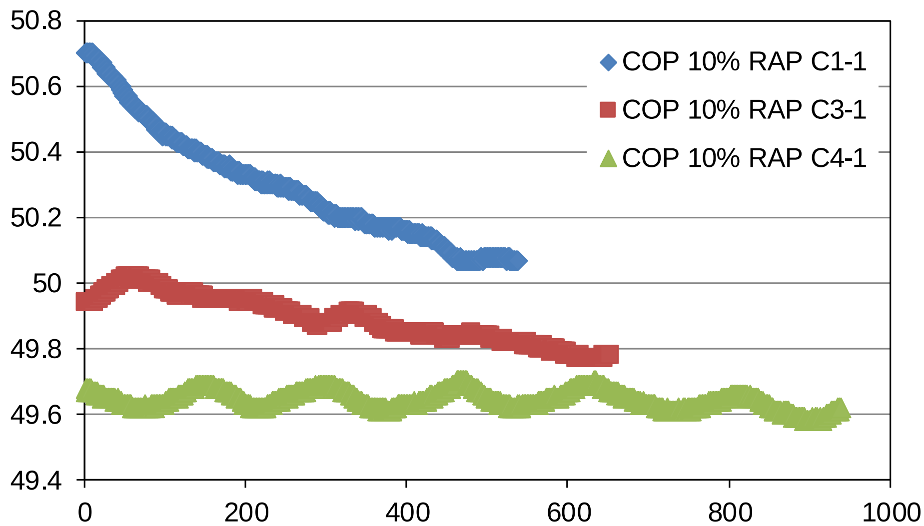
Accumulated strain versus number of cycles for all replicates of 10% RAP mix.



Permanent and recoverable strain ratio for number of cycles for all replicates of 10% RAP mix.



Accumulated strain versus number of cycles for all replicates of 10% RAP mix in log space.



Testing temperatures for all replicates of 10% RAP mix.

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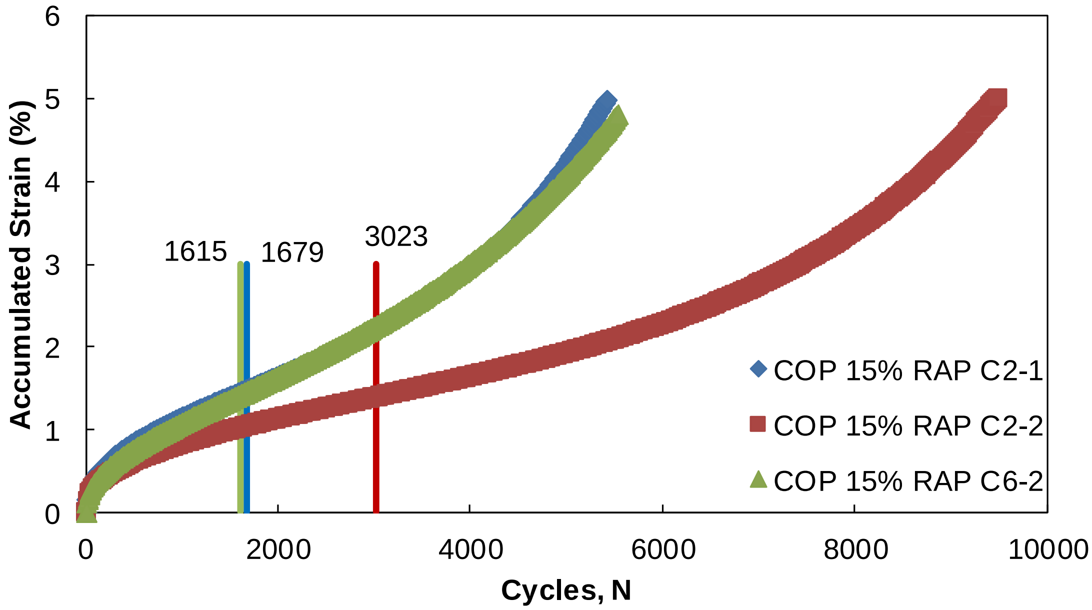
- 15% RAP Mix

Flow Number Results for All Replicates of 15% RAP Mix

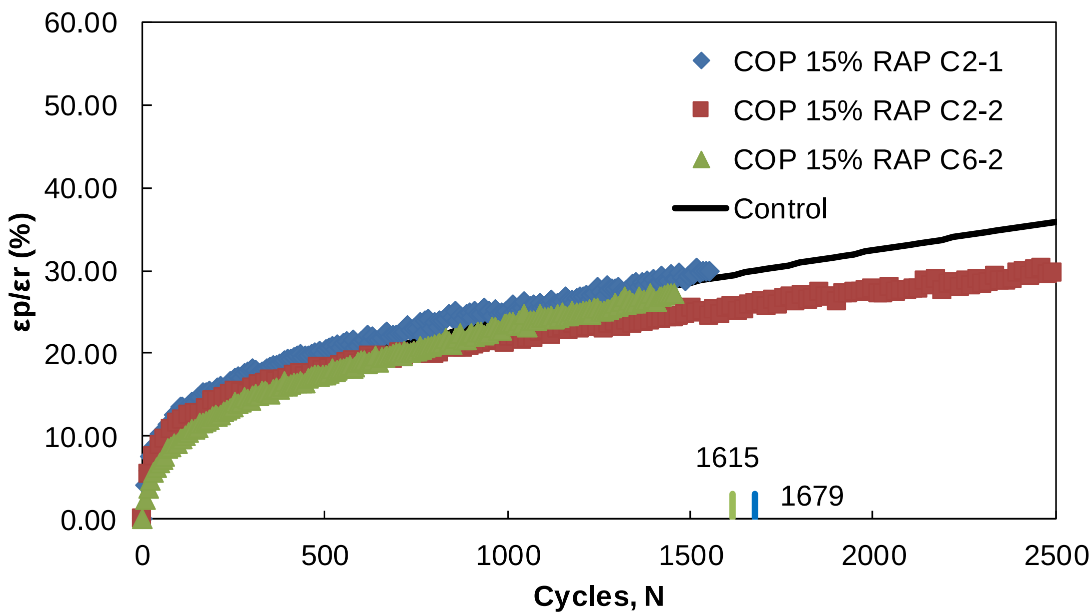
Mix	Specimen ID	Flow Number (Cycles)	Resilient Modulus at Failure (psi)	Axial Permanent Strain at Failure εp (%)	Axial Resilient Strain at Failure εr (%)	εp/εr	εp/εr at 5% εp
15%	COP 15% RAP C2-1	1679	118984	1.473	0.047	31.3	80.61
	COP 15% RAP C2-2	3023	130438	1.391	0.04	32.3	97.94
	COP 15% RAP C6-2	1615	113713	1.425	0.05	28.5	78.19
Average		**2106**	**121045**	**1.430**	**0.05**	**30.7**	**85.6**
Standard Deviation		795	8551	0.041	0.004	2	11
Coefficient of Variation		37.8%	7.1%	2.9%	7.5%	6.5%	12.6%

Testing Temperatures of All Replicates of 15% RAP Mix

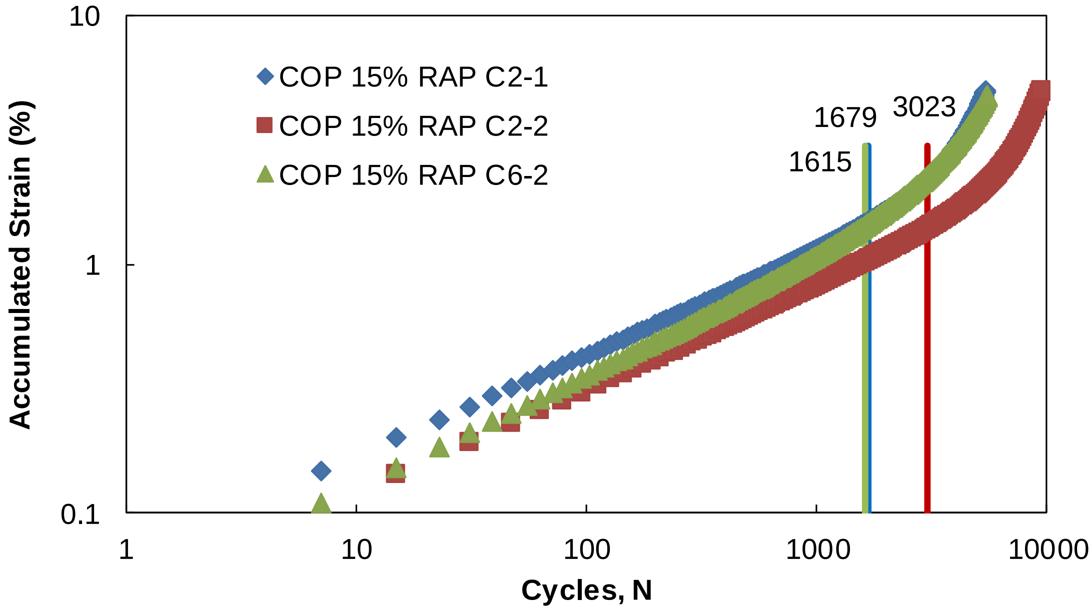
	Temperature			
	Average	S1	S2	S3
Temperature average	50.3	50.24	50.21	50.27
Minimum	50.06	50.1	50.08	49.98
Maximum	51.08	50.41	50.26	51.08
Difference	1.02	0.31	0.18	1.1
Thermocouple	50.0	49.6	50.0	50.4



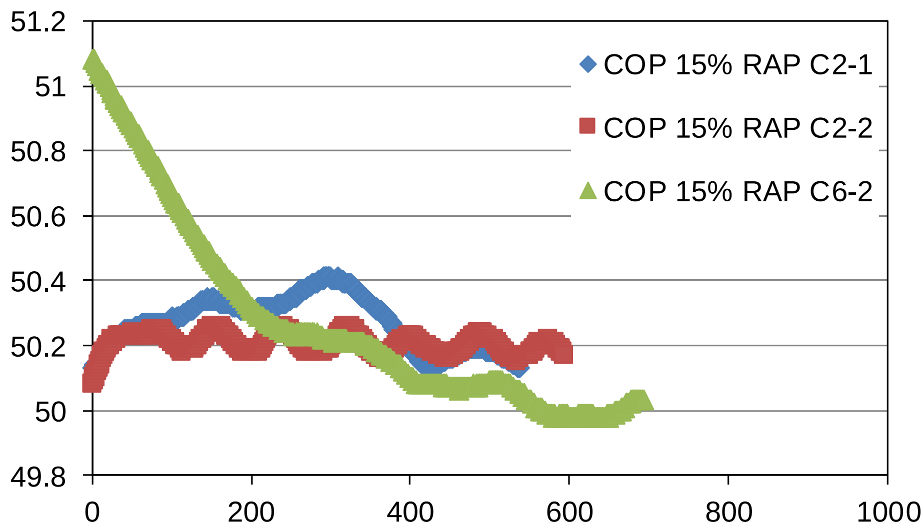
Accumulated strain versus number of cycles for all replicates of 15% RAP mix.



Permanent and recoverable strain ratio for number of cycles for all replicates of 15% RAP mix.



Accumulated strain versus number of cycles for all replicates of 15% RAP mix in log space.



Testing temperatures for all replicates of 15% RAP mix.

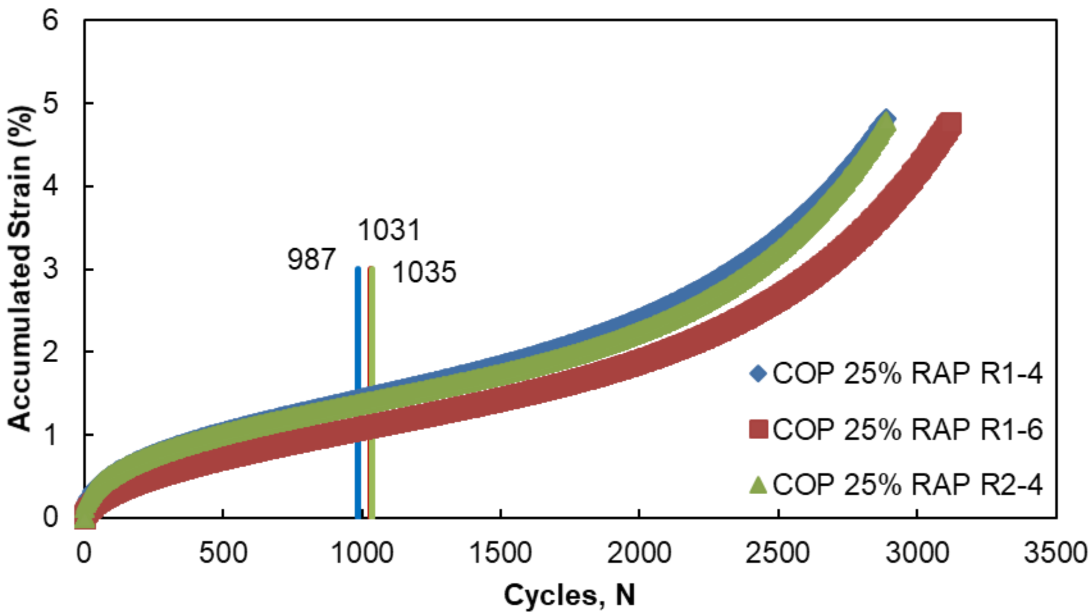
- 25% RAP SB Mix

Flow Number Results for All Replicates of 25% RAP SB Mix

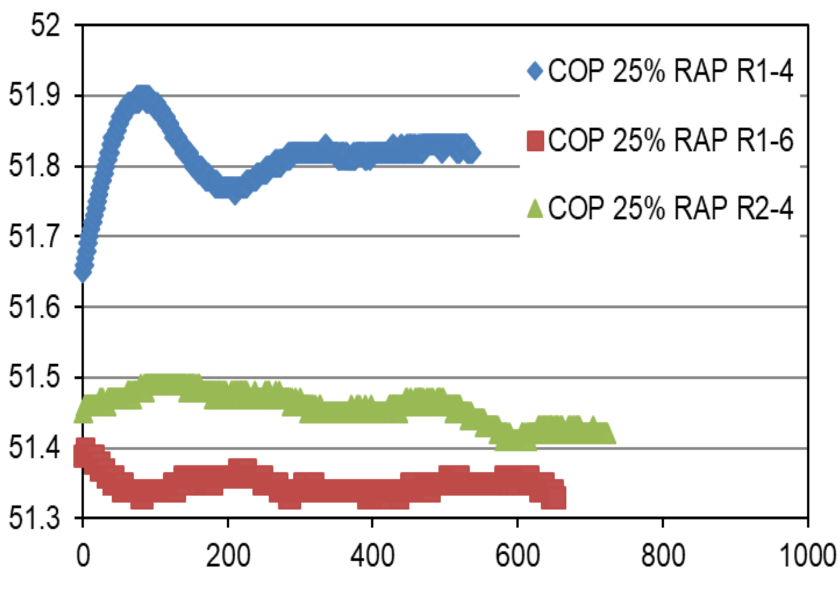
Mix	Specimen ID	Flow Number (Cycles)	Resilient Modulus at Failure (psi)	Axial Permanent Strain at Failure εp (%)	Axial Resilient Strain at Failure εr (%)	εp/εr	εp/εr at 5% εp
25%RAP	COP 25% RAP R1-4	987	94767	1.422	0.06	23.7	58.14
	COP 25% RAP R1-6	1031	102923	1.103	0.06	20.1	57.45
	COP 25% RAP R2-4	1035	92892	1.397	0.06	22.9	61.47
Average		**1018**	**96861**	**1.307**	**0.06**	**22.2**	**59.0**
Standard Deviation		27	5333	0.177	0.003	2	2
Coefficient of Variation		2.6%	5.5%	13.6%	5.5%	8.6%	3.6%

Testing Temperatures of All Replicates of 25% RAP SB Mix

	Temperature			
	Average	S1	S2	S3
Temperature average	51.5	51.82	51.34	51.46
Minimum	51.27	51.65	51.27	51.41
Maximum	51.9	51.9	51.4	51.49
Difference	0.63	0.25	0.13	0.08
Thermocouple	50.1	50.3	49.9	50.1
Chamber		49.2	49.2	49.2



Accumulated strain versus number of cycles for all replicates of 25% RAP SB mix



Testing temperatures for all replicates of 25% RAP SB mix

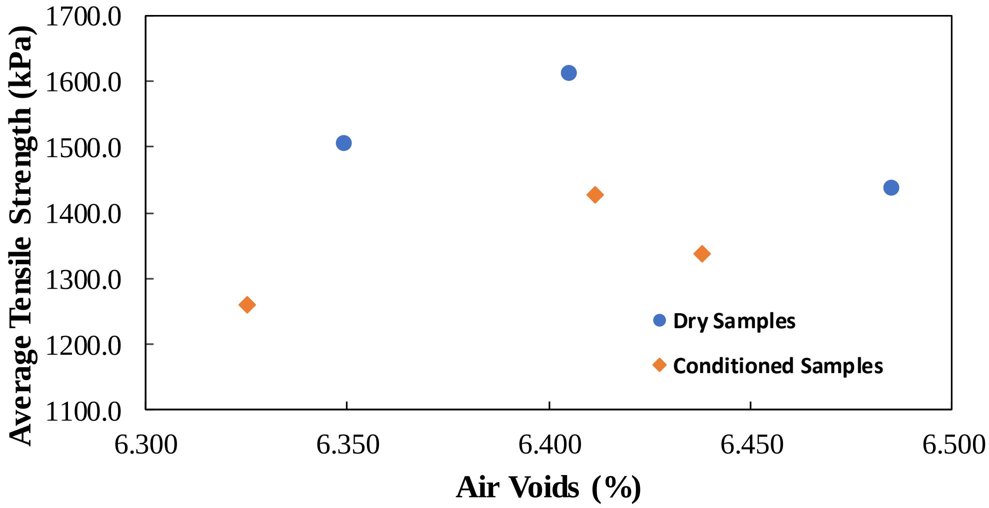
TENSILE STRENGTH RATIO (TSR)

Test Data for the Unconditioned Subset (0%, 10% and 15% RAP)

Condition		Unconditioned Subset								
RAP Content, %		0%			10%			15%		
Sample identification		1	2	3	4	5	6	7	8	9
		S1c-2	2-3T	2-3B	1-3T	1-3B	5(1)-2	2-3T	3-3T	4-3T
Diameter, mm (in.)	D	102.04	102.21	102.34	102.34	102.38	102.15	102.36	102.16	102.19
Thickness, mm (in.)	t	63.88	64.35	64.88	64.48	65.07	54.08	64.64	63.76	65.21
Dry mass in air, g	A	1192.1	1215	1216.2	1197.6	1207.6	1005.5	1198.5	1185.4	1205.4
SSD mass, g	B	1194.3	1220.4	1220.8	1206.6	1215.6	1007.6	1206.3	1192.7	1210.8
Mass in water, g	C	674.4	693.3	693.8	683.2	688	570.8	682.2	675.6	683.5
Volume (B – C), cm3	E	519.9	527.1	527	523.4	527.6	436.8	524.1	517.1	527.3
Bulk specific gravity (A/E)	Gmb	2.293	2.305	2.308	2.288	2.289	2.302	2.287	2.292	2.286
Maximum specific gravity	Gmm	2.458	2.458	2.458	2.452	2.452	2.452	2.445	2.445	2.445
% air voids [100(Gmm – Gmb)/Gmm]	Pa	6.715	6.222	6.111	6.684	6.654	6.119	6.471	6.241	6.504
Volume of air voids (PaE/100), cm3	Va	1192.1	1215	1216.2	1197.6	1207.6	1005.5	1198.5	1185.4	1205.4
Load, N (lbf)	P	15985	15662	14990	15695	14282	12479	15543	17197	17423
Saturated	5-10	---	---	---	---	---	---	---	---	---
Thickness, mm (in.)	t'	---	---	---	---	---	---	---	---	---
SSD mass, g	B'	---	---	---	---	---	---	---	---	---
Volume of absorbed water (B′ – A), cm3	J'	---	---	---	---	---	---	---	---	---
% saturation (100J′/Va)	S'	---	---	---	---	---	---	---	---	---
Load, N (lbf)	P'	---	---	---	---	---	---	---	---	---
Dry strength [2000P/πtD (2P/πtD)], kPa (psi)	S1	1561.1	1516.0	1437.3	1514.2	1364.8	1438.2	1495.7	1680.8	1664.7
Wet strength [2000P′/πt′D (2P/πt′D)], kPa (psi)	S2	---	---	---	---	---	---	---	---	---
Average tensile strength Dry subset, kPa	S1avg	1504.8			1439.1			1613.7		
Average tensile strength Wet subset, kPa	S2avg	---			---			---		
TSR (S2/S1)		---			---			---		

Test Data for the Conditioned Subset and TSR Results (0%, 10% and 15% RAP)

Condition		Conditioned Subset								
RAP Content, %		0%			10%			15%		
Sample identification		1	2	3	4	5	6	7	8	9
		T-D2	C2-2	3-3B	4-3T	5(1)-1	4-3B	3-3B	5c-1	1-3B
Diameter, mm (in.)	D	102.45	102.15	102.24	102.36	102.14	102.27	102.39	102.18	102.32
Thickness, mm (in.)	t	66.46	62.39	64.97	66.77	57.34	65.53	64.16	64.795	65.77
Dry mass in air, g	A	1223.0	1161.8	1216.3	1234.1	1059.4	1227.4	1188.5	1200.6	1223.4
SSD mass, g	B	1225.0	1163.3	1222.8	1243.1	1061.9	1235.8	1193.7	1202.8	1228.3
Mass in water, g	C	692.6	658.8	695.7	703.3	599.7	703.1	674.0	676.7	695.4
Volume (B – C), cm3	E	532.4	504.5	527.1	539.8	462.2	532.7	519.7	526.1	532.9
Bulk specific gravity (A/E)	Gmb	2.297	2.303	2.308	2.286	2.292	2.304	2.287	2.282	2.296
Maximum specific gravity	Gmm	2.458	2.458	2.458	2.452	2.452	2.452	2.445	2.445	2.445
% air voids [100(Gmm – Gmb)/Gmm]	Pa	6.544	6.311	6.122	6.761	6.522	6.031	6.466	6.664	6.105
Volume of air voids (PaE/100), cm3	Va	34.841	31.839	32.267	36.497	30.145	32.129	33.606	35.057	32.532
Load, N (lbf)	P	---	---	---	---	---	---	---	---	---
Saturated	5-10	min @	47 - 53		kPa (psi) or	350 - 400		mmHg (in.Hg)		
Thickness, mm (in.)	t'	66.56	62.21	65.06	66.50	57.31	65.40	64.09	65.01	65.73
SSD mass, g	B'	1248.4	1183.2	1237.8	1258.9	1080.5	1250	1210.4	1224.8	1244.8
Volume of absorbed water (B′ – A), cm3	J'	25.4	21.4	21.5	24.8	21.1	22.6	21.9	24.2	21.4
% saturation (100J′/Va)	S'	72.9	67.2	66.6	68.0	70.0	70.3	65.2	69.0	65.8
Load, N (lbf)	P'	13065	12839	13315	13584	12103	15048	15531	13346	15808
Dry strength [2000P/πtD (2P/πtD)], kPa (psi)	S1	---	---	---	---	---	---	---	---	---
Wet strength [2000P′/πt′D (2P/πt′D)], kPa (psi)	S2	1219.7	1286.3	1274.4	1270.5	1316.3	1432.5	1506.7	1279.1	1496.3
Average tensile strength Dry subset, kPa	S1avg	---			---			---		
Average tensile strength Wet subset, kPa	S2avg	1260.1			1339.7			1427.4		
TSR (S2/S1)		84			93			88		

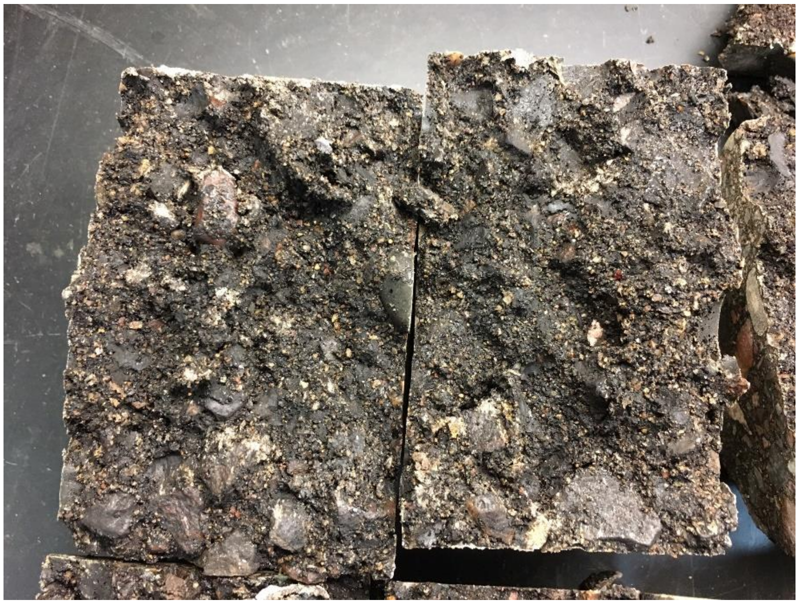


Average tensile strength versus air voids.

Preparation of the conditioned specimens prior to freeze.

Water bath of conditioned specimens at 140°F (60°C) for 24 hrs.

Split test for a conditioned specimen.



Specimen after split test showing a little striping.

Test Data for the Unconditioned Subset (0%, 25% and 25% SB RAP)

Condition		DRY SUBSET								
RAP Content, %		0%			25% SB			25%		
Sample identification		1	2	3	4	5	6	7	8	9
		S1c-2	2-3T	2-3B	2-2-B	2-5-T	2-6-T	8b	9t	10t
Diameter, mm (in.)	D	102.04	102.205	102.34	98.995	99.04	99.255	100	100	100
Thickness, mm (in.)	t	63.88	64.35	64.88	63.88	61.60	64.98	51.00	55.00	48.00
Dry mass in air, g	A	1192.1	1215	1216.2	1120.4	1073.2	1147.9	953.9	1033	913.7
SSD mass, g	B	1194.3	1220.4	1220.8	1122.1	1074.5	1149.8	955.1	1034.4	914.8
Mass in water, g	C	674.4	693.3	693.8	632.3	606.3	652.5	545.2	588.7	523.7
Volume (B – C), cm3	E	519.9	527.1	527	489.8	468.2	497.3	409.9	445.7	391.1
Bulk specific gravity (A/E)	Gmb	2.293	2.305	2.308	2.287	2.292	2.308	2.327	2.318	2.336
Maximum specific gravity	Gmm	2.458	2.458	2.458	2.456	2.456	2.456	2.476	2.476	2.476
% air voids [100(Gmm – Gmb)/Gmm]	Pa	6.715	6.222	6.111	6.862	6.670	6.015	6.012	6.393	5.645
Average % air voids	%	6.350			6.516			6.017		
Volume of air voids (PaE/100), cm3	Va	34.912	32.796	32.207	33.611	31.229	29.914	24.642	28.495	22.077
Load, N (lbf)	P	15985	15662	14990	15579	15180	15613	18378	20935	18347
Saturated										
Thickness, mm (in.)	t'									
SSD mass, g	B'									
Volume of absorbed water (B′ – A), cm3	J'									
% saturation (100J′/Va)	S'									
Load, N (lbf)	P'									
Dry strength [2000P/πtD (2P/πtD)], kPa (psi)	S1	1561.1	1516.0	1437.3	1568.5	1584.0	1541.2	2294.1	2423.2	2433.3
Wet strength [2000P′/πt′D (2P/πt′D)], kPa (psi)	S2									
Average tensile strength Dry subset, kPa	S1avg	1504.8			1564.6			2383.5		
Average tensile strength Wet subset, kPa	S2avg									
TSR (S2/S1)										

Test Data for the Conditioned Subset and TSR Results (0%, 25% and 25% SB RAP)

Condition		MOISTURE-CONDITIONED SUBSET								
RAP Content, %		0%			25% SB			25%		
Sample identification		1	2	3	4	5	6	7	8	9
		T-D2	C2-2	3-3B	1-1-B	2-1-B	2-5-B	8t	9b	10b
Diameter, mm (in.)	D	102.45	102.15	102.24	99.045	99.06	99.1	100	100	100
Thickness, mm (in.)	t	66.4575	62.385	64.9725	63.325	62.8	63.45	51	50	53
Dry mass in air, g	A	1223	1161.8	1216.3	1119.5	1095.8	1108.9	1010.7	941.3	952.4
SSD mass, g	B	1225	1163.3	1222.8	1121.7	1097.7	1110.4	1012.2	942.6	953.4
Mass in water, g	C	692.6	658.8	695.7	637	618.1	626.8	576.1	538.5	545.5
Volume (B – C), cm3	E	532.4	504.5	527.1	484.7	479.6	483.6	436.1	404.1	407.9
Bulk specific gravity (A/E)	Gmb	2.297	2.303	2.308	2.310	2.285	2.293	2.318	2.329	2.335
Maximum specific gravity	Gmm	2.458	2.458	2.458	2.456	2.456	2.456	2.476	2.476	2.476
% air voids [100(Gmm – Gmb)/Gmm]	Pa	6.544	6.311	6.122	5.958	6.970	6.636	6.398	5.922	5.699
Average % air voids	%	6.326			6.521			6.006		
Volume of air voids (PaE/100), cm3	Va	34.841	31.839	32.267	28.878	33.427	32.093	27.901	23.930	23.247
Load, N (lbf)	P									
Saturated	5 – 10 min @ 47 – 53 KPa or 350 – 400 mmHg									
Thickness, mm (in.)	t'	66.5625	62.2075	65.055	63.745	63.085	63.5	51	50	53
SSD mass, g	B'	1248.4	1183.2	1237.8	1139.8	1119.3	1130.5	1029.8	958.2	969.2
Volume of absorbed water (B′ – A), cm3	J'	25.4	21.4	21.5	20.3	23.5	21.6	19.1	16.9	16.8
% saturation (100J′/Va)	S'	72.9	67.2	66.6	70.3	70.3	67.3	68.5	70.6	72.3
Load, N (lbf)	P'	13065	12839	13315	12885	10538	11630	17832	17902	19306
Dry strength [2000P/πtD (2P/πtD)], kPa (psi)	S1									
Wet strength [2000P′/πt′D (2P/πt′D)], kPa (psi)	S2	1219.7	1286.3	1274.4	1299.2	1073.5	1176.6	2225.9	2279.4	2319.0
Average tensile strength Dry subset, kPa	S1avg									
Average tensile strength Wet subset, kPa	S2avg	1260.1			1183.1			2274.8		
TSR (S2/S1)		**84**			**76**			**95**		