GEORGIA DOT RESEARCH PROJECT 16-32
FINAL REPORT

EVALUATION OF STRUCTURAL INTEGRITY FOR A FOAMED ASPHALT BASE COURSE USING 100 % RECYCLED ASPHALT PAVEMENT

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Evaluation of Structural Integrity for a Foamed Asphalt Base Course Using 100 % Recycled Asphalt Pavement

Final Report

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16. Abstract

In recent years, the use of Reclaimed Asphalt Pavement (RAP) is becoming more common for asphalt pavement construction and maintenance, primarily because of the economic and environmental benefits. However, despite Georgia Department of Transportation's extensive use of RAP in its asphaltic concrete mixtures, thousands of tons of RAP continue to accumulate in contractors' asphalt plant stockpiles located in the urban areas around the state. The primary goal of this study was to evaluate the structural integrity of 100 % recycled asphalt mixtures using a foamed asphalt technology to determine whether these mixtures can effectively be used to replace conventional bound and unbound base courses.

The results of this study indicate that the structural layer coefficients of 100 % recycled foamed asphalt mixtures ranged from 0.22-0.27, based upon the Marshall Stability test and following the recommendations provided in the 1993 AASHTO *Guide for Design of Pavement Structures*. When a rejuvenator was added to the mixture, the mixture stiffness decreased considerably, which dropped the structural layer coefficients to 0.16-0.18 at a 6% rejuvenator dosage. There were further reductions in stability as more rejuvenator was added. According to Wirtgen's nomograph for 100 % recycled asphalt mixtures, the coefficients were estimated to be over 0.35 when a dry ITS was used for the coefficient estimation for no-rejuvenator mixtures. At a 6% rejuvenator dosage, the coefficients ranged from 0.24-0.30.

Based on the performance test results conducted in our laboratory, a 100 % recycled foamed asphalt mixture appears suitable for use as a base course in pavement systems in Georgia, replacing the current base courses.

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EXECUTIVE SUMMARY

The use of Reclaimed Asphalt Pavement (RAP) is rapidly gaining popularity and becoming a common practice in asphalt pavement construction and maintenance, primarily because of the economic and environmental benefits. However, despite the significant use of RAP in Georgia where 25 to 40 percent is typically used in mixtures, thousands of tons of RAP continue to accumulate in stockpiles at asphalt plants located near urban areas around the state. This is mostly due to GDOT's extensive use of mill and inlay construction methods on urban roadway rehabilitation projects.

Using higher RAP content in asphalt mix designs may be one possible solution, but valid concern arises in that the excessive inclusion of RAP in asphalt mixtures may cause premature pavement failure. These misgivings arise mainly because of uncertainty regarding the quality and actual quantity of effective recycled binder replacement in the RAP and a lack of nationally accepted guidelines and technology for designing a high RAP content asphalt pavement.

The primary goal of this study therefore was to evaluate the structural integrity of 100 % recycled asphalt pavement for use as base course in Georgia. A foamed asphalt technology was utilized in mixing and manufacturing the 100 % recycled asphalt mixtures. Foamed asphalt is a commonly used recycling technology that maximizes the use of RAP without the need for heat during the recycling process. This foamed asphalt technology produces recycled mixture that has the potential to supplement the traditional unbound and stabilized granular base that is currently used in pavement structures throughout the state.

SPECIFIC STUDY OBJECTIVES AND SCOPE

The specific objectives of this study were as follows:

- Identify foaming characteristics of Georgia's asphalt binder (PG 64-22) with respect to the Optimum Water Content (OWC) of the binder based on its Expansion Ratio and Half Life.

- Identify the material characteristics of RAP materials: the Optimum Moisture Content (OMC) of RAP, RAP binder stiffness, and rejuvenator dosage associated with the stiffness.
- Determine the Optimum Foamed Asphalt Cement Content (OFAC) of foamed asphalt mixtures through a foamed asphalt mix design.
- Identify the structural characteristics of 100 % recycled foamed asphalt mixtures using Marshall Stability, Indirect Tensile Strength with moisture susceptibility, and Semi-Circular Bending tests.
- Estimate the layer structural coefficients of 100 % recycled foamed asphalt mixtures for potential use as a base course in pavement systems in Georgia.

As the major performance tests for this study, three laboratory tests were considered: Marshall Stability (MS), Indirect Tensile Strength (ITS), and Semi-Circular Bending (SCB). The MS test was chosen because it is a familiar test that has been used by GDOT for asphalt mix design extensively in the past. The stability value provides a useful performance measure for describing the resistance of asphalt mixtures to rutting and shearing displacement. The MS test is also used in determining the structural layer coefficient in accordance with a correlation provided in the 1993 AASHTO *Guide for Design of Pavement Structures*. ITS was chosen because the Tensile Strength Ratio (TSR), which is the ratio between dry ITS and soaked ITS, is currently used by GDOT to evaluate an asphaltic concrete mixture’s moisture susceptibility. Also, the dry ITS is correlated with the layer coefficient of foamed asphalt mixtures and thus serves as a useful indicator of structural integrity. The SCB test was selected to evaluate the fracture potential of asphalt mixtures at intermediate temperatures.

RAP samples and asphalt binders (PG 64-22) collected from three asphalt plants were the major materials used in manufacturing 100% RAP foamed asphalt mixtures for this study. Two other ingredients were also considered, namely Portland cement and rejuvenating agents. The addition of a rejuvenator was evaluated to ascertain its effectiveness in counteracting – the age related hardening of the RAP binder, thus mitigating the cracking potential of 100% recycled foamed asphalt mixtures. This study utilized two types of rejuvenator and mixtures were fabricated at three dosage levels (6%, 12%, and 18%), along with a no-rejuvenator control mixture.

SUMMARY OF MAJOR FINDINGS

The specific findings of this study are summarized as follows:

- The OWC necessary to produce a high quality foamed asphalt cement was found to be around 2.7% (an average of the 2.9%, 2.6%, and 2.5% obtained for the asphalt cement from the three different sources) by weight of asphalt cement. At each of these OWCs, the resulting Expansion Ratio and Half Life met the minimum foaming conditions recommended by Wirtgen (ER > 8 times and HL > 6 sec.)
- An injection speed of 50 grams per second produced a better quality of foamed asphalt cement than 100 grams per second. There was no significant difference in the results obtained among the three asphalt cement temperatures used in this study: 160, 170, and 180°C. From a sustainability point of view, the lowest temperature (160°C) was therefore selected for mixing and manufacturing loose foamed asphalt mixtures.
- An OMC of 6% provided a maximum dry unit weight of RAP based on the average weight of dry RAP (5.8%, 5.9%, and 6.2%) for material obtained from the three different RAP sources.
- The extracted RAP binder was found to be very stiff, with a high temperature Performance Grade (PG) of 88 or 94. It was assumed that in order to decrease the viscosity of the aged binder to the recommended level of PG 64 ($G^*/\sin \delta$ of 2.2 kPa), approximately 16% to 20% rejuvenator was required.

- An asphalt cement content of 2.5% was found to be the OFAC for designing a 100 % recycled foamed asphalt mixture for the raw materials used in this study. The OFAC was determined based on two performance tests: Marshall Stability and Indirect Tensile Strength.
- The Marshall Stability at 25°C with no rejuvenator was found to be 4229 lb. on average for material from the three RAP sources. When a dosage level of 6%, 12%, and 18% rejuvenator was added, the stabilities were reduced to 2692 lb., 1990 lb., and 1674 lb.
- The Marshall Stability at 25°C can be used when designing a mix to find an OFAC, but is not recommended for estimating the structural layer coefficient because it tends to overestimate stability and is accordingly incompatible with the estimation method suggested by the 1993 AASHTO *Guide for Design of Pavement Structures*.
- There was some variability in stability among the RAP obtained from the three different sources for use in this study. However, the trend in the stability reduction with increasing rejuvenator dosage was consistent for all three.
- The addition of rejuvenator caused a significant reduction in both the Marshall Stability (24% to 66%) and the Conditioned Marshall Stability (27% to 65%) at 25°C.
- The Percent Retained Marshall Stability at 25°C indicated that the resistance of foamed asphalt mixtures to the detrimental effect of water was very effective at this temperature.
- The Marshall and Conditioned Marshall Stabilities at 60°C were considerably reduced compared to those at 25°C. The overall stability reduction was found to be 79.2% when combining all RAP sources, rejuvenator dosage, and the two stability groups.
- The Marshall Stability at 60°C with no rejuvenator was found to be 1203 lb. on average for the RAP from the three different sources. When a dosage level of 6%, 12%, or 18% rejuvenator was added, the stabilities were reduced to 534 lb., 340 lb., or 277 lb., respectively.

- An additional set of tests for the lower rejuvenator dosage levels (0%, 2%, 4%, and 6%) verified the trend of reduction in the Marshall Stability at 60°C with the increasing rejuvenator dose. Nearly no change in the stability was observed at a dosage level of 2%, while a noticeable stability reduction was found at 4% and 6% dose.
- The Percent Retained Marshall at 60°C was found to be consistently greater than 100% for all the mixture combinations tested. This result may be attributed to the fact that the specimens were conditioned in an oven rather than in a water bath. It is therefore not recommended that this property be used for the moisture damage evaluation of foamed asphalt mixtures at this temperature.
- In general, no significant differences in stability were found between the two rejuvenator types used in the study, with a few exceptions. This finding holds true when both 25°C and 60°C preconditioning temperatures were used.
- The effect of rejuvenator on the ITS was significant at a 6% dosage level, but the rate of reduction was diminished as more rejuvenator was added.
- The trend of the consistent reduction in the dry and soaked ITS values with the increase of rejuvenator doses was verified at lower dosage levels (2% and 4%).
- The ITS results (46 psi for the dry condition and 41 psi for the soaked condition) just met the minimum requirements for 100 % recycled foamed asphalt used by other state agencies. However, the TSR results did exceed the minimum requirements (over 80%) of the other agencies.
- The fracture energy of the foamed asphalt mixtures was significantly lower than that of HMA. However, if the brittleness (m-value) was considered, the fracture resistance of foamed asphalt mixtures was comparable to that of HMA.
- For no-rejuvenator mixtures, the fracture resistance, expressed in terms of the FI value, was found to be slightly lower than that of HMA. However, when a rejuvenator was added,

the mixtures became softened and showed a better performance than HMA. The FI values increased as higher rejuvenator dosages were added to the foamed asphalt mixtures.

- Based on the Marshall Stability at 60°C, the layer coefficients were estimated to be 0.22-0.27 with no addition of rejuvenator, according to the 1993 AASHTO *Guide for Design of Pavement Structures*. When rejuvenator was added, average coefficients of 0.17, 0.15, and 0.14 were found for dosages of 6%, 12%, and 18%, respectively.
- Based on the dry Indirect Tensile Strength, the layer coefficients for 100% RAP foamed asphalt mixtures were estimated to be 0.35 with no addition of rejuvenator according to the Wirtgen's manual. When rejuvenator was added, average coefficients of 0.25, 0.20, and 0.18 were found for dosages of 6%, 12%, and 18%, respectively.

CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this study, the following conclusions can be drawn:

- There is sufficient evidence to support the use of 100 % recycled foamed asphalt mixture as a base course in pavement systems in Georgia.
- Although rejuvenator increases the material's fracture resistance, the use of rejuvenator is not recommended in a 100 % recycled foamed asphalt mixture because the rejuvenator has an effect on foamed asphalt mixtures, substantially decreasing the structural integrity even at low dosage levels.
- It is recommended that GDOT develop a new mix design methodology for a 100 % recycled foamed asphalt mixture, along with appropriate laboratory test methods.
- To verify the long term structural integrity of a 100 % recycled foamed asphalt mixture, a pilot study is recommended in both laboratory and field. A Dynamic Modulus (|E*|) test and a Falling Weight Deflectormeter test are recommended for the laboratory and field evaluations, respectively.

- If a conventional bound or stabilized aggregate base is replaced by 100 % recycled foamed asphalt layer, a cost comparison study that includes aspects such as a life cycle cost analysis is needed to identify the potential economic benefits.

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1 INTRODUCTION

1.1 Background

Reclaimed Asphalt Pavement (RAP) is obtained through the rehabilitation or reconstruction of old asphalt pavement. The removed RAP materials are typically used as an alternate aggregate to virgin aggregate in a new or overlay asphalt pavement, preserving natural resources and conserving energy. The use of RAP is gaining popularity and is becoming a common practice in asphalt pavement construction and maintenance, primarily because of the economic and environmental benefits gained. Many highway agencies across the country allow a certain percentage of RAP in their asphalt mix design including the Georgia Department of Transportation (GDOT) that allows up to 25 percent and 40 percent RAP to be used in batch and drum plants, respectively [1].

Despite GDOT's generous use of RAP in mixes placed in Georgia, thousands of tons of RAP continue to accumulate in contractor asphalt plants' stockpiles located around the urban areas within the state due to the milling and inlay required on urban roadways. It is therefore imperative to find new ways to increase RAP consumption in Georgia. It has been suggested that a higher RAP content should be allowed in asphalt mix designs, but concerns arise when excess RAP content is added into asphalt pavement because it may result in premature structural failure. This is mainly attributed to uncertainty regarding the quality and content of RAP's binder replacement in the mix design process. Recycled binder can vary considerably, and there is a lack of nationally recognized guidelines and technology to support the design of 100 % recycled foamed asphalt base pavements for Georgia's roads.

Foamed asphalt is a promising recycling technology that maximizes the use of RAP without the need for heating during the recycling process. Foamed asphalt is created by swiftly injecting a small amount of cold water into hot asphalt cement binder. The water trapped in the asphalt liquid turns to steam due to the high temperature in the asphalt liquid and generates a foam in the asphalt cement. This foaming process dramatically decreases the viscosity of the asphalt binder and makes it possible for cold aggregates or RAP to be consistently mixed to create a uniform mixture that is easily compactable at ambient temperature. It should be noted that unlike Hot Mix Asphalt (HMA), where a full coating around individual aggregates is critically important, the RAP aggregates of foamed asphalt mixture are only partially coated by the foamed asphalt and behaves more like non-continuously bound materials. This new foamed asphalt technology produces a high RAP content asphalt mixture that has the potential to be used as a paving material for asphalt pavement construction. However, prior to its widespread adoption, it is vital that pavement designers consider the structural integrity of a 100 % recycled foamed asphalt base mixture based on high quality models strongly supported by scientific evidence.

According to the methods provided in the 1993 AASHTO *Guide for Design of Pavements Structures*, the structural integrity of pavement layers is usually explained in terms of the layer coefficient (a_i values). This coefficient is described as “a measure of the relative ability of a unit thickness (1 inch) of a given material to function as a structural component of the pavement.” [2]. The Federal Highway Administration (FHWA) provides no universally accepted structural layer coefficient for cold recycled asphalt mixes such as foamed asphalt layers, but it is generally accepted in the pavement community that a cold recycled asphalt mix is not the structural equivalent of HMA but performs better than untreated aggregate base courses. This indicates that foamed asphalt materials have the potential to be used as an adequate substitute for traditional bound or unbound aggregate base courses.

The current version of GDOT’s pavement design manual contains information about the structural coefficients of the layers for the various materials typically used in Georgia. For example, the a_i value of an asphaltic concrete layer ranges from 0.30 to 0.44, for a stabilized base layer with different stabilizers it ranges from 0.12 to 0.22, and for an untreated base layer, it ranges from 0.10 to 0.16 [3]. However, neither the design manual nor any of the other pavement design documents available from GDOT provide any information on the structural integrity of 100% recycled foamed asphalt base mixture. It is therefore imperative to evaluate the structural integrity of a 100 %

recycled mixture and determine its potential to be used as a structurally sound layer in the pavement system of Georgia before this potentially highly beneficial technology can be adopted in the state.

1.2 Specific Study Objectives and Scope

The main objective of this study was to evaluate the structural integrity of foamed asphalt mixture containing 100% RAP by determining its layer coefficient for potential use in pavement systems in Georgia. The practical implication of incorporating 100% RAP foamed asphalt into pavement is that this fully recycled material can potentially supplement the traditional unbound or stabilized aggregate base course currently used. The specific study objectives are as follows:

- Identify the foaming characteristics of Georgia's asphalt cement binder (PG 64-22) and determine the Optimum Water Content (OWC) of the binder based on two foaming properties: Expansion Ratio and Half Life.
- Identify the material characteristics of a 100 % recycled foamed asphalt mixture and determine the Optimum Moisture Content (OMC) of RAP and the Optimum Foamed Asphalt Cement Content (OFAC) of foamed asphalt mixture through a foamed asphalt mix design process.
- Identify the structural characteristics of 100 % recycled foamed asphalt mixtures utilizing Marshall Stability, Indirect Tensile Strength, and Semi-Circular Bending tests.
- Evaluate the moisture susceptibility of 100 % recycled foamed asphalt mixtures by examining their Tensile Strength Ratio.
- Determine the layer structural coefficients 100 % recycled foamed asphalt mixtures for potential use in pavement systems in Georgia.

1.3 Work Scope

In order to evaluate the structural integrity, the study selected three laboratory tests: Marshall Stability (MS), Indirect Tensile Strength (ITS), and Semi-Circular Bending (SCB). The MS was chosen because the stability value provides a useful performance measure that indicates the resistance of the foamed asphalt mixture to rutting and shearing displacement. Note that the MS is already being used by GDOT for a limited number of asphalt pavement design mix types following the 1972 AASHTO design method. The ITS test was chosen because it is widely used in the pavement community to measure the tensile strength of asphalt mixtures. The Tensile Strength Ratio (TSR), the ratio between the dry ITS and the wet ITS, is also currently utilized by GDOT to evaluate the moisture susceptibility of asphaltic concrete mixtures. In particular, ITS is correlated with the layer coefficient of foamed asphalt mixture and thus becomes an indicator of structural integrity. The SCB test was selected because the test can be used to evaluate the fracture or cracking potential of asphalt mixtures. Since the foamed asphalt mixture used in this study contains aged RAP aggregates, which may make the mixture too stiff and thus lead to premature cracking, the evaluation of the fracture potential is critically important.

RAP samples and asphalt cement binder (PG 64-22) collected from asphalt plants in Georgia were the major materials used to manufacture the 100% RAP foamed asphalt mixtures in this study. Two other ingredients were also considered: Portland cement and rejuvenator. Adding a small quantity of Portland cement (1% by weight of RAP) to recycled foamed mixtures is a common practice in a recycled foamed asphalt mix design. The inclusion of this cement additive accelerates the curing process due to the presence of water in the mixture, thus enabling a mixture to reach its intended strength earlier. The other ingredient considered when making the recycled foamed asphalt mixtures was the rejuvenator. Its intended use is to counteract the binder hardening of RAP and thus reduce the cracking potential of 100% recycled foamed asphalt mixtures. Two types of rejuvenator and various dosage levels (2%, 4%, 6%, 12%, and 18%) were considered, along with a control asphalt mixture containing no rejuvenator.

1.4 Major Work Procedure

A flow chart showing the overall work procedure is presented in Figure 1-1. The procedure consisted of six major parts, depicted as numbered boxes in the figure:

1) The project began by collecting raw material from three asphalt plants in Georgia (RAP and asphalt cement binder). Basic material characteristics were measured during this stage, including neat and recovered asphalt cement binder stiffness, asphalt cement binder content in the RAP, and RAP aggregate gradation, among others.
2) Prior to mixing and producing the recycled foamed asphalt mixtures, two water-related parameters were determined in this stage: the Optimum Water Content (OWC) of the foamed asphalt cement and the Optimum Moisture Content (OMC) of the recycled asphalt mixture.
3) During this stage, the mixing and producing foamed asphalt mixtures took place. Four different levels of asphalt cement content (2.0%, 2.5%, 3.0%, and 3.5%) were considered for the production of recycled foamed asphalt mixtures. The mixtures were compacted and cured based on the Marshall mix design procedure followed by the measurement of their volumetric properties (density and air voids).
4) Compacted specimens were subjected to a series of performance tests, including MS, Conditioned MS, and dry and soaked ITS, during this stage. Based on the test results, the Optimum Foamed Asphalt Cement Content (OFAC) was determined.
5) Once the single OFAC had been determined, additional sets of test specimens were manufactured both with and without the addition of rejuvenators. The rejuvenator dosages were selected based on Dynamic Shear Rheometer test results ($G^*/\sin\delta$). A series of laboratory tests (MS, Conditioned MS, ITS, and SCB) were conducted and the results then utilized to determine the structural coefficients.

6) Finally, the coefficients values were estimated based on the procedures provided in the 1993 AASHTO *Guide for Design of Pavement Structures* [1] and the Wirtgen Manual for Cold In-Place Recycling [4].

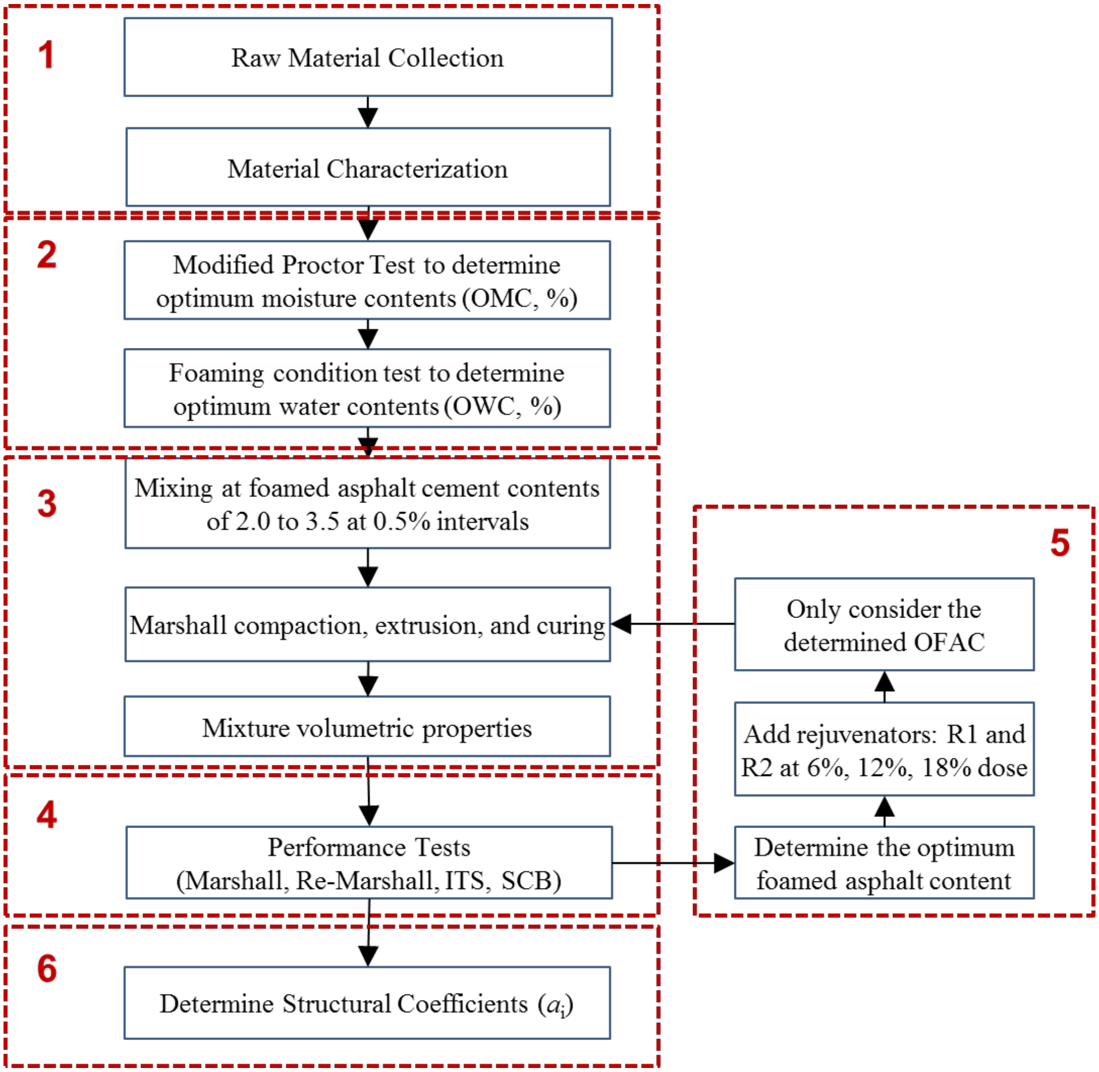


Figure 1-1 Project Work Procedure Chart

1.5 Literature Review

1.5.1 Foamed Asphalt

Foamed asphalt cement binder is produced by injecting small quantities of water assisted by compressed air into heated asphalt cement at 160-180°C. The water trapped in the hot asphalt liquid immediately evaporates due to the high temperature, creating bubbles filled with steam in the asphalt cement and expanding asphalt to around 15 to 20 times its original volume. Atmospheric pressure promptly begins to burst the resulting asphalt foam bubbles and the expanded volume is reduced back to the original asphalt volume. This foaming process is illustrated in Figure 1-2 [4].

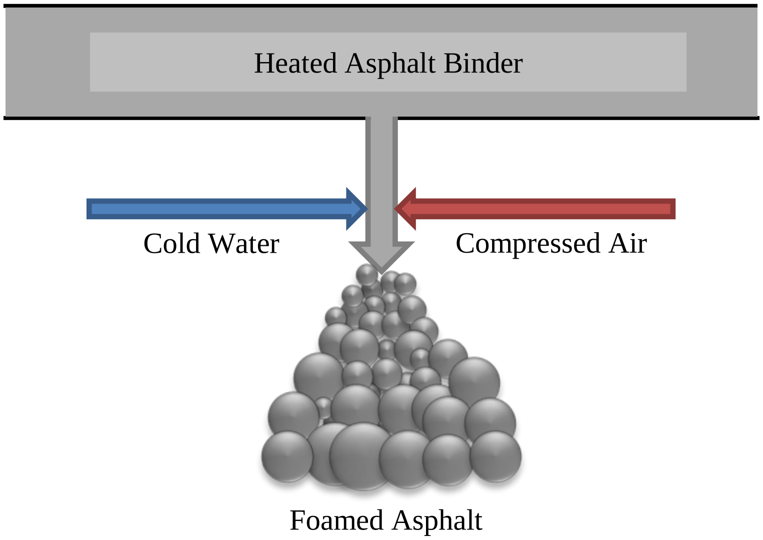


Figure 1-2 Illustration of Asphalt Foaming Process

The quality of the foamed asphalt cement produced using this process is described in terms of its Expansion Ratio (ER) and Half Life (HL, or $t_{1/2}$). The ER is a numerical, dimensionless value calculated as the ratio of the maximum volume of the foamed asphalt cement to the original volume of the asphalt binder. The HL is a time measured in seconds that represents the time taken for the bubbles to collapse to half the maximum volume. Depending upon the amount of water injected into the hot asphalt (the water content) and the temperature of the hot asphalt cement, the ER and HL values can vary considerably: a smaller water content leads to a low ER and a high HL, and as the water content rises, the ER increases and the HL decreases. Figure 1-3 shows a typical example of how the water content affects the properties of foamed asphalt cement.

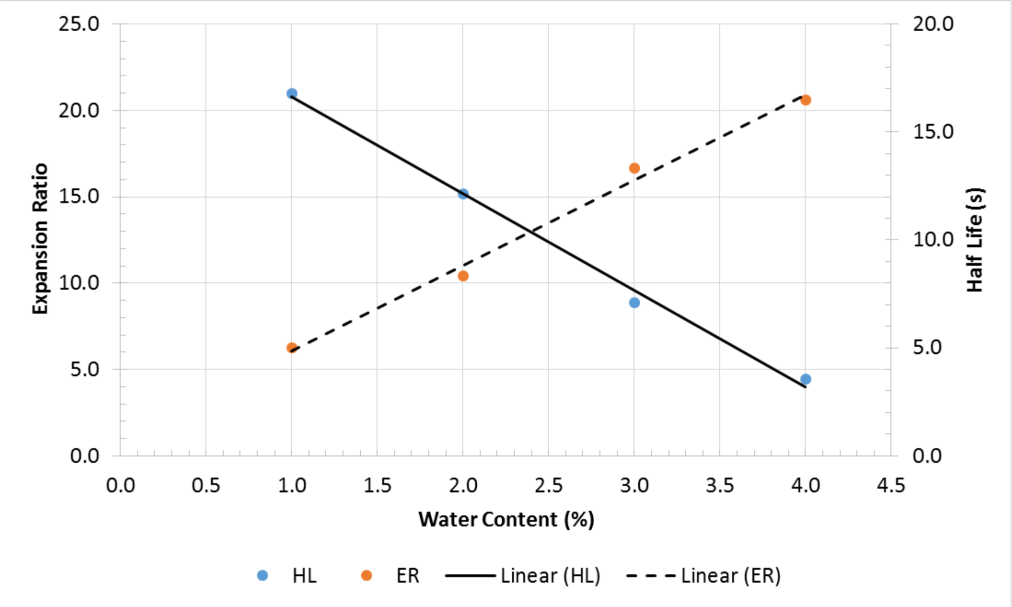


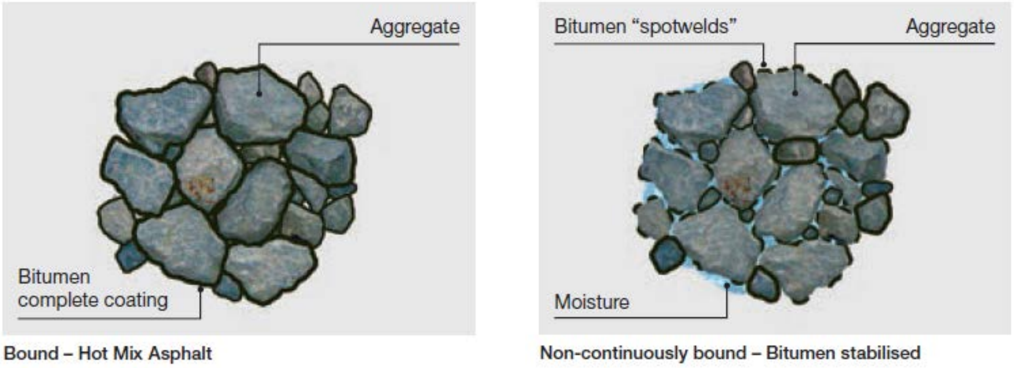
Figure 1-3 Influence of Water Content on Expansion Ratio and Half Life

Determining the Optimum Water Content prior to manufacturing recycled foamed asphalt mixtures is a critical step as it ensures that the foamed asphalt cement is dispersed consistently onto the RAP aggregates and uniformly mixed. Ideal foaming conditions for foamed asphalt cement have high values of both ER and HL. However, as the graph above shows, the trends in these two variables are opposite and hence it is crucial to identify a balanced water content in which both characteristics comply with the required criteria. The recommended criteria for these characteristics vary agency by agency. Table 1-1 shows the sample specifications adopted by the FHWA, agencies in different states, and Wirtgen (the Foamed Asphalt Equipment Manufacturer) [4, 5]. The ER minimum ranges from 8 to 15, though most agencies have adopted an ER of 10 as their minimum, while the HL ranges from 6 to 12. More details will be presented in Section 2.4. Determination of Optimum Foaming Conditions, regarding the way the Wirtgen's criteria were applied in this study to find the optimum ER and HL.

Table 1-1 Foaming Condition Specifications

	AZ	**IA**	**ME**	**NM**	**MD**	**FHWA**	**Wirtgen**
Expansion Ratio (times)	10	10	-	10	10	15	8
Half Life (second)	8	10	12	8	8	12	6

The foamed asphalt cement that is sprayed onto RAP aggregates creates a partial, non-continuous coat on the aggregate surface, binding individual aggregates together. The bond between aggregates is primarily a function of the asphalt mastic formed by the foamed asphalt liquid and fine RAP particles (usually passing a #200 sieve). Figure 1-4 shows the different bonding mechanisms for HMA and foamed asphalt mixture. It should be noted that although the presence of water is detrimental to HMA, it is actually required for a recycled foamed asphalt mixture. The water is added to the loose RAP aggregates prior to applying foamed asphalt cement, and the addition of the water in the RAP to a certain extent helps achieve better compaction.



Hot Mix Asphalt

Foamed Asphalt Mix

Figure 1-4 Aggregate Binding: Hot Mix Asphalt vs. Foamed Asphalt Mix, as described by Wirtgen [4]

1.5.2 Previous Studies on the Performance of Foamed Asphalt Mixtures

This section presents a brief description of a few selected research projects that were conducted by state transportation agencies seeking information on the structural layer coefficients of a foamed asphalt course containing a high RAP content.

The Virginia Department of Transportation (VDOT) has been actively conducting research on foamed asphalt mixtures since the early 2010s. In 2016, VDOT published a research report describing a field study where a layer of foamed asphalt material containing 100% RAP was used as a substitute for a traditional asphalt base course [6]. Three test sections were constructed at the National Center for Asphalt Technology (NCAT) and subjected to actual truck traffic of 10 million Equivalent Single Axle Loads (ESAL) over a two year period. The report's findings indicated that the pavement structures of the sections showed no observable distress damage (cracking or rutting) even after significant loading. The layer elastic moduli that were back-calculated from measurements made with a Falling Weight Deflectometer (FWD) on four locations of each section found structural coefficients ranging from 0.36 to 0.39 on average, based upon the 1993 AASHTO *Guide for Design of Pavement Structures* [2].

In another field study for the VDOT, a portion of I-81 around Staunton, VA, was constructed with 100% recycled foamed asphalt materials using three cold recycling technologies: Cold In-Place Recycling (CIR), Cold Central Plant Recycling (CCPR), and Full Depth Reclamation (FDR) [7]. The field FWD test results indicated that structural coefficients ranging from 0.37 to 0.44 were obtained, which they consider very high and noted that this would greatly contribute to the structural integrity of a pavement system, if incorporated. In addition to the field tests, two laboratory tests of the properties were also used to estimate two coefficients: the Resilient Modulus and dry ITS. Based on the resilient modulus, the layer coefficients were estimated to range from approximately 0.36 to 0.41 based on the 1993 AASHTO *Guide for Design of Pavement Structures*; the results for the dry ITS values fell within a comparable range of coefficients: 0.35-0.37. Note that the coefficient estimation with dry ITS is on the basis of a nomograph suggested by the Wirtgen Cold Recycling Manual [4].

In 2013, the Maryland State Highway Administration (SHA) conducted a study to develop appropriate guidelines for a foamed asphalt stabilized base course, focusing on the mix design, materials selection and conditions, construction, and quality assurance [5]. Various combinations of materials were used in this study including RAP, recycled concrete, and graded aggregates. Similar to the VDOT studies described above, this study also used resilient modulus and ITS in order to estimate the structural coefficients. Their results showed a wide range of estimated coefficients. For a mix composed of 40% RAP and 60% recycled concrete, the coefficient values ranged from 0.25 to 0.50. For another mix containing 100% RAP, the coefficients ranged from 0.30 to 0.48. As potential specifications, they recommended the use of coefficients as low as 0.30 and as high as 0.35, depending on the ITS and dynamic modulus.

Maine DOT conducted a field study in 2003 to examine the structural coefficient of foamed asphalt in FDR [8]. FWD tests were conducted for four different projects; through a back-calculation method, structural layer coefficients were estimated based on the AASHTO pavement design monograph. Unlike the Virginia and Maryland studies, the estimated coefficients were relatively low at around 0.22-0.23 for three of the projects, although one project did produce a higher coefficient of 0.35. However, considering the stiffness of a conventional aggregate base course, which typically ranges from 0.10 to 0.25 [9], any pavement layer with a coefficient greater than 0.20 could still be a viable option for a pavement structure.

Kansas DOT has also shown an interest in researching the potential use of foamed asphalt materials. In 2003, they conducted an accelerated testing procedure to evaluate the performance of foamed asphalt stabilized base in FDR [10]. The FWD tests performed after the construction of the test sections revealed a structural layer coefficient for the base layer of 0.18. One of the reasons that the coefficient value was relatively low here compared to other studies was that the materials contained conventional granular base materials.

The estimated structural coefficients found in the studies described above are summarized in Table 1-2.

Table 1-2 Estimated Structural Coefficients of Foamed Asphalt Layer

State	a_i	Major Basis for a_i Estimation	Recycling Method
KS [10]	0.18	FWD	FDR
MA [8]	0.22-0.35	FWD	FDR
MA [11]	0.26-0.32	N/A	FDR, CIR
MD [5]	0.30-0.35	Dynamic Modulus, ITS	Lab Scale Equipment
VA [6]	0.36-0.39	FWD	FDR
VA [7]	0.35-0.44	FWD, Resilient Modulus, ITS	CCPR

2 MATERIALS AND METHODS

2.1 Materials

The raw materials considered in this study include an asphalt cement binder (Performance Grade 64-22) and RAP, along with two additives: Portland cement and rejuvenator. An appropriate amount of water was also added during the foaming and mixing processes. This chapter describes the properties of each ingredient as measured in the Georgia Southern University (GSU) laboratory or as reported by suppliers.

2.1.1 Asphalt Binder

A single asphalt binder type, Performance Grade (PG) 64-22, was selected to manufacture the recycled foamed asphalt mixtures, as it is commonly used in asphalt pavement construction in Georgia. An ample amount of asphalt binder was transported to the GSU laboratory from three GDOT approved sources of bituminous materials. In order to evaluate the asphalt cement stiffness, a series of stiffness tests using a Dynamic Shear Rheometer (DSR) were conducted in accordance with AASHTO T 315 at three temperatures: 58, 64, and 70°C. The test results, expressed as $G^*/\sin\delta$, are presented in Table 2-1. According to the Performance Graded Asphalt Binder Specification [12], all three binders conformed to the minimum limit of $G^*/\sin\delta$, which is greater than 1.00 kPa at a high PG temperature (i.e., 64°C for this binder type) in an unaged, neat condition. The test results revealed no peculiarities other than the fact that the binder from Source 3 was slightly softer than the other two binders.

Table 2-1 Asphalt Stiffness, $G^*/\sin\delta$

Asphalt Source	**PG**	**$G^*/\sin\delta$ (Neat Condition)**		
		58°C	**64°C**	**70°C**
Source 1	64-22	4.32	1.91	0.91
Source 2	64-22	4.04	1.91	0.93
Source 3	64-22	2.95	1.32	0.75

2.1.2 Reclaimed Asphalt Pavement

RAP materials were supplied from three asphalt plants located in Georgia, denoted hereafter as A1, A2, and A3. Several RAP properties were measured prior to mixing and manufacturing test specimens. All RAP materials were air dried at ambient temperature (~25°C) in the laboratory for at least three days before the measurements were made. The residual water content in the RAP after air drying was measured for each RAP source in order to insure that none of the RAP contained a significant amount of water. Comparing the weights of air-dried and oven-dried RAP, the residual water in the air-dried RAP material was insignificant (0.15%, 0.27%, and 0.17% by weight of the oven-dried RAP for A1, A2, and A3, respectively).

As will be discussed in greater detail later, water is an essential part of this process and plays an important role in compacting a high-RAP content mixture. Therefore, the amount of water in the mix needs to be determined based on a standard compaction test to identify an Optimum Moisture Content (OMC). Previous studies recommend that a moisture content of 65%-95% of OMC or OMC-1% is optimum for RAP compaction [4, 5, 13-17]. A visual inspection of the mix after the water has been added and mixing is complete, is also critical in order to produce a quality test specimen. The actual water amount added to the RAP is usually adjusted during the mixing process by visually checking the mix conditions.

The asphalt cement content of each RAP source was determined by both a centrifuge solvent extractor (ASTM D2172, Method A) and an ignition oven (ASTM D6307) [18, 19]. The RAP asphalt cement contents found from both test methods are presented in Table 2-2. A RAP binder content of approximately 6% was found on averaging the three RAP sources. When the ignition oven was used, a 0.3% to 0.9% reduction in the binder content was observed. It should be noted that, for consistency purposes, this project only used the results from the Centrifuge Extraction for the experiments and data analyses.

Table 2-2 Asphalt Content in RAP

Test Method	RAP Source		
	A1	A2	A3
Centrifuge Extraction	6.0	6.0	5.8
Ignition Oven	5.7	5.2	4.9

The gradation (ASTM D5444) of the recovered aggregates from the extracted RAP was determined and the results presented in Table 2-3 [20]. The table also shows the gradation limits for recycled foamed asphalt mixtures recommended by Wirtgen and the Maryland SHA [4,5] for comparison. Figure 2-1 depicts the percent passing of each RAP along with the Wirtgen gradation envelope. The aggregates from the A2 and A3 sources were slightly finer than the Wirtgen recommendations, but generally met the Maryland SHA specifications.

Table 2-3 Sieve Analysis Results for RAP

Sieve (mm)	RAP Source			Wirtgen Recommendations	Maryland SHA Specifications
	A1	A2	A3		
19.0	100.0	100.0	100.0	65-100	60-100
12.5	92.8	99.4	100.0	-	-
9.5	73.2	94.1	89.2	48-80	-
4.75	51.5	70.9	61.8	35-62	30-70
2.36	37.0	52.7	47.6	25-47	-
1.18	32.7	39.7	37.8	18-36	-
0.60	28.8	30.0	28.8	13-28	-
0.30	20.8	19.8	23.0	9-22	-
0.15	9.4	9.2	14.5	6-17	-
0.075	7.1	5.3	8.2	4-12	5-15

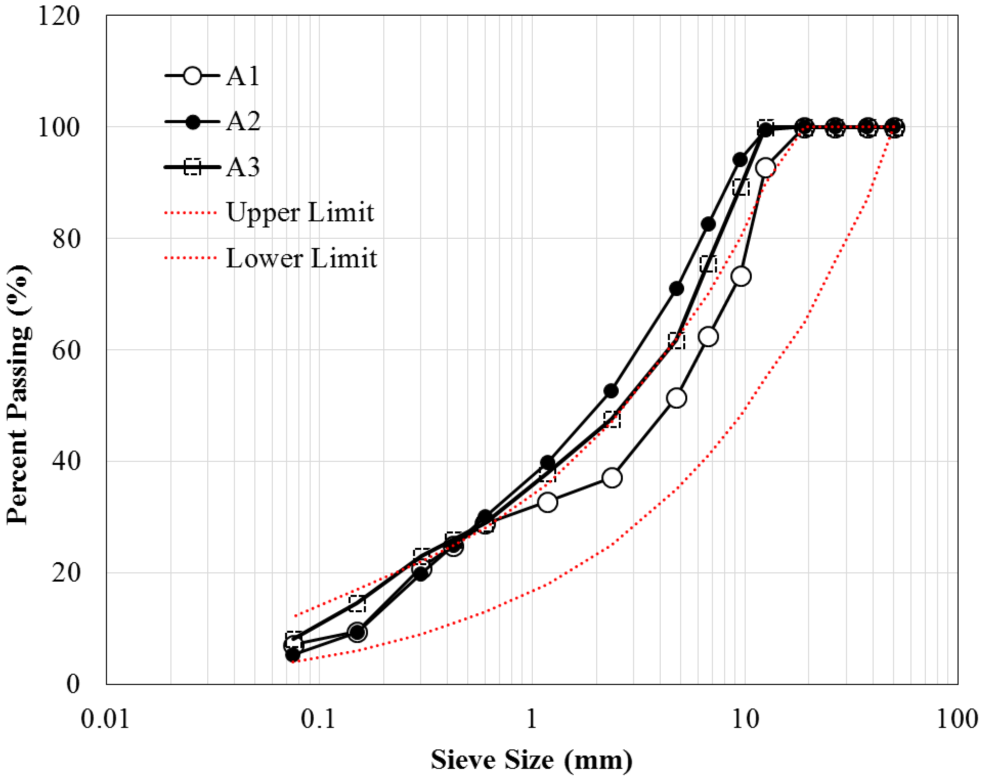


Figure 2-1 RAP Aggregate Gradations

It is important to note that the most crucial characteristic for recycled foamed asphalt aggregate gradation is the percent passing on No. 200 sieve (0.075 mm). It has been reported that fine grains create an asphalt mastic when combined with the sprayed foamed asphalt cement, which in turn creates a non-continuous bond between the aggregate particles [4, 5]. For this reason, Wirtgen and several state agencies limit the amount of fines in the recycled foamed asphalt mix design. Table 2-4 shows the limits set by several state agencies, along with a Wirtgen recommendations [4, 5]. All the RAP materials used in this study met the minimum requirement of the 0.075mm passing criteria suggested by Wirtgen and other state agencies, as indicated in the last row of Table 2-3.

Table 2-4 Gradation Requirement for Foamed Asphalt Aggregate Passing Through the 0.075 mm Sieve

	AZ	**Ontario**	**MN**	**NM**	**MD**	**Wirtgen**
% Passing 0.075 mm	5-20	7-15	7-15	4-20	5-15	> 4

The RAP binder extracted from the centrifuge solvent method was recovered by the Abson Recovery method (ASTM D1856) [21]. While it is understood that the centrifuge solvent extraction method actually releases RAP binder from the asphalt “primed” aggregate to an extent not possible when using RAP during cold recycling or hot asphalt mixture production, the recovered binder was further analyzed to measure the recovered binder viscosity. Similar to the neat asphalt binder analysis, the DSR test was conducted to estimate the stiffness of the recovered RAP binder in terms of G*/sin δ and the results are shown in Table 2-5.

Unlike the DSR results for the neat PG 64-22 binder shown earlier in Table 2-1, where the G*/sin δ values ranged from 1.32 to 1.91 kPa at 64°C, the recovered RAP binder was found to be extremely stiff as the data presented in the table show. At the same test temperature of 64ºC, the resulting G*/sin δ values of the recovered RAP binders went up to 32.2, 19.9, and 14.5 kPa for A1, A2, and A3, respectively. This finding is not unexpected because the RAP binder has aged (i.e., hardened) over the years as it was subjected to mixing, construction, and then a lengthy period of service.

The DSR test was continued by raising the test temperature from 58°C to 94°C in increments of 6°C in order to find a single temperature where G*/sin δ is close to that of the original binder. The results indicate that the high temperature performance grade were approximately 94, 88, and 88 for the A1, A2, and A3 RAP binders, respectively. The RAP binder stiffness in G*/sin δ at each of the various test temperatures is illustrated Figure 2-2.

Table 2-5 Stiffness of Recovered Asphalt from RAP

Test Temp. (°C)	G*/sin δ (kPa)		
	A1	**A2**	**A3**
58	61.45	38.21	28.41
64	32.20	19.90	14.46
70	16.93	10.25	7.20
76	9.25	5.50	3.70
82	5.17	2.97	1.98
88	2.92	**1.67**	**1.10**
94	**1.70**	0.99	0.63

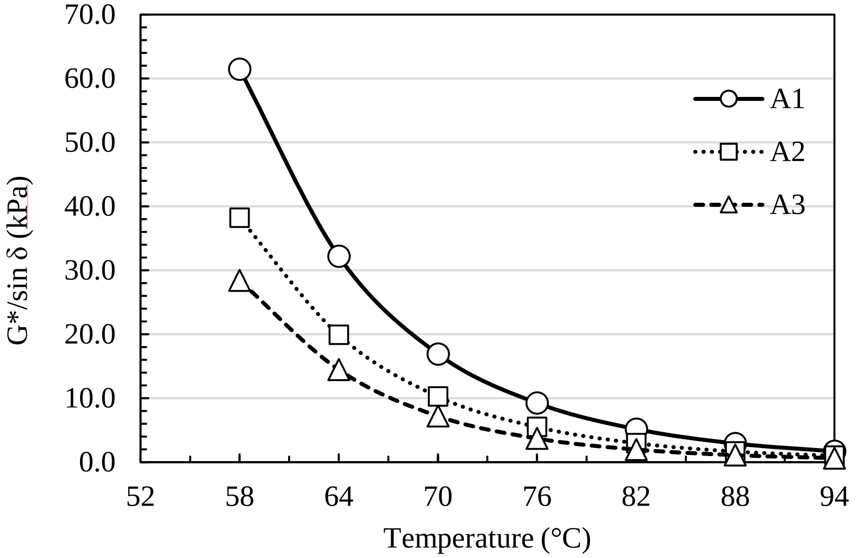


Figure 2-2 Stiffness of Recovered Asphalt from RAP at Various Temperatures

2.1.3 Portland Cement

In foamed asphalt mixtures, it is common practice to add Portland cement as an additive. Studies have shown that cement plays an important role in improving recycled foamed asphalt mixtures' performance. The advantages include better dispersion of foamed asphalt cement in the mix, an increased adhesion of asphalt mastic to the aggregates, an increase in the rate of initial strength gain during curing, and better resistance to moisture damage [4, 22, 23]. After considering these benefits, the experiments conducted for this study included a dose of 1.0% Type II Portland cement (by weight of RAP) in the mixture.

2.1.4 Rejuvenator

When a high-RAP content asphalt mixture is considered in a pavement structure design, one of the major concerns is that the mixture is likely to be too stiff, due mostly to the aged RAP binder, becoming more brittle and too much binder replacement being credited to the RAP binder thus reducing the required new AC content. This combines to increase the potential of greater age or oxidation related cracking over asphalt mixtures containing none to little RAP. In order to try and compensate for these potentially negative effects, the use of rejuvenators is becoming more common in an "HMA" production where a high content of RAP is used. The premise is that rejuvenators can restore the old asphalt cement coated around the RAP, especially at elevated temperatures, and the rejuvenated binder can then be combined with newly added asphalt binder to better coat the aggregates.

In this study, two similar liquid-type rejuvenators (Commercial names: Delta-S and Sylvaroad, denoted as R1 and R2 hereafter) were selected based on the GDOT recommendation. The photograph in Figure 2-3 shows the physical state and color of the selected rejuvenators, and Table 2-6 lists their physical characteristics as provided by the suppliers. It should be noted that the original experimental plan for the recycled foamed asphalt mix design stage did not consider rejuvenators in order to conduct the research more efficiently. Once a single Optimum Foamed Asphalt Cement Content (OFAC) had been determined after the completion of the mix design stage, a major set of performance experiments that included a consideration of the rejuvenators was carried out in order to examine the impact of the rejuvenators with regard to the mechanical behavior of the mixtures.

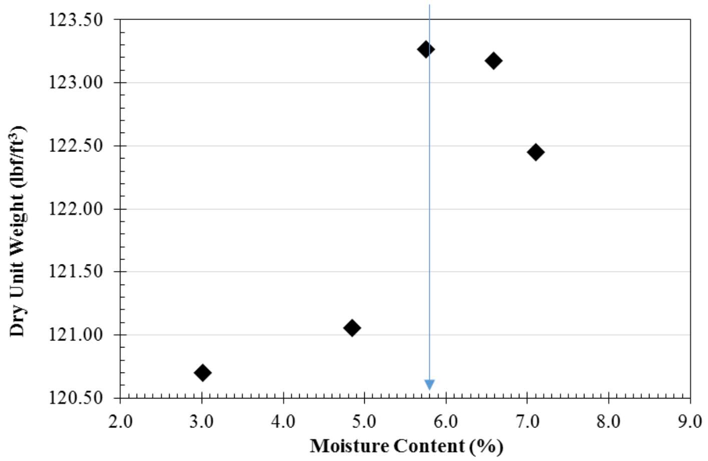
Figure 2-3 Physical State and Color of Rejuvenators

Table 2-6 Summary of Characteristics of Rejuvenators

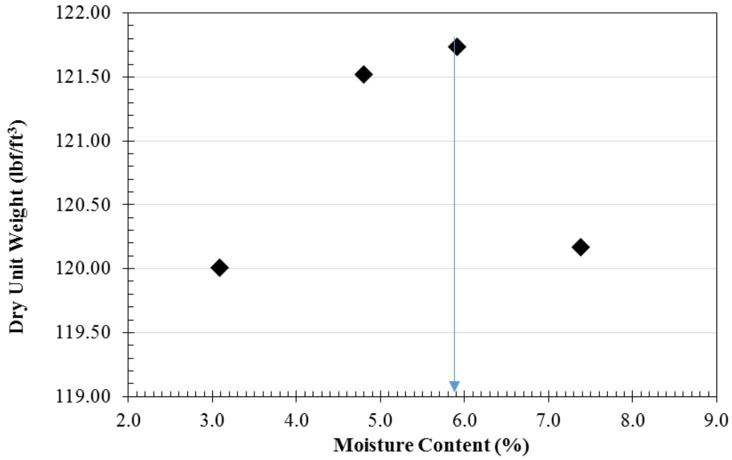
	R1 (Delta S)	**R2 (Sylvaroad)**
Physical State	Liquid	Liquid
Color	Yellow	Yellow
Boiling Point	300°F (149°C)	572°F (300°C)
Flash Point (ASTM D92)	500°F (260°C)	534.9°F (279.4°C)
Relative Density	7.747 lbs/gal (equivalent to 0.923 at 20°C)	0.927 at 20°C (ASTM D1475)
Dynamic Viscosity	49.6 cP at 19.5°C	N/A
Kinematic Viscosity	N/A	100.8 mm^2/s at 20°C (ASTM D445)

2.2 Determination of Optimum Moisture Content for RAP Compaction

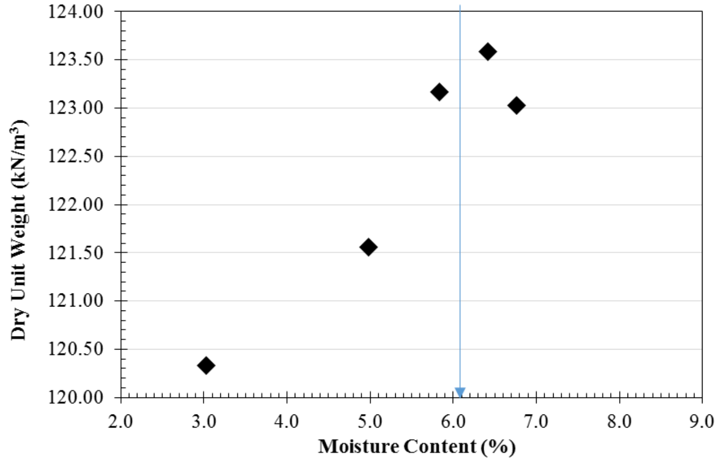
Just as water is essential to increase a soil's strength by means of soil compaction, RAP compaction also requires water to achieve its optimum compaction conditions. The Optimum Moisture Content (OMC) was therefore determined for each of the three RAP materials in accordance with the modified Proctor test (ASTM D1557) [24]. The standard test requires a 5-layer compaction with 25 rammer drops per layer in a 4-in diameter mold with a 10-lbf rammer dropped from a height of 18 inches. Initially, air-dried RAP was compacted at five different target water contents (3, 5, 7, 9, and 11% by weight of dried RAP) to determine the influence of water on the dry unit weight of RAP. During the compaction process, excess water was observed to be squeezed out of the mold when more than 9% water was added, leading to an erroneous calculation for the dry unit weight. The target water contents were therefore modified to 3, 5, 6, 7, and 8% and the compaction procedure repeated. The maximum dry unit weights were found to be at OMCs of 5.8, 5.9, and 6.2% for A1, A2, and A3, respectively. The relationships between the dry unit weights and the actual moisture content for the RAP sources are shown in Figure 2-4 and a summary of the results is presented in Table 2-7. As mentioned earlier, only 75% of the OMC was applied during the RAP mixing, as recommended by Wirtgen [4].



(a) A1 RAP Compaction Curve



(b) A2 RAP Compaction Curve



(c) A3 Compaction Curve

Figure 2-4 Relationship between Dry Unit Weight of RAP and Moisture Content

Table 2-7 Summary of Optimum Moisture Content for RAP

	A1 RAP	**A2 RAP**	**A3 RAP**
OMC (%)	5.8	5.9	6.2
Max. Dry Unit Weight (lb/ft^3)	123.3	121.8	123.7

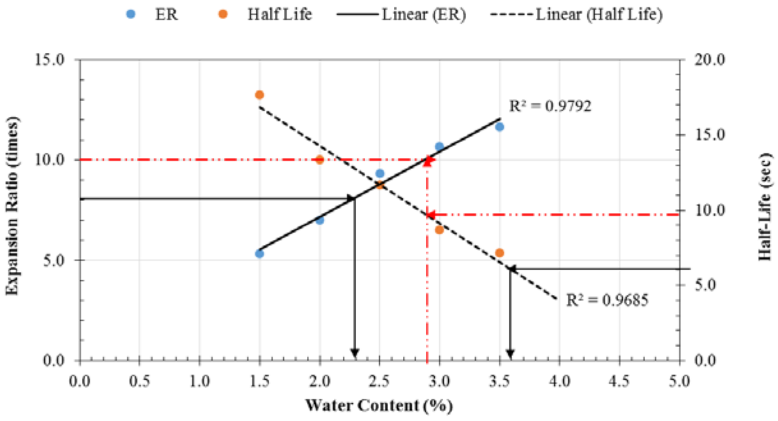
2.3 Determination of Optimum Foaming Conditions

Optimizing the foaming conditions is required to determine two essential foaming characteristics (ER and HL) prior to mixing. As described earlier in Section 1.5, the ER is defined as the ratio of the maximum asphalt cement volume to the original asphalt cement volume and the HL is defined as the elapsed time for the maximized asphalt cement volume to be reduced to half of the maximum volume. The optimum conditions for this study were determined through a series of foaming tests designed to reveal the effect of different foaming conditions (asphalt cement temperature, water content, and asphalt cement injection speed) using the Wirtgen foamed asphalt cement equipment (Model: WLB 10S) shown in Figure 2-5.

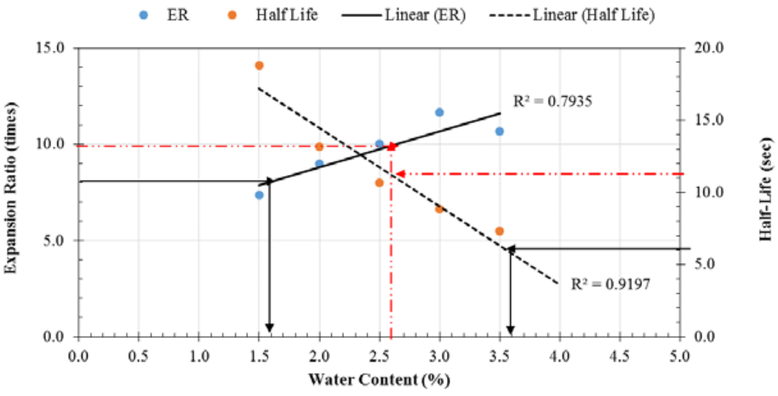
Figure 2-5 Wirtgen Asphalt Cement Foaming Equipment (Model: WLS 10S)

For the foaming asphalt cement temperature, three temperatures (160, 170, and 180°C) commonly used in other foamed asphalt research were tested, over a range of water contents from 1.5 to 3.5% in 0.5% increments [16, 25-27]. As an additional foaming condition, two asphalt cement injection speeds (50 and 100 grams per second) were evaluated. A fixed air pressure of 5.5 bar and a water pressure of 6.0 bar were chosen as they were programmed as the default values in the equipment. Asphalt binder heated at each temperature was injected into a 5-gallon metal bucket at each of the five water content levels, and the respective ER and HL values were simultaneously measured.

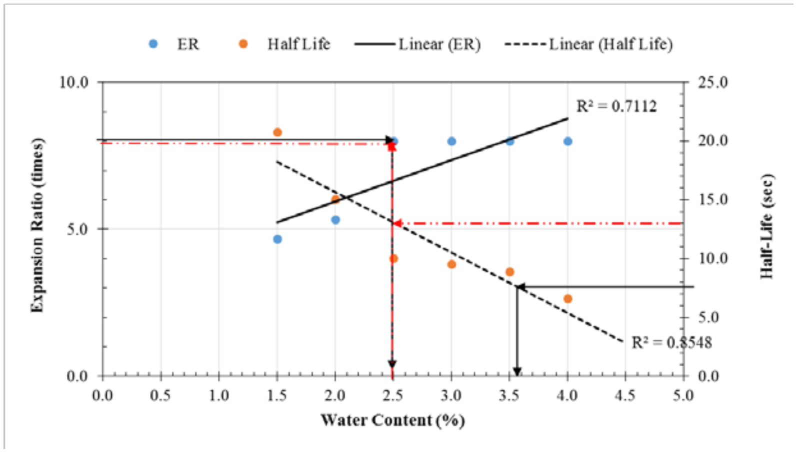
After completion of several foaming attempts with various temperature/water content/injection speed combinations, the relationships between water content and the various foaming characteristics shown in Figure 2-6 were established. It was found that the foamed asphalt cement was best characterized (i.e., the foamed asphalt cement showed relatively large ER and HL values) at a temperature of 160°C with an injection speed of 50 grams per second. As the data presented in the figure shows, the ER values increase but the HL values decrease as the water content increases, as expected. Given that higher ER and HL values lead to a better quality foamed asphalt mixture, a single water content level that meets the minimum of ER and HL was required. For example, a water content of 2.9% was found to be optimum when the ER and the HL were 10 times and 9.8 seconds, respectively, as illustrated in Figure 2-6(a). These ER and HL values meet the minimum criteria suggested by Wirtgen (ER > 8 and HL > 6). The results for the final foaming conditions for all three asphalt cement sources are summarized in Table 2-8.



(a) Foaming Characteristics of A1 Asphalt Binder



(b) Foaming Characteristics of A2 Asphalt Binder



(c) Foaming Characteristics of A3 Asphalt Binder

Figure 2-6 Determination of Optimum Foaming Conditions

Table 2-8 Summary of Optimum Foaming Conditions

Asphalt Cement Source	OWC (%)	ER (Times)	HL (sec)	*Criteria Pass?
A1	2.9	10.0	9.8	Yes
A2	2.6	9.8	11.2	Yes
A3	2.5	8.0	13.0	Yes

*Note: Based on the Wirtgen criteria (ER > 8 times and HL > 6 seconds)

2.4 Determination of Rejuvenator Dosage

As mentioned earlier, a major concern when using a 100 % recycled foamed asphalt mixture as a structural layer is that it may become excessively stiff due to aged or insufficient asphalt binder in the recycled mixture, which could cause premature cracking. It is plausible that adding rejuvenator to the mixture could help soften the mixture stiffness, thus ameliorating this problem.

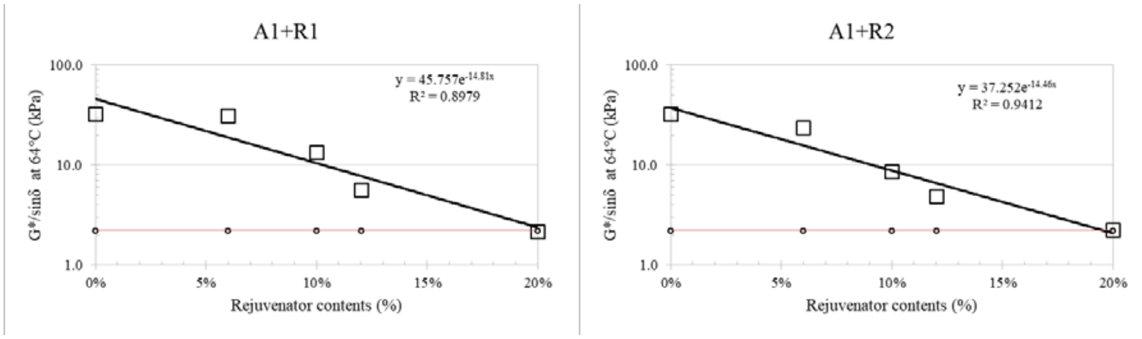
As the data presented earlier in Table 2-5 show, the extracted RAP binder was found to be very stiff, with high performance grade of around 94, 88, and 88 for the A1, A2, and A3 RAP sources, respectively. To determine an appropriate rejuvenator dosage for the 100 % recycled foamed asphalt mixtures, a series of DSR tests were conducted on each of the three recovered RAP binders at various rejuvenator contents at a fixed temperature of 64ºC, which corresponds to the high temperature performance grade of PG 64-22. A dosage of 6% by weight of recovered RAP binder was initially applied to the recovered RAP binder and G*/sin δ was measured, after which the dosage was increased to 10%, 12%, and 20% in turn to identify the impact on the recovered RAP binder stiffness. The goal was to observe how the stiffness of the aged RAP binder changed with the increasing rejuvenator doses and determine the optimum dosage for the recycled foamed asphalt mixtures.

The G*/sin δ values obtained from DSR at 64ºC on the recovered RAP binder containing various dosage levels of rejuvenator are illustrated in Figure 2-7 for all three RAP sources. Note that since two rejuvenators (R1 and R2) were considered, the figure contains six graphs (i.e., 3 RAP sources and 2 rejuvenators). The original binder (PG 64-22) stiffness is also presented for comparison at the 0% rejuvenator level in each graph.

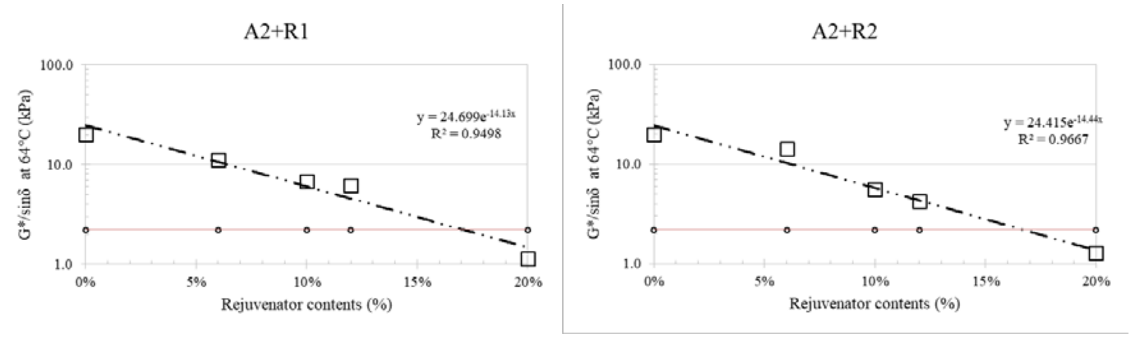
The figure clearly indicates the trend in the binder stiffness in terms of G*/sin δ with increasing rejuvenator dosage. With no rejuvenator added, the G*/sin δ value varied over the range from 20 to 30 kPa. As the rejuvenator dosage increased, this decreased at a constant rate in a logarithmic realm of G*/sin δ. With a 20% rejuvenator dose, the value dropped to close to or even below 2.2 kPa. It was also observed that the two rejuvenators exhibited very similar effects on the stiffness of the recovered RAP binder. Overall, the stiffness of the A2 and A3 RAP binders were found to be slightly softer than the A1 RAP binder, although the trend in the viscosity change was comparable between the two RAP binder types, as clearly indicated in the figure. The rejuvenator dosages found to be required in this study to lower the RAP binder viscosity to 2.2 kPa were approximately 20%, 17%, and 18% for A1, A2, and A3, respectively.

This high dosage requirement (close to 20%) to lower the viscosity of aged binder to a level of 2.2 kPa G*/sin δ is not surprising. This result is in agreement with the findings of recent research that suggested a novel method for determining the optimum rejuvenator dosage. Zaumanis et al. investigated the effect of various rejuvenator types and found that lowering the original high performance grade of aged RAP binder to more closely match that of the original binder requires a rejuvenator dose somewhere in the range from 16% to 28%, depending upon the rejuvenator type [28]. At the same time, however, it is generally impractical to use that high a dosage level in a high-RAP mixture because lowering the viscosity of the RAP binder does not necessarily mean the performance of the RAP mixture with the rejuvenator becomes similar to the performance of an asphalt mixture using virgin aggregates. It is also possible is that a high dosage of rejuvenator may be more practical for recycling HMA rather than cold asphalt such as emulsified or foamed asphalt pavement.

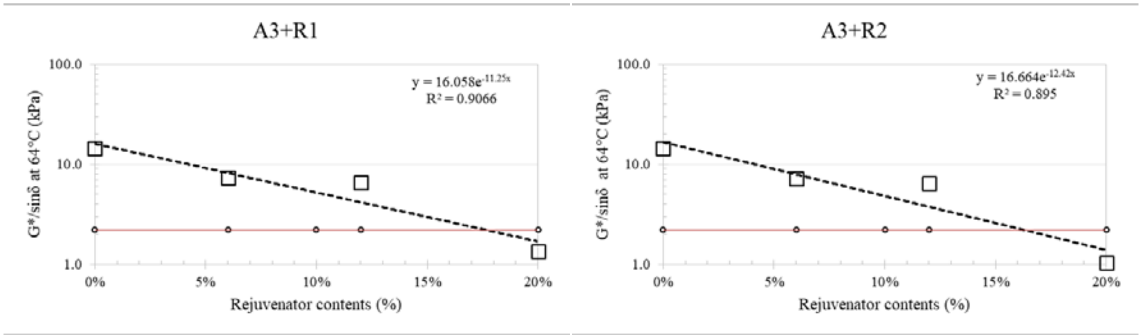
Based on practical considerations, the research team decided to use three dosage levels (6%, 12%, and 18%), along with control mix containing no-rejuvenator, in order to investigate the effect of incorporating a rejuvenator on the mixture performance of a 100 % recycled foamed asphalt mixture.



(a) G*/sin δ for A1 RAP



(b) G*/sin δ for A2 RAP



(c) G*/sin δ for A3 RAP

Figure 2-7 DSR Results at Different Rejuvenator Dosage Levels

2.5 Performance Tests

2.5.1 Marshall Stability Tests

The Marshall Stability is a measure of the resistance to plastic deformation of a compacted cylindrical specimen. The resistance or stability, expressed in pounds or Newtons, is measured at a constant deformation rate (50 mm/min) under loading and is a typical indicator that can then be used to determine an optimum asphalt cement content via the Marshall mix design method. Marshall specimens are manufactured using a Marshall compactor that compacts loose mix with a predetermined number of blows on each side (50 or 75 blows) with a standard hammer, as specified in the ASTM and AASHTO standards [29, 30]. A compacted Marshall specimen is cylindrical, with a height of 4 in. and approximately 2.5 inches in diameter.

In this study, the Marshall Stability test was conducted in accordance with AASHTO T 245 with the exception of specimen preconditioning [29]. The original standard test specifies regular and cutback specimens must be conditioned at temperatures of 60°C and 25°C, respectively, for 30 minutes in a water bath (or 2 hours in an oven) before testing. Although the standard does not specify a conditioning temperature for foamed asphalt mixtures, this study followed the cutback condition (25°C for 2 hours in an oven) due to a concern that the specimens could fall apart at an elevated test temperature of 60°C. However, after a few trial tests in the laboratory at Georgia Southern, it was found that the resulting stability was extremely high at 25°C, which could lead to an inaccurate estimation of the structural coefficients. Therefore, it was decided that the Marshall specimens should be conditioned at both 25°C and 60°C for 2 hours in an oven prior to testing (i.e., two different sets of Marshall specimens were prepared for subsequent testing: one set at 25°C and the other at 60°C).

In order to evaluate the retained stability of 100 % recycled foamed asphalt mixtures, a further set of three Marshall specimens was necessary to obtain "24-hour conditioned" Marshall stability samples according to GDT 53 [31]. This test is essentially the same as the standard Marshall Stability test (AASHTO T 245) except for the conditioning time. These three specimens were conditioned in a bath at the same temperature as that used for the Marshall Stability test (25°C or 60°C) for 24 hours before testing. These 24-hour conditioned specimens were then subjected to loading from an axial loading machine and the stability of each specimen was measured.

After completion of both the standard Marshall and 24-hour conditioned Marshall tests, the percent Retained Marshall stability was calculated using the following equation [31]:

$$\% \text{ Retained Marshall Stability} = (S2 / S1) \times 100$$

where, S1 = An average of Group 1 (30-minute water or 2-hour oven) Marshall Stability

S2 = An average of Group 2 (24-hour water conditioned) Marshall Stability

Table 2-9 lists the specimen conditions specified by the standard methods and the actual conditioning methods used in this study. Note that the actual conditions applied in this study deviated slightly from the standard procedure to take into account the nature of recycled foamed asphalt mixtures. Table 2-10 summarizes the number of specimens (per batch and total) and shows the various conditions (RAP sources, asphalt cement contents, rejuvenator types, and rejuvenator contents) used for the Marshall Stability tests. During the mix design stage, all the Marshall Stability tests were conducted at 25°C with a total of 144 specimens; once the OFAC had been determined, additional Marshall tests were carried out at both 25°C and 60°C with a total of 252 specimens. Figure 2-8 shows specimen conditioning in a water bath and the Marshall Stability test equipment used at the GSU laboratory.

Table 2-9 Specimen Conditions for Marshall Stability Tests

	Standard Conditions for HMA	Actual Conditions Used for Foamed Asphalt in this Study	Referenced Standard Method
Marshall Stability	Water for 30 min. (or Oven for 2 hours) at 60°C	• Water for 30 min. at 25°C* • Oven for 2 hours at 60°C**	AASHTO T 245
Conditioned Marshall Stability	Water for 24 hours at 60°C	• Water for 24 hours at 25°C* • Oven for 24 hours at 60°C**	GDT 53

* For both mix design and performance tests
** For performance tests only

Table 2-10 Number of Specimens for Marshall Stability Test

Laboratory Test	Test Temp.	Number of Specimens	
		Before Determining OFAC* (i.e., at various AC contents)	After Determining OFAC** (i.e., at OFAC)
Marshall Stability	25°C	9	3
Conditioned-Marshall Stability	25°C	3	3
Marshall Stability	60°C	0	3
Conditioned -Marshall Stability	60°C	0	3
Per Batch		12	12
Total Specimens		144 = 12 per batch x 4 AC x 3 RAP x No Rejuvenator	252 = 12 per batch x 1 AC x 3 RAP x (2 Rejuvenators x 3 Rej. Contents + 1 Control Mix)

* For mix design
** For performance tests only

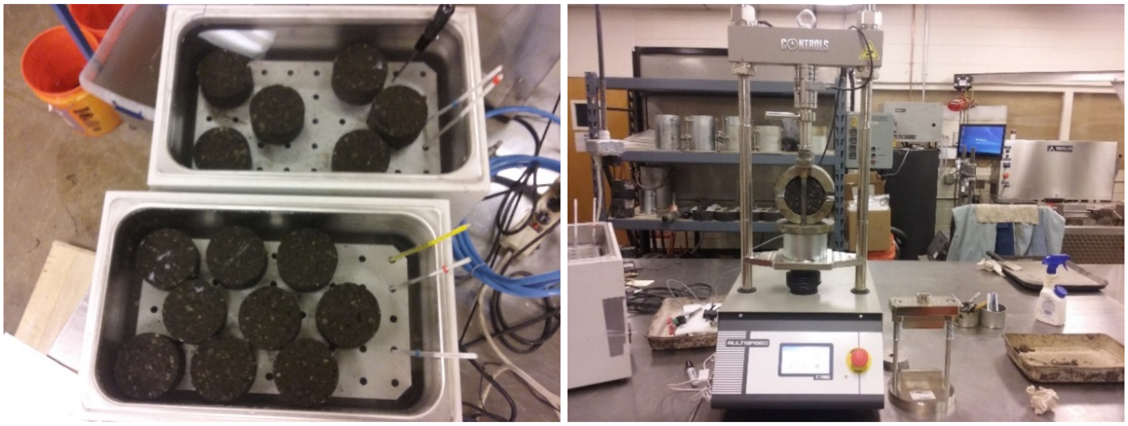


Figure 2-8 Marshall Specimen Conditioning and Stability Test

2.5.2 Indirect Tensile Strength Tests

Moisture-induced damage to asphalt pavements has been a major concern for decades. Among the numerous performance tests developed to evaluate moisture damage on asphalt pavement, Indirect Tensile Strength (ITS), along with its associated property, Tensile Strength Ratio (TSR), has been popular ever since it was first proposed in the early 1990s. ITS parameters are obtained in two specimen conditions: dry and soaked, as specified in AASHTO T 283 [32]. Dry ITS is measured as an average ITS value from a set of three dry conditioned specimens which are individually wrapped in plastic bags and placed in a water bath for 25°C for 2 hours. The other set of three specimens is immersed in a water bath at 60°C for 24 hours, followed by an additional 2-hour soak in a 25°C water bath before being tested to obtain an average soaked ITS value. The ratio between the dry and soaked ITS values (i.e., Tensile Strength Ratio or TSR = Soaked ITS / Dry ITS) is a common indicator when evaluating moisture-induced damage in asphalt mixtures.

ITS has been also used as a referencing parameter for evaluating foamed asphalt mixtures for mix design purposes (i.e., determining an OFAC) [4, 5, 33]. In particular, the dry ITS can be used as an indicator to estimate the structural coefficients based on the Wirtgen-developed correlation chart. In this study, the ITS test was conducted following AASHTO T 283 with a temperature modification. As provided in Table 2-11, the soaked ITS values were obtained at 25°C instead of the original temperature of 60°C. Table 2-12 summarizes the number of specimens before and after determining OFAC.

Table 2-11 Specimen Conditions for Indirect Tensile Strength Tests

	Standard Conditions	Actual Conditions Used	Referenced Standard Method
Dry ITS	Wrapped with a plastic bag in water for 2 hours at 25°C	Oven for 2 hours at 25°C	AASHTO T 283
Soaked ITS	Water for 24 hours at 60°C followed by an additional 2-hour in water at 25°C	Water for 24 hours at 25°C	AASHTO T 283 and Other Previous Studies [5,23,34]

Table 2-12 Number of Specimens for Indirect Tensile Test

Laboratory Test	Test Temp.	Number of Specimens	
		Before Determining OFAC* (i.e., at various AC contents)	After Determining OFAC** (i.e., at OFAC)
Dry ITS	25°C	3	3
Soaked ITS	25°C	3	3
Per Batch		6	6
Total Specimens		72 = 6 per batch x 4 AC x 3 RAP x No Rejuvenator	126 = 6 per batch x 1 AC x 3 RAP x (2 Rejuvenators x 3 Rej. Contents + 1 Control Mix)

* For mix design
** For performance tests only

It should be noted that AASHTO T 283 requires each specimen to be manufactured with a target of 7.0±0.5% air voids for HMA. For foamed asphalt mixtures, there are no guidelines with regard to the air void requirements. Numerous previous studies indicate that the air voids in foamed asphalt mixtures obtained from field cores are significantly higher and hence they adopt a higher level for air voids when designing foamed asphalt mixtures. For example, Khosravifar et al. (2015) found a range of 14.7% to 16.4% air voids in their foamed asphalt field cores, while Wu et al. (2013) used 15.3% air voids in their 100% recycled foamed asphalt mixtures [35, 36]. A research project conducted by He and Wong (2008) also found the air voids of foamed asphalt mixtures ranged from 10.8% to 12.9% [34]. In the present study, the research team used a constant weight of mixtures (10,800 grams) in a Marshall mold when manufacturing the Marshall specimens and applied a 75-blow compaction. The resulting air voids had a comparable air void level (approximately 13%, on average, for the Marshall Stability specimens) with the air void levels reported in previous studies [34-36].

2.5.3 Semi Circular Bending Test

The use of RAP helps increase the stiffness of asphalt mixtures, resulting in improved rutting resistance. However, this is countered by the effect of the increased stiffness of high-RAP mixtures, which make the mixtures more susceptible to cracking. The Semi Circular Bending (SCB) test was developed in order to evaluate the cracking or fracture potential of asphalt mixtures using a unique geometry. Two standard procedures are available for SCB: AASHTO TP 105-13 and TP 124-16 [37, 38]. TP 105 was developed to determine the fracture energy of asphalt mixtures using the SCB geometry. This procedure is known to be particularly useful in evaluating the fracture resistance at low temperatures, as the test is performed at a temperature that is set at a low PG plus 10 (e.g., for PG 64-22, the test temperature is -12°C = -22 +10). Apart from the low temperature, TP 124 follows a similar test procedure to that of TP 105. One of the distinct features of TP 124 is that the procedure utilizes not only the fracture energy (G_f) but also the post-peak slope (m) in the fracture potential evaluation. The flexibility index (FI), which is obtained by dividing the fracture energy by the slope (i.e., $FI = G_f/m \text{ x } A$ where A is a unit conversion and scaling factor), is a major parameter that determines the fracture potential of asphalt mixtures. TP 124 is predominantly used to evaluate the fracture resistance at intermediate temperatures as the test is performed at 25°C. Since the temperature of subsurface asphalt pavement never experiences subzero temperatures and is mostly intermediate in Georgia, it was decided to use AASHTO TP 124 for this 100 % recycled foamed asphalt mixture research. The following subsections recapitulate several important points of SCB based on TP 124.

2.5.3.1 Preparation of Test Specimens

Unlike the Marshall and ITS tests, for which cylindrical specimens 4 in. in height and approximately 2.5 in. in diameter are manufactured using a Marshall compactor, the specimens for SCB are produced using a Superpave Gyratory Compactor (SGC) with a compaction height of approximately 160 mm and a diameter of 150 ± 8 mm. From the center of the SGC plug, two 50±1 mm thick slices are obtained by cutting the plug in half. Each slice is again cut in half, yielding two identical semicircle-shaped specimens. A total of four replicates are fabricated from each SGC plug. A notch is created in the center along the axis of loading at a depth of 15 ± 1 mm and 1.5 ± 0.1 mm in width. The specimens are then dried in an oven at 25°C for 2 hours before testing. This specimen preparation steps are illustrated in Figure 2-9 showing the SGC plugs, slices, and SCB specimens prepared at GSU.

Figure 2-9 Specimen Preparation for Semi Circular Bending Test

2.5.3.2 Test Procedures and Equipment

The specimens were conditioned at 25°C and then transferred to the test equipment; the test had to be completed within 5 minutes. The test equipment used in this study is shown in Figure 2-10. An SCB specimen was placed in the loading jig and a small contact load applied. The test started with a loading rate of 50 mm/min and continued until the load dropped below 0.1 kN.

2.5.3.3 Parameters and Data Analysis

A typical SCB test result is illustrated in Figure 2-11. The relationships between the loads applied and the corresponding displacements are plotted as a continuous curve. The area under the curve is defined as the work of fracture (W_f), which is essential for calculating the fracture energy, G_f, and a useful indicator for crack resistance, the Flexibility Index (FI). In order to calculate the area, the load-displacement curve in the figure is divided into two curves designated y_1 and y_2, corresponding to before and after the peak load, respectively. Each curve is then fitted with an appropriate function to apply an analytical integration scheme. In most cases, the first curve, y_1, is fitted by a three-order polynomial equation and the second curve, y_2, by an exponential-based function. Figure 2-12 shows the two curves (before and after the peak load) and their respective regression equations.

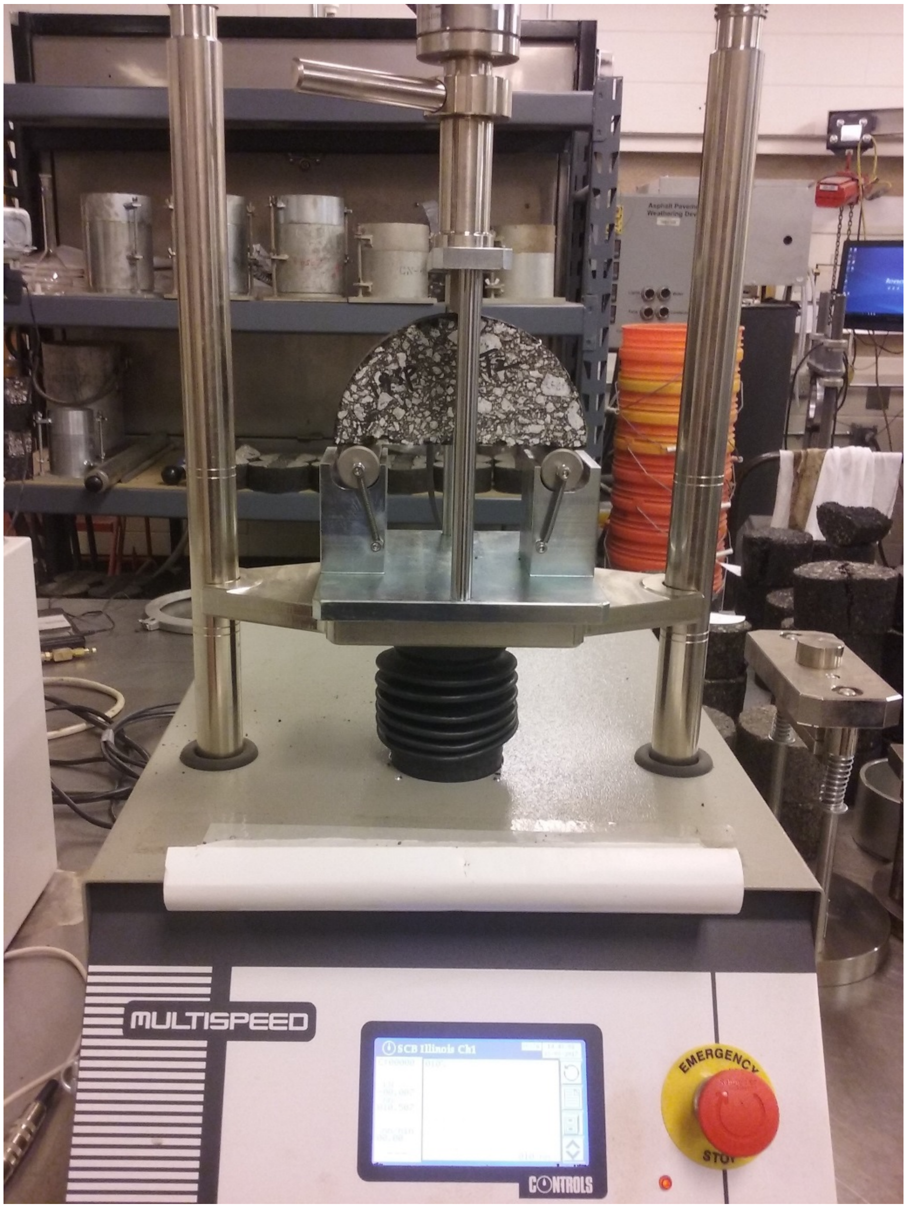


Figure 2-10 Equipment for Semi Circular Bending Test

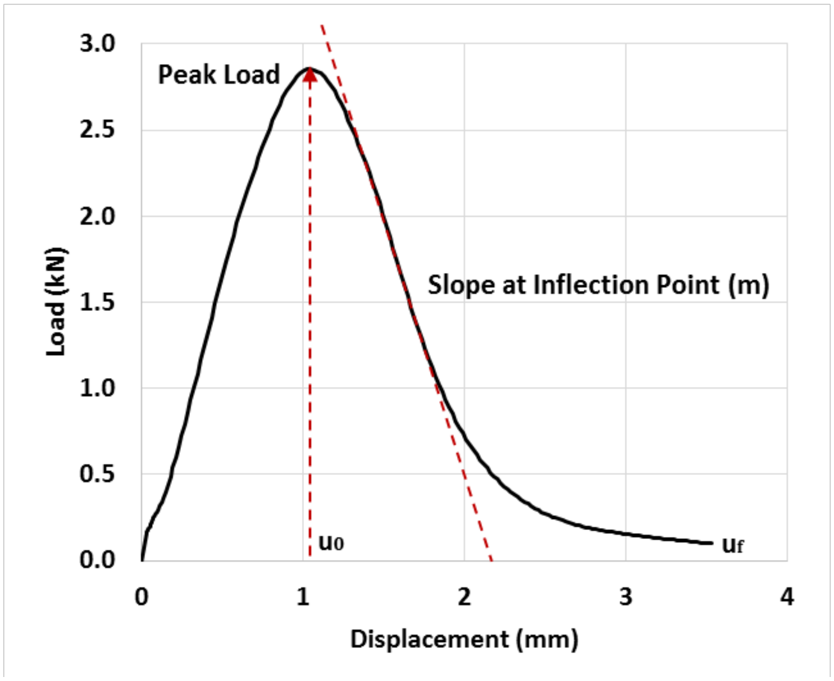


Figure 2-11 Sample SCB Test Result

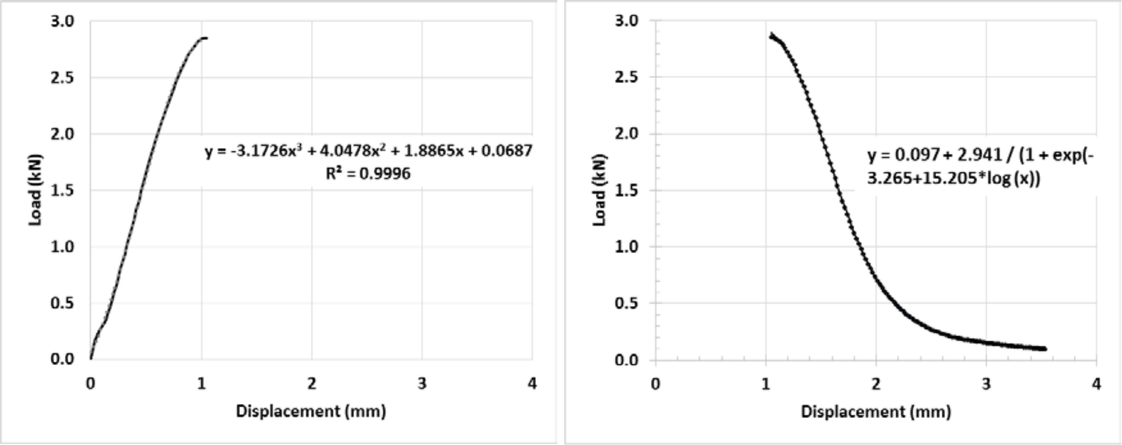


Figure 2-12 Sample Curve Fitting

Once these two functions have been determined, the following steps are applied to yield FI:

Step 1: Using an integration technique, the areas of the two curves are found. Mathematically, this is described as follows:

$$W_f = \int_{0}^{u0} y_1 + \int_{u0}^{ufinal} y_2$$, where W_f (Joule) = Work of Fracture and u_{final} (mm) = final displacement

Step 2: The fracture energy, G_f, (Joules/m_2) is calculated by:

$$G_f = \frac{W_f}{Area_{lig}} \times 10^6$$, where $Area_{lig}$ (mm^2): Specimen cross-sectional area above a notch

Step 3: The post peak slope, m, is found from the derivative of y_2. An example of finding an m-value is shown in Figure 2-13.

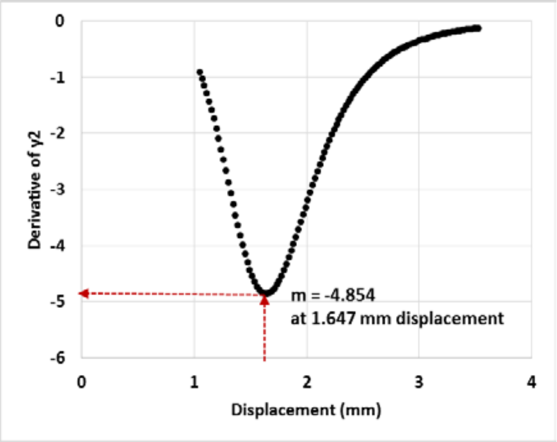


Figure 2-13 Finding a Post Peak Slope from the Derivative of the Y_2 Curve

Step 4: The Flexibility Index, FI, is then calculated:

$$FI = \frac{G_f}{|m|} \times A$$, where A = unit conversion and scaling factor (0.01)

The FI value obtained from an SCB test describes the ability of recycled foamed asphalt mixtures to resist cracking at an intermediate temperature: the higher the FI value of an asphalt mixture, the less brittle and the greater its resistance to cracking compared to other mixtures.

2.5.3.4 Test Conditions and Number of Specimens

This study followed the standard test conditions specified in AASHTO T 124, where the specimens were conditioned at 25°C in an oven and tested at the same temperature. Per batch, three gyratory plugs were manufactured and four specimens obtained from each of the plugs (i.e., a total of 12 specimens were produced per batch). For comparison purposes, one batch of HMA was also prepared. Unlike the Marshall and ITS tests, only one rejuvenator was included in the mixing process because the earlier tests found no noticeable difference between the two rejuvenators. Dosage levels used for SCB were 6% and 12%. The matrix of specimens for SCB considered in this study is summarized in Table 2-13.

Table 2-13 Number of Specimens Used for the Semi-Circular Bending Test

Laboratory Test	Test Temp.	Number of Specimens
		After Determining OFAC** (i.e., at OFAC)
Semi-Circular Bending	25°C	12 = 3 plugs x 4 specimens
Per Batch		12
Total Specimens		120 = 12 per batch x 1 AC x 3 RAP x (1 Rejuvenators x 2 Rej. Contents + 1 Control Mix) + 12 HMA specimens

2.6 Experimental Plan

The overall experimental plan and work flow for the performance tests are presented in Figure 2-14. As described earlier, various material combinations from three RAP sources (A1-A3), two rejuvenators (R1 and R2), and three rejuvenator contents (6, 12, and 18%) were considered in this research. The next chapter explains the procedures used to determine the OFAC in the figure. The results of the three performance tests are then presented in Chapter 4.

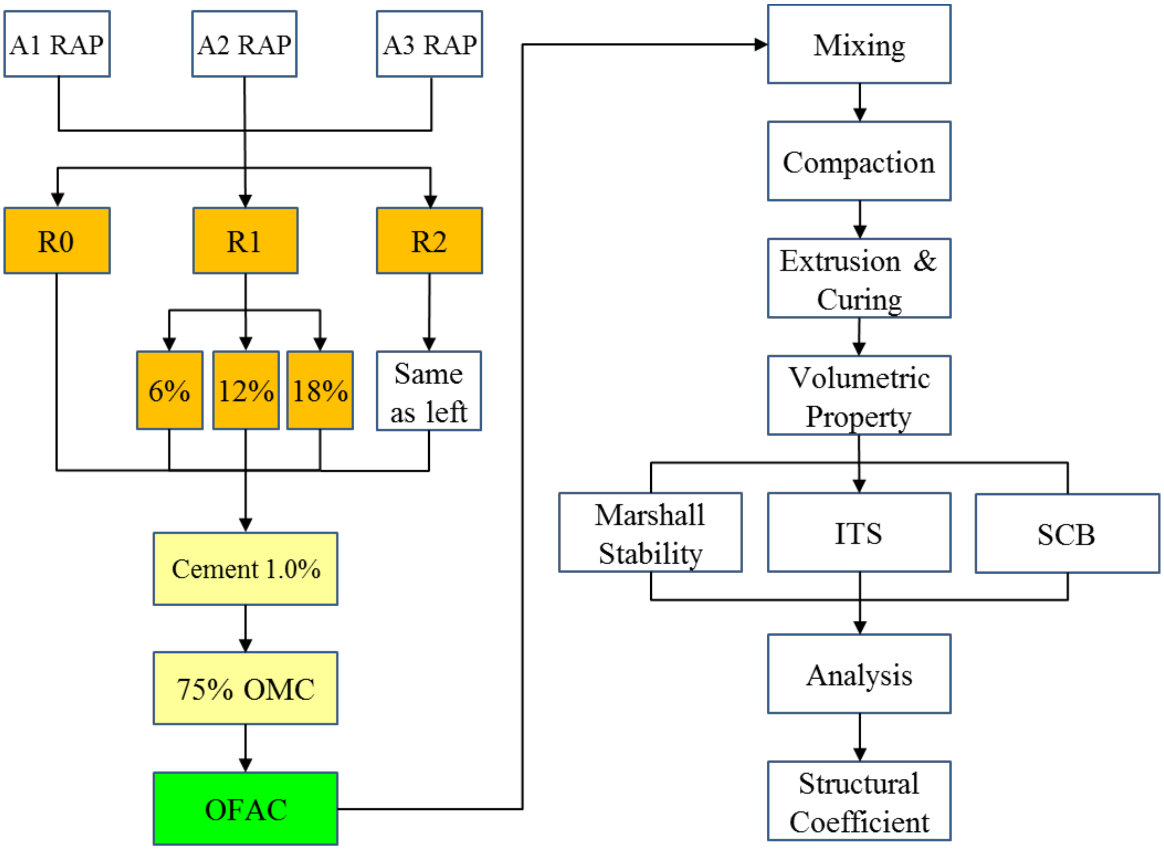


Figure 2-14 Experimental Plan and Work Flow

3 FOAMED ASPHALT MIX DESIGN

Once the foaming, OMC, and OWC conditions described in the preceding chapter had been determined, the 100 % recycled foamed asphalt mix design at the heart of this study was implemented. The objective of the 100 % recycled foamed asphalt mix design was to find an OFAC that represents a single asphalt cement content at which the performance of recycled foamed asphalt mixtures would be superior to other mixtures manufactured with other asphalt contents in terms of their physical performance. Since there is no universally accepted mix design method for a 100% RAP foamed asphalt mixture, this study followed the standard Marshall mix design with necessary modifications.

The OFAC was determined based upon the Marshall Stability and ITS. The Percent Retained Stability and TSR results were also checked to reveal any reduction in stability and indirect strength due to the action of water on high-RAP foamed asphalt mixtures. The following subsections describe the mix design procedure applied to identify the OFAC, including batching, mixing, compacting, curing, and laboratory tests. Note that no rejuvenator was included in the original mix design; instead, the effect of a rejuvenator on 100% recycled foamed asphalt mixtures was evaluated separately with a single OFAC and the results presented later in Chapter 4: Performance Test Results and Discussion.

3.1 Batching

The batch process involves measuring the right amount of each ingredient by weight prior to introducing the ingredients into a mixer. The ingredients of the recycled foamed asphalt mixture used in this study were RAP, Portland cement, water for compaction, water for the foamed asphalt cement, and neat asphalt cement. The mix design process for this study required the production of a set of 18 Marshall specimens per batch for the selected performance tests (nine for Marshall stability tests, three for conditioned Marshall, and six ITS). Each specimen weighed approximately

1,100 grams and three measurements of theoretical maximum specific gravity (G_{mm}) per batch were also required. Note that each G_{mm} measurement usually required approximately 1,500 grams. This led to a minimum RAP weight of 24,300 grams (18 Marshall specimens x 1100 grams + 3 G_{mm} x 1500 grams = 24,300 grams), which when an extra 700-grams of RAP per batch were included came to a total of 25,000 grams of RAP per batch. To illustrate the computation of the mass of the individual ingredients for one batch, a step-by-step sample calculation is provided for the A1 RAP, as follows. The final amounts calculated are summarized in Table 3-1:

- *Step 1*: Measure 25,000 grams of air-dried RAP and place it into the mixer. Note that this air-dried RAP still contains a small amount of water, which is predetermined.
- *Step 2*: Calculate the weight of pure RAP without the known amount of water in the RAP
    - For A1, 0.15% water content in the RAP, 25000 / (1 + 0.0015) = 24,963 grams
- *Step 3*: Calculate the amount of water to be added for RAP compaction from OMC.
    - For A1, OMC = 5.8%, only use 75% of OMC, hence 4.35%
    - Considering the existing 0.15% water content, the actual water content to be added will be 4.20% = 4.35% - 0.15%
    - The final amount of water to be added will be 1,048 grams = 24,963 grams of RAP x 0.042
- *Step 4*: Calculate the amount of Portland cement (1% of RAP) to be added
    - 250 grams = 24,963 grams of RAP x 0.01
- *Step 5*: Calculate the amount of foamed asphalt cement to be sprayed on the RAP-cement mix
    - When a 2% foamed asphalt cement content is used, the asphalt cement amount will be 504 grams = (24,963 grams of RAP + 250 grams of Cement) x 0.02

Table 3-1 Summary of a Sample Calculation for One Batch of Foamed Asphalt Mix

	RAP	Residual Water in RAP	Water for Compaction	Cement	*Foamed Asphalt (2%)	Total
Mass (g)	24,963	36	1,048	250	504	26,801

*Note: The actual foamed asphalt content varies from 2.0% to 3.5%

3.2 Mixing, Compacting, and Curing

With the masses calculated according to the steps in the proceeding section, the mixing process can now proceed. Because the sequence in which materials are added to the mixer is important, the following sequence for mixing was used consistently throughout for manufacturing the foamed asphalt mixtures to eliminate any uncertainty related to the material introduction order:

1) Add 100% RAP in a mixer (Wirtgen Model: WLM 30 in Figure 3-1)
2) Start to rotate the mixer
3) Add 1% Portland cement (by weight of RAP) in the mixer and continue mixing for 1.5 minutes
4) Add water (75% of OMC as pre-determined for RAP compaction) in the mixer
5) Continue mixing for 1.5 minutes and inspect the mix
6) Couple the mixer with the foamed asphalt cement equipment (Figure 3-2)
7) Inject foamed asphalt cement into RAP and continue mixing until the loose mixture is uniformly mixed (at least 3 minutes)
8) Open the mixer and inspect the mix (Figure 3-3)

Figure 3-1 Foamed Asphalt Mixer (Wirtgen Model: WLM 30)

Figure 3-2 Laboratory Scale Foamed Asphalt Plant

Figure 3-3 RAP after Mixing with Cement, Water, and Foamed Asphalt Cement

The loose recycled foamed asphalt mix from the mixer was then transferred to an air-tight plastic container from which an 1100-gram loose mix was taken for compaction to manufacture a single Marshall specimen. The Marshall compactor was used to make a standard 4-in. diameter by approximately 2.5-in. height Marshall specimen. This procedure is depicted in Figure 3-4. Post-compacted specimens were left in the mold at ambient temperature overnight in the laboratory before being extruded in the following day. After extrusion, all 18 specimens were placed in the air-drift oven at 40°C for 72 hours for curing. A portion of loose mix was used to measure the theoretical maximum unit weight for volumetric measurements. Air voids in the specimens that had completed the 72-hour curing period were measured in accordance with AASHTO T 166 prior to an additional conditioning for performance testing, if necessary [39]. The photograph in Figure 3-5 show the extrusion and curing procedure.

Figure 3-4 Marshall Compaction

Figure 3-5 Specimen Extrusion and Oven Curing

3.3 Laboratory Tests for Recycled Foamed Asphalt Mix Design

The Marshall Stability test was conducted in accordance with AASHTO T 245 with the exception of the conditioning and test temperatures, as described in Section 2.5.1. As noted earlier, the original standard test specifies regular and cutback specimens should be conditioned at temperatures of 60°C and 25°C, respectively, for 30 minutes before testing. The mix design of this study followed the cutback condition (25°C for 30 minutes) due to a concern that the specimens could fall apart at an elevated test temperature of 60°C.

For each foamed asphalt cement content (2.0% to 3.5%, in 0.5% increments), nine specimens were tested and an average value calculated to obtain the Marshall Stability. For the conditioned Marshall Stability test, a set of three specimens were conditioned in a bath at 25°C for

24 hours before testing. After completion of both Marshall tests, the Percent Retained Marshall stability was calculated.

For the dry and soaked ITS tests, a set of three specimens were conditioned at 25°C in an oven for 24 hours and a parallel set of three maintained in a water bath at the same temperature for 24 hours. After testing each set of specimens, the TSR was calculated based on the dry and soaked ITS values obtained from the average value measured for each set of specimens. The test conditions for these performance tests are listed in Table 3-2.

Table 3-2 Test Conditions for Foamed Asphalt Mix Design

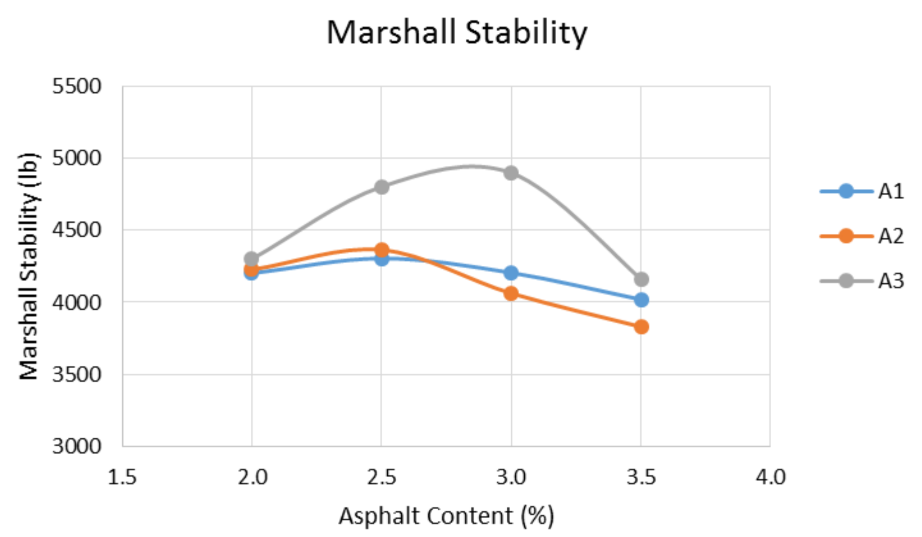
Test	**Test Conditions**			
	Replicates (18 ea.)	**Temperature**	**Conditioning Time**	**Water or Oven**
Marshall Stability	9	25°C	30 minutes	Water
Conditioned Marshall	3	25°C	24 hours	Water
Dry Indirect Tensile Strength	3	25°C	24 hours	Oven
Soaked Indirect Tensile Strength	3	25°C	24 hours	Water

3.4 Determination of Optimum Foamed Asphalt Cement Content

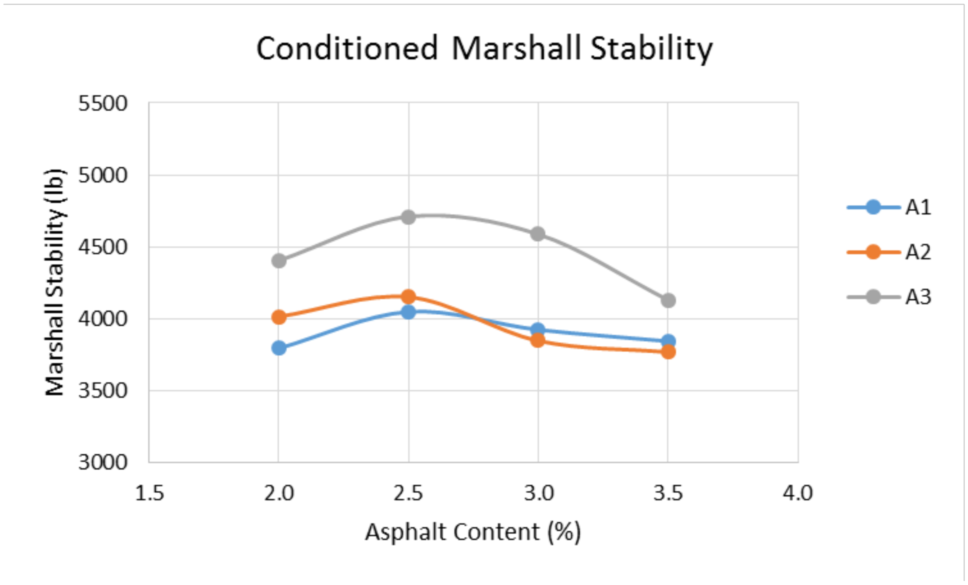
The OFAC determination was based on the laboratory test results from Marshall Stability, Conditioned Marshall Stability, and the dry and soaked ITS. Neither the % Retained Marshall stability nor the TSR results were used in finding the OFAC, but instead used to confirm that the results would meet the minimum requirement of 80% with respect to a moisture susceptibility evaluation. Test specimens were manufactured at four foamed asphalt cement contents: 2.0% to 3.5%, in 0.5% increments.

The mix design test results are presented in Figure 3-6. Figures 3-6(a) and (b) show that both the Marshall stability and the ITS values were highest for a 2.5% foamed asphalt cement content, gradually decreasing afterwards as more asphalt is added for both A1 and A2 RAP materials; A3 RAP exhibited a superior performance at 3.0%. Figures 3-6(c) and (d) provide evidence to show that the mixtures generally perform better at an asphalt cement content of 2.5% or 3.0%. Based on this mix design test result, 2.5% foamed asphalt cement was selected as the OFAC and an asphalt cement content of 2.5% used thereafter to manufacture the foamed asphalt specimens utilized to evaluate structural integrity.

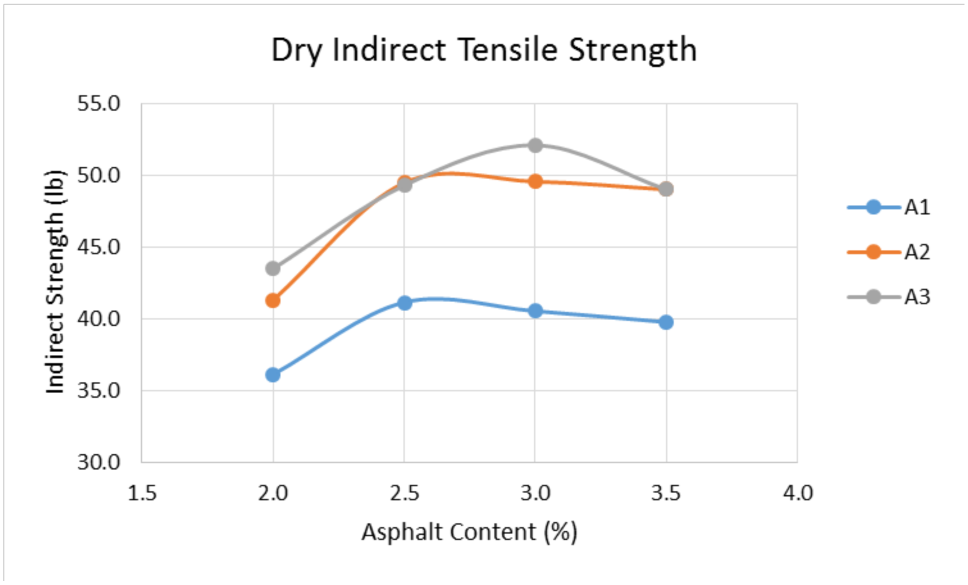
The % Retained Marshall stability and TSR values calculated from the Marshall and ITS results are summarized in Table 3-3. They are all above 80% regardless of the asphalt content, indicating that the mixtures are not susceptible to water damage at 25°C.



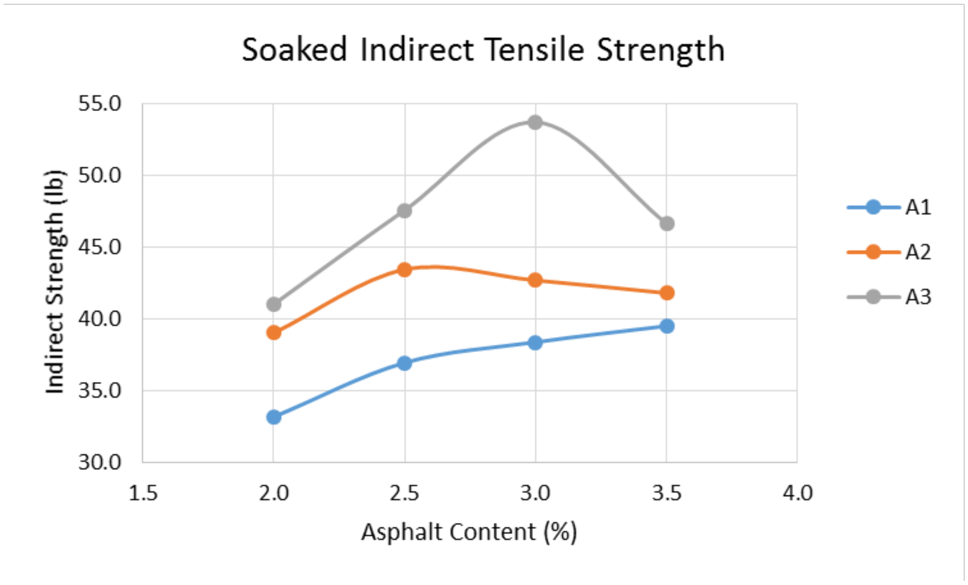
(a) Marshall Stability at 25ºC at Various Foamed Asphalt Contents



(b) Conditioned Marshall Stability at 25ºC at Various Foamed Asphalt Contents



(c) Dry Indirect Tensile Strength at Various Foamed Asphalt Contents



(d) Soaked Indirect Tensile Strength at Various Foamed Asphalt Contents

Figure 3-6 Performance Test Results for Foamed Asphalt Mix Design

Table 3-3 Percent Retained Stability and TSR Results at Various Foamed Asphalt Contents

Mix Property	**Foamed Asphalt Cement Content (%)**			
	2.0	**2.5**	**3.0**	**3.5**
% Re-Stability	102.2	98.0	93.6	99.2
TSR (%)	94.3	96.5	103.1	95.2

4 PERFORMANCE TEST RESULTS AND DISCUSSION

This chapter presents the results obtained from the three performance tests conducted for this research, namely the Marshall Stability and Conditioned Marshall Stability at 25ºC and 60ºC, Indirect Tensile Strength, and Semi-Circular Bending, and discusses their implications. Not that these results are all for mixtures manufactured with the same asphalt cement content of 2.5%, selected because it identified as the OFAC in the mix design stage (Chapter 3). The test results were analyzed in terms of a number of different aspects, including the effect of the rejuvenator dosage, rejuvenator type, and the test temperature used to measure the Marshall Stability (25ºC vs. 60ºC). The main thrust of this chapter is to provide evidence related to the potential structural integrity of 100 % recycled foamed asphalt mixtures if used as a base layer in pavement systems. A later section (Section 4.4) will discuss the estimated structural coefficients based on the performance test results in accordance with the method described in the 1993 AASHTO *Guide for Design of Pavement Structures*.

4.1 Marshall Stability Test Results

The Marshall and Conditioned Marshall Stability tests were conducted at two temperatures: 25°C and 60°C. A test temperature of 25°C was initially considered based on research conducted for the Maryland SHA that recommended the intermediate temperature due to concerns that specimens could become too weak and fall apart if subjected to pre-conditioning at 60°C [5]. For a recycled foamed asphalt mix design, 25°C would be a plausible temperature. However, as mentioned in Chapter 2, trial tests indicated that the stability results seemed extremely high at 25°C, which would lead to an inaccurate estimation of the structural coefficients. It was therefore decided that the Marshall tests should be conducted at both 25°C and 60°C; the results obtained at both temperatures are reported here. Bear in mind that 60°C is the standard test temperature for HMA, as specified in both the AASHTO and ASTM standards [29, 30].

4.1.1 Marshall Stability and Effect of Rejuvenator at 25ºC

Figures 4-1 and 4-2 illustrate the results of the Marshall and Conditioned Marshall Stability tests, respectively, at 25°C for three rejuvenator dosage levels (6%, 12%, and 18%) and two rejuvenators (R1 and R2). In the figures, the stability labeled R0 is included in order to compare the results with those obtained for control mixtures (R0) in which no rejuvenator was applied. The vertical error bars shown in the figures represent the Confidence Interval (CI) for the purposes of the statistical analyses. The CI range was calculated using the following equation, which is a function of the average and standard deviation of specimens at the 95% level.

$$\bar{x} - t_{\alpha/2}\frac{s}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2}\frac{s}{\sqrt{n}}$$

where $\bar{x}$ = sample average, $t_{\alpha/2}$ = the t-value with n-1 degrees of freedom, s = sample standard deviation, and n = the number of specimens.

Overall, the stability results at 25°C were very high, ranging from 3678 to 4675 lb. for R0, depending on the RAP sources. The high stability values of the R0 mixtures were mainly attributed to the test temperature of 25°C which is substantially lower than the standard test temperature of 60°C. Unfortunately, these results could not be used in estimating the structural coefficients as the base strength parameters provided in the 1993 AASHTO *Guide for Design of Pavement Structures* are estimated based on Marshall Stability values ranging from 0 to 2,000 lb.

When rejuvenators were added into the recycled foamed asphalt mixtures, the stability decreased considerably even at the smallest dosage level of 6%. As a more rejuvenator (12 and 18%) was incorporated into the mixture, the stability continued to decrease but the rate of stability reduction was slightly reduced. This trend was consistent across all three RAP sources, although there was some variability among the three RAP sources. The percentage reduction in stability was calculated for each dosage level in comparison with the stability of the control mixture (i.e., the difference in stability between the no-rejuvenator specimen group and the rejuvenator-added specimen group divided by the no-rejuvenator specimen group), as summarized in the last column of Table 4-1. With rejuvenator added, the reduction in stability ranged from 24% to 66% relative to R0, depending on the dosage rate and RAP sources.

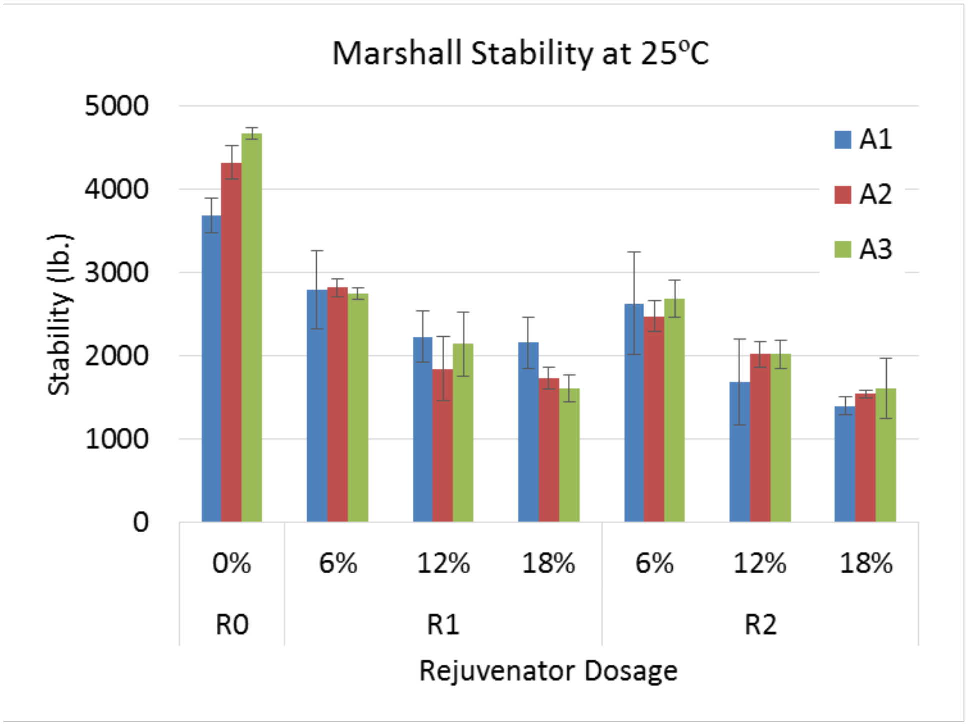


Figure 4-1 Marshall Stabilities at 25ºC with Various Rejuvenator Dosages

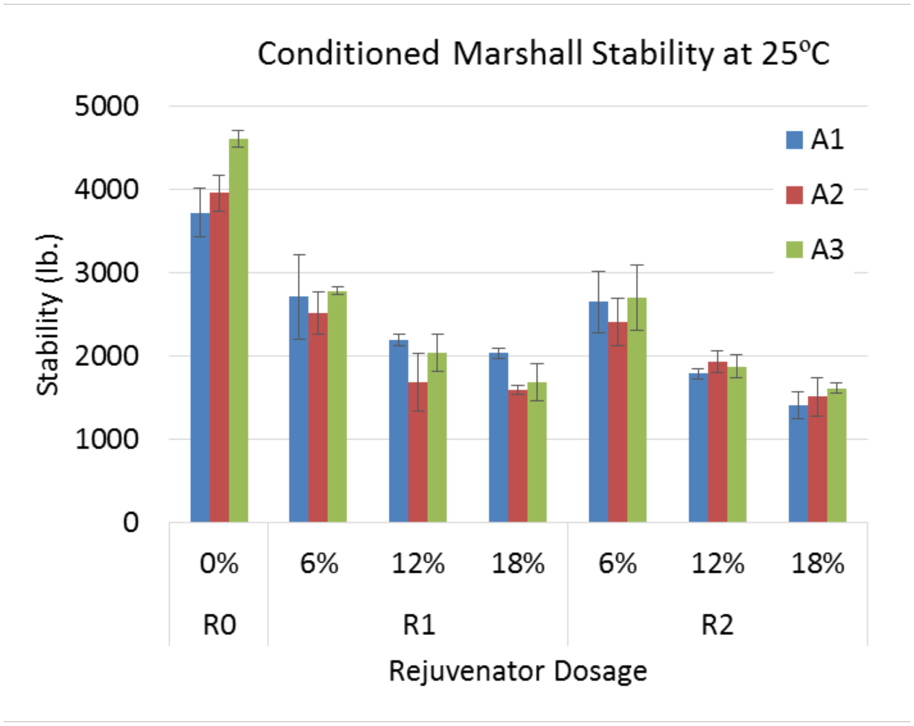


Figure 4-2 Conditioned Marshall Stabilities at 25°C with Various Rejuvenator Dosages

Table 4-1 Marshall and Conditioned Stability at 25°C

Property	Rejuvenator Type	Dosage Level (%)	A1		A2		A3	
			MS (lb)	Reduction (%)	MS (lb)	Reduction (%)	MS (lb)	Reduction (%)
MS	R0	0	3687	-	4325	-	4675	-
	R1	6	2796	24.2	2817	34.9	2748	41.2
		12	2231	39.5	1843	57.4	2140	54.2
		18	2156	41.5	1724	60.1	1610	65.6
	R2	6	2630	28.7	2477	42.7	2685	42.6
		12	1686	54.3	2017	53.4	2020	56.8
		18	1399	62.1	1543	64.3	1613	65.5
Cond-MS	R0	0	3724	-	3957	-	4612	-
	R1	6	2709	27.3	2519	36.3	2783	39.7
		12	2191	41.2	1687	57.4	2039	55.8
		18	2034	45.4	1589	59.8	1692	63.3
	R2	6	2647	28.9	2409	39.1	2699	41.5
		12	1790	51.9	1930	51.2	1874	59.4
		18	1412	62.1	1512	61.8	1616	65.0

For both the Marshall and Conditioned Marshall results, some variability in stability among the various RAP sources was found as the CI ranges shown in the figures did not always overlap. For example, the average stability of R0 between A1 and A3 showed an apparent discrepancy. On the other hand, no significant difference in stability was observed in other cases. However, the trend of stability reduction with rejuvenator addition was consistent throughout.

The Conditioned Marshall Stability showed a similar pattern in terms of the trend of stability reduction with the addition of rejuvenator. The reduction ranged from 27% to 65% relative to R0, depending on the dosage rate and RAP sources.

Based on both the Marshall and Conditioned Marshall Stability results, the Percent Retained Marshall Stability was calculated and the results are presented in Figure 4-3. The Percent Retained Marshall Stability is typically used to evaluate the reduction in stability that results from the action of water and is thus utilized to estimate a material's resistance to the detrimental effects of water. At 25°C, which is lower than the standard temperature of 60°C, the resistance to water damage was excellent. The % Retained Stability values for every combination of foamed asphalt mixtures was above the typical threshold of 80% Re-MS.

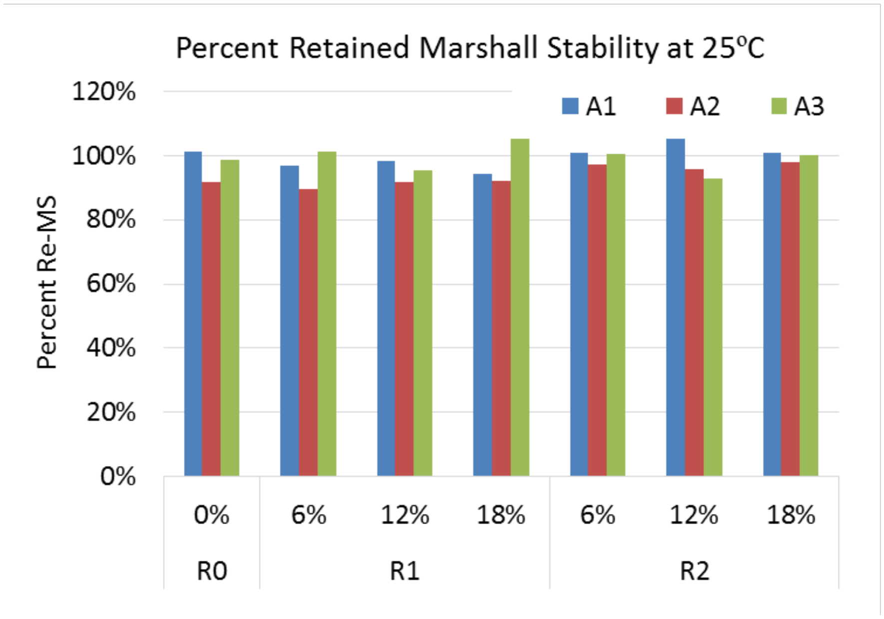


Figure 4-3 Percent Retained Marshall Stability at 25ºC

In summary, the major findings from these results are as follows:

- The Marshall Stability at 25°C can be used as part of the mix design process to find an OFAC, but is not recommended for estimating the structural layer coefficient because it overestimates stability and is also incompatible with the estimation method suggested by the 1993 AASHTO *Guide for Design of Pavement Structures*.

- There is some variability in stability among the three RAP sources used in this study. However, the trend of stability reduction with increasing rejuvenator dosage is consistent.
- The addition of rejuvenator causes a significant reduction in both the Marshall Stability (which fell by between 24% and 66%) and the Conditioned Marshall (where it fell by between 27% and 65%) at 25°C.
- The Percent Retained Marshall indicates that the resistance of recycled foamed asphalt mixtures to the detrimental effect of water is very effective at 25°C.

4.1.2 Marshall Stability and Effect of Rejuvenator at 60ºC

A similar data analysis was carried out to determine the Marshall and Conditioned Marshall Stabilities at a higher test temperature, 60°C, which is the standard preconditioning temperature specified in AASHTO T 245 [29]. This analysis also examined the effect of rejuvenator dosage on both stability measures. The results are depicted in Figures 4-4 and 4-5. At this temperature, the stability was considerably lower than at 25°C, as expected, showing a stability of 986 lb. to 1512 lb. for R0 of the three RAP sources, far below the values at 25°C, which ranged from 3687 to 4675 lb. for the same mixture group.

When rejuvenators were added to the mixtures, the stability reduction showed a similar pattern to that at 25°C. A considerable reduction in stability (53% on average for the three RAP sources) was exhibited at a 6% dosage level, in comparison with the control mixture, R0. As the dosage level increased to 12% and then 18%, the stability was further reduced but the rate of reduction was slightly diminished.

The stability in the samples containing the rejuvenator was quite low at this temperature. The lowest stability was 400 lb. and the highest 696 lb. at a 6% dosage, which would be considered unstable for an HMA layer. However, if used as a base course, the structural coefficient would be equivalent to 0.16 and 0.19 for the lowest and highest stability according to the 1993 AASHTO *Guide for Design of Pavement Structures*, which may be considered acceptable as a replacement for a traditional unbound base course. A further discussion of the structural integrity is provided in Section 4.4.

Comparing the stability reduction patterns obtained for the Marshall and Conditioned Marshall Stabilities, the two are very similar at this temperature (Figure 4-5). The Marshall and Conditioned Marshall results, along with the stability reduction with and without rejuvenators, are summarized in Table 4-2.

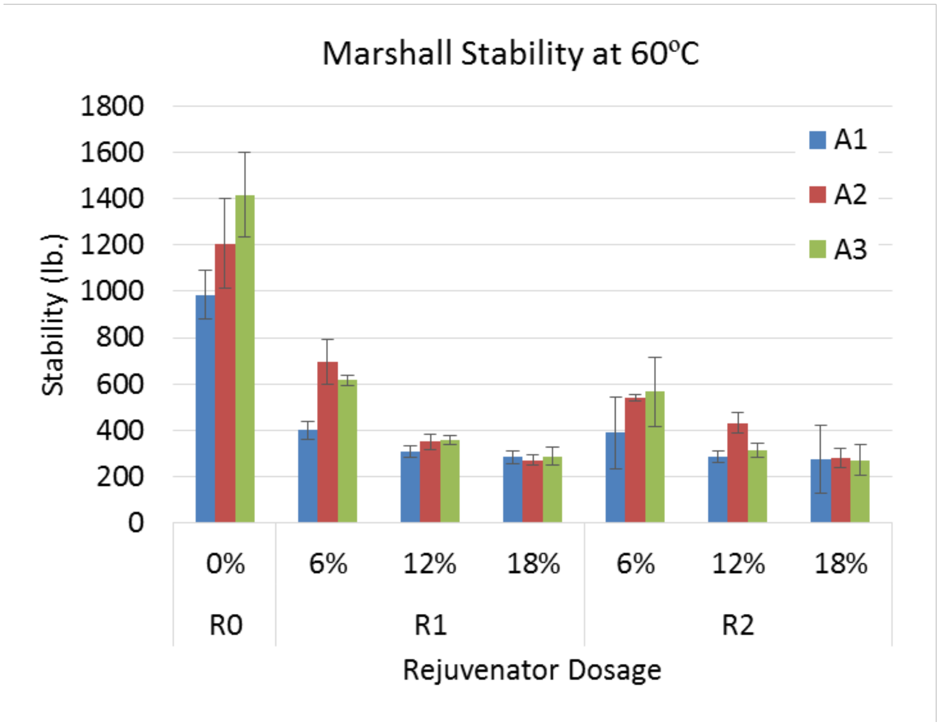


Figure 4-4 Marshall Stabilities at 60°C with Various Rejuvenator Dosages

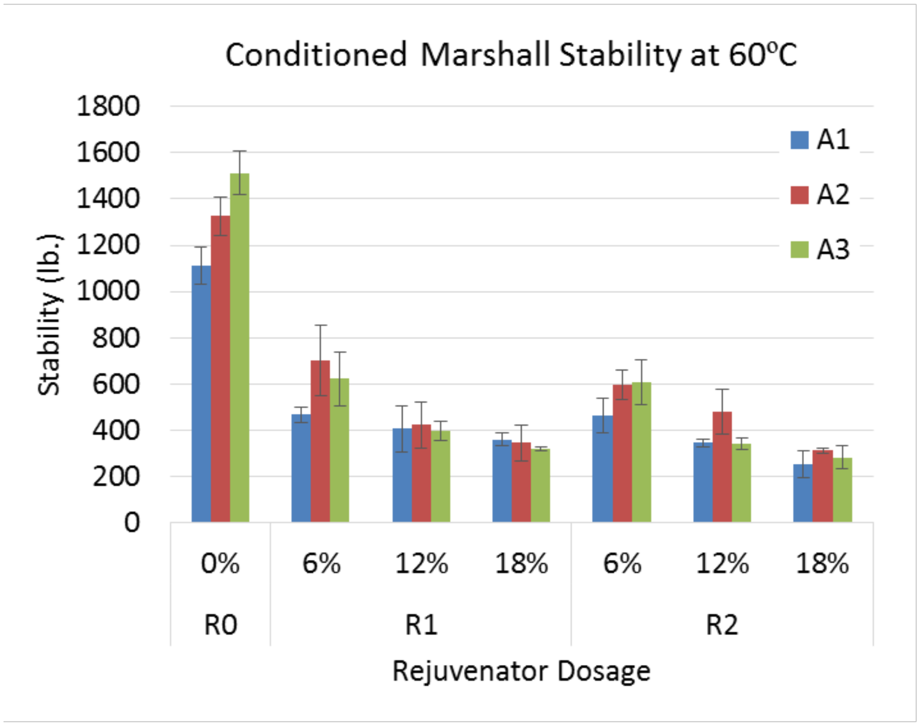


Figure 4-5 Conditioned Marshall Stabilities at 60ºC with Various Rejuvenator Dosages

Table 4-2 Marshall and Conditioned Stability at 60°C

Property	Rejuvenator Type	Dosage Level (%)	A1		A2		A3	
			MS (lb)	Reduction (%)	MS (lb)	Reduction (%)	MS (lb)	Reduction (%)
MS	R0	0	986	-	1207	-	1417	-
	R1	6	400	59.4	696	42.3	615	56.6
		12	305	69.0	350	71.0	357	74.8
		18	283	71.3	270	77.6	286	79.8
	R2	6	389	60.6	540	55.3	567	60.0
		12	286	70.9	431	64.3	312	78.0
		18	273	72.3	279	76.9	270	80.9
Cond-MS	R0	0	1111	-	1325	-	1512	-
	R1	6	467	58.0	701	47.1	623	58.8
		12	405	63.5	422	68.2	396	73.8
		18	360	67.6	345	74.0	317	79.0
	R2	6	461	58.5	598	54.9	607	59.9
		12	345	68.9	480	63.8	341	77.4
		18	251	77.4	311	76.5	282	81.3

The Percent Retained Marshall Stability at 60°C was calculated based on the results obtained for the two stability groups (Marshall vs. Conditioned Marshall) and the results are presented in Figure 4-6. Note that according to the original test standard (GDT 53), a specimen group should be conditioned in a water bath maintained at 60°C. Instead, in this study, an air-drifted oven was used to condition the specimen group due to concerns over potential mixture failure during conditioning. This may explain why the Percent Retained Marshall results obtained were all higher than 100%. This result should therefore not be used as an indicator of moisture susceptibility for foamed asphalt mixtures. Rather, more attention needs to be paid to the Tensile Strength Ratio specified in AASHTO T 283 [32].

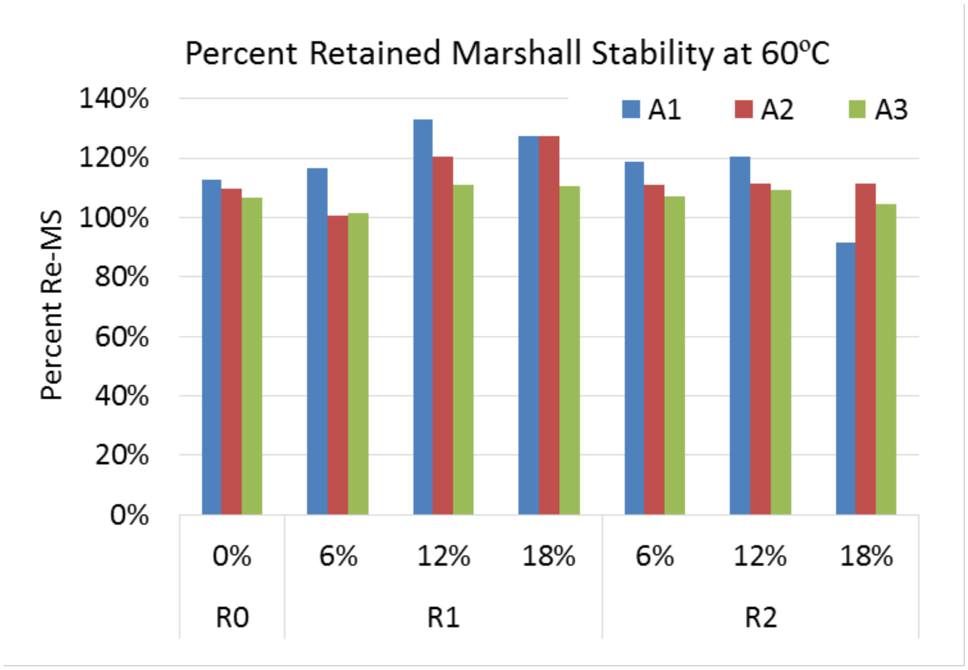


Figure 4-6 Percent Retained Marshall Stability at 60ºC

As shown in Figure 4-4, the Marshall Stability was considerably reduced with the lowest dosage level of rejuvenator of 6% added in 100% recycled foamed asphalt mixtures. In order to further verify the effect of rejuvenator on the Marshall Stability at lower rejuvenator dosages (i.e., lower than 6%), an additional set of testing was planned and conducted. The material and experiment information of this additional work is provided in Table 4-3. For a succinct verification, the experimental plan included a single RAP source (A2) and a single rejuvenator (R1) with four rejuvenator dosage levels. Six replicates per each dosage level were produced and tested at 60°C.

The other foaming, mixing, curing, and test conditions were set as the same as the original experiments described in Chapters 2 and 3.

Table 4-3 Material and Experiment Information for Supplemental Testing

RAP Source and Asphalt Binder	A2 and PG 64-22
Rejuvenator Type	R1
Rejuvenator Dosage Levels	0%, 2%, 4%, and 6%
Number of Specimens	6 Replicates x 4 Dosages = 24 for Marshall 3 Replicates x 4 Dosages = 12 for Dry ITS 3 Replicates x 4 Dosages = 12 for Soaked ITS

Figure 4-7 shows the results of the Marshall Stability at different doses of rejuvenator. There was statistically no significant change in the stability between no-rejuvenator and 2% dose. As the dosage level was increased to 4%, the effect on the stability reduction began to be noticeable and the stability was further reduced at 6%. Figure 4-8 shows the Marshall Stability results from both original and additional tests depicting the stability reduction from 0% to 18% rejuvenator dose.

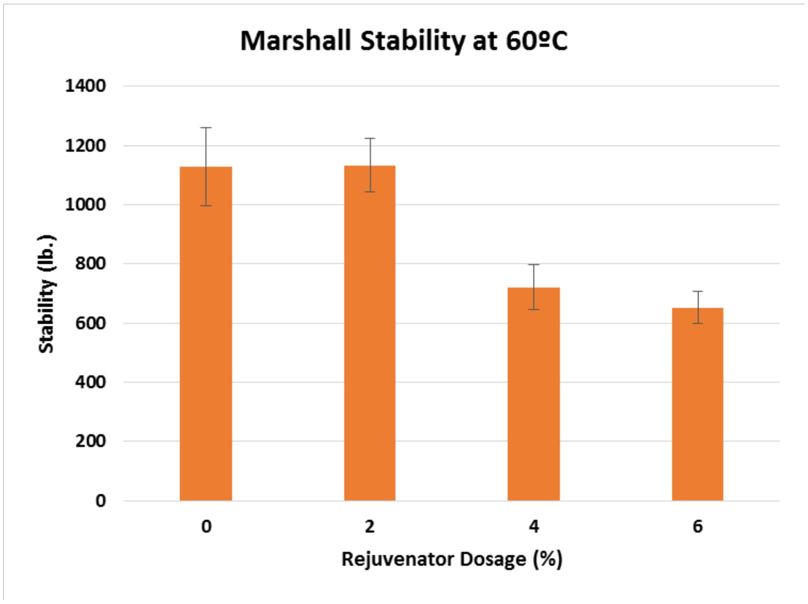


Figure 4-7 Marshall Stability at Lower Rejuvenator Dosage Levels

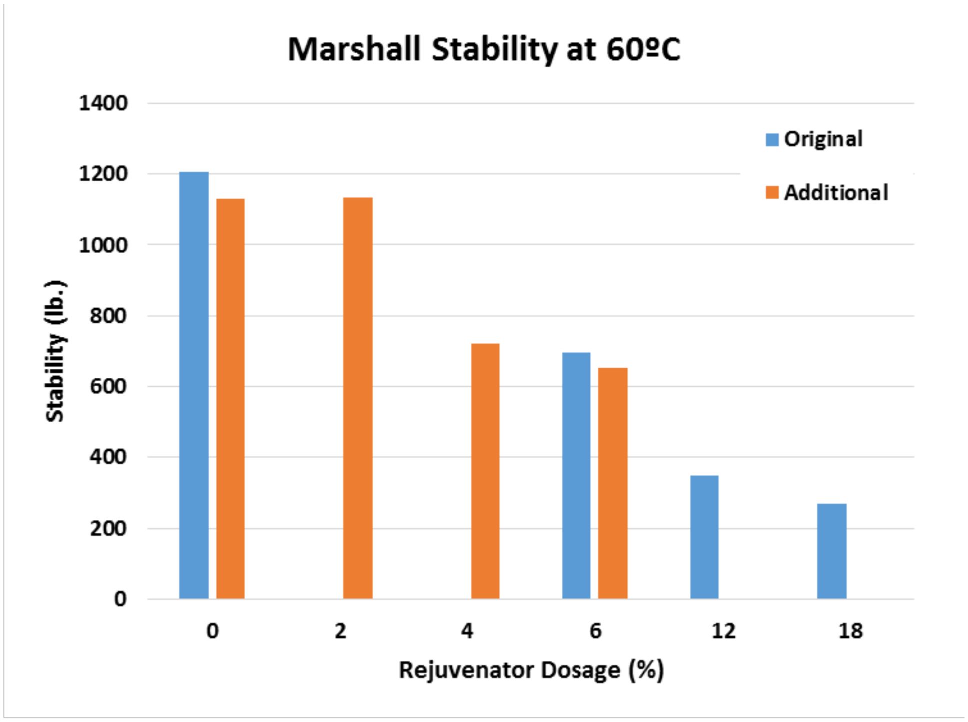


Figure 4-8 Marshall Stability Test Results at 60°C (Original + Additional)

In summary, the major conclusions that can be drawn from these results are as follows:

- The Marshall and Conditioned Marshall Stabilities at 60°C are considerably lower than those measured at 25°C. The overall stability reduction was found to be 79.2% when combining all RAP sources, rejuvenator dosages, and the two stability groups.
- The Marshall Stability with no rejuvenator was found to average 1203 lb. for the three different RAP sources, which is equivalent to an estimated structural coefficient of 0.21. When dosage levels of 6%, 12%, and 18% rejuvenator were added, the stabilities dropped to 534 lb., 340 lb., and 277 lb., respectively. The respective layer coefficients were estimated to be 0.16, 0.15, and 0.13.
- The Percent Retained Marshall at 60°C was consistently greater than 100% for every mixture combination. This result may be attributed to the fact that the specimens were conditioned in an oven, rather than a water bath. It is therefore not recommended that this

property be used for moisture damage evaluations of foamed asphalt mixtures at this temperature.

4.1.3 Effect of Test Temperature (25ºC vs. 60ºC) on Marshall Stabilities

As indicated in the previous two sections, the difference in stability between the two preconditioning temperatures is significant. This section discusses these findings in more detail, making a direct comparison of the two groups (25°C versus 60°C) in order to identify the reduction in stability that occurs. Figures 4-9 and 4-10 show the stability values from an average of three RAP sources. The percent reduction in stability is calculated and summarized in Table 4-4. As described in the previous sections, the stability dropped markedly as the test temperature rose from 25°C to 60°C. As the data shown in Table 4-4 reveal, when no rejuvenator was present in the mixture the average reductions in stability due to the temperature change were 72% and 68% for the Marshall and Conditioned Marshall Stabilities, respectively.

This temperature-induced reduction in stability became even greater when rejuvenator was used. The average rate of the reduction in the Marshall Stability rose to 80%, 83%, and 83% with dosages of 6%, 12%, and 18%, respectively, while the Conditioned Marshall Stability was reduced by 78%, 79%, and 81% the same dosages. Overall, a roughly 79.2% reduction in stability was observed due to the addition of rejuvenator when the preconditioning temperature was increased to 60°C.

This finding suggests that a high-RAP foamed asphalt mixture is more sensitive to the presence of a rejuvenator at any dosage level at an elevated temperature than at a lower test temperature when it comes to its Marshall Stability. Assuming the structural integrity is evaluated in terms of its Marshall Stability at 60°C, adding rejuvenator to a foamed asphalt mixture will thus significantly weaken the stability of a high-RAP foamed asphalt mixture.

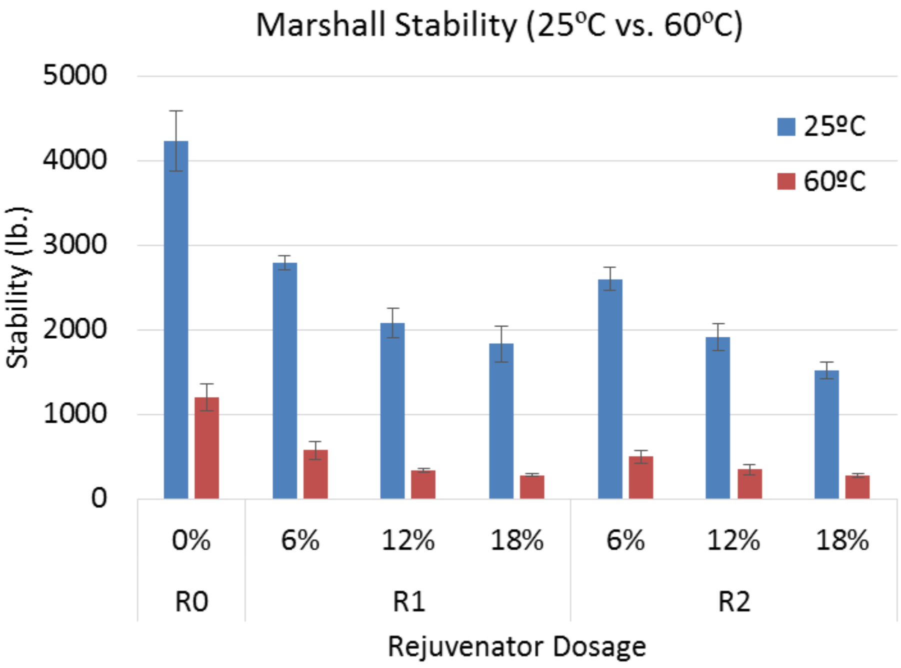


Figure 4-9 Marshall Stabilities at 25°C and 60°C (Average of Three RAPs)

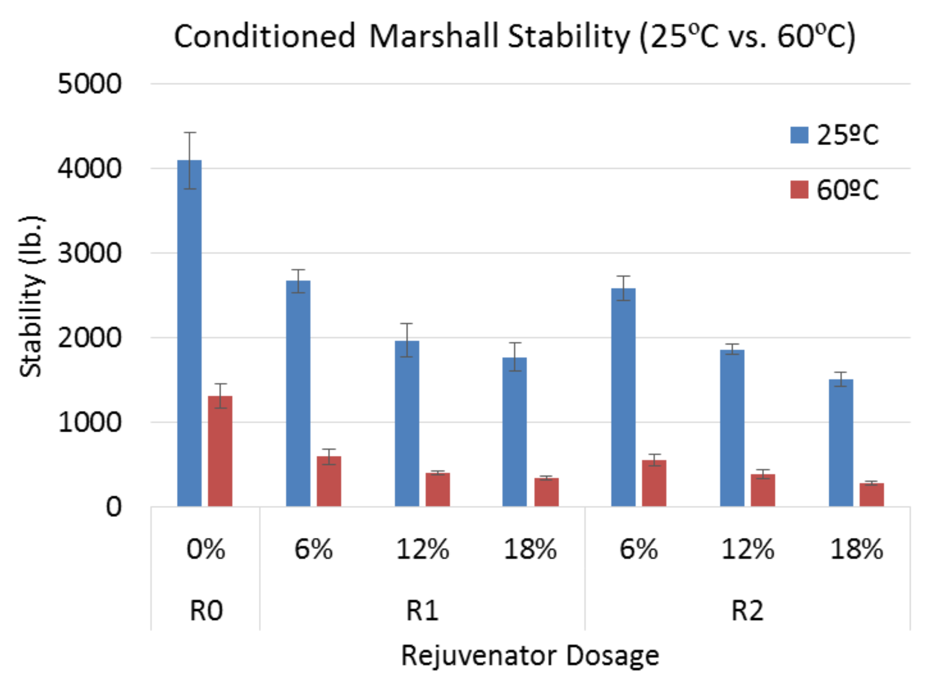


Figure 4-10 Conditioned Marshall Stabilities at 25°C and 60°C (Average of Three RAPs)

Table 4-4 Comparison of Marshall Stabilities (MS) at 25°C and 60°C

Property	Rejuv. Type	Dosage Level (%)	A1			A2			A3		
			MS (lb)		Red. (%)	MS (lb)		Red. (%)	MS (lb)		Red. (%)
			25°C	60°C		25°C	60°C		25°C	60°C	
MS	R0	0	3687	986	73.3	4325	1207	72.1	4675	1417	69.7
	R1	6	2796	400	85.7	2817	696	75.3	2748	615	77.6
		12	2231	305	86.3	1843	350	81.0	2140	357	83.3
		18	2156	283	86.9	1724	270	84.3	1610	286	82.2
	R2	6	2630	389	85.2	2477	540	78.2	2685	567	78.9
		12	1686	286	83.0	2017	431	78.6	2020	312	84.5
		18	1399	273	80.5	1543	279	81.9	1613	270	83.2
Cond-MS	R0	0	3724	1111	70.2	3957	1325	66.5	4612	1512	67.2
	R1	6	2709	467	82.8	2519	701	72.2	2783	623	77.6
		12	2191	405	81.5	1687	422	75.0	2039	396	80.6
		18	2034	360	82.3	1589	345	78.3	1692	317	81.3
	R2	6	2647	461	82.6	2409	598	75.2	2699	607	77.5
		12	1790	345	80.7	1930	480	75.1	1874	341	81.8
		18	1412	251	82.2	1512	311	79.4	1616	282	82.5

4.1.4 Effect of Rejuvenator Type (R1 vs. R2) on Marshall Stabilities

The effect of the rejuvenator type on both the Marshall and Conditioned Marshall Stabilities was investigated by comparing the results obtained for the two rejuvenators used in this study. Figures 4-11 and 4-12 compare the stability results at three dosage levels and at two test temperatures. Note that the stability values in the figures were averaged over samples made from the three different RAP sources.

Examining the CI of the stabilities between the two rejuvenators shown in these figures, in a few cases there is a slight difference in the stability obtained for the different rejuvenators between the two temperatures. However, no sufficient statistical evidence was found in any of the other investigations of the effect of rejuvenator type on either the Marshall or Conditioned Marshall Stabilities conducted for this study. This finding holds true for both the 25°C and 60°C preconditioning temperatures.

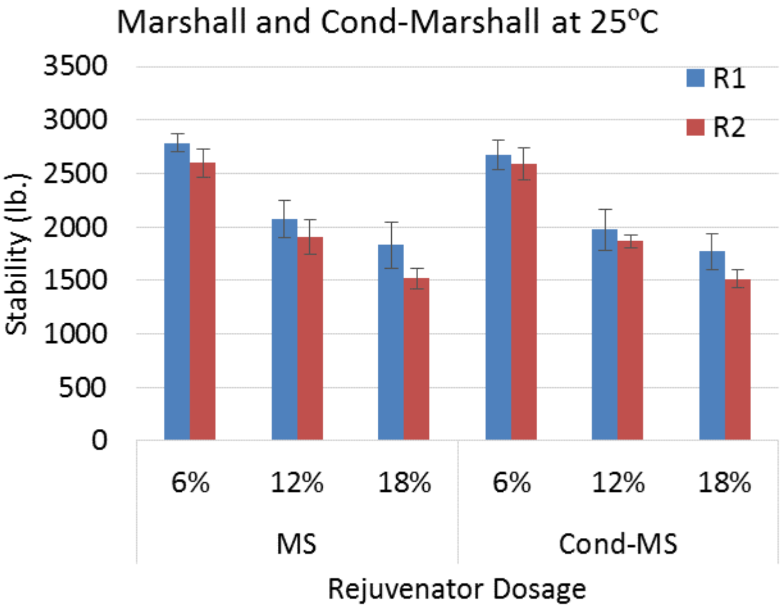


Figure 4-11 Marshall and Conditioned Marshall Stabilities for R1 and R2 at 25°C

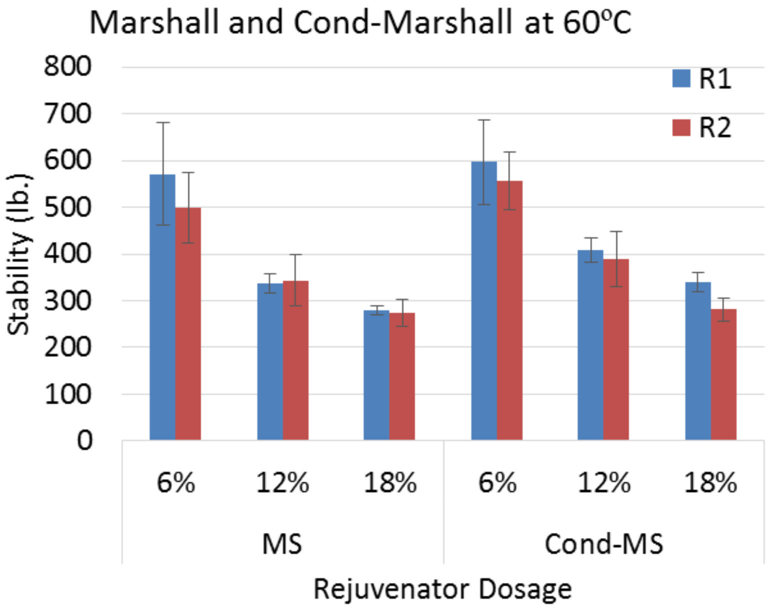


Figure 4-12 Marshall and Conditioned Marshall Stabilities for R1 and R2 at 60°C

4.2 Indirect Tensile Strength Test Result

The results of the ITS tests conducted on the 100 % recycled foamed asphalt mixtures are presented in this section. As in the preceding section, the results are analyzed to determine the effects of different rejuvenator dosage levels, RAP sources, and rejuvenator types. Unlike the Marshall tests, ITS was only evaluated at a single temperature of 25°C, which is the standard temperature specified in AASHTO T 283 [32].

4.2.1 Indirect Tensile Strength and Effect of Rejuvenator

Figures 4-13 and 4-14 show the dry and soaked ITS results, respectively, at three rejuvenator dosage levels of both rejuvenators, along with the results for the control mixtures containing no rejuvenator (R0). When no rejuvenator was incorporated, the ITS values ranged from 38 to 52 psi (an average of 46 psi) for the dry condition ITS and from 35 to 46 psi (an average of 41 psi) for the soaked condition ITS. When rejuvenators were added, the reduction in strength was significant even at the lowest 6% dosage level and as more rejuvenator was added both the dry and soaked ITS values continued to decrease, although the rate of reduction did diminish slightly. At the 6%, 12%, and 18% dosage levels, the dry ITS dropped by 35%, 53%, and 60%, respectively, while the soaked ITS fell 31%, 50%, and 57% at the same dosage levels. The average ITS values were calculated based on two rejuvenators and three RAP sources. These trends are very similar to those seen in the Marshall and Conditioned Marshall Stability results reported in the previous sections. The individual ITS test results are summarized in Table 4-5.

Based on the dry and soaked ITS results, TSR was calculated for R0 and the recycled foamed asphalt mixtures containing rejuvenators. The results are shown in Figure 4-15. The TSR results were consistently above 80% for all the recycled foamed asphalt mixture combinations, which can be interpreted as indicating a satisfactory performance with respect to moisture susceptibility. No clear trend was found in TSR for the effect of rejuvenator dosage level.

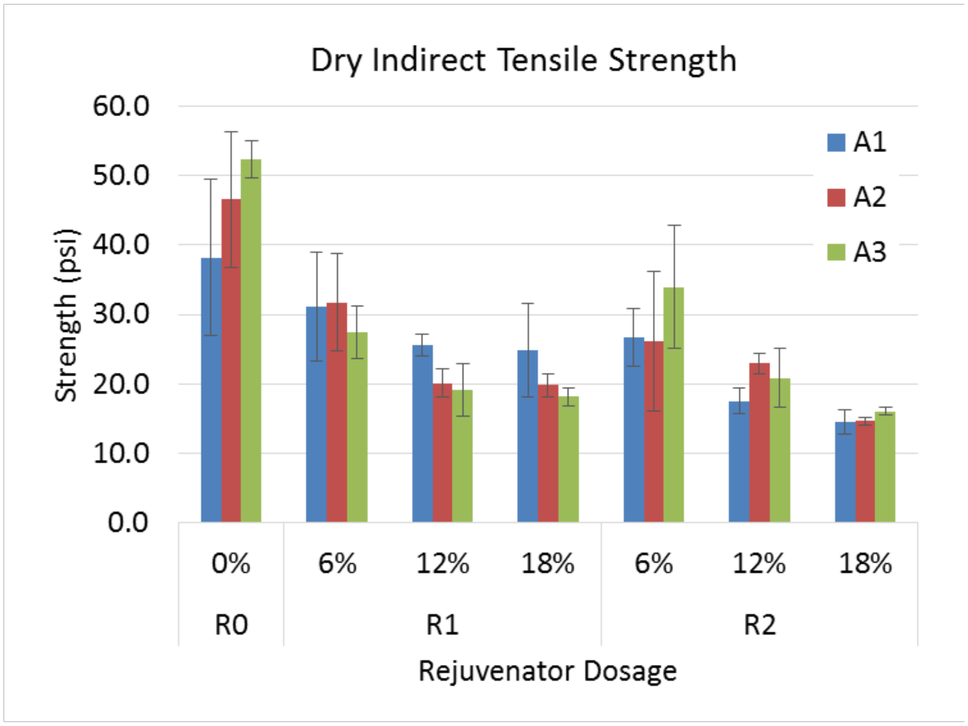


Figure 4-13 Dry Indirect Tensile Strength Results

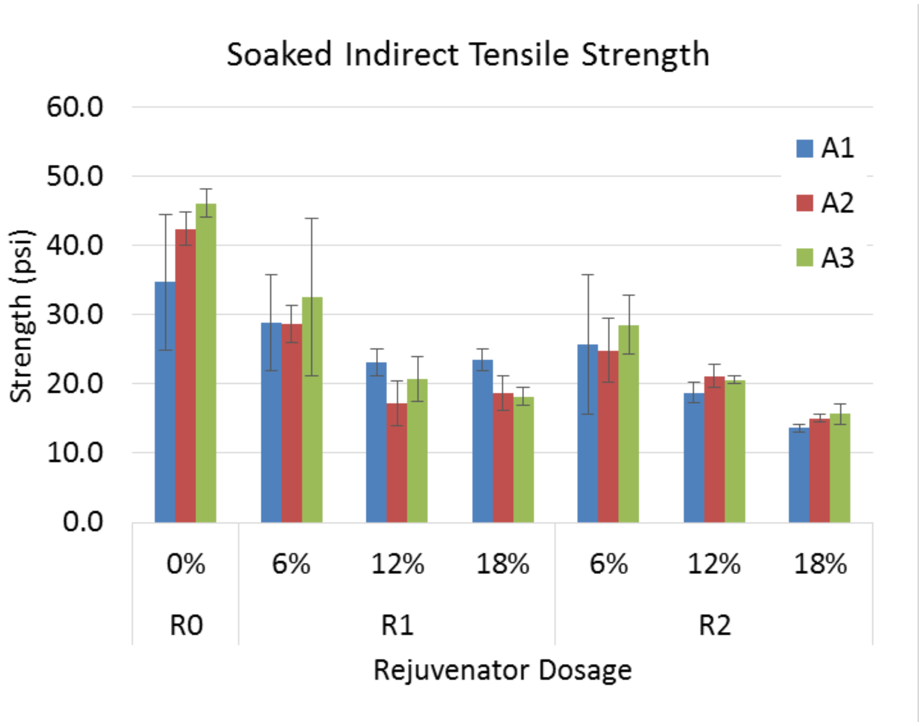


Figure 4-14 Soaked Indirect Tensile Strength Results

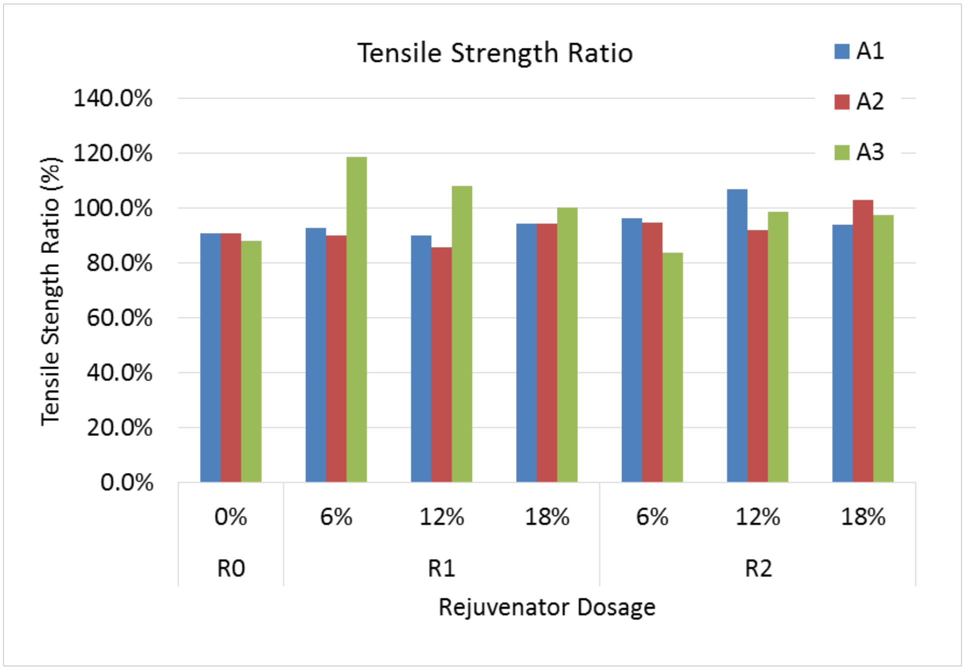


Figure 4-15 Tensile Strength Ratio of Foamed Asphalt Mixtures

Table 4-5 Percent Reduction in ITS with Rejuvenator

Property	Rejuvenator Type	Dosage Level (%)	A1		A2		A3	
			ITS (psi)	Reduction (%)	ITS (psi)	Reduction (%)	ITS (psi)	Reduction (%)
Dry ITS	R0	0	38.2	-	46.6	-	52.4	-
	R1	6	31.1	18.5	31.8	31.8	27.4	47.6
		12	25.6	33.0	20.1	56.8	19.1	63.5
		18	24.8	35.0	19.8	57.6	18.1	65.4
	R2	6	26.7	30.2	26.2	43.8	34.0	35.2
		12	17.5	54.2	22.9	50.8	20.9	60.2
		18	14.5	62.1	14.6	68.6	16.0	69.4
Soaked ITS	R0	0	34.7	-	42.4	-	46.1	-
	R1	6	28.8	16.8	28.6	32.4	32.5	29.4
		12	23.1	33.5	17.3	59.3	20.7	55.1
		18	23.4	32.4	18.6	56.0	18.2	60.6
	R2	6	25.7	26.0	24.8	41.4	28.5	38.1
		12	18.7	46.0	21.1	50.2	20.6	55.4
		18	13.6	60.7	15.0	64.5	15.7	66.0

It is quite difficult to determine whether the ITS results shown above are acceptable or even reasonable because there are no universally accepted guidelines in the United States for appropriate ITS values for foamed asphalt mixtures containing 100% RAP, although a few agencies have set their own thresholds for minimum dry or soaked ITS; these are shown in Table 4-6. Previous research in this area has shown that the range of ITS results obtained can be very wide because they depend on so many variables, including the asphalt content, gradation type and amount of fines, additives, type of recycling, and amount of RAP in the mix, among other factors. For example, in their investigation of foamed asphalt mixes Kim et al. (2011) reported that the ITS ranged from roughly 300 to 600 kPa (equivalent to 43-87 psi) for the dry condition and 200 to 600 kPa (equivalent to 29-87 psi) for the soaked condition, with three different aggregate gradations and other variables [27]. Fu et al. (2008) reported a set of ITS test results that varied by approximately 400-950 kPa (equivalent to 58-138 psi) for the dry condition and 80-250 kPa (equivalent to 80-36 psi) for the soaked condition in their study of aggregate gradations containing about 10% fines [23]. They also found that Maryland materials had an ITS of around 60-70 psi when the dry ITS results were used to determine the structural layer coefficients.

Several state transportation agencies have adopted the dry and/or soaked ITS in their specifications for foamed asphalt stabilized base courses in order to ensure that the base layer is strong enough to resist tensile stress and moisture damage (Table 4-6; note that the state agencies shown in the table use the same curing and preconditioning temperatures and times as those used in this research). The minimum ITS value required by these agencies is 45 psi for both the dry and soaked conditions. Our test results for Georgia's 100 % recycled foamed asphalt mixtures did just meet this minimum specification for dry ITS but did not meet the specification for soaked ITS. However, it is interesting that our TSR results do meet the minimum requirement (50% to 70%) that is typically adopted by other US state transportation agencies.

Table 4-6 Example Specifications for Foamed Asphalt Stabilized Base Layers

State	Curing Condition	Preconditioning		Indirect Tension Criteria (Minimum)		
		Dry ITS	Soaked ITS	Dry ITS	Soaked ITS	TSR
AZ	40°C	25°C	24-hour soak at 25°C	-	45 psi	50%
NM	40°C	25°C	24-hour soak at 25°C	-	45 psi	50%
VA	40°C	25°C	24-hour soak at 25°C	45 psi	-	70%

As the Marshall Stability, an additional set of ITS testing was conducted to verify the rejuvenator effect on the indirect strength and TSR. The test results are presented in Figures 4-16 and 4-17 for dry and soaked ITS, respectively. As clearly seen in the figures, the indirect strength values gradually go down as more rejuvenator is added for both dry and soaked conditions, and this trend is found consistent with the Marshall Stability. A similar result was found on TSR at these lower rejuvenator doses as shown in Figure 4-18. These findings verify that rejuvenator has a softening effect on 100% recycled foamed asphalt mixtures.

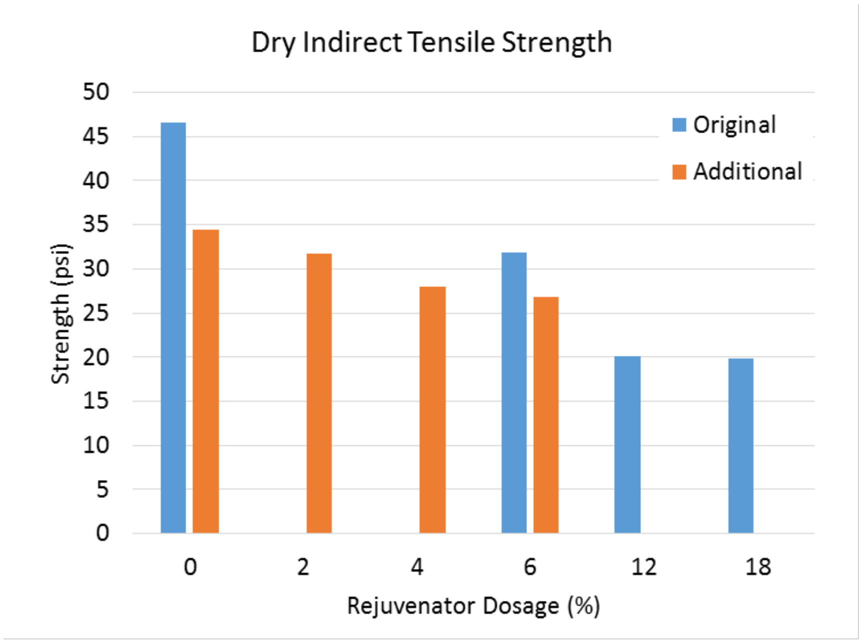


Figure 4-16 Effect of Rejuvenator on Dry ITS at Lower Dosage Levels

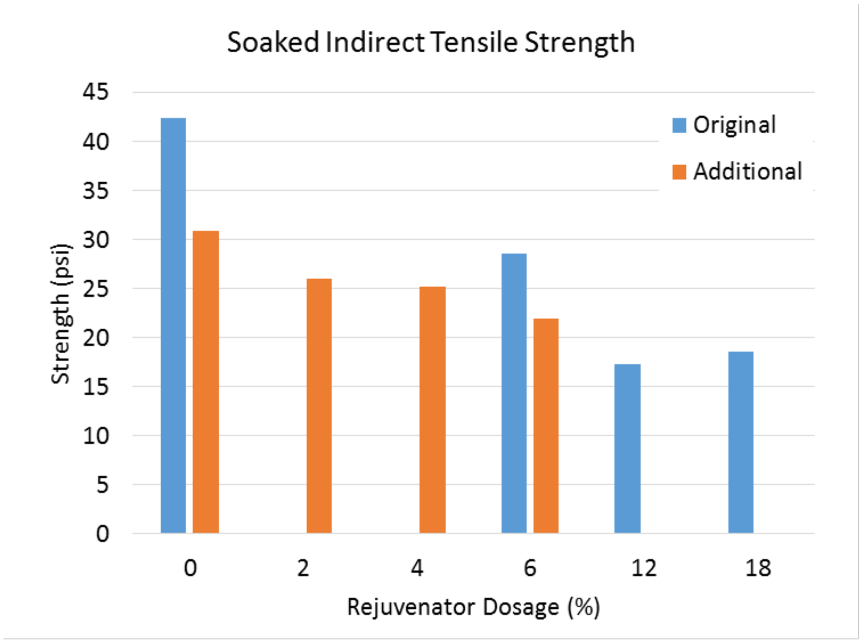


Figure 4-17 Effect of Rejuvenator on Soaked ITS at Lower Dosage Levels

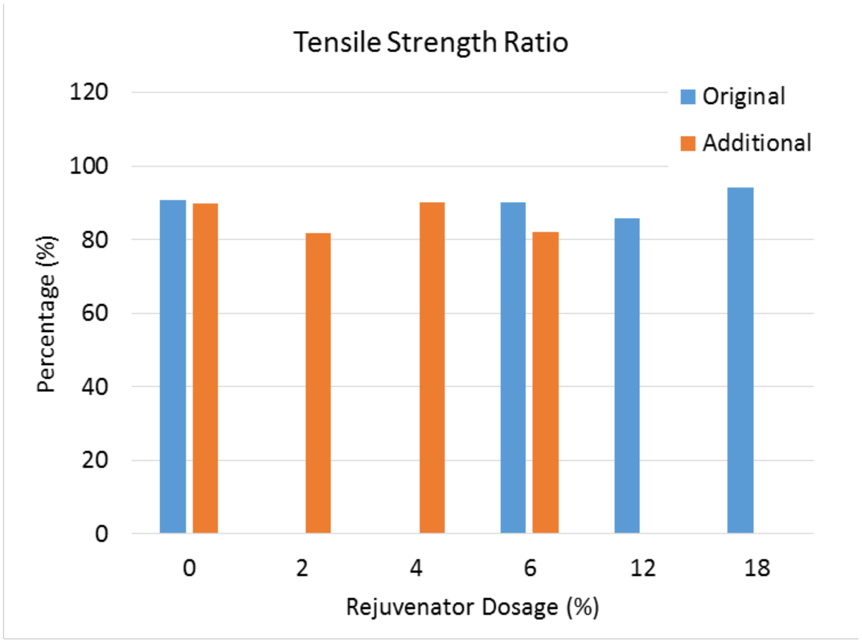


Figure 4-18 Effect of Rejuvenator on Tensile Strength Ratio at Lower Dosage Levels

In summary, the major findings from these results are as follows:

- The effect of rejuvenator on the ITS was significant at a 6% dosage level, but the rate of reduction diminished as more rejuvenator was added.

- The ITS results (46 psi for the dry condition and 41 psi for the soaked condition) barely meet the minimum requirements used in other state agencies. However, the TSR results comfortably exceed the minimum requirements (over 80%) set by the other agencies.

4.2.2 Effect of Rejuvenator Type (R1 vs. R2) on Indirect Tensile Strength

The effect of the two different types of rejuvenator on ITS were also evaluated and the results are shown in Figure 4-19. As with the rejuvenator effect on the Marshall stability, there was insufficient statistical evidence to confirm a significant effect on ITS related to the rejuvenator type. However, an exception was observed when an 18% dosage level was used. At this high dosage level, the R2 rejuvenator was responsible for a greater reduction in both dry and soaked ITS.

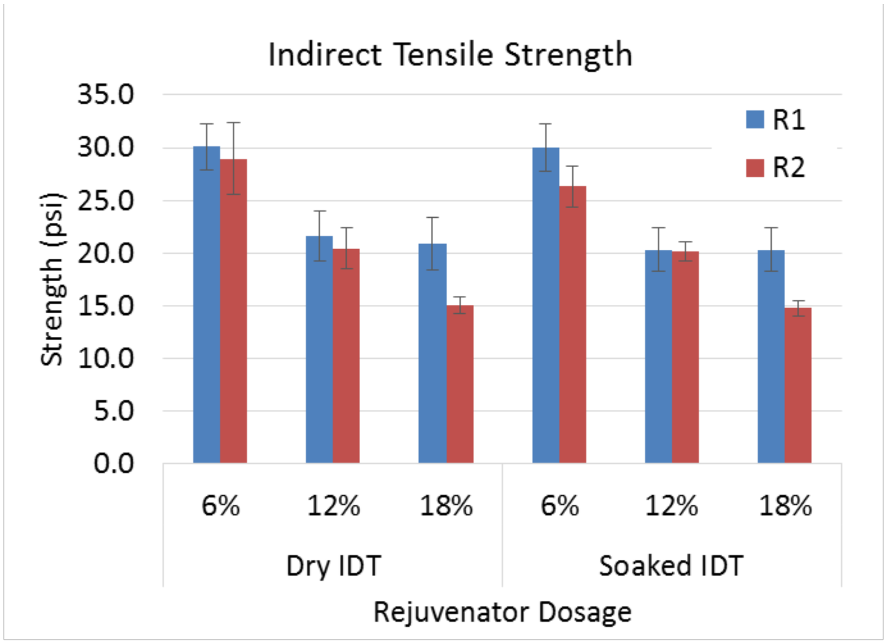


Figure 4-19 Effect of Rejuvenator on Indirect Tensile Strength

4.3 Semi-Circular Bending Test Results

The Fracture Energy (FE) results obtained from the SCB test are illustrated in Figure 4-20. The SCB tests were conducted on both HMA and foamed asphalt mixtures without rejuvenator (R0) and with rejuvenator (R1). Only two rejuvenator dosage levels (6% and 12%) were considered.

Comparing the FE values obtained for HMA and the other recycled foamed asphalt mixtures shown in the figure, the FE of HMA is considerably higher than that of any of the foamed asphalt mixtures. This finding is not surprising as HMA is expected to have a higher stiffness than foamed asphalt materials. However, when the mixture parameter that explains the degree of brittleness (the post peak slope, m, shown in Figure 4-21) is incorporated into the FE, the cracking resistance is actually better represented by the Flexibility Index (FI). Figure 4-21 depicts the degree of brittleness among different mixtures. HMA has the highest m-value, implying it is relatively brittle compared to the foamed asphalt mixtures; foamed asphalt mixtures have much lower m-values, showing they are soft and become even softer as more rejuvenator is added, further reducing their brittleness.

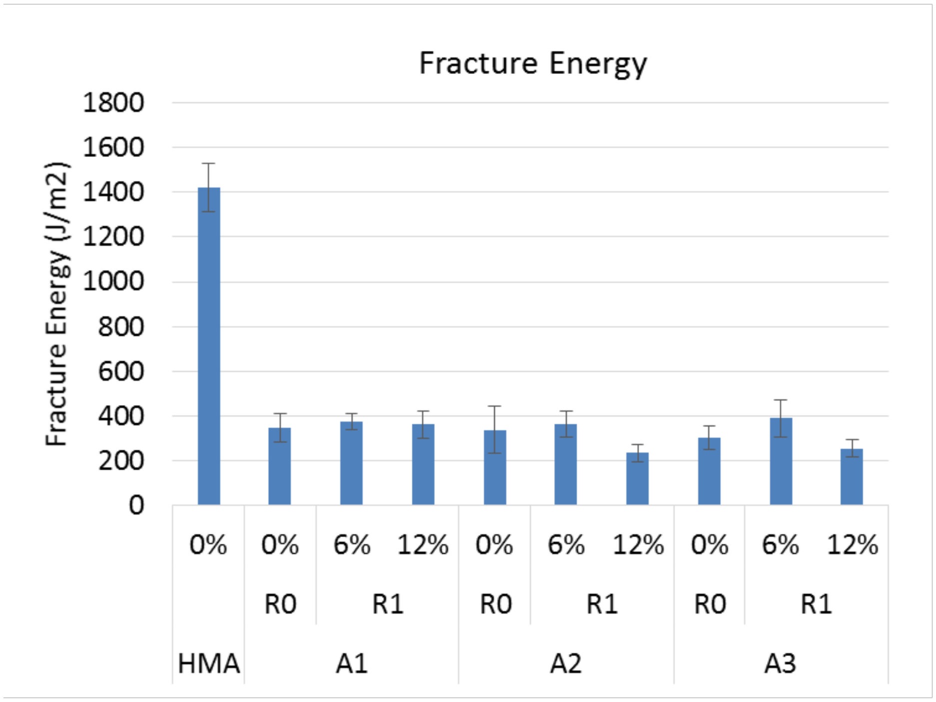


Figure 4-20 Fracture Energy Results from Semi Circular Bending Tests

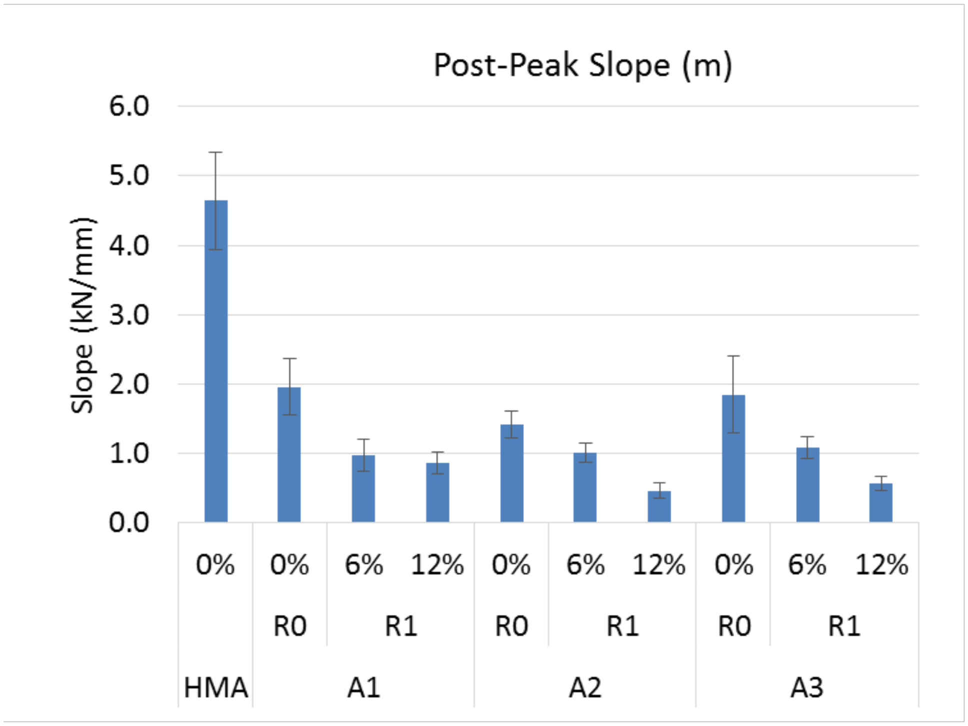


Figure 4-21 Post Peak Slope Results from Semi Circular Bending Tests

The FI, which characterizes the nature of asphalt mixtures in terms of their resistance to cracking, was calculated for HMA and the other recycled foamed asphalt mixtures and the results are presented in Figure 4-22. There are several important trends in the data. First, unlike HMA's FE, which is significantly higher than that of the foamed asphalt mixtures, its FI is actually comparable to those of the foamed asphalt mixtures. In particular, HMA seems more resistant to cracking than the foamed asphalt mixtures when no rejuvenator is used (R0). This finding can be attributed to the fact that 100% RAP mixtures contain aged asphalt binder with only a limited amount of new asphalt binder, which will make the whole mixture relatively stiff, brittle and low in effective binder thus more prone to cracking. Second, when a 6% rejuvenator is added to the recycled foamed mixture, the FI value rises above those of either the HMA or the R0 mixtures. This finding is reasonable because when foamed mixtures are softened with a rejuvenating agent they become less brittle and thus more resistant to cracking. Third, as the dosage of rejuvenator applied in the mix increases, so does the FI value, indicating that the mixtures are becoming even softer. The numerical results obtained from the SCB tests are summarized in Table 4-7.

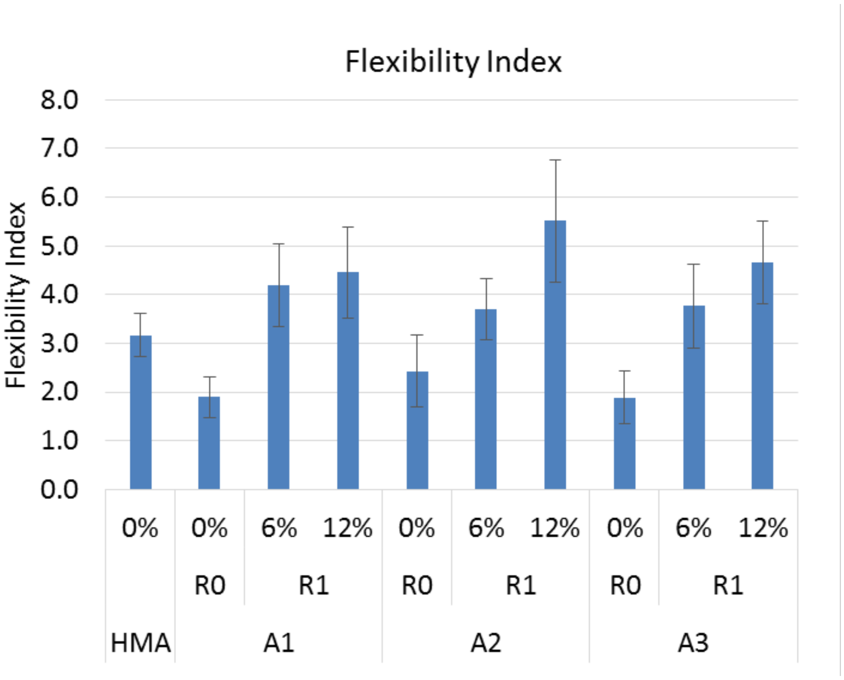


Figure 4-22 Flexibility Index Results from Semi Circular Bending Tests

Table 4-7 Summary of Semi-Circular Bending Test Results

Property	Rejuvenator Dosage (%)	A1	A2	A3	Average
FE	0	347.1	338.2	303.8	347.1
	6	376.9	363.4	388.4	376.3
	12	362.0	234.6	254.6	283.7
m-value	0	1.96	1.42	1.85	1.7
	6	0.98	1.01	1.08	1.0
	12	0.86	0.46	0.57	0.6
FI	0	1.89	2.43	1.89	2.1
	6	4.19	3.70	3.77	3.9
	12	4.45	5.51	4.67	4.9

The major findings from these results are as follows:

- The fracture energies of the foamed asphalt mixtures are significantly lower than that of HMA. However, if the brittleness (expressed as an m-value) is taken into account, the fracture resistances of the recycled foamed asphalt mixtures are comparable to that of HMA.
- For R0 mixtures (no rejuvenator), the fracture resistance (expressed in terms of the FI) of the recycled foamed asphalt is slightly lower than that of HMA. However, when a rejuvenator is added, the mixtures become softer and turn in a better performance than HMA. The FI values increase further as the rejuvenator dosage added to the foamed asphalt mixtures rises.

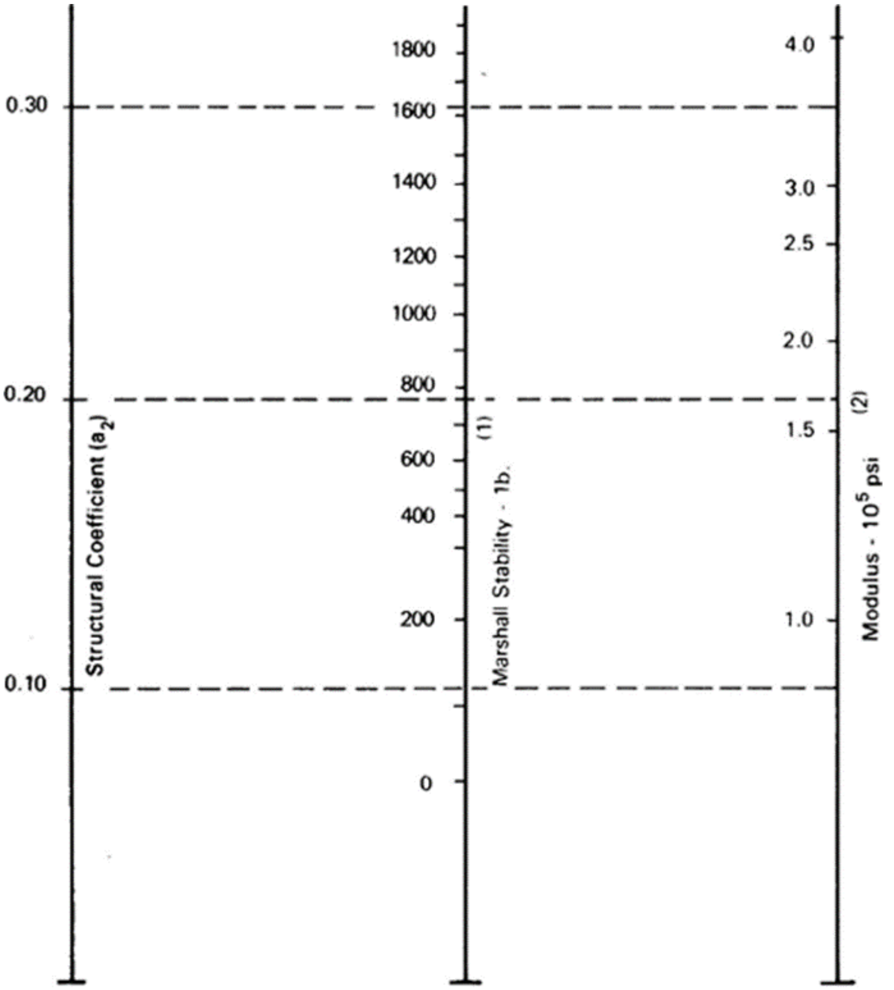
4.4 Structural Coefficient Estimation

The performance test results presented in the preceding sections are summarized in Table 4-8. The results can be categorized in terms of three major asphalt mixture performance indicators: 1) the Marshall Stability, 2) the Indirect Strength with moisture susceptibility, and 3) the Fracture Potential. The ranges for each property result per rejuvenator dosage level (0 to 18%) are listed in the table; the average value for the RAP obtained from the three different sources and the two rejuvenators is shown in parenthesis. Note that the FI results were obtained based on a single rejuvenator at only two rejuvenator levels (6% and 12%).

For practical purposes, the Marshall Stability at 60°C and the ITS were selected from amongst the properties given in the table for the estimation of structural layer coefficients for a bituminous-treated base course. This is because there is currently no method available to correlate any of the other properties with structural coefficients. For Marshall Stability, the 1993 AASHTO *Guide for Design of Pavement Structures* provides empirical relationships between the Marshall Stability and/or the Resilient Modulus and structural coefficients for bituminous-treated bases, as shown in Figure 4-23 [2]. For ITS, Wirtgen has developed the structural coefficient nomograph shown in Figure 4-24 to link ITS, the material's shear properties (friction and cohesion), and its California Bearing Ratio, although no basis on how the nomograph was developed is reported [4].

Table 4-8 Summary of Performance Test Results

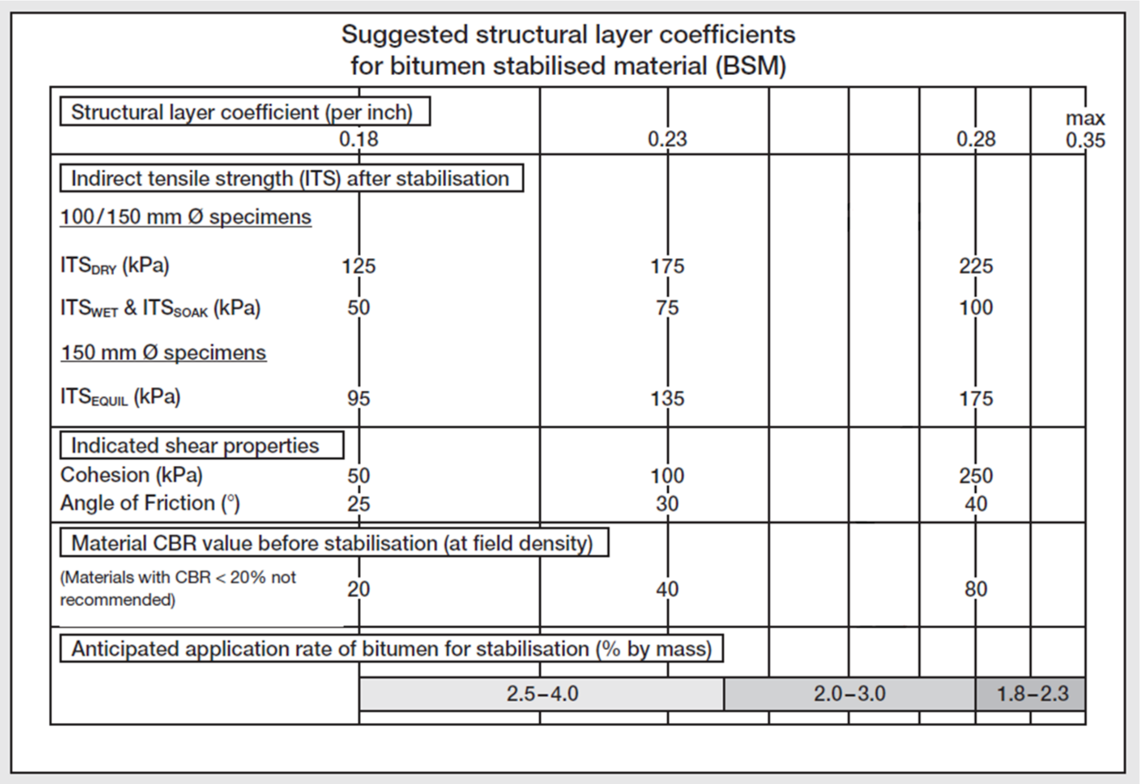
Performance Test Result at OFAC	Rejuvenator Dosage (%)			
	0	6	12	18
MS (lb) at 25°C	3687-4678 (4229)	2477-2817 (2692)	1686-2231 (1990)	1399-2156 (1674)
Cond-MS (lb) at 25°C	3724-4612 (4098)	2409-2783 (2628)	1687-2191 (1919)	1412-2034 (1643)
Re-Marshall (%) at 25°C	92-101 (97.0)	89-101 (97.7)	92-106 (96.6)	92-105 (98.8)
MS (lb) at 60°C	986-1417 (1203)	389-696 (534)	286-357 (340)	270-286 (277)
Cond-MS (lb) at 60°C	1111-1512 (1316)	461-701 (576)	341-480 (398)	251-360 (311)
Re-Marshall (%) at 60°C	107-113 (109.8)	101-117 (109.2)	111-133 (117.6)	92-128 (112.2)
Dry ITS (psi)	38.2-52.4 (45.7)	26.2-31.8 (29.5)	17.5-25.6 (21.0)	14.5-24.8 (18.0)
Soaked ITS (psi)	34.7-46.1 (41.0)	24.8-32.5 (28.2)	17.3-23.1 (20.2)	13.6-23.4 (17.4)
TSR (%)	88-91 (89.9)	84-119 (96.1)	90-107 (96.9)	94-103 (97.2)
FI	1.9-2.4 (2.1)	3.7-4.2 (3.9)	4.5-5.5 (4.9)	-



(1) Scale derived by correlation obtained from Illinois.

(2) Scale derived on NCHRP project (3).

Figure 4-23 Variation in a_2 for Bituminous Treated Bases, AASHTO *Guide* [2]



Suggested structural layer coefficients
for bitumen stabilised material (BSM)

Structural layer coefficient (per inch)	0.18	0.23	0.28	max 0.35
Indirect tensile strength (ITS) after stabilisation				
100/150 mm Ø specimens				
ITS$_{DRY}$ (kPa)	125	175	225	
ITS$_{WET}$ & ITS$_{SOAK}$ (kPa)	50	75	100	
150 mm Ø specimens				
ITS$_{EQUIL}$ (kPa)	95	135	175	
Indicated shear properties				
Cohesion (kPa)	50	100	250	
Angle of Friction (°)	25	30	40	
Material CBR value before stabilisation (at field density) (Materials with CBR < 20% not recommended)	20	40	80	
Anticipated application rate of bitumen for stabilisation (% by mass)	2.5–4.0	2.0–3.0	1.8–2.3	

Figure 4-24 Suggested Structural Layer Coefficients for Bitumen Stabilized Material [4]

Based on the test results summarized in Table 4-8 and the correlations shown in Figures 4-23 and 24, the coefficients were estimated and these are presented in Table 4-9. When no rejuvenator is used, the 100% recycled foamed asphalt mixtures have structural coefficients ranging from 0.22 to 0.27. When rejuvenators are added, the coefficients decrease to average values of 0.17, 0.15, and 0.14 for the 6%, 12%, and 18% dosage levels, respectively.

The layer coefficients estimated from dry ITS show a tendency to overestimate the capacity in comparison to those from Marshall Stability. The estimated layer coefficient for no-rejuvenator recycled foamed asphalt mixtures was found greater than 0.35 which is considered a lot higher than the coefficient of conventional granular base courses. When rejuvenator is added, the coefficients are decreased to an average of 0.25, 0.20, and 0.18 for 6%, 12%, and 18% dosage levels, respectively.

Table 4-9 Estimated Structural Coefficients Based on the Marshall Stability and Dry ITS

	Structural Coefficients (per inch)			
Dosage Level (%)	0	6	12	18
MS (lb) at 60°C	986-1417 (1203)	389-696 (534)	286-357 (340)	270-286 (277)
Structural Coefficients (a_2)	**0.22-0.27 (0.24)**	**0.16-0.18 (0.17)**	**0.13-0.16 (0.15)**	**0.14-0.14 (0.14)**
Dry ITS (psi)	38.2-52.4 (45.7)	26.2-31.8 (29.5)	17.5-25.6 (21.0)	14.5-24.8 (18.0)
Dry ITS (kPa)	263-361 (315)	184-234 (204)	121-176 (145)	100-171 (124)
Structural Coefficients (a_2)	**Over 0.35 (0.35)**	**0.24-0.30 (0.25)**	**0.18-0.23 (0.20)**	**n/a-0.23 (0.18)**

5 FINDINGS AND CONCLUSIONS

This study evaluated the structural integrity of 100 % recycled foamed asphalt mixtures through a thorough examination of their mechanical and performance properties in the laboratory. The experiments conducted for this study included the Marshall Stability, Conditioned Marshall Stability, Retained Marshall Stability, Indirect Tensile Strength, and Semi-Circular Bending Tests. These tests assess the performance characteristics of the mixtures associated with stiffness, indirect strength, moisture susceptibility, and fracture resistance. This chapter presents a summary of the study's findings, conclusions, and recommendations for GDOT.

5.1 Summary of Findings

The major findings from the study are summarized in terms of the following three categories: 1) Material Characteristics and Mix Design, 2) Performance Tests, and 3) Structural Layer Coefficients:

5.1.1 Material Characteristics

- The Optimum Water Content necessary to produce a high quality foamed asphalt cement was found to be around 2.7% (an average of the values obtained for the asphalt obtained from the three different sources: 2.9%, 2.6%, and 2.5%) by weight of asphalt binder. At each of the OWCs, the resulting Expansion Ratio and Half Life met the minimum foaming conditions recommended by Wirtgen (ER > 8 times and HL > 6 sec.)
- An injection speed of 50 grams per second produced a better quality foamed asphalt cement than a faster injection speed of 100 grams per second. No significant difference due to the asphalt cement temperature used was observed among the three asphalt temperatures tested: 160, 170, and 180°C. From a sustainability point of view, the lowest temperature (160°C) was therefore selected for mixing and manufacturing the loose recyled foamed asphalt mixtures.

- The Optimum Moisture Content that provided a maximum dry unit weight of RAP was found to average 6.0% by weight of the dry RAP (5.8%, 5.9%, and 6.2% for the three RAP sources).
- The extracted RAP binder was found to be very stiff, with a high PG of 88 or 94. In theory, in order to decrease the viscosity of the aged binder to PG 64 ($G^*/\sin\delta$ of 2.2 kPa), approximately 16% to 20% rejuvenator was required.

5.1.2 Mix Design and Performance Tests

- An asphalt cement content of 2.5% was identified as the OFAC for designing a 100 % recycled foamed asphalt mixture for the raw materials used in this study. The OFAC was determined based on two performance measures: the Marshall Stability and the Indirect Tensile Strength.
- The Marshall Stability at 25°C with no rejuvenator was found to average 4229 lb. across the three RAP sources. When dosage levels of 6%, 12%, and 18% of rejuvenator were applied, the stabilities dropped to 2692 lb., 1990 lb., and 1674 lb., respectively.
- The Marshall Stability at 25°C can be used for mix designs to identify an OFAC, but it is not recommended that this value is used to estimate the structural layer coefficient because it appears to substantially overestimate the stability and is accordingly incompatible with the estimation method suggested by the 1993 AASHTO *Guide for Design of Pavement Structures*.
- There was some variability in stability among the three RAP sources used in this study. However, the trend of the stability reducing as the rejuvenator dosage increased was consistent throughout.
- The addition of rejuvenator caused a significant reduction in both the Marshall Stability (where it fell by between 24% and 66% as the dosage level increased) and the Conditioned Marshall Stability (where it fell by between 27% and 65%) at 25°C.

- The Percent Retained Marshall Stability indicated that100 % recycled foamed asphalt mixtures were highly resistant to the detrimental effect of water at 25°C.
- The Marshall and Conditioned Marshall Stabilities at 60°C were considerably lower than those measured at 25°C. The overall reduction in stability was found to be around 79.2% when combining all RAP sources, rejuvenator dosages, and the two stability groups.
- The Marshall Stability at 60°C with no rejuvenator was found to average 1203 lb. across the three RAP sources. When dosage levels of 6%, 12%, and 18% rejuvenator were added, these stabilities dropped to 534 lb., 340 lb., and 277 lb.
- An additional set of tests for the lower rejuvenator dosage levels (0%, 2%, 4%, and 6%) verified the trend of reduction in the Marshall Stability at 60°C with the increasing rejuvenator doses. Nearly no change in the stability was observed at a dosage level of 2%, while a noticeable stability reduction was found at 4% and 6% dose.
- The Percent Retained Marshall Stability at 60°C was consistently above 100% for all the mixture combinations tested. This is likely because the specimens were conditioned in an oven, not in a water bath. It is therefore not recommended that this property be used to conduct moisture damage evaluations of foamed asphalt mixture at this temperature.
- There was no significant difference in stability between the two rejuvenators types used in the study in the great majority of the cases tested. This finding holds true for both the 25°C and 60°C preconditioning temperatures.
- The effect of rejuvenator on the ITS was significant at a 6% dosage level, but the rate of reduction diminished as more rejuvenator was added.
- The trend of the consistent reduction in the dry and soaked ITS values with the increase of rejuvenator doses was verified at lower dosage levels (2% and 4%) through an additional set of testing.

- The ITS results (46 psi for the dry condition and 41 psi for the soaked condition) barely met the minimum requirements used by other state agencies. However, the TSR results exceeded the minimum requirements (over 80%) set by the other agencies by a comfortable margin.
- The fracture energies of the recycled foamed asphalt mixtures were significantly lower than that of HMA. However, if the brittleness (m-value) was considered, the fracture resistances of the foamed asphalt mixtures were comparable to that of HMA.
- For no-rejuvenator mixtures, the fracture resistance, expressed in terms of the FI value, was found to be slightly lower than that of HMA. However, when a rejuvenator was added, the mixtures became softer and exhibited a better performance than HMA. The FI values increased as more rejuvenator was added to the foamed asphalt mixtures.

5.1.3 Structural Layer Coefficients

- Based on the Marshall Stability at 60°C, the layer coefficients were estimated to be 0.22-0.27 with no rejuvenator, according to the 1993 AASHTO *Guide for Design of Pavement Structures*. When rejuvenator was added, average coefficients of 0.17, 0.15, and 0.14 were found for the 6%, 12%, and 18% dosages, respectively.
- Based on the dry Indirect Tensile Strength, the layer coefficients for 100% recycled foamed asphalt mixtures were estimated to be around 0.35 with no addition of rejuvenator, according to the Wirtgen's manual. When rejuvenator was added, average coefficients of 0.25, 0.20, and 0.18 were estimated for the 6%, 12%, and 18% dosages, respectively.

5.2 Conclusions and Recommendations

Based on these findings, the following conclusions can be drawn. Recommendations for the GDOT mix design are also provided.

- There is sufficient evidence to show that the 100 % recycled foamed asphalt mixture is sufficiently stiff to be used as a base course in pavement systems in Georgia. A fracture within recycled foamed asphalt mixture is less of a concern because the recycled foamed asphalt layer is usually covered by thick asphalt pavement layers.
- Although the addition of a rejuvenator increases the material's fracture resistance, the use of a rejuvenator is not recommended in a 100 % recycled foamed asphalt mixture because the rejuvenator has a debilitating effect on such mixtures, substantially decreasing their structural integrity even at relatively small dosages.
- It is recommended that GDOT develop a new mix design methodology for 100 % recycled foamed asphalt mixtures, along with a set of appropriate laboratory test methods.
- To verify the long term structural integrity of a 100 % recycled foamed asphalt mixture in a realistic performance test, a pilot study in the field is recommended. Dynamic Modulus (|E*|) and Falling Weight Deflectormeter tests are recommended for the laboratory and field evaluations, respectively.
- If a conventional granular aggregate base is to be replaced by a 100 % recycled foamed asphalt layer, a cost comparison needs to be conducted to quantify the potential economic benefits.

REFERENCES

1. Copeland, A. (2011). *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*. Publication FHWA-HRT-11-021. FHWA, U.S. Department of Transportation.

2. AASHTO (1993). *AASHTO Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington D.C.

3. *Pavement Design Manual: Appendix D-Structural Coefficients*. Georgia Department of Transportation. http://www.dot.ga.gov/PartnerSmart/DesignManuals/Pavement/Pavement%20Design%20Manual.pdf, Accessed Jan. 27, 2018.

4. Wirtgen (2012). *Wirtgen Cold Recycling Technology (1st edition)*. Wirtgen GmbH, Windhagen, Germany.

5. Schwartz, C. W. and Khosravifar, S. (2013). *Design and Evaluation of Foamed Asphalt Base Materials*. Final Report MD-13-SP909B4E. University of Maryland, College Park, MD.

6. Diefenderfer, B. K., Sanchez, M. D., Timm, D. H. and Bowers, B. F. (2016). *Structural Study of Cold Central Plant Recycling Sections at the National Center for Asphalt Technology (NCAT) Test Track*. Final Report VTRC 17-R9. Virginia Transportation Research Council, Charlottesville, VA.

7. Diefenderfer, B. K. and Apeagyei, A. K. (2014). *I-81 In-Place Pavement Recycling Project*. Final Report VCTIR 15-R1. Virginia Center for Transportation Innovation and Research, Charlottesville, VA.

8. Marquis, B., Peabody, D., Mallick, R., and Soucie, T. (2003). *Determination of Structural Layer Coefficient for Roadway Recycling Using Foamed Asphalt*. Final Report. http://rmrc.wisc.edu/wp-content/uploads/2012/10/p26final.pdf, Maine Department of Transportation & Worcester Polytechnic Institute. Accessed Aug 15, 2017.

9. Locander, R. (2009). *Analysis of Using Reclaimed Asphalt Pavement (RAP) as a Base Course Material*. Final Report CDOT-2009-5. Colorado Department of Transportation DTD Applied Research and Innovation Branch, Denver, CO.

10. Romanoschi, S., Mustaque, H., Lewis, P., and Dumitru, O. (2004). *Accelerated Testing for Studying Pavement Design and Performance*. Final Report FHWA-KS-03-8. Kansas Department of Transportation, Division of Operations, Bureau of Materials and Research, Topeka, KS.

11. *Highway Design Guide (February 2015 Edition).* Maine Department of Transportation. http://maine.gov/mdot/hdg/docs/hdg-revised%202-2015.pdf, Accessed Feb. 3, 2018.

12. AASHTO (2016). Standard Specification for Performance-Graded Asphalt Binder. *AASHTO M 320*, Washington, DC.

13. Lee, D. Y. (1981). Treating Marginal Aggregates and Soil with Foamed Asphalt. *Proc. Association of Asphalt Paving Technologists,* Vol. 50, pp. 211-250.

14. Bissada, A. F. (1987). Structural Response of Foamed-Asphalt-Sand Mixtures in Hot Environments. *Transportation Research Record: Journal of Transportation Research Board*, No. 1115, Transportation Research Board, Washington DC. pp. 134-149.

15. Fu, P., Jones, D., and Harvey, J. T. (2011). Micromechanics of the Effects of Mixing Moisture on Foamed Asphalt Mix Properties. *Journal of Materials in Civil Engineering,* Vol. 22, No. 10, pp. 985-995.

16. Kim, Y., and Lee, H. (2006). Development of Mix Design Procedure for Cold In-Place Recycling with Foamed Asphalt. *Journal of Materials in Civil Engineering,* Vol. 18, No. 1. pp. 116-124.

17. Jones, D., Fu, P., Harvey, J., and Halles, F. (2008). *Full-Depth Pavement Reclamation with Foamed asphalt*. Final Report UCPRC-RR-2008-07. University of California, Pavement Research Center, Berkeley, CA.

18. ASTM (2017). Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures. ASTM D2172, West Conshohocken, PA.

19. ASTM (2016). Standard Test Methods for Asphalt Content of Asphalt Mixture by Ignition Method. ASTM D6307, West Conshohocken, PA.

20. ASTM (2015). Standard Test Methods for Mechanical Size Analysis of Extracted Aggregate. ASTM D5444, West Conshohocken, PA.

21. ASTM (2015). Standard Test Methods for Recovery of Asphalt from Solution by Abson Method. ASTM D1856, West Conshohocken, PA.

22. Ruckel, P. J., Acott, S. M., and Bowering, R. H. (1983). Foamed-Asphalt Paving Mixtures: Preparation of Design Mixes and Treatment of Test Specimens. *Transportation Research Record: Journal of Transportation Research Board*, No. 911, Transportation Research Board, Washington DC. pp. 88-95.

23. Fu, P., Jones, D., Harvey, J. T., and Bukhan, S. A. (2008). Dry and Soaked Laboratory Tests for Foamed Asphalt Mixes. *Journal of the Association of Asphalt Paving Technologists,* Vol. 77. pp. 71-106.

24. ASTM (2015). Standard Test Methods for Laboratory Compaction Characteristics of Soil using Modified Effort. ASTM D1557, West Conshohocken, PA.

25. Brennen , M., Tia, M., Altschaeffl, A., and Wood, L. E. (1983). Laboratory Investigation of the Use of Foamed Asphalt for Recycled Bituminous Pavements. *Transportation Research Record: Journal of Transportation Research Board*, No. 911, Transportation Research Board, Washington DC. pp. 80-87.

26. Mohammad, L. N., Abu-Farsakh, M. Y., Wu, Z., and Chris, A. (2003). Louisiana Experience with Foamed Recycled Asphalt Pavement Base Materials. *Transportation Research Record:*

Journal of Transportation Research Board, No. 1832, Transportation Research Board, Washington DC. pp. 17-24.

27. Kim, Y., Im, S., and Lee, H. (2011). Impacts of Curing Time and Moisture Content on Engineering Properties of Cold In-Place Recycling Mixtures Using Foamed or Emulsified Asphalt. Journal of Materials in Civil Engineering, Vol. 23, No. 5, pp. 542-553.

28. Zaumanis, M., Mallick, R. B., and Frank, R. (2014). Determining Optimum Rejuvenator Dose for Asphalt Recycling Based on Superpave Performance Grade Specifications. *Construction and Building Materials*, Vol. 69, No. 30, pp. 159-166.

29. AASHTO (2014). Standard Method of Test for Resistance to Plastic Flow of Asphalt Mixtures Using Marshall Apparatus. *AASHTO T 245*, Washington, DC.

30. ASTM (2015). Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures. *ASTM D6927*, West Conshohocken, PA.

31. *GDT 53-Measurement of Reduction in Marshall Stability of Bituminous Pavements Cause by Immersion in Water*. Georgia Department of Transportation. http://www.dot.ga.gov/PartnerSmart/Business/Source/gdt/gdt053.pdf, Accessed Sep. 16, 2017.

32. AASHTO (2014). Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. *AASHTO T 283*, Washington, DC.

33. Asphalt Academy (2009). *Technical Guideline: Bitumen Stabilised Materials, A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Meterials.* Pretoria, South Africa.

34. He, G. and Wong, W. (2008). Effects of Moisture on Strength and Permanent Deformation of Foamed Asphalt Mix Incorporating RAP Materials. *Construction and Building Materials*, Vol. 22, No. 1, pp. 30-40.

35. Khosravifar, S., Schwartz, C. W., and Goulias, D. G. (2015). Mechanistic Structural Properties of Foamed Asphalt Stabilised Base Materials. *International Journal of Pavement Engineering*, Vol. 15, No. 1, pp. 27-38.

36. Wu, Z., Mohammad, L. N., Zhang, Z. (2013). Accelerated Loading Evaluation of Foamed Asphalt Treated RAP Layers in Pavement Performance. International Journal of Pavement Research and Technology, Vol. 6, No. 4, pp. 395-402.

37. AASHTO (2013). Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry. *AASHTO TP 105*, Washington, DC.

38. AASHTO (2016). Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB) at Intermediate Temperature. *AASHTO TP 124*, Washington, DC.

39. AASHTO (2013). Standard Method of Test for Bulk Specific Gravity of Compacted Hot Mix Asphalt Using Saturated Surface-Dry Specimens. *AASHTO TP 166*, Washington, DC.