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Laboratory Testing and Economic Analysis of High RAP Warm Mixed Asphalt

Final Report

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16. Abstract

This report contains laboratory testing, economic analysis, literature review, and information obtained from multiple producers throughout the state of Mississippi regarding the use of high RAP (50 % to 100%) mixtures containing warm mix additives. The goal of the research was to determine if such a concept was feasible within Mississippi, The project was broad in context and provides information related to many parameters. The result of the research was the concept was feasible.

Economic data was obtained from ten producers in October of 2008 and used in conjunction with Mississippi virgin asphalt price records to perform economic analysis regarding high RAP mixtures, as well as issues pertaining to warm mix additives. The analysis was not comprehensive but provided valuable information. The result was there was no evidence to suggest the concept would be prohibited by economics.

Laboratory testing was performed on hundreds of gyratory compacted samples with varying RAP contents, RAP sources, Sasobit® contents, virgin asphalt quantities, and temperature to investigate compactability and indirect tensile strength of the samples. The results provided no evidence that acceptable air voids could not be achieved at warm mix temperatures using only moderate amounts of virgin asphalt. Indirect tensile strengths were much greater in high RAP mixtures, which could indicate cracking potential. More research is needed to make definitive statements.

Multiple producers of asphalt within Mississippi were contacted to discuss issues related to increased RAP percentage and the use of warm mix additives. The data provided was incorporated into select portions of the research. Overall, the research found no reason to believe that high RAP warm mixed asphalt was not feasible and recommended additional research that would further the cause.

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CHAPTER 1-INTRODUCTION

1.1 General and Background Information

In the early 1970s there was a growing interest in recycling asphalt pavement. That interest was driven by factors still existing today: virgin aggregate shortage, high binder prices, and disposal restrictions. During the 1970's, there was some hesitancy to incorporating recycled asphalt pavement (RAP) back into hot mix asphalt (HMA) because of a lack of understanding of RAP properties, incorporation of RAP into mix design, production processes, equipment, potential for emission problems, and field performance.

Recycled asphalt pavement has been used for at least 35 years. Within the last 10 years, a renewed interest in maximizing its potential has occurred. A steady increase in petroleum prices since approximately 2005 has led to record prices for asphalt binder in 2008 that is forcing DOT's to adjust construction schedules. It is uncertain what will happen beyond 2008, but in any event RAP is a key pavement construction resource that is not fully understood. An additional complexity in Mississippi is the lack of abundant aggregate sources. Crushed gravels are by far the primary source of materials within the borders of Mississippi. Some of the best aggregates available in Mississippi are likely in pavements currently in service.

Recycled asphalt pavement properties as a constituent of HMA have the potential to be superior to combinations of virgin aggregates and binder, due to residual particle coatings. This can be especially significant with high absorption aggregates. This potential, though, can only be achieved through technically sound material characterization and mix design. The tools available in current practice are not adequate to maximize RAP use and potential.

Warm mix asphalt additives have been developed over the past few years and have shown promise to improve the asphalt industry. They are being studied nationwide by numerous researchers. These materials could improve multiple parameters including emissions, energy use, and some construction parameters related to the inclusion of high RAP contents within HMA. Warm mix additives used in conjunction with high RAP content mixtures, though, have not been investigated in sufficient detail.

1.2 Objectives

The objectives of this research are stated in the bullets that follow. In general, the project was not intended to solve any problem to completion, rather to provide an assessment of feasibility of using high RAP content asphalt mixtures, specifically warm mixed asphalts containing high percentages of RAP. The results of the broad assessment were to result in recommendations for future research needs, provided the concept was deemed feasible.

- Perform literature review regarding studies of high RAP content asphalt mixtures, high RAP warm mixed asphalt, economic ramifications of RAP use, characterization methods of value for future work, and similar.
- Conduct economic analysis of high RAP mixtures, alongside analysis related to warm mixed asphalt. The goal of this work was to determine if there is any potential economic benefit within Mississippi provided a technically sound mixture can be

produced. The goal was not to provide a comprehensive assessment of all factors simultaneously, especially those related to full scale production rates.

- Test high RAP content mixtures, the majority of them containing warm mix additives, to determine volumetric properties and indirect tensile strength.
- Discuss the concepts of elevated RAP content mixtures and parameters related to warm mixed asphalt with producers within Mississippi.
- Use all data obtained to provide an assessment of feasibility of the concept of high RAP warm mixed asphalt materials.
- Develop recommendations for future research for any concepts deemed feasible.

1.3 Scope

Materials were obtained from multiple sources within Mississippi representing a wide range of materials and mix designs. The primary intended use for the product of this research project is as a base layer in low and medium traffic roads. To this end, compaction efforts, and material quantities were selected at reasonable values and held constant throughout testing.

The primary thrust of the research focused on mixture performance rather than the individual constituents making up the mixture. Approximately 400 samples were compacted and tested for bulk specific gravity (G_{mb}) and indirect tensile strength (S_t), and approximately 90 samples were tested for theoretical maximum mixture specific gravity (G_{mm}). Volumetrics, compactibility, and indirect tensile strength were selected as key variables for a material likely to serve in the base layer of an asphalt pavement structure. A mixture with acceptable behaviors with regards to these parameters may have potential for future evaluation, while a material with unacceptable volumetrics and/or inadequate tensile strength would not be acceptable for the end use.

The research was broad in nature and did not necessarily aim to develop any one component to completion. Experimental work consisted of many factors and levels with few repetitions so there is not a high level of statistical confidence in any one data point. The testing was intentionally broad to provide a solid foundation for any future research. Complimentary economic analysis and discussion with Mississippi asphalt producers was intended to compliment laboratory testing to provide the feasibility assessment.

Chapter 2 provides the review of literature, while Chapter 3 contains all economic analysis. The economic analysis made use of virgin asphalt prices from the past three decades alongside information obtained in October of 2008 from ten different asphalt producers. The experimental program is described in Chapter 4, and the test results from all testing are presented in Chapter 5. Chapter 6 is the assessment of feasibility. Therein, summaries of a detailed series of questions presented to three asphalt producers are provided and incorporated into the economic analysis of Chapter 3 and test results of Chapter 5 to assess feasibility of the concepts tested. Recommendations of future research are provided at the end of Chapter 6. Chapter 7 provides conclusions and recommendations, and Chapter 8 contains citations of all sources used to complete the research. The report concludes with Appendix A where all experimental data is presented.

CHAPTER 2-LITERATURE REVIEW

2.1 Overview of Literature Review

The review of literature was performed to find information related to use of RAP, but more specifically high RAP contents. Information related to low to moderate RAP contents (say 30% or less) was selectively included. Sasobit® was the only warm mix additive evaluated in the study, therefore specific details related to Sasobit® were included. Otherwise, warm mixed additives were discussed in general terms based on performance and other key items. RAP use in conjunction with warm mixed additives was prioritized during review of literature.

Al-Qadi et al. (2007) is a literature review related to the use of RAP. Some of the sources referenced in Al-Qadi et al. (2007) are included in this document, while others are not referenced since they provide no additional insight into the objectives of the current work. According to the literature review of Al-Qadi et al. (2007), various researchers have investigated the proper methods of utilizing RAP, alongside its corresponding performance characteristics, with widely mixed results providing no clear conclusions. In some studies given parameters have been reported superior, while in other studies given parameters have been reported inferior.

The majority of investigations since the adoption of Superpave have incorporated less than 50% RAP; often much less. This is significant for the current study since all laboratory investigation was for 50% to 100% RAP. Information found during review of literature has been separated into similar categories and presented in the following sections.

2.2 History of RAP Use

As a result of the desire to understand RAP more completely, the FHWA initiated Demonstration Project No. 39, Hot Recycling of Asphalt Pavement Materials. Reasoning for the demonstration project was stated in the background section (FHWA 1979).

> *"The pressing need to conserve energy and minimize costs in highway construction requires that special effort be made to identify and make the maximum use of procedures that will result in reduced energy usage and minimum cost. Because recycling of asphalt pavements has the potential to be an effective method of conserving energy and materials and reducing costs, it is FHWA's policy that recycled asphalt concrete, defined as asphalt concrete containing salvaged paving materials including the use of suitable reclaimed material from other projects, be allowed for use on all projects. States with insufficient experience to properly evaluate the reuse of these materials should take immediate steps to initiate experimental projects."*

There was no limit placed on use of softening agents, added asphalt grade, or percent of RAP. Some projects used 100 percent RAP but it was recognized that batch plants were generally limited to 50 to 70 percent RAP. There were problems of production, emissions, and achieving consistent mixture properties.

A synthesis of highway practice performed in 1978 addressed multiple facets of recycling, including central hot mix plants (Copas and Pennock 1978). During the same period, White (1977) studied 100% RAP in the laboratory in conjunction with two soft asphalt binders (AC-10-127 pen; AC-5-270 pen) and reported that an addition of 1.75% asphalt content was satisfactory in the laboratory for the conditions encountered, and noted that the approach taken was only one of the possibilities. Viscosity modifiers were used by Dunning et al. (1975). They selected to create a target blend viscosity and specimens were compacted by the Marshall method to determine the optimum additional asphalt content. Based on the results, addition of up to 1.5% AR-8000 asphalt binder to recycled pavement was recommended.

The problems observed during the period of the late 1970's to the early 1980's drastically reduced research and implementation of high RAP content mixtures. Many of the problems disappeared with HMA mixtures using lower percent RAP, advent of new equipment (drum mixing plants, milling machines, etc), and industry experience. Into the present day, HMA mixes with RAP in the 10 to 25 percent range are routinely used.

The state of knowledge of high RAP content mixtures did not fully develop over the years from the initial wave of research into present day. A possibility is the lack of inertia and the comfort that was developed when using small RAP quantities. The approaches taken to evaluate RAP, thus, were likely not fully developed and stayed along familiar research paths. Study of only the constituents such as the asphalt binder may only provide limited additional information. As noted by Karlsson and Isacsson (2006);

> *"Generally, most types of negative observations of recycled asphalt performance have been attributed to parameters of great importance in method selection (bearing capacity) and mix design (inadequate binder content, binder stiffness, and/or aggregate gradation). However, studying material properties of reclaimed asphalt is difficult due to its complex constitution and unknown history."*

Note that many of the failures of high RAP content mixes have occurred when unprocessed RAP has been used in HMA plants not equipped to handle the high contents (Bonaquist 2007). White (1977) noted problems of this nature some three decades prior while studying the effect of crushing on mixture voids. After approximately three decades of investigation, a comprehensive understanding of very high RAP mixtures is not available. This is significant in the current environment with high demands on materials and premium prices for virgin materials. A recent document written by Brock and Richmond (2007) indicated the amount of recycling will likely increase over the next 20 years.

2.3 RAP Bituminous Materials and Their Interaction

A long standing question about RAP is; what measures can be taken to account for the aged binder? To date a procedure that can truly account for the behaviors is unavailable. As a matter of fact, many of the original concepts appear to be re-surfacing with the new generation of materials engineers. Quoting White (1977): "*Recyclable material evaluation: Asphalt concrete to be recycled should be evaluated to establish a base line for the mix*

design. This evaluation as a minimum should include field density, extraction and recovery of the asphalt, gradations, and aggregate and asphalt cement classification."

Stiffness of the RAP binder is believed to be a key to producing successful high RAP mixtures; excessive stiffness may cause cracking and compaction problems. During a literature review, Al-Qadi et al. (2007) identified six primary mechanisms associated with age hardening. They are:

1. Oxidation through diffusive reactions between binder and oxygen,
2. Volatilization (evaporation) of lighter binder materials, largely during construction,
3. Polymerization via chemical reaction of molecular components,
4. Thixotropy caused by long structure formation within binder,
5. Syneresis due to the exudation of thin and oily components, and
6. Separation via removal of oils, resins, and asphaltenes by absorptive aggregates.

The greater the pavement damage where RAP was obtained, the greater the changes in binder properties relative to their original state (Al-Qadi et al. 2007). RAP binder can be softened/rejuvenated using materials including flux oil, lube stock, slurry oil, lubricating oils, extender oils, and other specialty blends of bituminous materials.

Two key attributes related to RAP binders are: 1) the total asphalt content within RAP; and 2) the extent of blending that occurs between the RAP asphalt and virgin asphalt. These two parameters are critical to the use of high RAP contents. They are discussed in the following sections.

2.3.1 Determination of RAP Asphalt Content

Measurement of RAP asphalt content poses several issues. Both ignition methods and solvent extraction have positive and negative aspects, especially with RAP. A portion of the asphalt materials community has expressed concern that the asphalt content determined via these two methods could be very different. Ignition methods require correction factors for aggregate loss that can be difficult to determine for RAP (Prowell and Hurley 2005). Hurley and Prowell (2005) indicated a furnace using Tempyrox technology and an internal scale might be able to address the issue for RAP. On the other hand, Huang et al. (2005) reported the same asphalt content (6.8%) from both ignition and extraction procedures.

The state of Oregon uses ignition methods to determine RAP asphalt content and assumes a 0.50% aggregate correction factor, but notes the potential for error in doing so (Thompson 2003). At present RAP contents are limited to 30%, so increasing this value without properly accounting for binder in the RAP could be detrimental to payments and performance. Thompson (2003) attempted to account for the variability using two forms of equations without success.

Peterson et al. (2000) examined several solvent extraction methods in preparation for NCHRP 9-12 and chose the Asphalt Institute TP-2 test method using an n-Propyl Bromide solvent. The authors felt it offered the best combination of safety, accuracy, and repeatability.

2.3.2 Blending of RAP and Virgin Binders

There are three primary theories of blending when utilizing RAP materials within HMA. The first is that the RAP is a black rock. Asphalt binder of the black rock does not

affect the HMA mix. The second theory is that the asphalt binder within the RAP becomes fluid during production and construction and totally blends with the virgin asphalt binder, resulting in a relatively stiffer binder coating of the aggregates. The final theory is that the asphalt binder partially blends with the new asphalt binder. In this instance, there is a zone of binder blending where the properties of the asphalt binder range from being similar to the virgin binder to the very stiff binder of the RAP.

The extent of blending has been widely disputed. Some claim mixes have near 100% blending and that it can occur relatively quickly, while others believe little blending occurs. Stephens et al. (2001) notes current design methods assume complete blending and states this does not occur. To investigate the matter, the authors conducted a study including multiple components. One component of the research tested twelve mixtures to investigate blending. Eleven contained the same virgin aggregate, RAP (15%), and virgin binder. Mixture twelve used the same aggregate structure by removing RAP binder in an ignition oven and using the aggregate alongside virgin aggregate and binder. The RAP was pre-heated between 0 to 540 minutes to assess blending.

Specimens were prepared by Stephens et al. (2001) in the Superpave Gyratory Compactor under 600 kPa pressure and 125 gyrations. Six replicates were made of each mixture. Specimens were tested at 36 C (97 F), three in unconfined compression and three in indirect tension. Results were that pre-heating time noticeably affected load to failure of unconfined compression and indirect tensile specimens. For the indirect tensile specimens, a 29% increase occurred with RAP addition and no pre-heating, and a 48% increase occurred within the RAP mixtures between no pre-heating and 4 hours of pre-heating.

A key summary of the literature of Al-Qadi et al. (2007) is quoted as follows: *"Research has shown that typical recycling projects have achieved blending of the RAP binder and the virgin binder, but have not been able to predict a-priori what the percentage of the RAP binder that effectively combines with the new binder will be. The blending is somewhere between 0 (black rock) and 100% (complete combining of the two binders)."* This finding led to the statement that before higher RAP percentages can be utilized, methods to determine blending potential and account for relative RAP effectiveness must be developed.

If total blending is assumed and no blending occurs the result is a very soft binder with inadequate stiffness and too little asphalt. The reverse is no blending assumed and total blending occurring. The result is a very stiff mixture with excess asphalt. Any blending of binders that does occur is believed to be time dependent.

There are numerous factors that can affect how the RAP truly acts within an HMA mixture. Factors related to production, storage, transportation, and placement can all affect how much blending takes place. The amount of blending can have a significant effect on performance. In order for blending of the new and old asphalt binder to take place, there must first be heat transfer between the new and old asphalt binder. This heat transfer begins in the production stage. The amount of time that the RAP materials are mixed with the virgin materials will depend upon the type and configuration of the HMA production facility.

The existence of large storage silos can also affect the level of blending that occurs. In order to move the produced mixture from the discharge point to the silo, long slat conveyors are generally used. Additional mixing takes place on the slat conveyors. Within the storage silos, the mixture is held at an elevated temperature. The longer the mixture is

stored the more time for the aged RAP asphalt to become heated which increases the potential for blending of the aged and virgin bituminous materials.

Once the HMA is produced, it is placed into haul trucks and transported to the paving site. Depending upon the length of haul time, the amount of blending may change. Long haul times will allow for more blending and short haul times will result in less blending.

In addition to these production/construction issues, the properties of the RAP itself will likely affect the amount of blending that occurs. RAP taken from the roadway via cold milling will generally be a graded material. Crushing and processing is sometimes used to produce a consistent RAP material. The resulting gradation of the RAP material will affect the potential for blending. Within the HMA production process, the finer particles contained within the RAP will become heated first and the larger particles will take longer to reach the intended mixing temperature. Research and experience has shown that the asphalt content of the finer fraction of RAP is higher than the coarser fraction (Khedaywi and White 1995). Therefore, since more asphalt binder is contained within the fine fraction and these materials will reach temperature quicker, there is more potential for RAP materials containing large fine fractions to blend with the virgin materials more than RAP materials containing larger coarse fraction.

The properties of the RAP binder will also affect the potential for blending. RAP materials that contain very oxidized and hard binders will require more heat, mixing and time for blending to occur. As highlighted by the above discussion, there are numerous factors that can influence the amount of blending that occurs in RAP mixtures.

Blending charts have been used when over 25% RAP is included in Superpave mixtures. Blending charts developed by many researchers (notably the Asphalt Institute) have been the primary mechanism to evaluate RAP for nearly two decades. Specifications dealing with mix design of HMA with RAP are: *AASHTO M323: Superpave Volumetric Mix Design; ASTM D 3515: Standard Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures*; and *ASTM D 4887: Standard Practice for Preparation of Viscosity Blends for Hot Recycled Bituminous Materials.* These standards rely on blending charts to assess the effect of RAP on the mix design. For relatively low percentages of RAP this approach can be successful. For high percentages of RAP, this approach may not have the ability to capture the performance of the mixture.

AASHTO M323 specifications recommend softer virgin binder when over 15% RAP is used, and the recommendations assume complete mixing of new and recycled binder. At *low* RAP contents (up to 15%), M323 ignores the effect of the RAP. At *intermediate* RAP contents (up to 40%) NCHRP 9-12 (McDaniel et al. 2001) recommended use of blending charts. At *high* RAP contents (50% or higher) more understanding and control will likely be required. At *high* contents, RAP gradation will be critical to both mix design and performance. Furthermore, the transition from *intermediate* to *high* RAP contents will require a better understanding of the effects of the aged binder on compaction and performance. Approaches taken to date do not address the fundamental issue necessary for incorporation of *high* RAP contents where performance requirements are the same or greater than virgin mixtures. True behavior is partial blending of portions of these materials that amalgamates the particles together; the extent is a function of many variables including temperature, time, and additives (e.g. warm mix additives).

McDaniel et al. (2001) addressed two main questions in addition to the aforementioned contributions: does the RAP binder act as part of the cohesive binder or is it

inert (i.e., a "black rock") and, if the RAP binder does blend, how does it affect the composite binder and the mixture? Three very different RAP sources and RAP contents up to 40% were evaluated. The guiding principle was that mixes with and without RAP should meet the same requirements.

In the end, when the results of the black rock, binder, and mixture studies were considered, a consistent pattern emerged. Low RAP contents had negligible effect, high RAP contents had a significant effect and the results were mixed in the intermediate range. This supported the concept of a tiered system for RAP.

The recommendations of NCHRP 9-12 were adopted by AASHTO. The current specification, then, prescribes that up to 15% RAP by weight of mix may be added without changing the virgin binder grade. At RAP contents higher than 15% up to 25%, the virgin binder grade is adjusted one grade softer to account for the stiffening effect of the hardened RAP binder. At RAP contents above 25%, a detailed design is necessary to select the properties of the virgin binder or to determine the amount of RAP that can be used with a given virgin binder.

A regional pooled fund study in the Midwest looked at three more RAP sources at contents up to 50%. This study showed that the NCHRP results generally held true for the materials tested (McDaniel et al. 2002). This study included a comparison of plant produced mixes to a linear blending chart. In two of the three cases, linear blending worked very well. In the third case, however, the mixture was consistently stiffer than expected based on linear blending, perhaps showing the effects of plant production variables.

The properties of the aggregates contained within the RAP can also affect the amount of old (RAP) asphalt binder available for blending. Aggregates contained within the RAP that are highly absorptive will have old asphalt binder that is absorbed into the aggregate particles. It is highly unlikely that this absorbed asphalt binder will become blended with the new asphalt binder. Therefore, asphalt binder content of the RAP alone may not always indicate the potential for blending. This is especially true in Mississippi. Note, though, that this material is not worthless since it prevents absorption of virgin asphalt, it should not be considered effective binder (P_{be}).

2.4 Laboratory Characterization

Several researchers have performed laboratory characterization work related to asphalt mixtures containing RAP. Additionally, test methods that have been successfully utilized to study fundamental asphalt behaviors have also been identified. The following sections discuss pertinent information of each category.

2.4.1 Laboratory RAP Properties

A comprehensive study of RAP binders mixed with virgin binders was performed by Lee et al. (1999). As RAP binder percentage was increased, the stiffness, G*/sinδ, and creep stiffness values increased. It was considered that Superpave binder criteria of G*sinδ and BBR parameters of stiffness and slope could be used to determine maximum amount of RAP binder to prevent thermal cracking.

Daniel and Lachance (2005) performed laboratory testing on HMA with up to 40% RAP (extracted binders graded at PG 94-14 and PG 82-22) combined with virgin PG 58-28

binder. The results showed an increase in VMA and VFA due to the RAP. To assess the effect of aging, RAP was aged between 2 to 8 hours and observations indicated there was an optimum heating time to allow softening, break down, and blending of virgin materials. Further research into this issue was recommended to simulate plant operations in the lab for mix design purposes.

Huang et al. (2005) investigated how much aged RAP asphalt binder will be blended into virgin asphalt binder under normal mixing conditions. One set of experiments combined minus No 4 RAP (10 to 30%) with plus No 4 aggregate (no binder) and there was a relatively consistent loss of asphalt from the RAP fraction (6.8% to 6.0% or 11% of the aged binder). This binder could be viewed as available to blend with virgin asphalt. Additional experiments where 20% RAP was mixed with virgin binder and aggregate were performed to allow staged extraction of the film thickness. The testing indicated two distinct viscosity zones. The outer portion (≈ 40% of the film thickness) appeared to blend with the virgin binder, while the inner portion (≈ 60%) of the film thickness) retained much of the pure RAP properties.

Staged extraction was used in combination with the Abson recovery method in Iowa as early as the 1970's (Zearley 1979). Increased penetration values were observed for the inner layers of the RAP asphalt coating. The aggregate in question had a high shale content and it was surmised that this contributed to the results. Experiments of determining asphalt content on plus 4.75 mm (No 4 sieve) and the minus 4.75 mm RAP found asphalt contents of 3.0% and 6.8% for the coarse and fine fractions, respectively. The approximate asphalt film thicknesses were calculated for the coarse and fine aggregate fractions, and were found to be identical. Bonaquist (2007) used mixture modulus of plant produced mix to estimate the effective binder modulus. This value was subsequently compared to extracted binder properties to assess the degree of mixing.

Zofka et al. (2005) discussed a technique by which the bending beam rheometer (BBR) was used to test thin beams of mixture cut from cores. The purpose of the research was to investigate the possibility of determining low temperature binder properties without extracting the binder from RAP mixtures. Limited tests using this technique proved useful in obtaining reasonable values for the mixture stiffness.

After removing the top 10 mm (0.40 in) from the top of gyratory prepared cores, six slices, each 12 mm (0.47 in) thick were cut in succession from the top down. Each 12 mm (0.47 in) thick slice was cut transversely to yield six 8 mm (0.31 in) thick rectangular beams. The ends of each beam were trimmed to provide beam dimensions of 8 x 12 x 101 mm (0.31 x 0.47 x 3.98 in).

Due to the fact that measured deflections are small, software modifications were performed to increase the deflection resolution. Using the modified BBR software and a load of 450 g (0.99 lb), creep tests were performed on beams at -18°C (-0.4 F) and -24°C (-11.2 F) after conditioning for one hour. Deflection curves generated by Zofka et al. (2005) are similar to curves typically found from binder testing with the exception that measured deflections are much smaller. Testing of beams cut from various locations within the core specimen revealed that the specimen location had little if any effect on the results of measured BBR deflections.

Whitcomb et al. (1981) produced a series of laboratory mixtures with approximately 80% RAP and 0.3 to 0.5% additional AR 4000W asphalt. A recycling agent (Cyclogen) was also included to reduce the viscosity of the combined asphalt and improve mixture properties.

Results indicated that the viscosity of asphalt recovered post mixing with virgin material and recycling agent was noticeably lower than that for asphalt extracted from the original RAP. The recycled mixes displayed better fatigue properties and lower stiffnesses than the all virgin material control. The all virgin material control was designed to have similar gradation and an asphalt viscosity close to the predicted final viscosity of the recycled mixes. The resilient modulus as determined in the indirect tensile was recommended as a measure of mixture stability for high RAP mixes.

Noureldin and Wood (1989) tested three mixtures containing RAP in combination with recycling agents and compared them to a virgin control made with the same gradation specification and an AC-20 binder. The three recycling agents were proportioned with the RAP binder to produce final recovered asphalt that met the AC-20 specifications for penetration and viscosity. Samples of the mixtures were compacted in the California kneading compactor and then Resilient Modulus and Marshall stabilities were determined. Based on the results they found that Resilient Modulus was an effective indicator of changes in binder/rejuvenator type and binder content. The Marshall stability values were less sensitive to changes in binder content and type but was capable of rating mixtures based on strength.

Laboratory work done by Watson et al. (2008) on stone matrix asphalt used varying levels of RAP up to 30%. Two RAP sources were utilized and one of the sources was further split into plus and minus 4.75 mm fractions. DSR and BBR testing was performed on combined and extracted asphalt binder to determine performance grading. The addition of 10% RAP did not change the PG grading of PG 76-22 compared to the 0% RAP mixture. At 20 % RAP content the high temperature grade was increased to PG 82 for one RAP source. At 30% RAP content the high temperature binder grade was increased to PG 82 for both conglomerate RAP sources and the low temperature grade was increased to PG -16 for the minus 4.75 mm fractionated RAP. Samples of the mixtures were compacted and tested for moisture damage potential (TSR), rutting susceptibility (APA), flexural beam fatigue, and Creep compliance. Results determined that the TSR values did not increase significantly with increased RAP percentage but the unconditioned and conditioned tensile strengths did. The mixes were not found to be susceptible to rutting. No significant effects due to RAP content were seen for thermal cracking as measured by m-value in the creep compliance test. The fatigue life of the 30% RAP mixes was observed to be lower than 0% RAP mixes.

2.4.2 Test Methods of Interest

Lee et al. (1983) developed a testing approach for RAP mixtures to measure the distribution of a recycling agent using dye chemistry. Carpenter and Wolosick (1980) studied the effects of asphalt modifiers on RAP with time after mixing. They found that time-dependant diffusion of asphalt modifiers through the recycled asphalt caused variations in the resilient modulus with time. This indicates the sensitivity of the resilient modulus test to variations in asphalt binder viscosity. Split tension tests have been effective in detecting minor changes due to recycling agents or laboratory aging conditions (Epps et al. 1980).

In a study for the Foundation for Pavement Preservation (FP^2) coordinated by the National Center for Asphalt Technology (NCAT) and Western Research Institute (WRI), torsional creep testing (TCT) was performed with a dynamic shear rheometer (DSR) to measure the effect of cores treated with various rejuvenators (Reinke 2005). The TCT

proved to be suitable for identifying the impact of various rejuvenating additives on in service pavements. The technique was sensitive enough to distinguish the presence of rejuvenator in the top 10 mm (0.4 in) of the pavement compared to the second 10 mm (0.4 in) of the pavement. The TCT may also be used to evaluate the effective blending of virgin asphalt, rejuvenating additive or combinations in HMA mixtures with various RAP contents. It is believed that blending of asphalts in these HMA mixtures would be similar to that of HMA rejuvenators applied to the surface of pavements.

The TCT is recommended to determine the effects of using RAP in HMA mixtures. Either laboratory or field samples can be tested using the TCT. Samples are sawn to 10 x 12 x 50 mm (0.40 x 0.47 x 1.97 in) and tested. Figure 2.1 shows a TCT sample in the DSR.

Figure 2.1. Torsional Creep Test Sample (Reinke 2005)

The PURWheel Laboratory Wheel Tracking Device was originally designed as a flexible, general-purpose tester. The test environment can be either hot/wet or hot/dry. Test temperatures can vary from room temperature to 65°C. Different wheels can be mounted for testing (steel, rubber-coated, or pneumatic wheels are available). Two widths of steel wheels can be used, one the same diameter and size as the steel wheel used on the Hamburg Steel Wheel Tester (Aschenbrener and Curier 1993). However, wheel speed in the Hamburg device varies because its movement is controlled by a crank mechanism. By design the wheel in the PURWheel moves at constant velocity during loading cycles. Other added features of the PURWheel are a transverse mechanism to incorporate wheel wander, a larger sample box to minimize boundary effects, and the instrumentation to measure rut depth through entire length of a slab specimen.

The PURWheel is recognized to have significant potential for evaluating HMA *stripping* and *rutting* performance. Tests can be conducted on laboratory compacted specimens as well as specimens taken from in-service pavements. Studies have demonstrated stripping can be quantitatively evaluated in a laboratory controlled

environment (Habermann 1994). With adequate control of temperature, moisture and wheel load, both rutting performance and *moisture susceptibility* of asphalt concrete can be examined in a short period of time (Pan and White 1997). All these behaviors need to be evaluated for elevated RAP specimens.

2.5 Mix Design

Kallas (1984) proposed modifications to the Hveem and Marshall mix design methods to incorporate RAP with the use of blending charts. A drawback of the approach was that it did not address the issue of binder blending directly but instead experimentally determined the optimum recycling agent or new asphalt content. Five mix designs were performed with five different RAP sources from five different states using between 40 to 52% RAP. High variability in RAP was noted as a potential issue when using RAP. High variability in RAP and mixtures containing RAP has been noted by others including Solaimanian and Tahmoressi (1996) who analyzed four field projects in Texas that contained 35 to 50% RAP.

More recently, the state of Illinois has recognized that 100% contribution from residual RAP asphalt may be inaccurate (Al-Qadi et al. 2007). As of 2007, Illinois HMA mix designs with RAP include a 100% contribution. Many (if not most) other states use similar practices. According to Al-Qadi et al. (2007), the Illinois DOT allowed up to 30% RAP in HMA designed according to Superpave; with notable exception of up to 50% RAP in shoulders and stabilized sub-bases. High RAP content mix designs that adequately account for all parameters are not available.

McDaniel et al. (2001) noted that designing mixtures conforming to Superpave specifications may not be feasible in mixtures with greater than 40% RAP due to the high fines content of many RAP stockpiles. If pavement to be recycled has a high percentage of minus No 200 material, it may be hard to use it since it will have even more minus No 200 material after milling (Roberts et al. 1996).

Two major obstacles in designing high RAP content mixes were identified by Newcomb et al. (2007). The first being stiffness of the aged RAP binder. Use of a softer binder grade to compensate could introduce problems with mixing and diffusion of the binders. The resulting pavement would be vulnerable to damage early in its life before adequate dispersion and diffusion has taken place to reach the target asphalt blend properties. Secondly, use of large RAP percentages can lead to excessive fines due to the often finely crushed nature of RAP from the milling process.

With regard to design, Chehab and Daniel (2006) used the MEPDG software (Level 3) and determined RAP content and binder grade are significant variables. The high temperature portion was found to have a significant effect on predicted amounts of thermal cracking and permanent deformation. The effective binder grade, therefore, is significant to agencies desiring to implement the ME approach (most if not all states eventually).

2.6 Asphalt Mixtures With RAP and Sasobit® Warm Mixed Additive

Sasobit® is an organic hydrocarbon based wax produced by the *Fischer-Tropsch* process (SasolWax 2004). It is manufactured by Sasol Wax GmbH. It has been used in Europe for a number of years and has performed well in service (D'Angelo et al. 2008).

Above its melting point of 100 C (212 F) Sasobit® reduces the measured asphalt viscosity which permits reduction of the mix temperature and promotes asphalt mixing and compaction. Below its melting point Sasobit® solidifies into a lattice structure that stiffens the asphalt binder (SasolWax 2004) and (Mallick at al. 2008). The reduction in mix temperature with Sasobit® is thought to reduce binder aging which will help compensate for its stiffening effects (Hurley and Prowell 2005b).

Laboratory investigation of Sasobit's® effects on volumetric criteria, mix stiffness with indirect resilient modulus, rutting potential in the APA, and moisture sensitivity with the TSR test and the Hamburg wheel tracking device has been performed (Hurley and Prowell 2005b). Three PG binder grades and two different aggregate types (granite and limestone) with similar gradations were used at a range of temperatures. Volumetric criteria were met in mixes with Sasobit® and air voids were generally reduced compared to the control specimens. Results indicated that the potential for rutting was reduced with the use of Sasobit® and the resilient modulus was not significantly affected. Moisture sensitivity was found to be a potential issue with Sasobit® due to incomplete aggregate drying at lower mixing temperature.

A number of field trials with Sasobit® have been constructed in the United States. Hurley and Prowell (2008) reported on two test sections constructed with Sasobit® in Milwaukee and St. Louis that mix properties were identical or improved in comparison to the virgin controls. The exception being a possibly increased susceptibility to moisture damage as indicated by laboratory tests run on the field mixed asphalt. Two trial pavement sections with Sasobit® were placed in late 2006 in Virginia (Diefenderfer et al. 2007). The mixtures used for the sections contained 20% and 10% RAP. 1.5% Sasobit® by total binder weight was added to both mixtures. No significant changes in volumetric properties or rut measurements in the APA were seen. One trial section did not meet the TSR requirements but it was thought this was likely due to high stockpile moisture conditions and lower mix temperature during production.

Mallick et al. (2007) investigated use of 100% RAP as a base layer by the addition of 2.0% neat PG 64-28 asphalt binder in the laboratory. Sasobit® at 1.0% and 1.5% of total asphalt content was tested in 100% RAP at 125 C and compared to 100% RAP without Sasobit® at 150 C. The resulting mixtures were evaluated for workability, compactibility, resilient modulus, moisture sensitivity, and indirect tensile strength. Workability was measured by means of a torque testing device and used essentially as a relative comparison of the effort required to stir the mix, i.e. stiffness. The workability of the mixtures was determined after mixing and then at regular intervals as the mixture cooled. Compactibility was estimated by counting the number of roller passes required to reach density in a slab compacting apparatus.

Workability results indicated that the use of Sasobit® at 125 C either increased the workability (mix was less stiff) or was nearly the same as the 150 C mix without Sasobit®. Resilient Modulus was measured and no statistical difference was found between the 150 C RAP mix and the Sasobit® with RAP mixes. Tensile strength was significantly lower for the 1.0% Sasobit® mix compared to the no Sasobit® mix in the dry state and after one freeze-thaw conditioning cycle but the retained strength values were not statistically different. Of note were the average unconditioned tensile strengths for the 100% RAP at 150 C and with 1.0% Sasobit at 125 C of 1132 and 729 kPa, respectively.

Similar laboratory work performed by Mallick et al. (2008) used 75% RAP with Sasobit® and varying grades of additional virgin binder for base courses. The goal was to create mixtures containing 75% RAP with similar performance properties to a control mixture. The softer grades of additional asphalt were designed to lower the overall mix stiffness of the mixtures containing RAP. The Sasobit® product used was Sasobit® H8 which has a slightly lower melting point than standard Sasobit®. The Sasobit® H8 was added in terms of total asphalt content. The control mix was consisted of 75% extracted RAP aggregate mixed with 25% virgin aggregate and neat PG 64-28 binder at 150 C (the specified mixing temperature for this binder). Mixtures were prepared with 75% RAP and 1.5% neat PG 52-28 mixed at the binder's specified mixing temperature of 135 C and also at 125 C with 1.5% Sasobit H8. Additional mixtures were made with neat PG 42-42 binder at 125 C with and without Sasobit® H8. Tests for air voids, tensile strength, stiffness, and rutting were designated as the comparison criteria.

Air voids of the mixtures were similar to the control with the exception of the mix with PG 42-42 binder at 125 C and no Sasobit® H8 which were slightly higher. The control mix with PG 64-28 binder had the highest average tensile strength (at – 10 C) of any of the mixtures while the mix with PG 42-42 binder and Sasobit® H8 had the lowest. This indicates a reduction in overall mixture stiffness and potential for low-temperature cracking with the use of a much softer neat asphalt binder. Rut depths were less than 4 mm for all mixes but were lowest for the mixtures containing PG 52-28 binder. The seismic moduli of the mixes were also used to evaluate their relative stiffness. The results indicated that the mix produced with PG 42-42 binder and Sasobit® H8 had a significantly lower modulus than mixtures produced with PG 52-28 binder.

Similar levels of performance to conventional HMA for 75% RAP mixtures was possible with the use of very soft grades of asphalt binder and Sasobit® H8 warm mix additive. Similar air voids and comparable mixture stiffness was observed in the mixtures as well as an equal or decreased rutting potential. Although mix temperatures were not greatly reduced (this was intentional), the addition of Sasobit® H8 to mixes containing RAP produced air voids comparable to RAP mixes at standard mix temperature without the additive.

Kristjansdottir et al. (2007) presented a case study in Maryland where Sasobit® was used as workability and compaction aid for mixtures with 35 to 45% RAP. Production temperatures were 138 to 166 C (280 to 330 F) and compaction temperatures were 135 to 154 C (275 to 310 F). No adverse affects were reported based on laboratory and field data (primarily construction) and the authors note that long term performance data is needed to make comparative assessments.

Prowell and Hurley (2007) summarize thirteen field test sections that incorporate Sasobit®. They contain 0 to 45% RAP (6 with 0% RAP, 5 with 10 to 25% RAP, 1 with 35% RAP, and 1 with 45% RAP). Combined benefits of WMA RAP are not completely understood and require further exploration and documentation.

2.7 Other Warm Mix Additive Information

A demonstration project conducted in South Carolina using the *Double Barrel Green System* used 50% RAP (Boggs 2008). The RAP was fractionated into three sizes prior to production. A total of 15,000 tons of warm mixed asphalt containing RAP was placed,

approximately half as surface course. Measured field densities were nearly identical between the WMA and HMA control section and were reached at temperatures as low as 88 C (190 F). Rutting tests conducted in the APA on plant produced mix had lower measured rut depths for WMA than the HMA control (2.9 mm for WMA and 4.4 mm for HMA).

A warm mix demonstration project was constructed in Memphis, TN (Nelson 2008). One of the mixes tested was a Mississippi gravel surface specification mix. No difficulties were encountered reaching density at the reduced production and lay down temperatures.

Kristjansdottir et al. (2007) states reduced viscosity makes the best case for widespread WMA technology adoption. HMA producers are unlikely to adopt WMA technology solely to lower emissions under current regulations, and energy consumption doesn't appear to be sufficient for economical justification. Reduced viscosity was believed to be the best case because: 1) cooler weather compaction problems can be alleviated; 2) less compaction equipment can be used; and 3) risk is lowered when trying to compact stiff mixtures.

2.8 Field Experience with High RAP Contents

As early as 1975, Utah was experimenting with asphalt recycling (Betenson 1979). An initial trial section yielded good results and a second, larger field trial was conducted with 77%, 80%, and 100% RAP in 1977. The 100% RAP required 1.5% of AC-10 virgin asphalt and 0.5% of a softening agent with the goal of combined asphalt graded as an AC-5. Severe problems with emissions requirements were seen during the production of the mix. This was likely due to the way in which the RAP was introduced directly into the drum plant. The resilient moduli of cores taken from the pavement containing RAP one year after placement were lower than those for the conventional 100% virgin mix placed at the same time.

In 1977, Arizona produced a recycled asphalt mix with 80% RAP and 20% virgin aggregate in a drum mix plant (McGee and Judd 1978). Virgin AR 2000 binder (2.7%) was combined with 50% of an aromatic extender oil and added to the RAP mix. The overall asphalt content of the final mix as determined by extraction was 5.3%. The mix output temperature of from the plant was reduced to around 200 F and 2% moisture was added to the aggregate to meet emissions requirements.

Little and Epps (1980) evaluated 25 field projects constructed between 1974 and 1978 involving levels of RAP of 30 to 100% with most utilizing 70% RAP or more. Both surface and base courses were included. Cores taken from the pavements and in place FWD testing were used to characterize the performance of these recycled pavements. An analysis was conducted to determine the appropriate pavement design structural coefficients for these pavement layers as used in the 1972 AASHTO Guide. It was found that "*based on the structural coefficient evaluation, recycled materials used as surface courses are comparable to conventional asphalt concrete surfaces.*" The surface courses containing RAP were found to be slightly stiffer compared to ordinary HMA surface layers. Little and Epps (1980) felt that recycled materials, while stiffer than conventional materials, would perform adequately in relatively thick pavement systems. However, the potential for fatigue cracking of recycled materials in thinner pavement systems was felt to be higher than conventional pavements and would warrant extensive further investigation.

Paul (1996) compared pavements containing RAP to virgin mixtures. Pavements were constructed between 1978 and 1982 and were 6 to 9 years old at the time of evaluation.

RAP percentages of 20 to 50% were incorporated and there were no significant differences found between the recycled and virgin mixtures. Evaluation was based on structural and serviceability aspects with a pavement condition rating (PCR) score and deflection measurements. Ten locations were sampled per roadway to determine material properties with time (e.g. asphalt content, viscosity, penetration, ductility, and gradation).

Kandhal et al. (1995) studied five projects that each consisted of a recycled section and a control section containing between 10 to 25% RAP. Laboratory and field characterization was performed, and paired *t*-testing indicated no significant differences between the RAP and virgin sections when the pavements had been in service 18 to 27 months. A state of recycling practice conducted by FHWA determined that well controlled and constructed pavements containing RAP had performed well up to 17 years after construction (Sullivan 1996).

A recent review of the potential for use of RAP in airfield pavements (Hajj et al. 2008) found that previous use of RAP (less than 20%) in airfield pavements had performed acceptably or that the excessive distresses were not due to use of RAP. A municipal airfield in Illinois had used 100% RAP as a base course underneath a new HMA overlay and was performing well after five years.

2.9 Production Parameters

Several years ago Bloomquist et al. (1993) stated that in excess of 80% RAP could only be used if: 1) RAP is lean in asphalt, and additional soft asphalt could be incorporated without virgin aggregate; and 2) RAP contains a soft binder that need not be rejuvenated. Bloomquist et al. (1993) further states that microwave heating technology was the only way to utilize in excess of 80% RAP due to smoke emission problems. It was further stated that 30 to 50% RAP was the upper limit for conventional plants to allow local air quality compliance requirements.

According to Brock and Richmond (2007) 50% RAP seems to be the current practical limit for HMA producers, and that mixes with up to 50% RAP can be produced if RAP is processed and treated the same as virgin materials. In present time, one of the most significant changes is the capability asphalt producers have to fractionate RAP into more carefully controlled stockpiles. This allows better control of the gradation and affects the percentage of RAP binder included in different RAP fractions. Treating RAP more carefully than current practice, including crushing and screening into two or more stockpiles based on gradation will be key to incorporating large amounts of RAP into mixes (Brock and Richmond 2007).

With regard to warm mixed asphalt, Kristjansdottir et al. (2007) references multiple studies with multiple warm mix products that show 20 to 75% reduction in energy consumption depending on several factors. Sasobit® reduced energy consumption approximately 20%. Kristjansdottir et al. (2007) also reported emissions from WMA are 30 to 98% of HMA emissions.

2.10 Economics Parameters

A number of case studies and economic analyses of recycled asphalt pavements in the 1970s and 1980s were reviewed but are too old for direct applicability to this project. They

included Halstead (1980), Servas et al. (1984), Ruth et al. (1981), Epps et al. (1976), Dunning (1983), Smith (1980), and Kari et al. (1979). No methods or other information was found in these studies that could be used in the current methods. RAP use of 20 to 50% was estimated to provide a cost savings of 20 to 50% when material and construction costs were considered (Kandhal and Mallick 1997). Note that HMA was considered to cost $11.40 per ton in the analysis so the findings are difficult to translate into the current market.

Recent methods of calculating material costs with RAP were also investigated. NAPA (2007) accounts for all RAP asphalt in savings calculations. The authors use simple calculations that account for all RAP asphalt to determine the value of RAP and indicate their approach clearly demonstrates its value. Kristjansdottir et al. (2007) assessed financial implications of warm mixed asphalt with up to 50% RAP. The calculations were straightforward and included material costs, as well as a variety of other costs (energy, trucking, and placement). The other costs were constant with RAP content. RAP was valued at $5 per ton, virgin aggregate at $15 per ton, and virgin asphalt at $400 per ton. A 50% RAP mixture was said to be 76% of the cost of a 0% RAP mixture. In a similar manner, economic analysis of Brock and Richmond (2007) show RAP at very little to no cost.

Economic information related to warm mixed additives was not plentiful. Economic calculations performed by Kristjansdottir et al. (2007) for locations within and outside the US showed fuel costs must be relatively expensive (calculations used $0.58 to $0.79/L ($2.20 to $3.00/gal)) for energy costs to offset WMA expenses. At these fuel prices an energy savings on the order of 50% was required to offset the costs. Over time, though, WMA costs are expected to decrease.

CHAPTER 3-ECONOMIC CONSIDERATIONS

3.1 Overview of Economic Analysis

This chapter summarizes the state of knowledge as it pertains to the economics of warm mixed asphalt with high RAP contents in Mississippi. As seen in the remainder of the chapter, information is sporadic and does not allow conclusive statements of overall economics. English units are used exclusively in this chapter since economic analyses in Mississippi are conducted in terms of tons and gallons. A key assumption made in this report is that all mixtures evaluated have the same field performance. Literature provided little to no data of direct relevance to incorporate into the analysis conducted. The literature review has been provided in Chapter 2.

To properly examine economic implications of any condition it is important to identify the relevant factors and to choose an appropriate method of analysis. Four categories of factors were investigated in this report: 1) equipment and other direct capital costs, 2) construction costs, 3) production costs, and 4) material costs. These factors are discussed in the following sections; albeit to different levels of resolution.

3.2 Equipment and Other Direct Capital Parameters

Equipment and other capital parameters pertaining to this research consist of two categories: 1) Sasobit® introduction into the mixture, and 2) expenditures to modify facilities and allow elevated RAP levels. Warm mix additives (i.e. Sasobit®) will not likely be used with all mixes to be produced at a given facility so the most logical method to introduce the material into the mix may be a pneumatic feed device. The cost of such an installation is an up front capital cost. Kristjansdottir et al. (2007) reported that to purchase and install one of these specialized pneumatic feeders is on the order of $40,000. Renting such equipment may also be an option but is not presented here. The preferred method when using a pneumatic feeder would be to blow the pellets in just before or at the same time as the asphalt is added, but before mixing (Prowell and Hurley 2007).

The location of RAP introduction into the plant at high RAP contents is a concern. One option would be to feed the RAP into the plant closer to the location of the virgin aggregates. Another potential option is a preheating auger for the RAP which is discussed in Chapter 6. If such an auger were to be utilized it would also be a capital investment to be depreciated over its service life. Cost data for this device was not available.

Capital costs for elevated RAP contents and/or warm mix additives will be a factor in increased use. They must be part of the overall financial planning for an asphalt producer but are out of the scope of this study. Note other warm mix additives and/or RAP preheating devices would have different equipment and capital costs.

Sasobit® can be blended into the asphalt binder at the terminal or asphalt plant since high shear mixing is not required (Prowell and Hurley 2007). One disadvantage of terminal blending is the contractor's facility may have limited storage tanks which could hinder production of other types of mixtures. It is unlikely that a producer will provide exclusively warm mixed asphalt in the near future. Estimates of cost to haul and blend the material at the terminal to avoid the need for a pneumatic feed (or equivalent) at the plant were estimated to be between $1.80 and $2.70 per ton, depending on the Sasobit® quantity, based on

information from material suppliers. The cost was assumed to be equal to the raw material cost, or stated another way the material blended at the terminal costs approximately double of material introduced pneumatically at the asphalt plant. The benefit, though, is no up front investment is needed.

3.3 Construction Parameters

One of the purported benefits of warm mix additives is the ability to improve compaction and help stiff mixes achieve density (Prowell and Hurley 2007). Its use is not reported to significantly affect any other aspects of construction. Improvement of the compaction properties of asphalt mixes in the field could conceivably translate to an economic savings by reducing equipment time and labor or reduce the percentage of lots out of specification. Quantifying this behavior would require careful comparison of mixes with and without warm mix additives in a field trial and is beyond the scope of this research.

The reduction in mix temperature and improved compaction of mixes at lower temperatures with Sasobit® have been cited as permitting longer haul distances between the plant and construction location as well as allowing paving operations to be conducted in cooler weather (Prowell and Hurley 2007). Prowell and Hurley (2007) also state that "the rate of cooling is driven by the difference in temperature between the asphalt mixture and ambient air, so that a mixture produced at a lower temperature will cool at a slower rate." An asphalt producer that can provide mix to an extended area due to longer haul distances, as well as mix that could be successfully placed earlier and later in the paving season, obtains an additional benefit that could allow more efficient and profitable production. Since this economic benefit would encompass issues outside of the extent of this study, it will be left to the producer to determine the economic benefits.

3.4 Asphalt Production Parameters

Aside from equipment and direct capital parameters, production parameters as discussed in this report deal only with warm mix additives and are of two types: 1) reduction in emissions by use of warm mix additives, and 2) savings due to reduced energy consumption from reduced mix temperatures. Limited studies of emissions reduction have been conducted but in general a lower asphalt mix temperature leads to lower emissions (Prowell and Hurley 2007). The monetary value of reduced emissions are difficult to quantify but as air quality regulations become more stringent the benefits will become more pronounced.

Production costs could be one of the primary parameters affecting the economics of high RAP content warm mixed asphalt. Reduced tons of mixture per hour could drastically affect economics and have been stated by one Mississippi producer to be the most significant concern of elevated RAP mixtures due to fixed costs of asphalt plants and fixed construction costs (salaried employees and equipment). Specific details of this behavior are beyond the scope of this report and for the most part are speculation at very high RAP contents (in excess of 50%). Below 50% RAP, at least one Mississippi producer stated in phone conversation that they can produce hot mix asphalt with 30% RAP without slowing production. This producer has one facility where RAP is stored in the open air and another plant with half the RAP covered. No differences in production have been observed in these

two cases. This same producer expressed concern regarding production rates in excess of 45% RAP in absence of some type of pre-heating devices. Chapter 6 contains additional details regarding elevated RAP contents obtained from Mississippi producers. As seen, specific information is not prevalent. Full scale production of elevated RAP materials will be required to provide specific insight. Nationally, several projects have used less than 50% RAP, but excess of 50% RAP would be considered rare.

It should be pointed out, however, that production of high content RAP mixes while using warm mix additives is new and may or may not be of concern. Because of the lower production temperatures (due to the WMA additives), emissions are not as much of a concern. Therefore, RAP may be able to be added through the virgin aggregate feeds. This will need to be evaluated in future work, if warranted.

Heating costs are substantial in asphalt production. Section 3.4.1 investigates moisture conditions as they will affect heating costs. Section 3.4.2 investigates thermodynamics of mixtures, and includes potential effects of warm mix additives.

3.4.1 Effects of Moisture on Production

Detailed investigations of RAP stockpile moisture conditions are not common, or at least are not widely published. Stockpile moisture is measured in asphalt production with or without RAP, but from what information the authors have obtained it appears to be taken mostly at the edge of the stockpile. Key facets of RAP acquisition and storage include the large quantity of water used during cold planning (*CP*), moisture removal during hauling, and the ability of the stockpile to dry out from the initial moisture and future rainfall.

During *CP* (i.e. milling), water is required to cool the cutting bits and secondarily to control dust. Up to 2,000 gal of water per hour are used during the milling process. The amount of water used during milling is expected to vary widely depending on the material and equipment operator. Phone conversation with a large company who manufactures asphalt equipment including milling machines (*Roadtec)* in April 2008 indicated a wide discrepancy of water use quantities that would be expected to vary depending on the material and the contractor, and that they were not aware of standard values used within the milling industry.

Conversation with a local company (*J.C. Cheek Contractors, Inc*) who routinely performs milling roughly estimated they use 4,000 to 5,000 gal of water during a typical day when they mill approximately 1,200 tons of material. This could be crudely translated to 1.4 to 1.7% moisture added during milling. The company representative also indicated that by the time a typical load of milled RAP is transported from the job site to the stockpile that it has dried a considerable amount. Personal communication with asphalt industry experts revealed an estimated value on the order of 1.0 to 2.0% moisture added during milling. Other responses revealed estimates of 0.8 to 1% for smaller milling machines used for city and county projects. The consultation also revealed up to 15 gal of water per ton of milled asphalt could be used depending on asphalt texture (6.3% moisture).

Data obtained regarding milling and hauling did not provide conclusive information regarding RAP stockpiles moisture conditions. More data regarding moisture conditions of RAP stockpiles as a function of: 1) depth into stockpile; 2) size of stockpile; 3) type of stockpile (i.e. fractionated or not); 4) with time; and 5) with regards to rainfall events is needed. Information obtained from literature, local asphalt producers, and by the MSU

research team from sampling RAP stockpiles provided additional information. Information from producers and MSU sampling are summarized in this chapter while more information is provided in Chapter 6.

Based on limited information, it appears RAP stockpiles have a tendency to increase/decrease in moisture content over time. Moisture contents of 5% (+) have been measured for stored RAP (Smith 1980). Decker and Young (1996) found that during periods of excessive precipitation RAP stockpile moisture contents can reach 8%. To successfully produce asphalt mixes consisting primarily of RAP the moisture content will have to be seriously considered since heating is often more limited than for virgin aggregates.

Phone conversation with one Mississippi asphalt producer indicated their RAP stockpile moisture contents remained relatively constant in the interior of the pile. The variability was indicated to occur in the first two feet from the edge of the pile. The producer also indicated RAP stockpiles, in general, tend to shed moisture making their internal moisture contents less than that for a coarse aggregate stockpile (e.g. crushed gravel).

Moisture contents were taken from the four sources of RAP obtained and tested in this report. Details are found in Chapter 4. For purposes of this section, the sources can be divided into two categories: 1) obtained directly from milling; and 2) obtained from stockpiles at asphalt production facilities. The results can be found in Table 3.1 alongside producer data described in Chapter 6.

Table 3.1. Summary of Moisture Content Data

Type	Source[1]	Category	n	Avg.	St. Dev.
Bulk	PL	Milling[2]	8	7.5	0.93
	MS-25	Stockpile	1	7.3	---
Crust	MS-25	Stockpile	1	1.2	---
	Bonds	Stockpile	1	1.8	---
Surface[3]	I-55	Stockpile	4	5.0	0.15
	SP	Stockpile	3	4.9	2.10
	MS-25	Stockpile	2	7.6	0.65
	APAC[5]	Stockpile	9	5.2	0.94
Interior[4]	MS-25	Stockpile	2	8.7	0.07
	Bonds	Stockpile	1	5.2	---
Low Setting[6]	Superior	Stockpile	---	2.0	---
High Setting[6]	Superior	Stockpile	---	5.7	---

1: Chapter 4 Terminology
2: Obtained directly after milling but before hauling
3: Near surface (within 2 ft) but not from the outer crust (outermost 3 to 4 in)
4: Interior of Stockpile (more than 2 ft from outermost portion of stockpile)
5: Weekly values were taken over a three month period and averaged from nine plants throughout Mississippi
6: Moisture content values used to account for moisture conditions within stockpiles

As seen in Table 3.1, moisture values measured in the stockpiles can be quite high. These values are not intended in any to predict moisture content, rather to show possible values.

One parameter to note that is not considered herein is some warm mix products (e.g. foamed asphalt) add moisture to the mixture. The significance lies with the virgin aggregate sources used in Mississippi (overwhelming majority of aggregates are high absorption gravels), and the RAP stockpile moisture considerations. One of the most substantial

problems experienced within the state paving operations is tender mixes during compaction; moisture is known to be a very common cause of tenderness.

One of the primary perceived advantages of the Sasobit® warm mix additive, and a reason it was chosen for inclusion in this study, is that no additional water is added to the mix. Sasobit® is an organic synthetic wax additive produced from coal or natural gases by the Fischer-Tropsch process (Prowell and Hurley 2007).

3.4.2 Thermodynamics of Asphalt Mixtures

The changes in energy required to produce a ton of warm mix asphalt compared to a ton of hot mix asphalt can be approached from a thermodynamic standpoint. Once the estimated reduction in mix temperature due to the use of warm mix additives is known, a simple estimate of energy cost savings can be made by neglecting the plant's energy losses. No data was available with regards to these losses in production of warm mix or hot mixed asphalt. The actual energy savings will be less than the simple estimate due to heat losses within the plant and the threshold amounts of energy required to operate the plant at any mix temperature. An analysis of exact energy savings will be dependent on the specific asphalt plant and production process. Among the factors is efficiency of the plant, energy losses within the plant due to insulation, and similar. A complete energy survey of a given plant would be necessary to properly quantify these variables, however the approximate energy requirement calculations provided in this report will allow for reasonable comparison of asphalt mix alternatives.

A simple thermodynamic model paralleling the work of Harder et al. (2008) was used for the asphalt production process. It is created by determining the amount of heat required to raise the mix components from ambient temperature to the mix temperature. The three components of an asphalt mix are: 1) aggregate, 2) asphalt binder, and 3) moisture contained in the aggregate. The required heat is calculated for the aggregate and asphalt binder by multiplying the mass of the component by its specific heat and the difference between the mix temperature and ambient, or initial, temperature. For the moisture in the mix the same procedure is used only with the addition of a phase change from liquid to vapor at 212 F. Additionally the specific heat of water as a vapor is different than for water as a liquid.

The amount of potential energy savings due to change in mix temperature depends on the moisture content of aggregate as well as initial and final temperatures of mixture. The reduction in energy required to produce the mixture directly translates into a savings to the asphalt producer by reducing fuel consumption. The aforementioned thermodynamic model used by Harder et al. (2008) that could also be found in many thermodynamics references is used to illustrate the influence of aggregate moisture content on energy reduction as shown in Table 3.2. Table 3.3 uses Table 3.2 data to illustrate relative influences in energy at a given moisture content.

As seen in Table 3.3, as the aggregate moisture increases the energy savings decrease because there is more material that must undergo the phase change, which requires noticeable energy. The importance of reducing stockpile moisture (RAP or virgin aggregate) is apparent when a reduction of moisture from 8.0% to 2.0% is considered at a typical hot mixed temperature of 310 F. These values were selected as examples by using the data in Table 3.1. The difference in energy required is 133,328 BTU per ton. If a plant is operated on diesel fuel (diesel has net heating value of 132,000 BTU per gallon) that costs $4.00 per

gallon then that energy difference equates to $4.04 per ton of mix produced. For a plant producing 2,000 tons per day (many plants can easily reach this capacity) the daily cost reduction is $8,080. This reduction does not consider costs to lower moisture (e.g. placing material in covered areas).

The data presented clearly demonstrates the importance of RAP stockpile moisture conditions (See Section 3.4.1). The example provided incorporated the relative extremities of values found during the investigation of this report and therefore should be taken as a maximum value based on the data available. More information is needed for complete quantification of these behaviors.

Table 3.2. Energy Required to Heat One Ton of Asphalt

w (%)	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Temp (F)	Result[1]	Result[1]	Result[1]	Result[1]	Result[1]	Result[1]	Result[1]	Result[1]	Result[1]	Result[1]
190	51057	52865	54673	56482	58290	60098	61907	63715	65523	67331
200	55575	57543	59512	61480	63448	65417	67385	69353	71322	73290
210	60093	62222	64350	66478	68607	70735	72863	74992	77120	79249
220	84046	105770	127493	149216	170939	192662	214385	236108	257832	279555
230	88460	110239	132017	153796	175574	197353	219131	240910	262688	284467
240	92874	114708	136541	158375	180209	202043	223877	245711	267545	289379
250	97287	119177	141066	162955	184844	206733	228623	250512	272401	294290
260	101701	123646	145590	167535	189479	211424	233369	255313	277258	299202
270	106115	128115	150114	172114	194114	216114	238114	260114	282114	304114
280	110528	132584	154639	176694	198750	220805	242860	264916	286971	309026
290	114942	137053	159163	181274	203385	225495	247606	269717	291827	313938
300	119355	141522	163688	185854	208020	230186	252352	274518	296684	318850
310	123769	145991	168212	190433	212655	234876	257098	279319	301540	323762
320	128183	150460	172736	195013	217290	239567	261843	284120	306397	328674
330	132596	154929	177261	199593	221925	244257	266589	288921	311254	333586

Note: Ambient temperature taken as 77 F and P_b was taken as 6.0%. Heat losses were neglected.
1: Units of BTU per ton

The reduction in energy consumption due to mix temperature reduction with warm mix additives such as Sasobit® is significant but not as large as that for moisture reduction. At a moisture content of 8.0%, the energy savings from a 70 F temperature reduction is 33,608 BTU per ton. At a moisture content of 2.0%, this value is 31,283 BTU per ton at 70 F. Note the reference properties seen in Table 3.2 when considering this data. With $4.00

per gallon diesel fuel with 132,000 BTU per gallon 8.0% and 2.0% moisture contents result in cost savings per ton of mixture of $1.02 and $0.95, respectively.

Table 3.3. Energy Savings for a 70 F Reduction in Mix Temperature

	Total Energy BTU/ton			
Mix Moisture %	**310 F**	**240 F**	**Change**	**Savings %**
1.0	123769	92874	30895	25.0
2.0	145991	114708	31283	21.4
3.0	168212	136541	31671	18.8
4.0	190433	158375	32058	16.8
5.0	212655	180209	32446	15.3
6.0	234876	202043	32833	14.0
7.0	257098	223877	33221	12.9
8.0	279319	245711	33608	12.0
9.0	301540	267545	33995	11.3
10.0	323762	289379	34383	10.6

Note: Ambient temperature is 77 F and P_b was taken as 6.0%. Heat losses were neglected.

The October 2008 price of Sasobit® as obtained from company representatives was $1.50/lb plus freight and handling. Using P_b of 6.0% results in prices of $1.80 and $2.70 per ton of asphalt for 1.0% and 1.5% Sasobit®, respectively. Freight, handling, and blending into liquid asphalt was estimated to be equal to the cost of the product, or $3.60 and $5.40 for 1.0% and 1.5% Sasobit®, respectively.

Based purely on mixture temperature reduction, the use of Sasobit® is justified at 0.3 to 0.5%. The benefits of reducing mixture temperature go beyond the immediate reduction of fuel costs and Sasobit® does more than simply reduce the mixture temperature. Providing adequate compaction and mixing for RAP are also important functions of Sasobit® that must be considered as part of its value.

3.5 Material Costs

The focus of the economic calculations were related to materials. Sasobit® was not included in this analysis since its economic ramifications are dealt with in previous portions of the chapter. Calculations in this section use a large amount of information related specifically to paving in Mississippi. The variables considered in the analysis were:

- Blend of aggregates
- Virgin asphalt binder price
- Virgin aggregate price
- Absorption of liquid asphalt
- Amount of asphalt in RAP that behaves as asphalt in new mixture

The following sections address each of these items to provide reasonable estimates of material cost ramifications. A significant amount of information is presented pertaining to Mississippi materials, and placing a value on RAP was found to be one of the more difficult aspects of the analysis.

3.5.1 Virgin Control Mixtures

Two 100% virgin mixes were used for comparison of economics with respect to mixtures containing RAP. Table 3.4 summarizes the properties used during the analysis. Mixture A is the virgin control mixture developed in Chapter 4 (aggregate blend 3 in Chapter 4 terminology), and Mixture B is an alternate design with a higher percentage of limestone to represent portions of Mississippi that would be prone to higher limestone percentages (no testing of this mixture was performed). Producers in MDOT Districts 3 and 6 would be candidate users of Mixture B. Data from testing of Mixture A was used at various locations in the analysis to provide reasonable estimates of properties.

Table 3.4. Properties of 100% Virgin Mixes Used as Control Samples

Property	Mixture A	Mixture B
Crushed Gravel (%)	81	49
Limestone (%)	8	40
CS (%)	10	10
HL (%)	1	1
G_{se}	2.478	--
G_{sb}	2.425	--
G_{mm}	2.285	--
P_b	6.00	5.82
P_{ba}	0.91	0.71
P_{be}	5.15	5.15
Abs[1]	3.1	2.4
P_{ba}/Abs	29.4	29.4[2]
P_s	94.00	94.18

1: Weighted average of individual absorption values.
2: Taken as same value measured in Mixture A.

3.5.2 Virgin Asphalt Binder Costs

Mississippi Petroleum index values were extracted for the past three decades for use in this analysis. Tables 3.5 through 3.7 separate the data according to decade and provide summary information of each year and the decade as a whole. The yearly average values over this period are plotted in Figure 3.1. As seen, the average yearly price, in general, fluctuated between $100 to $200 until the past three years. During those periods, dramatic increases in price have occurred. Such dramatic increases have changed mindsets in ways that would not have been considered just a few years ago.

The value of recycling asphalt has increased proportionally to the value of the virgin asphalt binder price. Using additional RAP has many potential benefits including using less virgin binder when the price is excessively high by re-using asphalt that was purchased at a much lower price in previous years. An additional benefit is this would relieve some demand for virgin asphalt that would be expected to lower the price.

Table 3.5. PG 67-22 Prices From Mississippi Petroleum Index in the 1980's

	Prices are in dollars per ton									
Year	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**
Jan	103	130	166	147	150	172	172	92	123	99
Feb	114	142	154	147	152	172	171	88	123	102
Mar	130	160	154	146	154	173	169	96	116	104
Apr	129	167	153	148	158	174	161	99	112	103
May	129	168	151	148	160	175	148	106	110	104
June	129	168	150	148	164	176	137	112	109	106
July	129	168	151	148	167	176	131	122	108	104
Aug	129	168	146	149	168	174	113	123	198	102
Sept	129	168	147	149	169	173	111	125	106	102
Oct	129	168	146	151	170	173	102	126	103	102
Nov	129	166	146	152	171	173	98	123	99	102
Dec	129	166	147	152	171	173	96	123	100	102
Avg.	***126***	***162***	***151***	***149***	***163***	***174***	***134***	***111***	***117***	***103***
Summary: n = 120; mean = $139, standard deviation = $27.0										

Table 3.6. PG 67-22 Prices From Mississippi Petroleum Index in the 1990's

	Prices are in dollars per ton									
Year	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
Jan	102	136	84	89	101	101	120	125	124	118
Feb	102	137	84	96	101	101	120	126	124	117
Mar	104	129	84	97	101	109	120	127	125	117
Apr	105	117	81	98	101	113	120	127	125	117
May	105	109	80	102	101	114	120	127	124	118
June	105	104	81	102	101	115	120	127	122	118
July	104	98	81	103	101	119	119	127	121	120
Aug	102	94	85	103	101	119	121	127	120	120
Sept	114	90	88	101	101	121	122	125	119	122
Oct	128	86	88	101	101	121	122	124	119	127
Nov	135	85	89	101	101	121	122	125	119	132
Dec	136	86	89	101	101	120	125	125	118	140
Avg.	***112***	***106***	***85***	***100***	***101***	***115***	***121***	***126***	***122***	***122***
Summary: n = 120; mean = $111, standard deviation = $14.8										

Readily available tools that allow use of high RAP contents could have dramatic cost implications provided they were ready for implementation. They could help MDOT during periods where the virgin asphalt price remains high for long periods (e.g. 2008), as well as help during short durations where there is a large short term spike in virgin asphalt price (e.g. September 2005). The reverse of this would be to use less RAP during periods where virgin asphalt prices are lower. The following section performs economic calculations of RAP to provide additional information.

Table 3.7. PG 67-22 Prices From Mississippi Petroleum Index in the 2000's

	Prices are in dollars per ton								
Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Jan	145	179	151	182	187	190	224	348	312
Feb	151	174	146	193	186	191	251	338	337
Mar	159	174	151	201	186	188	251	333	348
Apr	176	171	160	160	182	189	275	327	353
May	179	171	168	200	180	189	314	320	393
June	181	170	180	198	181	189	368	320	512
July	181	163	186	194	182	192	372	320	588
Aug	181	161	185	184	191	198	376	316	708
Sept	181	157	187	190	191	226	382	309	788
Oct	181	160	182	188	194	227	375	309	708
Nov	181	160	183	186	194	224	358	305	---
Dec	180	157	181	186	192	226	351	301	---
Avg.	***173***	***166***	***172***	***189***	***187***	***202***	***325***	***321***	***505***
Summary: n = 106; mean = $244, standard deviation = $118.5									

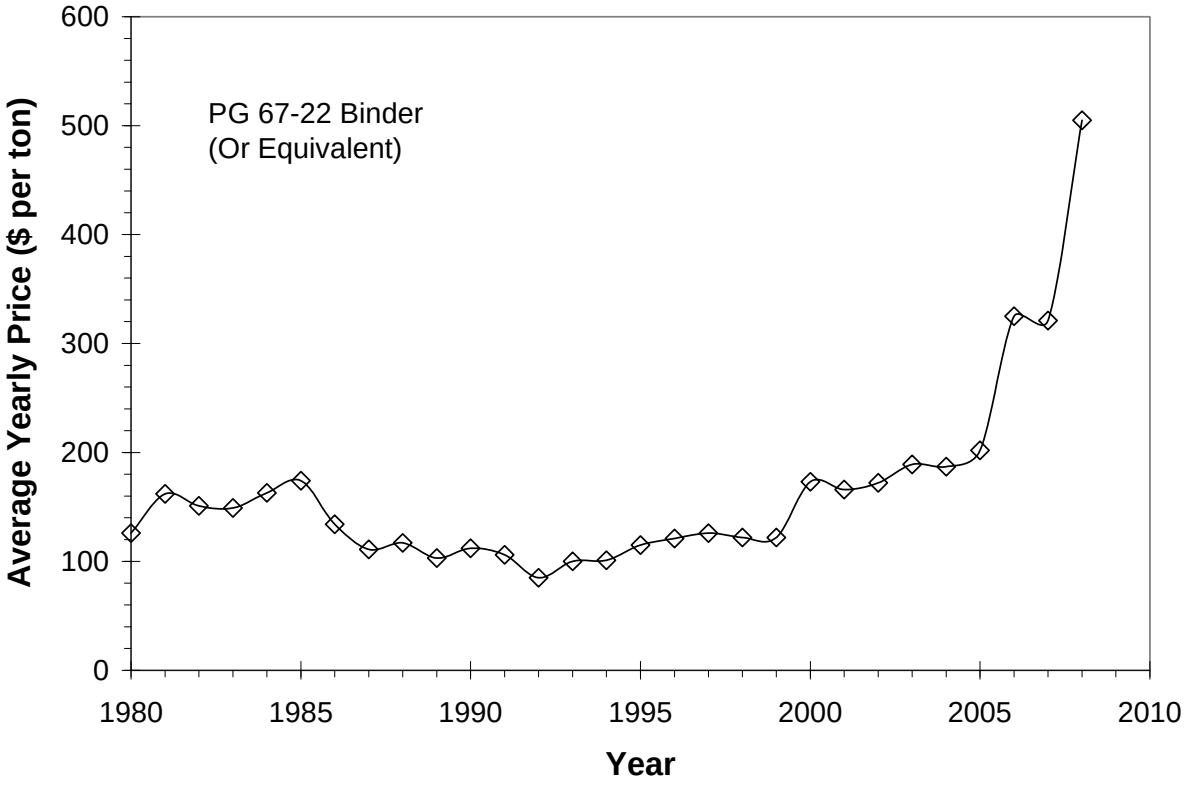


Figure 3.1. Yearly Price of Virgin Liquid Asphalt in Mississippi

3.5.3 Virgin Aggregate Costs

Virgin aggregate prices as of October 2008 were obtained from 10 different asphalt plants representing the entire state of Mississippi. The plants represent all six MDOT districts and encompass the state, which for purposes of discussion was broken into five groups: 1) central, 2) northwest (NW), 3) northeast (NE), 4) southwest (SW), and 5) southeast (SE). The overwhelming majority of asphalt produced within Mississippi consisted of four types of virgin aggregate. Table 3.8 summarizes the value per ton for each of these aggregates on the grounds of the production facility (include costs for material at quarry/pit, hauling, and other costs to place in stockpile ready to produce asphalt concrete). The costs provided encompass typical sizing and crushing requirements. Hydrated lime (HL) is also

Table 3.8. Virgin Aggregate Prices in Mississippi as of Oct 2008

Material	MDOT District	Region	Producer	Cost per Ton
Crushed Gravel	1	NE	4	$14 to $15
	1	NE	5	$15 to $16
	2	NW	7	$14 to $16
	3	NW/SW	8	$22 to $26
	3	NW/SW	10	$18 to $22
	5	Central	9	$13 to $14
	5	Central	2	$17 to $18
	6	SE	3	$21 to $22
	6	SE	6	$21 to $22
	7	SW	1	$14 to $16
Limestone	1	NE	4	$19 to $22
	1	NE	5	$15 to $16
	2	NW	7	$16 to $18
	3	NW/SW	8	$26 to $30
	3	NW/SW	10	$24 to $28
	5	Central	9	$33 to $38
	5	Central	2	$28 to $30
	6	SE	3	$22 to $23
	6	SE	6	$28 to $30
	7	SW	1	$30 to $34
Coarse Sand (CS)	1	NE	4	$ 8 to $9
	1	NE	5	$12 to $13
	2	NW	7	$9 to $12
	3	NW/SW	8	$10 to $14
	3	NW/SW	10	$8 to $12
	5	Central	9	$7 to $8
	5	Central	2	$8 to $9
	6	SE	3	$6 to $7
	6	SE	6	$7 to $8
	7	SW	1	$ 3 to $5

included but its costs did not vary substantially, so a value of $125/ton was used to represent the cost to the entire state. At 1% of the total aggregate weight, this translates to approximately $1.18 per ton of asphalt mixture.

Table 3.9 reduces the data in Table 3.8 to provide the range of prices within each MDOT district. Noticeable discrepancy exists between some locations. Hauling costs greatly affect virgin aggregate prices so a single solution will not be applicable throughout the state of Mississippi.

Table 3.9. Ranges of Virgin Aggregate Prices per Ton by MDOT District

District	Gravel	Limestone	CS
1	$14 to $16	$15 to $22	$8 to $13
2	$14 to $16	$16 to $18	$9 to $12
3	$18 to $26	$24 to $30	$8 to $14
5	$13 to $18	$28 to $38	$7 to $9
6	$21 to $22	$22 to $30	$6 to $8
7	$14 to $16	$30 to $34	$3 to $5

3.5.4 RAP Material Costs

The value of RAP is largely a function of the amount of asphalt contained in the material that acts as binder in the new mixture. The aggregate in the RAP is also valuable, but in the current economic market it is much less valuable than the asphalt. The authors of this report believe accounting for all asphalt in RAP in all cases is not appropriate. Examples of economic calculations from other studies follow this paragraph.

NAPA (2007) accounts for all RAP asphalt in savings calculations. The authors use simple calculations that account for all RAP asphalt to determine the value of RAP and indicate their approach clearly demonstrates its value. Kristjansdottir et al. (2007) assessed financial implications of warm mixed asphalt with up to 50% RAP. The calculations were straightforward and included material costs, as well as a variety of other costs (energy, trucking, and placement). The other costs were constant with RAP content. RAP was valued at $5 per ton, virgin aggregate at $15 per ton, and virgin asphalt at $400 per ton. A 50% RAP mixture was said to be 76% of the cost of a 0% RAP mixture.

Both aforementioned approaches treat RAP as a cheaply obtained commodity but one year after their publication date, Mississippi producers are reluctant to sell RAP, if they will sell it at all. Regardless, its value with current virgin asphalt prices (on the order of $700 per ton) is much higher than that presented. Even with moderate virgin asphalt prices its value is more than what is taken in many approaches. Accounting only for milling and hauling costs assumes the material has no value in place.

Based on many phone conversations, the value of RAP materials is not quantified in the same manner from producer to producer within Mississippi. All producers, though, valued the material highly in the current environment of elevated virgin asphalt prices. Overall, the value of RAP on the stockyard of an asphalt production facility in early October of 2008 was on the order of $30/ton. This value varied from just below $30 to $40 under ideal circumstances and extremely high virgin asphalt prices, but the general consensus according to the producers was $30. Data obtained from a single producer in November of 2007 valued RAP at $20 per ton. No producer was particularly interested in selling RAP,

though it has been sold in recent months on occasion. Prices to obtain RAP were $15 per ton or less, which included milling, hauling, and other costs.

The value of RAP in the economic analysis of this section was $10/ton for the stone portion, plus absorbed asphalt, plus market price for any asphalt that acted as binder in the new mixture. Eq. 3.1 summarizes the approach.

$$RAP_{(\$)} = Agg_{(\$)} + \left[P_{b(R)} - P_{bu(RS)}\right] * \left[AC_{V(\$)} \Big/ 100 \right] \quad (3.1)$$

Where,

$RAP_{(\$)}$: Value of RAP per ton
$Agg_{(\$)}$: Market value of aggregate in RAP per ton ($10 in this analysis)
$P_{b(R)}$: Percent of aged RAP binder with respect to total RAP mixture mass (5.5%)
$P_{bu(RS)}$: Percent RAP asphalt concrete on the surface of the RAP aggregate that was originally effective binder but now is inert
$AC_{V(\$)}$: Market value of virgin asphalt per ton

Note the amount of asphalt acting as binder in the new mixture ($P_{bu(RS)}$) was an unknown quantity and was plotted for all possible values. The work provided in Chapters 4 and 5 aims to provide information related to this matter. The authors are of the opinion that in practically all circumstances the portion of the asphalt in a RAP material that acts as asphalt binder in a new mixture will be greater than zero (i.e. it is not a black rock) and less than or equal to the effective binder of the original mixture made using what is now RAP.

A total RAP asphalt content of 5.5% was used for analysis based on producer data and laboratory testing of Mississippi RAP provided later in this document. The analysis was thus conducted by allowing a maximum of 85% of the asphalt in the RAP (i.e. 4.7%) to act as effective binder; the ratio of P_{be}/P_b of Table 3.4. Blend A was used to arrive at this value which is a reasonable estimate for this analysis. The absorbed asphalt in the RAP is not believed to be of a benefit in terms of binding the new mixture together. This material, though, eliminates absorption of virgin asphalt binder into RAP aggregates in the new mixture. Note P_{ba} typically increases (i.e. P_{be} decreases) with aging time for the same aggregate structure. The values incorporated would be typical of Mississippi asphalt mixtures; they use a relatively short aging period.

Based on conversations with multiple asphalt producers throughout Mississippi in October of 2008, $15 per ton was selected as the upper end cost for milling, hauling, and handling RAP material. As seen in Figure 3.2, this cost allows an economic benefit for most of the plausible conditions as long as at least a moderate portion of the asphalt within the RAP behaves as asphalt binder in the new mixture. Figure 3.2 shows RAP in a state where all asphalt can be treated as the equivalent of virgin asphalt ($P_{bu(RS)} = 0$) to a black rock that will not absorb virgin asphalt ($P_{bu(RS)} = 4.7\%$ for the materials considered in this analysis). Note P_{be}/P_b of Mixture A (Table 3.4) was used to limit $P_{bu(RS)}$ from 0 to 4.7%. This plot will be used alongside data from Sections 3.5.1 to 3.5.3 to calculate economic ramifications for various combinations of materials.

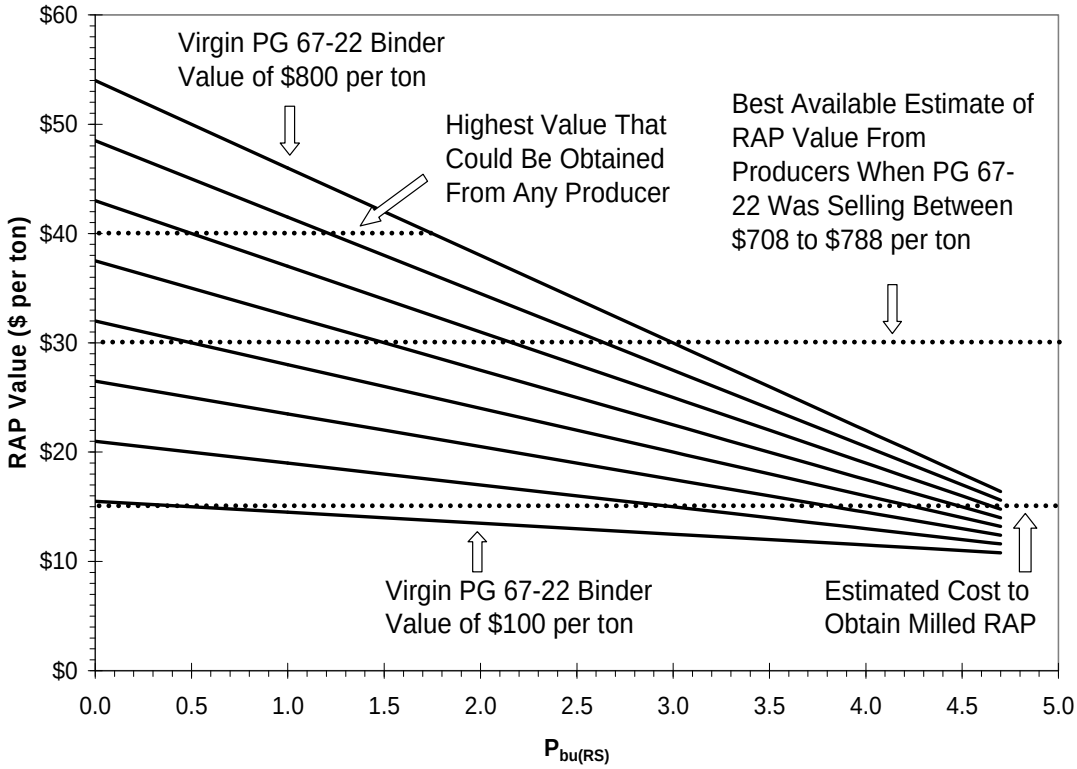


Figure 3.2. Value of RAP as a Function of Utilization of RAP Binder

3.5.5 Economic Analysis of Mixtures Containing Virgin and RAP Material

Relative proportions of Mixtures A and B were investigated to assess the value of the RAP material as a function of $P_{bu(RS)}$. Absorption was addressed in these two mixtures as shown in Table 3.4. P_{be} of both mixtures was the same, but Mixture A requires a P_b of 6.00% while Mixture B only requires 5.82%. Data obtained for virgin aggregates was for October 2008, so the corresponding virgin asphalt price of $708 per ton was used throughout this section. Mid range values of virgin aggregate prices in Tables 3.8 and 3.9 were used in all calculations performed in this section.

An equation (Eq. 3.2) was developed to evaluate the reduction in cost of virgin materials as a result of introduction of RAP under different circumstances. The equation developed is not exact; it is accurate to within a few cents per ton. As an example, Mixture A with 100% RAP should produce a cost of virgin material of $4.72, but the equation results in values of $4.61 to $4.65 depending on the district. The approximation lies in calculation of virgin aggregate costs and would require iteration to correct. For purposes of this analysis, the equation developed is well within the needed accuracy.

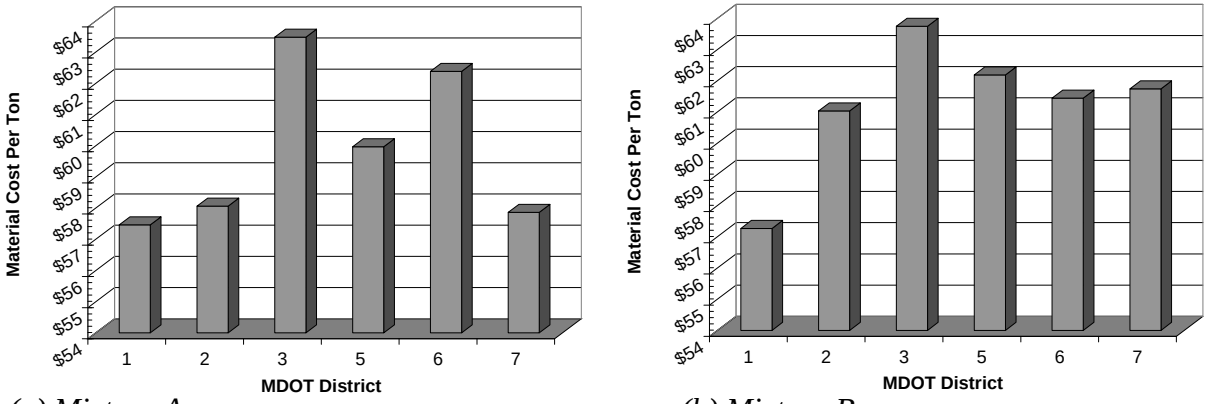
$$VM_{\$} = \left[P_s - \left(RAP_{\%}\left(1 + P_{bu(RS)} - P_{b(R)}\right)\right)\right] * \left[CG_{\%}\left(CG_{\$}\right) + LS_{\%}\left(LS_{\$}\right) + CS_{\%}\left(CS_{\$}\right)\right]$$

$$+ HL_{\$} + \left[P_b - RAP_{\%}\left(P_{b(R)} - P_{bu(RS)}\right)\right] * \left[AC_{V(\$)}\right] \qquad (3.2)$$

Where,

$VM_{\$}$:	Cost per ton of virgin materials in mixture
P_s:	Percent stone (aggregate) in mixture
$RAP_{\%}$:	Percent RAP in mixture
$CG_{\%}$:	Percent of aggregate that is crushed gravel
$CG_{\$}$:	Cost of crushed gravel (Table 3.9)
$LS_{\%}$:	Percent of aggregate that is limestone
$LS_{\$}$:	Cost of limestone (Table 3.9)
$CS_{\%}$:	Percent of aggregate that is coarse sand
$CS_{\$}$:	Cost of coarse sand (Table 3.9)
$HL_{\$}$:	Cost of hydrated lime
P_b:	Design asphalt content

Figure 3.3 plots prices of Mixture A and Mixture B as if they were produced in all MDOT districts. These values should be taken as baseline values in all further analysis. RAP was added to both mixtures while keeping the relative proportions of virgin aggregate the same. The amounts of RAP asphalt not utilized ($P_{bu(RS)}$) have also been included in the calculations. Table 3.10 provides the cost of virgin materials for each case, and Table 3.11 subtracts the Table 3.10 values from those in Figure 3.3 to show the reduction in virgin material costs. Table 3.11 could be viewed as the value of the RAP provided the aggregate was of the same value as virgin aggregate. Note Figure 3.2 valued RAP aggregate at $10 per ton to provide a relative comparison, but for the analysis of this section is was taken as replacement for virgin aggregate at market price. The result for high virgin aggregate prices (Table 3.9) is that the RAP value increases a few dollars per ton relative to Figure 3.2.



(a) Mixture A *(b) Mixture B*

Figure 3.3. Material Costs for Mixtures A and B (0% RAP)

The data in Table 3.11 shows that RAP has the potential to have higher value than that placed on it by any producer contacted. The upper end value obtained from producers was $40 per ton with the typical value at $30 per ton. When the calculations were performed and all RAP binder could be utilized in the new mixture the value was calculated between $53 to $60 per ton. On the other end of binder utilization (black rock with zero absorption)

the value was calculated at $20 to $28 per ton. This value far exceeds the cost to mill and haul RAP ($15 per ton or less), but is a grossly inefficient use of the material.

Table 3.10. Virgin Material Costs With Varying RAP Contents

	Mixture	A			B		
	$P_{bu(RS)}$	0.0	2.4	4.7	0.0	2.4	4.7
District	RAP (%)	$/ton[1]	$/ton[1]	$/ton[1]	$/ton[1]	$/ton[1]	$/ton[1]
1	25	44.26	48.42	52.40	43.80	47.95	51.93
	50	31.05	39.37	47.35	30.33	38.64	46.60
	75	17.85	30.33	42.29	16.86	29.32	41.26
	100	4.65	21.29	37.23	3.40	20.01	35.93
2	25	44.71	48.86	52.85	46.62	50.75	54.71
	50	31.35	39.66	47.63	32.21	40.47	48.38
	75	18.00	30.47	42.21	17.79	30.18	42.05
	100	4.64	21.27	37.20	3.38	19.90	35.73
3	25	48.76	52.88	56.83	48.56	52.76	56.70
	50	34.04	42.29	50.19	33.56	41.03	49.66
	75	19.33	31.69	43.54	18.47	30.80	42.64
	100	4.61	21.10	36.90	3.37	19.82	35.58
5	25	46.13	50.28	54.25	47.48	51.61	55.56
	50	32.30	40.59	48.53	32.78	41.03	48.93
	75	18.47	30.90	42.81	18.08	30.45	42.30
	100	4.63	21.21	37.09	3.38	19.87	35.67
6	25	47.94	52.07	56.03	46.93	51.05	55.01
	50	33.50	41.76	49.67	32.41	40.67	48.57
	75	19.06	31.45	43.32	17.90	30.28	42.14
	100	4.62	21.13	36.96	3.38	19.89	35.71
7	25	44.56	48.72	52.70	47.15	51.27	55.23
	50	31.25	39.57	47.54	32.56	40.81	48.71
	75	17.95	30.42	42.37	17.97	30.34	42.20
	100	4.64	21.27	37.21	3.38	19.88	35.69

1: $ per ton of virgin material only. RAP costs not included.

It can clearly be seen in Table 3.11 that the key variable in valuing RAP is the amount of the asphalt contained within the RAP that beneficial in a new mixture. This variable is explored from a technical perspective in Chapters 4 and 5. A proper mix design is needed that can evaluate this term in the presence of key parameters: RAP asphalt properties, mixing/compaction temperatures, aging period, warm mix additives, and similar. Otherwise, the producer is guessing at this term which leaves both the economic analysis and technical portions of the process in question.

The economic calculations show the value of RAP assuming equivalent performance to a virgin mixture. They show RAP to be a highly valuable material, but in order to maximize value, rational mix designs are required to account for elevated RAP contents. RAP should not be used in ways where low quantities of the binder are not re-activated and behave as binder since this causes the value of the material to reduce drastically.

The calculations also show the magnitude of value of RAP in terms of the current virgin material prices. Using high RAP during times of high virgin material prices is logical. Not only does it drastically decrease the price of the virgin materials per ton, but it also lessens the demand on these materials which should in turn lower their price. It makes economical sense to use low RAP content mix designs during times where virgin asphalt is relatively cheap and to use high RAP content mix designs when virgin asphalt is expensive. This maximizes the effectiveness of the RAP.

Table 3.11. Virgin Material Cost Savings With Varying RAP Contents

	Mixture	**A**			**B**		
	$P_{bu(RS)}$	**0.0**	**2.4**	**4.7**	**0.0**	**2.4**	**4.7**
District	**RAP (%)**	**$/ton[1]**	**$/ton[1]**	**$/ton[1]**	**$/ton[1]**	**$/ton[1]**	**$/ton[1]**
1	25	13.20	9.04	5.06	13.47	9.31	5.33
	50	26.41	18.09	10.11	26.94	18.63	10.67
	75	39.61	27.13	15.17	40.40	27.94	16.00
	100	52.81	36.17	20.23	53.87	37.26	21.34
2	25	13.35	9.20	5.22	14.41	10.28	6.33
	50	26.71	18.40	10.43	28.83	20.57	12.65
	75	40.06	27.59	15.65	43.24	30.85	18.98
	100	53.42	36.79	20.86	57.65	41.13	25.31
3	25	14.72	10.59	6.64	15.09	10.98	7.04
	50	29.43	21.29	13.29	30.19	21.96	14.08
	75	44.15	31.78	19.93	45.28	32.94	21.12
	100	58.86	42.37	26.58	60.37	43.92	28.16
5	25	13.83	9.69	5.72	14.70	10.58	6.63
	50	27.67	19.38	11.44	29.40	21.16	13.26
	75	41.50	29.07	17.15	44.11	31.76	19.89
	100	55.33	38.76	22.87	58.81	42.32	26.52
6	25	14.44	10.31	6.35	14.52	10.39	6.43
	50	28.88	20.62	12.71	29.03	20.78	12.87
	75	43.32	30.93	19.06	43.55	31.17	19.30
	100	57.76	41.25	25.42	58.06	41.56	25.74
7	25	13.30	9.15	5.16	14.59	10.47	6.51
	50	26.62	18.29	10.33	29.18	20.93	13.02
	75	39.91	27.44	15.49	43.77	31.40	19.54
	100	53.22	36.59	20.65	58.36	41.86	26.05

1: $ per ton of virgin material only. RAP costs not included.

CHAPTER 4-EXPERIMENTAL PROGRAM

4.1 Experimental Program Overview

A large portion of the research effort dealt with the experimental program, all of which was laboratory investigation. In general, the program consisted of large quantities of factors and levels but with few repetitions. The focus was high RAP mixes, especially when combined with warm mix additives. One warm mix additive (Sasobit®) was used throughout testing. Key variables of the experimental program were compacted specimen air voids, change in height during compaction, and indirect tensile strength at 25 C (77 F). These variables were evaluated at varying combinations of asphalt content, warm mix additive content, RAP content, and temperature. Complimentary Superpave mix design properties and other fundamental properties were also measured for the materials. These properties are discussed and provided in the following section since they are considered fundamental properties and were only determined to allow determination of the parameters of interest. The methods used to obtain the parameters of interest are discussed in this chapter, while the results and corresponding discussion are contained in Chapter 5.

4.2 Materials Tested

4.2.1 RAP Materials Tested

Laboratory testing was performed on Mississippi RAP obtained from four sources: 1) parking lot on the *Mississippi State University* campus (referred to hereafter as *PL*), 2) producer stockpile in Louisville, MS (referred to hereafter as *SP*), 3) Mississippi State Highway 25 near Aberdeen (referred to hereafter as *MS-25*), and 4) Interstate 55 near Grenada, MS (referred to hereafter as *I-55*). These sources were selected to encompass the properties representative of RAP within *Mississippi Department of Transportation* (*MDOT*) activities. Selection of the sources was made in conjunction with MDOT personnel, and was assisted by discussion with asphalt producers within the state. The group was in agreement that the geographic location within the state was not significant.

PL represents a private/municipal material where original property requirements are often relatively low. The lot was in very poor condition at the time of milling and represents the lowest quality RAP of interest. A depth of 37 mm (1.5 in) was milled on June 6, 2007, and the material would be categorized most closely in terms of MDOT as an ST mix (50 design gyrations). Note it is not an original MDOT mixture (rather a private mixture) but could ultimately be used in an MDOT project as seen later in this report. The original properties of this material were not available through the owners of the lot. A photograph of the lot can be seen in Figure 4.1(a).

SP is representative of a typical Mississippi RAP stockpile where a variety of materials are present. In this particular stockpile, however, nearly all of the material was acquired off MDOT highways. The material was obtained on November 16, 2007, and a photograph of the stockpile can be seen in Figure 4.1(b).

MS-25 was selected to represent an intermediate traffic mix commonly used on lower volume roads and state highways. It would currently be categorized as an ST or MT mix (65 design gyrations) by MDOT. The material was obtained from State Highway 25 in Monroe

county. It was a low volume design, the material was obtained on November 16, 2007, the project was 12 km (7.5 mi), and the maximum depth of milling was 50 mm (2 in) See Figure 4.1(c) for a photograph of the stockpile.

I-55 represents a high traffic mix and would consist of the highest quality material used within Mississippi paving activities. It would currently be categorized as an HT mix (85 design gyrations) by MDOT. The *I-55* RAP came from a 22.5 km (14 mi) stretch of four lane roadway. The material was acquired from the stockpile seen in Figure 4.1(d) on September 6, 2007. The material was originally placed in 1992. In general the material was from a 125 mm (5 in) binder course developed with Marshall Mix Design. Within the section milled, both polymer modified and non polymer modified binders were used, along with varying amounts of sand in the aggregate blend.

(a) Acquisition of PL Material

(b) Acquisition of SP Material

(c) Acquisition of MS-25 Material

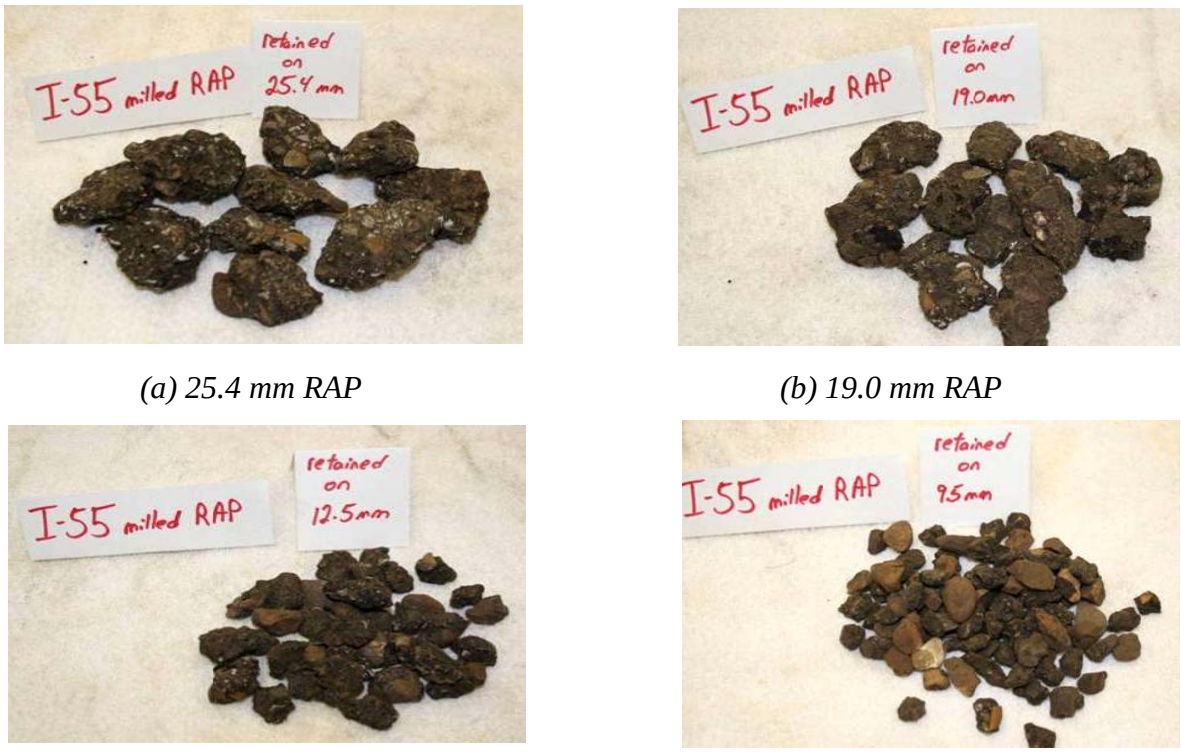
(d) Acquisition of I-55 Material

Figure 4.1. Photos of RAP Sources Sampled and Tested

Table 4.1 shows the material gradations as obtained from the sources. As seen, there are amounts of material retained on the 19 mm (3/4 in) sieve. It was hypothesized that all material greater than 19 mm was a conglomerate of particles that if properly processed would grade into the lower sieve sizes. Therefore, the asphalt content was determined on the gradations listed in Table 4.1 and was used throughout this research. Figure 4.2 is a photo of the *I-55* material that demonstrates the difference in texture of each of the sieve sizes; note the vast difference in the appearance of the particles retained on the 12.5 mm (many individual aggregates) and 19 mm (mostly conglomerates of smaller particles) sieve sizes. Data obtained from producers verified the hypothesis that all particles were finer than 19 mm; producer data can be found in Chapter 6.

Table 4.1. Bulk Gradations of RAP Sources (Asphalt Not Extracted)

	Percent Passing			
Sieve Size (mm)	**PL**	**I-55**	**MS-25**	**SP**
50.0	100.0	100.0	100.0	100.0
37.5	99.0	95.8	96.9	98.0
25.0	98.2	92.3	93.8	96.3
19.0	97.4	88.7	90.1	93.6
12.5	94.4	80.4	85.5	83.3
9.5	88.0	71.4	79.9	72.2
4.75	56.7	42.3	53.9	45.5
2.36	35.8	26.6	34.9	33.9
1.18	25.7	16.8	22.1	26.3
0.60	17.6	10.8	14.9	18.7
0.30	6.6	4.4	6.4	4.6
0.15	2.1	1.5	2.0	1.4
0.075	0.8	0.2	0.6	0.2



(a) 25.4 mm RAP

(b) 19.0 mm RAP

(c) 12.5 mm RAP

(d) 9.5 mm RAP

Figure 4.2. Representative RAP Material Appearance

The Table 4.2 gradations are the Table 4.1 gradations adjusted after scalping all particles greater than 19 mm (3/4 in). Table 4.2 also shows fundamental properties of the RAP materials. The columns of data in Table 4.2 will be discussed in more detail later in the report. Extraction of binder led to the P_b values of Table 4.3.

Table 4.2. Properties of Materials Tested Prior to Asphalt Extraction

Sieve Size (mm)*	Test Protocol	Percent Passing				Max Range of Values[5]
		PL**	I-55	MS-25	SP	
50.0	T 27	100.0	100.0	100.0	100.0	0.0
37.5	T 27	100.0	100.0	100.0	100.0	0.0
25.0	T 27	100.0	100.0	100.0	100.0	0.0
19.0	T 27	100.0	100.0	100.0	100.0	0.0
12.5	T 27	96.9	90.7	94.9	89.0	5.9
9.5	T 27	90.4	80.9	88.7	77.1	11.6
4.75	T 27	58.2	47.8	59.9	48.7	12.1
2.36	T 27	36.8	30.0	38.7	36.3	8.7
1.18	T 27	---	19.0	24.6	28.1	9.1
0.60	T 27	---	12.1	16.5	19.9	7.8
0.30	T 27	---	5.0	7.1	4.9	2.2
0.15	T 27	---	1.6	2.2	1.5	0.7
0.075	T 27	---	0.3	0.6	0.3	0.3
G_{mm}	T 209	2.380	2.333	2.306	2.267	0.066
LA Abs[1]	C 131	---	2.3	5.6	6.7	4.4
FAA[2]	T 304	---	44.2	47.2	46.3	3.0
F & E[3]	D 4791	---	9.1	18.2	27.3	18.2
G_{sb}[4]	C 128	2.317	2.250	2.266	2.252	0.016
G_{sa}[4]	C 128	2.390	2.340	2.329	2.341	0.012
Absorption[4]	C 128	1.3	1.7	1.2	1.7	0.5

* Material (+) 19 mm scalped relative to Table 4.1 to develop laboratory batching gradation.
** Material not processed beyond the 2.36 mm sieve.
1) LA Abs based on grading designation C of the test procedure.
2) FAA based on Method A of the test procedure.
3) F & E is percentage of flat plus percentage elongated based on a 2:1 max to min ratio.
4) Tested for the fine aggregate only with asphalt cement coating intact.
5) Range of I-55, MS-25, and SP materials only.

The gradations shown in Table 4.2 provide several noteworthy items. First, note that there are very few particles finer than 0.075 mm (i.e. dust) prior to extraction of the binder. When compared to the gradations of the same materials after asphalt extraction (Table 4.3), there is up to 4.1% dust, and the quantity varies vary noticeably from source to source. Additionally, the quantity of particles passing any one sieve varies noticeably more once the binder is extracted. This is expected since the milling operation does not separate each stone particle in an asphalt pavement, while asphalt extraction does separate each individual stone particle.

Binder properties shown in Table 4.3 are also noteworthy. All sources were in the vicinity of the same total asphalt content, but there was up to 0.6% difference between sources. Of more potential significance is the viscosity of the samples. Both the *PL* and *I-55* materials had extremely high viscosities. The *SP* material was intermediate with respect to all the materials, while *MS-25* had by far the lowest viscosity.

Many of the remaining properties of the materials have been provided for general information and have not been used directly in the research program. Angularity and

abrasion properties were not considered in developing any of the gradations of this research program in terms of the RAP aggregates (either prior to or post binder extraction).

Table 4.3. Properties of Materials Tested After Asphalt Extraction

		Percent Passing				Max Range
Sieve Size (mm)	**Test Protocol**	**PL**	**I-55**	**MS-25**	**SP**	**of Values[5]**
50.0	T 27	100.0	100.0	100.0	100.0	0.0
37.5	T 27	100.0	100.0	100.0	100.0	0.0
25.0	T 27	100.0	100.0	100.0	100.0	0.0
19.0	T 27	100.0	100.0	100.0	98.4	1.6
12.5	T 27	98.8	96.3	99.4	92.8	6.6
9.5	T 27	95.3	89.6	97.6	84.6	13.0
4.75	T 27	70.1	61.9	75.0	59.1	15.9
2.36	T 27	51.4	41.6	53.7	47.0	12.1
1.18	T 27	40.8	31.8	41.1	40.8	9.3
0.60	T 27	33.2	24.7	32.9	34.3	9.6
0.30	T 27	18.8	13.3	16.3	17.4	4.1
0.15	T 27	5.9	5.9	7.7	7.5	1.8
0.075	T 27	2.2	1.4	1.7	4.1	2.7
FAA	T 304A	---	41.5	41.3	42.3	1.0
CAA	D 5821	---	96	96	94	2
G_{sb}[1]	C 128	2.494	2.441	2.479	2.482	0.041
G_{sa}[1]	C 128	2.623	2.595	2.586	2.607	0.021
Absorption[1]	C 128	2.0	2.4	1.7	1.9	0.7
Viscosity[2]	T 316	56.2	52.9	9.1	26.5	43.8
P_b (% mix)[3]	T 164	5.5	5.7	5.6	5.1	0.6
F & E[4]	D 4791	---	20.8	42.4	21.4	21.6

1) Tested for the fine aggregate only.
2) Samples tested at 135 C and data reported in Pa•s
3) These values were obtained using 8 to 9 washings of TCE with 45 minute soaking periods each. MS-25 had a P_b value of 4.9% after three 45 minute soakings.
4) F & E is percentage of flat plus percentage elongated based on a 2:1 max to min ratio.
5) Range of I-55, MS-25, and SP materials only.

4.2.2 Virgin Aggregates Tested

Five virgin aggregate stockpiles were tested as part of this program. They were obtained from a local asphalt producer and their properties are shown in Table 4.4. As seen, the materials consisted of crushed gravel, limestone, coarse sand, and hydrated lime. These materials were selected since they have been used as the virgin aggregates within an MDOT approved ST mix design alongside RAP.

Gravels make up a significant amount of the aggregates used in Mississippi paving. Any method that does not rely heavily on gravel aggregates could face difficulty in being implemented by many producers. Note the relatively low bulk specific gravities of the gravels (relative to limestone or granite) and the high absorption values. These absorptions are not uncommon in the gravels used within Mississippi. They are approaching the upper end of values, but are not an anomaly. Absorption of crushed gravels can be lower than these

values, but the overwhelming majority of Mississippi gravels with have absorption values between 2 to 4%.

Table 4.4. Properties of Virgin Aggregates Tested

Size	19.0 mm	12.5 mm	#810	---	---
Type	CR[1]	CR	LS[2]	CS[3]	HL[4]
Source	Scribner Pit	Scribner Pit	Vulcan	Scribner Pit	Falco
Location	Hamilton[5]	Hamilton	Russellville[6]	Hamilton	---
Sieve Size (mm)	**Passing (%)**	**Passing (%)**	**Passing (%)**	**Passing (%)**	**Passing (%)**
50.0	100.0	100.0	100.0	100.0	100.0
37.5	100.0	100.0	100.0	100.0	100.0
25.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0
12.5	77.0	100.0	100.0	100.0	100.0
9.5	58.0	92.0	100.0	100.0	100.0
4.75	29.0	47.0	92.0	95.0	100.0
2.36	16.0	26.0	68.0	82.0	100.0
1.18	11.0	16.0	53.0	72.0	100.0
0.60	9.0	11.0	41.0	55.0	100.0
0.30	7.0	8.0	27.0	21.0	100.0
0.15	5.0	7.0	19.0	2.0	100.0
0.075	4.0	5.2	14.8	0.5	100.0
G_{sb}	2.391	2.395	2.625	2.572	2.300
G_{sa}	2.611	2.625	2.711	2.644	2.300
Abs	3.52	3.66	1.21	1.06	0.00

1) Crushed Rock
2) Limestone
3) Coarse Sand
4) Hydrated Lime
5) Hamilton, MS
6) Russellville, AL

4.2.3 Asphalt Binders and Warm Mix Additives Tested

A neat PG 67-22 binder was used throughout testing. The virgin binder was heated to its Superpave viscosity temperature of 154.5 C (310 F) throughout testing. Binder was not held in an oven at this temperature for more than six consecutive hours. PG 67-22 binder is very common in Mississippi.

Sasobit® was the only warm mix additive tested. The binder was heated to 127 C (260 F) to mix in the Sasobit® wax pellets, when applicable. A paddle mixer was used to mix in the pellets that were slowly added into the binder. If all the pellets are added at once even dispersion may not occur. Once added and mixed, the Sasobit® will not settle in the binder. Separate containers were made for 1.0% and 1.5% Sasobit®, which was based on total binder weight in the container. Sasobit® was added to compensate for RAP binder by heating it to just below its melting temperature, and placing it into the pool of liquid asphalt formed inside

the mixing bucket (Figure 4.3). The Sasobit® added to compensate for the RAP binder was added based on the total extracted asphalt cement content of the RAP.

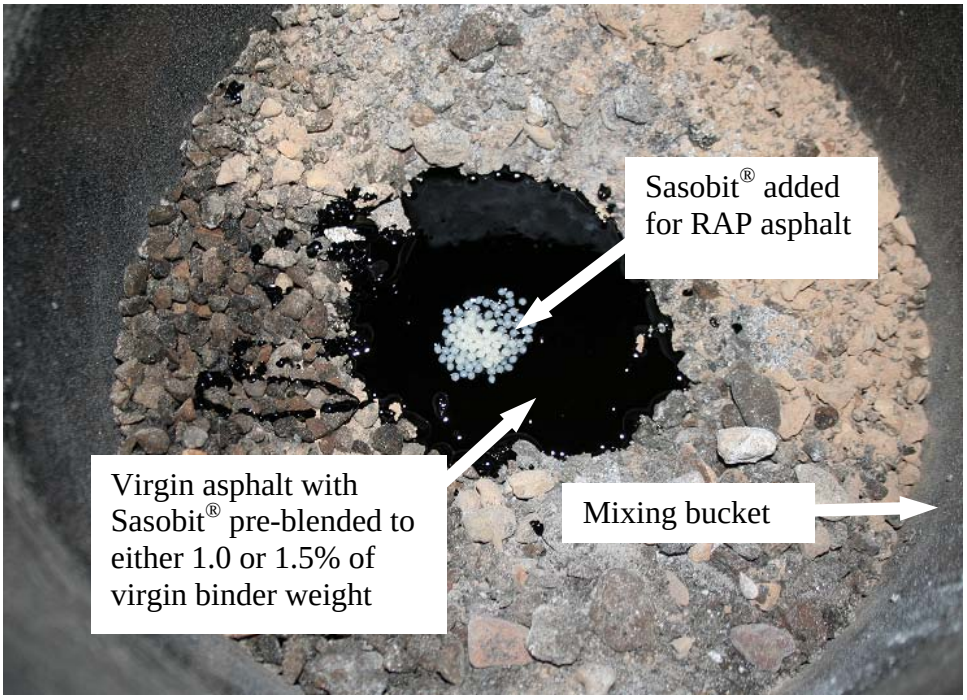


Figure 4.3. Addition of Sasobit® to Mixture

4.3 Blends of Materials

The experimental program consisted of 13 aggregate blends composed of various amounts of 9 stockpiles (5 virgin stockpiles and 4 RAP stockpiles). The gradations of these individual stockpiles can be seen in Table 4.3 (RAP) and Table 4.4 (virgin).

Table 4.5. Stockpile Quantities Used to Develop Blends to be Tested

	Stockpiles								
	19.0 mm	**12.5 mm**	**#810**			***PL***	***I-55***	***MS-25***	***SP***
Blend	**CR**	**CR**	**LS**	**CS**	**HL**	**RAP**	**RAP**	**RAP**	**RAP**
1	43	10	32	14	1	0	0	0	0
2	22	37	10	15	1	0	0	0	15
3	43	38	8	10	1	0	0	0	0
4	0	0	0	0	0	100	0	0	0
5	0	0	0	0	0	0	100	0	0
6	0	0	0	0	0	0	0	100	0
7	0	0	0	0	0	0	0	0	100
8	24	0	0	0	1	0	75	0	0
9	24	0	0	0	1	0	0	75	0
10	20	04	0	0	1	0	0	0	75
11	23	23	3	0	1	0	50	0	0
12	41	8	0	0	1	0	0	50	0
13	26	23	0	0	1	0	0	0	50

Table 4.6. Composite Gradations of all Blends Tested

Sieve	Blend % Passing												
(mm)	1	2	3	4	5	6	7	8	9	10	11	12	13
50.0	100	100	100	100	100	100	100	100	100	100	100	100	100
37.5	100	100	100	100	100	100	100	100	100	100	100	100	100
25.0	100	100	100	100	100	100	100	100	100	100	100	100	100
19.0	100	100	100	100	100	100	98.4	100	100	100	100	100	100
12.5	90.1	94.6	90.1	98.8	96.3	99.4	92.8	91.7	94.0	90.0	92.9	90.3	90.4
9.5	81.1	86.8	78.9	95.3	89.6	97.6	84.6	82.1	88.1	79.7	83.3	80.9	79.5
4.75	60.9	58.9	48.2	70.1	61.9	75.0	59.1	54.4	64.2	53.0	52.2	54.2	48.9
2.36	43.7	40.9	31.4	51.4	41.6	53.7	47.0	36.0	45.1	40.5	33.5	36.5	34.6
1.18	34.4	31.6	23.3	40.8	31.8	41.1	40.8	27.5	34.5	34.4	24.7	27.3	27.9
0.60	26.8	24.4	17.8	33.2	24.7	32.9	34.3	21.7	27.8	29.0	19.2	22.0	23.0
0.30	16.4	14.7	11.3	18.8	13.3	16.3	17.4	12.7	14.9	15.8	11.9	12.7	13.4
0.15	10.2	8.7	7.5	5.9	5.9	7.7	7.5	6.6	8.0	7.9	7.3	7.5	7.7
0.075	8.0	6.5	5.9	2.2	1.4	1.7	4.1	3.0	3.2	5.1	4.3	3.9	5.3

All blends were developed by selecting percentages of the 9 available stockpiles. Table 4.5 summarizes the blending data in terms of stockpile percentage and Table 4.6 shows the composite gradations of each blend. All blends were nominal maximum aggregate size (NMAS) of 12.5 mm.

Blend 1 was an attempt to develop a universal gradation for the entire research. Blend 2 was an attempt to re-produce an MDOT approved ST mix with the notable exception of using one of the RAP sources of Table 3 (*SP*) instead of the original RAP source; 15% RAP incorporated. Blend 3 was a 100% virgin mix ultimately used as the control in the research. Blends 4 through 7 consisted of 100% RAP at the stockpile gradations (post extraction) after the large particles had been scalped. Blends 8 through 10 consisted of 75% RAP and 25% virgin material, and blends 11 through 13 consisted of 50% RAP and 50% virgin material.

The final experimental program compared blend 3 to blends 5 through 13. Initially, the research team attempted to make a single gradation that could be used for all blends regardless of RAP content or material source (RAP or virgin). The result was Blend 1, which did not meet MDOT 12.5 mm Superpave requirements for all possible cases, but it was very close and was the best that could be developed. The problem with this blend was it plotted too close to the maximum density line, which can result in low compacted air voids. As seen in Section 5.1, this proved to be the case.

When the *SP* RAP material was used as replacement of the original RAP source for the MDOT approved mixture, the compacted air voids were too low as seen in Section 5.1. The RAP material used was the closest material the research team had available, but it differed somewhat in gradation relative to the original design. In lieu of fabricating the original blend or trying to locate the original source, the research team elected to produce a 100% virgin aggregate blend to serve as the primary control material.

The materials sampled do not represent all materials available within Mississippi, and even they could not be used in wide ranges of percentages to form a universal gradation. The problem would become more complex if additional materials were involved. Gradation is very difficult to control with multiple sources and blends within an experimental program. In lieu of the inability to provide a control with a gradation that could be universally produced, the research team elected to compare the warm mixed high RAP content blends under

consideration with a typical blend and compare results on the sole basis of performance. Since all the factors could not be fully controlled (e.g. gradation) performing a true experimental design was not feasible. From an experimental approach, a true experimental design is more logical, but from a production approach the concept of equivalent performance has its advantages.

Blend 3 was developed using 100% virgin material from the sources listed in Table 4.4. It was developed to represent a reasonable 100% virgin mixture, though they are not common in current Mississippi practice; most mixtures have 10 to 15% RAP. Blends containing virgin material were developed to have a gradation as close as possible to Blend 3 to standardize the comparison as much as possible. This is a notable approximation in the experimental comparison, but it is a common approach.

4.4 Specimen Preparation

All aggregates were washed, sized, and batched to within 10 g of the target weight. They were heated to the mixing temperature; this took less than 60 min based on measurements so aggregates were heated for 65 min after the oven had reached equilibrium temperature. Aggregate mixing temperatures were equal to short term aging temperatures in the majority of testing. This parameter varied throughout testing and is the temperature indicated in the data provided in this report. The notable exception was determination of the Superpave hot mix asphalt properties where aggregate was heated to 171 C (340 F), mixed, and aged at 154.5 C (310 F).

A bucket mixer was used to prepare all specimens. Heated aggregate was first introduced into the heated bucket, and a small indention was made in the center of the aggregate to allow the heated binder to be poured without touching the bucket. Additional heated Sasobit® was sprinkled into the heated binder pool to account for the binder in the RAP (See Section 4.2.3).

Mixing of a sample was performed for approximately 3 min until an adequate consistency was achieved. During mixing, the operator continually used a trowel to prevent material from being lodged in the extremities of the bucket. Mixing was deemed a critical aspect and was handled by a single operator. The mixed sample was immediately placed in a covered pan in an oven while the bucket was subsequently scraped over a hot plate to within 10 g of its original weight. The scraped material was added to the mixed asphalt. All material was out of the oven less than 10 min during mixing. The asphalt was then short term aged for 90 min according to MDOT specifications.

Compaction occurred at 5.6 to 8.3 C (10 to 15 F) below the mixing temperature for all specimens. A hand held infrared device was used to measure temperature prior to compaction. Two SGC compaction sequences were performed using a large Pine compactor: 1) 75 gyrations at 570 kPa pressure (used for initial suite of 100% RAP compactions); and 2) 50 gyrations at 600 kPa pressure for all other compaction. The samples were cooled under a fan for a few minutes prior to full extrusion from the mold.

4.5 Experimental Design

The experimental design of this research was to test a large amount of factor-level combinations with a low amount of repetition. The rational was to encompass the overall property thresholds rather than to focus more efforts on limited parameters. This approach provides a better overall understanding of the problem but does not, by and large, provide sufficient data for statistical analysis.

The experimental design contained five major components: 1) determination of fundamental material properties and development of material blends for testing; 2) determination of asphalt content for control specimens; 3) testing of control specimens; 4) testing of 100% RAP suites with no added asphalt to provide fundamental behavioral information; and 5) testing of factor level combinations of interest for comparison to control specimens. Component 1 has already been discussed in the aforementioned portions of this chapter. Component 2 consisted of testing blends 1 through 3 to select the most suitable characteristics of the control specimens. Component 3 consisted of developing and testing control specimens in the same manner as the warm mixed high RAP specimens of interest by compacting and testing five replicates at each factor-level combination.

The key facets of component 4 were to determine an appropriate warm mix test temperature and provide insight into development of a mass component diagram suitable for warm mixed asphalt with high RAP contents. Component 4 investigated five factors at varying levels as shown in Figure 4.4 by testing two replicates of each factor-level combination.

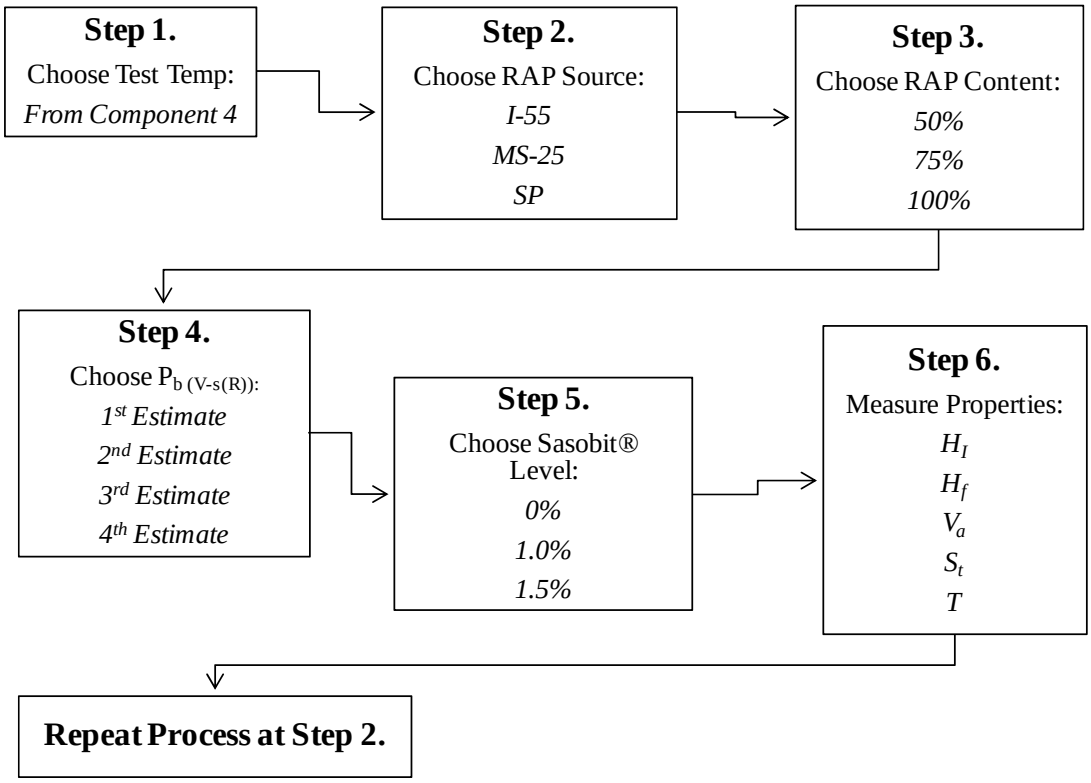


Figure 4.4. Test Sequence for 116 C (240 F) Samples

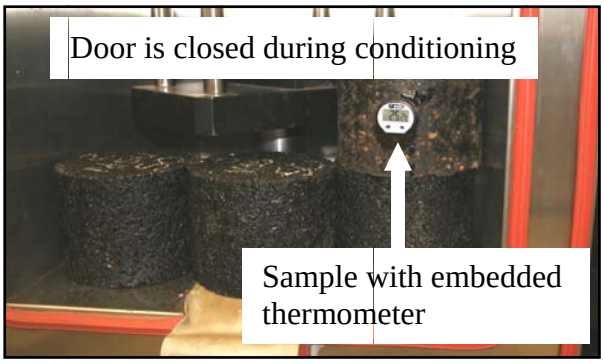
As seen in Figure 4.4, a tiered approach was taken to estimate the additional virgin asphalt needed for adequate compensation of the RAP portion of the mixture. This term is designated $P_{b\ (V\text{-}s(R))}$ later in the document (Section 5.3). A set of samples was compacted to determine air voids for each mixture containing RAP with no additional virgin binder for the RAP portion of the sample; only virgin asphalt for the virgin aggregates (referred to in Figure 4.4 as *1st Estimate*). A second set of samples was compacted where the amount of additional binder was the same for all RAP sources and percentages and was believed to be in excess of that needed (*2nd Estimate*). From these data points a third estimate was made for each RAP source, either above or below the second estimate based on the air voids data determined from testing. A fourth and final estimate was then made to target 4.0% air voids. For the first, second, and third estimates samples were compacted with 1.0% and 1.5% Sasobit®. For the fourth estimate 0%, 1%, and 1.5% Sasobit® samples were included.

The properties shown in step 6 of Figure 4.4 are: H_I is initial height of specimen at zero gyration; H_f is final height of specimen after last gyration; V_a is the compacted specimen air voids; S_t is the compacted specimen indirect tensile strength; and T is the time to failure of the indirect tensile specimens. These properties were subsequently compared to the control specimens.

4.6 Determination of Material Properties

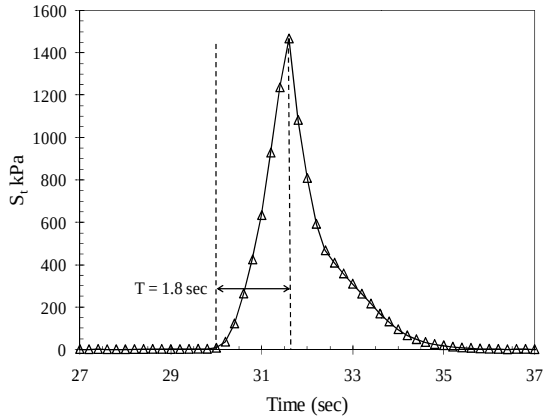
The properties referenced in Figure 4.4 were measured as discussed in the following paragraphs. Indirect tensile strength and time to failure were determined using the unconditioned protocol of *AASHTO T 283*. The compacted samples were brought to thermal equilibrium of 25 C (77 F) by placing them in the environmental chamber of the Interlaken test equipment as seen in Figure 4.5a. A sample of comparable mass was placed in the chamber with the test specimens that had a thermometer embedded into its center to ensure sufficient conditioning had taken place prior to testing. Load-time data was recorded at a frequency of 5 Hz. This information was used to plot load versus time to find the time from initial load application to indirect tensile failure of the sample (T) as well as the indirect tensile strength at failure (S_t). The length of each specimen was measured and this value used to calculate the tensile strength. Figure 4.5b is a photo of testing, and Figures 4.5c and 4.5d are typical response curves that label the time to failure. Note the 100% virgin specimens fail more slowly than the 100% RAP specimens.

The initial and final sample heights were measured during compaction by the *Superpave Gyratory Compactor (SGC)*. Air voids are directly related to the bulk specific gravity of compacted samples (G_{mb}) and the maximum mixture specific gravity (G_{mm}). G_{mb} was measured using the CoreLOK device, while G_{mm} was determined using *AASHTO T 209* protocol. The initial suite of 100% RAP samples had high air voids so their G_{mb} values could not be determined by *AASHTO T 166* due to large number of interconnected voids within the samples. Once this was determined the CoreLOK device was used for consistency in data collection. G_{mm} values were directly measured.

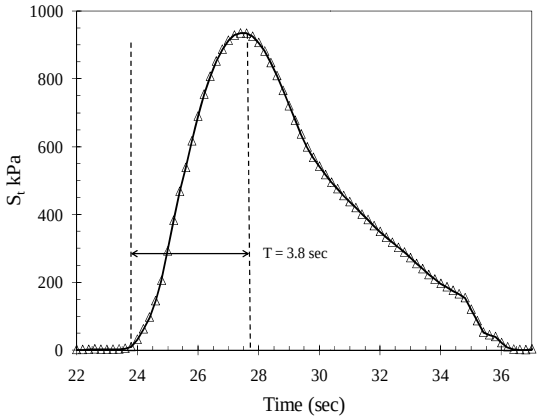


(a) Conditioning Samples

(b) Indirect Tensile Strength Testing



(c) Typical 100% RAP Response



(d) Typical 100% Virgin Response

Figure 4.5. Indirect Tensile Strength Testing

CHAPTER 5 - TEST RESULTS AND DATA ANALYSIS

5.1 Determination of Control Specimen Asphalt Content

The majority of the items pertinent to determination of an asphalt content suitable for control specimens was discussed in Chapter 4. All samples discussed in this section were hot mix asphalt aged and compacted at 154 C (310 F). 50 gyrations at a 600 kPa pressure were used throughout this section.

Results of blend 1 testing can be found in Table A.1 of Appendix A. As seen, the air voids are very low at asphalt contents reasonable for high absorption gravel mixtures. To achieve reasonable air voids with this mixture would require an asphalt content too low for performance. In a similar manner, blend 2 results can be found in Table A.2. The air voids were too low for this specimen; presumed cause was different RAP source than the original design. Neither of these blends were considered suitable to serve as a control for comparison to warm mixed RAP samples.

Results of blend 3 testing are provided in Table A.3. As seen, an asphalt content between 6.0 to 6.1% provides the needed air voids. To ensure this value was reasonable and to provide an independent quality control measure for the entire project, five samples were sent to the MDOT materials lab in Jackson, MS for compaction and volumetric calculations. The samples were pre-weighed, batched, and sent to MDOT with samples of project asphalt. Blend 3 was utilized and the results can be seen in Table 5.1. The results of testing between the MSU and MDOT labs were reasonable but not fully acceptable to the MSU research team. After obtaining the MDOT results, the MSU research team calibrated their device and V_a values reduced on the order of 0.3%. The remainder of testing described in this report after this juncture used the calibration settings.

Table 5.1. Independent Volumetric Verification Samples-MDOT Materials Lab

Blend	Asphalt Content	Aggregate Mass (g)	G_{mm}	Test	G_{mb}	V_a (%)	S_t at 25 C kPa (psi)
3	5.5	4,100	2.305	1	2.183	5.3	---
				2	2.179	5.5	---
				Avg.	**2.181**	**5.4**	**---**
3	6.0	4,100	2.300	1	2.200	4.3	1218 (176.7)
				2	2.209	4.0	1170 (169.7)
				3	2.202	4.2	1103 (160.0)
				Avg.	**2.204**	**4.2**	**1164 (168.8)**

Note: MSU Laboratory obtained V_a of 5.9% at 5.5% asphalt content, and obtained V_a of 3.9 to 4.8% at asphalt contents of 6.0 and 6.1%.

For the remainder of this project, the virgin binder added to the virgin aggregate was 6.0% as defined in Eq. 5.1. Based on the combined results and the desired end use of this value it was deemed sufficiently accurate. Addition of virgin binder was handled separately in conceptual terms between the virgin aggregate and RAP. Note additional virgin binder was often added to account for the RAP. A shortcoming of the approach is that the 6.0% asphalt was held constant regardless of the virgin aggregate proportions in the blend (e.g. blends 8 through 13). For a final analysis, there would be multiple asphalt contents (one for

each virgin aggregate blend) but for purposes of this study using a single value was deemed reasonable.

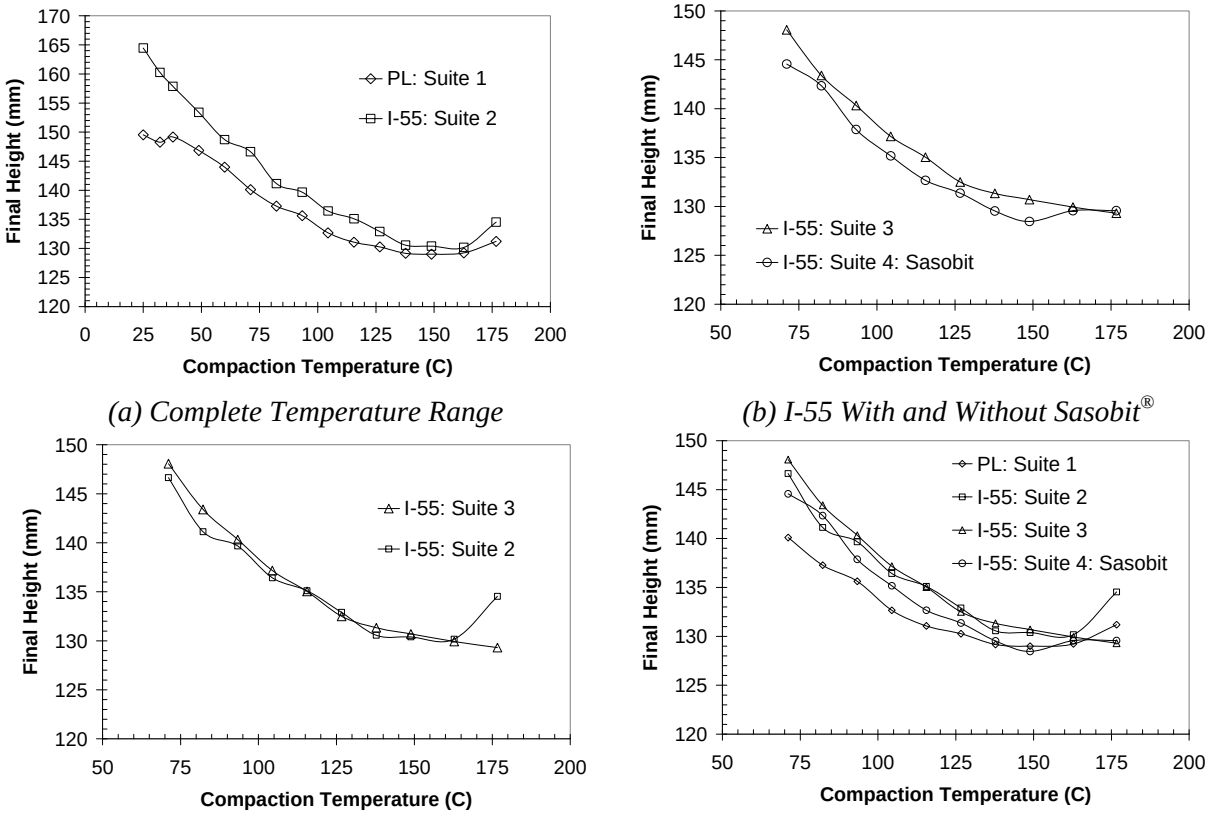
$$M_{b(V-s(V))} = \frac{\lfloor M_{s(V)} \rfloor * \lfloor P_{b(V-s(V))} \rfloor}{100 - P_{b(V-s(V))}} \quad (5.1)$$

Where,

$M_{b(V-s(V))}$ = Virgin asphalt binder to add to account for virgin aggregate (g)
$M_{s(V)}$ = Mass of virgin aggregate contained in the sample (g)
$P_{b(V-s(V))}$ = Asphalt content to add to virgin aggregate (6.0%)

5.2 Results of 100% RAP Testing With No Added Asphalt

Four compaction suites were performed with 100% RAP to provide a baseline of information about the characteristics of the material; See Table 5.2. The mixing/aging was performed between 25 C to 177 C (77 to 350 F). Figure 5.1 shows the test results in terms of final compaction height. All data in Figure 5.1 and the remaining figures in this section are the average of three data points; raw data can be found in Tables A.4 through A.9.



(a) Complete Temperature Range

(b) I-55 With and Without Sasobit®

(c) I-55 at Varying Ages

(d) All Data Above 71 C

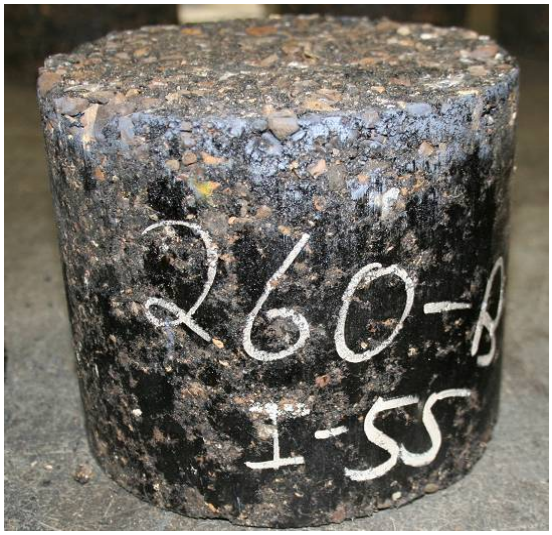
Figure 5.1. Compaction of 100% RAP (5,000 g Samples)

Table 5.2. 100% RAP Compaction Suites

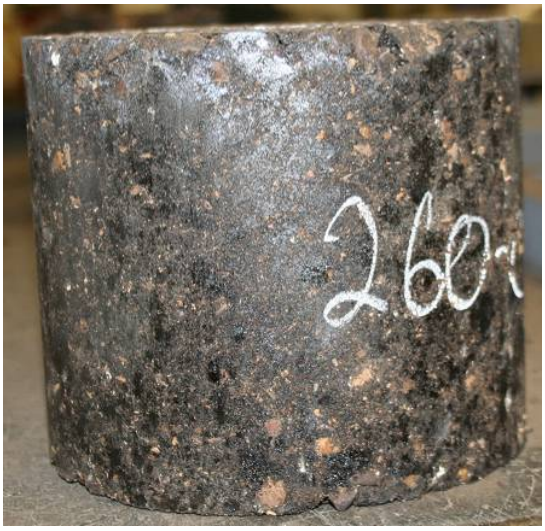
Suite	Material Source	Blend	Aging Period	Sasobit*	G_{mm}
1	PL	4	4 hr	No	2.380
2	I-55	5**	4 hr	No	2.341
3	I-55	5	2 hr	No	2.333
4	I-55	5	4 hr	Yes	2.333

** 1.6% Sasobit®* used since testing performed prior to determination of asphalt content (1.5% was target).
*** Slightly different blend but differences insignificant to research goals.*

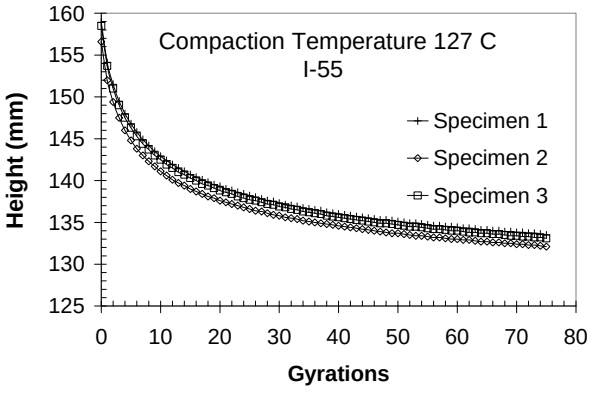
The consistency of the samples can be seen in Figure 5.2. At lower temperatures (e.g. below 71 C (160 F)) the samples are somewhat less consistent than above 71 C (160 F). Figure 5.2 shows samples and compaction curves at 127 C (260 F), which is the midpoint of temperatures exceeding 71 C (160 F). Visually, the 100% RAP samples above 71 C (160 F)



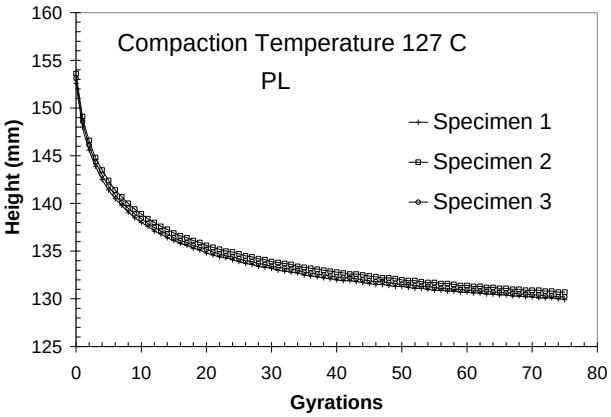
(a) I-55 Sample



(b) PL Sample



(c) I-55 Sample Compaction Results

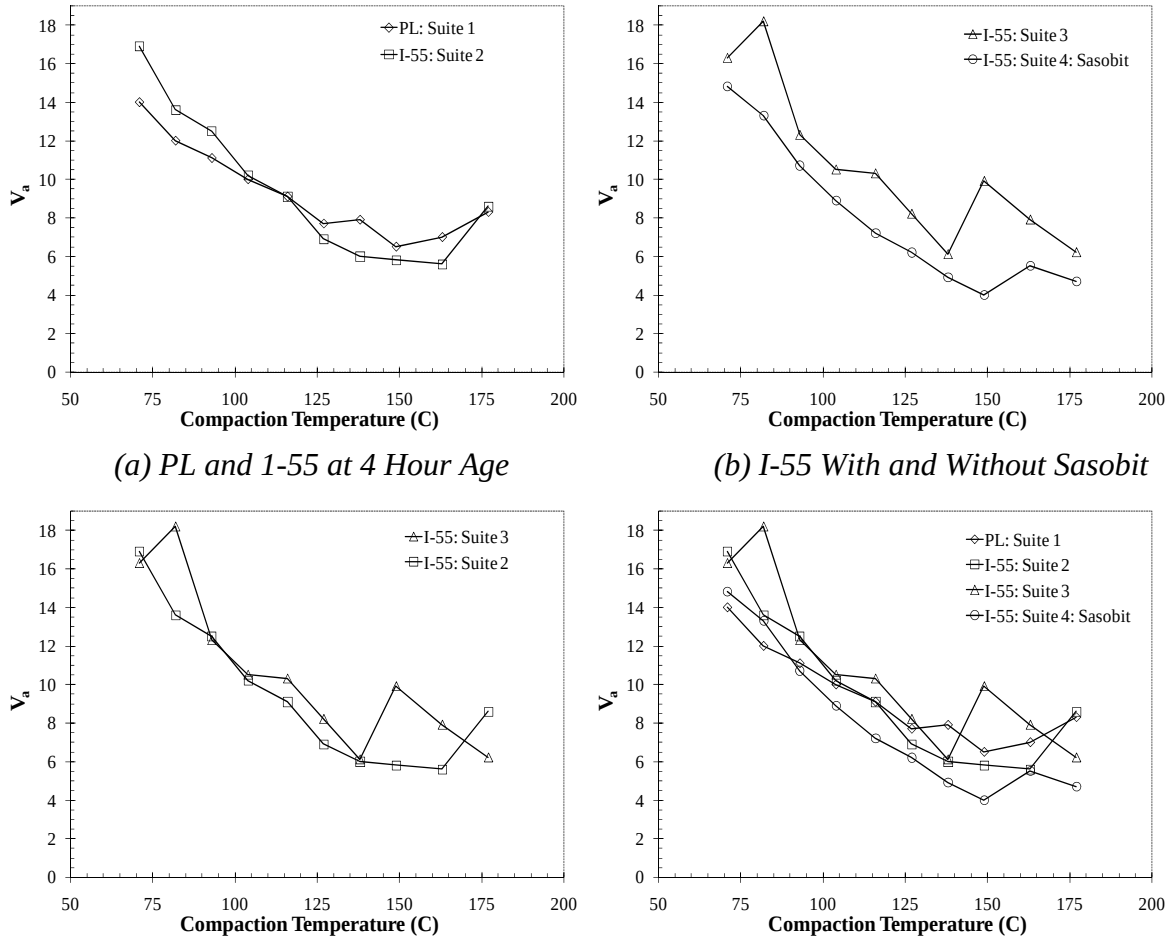


(d) PL Sample Compaction Results

Figure 5.2. Compacted 100 % RAP Samples (5,000 g)

are similar to standard HMA, with the possible exception of the rich dark color commonly observed in HMA. As the compaction temperature increased, so did the darkness of the samples. Below 71 C (160 F), the samples resemble dark colored compacted aggregate. Figure 5.1 shows temperature has a noticeable effect on compactibility. Reduction in compactability is observed at extreme temperatures. Sasobit® improved the compaction of the *I-55* material, and the difference between aging the *I-55* material 2 hours and 4 hours was negligible.

The air voids (V_a) for the samples above 71 C (160 F) are shown in Figure 5.3. Similar trends are seen in the air void data and the final height data of Figure 5.1. The greater variability in the air void data may be due to the variations in G_{mm} within the individual samples and that of the sample tested; within sample variability. The actual aggregate (i.e. stone) gradation within the RAP samples would also vary, which would account for some of the between sample variability at higher temperatures (affecting Figure 5.1 and Figure 5.3) and the actual G_{mm} of the sample in the mold and that used for a reference (within sample



(a) PL and 1-55 at 4 Hour Age

(b) I-55 With and Without Sasobit

(c) I-55 at Varying Ages-No Sasobit

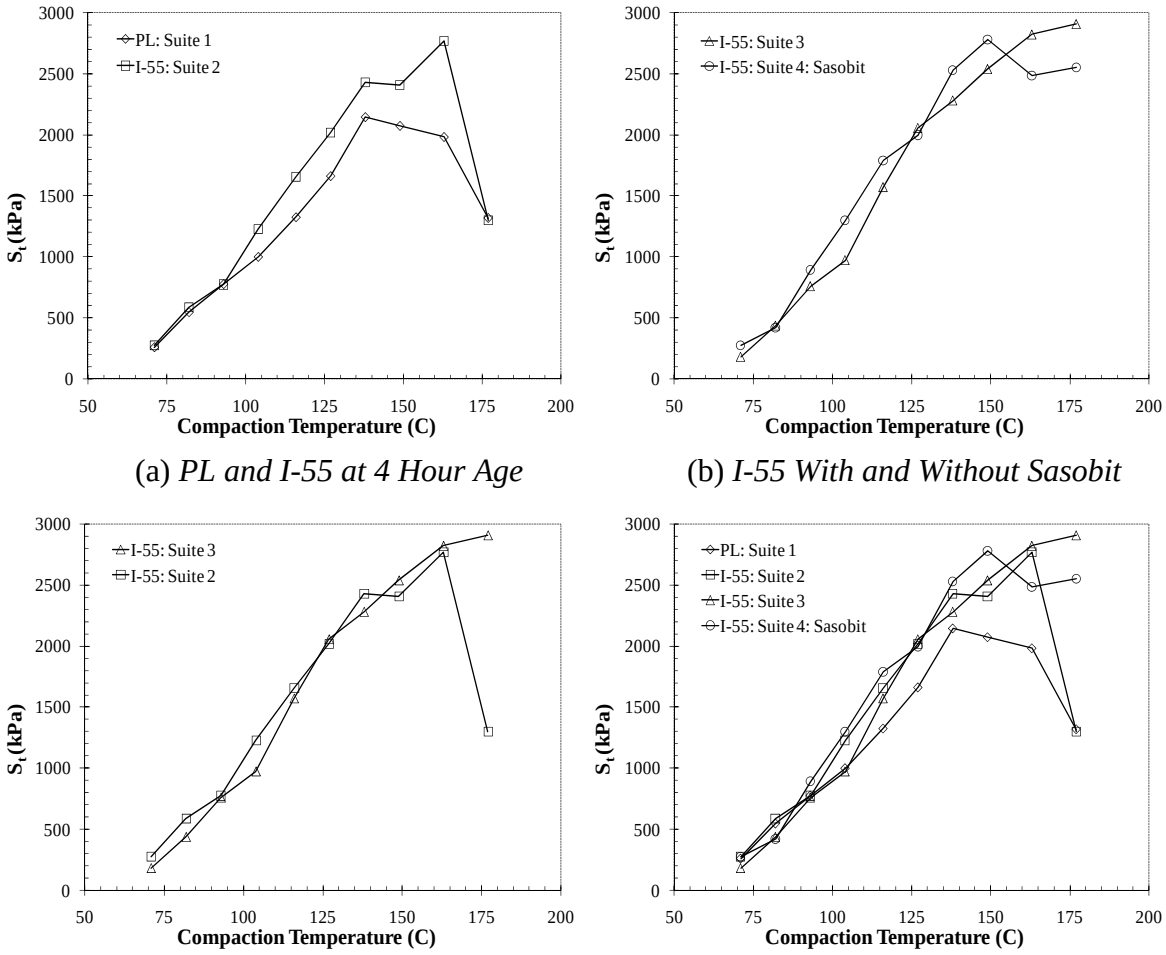
(d) All Data

Figure 5.3. V_a for 100% RAP Samples Compacted Above 71 C (160 F)

variability affecting Figure 5.3). A larger RAP particle that consists of a conglomerate of smaller particles bound together will break down under the effects of temperature on the

binder and mixing action into smaller particles and potentially change the gradation. This would be expected to become more significant at higher temperatures.

The indirect tensile strength (S_t) of all samples above 71 C (160 F) is seen in Figure 5.4. The tensile strength increases as a function of compaction temperature. The same suites that were seen to be less compactable at high temperatures with higher final compacted heights exhibit a corresponding increase in air voids and a reduction in tensile strength. The measured tensile strengths of the *PL* samples was generally lower than that for the *I-55* material; this is reasonable considering the higher quality nature of the *I-55* RAP source. Sasobit® was observed to lower the air voids with no significant change in tensile strength. Aging of 2 hr versus 4 hr was not observed to affect S_t.



(a) *PL and I-55 at 4 Hour Age*

(b) *I-55 With and Without Sasobit*

(c) *I-55 at Varying Ages*

(d) *All Data*

Figure 5.4. S_t for 100% RAP Samples Compacted Above 71 C and Tested at 25 C

In general it was observed that the 100% RAP samples exhibited definite livening of the aged RAP bitumen and increased cohesiveness at temperatures above 71 C (160 F). This was shown by a decrease in measured air voids with increased mixing/compaction temperatures and by an increase in indirect tensile strength with mixing/compaction temperature. This trend continued until 149 C (300 F), whereupon minimum air voids and

maximum tensile strength was observed. Above 149 C (300 F), a leveling off of increase in air voids was noted as well as an equal or decreased tensile strength.

This relatively simple suite of testing demonstrates RAP bitumen is not inert in all conditions. It also demonstrates that RAP bitumen behaves differently under key parameters (e.g. temperature). To successfully design asphalt containing high RAP contents, the RAP must be considered an engineered material and not a commodity.

From the initial suites an appropriate mixing/aging temperature for further testing was chosen. Figure 5.1d was the primary resource used to arrive at a mixing/aging temperature of 116 C (240 F). As seen, 116 C (240 F) and 127 C (260 F) were the highest temperatures on the initial slope where additional temperature provided a proportional change in height. 116 C (240 F) was chosen in favor of 127 C (260 F) since an acceptable product at a lower temperature is desired. At higher temperatures the curve begins to flatten indicating less relative temperature effects.

An analysis of variance was conducted on initial suites 2, 3, and 4 that contained *I-55* RAP material. Response variables of V_a and S_t were used and the results are shown in Tables 5.3 and 5.4. Variation in results due to gradation and aging period were deemed minor based on the plots of the data in Figures 5.3 and 5.4 and were not included in the ANOVA. For both choices of response variable the interaction between Sasobit® and temperature was not found to be significant. When V_a is the response variable the calculated P-value for Sasobit® is less than 0.01% indicating a significant effect on air voids due to Sasobit®. Tensile strength is not significantly affected by level of Sasobit® as demonstrated by the P-value of 11.74% calculated in Table 5.4. Temperature is a significant factor affecting both air voids and tensile strength.

Table 5.3. ANOVA for 100% *I-55* RAP Suites - V_a as Response Variable

Source	d.f.	SS	Adj. MS	F-stat	P-value	Significant*
Total Corrected	89	2216.3				
Sasobit	1	241.28	241.28	20.66	<0.0001	Yes
Temp	9	953.26	105.92	9.07	<0.0001	Yes
Sasobit*Temp	9	93.285	10.365	0.89	0.5410	No
Error	70	817.69	11.681			

** Significance at 95 percent confidence level.*

Table 5.4. ANOVA for 100% *I-55* RAP Suites - S_t as Response Variable

Source	d.f.	SS	Adj. MS	F-stat	P-value	Significant*
Total Corrected	89	73926406				
Sasobit	1	232316.2	232316.2	2.51	0.1174	No
Temp	9	59554065	6617118.4	71.59	<0.0001	Yes
Sasobit*Temp	9	816861.5	90762.39	0.98	0.4626	No
Error	70	6470410.2	92434.43			

** Significance at 95 percent confidence level.*

5.3 Component Diagram of High RAP Content Samples

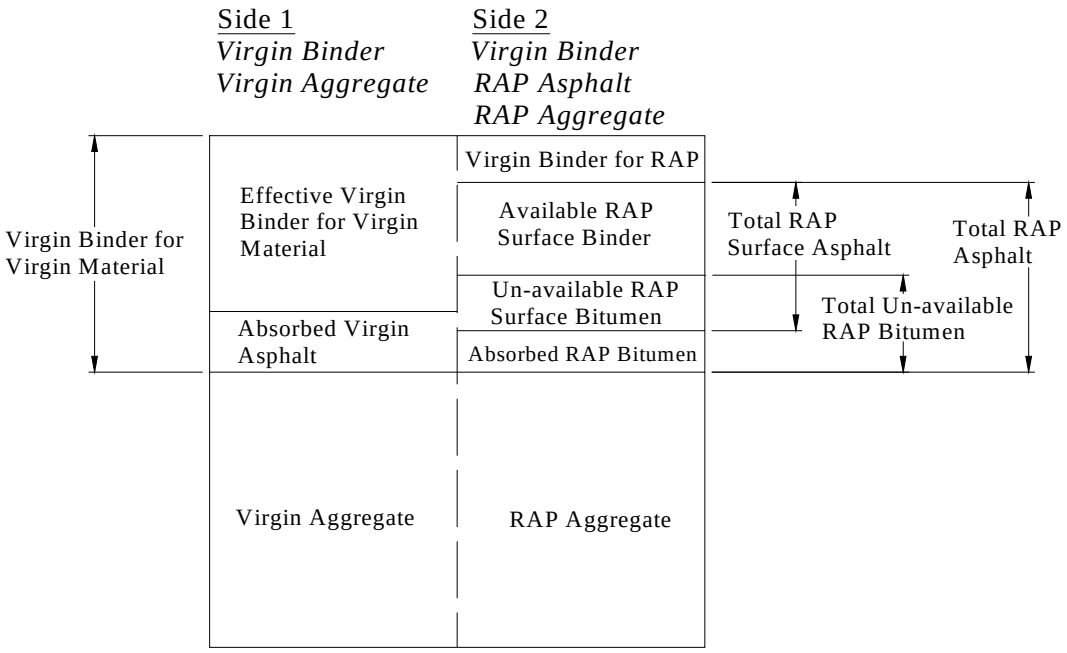
After a literature review and evaluation, an initial hypothesis was developed that the bitumen within the RAP sample would only partially blend with the virgin material in a

mixture, based on several parameters. They are: 1) mixing temperature and time; 2) fundamental properties of the RAP source (e.g. asphalt viscosity, absorbed asphalt, total asphalt); and 3) additives. This led to the conceptual model of asphalt mixtures containing high amounts of RAP that was used in this study. The model is an extension of the standard Superpave nomenclature and variable notation and utilizes existing terms whenever possible to minimize confusion.

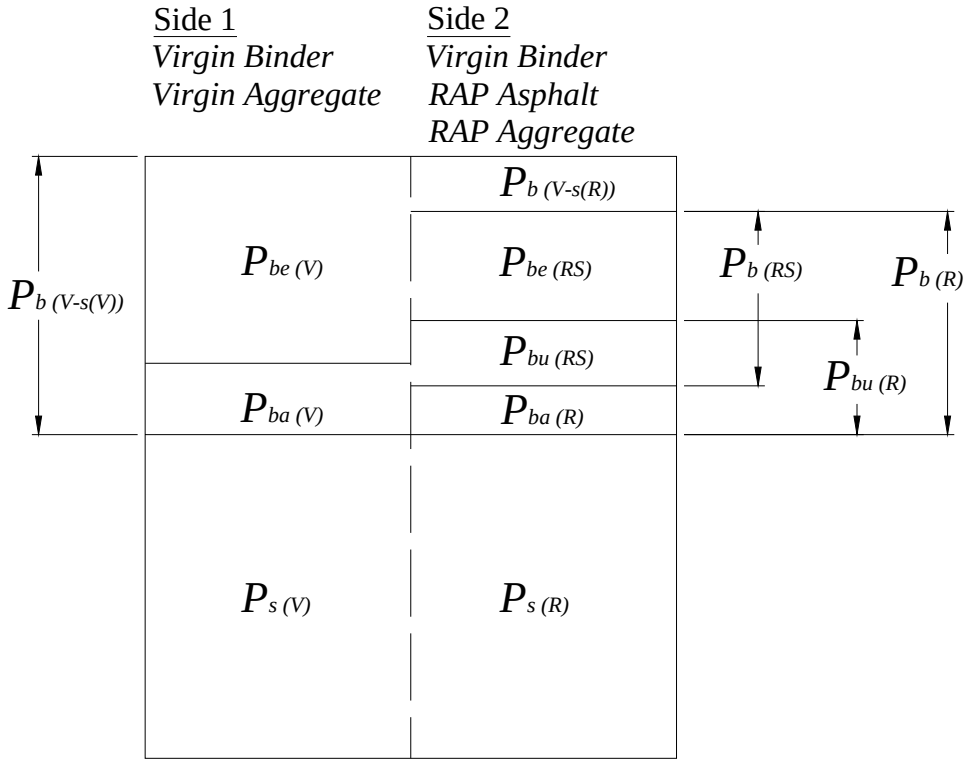
The total asphalt mixture was treated initially as two separate and distinct categories of material: 1) virgin material (aggregate and virgin binder for virgin aggregate); and 2) RAP material (aggregate, aged bitumen, and virgin binder for RAP). The two categories of material were considered as separate in concept to allow batching and visualization but are indistinguishable in a physical sample of the mix. Figure 5.5a is a visual representation of this concept for a mixture of 50 percent virgin material and 50 percent RAP material. If more of one material exists, the widths of the diagram are adjusted accordingly. The diagram is based on mass of mix components and does not include the air in a compacted sample. Air voids are addressed in the composite mixture; this concept is for visualization and batching. The concept is easily extended to different levels of RAP and virgin aggregate as the terms will be the same only the relative proportions will be different.

The virgin material, left side of diagram, has three parts: 1) virgin aggregate; 2) virgin binder absorbed by virgin aggregate; and 3) effective virgin binder for the virgin aggregate. The virgin material side of the diagram is handled much the same as an HMA component diagram. The sum of the absorbed and effective virgin binder for virgin aggregate is the total virgin binder required for virgin aggregate. The sum of the two binder components are all the virgin binder needed for an acceptable mix if only virgin aggregate is used (6% in this study as per previous data).

RAP aggregate was considered as part of the basic aggregate structure of the mix and was based on extracted gradations. The aged bitumen of RAP was thought of as being two types, that fraction of the bitumen available for blending and that fraction not available for blending in the overall mix. The total aged RAP bitumen is composed of RAP bitumen absorbed by RAP aggregate and RAP bitumen on the surface of the RAP aggregate particles. The surface RAP bitumen can be further subdivided into available surface binder and unavailable surface bitumen. A portion of the unavailable bitumen is the amount initially absorbed into the voids of the asphalt during the original mixing, while the remainder is hardened bitumen that does not effectively re-animate during the mixing/aging process. The available RAP binder can blend with the virgin binder and act as binder. The ratio of available binder to unavailable bitumen in the total RAP bitumen contribution may vary based on mixing temperature, RAP asphalt properties, and warm mix additives. In summary, the RAP material on the right side of Figure 5.5a has 5 parts: 1) RAP aggregate; 2) absorbed RAP bitumen; 3) unavailable RAP surface bitumen; 4) available RAP surface binder; and 5) virgin binder for RAP aggregate. Items 1 to 3) are ideally to be considered as RAP aggregate in batching and volumetric calculations. The difficulty, though, will be knowing beforehand the magnitude of these values.



(a) Description of Mass Diagram Terms



(b) Mass Diagram Nomenclature (See Next Page for Nomenclature Descriptions)

Figure 5.5. Mass Component Diagram for High RAP Content Mixtures

Additional information pertaining to Figure 5.5 is as follows. P, V, and M indicate percent, volume, and mass, respectively. A subscript (V) denotes virgin material while a subscript (R) denotes RAP material. (RS) signifies RAP Surface for bitumen while (V-s(V) and (V-s(R)) indicate virgin for virgin aggregate (stone) and RAP aggregate (stone) respectively. Each of these terms is expressed as percent in Figure 5.5 but there are equivalent terms for mass and volume of these components. The exact meaning of each term is as follows and equations are provided as necessary.

Figure 5.5 Nomenclature Descriptions:

$P_{s\,(V)}$: Percent virgin aggregate by mass with respect to the total mass of aggregate (virgin and RAP with asphalt extracted).

$P_{b\,(V\text{-}s(V))}$: Percent virgin asphalt binder for virgin aggregate (See Eq. 5.2).

$P_{ba\,(V)}$: Percent absorbed virgin asphalt concrete by percent mass of virgin aggregate.

$P_{be\,(V)}$: Percent effective virgin asphalt concrete for virgin aggregate with respect to total mass of Side 1 of Figure 4.5.

$P_{s\,(R)}$: Percent of RAP aggregate by mass with respect to total mass of aggregate (virgin and RAP with asphalt extracted).

$P_{b\,(R)}$: Percent of aged RAP bitumen with respect to total RAP mixture mass (asphalt content from extraction or ignition of the RAP only).

$P_{bu\,(R)}$: Percent RAP bitumen that is inert by mass of RAP mixture.

$P_{ba\,(R)}$: Percent absorbed RAP bitumen by percent mass of RAP mixture (unknown quantity).

$P_{b\,(RS)}$: Percent RAP bitumen on the surface of the RAP aggregate that was effective asphalt when the material was originally placed.

$P_{bu\,(RS)}$: Percent RAP bitumen on the surface of the RAP aggregate that was originally effective binder but now is inert and behaves as aggregate (unknown quantity).

$P_{be\,(RS)}$: Percent RAP binder on the surface of the RAP aggregate by mass of RAP mixture that was originally effective binder and remains effective binder.

$P_{b\,(V\text{-}s(R))}$: Percent additional virgin binder added by mass of Side 2 mixture to provide desired performance.

$P_{b(V)}$: Percent virgin asphalt by mass of total mixture (Side 1 and Side 2) needed for the entire sample (See Eq. 5.3).

P_b: Percent asphalt acting as binder over the duration of mixing/compaction (See Eq. 5.4).

$$P_{b(V-s(V))} = \left[\frac{M_{b(V-s(V))}}{M_{b(V-s(V))} + M_{s(V)}} \right] 100 \tag{5.2}$$

$$P_{b(V)} = \left[\frac{M_{b(V-s(V))} + M_{b(V-s(R))}}{M_{b(V-s(V))} + M_{b(V-s(R))} + M_{b(R)} + M_{s(V)} + M_{s(R)}} \right] 100 \tag{5.3}$$

$$P_b = \left[\frac{M_{b(V-s(V))} + M_{b(V-s(R))} + M_{be(RS)}}{M_{b(V-s(V))} + M_{b(V-s(R))} + M_{b(R)} + M_{s(V)} + M_{s(R)}} \right] 100 \quad (5.4)$$

It is important for the reader to recognize that the research team has used the terms bitumen and binder selectively and they have different meanings in many cases. The term bitumen refers to all the bituminous material while the term binder refers only to material acting in a manner that is binding together aggregates. Bituminous material within a RAP particle that remains inert would be referred to as bitumen while bituminous material that livens during re-use and acts to secure the mixture would be referred to as binder.

$P_{bu(RS)}$ and $P_{ba(R)}$ are unknown quantities that cannot be decoupled (at least not without an exhaustive effort that would not be performed in practice). The goal of the research team was to determine the total portion of $P_{b(R)}$ these two terms represent. Once this is known, the remaining bituminous material of the RAP serves as binder. Note $P_{ba(R)}$ is referenced to the total RAP mixture and not the RAP aggregate as is common with absorbed bituminous materials. This was performed to allow the terms to have a common reference for calculations.

5.4 Warm Mixed Test Specimens

Based on the results of the initial 100% RAP testing (See Section 5.2), 116 C (240 F) was determined to be the optimum temperature for this testing program. Mixing and aging of the samples was performed at 116 C (240 F). The 116 C (240 F) compaction and testing suite consisted of the following testing that included 0%, 1.0%, and 1.5% Sasobit®: 1) 100% virgin aggregate control testing of blend 3; and 2) blends 5 through 13 that contain multiple RAP sources and levels to allow investigation the interactions between RAP and virgin aggregate as well as between virgin and RAP binder. The samples were composed of a total aggregate weight (virgin and RAP) of 4100 g (9.02 lb). Two replicates were compacted in the SGC to 50 gyrations with 600 kPa (87 psi) of pressure at temperatures between 110 C (230 F) and 113 C (235 F). The following sections summarize the results of testing.

5.4.1 Warm Mixed 100% Virgin Control Specimens

Blend 3 samples were compacted (100% virgin aggregate) with 6.0% asphalt content that were mixed and aged at 116 C (240 F) to act as a control for the samples containing a mixture of RAP and virgin aggregate that were handled in the same manner. The 100% virgin control samples were used to evaluate the effect of Sasobit® level on air voids and tensile strength. Table 5.5 summarizes test results, and Table A.10 provides all data.

An analysis of variance was conducted to evaluate the significance of Sasobit® on V_a and S_t of the 100% virgin control samples. The results of this are shown in Table 5.6 and Table 5.7. Sasobit® was determined to significantly affect V_a and S_t of the samples.

Table 5.5. Warm Mixed Control Test Results-Avg Values

Sasobit® (%)	V_a (%)	S_t kPa (psi)	T (sec)
0.0	4.7	894 (129.7)	2.5
1.0	3.7	952 (138.1)	3.4
1.5	3.1	989 (143.5)	2.9

Table 5.6. ANOVA for 100% Virgin Aggregate Control - V_a as Response Variable

Source	d.f.	Adj. MS	F-stat	P-value	Significant*
Total Corrected	14				
Sasobit	2	2.9307	40.15	<0.0001	Yes
Error	12	0.0730			

** Significance at 95 percent confidence level.*

Table 5.7. ANOVA for 100% Virgin Aggregate Control - S_t as Response Variable

Source	d.f.	Adj. MS	F-stat	P-value	Significant*
Total Corrected	14				
Sasobit	2	11577	33.37	<0.0001	Yes
Error	12	347.0			

** Significance at 95 percent confidence level.*

5.4.2 Warm Mixed RAP Test Specimens

In Figures 5.6 through 5.8 the test results of air voids and indirect tensile strength are shown for the three RAP sources as a function of virgin binder added to account for the RAP, $P_{b\ (V\text{-}s(R))}$ in the nomenclature of Figure 4.5. Raw data can be seen in Tables A.11 to A.19. The numerals on the air voids plots denote the order in which trial asphalt binder contents were compacted (estimate numbers of Figure 4.4). Blends 5 through 13 were aged and compacted at 116 C (240 F) with 100% RAP, including Sasobit® (1.0 and 1.5%), and with 0% $P_{b\ (V\text{-}s(R))}$. This was the first estimate as denoted in Figure 4.4.

To develop the second estimate, visual observations were first made that *I-55* was the sample with mean overall characteristics. Secondly, *I-55* RAP was used to estimate the amount of virgin binder to add to the RAP aggregate to decrease the air voids. Samples of *I-55* were tested by adding virgin binder according to Table 5.8 and observing the mixing and compaction characteristics. Note that different RAP sources (I-55, *MS-25,* and *SP)* contained different amounts of asphalt, so an estimate based off aggregate weight was more universal. The intent of testing was to determine an amount of virgin binder to add that would produce less than 4% air voids. The rational was that when no asphalt was added the air voids were well above 4% and having a value below 4% would bound the problem for additional testing. A value of 2% was selected.

Table 5.8. 100% *I-55* RAP Test Results With Varying Virgin Binder Contents

By Agg. Wt.[1]	By Total Wt.[2] $P_{b\ (V\text{-}s(R))}$	Total AC%[3]	H_I[4] (mm)	H_F[5] (mm)	G_{mm}[5]	G_{mb}	V_a (%)	T[7] (sec)	S_t kPa (psi)
0.5	0.4	6.1	140.0	117.4	2.340	2.148	8.2	1.8	1827 (265.0)
1.0	0.9	6.5	140.9	117.5	2.326	2.154	7.4	2.4	2041 (296.0)
2.0	1.8	7.5	135.9	113.8	2.298	2.232	2.9	2.5	3072 (445.6)
3.0	2.7	8.4	135.4	114.5	2.271[8]	2.241	1.3	2.5	2932 (425.2)
4.0	3.6	9.3	135.2	115.8	2.245	2.239	0.3	2.5	2601 (377.3)
5.0	4.5	10.2	133.7	117.3	2.219	2.227	~0	2.5	2185 (316.8)

Samples heated, mixed, and compacted at 154 C (240 F) and 50 gyrations
1: Additional Virgin Binder based on Aggregate Weight
2: Additional Virgin Binder based on Total Weight
3: Total Asphalt Content based on Total Weight
4: Initial Height of Sample as measured in SGC
5: Final Height of Sample as measured in SGC
6: G_{mm} estimated based on G_{se} = 2.553 calculated for the 2.7% $P_{b\ (V\text{-}s(R))}$ sample
7: Time to peak tensile strength
8: As determined by AASHTO T 209

Based on Table 5.8 and aforementioned discussion a second estimate of 2.0 % $P_{b\ (V\text{-}s(R))}$ was made and tested for all RAP aggregate sources and contents at 1.0% and 1.5% Sasobit®. This is denoted by numeral 2 on Figures 5.5 to 5.8. As expected, the binder content was too high for most combinations of RAP aggregate source and content and resulted in a measured air voids of less than the target of 4.0%. From the first two trials a third estimate of additional virgin binder for RAP was produced by estimating the additional virgin binder content needed to bracket 4.0% air voids for each RAP source at the 75% level. The third estimate was tailored to each RAP source and not to each aggregate blend. For the *I-55* RAP source this required an extrapolation from the previous results and for the *MS-25* and *SP* this only required interpolation between the previous two additional binder levels.

A fourth and final estimate was made of $P_{b\ (V\text{-}s(R))}$ for each RAP aggregate source and each RAP level. In addition to the 1.0% and 1.5% Sasobit® levels, a control of 0% Sasobit® was compacted at the same mixing and compaction temperature to estimate the effect of the Sasobit®. Note that for the *SP* RAP source at the 75% level a fourth estimate was not needed since the third estimate yielded air voids of 4.0% and only a 0.0% Sasobit® sequence was needed. Table 5.9 summarizes the estimates and the binder added to account for the RAP.

In general it can be seen that the air voids decrease with additional virgin binder added for the RAP aggregate for all combinations of RAP source and level. There is some variability in the testing results that may be masking some behaviors of interest. Indirect tensile strength typically increases or remains relatively constant with an increase in $P_{b\ (V\text{-}s(R))}$. As the level of RAP aggregate in the total sample increases the tensile strength shows a earlier and more dramatic increase with additional virgin binder for RAP. This trend is particularly noticeable in the 100% RAP aggregate samples.

It is also informative to look at the variation in air voids and tensile strength as a function of total asphalt content; this includes all bitumen in RAP regardless of its contribution to the mixture. This serves as a complement to response variable variation as a function of additional virgin binder for RAP $P_{b\ (V\text{-}s(R))}$. Figures 5.9 to 5.11 show the same air voids and tensile strength data only as a function of total asphalt content. When the data is

examined in this way it is seen that the total asphalt content needed to achieve 4% air voids is not greatly different for each level of a RAP aggregate source.

Table 5.9. Test Sequences for $P_{b\ (V\text{-}s(R))}$

RAP Source	Estimate Level	RAP Content	$P_{b\ (V\text{-}s(R))}$
I-55	1st	50, 75, or 100	0.0
	2nd	50, 75, or 100	2.0
	3rd	50, 75, or 100	2.5
	4th	50	2.8
	4th	75	2.1
	4th	100	1.5
MS-25	1st	50, 75, or 100	0.0
	2nd	50, 75, or 100	2.0
	3rd	50, 75, or 100	0.7
	4th	50	0.4
	4th	75	0.5
	4th	100	0.6
SP	1st	50, 75, or 100	0.0
	2nd	50, 75, or 100	2.0
	3rd	50, 75, or 100	1.3
	4th	50	1.1
	4th	75	1.3
	4th	100	0.9

Table 5.10 provides insight into the relative effects of Sasobit®. This table presents the results from compacting ten replicate samples at a single asphalt binder content, but with varying levels of Sasobit®. An analysis of variance was conducted to evaluate whether the inclusion of the warm mix additive improved the compactibility of the high RAP content mixes. The analysis of variance was conducted to determine if differences existed in the air void contents with the addition of the warm mix additive. If the warm mix additive did improve the compactibility of the mixtures at a given temperature, the air voids should decrease. Results of the analysis of variance are presented in Table 5.11. This table showed significant differences in the measured air void contents (p-value of 0.01) at a 95 percent level of confidence. Since there were significant differences in the air void content data, a Duncan's multiple range test was conducted. The Duncan's multiple range test is used to rank means in order differentiate means that are different. Results of the Duncan's multiple range test indicated that there were no significant differences between air voids when either 1.0 or 1.5 percent Sasobit® was added; however, both the 1.0 and 1.5 percent Sasobit® data were significantly different than those samples not containing the warm mix additive. The data also suggested that the samples containing Sasobit® had lower air void contents than did the samples that did not. This would indicate that the addition of Sasobit® did improve the compactibility.

Table 5.10. Test Results of 75% *I-55* RAP to Investigate Sasobit® Effectiveness

$P_{b\ (V\text{-}s(R))}$[1]	G_{mm}[2]	S[3]	Rep	G_{mb}	H_I[4] (mm)	H_F[5] (mm)	V_a	T[6] (sec)	S_t kPa (psi)
2.1	2.297	0.0	1	2.202	138.4	115.3	4.1	2.5	2681 (388.8)
			2	2.186	139.5	116.1	4.8	2.5	2279 (330.5)
			3	2.169	139.8	116.0	5.6	2.5	2454 (356.0)
			4	2.194	139.8	115.4	4.5	2.5	2488 (360.8)
			5	2.203	138.0	114.8	4.1	2.5	2406 (349.0)
			6	2.198	139.8	115.6	4.3	2.5	2543 (368.8)
			7	2.198	139.4	115.3	4.3	2.5	2733 (396.4)
			8	2.195	136.3	112.8	4.4	2.5	2504 (363.2)
			9	2.192	139.0	115.4	4.6	2.5	2587 (375.2)
			10	2.196	139.1	115.4	4.4	2.5	2614 (379.2)
			Avg.	**2.190**	**138.9**	**115.2**	**4.5**	**2.5**	**2529 (365.4)**
2.1	2.297	1.0	1	2.186	138.3	115.1	4.8	2.5	2515 (364.7)
			2	2.190	139.4	114.2	4.7	2.5	2379 (345.0)
			3	2.217	137.5	114.3	3.5	2.5	2662 (386.1)
			4	2.216	136.9	114.2	3.5	2.5	2685 (389.5)
			5	2.214	137.3	114.4	3.6	2.5	2822 (409.3)
			6	2.213	137.2	114.6	3.7	2.5	2427 (352.0)
			7	2.203	139.0	115.5	4.1	2.5	2554 (370.4)
			8	2.214	137.4	114.6	3.6	2.5	2757 (399.9)
			9	2.215	138.0	114.8	3.6	2.5	2759 (400.2)
			10	2.217	137.5	114.7	3.5	2.4	2780 (403.2)
			Avg.	**2.209**	**137.9**	**114.6**	**3.9**	**2.5**	**2634 (382.0)**
2.1	2.297	1.5	1	2.204	139.2	115.7	4.0	2.5	2127 (308.5)
			2	2.197	139.0	115.3	4.4	2.5	2118 (307.2)
			3	2.196	139.5	115.5	4.4	2.4	2441 (354.1)
			4	2.204	139.1	115.3	4.0	2.3	2420 (351.0)
			5	2.198	139.0	115.3	4.3	2.5	2610 (378.6)
			6	2.201	139.0	115.1	4.2	2.4	2608 (378.2)
			7	2.205	137.7	115.0	4.0	2.4	2713 (393.5)
			8	2.219	137.7	114.9	3.4	2.5	2591 (375.8)
			9	2.198	137.9	115.0	4.3	2.5	2656 (385.3)
			10	2.204	137.9	114.9	4.0	2.4	2722 (394.8)
			Avg.	**2.203**	**138.6**	**115.2**	**4.1**	**2.4**	**2501 (362.7)**

1: $P_{b(V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass
2: G_{mm} did not vary based on Sasobit content
3: % Sasobit added to the binder by total binder mass
4: Initial height of sample measured by SGC
5: Final height of sample measured by SGC
6: Time to peak load in indirect tensile test

Table 5.12 summarizes time to indirect tensile failure (*T*) and change in height due to compaction (H_I-H_F). For ease of reference, all data has been provided in a single table. The results show the samples with high RAP contents failing more quickly than predominately virgin samples. This is not a desirable behavior and indicates brittleness. More detailed

investigation into this issue should be conducted to determine if it can be controlled to an acceptable level.

Table 5.11. Test Results ANOVA of 75% *I-55* RAP to Investigate Sasobit® Effectiveness

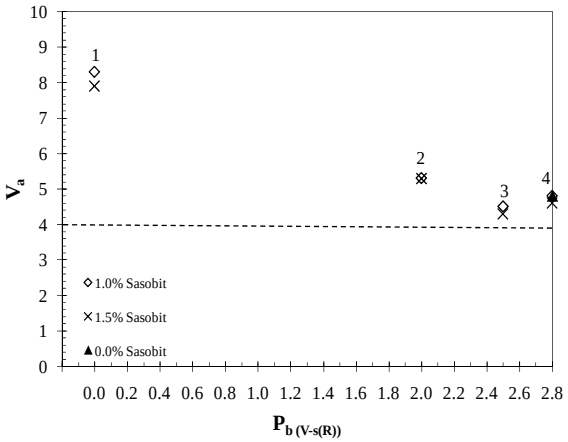
Source	d.f.	Adj. MS	F-stat	P-value	Significant*
Total Corrected	29				
Sasobit	2	1.080	6.09	0.007	Yes
Error	27	0.178			

** Significance at 95 percent confidence level.*

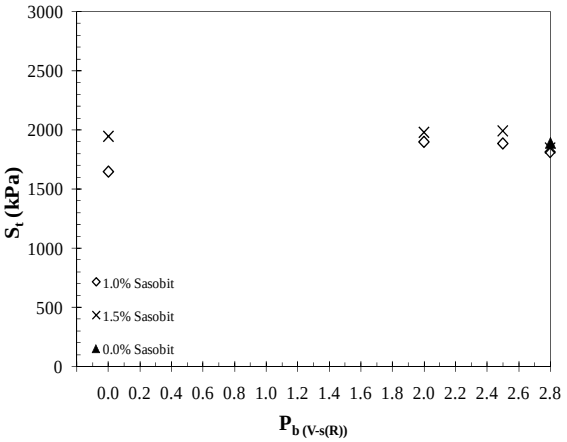
The change in sample height during compaction in the SGC can be used to evaluate the relative compactibility of mixtures and make relative comparisons between different mixtures. However, the height of samples at zero gyrations may provide a better estimate of compactibility. Figure 5.12 presents the relationship between sample height and compaction temperature for Blend 4. This figure shows two different relationships. One relationship is for the difference in sample height from zero gyrations to the final gyration and the other is simply for the height of sample at zero gyrations. Based on the figure, the height of the sample at zero gyrations appears to provide a measure of compactibility for the different samples. As temperature increases (thus, compactibility should increase), the height of the sample at zero gyrations decreases, meaning more compaction.

Table 5.12. Time to Failure and Compaction Height Test Results

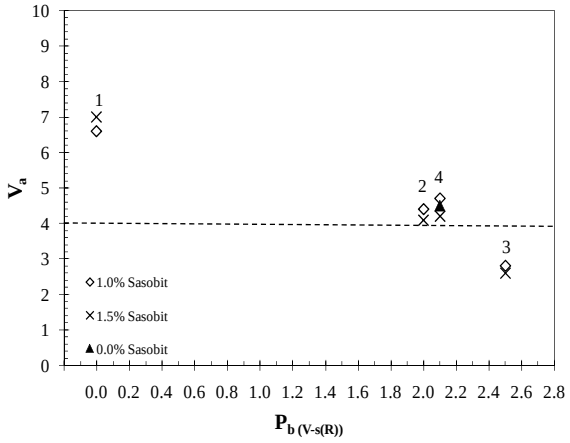
			Range of Values	
RAP Content (%)	**Blend**	**Table**	T **(sec)**	$H_I - H_F$ **(mm)**
0	1	A.1	2.8 to 5.0	21.3 to 24.8
15	2	A.2	2.8 to 3.8	21.3 to 23.8
0	3	A.3	3.0 to 4.4	24.4 to 28.3
100	4	A.5	1.2 to 2.0	19.9 to 24.7
100	5	A.7	1.3 to 1.9	22.8 to 25.7
100	5	A.8	1.4 to 2.5	22.5 to 33.0
100	5	A.9	1.5 to 2.4	20.0 to 25.6
0	3	A.10	2.5 to 4.0	25.6 to 26.7
50	11	A.11	2.0 to 3.8	25.0 to 27.1
75	8	A.12	1.8 to 3.4	22.8 to 25.2
100	5	A.13	1.4 to 3.0	20.8 to 22.5
50	12	A.14	2.5 to 3.8	18.7 to 24.2
75	9	A.15	2.2 to 5.0	19.8 to 23.8
100	6	A.16	1.6 to 3.8	20.0 to 22.1
50	13	A.17	2.4 to 3.4	22.0 to 23.4
75	10	A.18	2.0 to 3.6	18.6 to 21.2
100	7	A.19	1.4 to 2.8	17.9 to 20.0



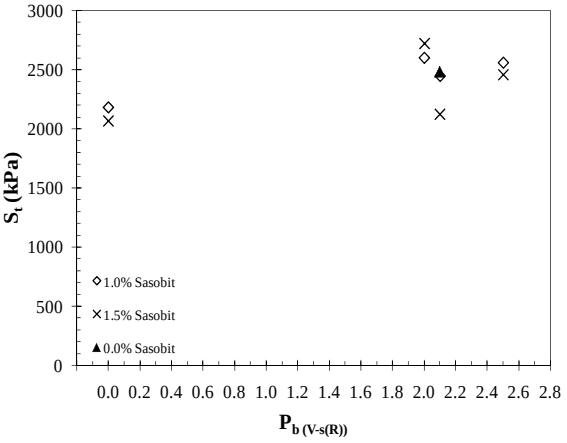
(a) V_a for 50% RAP Aggregate



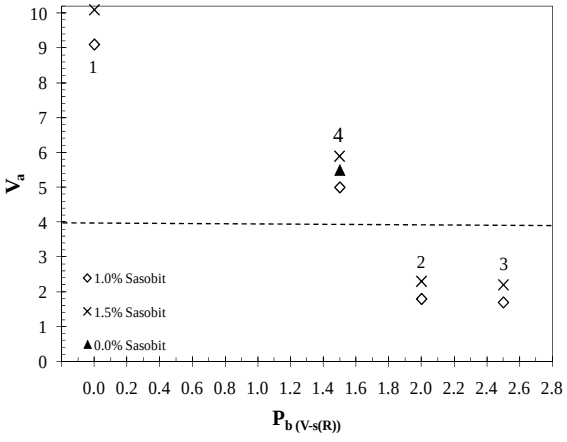
(b) S_t for 50% RAP Aggregate



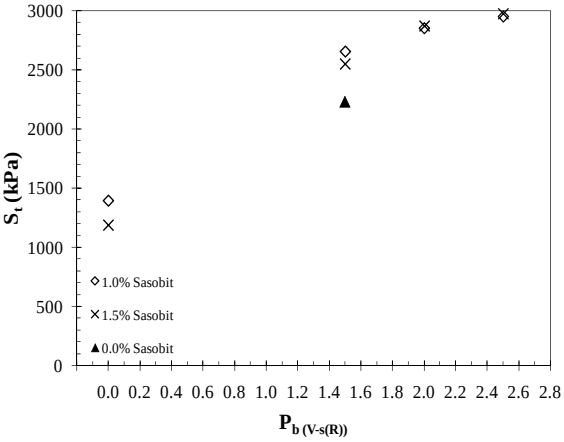
(c) V_a for 75% RAP Aggregate



(d) S_t for 75% RAP Aggregate

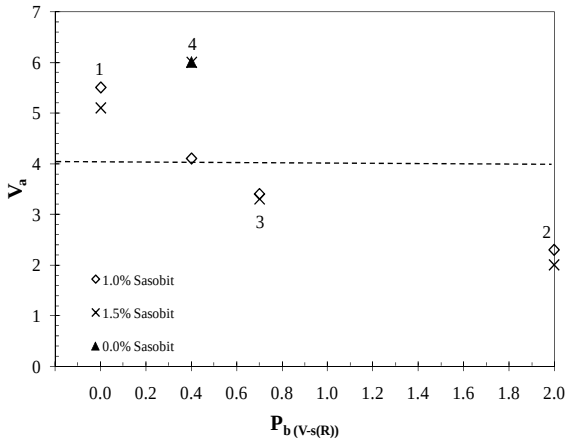


(e) V_a for 100% RAP Aggregate

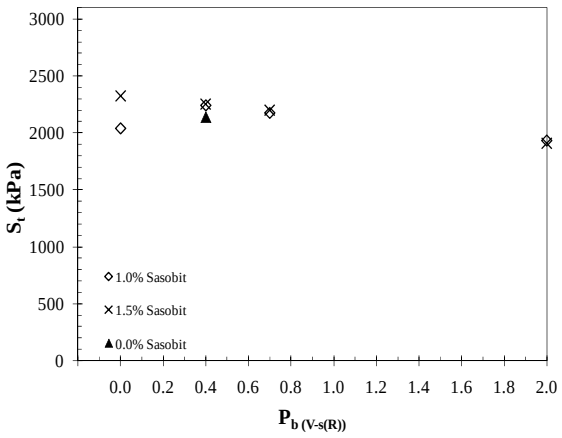


(f) S_t for 100% RAP Aggregate

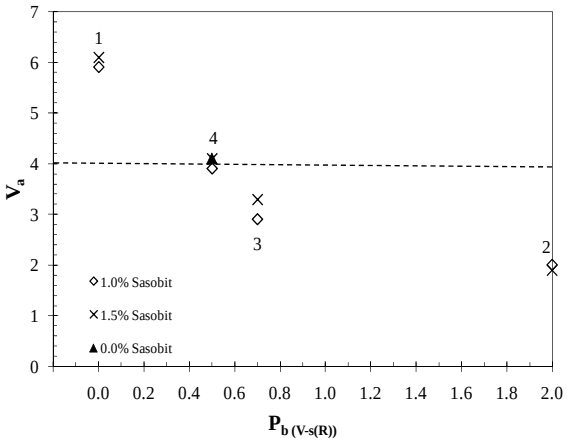
Figure 5.6. V_a and S_t Results for *I-55* RAP Aggregate Source and $P_{b\ (V\text{-}s(R))}$



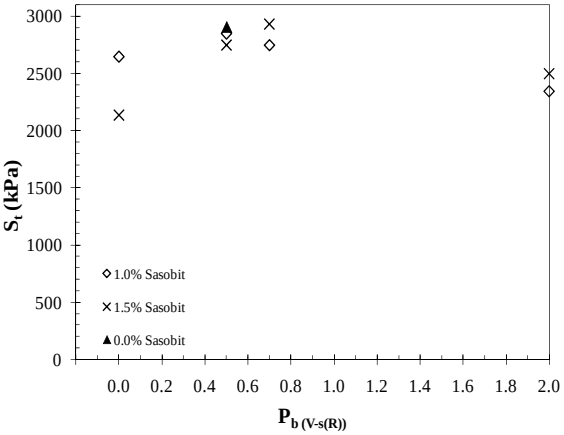
(a) V_a for 50% RAP Aggregate



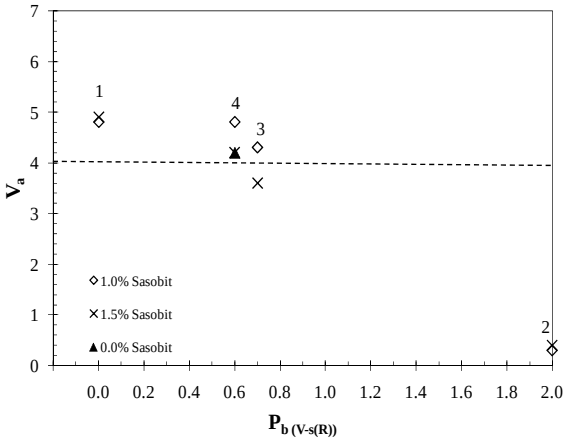
(b) S_t for 50% RAP Aggregate



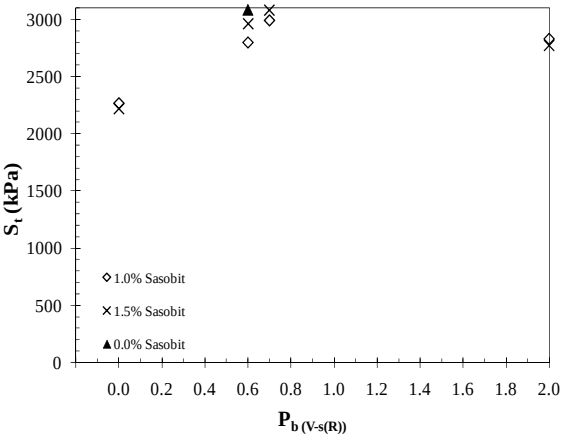
(c) V_a for 75% RAP Aggregate



(d) S_t for 75% RAP Aggregate

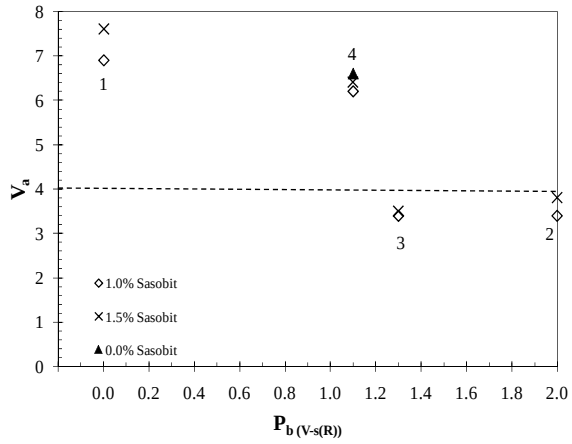


(e) V_a for 100% RAP Aggregate

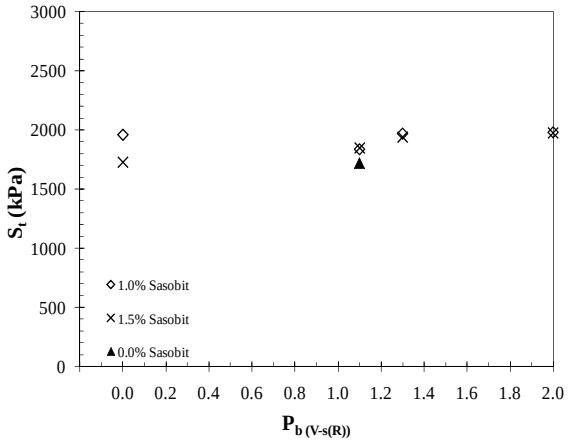


(f) S_t for 100% RAP Aggregate

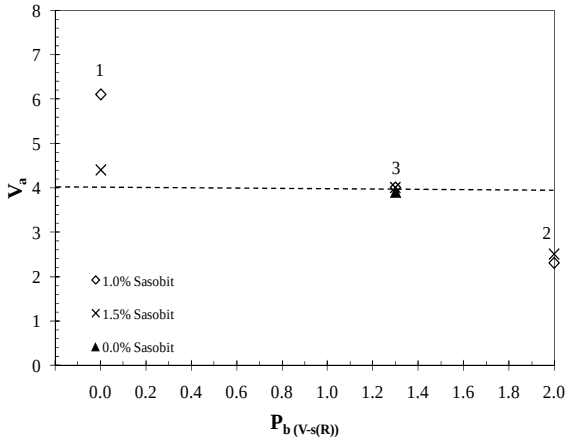
Figure 5.7. V_a and S_t Results for *MS-25* RAP Aggregate Source and $P_{b\ (V\text{-}s(R))}$



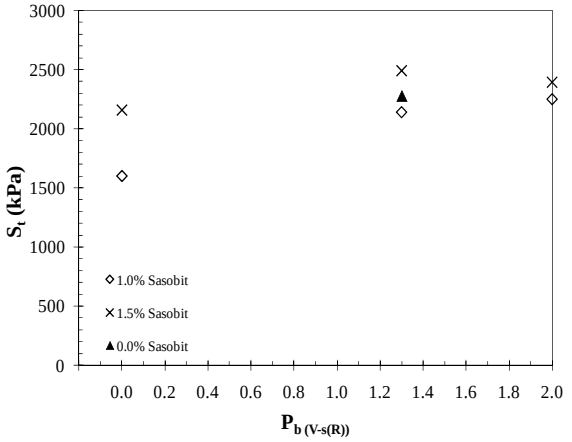
(a) V_a for 50% RAP Aggregate



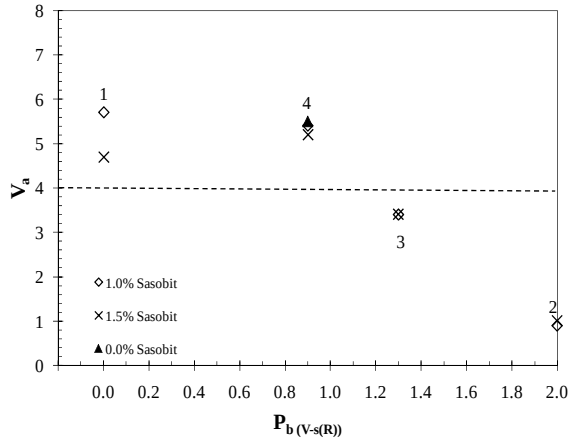
(b) S_t for 50% RAP Aggregate



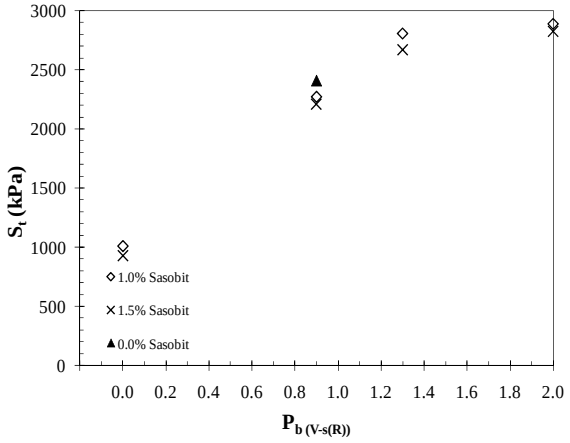
(c) V_a for 75% RAP Aggregate



(d) S_t for 75% RAP Aggregate

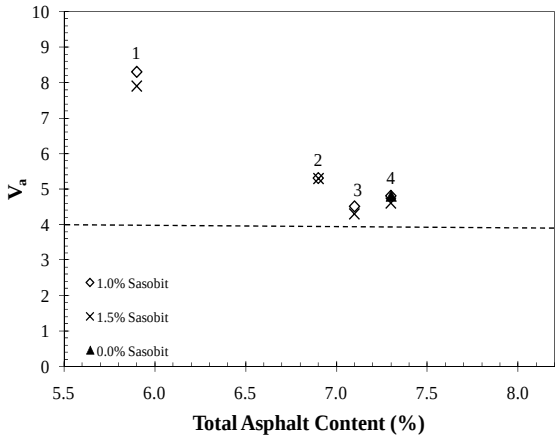


(e) V_a for 100% RAP Aggregate

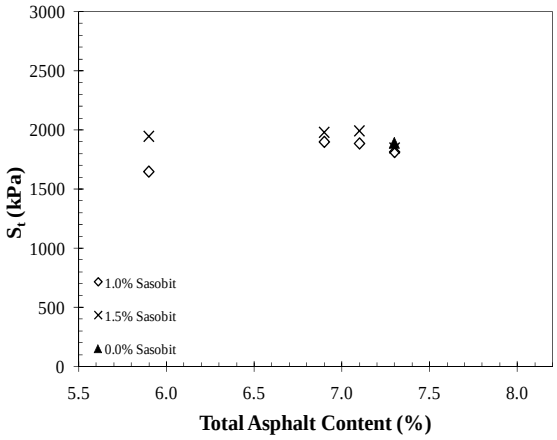


(f) S_t for 100% RAP Aggregate

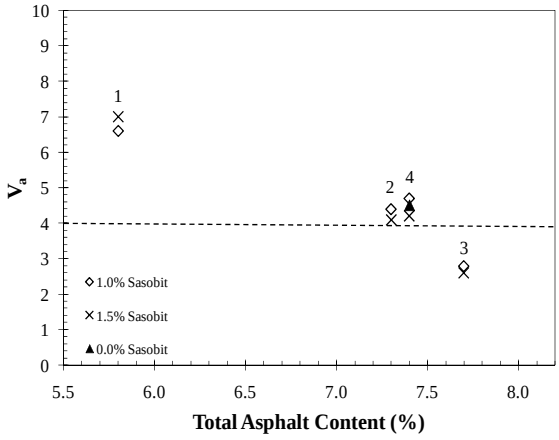
Figure 5.8. V_a and S_t Results for *SP* RAP Aggregate Source and $P_{b\ (V\text{-}s(R))}$



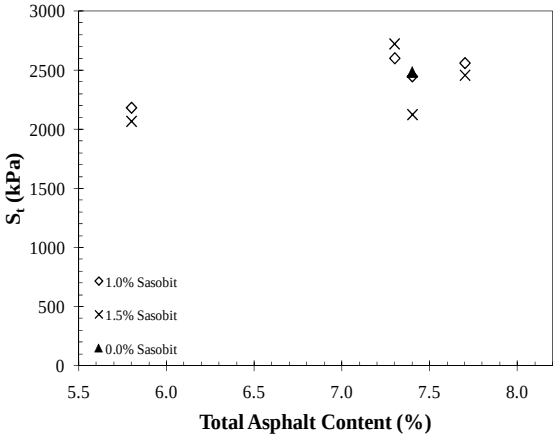
(a) V_a for 50% RAP Aggregate



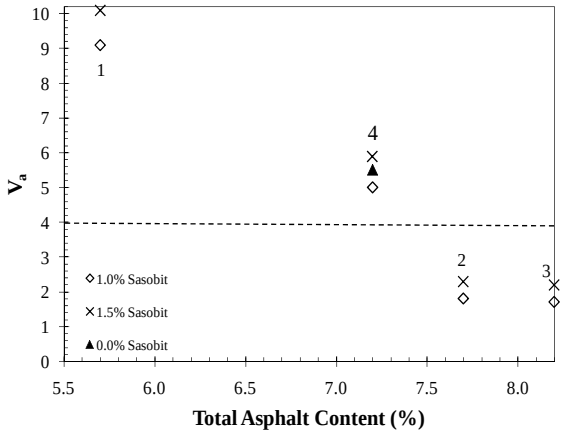
(b) S_t for 50% RAP Aggregate



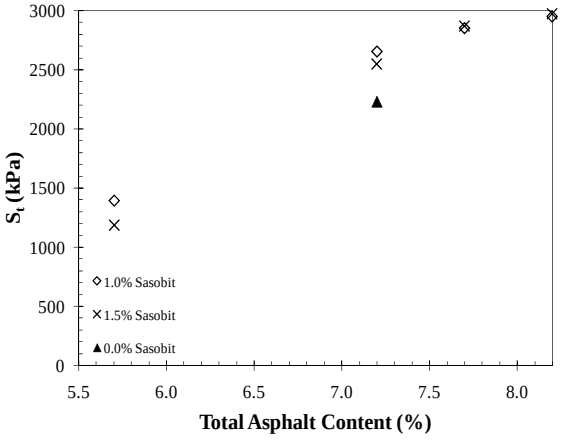
(c) V_a for 75% RAP Aggregate



(d) S_t for 75% RAP Aggregate

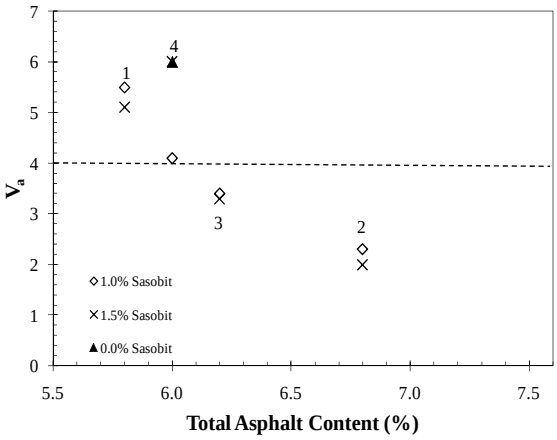


(e) V_a for 100% RAP Aggregate

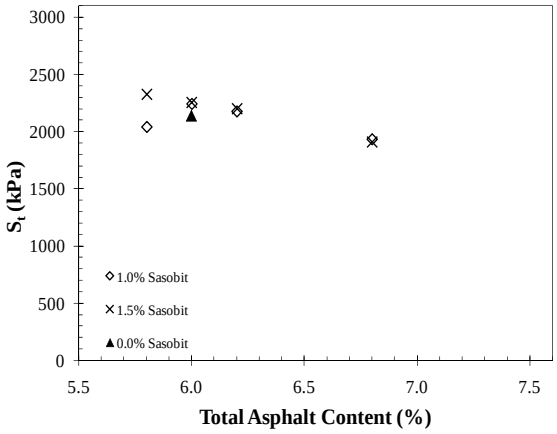


(f) S_t for 100% RAP Aggregate

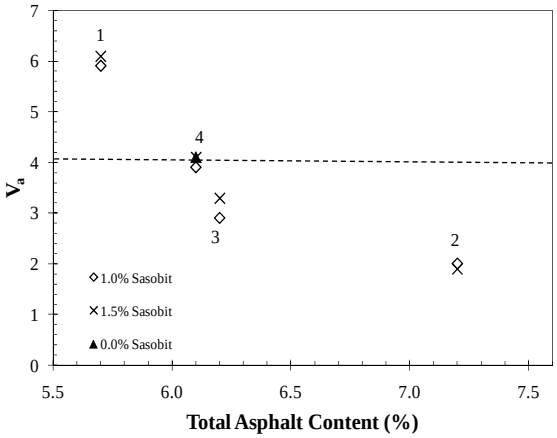
Figure 5.9. V_a and S_t Results for *I-55* RAP Aggregate Source and Total AC %



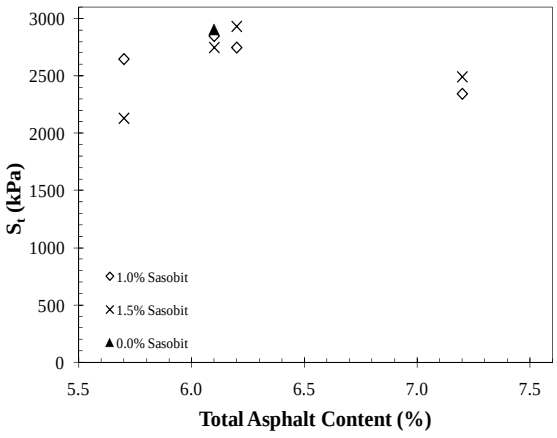
(a) V_a for 50% RAP Aggregate



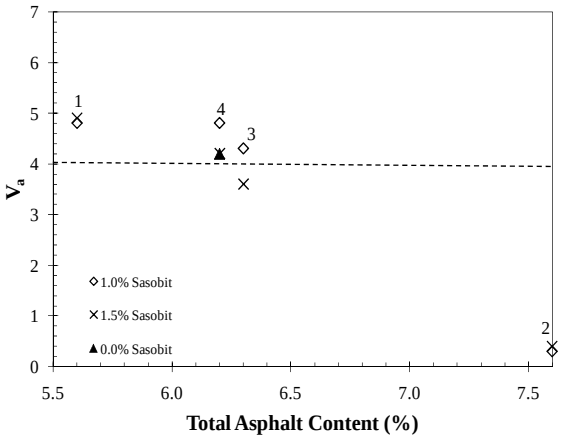
(b) S_t for 50% RAP Aggregate



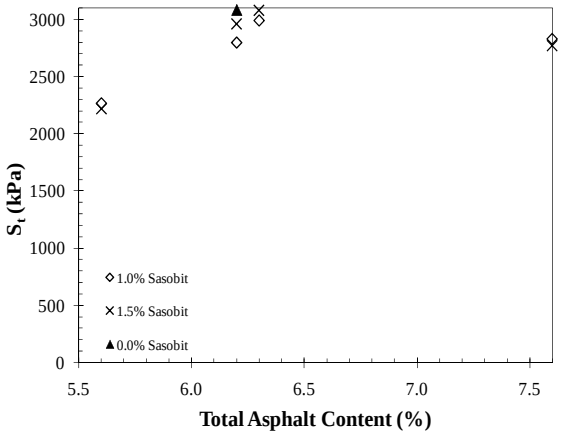
(c) V_a for 75% RAP Aggregate



(d) S_t for 75% RAP Aggregate

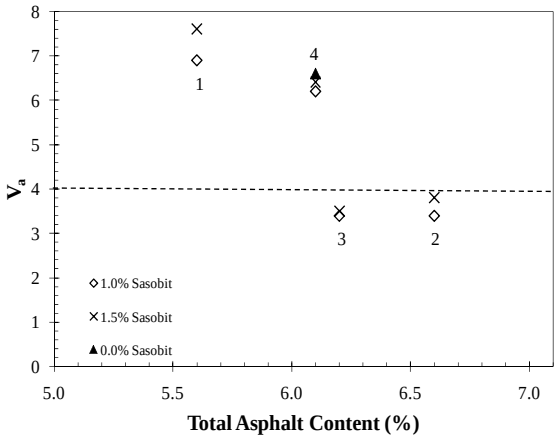


(e) V_a for 100% RAP Aggregate

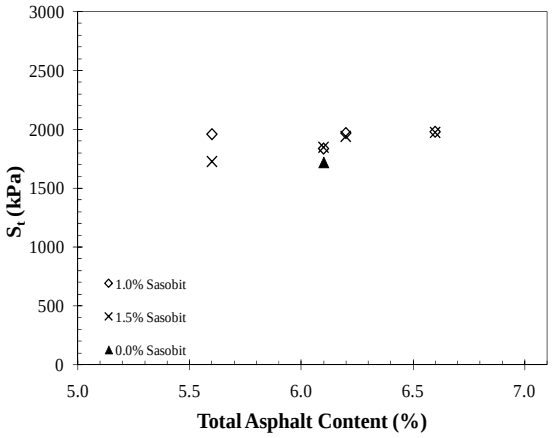


(f) S_t for 100% RAP Aggregate

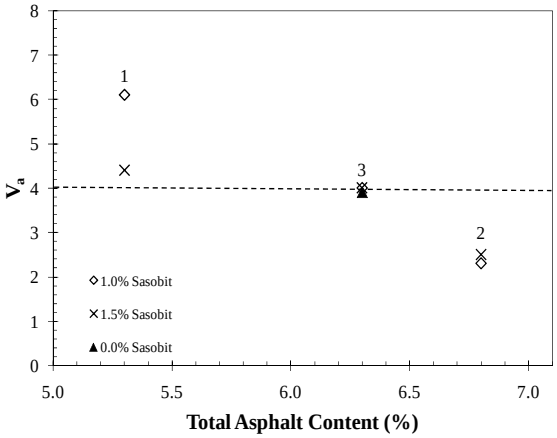
Figure 5.10. V_a and S_t Results for *MS-25* RAP Aggregate Source and Total AC %



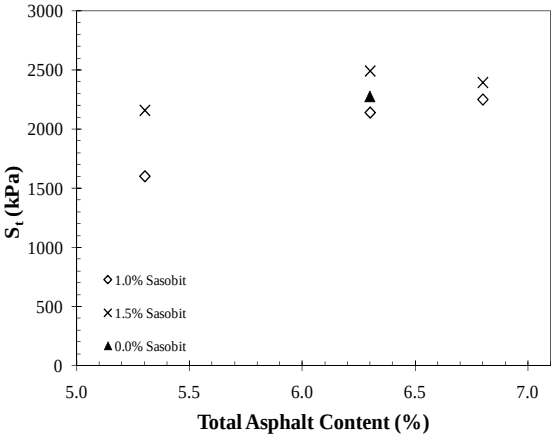
(a) V_a for 50% RAP Aggregate



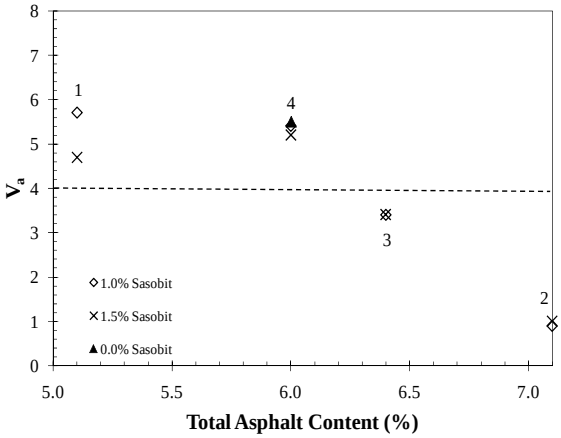
(b) S_t for 50% RAP Aggregate



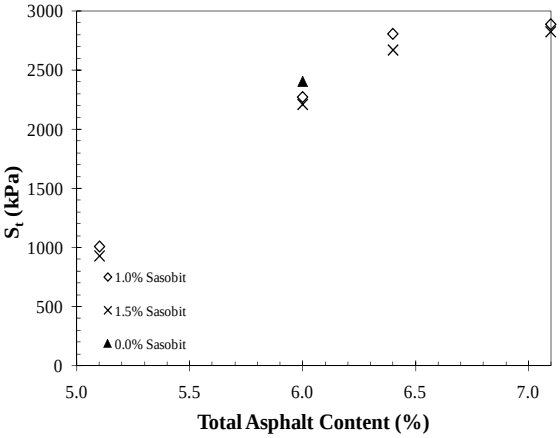
(c) V_a for 75% RAP Aggregate



(d) S_t for 75% RAP Aggregate



(e) V_a for 100% RAP Aggregate



(f) S_t for 100% RAP Aggregate

Figure 5.11. V_a and S_t Results for *SP* RAP Aggregate Source and Total AC %

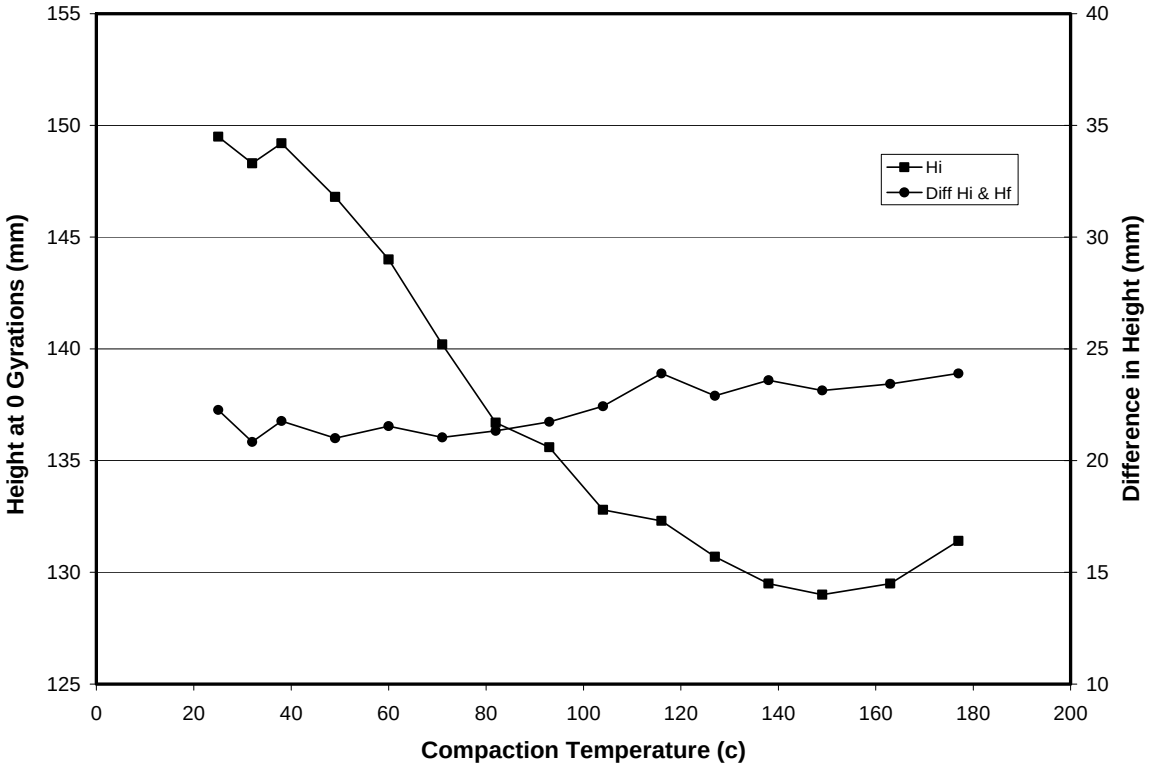


Figure 5.12. Relationships between Sample Heights and Compaction Temperature

CHAPTER 6-FEASABILITY ASSESSMENT

6.1 Feasibility of High RAP Mixtures

A primary goal of the research was to determine the likelihood that additional investigation would be worthwhile; i.e. is the concept feasible? Based upon the data and analyses presented up to this point within the report, the answer to this question is yes. Economic analysis presented in Chapter 3 resulted in no evidence that high RAP and/or warm mixed asphalt would be prohibitive. Specific details of economics are left for Chapter 3, but the concept of elevated RAP mixtures, and/or warm mix additives have provided no evidence of being economically prohibitive.

Technical parameters related to laboratory behavior are discussed in Chapters 4 and 5. They show elevated RAP mixtures containing warm mix additives can be compacted to acceptable air voids using low to moderate amounts of virgin asphalt. A potential drawback is that their tensile strengths could be indicators of brittleness and cracking potential, but no definite information is available regarding these matters in this report. It is also unclear whether the brittle nature of high RAP content mixes would be a concern as base courses on lower volume roadways. The following section provides specific information from asphalt producers that provided the RAP materials for this investigation. The information should provide an assessment of RAP properties on a larger scale in Mississippi. The final section of this chapter describes key parameters deserving additional investigation.

6.2 Producer Information Related to High RAP Mixtures

Information was graciously provided by three of Mississippi's primary asphalt producers. The information was obtained between late 2007 and early 2008 to provide more understanding of Mississippi RAP practices, properties, and similar. The information provided by each of the three producers has been separated both by property and also by producer for ease of use.

6.2.1 Moisture in RAP Stockpiles

APAC Mississippi: Table 6.1 contains moisture data for nine of their plants in Mississippi. The data shown are the average of weekly moisture data taken over a three month period in

Table 6.1. *APAC Mississippi* Moisture Data

Plant Location	Average RAP Moisture Content
Meridian	3.8
Jackson/Canton	4.2
Vicksburg	4.7
Yazoo City	4.8
Greenville	5.1
Starkville	5.9
Hamilton	6.5
Guntown/Corinth	6.3
Columbus	5.8

the spring of 2008. Note that the data in Table 6.1 is for uncrushed material and that samples from the Meridian and Greenville plants were also crushed. Once crushed, the moisture of these materials reduced to 3.4 and 4.6%, respectively. The reduction is likely attributable to drying while handling.

Bonds Construction: Tupelo plant graded stockpile had 1.8% moisture for December 2007 testing, which was taken relatively close to the surface of the pile. Moisture obtained in June of 2008 was 5.2%, which was taken by removing crust and sampling a reasonable depth into the pile.

Superior Asphalt: They have developed moisture content data for RAP stockpiles for use within their plant operations. The majority of the moisture content testing occurs an estimated 0.6 m (2 ft) into the face of the stockpile. It has been observed that water tends to run off the stockpiles more than it does into it. The interior of the pile is believed to be at a relatively consistent value. Moisture content data is used to adjust plant settings and is reported from highest to lowest: 1) the day after a rainfall moisture values are 4.5 to 5.7%; 2) three days after a rainfall moisture values are 3.5 to 5.0%; 3) five days after a rainfall moisture values are 3.0 to 4.5%; and 4) dry for weeks moisture values are 2.0 to 3.0%.

6.2.2 Origin and Stockpiling of RAP

APAC Mississippi: All private RAP material is kept in one stockpile and is separate from MDOT projects. Multiple and routine small projects are common and they typically each result in 200 to 300 tons of material. Once the stockpile is of sufficient size, it is processed, fractionated, and used within private mixtures. Representatives of the company noted the large quantities of sand (≈ 30%) commonly contained within private mixes to allow a slick and smooth finish to be obtained. Large sand quantities can affect mixture stability. The majority of the RAP obtained, though, is from MDOT projects. This was noted to be the most consistent material. Large MDOT projects are commonly separated into stockpiles to allow more consistent production.

Bonds Construction: RAP obtained from MDOT, State Aid, Natchez Trace, and private projects were separated into: 1) Graded stockpile that contains the vast majority of the material; 2) Shoulders and widening stockpile that is used only for private mixes; and 3) Plant screenings stockpile that is milled periodically to generate additional RAP. During the off season for paving the graded stockpile is screened to separate fine material for surface courses; primary motivation is to give salaried employees work that will increase efficiency during early paving season. All the RAP being used is from their own milling work, and their work radius is around 80 km (50 miles).

Superior Asphalt: Typically have a base millings stockpile (due to maximum aggregate size) and a second stockpile for all other RAP (MDOT and private). An estimated 90% of all RAP is obtained from MDOT projects. Separating the primary stockpile into coarse and fine fractions has been considered.

6.2.3 Specific Gravities of RAP

The specific gravity and absorption of RAP materials for all producers can be seen in Table 6.2. All producers extract RAP binder prior to testing. This note was made because of the issues that could arise with very high RAP contents when incomplete blending is not assumed. The methods to measure and account for specific gravities in calculation may warrant investigation.

Table 6.2. Producer RAP Specific Gravities

Company	Location	G_{sb}	G_{sa}	%Abs
APAC Mississippi	Columbia	2.555	2.636	1.24
	Meridian	2.559	2.641	1.21
	Jackson/Canton	2.580	2.652	1.29
	Vicksburg	2.548	2.631	1.28
	Yazoo City	2.560	2.630	1.14
	Greenville	2.571	2.646	1.10
	Hamilton	2.468	2.575	1.68
	Guntown/Corinth	2.575	2.652	1.13
	Columbus	2.612	2.612	1.49
Bonds Construction	Tupelo[1]	2.461	2.641	----
	Tupelo[2]	2.450	2.598	2.33
Superior Asphalt[3]	Brooksville	2.538	2.615	1.16
	Byram	2.533	2.628	1.40
	Louisville	2.563	2.614	0.85
	Gulfport	2.615	2.684	0.98

1: Obtained in December 2007
2: Obtained in 2000
3: Run coarse and fine then combine using flask method

6.2.4 RAP Asphalt Content

Asphalt contents of the producers can be seen in Table 6.3. As seen, all but two of the data points were in the 5%'s. *APAC Mississippi* noted their preference of the ignition method was so they could run multiple ignition results per extraction result. They favored the repetition of the ignition oven method.

Table 6.3. Producer RAP Asphalt Contents

Company	Location	Method	AC (%)
*APAC Mississippi**	Columbia	Ignition	5.7
	Meridian	Ignition	5.5
	Jackson/Canton	Ignition	5.0
	Vicksburg	Ignition	5.2
	Yazoo City	Ignition	4.5
	Greenville	Ignition	5.1
	Hamilton	Ignition	5.2
	Guntown/Corinth	Ignition	4.6
	Columbus	Ignition	5.3
Bonds Construction	Tupelo	Rotorex Extraction	5.0 to 5.5
Superior Asphalt	Brooksville	Ignition	5.2 to 5.7
	Byram	Ignition	5.0 to 5.4
	Louisville	Ignition	5.1 to 5.5
	Gulfport	Ignition	6.2

** Average values taken over a three month period in the spring of 2008*

6.2.5 RAP Gradations

APAC Mississippi: Gradation records are consistent, but producer is fractionating to eliminate any potential gradation concerns. Producer noted fractionating was the best method to keep consistency. Current practice has two people accountable for all RAP crushing within the state. A new philosophy within the company is potentially to take gradations before and after crushing. Previous practices only took gradations after crushing. It was noted that anything over 15% RAP without fractionating can exceed the job mix formula. It was also noted that finer mixes (e.g. 9.5 mm) often need crushed RAP. For the last 3 to 4 years the practice in the area has been to crush enough 9.5 mm material to last for the entire job. Relatively recent gradation data can be seen in Table 6.4.

Table 6.4. Gradation Records for *APAC Mississippi*

Source	Columbia	Meridian	Jackson	Canton	Vicksburg	Greenville	Hamilton	Columbus
19 mm[1]	100	100	100	100	100	100	100	100
12.7 m[1]	100	100	100	99	100	92	100	100
9.5 mm[1]	93	93	99	95	92	86	96	96
No. 4	67	68	70	72	70	63	73	69
No. 8	49	51	51	57	54	48	56	50
No. 30	40	32	29	34	34	28	39	30
No. 50	16	22	18	23	19	16	18	18
No. 200	7.8	8.7	8.8	8.4	7.6	7.7	8.5	7.2

1: 19 mm = ¾ in, 12.7 mm = ½ in, and 9.5 mm = 3/8 in.

Bonds Construction: RAP is relatively consistent in terms of gradation, with the exception of black base materials constructed some time ago. Approximately half the material is (-)No 8, and (+)12.7 mm (0.5 in) particles are rare. Table 6.5 shows gradation records for the Tupelo plant.

Table 6.5. Gradation Records for *Bonds Construction* (Percent Passing)

Source	Tupelo[1]	Tupelo[2]
19 mm (3/4 in)	100*	100
12.7 mm (1/2 in)	100	100
9.5 mm (3/8 in)	94.8	95.3
No. 4	70.2	73.3
No. 8	51.1	52.1
No. 16	40.6	39.1
No. 30	29.7	31.4
No. 50	19.6	21.2
No. 100	11.8	12.7
No. 200	7.6	9.4

1: Obtained December 2007
2: Obtained in 2000

Superior Asphalt: Gradations consistent with location and over time. Table 6.6 shows gradation records for several plants.

Table 6.6. Gradation Records for *Superior Asphalt* (Percent Passing)

Source	Brooksville			Bryam			Louisville			Gulfport
19 mm (3/4 in)	100	100	100	100	100	100	100	100	100	100
12.7 m (1/2 in)	98	94	96	100	100	92	90	92	97	100
9.5 mm (3/8 in)	86	82	90	91	93	88	88	85	88	99
No. 4	64	57	67	69	69	67	60	62	60	78
No. 8	48	44	52	51	49	45	45	47	47	55
No. 16	41	34	41	40	37	39	38	41	39	42
No. 30	35	29	36	32	28	30	35	35	34	32
No. 50	19	17	22	18	15	19	21	20	19	19
No. 100	12	13	13	10	9	11	10	10	11	11
No. 200	7.5	6.3	8.0	6.5	6.8	6.4	5.5	6.6	6.0	7.9

6.2.6 Consistency of Properties

APAC Mississippi: Do notice some fluctuation, especially over large jobs, but it is not necessarily excessive as long as all parameters are properly monitored.

Superior Asphalt: Do not see significant variability over time.

Bonds Construction: Do not see significant variability over time.

6.2.7 Benefits of Additional RAP Usage

APAC Mississippi: The maximum amount of material for surface mixes was approximated at 25% provided crushing and fractionating were performed. Approximately 40% was said to be the maximum desired RAP content for any type of mix. Note there may begin to be a problem obtaining RAP in some areas and running out with approved mix designs containing noticeable RAP quantities could be troublesome. More economical RAP mixtures could lead

to advantageous conditions such as mill and overlay projects rather than overlay only projects.

Bonds Construction: They use as much RAP as allowed by the mix design, and anticipate a more economical mix with increased RAP up to a threshold level. At the threshold, heating costs would likely offset the RAP benefits. The plant in Tupelo uses a counter flow drum and the RAP is introduced immediately before the post drum mixing, so the virgin materials heat the entire mix. It was noted this could be different for different plant types.

Superior Asphalt: They would be interested in increasing the percentage of RAP. They can usually obtain the RAP they need.

6.2.8 Warm Mix Additive Experience

APAC Mississippi: No significant WMA experience. Small amounts placed but on private projects.

Bonds Construction: Have no significant experience with WMA, but plans are underway to construct small pilot section in near future.

Superior Asphalt: Have no significant experience with WMA.

6.3 Key Parameters Deserving Additional Investigation

6.3.1 Laboratory Parameters

For amalgamation of RAP and virgin aggregates, the research team believes a zone exists within the asphalt film where the binder becomes brittle enough to provide potential for cracking and raveling to increase. A *blending zone* on the exterior of the film encompassing a *black rock* highlights the problematic issue of selection of the appropriate virgin asphalt content that have been discussed in previous portions of the report. Laboratory testing is needed to further investigate this concept of a blending zone.

Testing the asphalt binder (RAP and virgin) as part of the mixture is believed to be the most logical approach as opposed to binder extraction and testing. There are numerous tests available for evaluating the asphalt binder within a mix. The researchers have identified four tests: the Torsional Creep Test (TCT), Bending Beam Rheometer (BBR), dynamic modulus (E^*), and Indirect Tensile Creep (IDT). Of these four tests, the E^* and IDT are tests commonly used to evaluate mixtures. The E^* test can be used to characterize mixtures at low, intermediate and high temperatures. Results from the E^* test should provide an overall estimate of binder stiffness (for similar aggregate type, gradation, and asphalt content). The IDT was included within the Superpave analysis system for mixes and allows for the evaluation of binders (mixtures) at low temperatures. The TCT and BBR tests for mix are not as common, as such, each was described in the literature review of Chapter 2. A suite of laboratory testing containing some to all of these tests is recommended.

While binder extraction from RAP is necessary to obtain a relatively accurate binder content in the RAP and for comparative purposes of binder properties, BBR testing of RAP

mixtures should provide an accurate and rapid method to determine mixture/binder stiffness in laboratory prepared or field specimens. Testing of 100% RAP samples is recommended to provide a baseline of properties. As seen in Chapter 5, compaction of repeatable 100% RAP samples is possible and provides behavioral data that can be used to design high RAP mixtures by accounting for the bituminous material in an appropriate fashion.

The PURWheel is recognized to have significant potential for evaluating HMA *stripping* and *rutting* performance. PURWheel testing should also be conducted under water to evaluate moisture damage potential. All the aforementioned are potential areas of concern and should be investigated in future studies.

Future laboratory work should focus more on specific behaviors than did this study. This study was intentionally broad in nature, but before proceeding to full scale production a carefully controlled suite of tests including sufficient factor-level combinations and replication should be performed. Mixtures that perform well at that level should then be produced at asphalt plants as discussed in the following section.

6.3.2 Full Scale Production Parameters

Once mixtures containing high RAP with warm mix additives are successfully designed in the laboratory and tested for all behaviors of interest, full scale production will be necessary. Additional research where three plant types (counter flow, parallel flow, and double drum) produce the candidate mixtures would be worthwhile. Producing 1,000 to 2,000 tons of the two or three most promising mixtures from each plant would provide data that cannot be obtained any other way in the areas of: 1) production capacity, 2) field compactability, 3) necessary stockpile handling (primarily moisture content), and 4) in place performance properties (e.g. tensile strength, dynamic modulus, and rut resistance). Having research and plant personnel on site to: 1) monitor items such as plant controls (extremely valuable in diagnosing feasibility of efficient production), 2) take samples from stockpiles, belt feeders, storage silo, trucks, and in place would provide invaluable data in the context of efficiency of producing the high RAP WMA mixes.

Production feasibility should be of utmost importance in future research. One item worthy of investigation is the *Heated Auger Plant* shown in Figures 6.1 and 6.2. Figure 6.1 shows the augur that translates the RAP, which resides within the plant shown in Figure 6.2. The plant has conventional cold feed bins, a pug mill (not shown), and mechanisms to add binder. There are hot oil lines within in the auger flights that transfers heat to the RAP material. Both the outer shell and the auger have independent drive controls. The auger turns slowly (≈ 4 to 5 rpm), allowing the RAP marinating time to be controlled.

Additional technology possibly warranting investigation is the specialty drum mixer discussed in CEI (2008). The mixer is said to produce up to 180 ton/hr at up to 50% RAP, and is designed for contractors with smaller project needs. Multiple bins are available to accommodate different RAP gradations, and there is an inlet into the drum dedicated to RAP. Future work should include contact of plant manufacturers to determine the most appropriate location to introduce both the RAP and WMA additives. Options for WMA additives could include: 1) pumped from delivery truck into drum; and 2) through cold feed. A potential concern in implementation of high RAP would be material sticking in the mixer due to moisture problems (or similar). This could result in many undesirable characteristics including having to cease production and dislodge the material. Other parameters related to

stockpiling also must be considered. Cold feeds may be limited (typically 7 or less), stockyard space may be an issue, or similar.

Figure 6.1. Photo of Heated Auger

Figure 6.2. Overall View of Heated Auger Plant

It is anticipated higher percents of RAP will require additional processing and will include fractionating. This may break down dense conglomerated particles and affect the recycled mixture's volumetric properties. Also, a greater percentage of finer particles may cause a discrepancy in binder content between coarse and fine fractions. Use of covered stockpiles for RAP material in addition to good stockpile management practices has the potential to reduce moisture contents resulting in significant cost savings. Material processing along with production can affect the degree of emissions from plants. Emissions (aka *blue smoke)* was a factor limiting high RAP content production for some time. Modern drum plants have much improved facility for heating mixtures incorporating higher RAP contents.

CHAPTER 7-CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

The objective of this project was to evaluate the potential for using high RAP content mixes as a base layer on low and medium level traffic highways. The scope of the study was limited since this was a concept study; however, the results of the study do suggest that it is possible to develop a mixture containing high RAP contents for the stated purpose. Also included within the research was investigation of warm mix additives. These additives were included in order to determine whether their inclusion could potentially allow for easier construction in the field as well as reduce production temperatures. The answer to both of these questions is yes.

The aforementioned conclusions were developed with a combination of literature review, economic analysis, laboratory testing, and consultation with producers of asphalt within Mississippi. Consultation with ten producers of asphalt within Mississippi and the past three decades of virgin asphalt PG 67-22 (or equivalent) prices were used as the basis of the economic analysis. The majority of the calculations focused on the material cost implications of higher RAP mixtures. Laboratory testing resulted in approximately 400 compacted samples tested for volumetric properties and indirect tensile strength. Approximately 90 samples were prepared and tested for maximum mixture specific gravity. The analysis of the data relied primarily on statistics.

This study has the potential to increase in value as additional research is conducted. Testing of 100% RAP samples provides a baseline of behavior that can be used to develop mix designs at varying RAP contents by understanding key parameters. A significant amount of testing of 100% RAP samples was conducted in this research. Additionally, the preliminary component diagram developed of high RAP mixtures could also prove more useful as additional work is performed.

7.2 Recommendations

Based upon the results of this research project, it is recommended that an additional study be conducted in order to more thoroughly evaluate the potential for high RAP content mixes for low and medium traffic volume roadways. Subsequent research should be conducted within two phases.

Included within the first phase of research should be development of a method for designing high RAP content mixes and selection of test methods and criteria for specifying these mixtures. All RAP sources may not have the needed characteristics for this proposed high RAP content mix to be successful. Screening tests are needed to ensure that the RAP properties are adequate. A method for selecting the proper amount of virgin asphalt for laboratory mix designs is also needed, which must allow for selection of the proper amount of virgin asphalt to produce a job mix formula. Finally, laboratory performance tests are needed in order to proof the design mixes. The laboratory test could be as simple as an indirect tension test as used herein, or a slightly more complicated testing may be required.

The research should also further evaluate the potential concerns expressed by the contractors on how to produce the mixtures as the second phase of research. This would involve a field trial in which a design high RAP content is produced and placed. Techniques

for successful production and placement are vital for high RAP content mixes to be a viable option on Mississippi's roadways. This phase of research should also address handling and quality of RAP materials. Current practice of the *Mississippi Department of Transportation (MDOT)* does not incorporate many requirements or restrictions on the quality or handling of the material. In the past, MDOT requested information regarding the origin of the RAP, but they have not done so in a few years. The attributes (positive and negative) of this approach should be investigated.

CHAPTER 8-REFERENCES

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APPENDIX A

RAW TEST DATA

Table A.1. Compaction Data for Blend 1 at 154 C (310 F)

P_b	G_{mm}	Rep	G_{mb}	H_I[1] mm	H_F[2] mm	V_a	T[3] sec	S_t kPa (psi)
4.5	2.393[4]	1	2.274	140.9	116.9	~~5.0~~	2.8	1896 (275.0)
		2	2.267	141.3	117.2	~~5.3~~	3.0	1793 (259.9)
		3	2.266	141.7	117.5	~~5.3~~	5.0	1573 (228.1)
		Avg.	**2.269**	**144.3**	**117.2**	**~~5.2~~**	**3.6**	**1754 (254.4)**
5.0	2.357	1	2.302	142.9	118.8	2.3	3.4	1666 (241.6)
		2	2.296	143.3	118.5	2.6	3.4	1811 (262.6)
		3*	2.296	139.0	115.8	2.6	3.2	1827 (264.9)
		Avg.	**2.298**	**141.7**	**117.7**	**2.5**	**3.3**	**1768 (256.4)**
5.5	2.344	1	2.302	141.9	118.9	1.8	3.4	1510 (219.1)
		2	2.302	142.6	119.3	1.8	3.6	1440 (208.9)
		3*	2.304	138.7	116.3	1.7	3.4	1555 (225.5)
		Avg.	**2.303**	**141.1**	**118.2**	**1.8**	**3.5**	**1502 (217.8)**
6.0	2.335	1	2.313	140.4	118.9	0.9	5.0	1090 (158.1)
		2	2.309	141.1	119.0	1.1	3.6	1496 (216.9)
		3*	2.317	136.9	115.6	0.8	4.0	1396 (202.4)
		Avg.	**2.313**	**139.5**	**117.8**	**0.9**	**4.2**	**1327 (192.5)**

* Samples were 4400 grams aggregate mass. All other samples were 4500 grams aggregate mass.

1: Initial height of sample measured by SGC

2: Final height of sample measured by SGC

3: Time to peak tensile strength

4: Due to incomplete coating of virgin absorptive aggregate, test could not be properly run. Reran test to check value and determined G_{mm} = 2.401.

Table A.2. Compaction Data for Blend 2 at 154 C (310 F)

P_b	G_{mm}	Rep	G_{mb}	H_I[1] mm	H_F[2] mm	V_a	T[3] sec	S_t kPa (psi)
5.4	2.294	1	2.280	131.0	109.4	1.2	3.2	1845 (267.6)
		2	2.278	131.0	109.5	1.1	2.8	1890 (274.1)
		3	2.284	130.9	109.3	0.9	3.2	1851 (268.5)
		4	2.278	130.5	109.2	1.1	3.6	1632 (236.7)
		5	2.272	130.8	109.5	1.4	3.0	1765 (255.9)
		6	2.272	131.0	109.6	1.8	3.2	1791 (259.7)
		7	2.270	131.5	110.0	1.5	3.4	1698 (246.2)
		8	2.278	131.1	109.6	1.2	3.4	1921 (278.5)
		9	2.276	131.0	109.7	1.4	3.0	1896 (275.0)
		10	2.266	131.6	109.9	1.7	3.4	1754 (254.3)
		11	2.275	142.0	118.2	0.8	3.4	1791 (259.7)
		12	2.264	141.2	117.8	1.3	3.8	1874 (271.8)
		Avg.	**2.274**	**132.9**	**111.0**	**1.3**[4]	**3.3**	**1809 (262.4)**

* All samples were 4100 grams aggregate mass.

1: Initial height of sample measured by SGC

2: Final height of sample measured by SGC

3: Time to peak tensile strength

4: Low air voids are attributed to use of different RAP source (*SP*) than was approved in original mix.

Table A.3. Compaction Data for Blend 3 at 154 C (310 F)

P_b	G_{mm}	Rep	G_{mb}	H_I[1] mm	H_F[2] mm	V_a	T[3] sec	S_t kPa (psi)
5.0	2.297	1*	2.128	152.6	124.9	6.5	3.4	1051 (152.4)
		2*	2.144	152.8	124.5	6.5	3.0	1159(168.1)
		3*	2.153	153.3	125.2	7.3	3.8	1277 (185.2)
		4	2.147	142.4	117.1	6.7	3.4	1199 (173.9)
		5	2.148	142.3	116.5	6.3	3.0	1257 (182.3)
		Avg.	**2.144**	**147.8**	**120.9**	**6.7**	**3.3**	**1189 (172.4)**
5.5	2.294	1*	2.145	153.4	125.6	6.5	3.8	1024 (148.5)
		2*	2.150	151.8	124.3	6.3	3.8	994 (144.1)
		3	2.170	141.7	116.1	5.4	3.0	1180 (171.2)
		4	2.168	141.9	116.2	5.5	3.0	1213 (175.9)
		Avg.	**2.158**	**147.2**	**120.6**	**5.9**	**3.4**	**1103 (165.2)**
6.0	2.285	1*	2.177	150.6	123.8	4.7	3.8	1045 (151.6)
		2*	2.163	151.1	123.7	5.3	3.6	1002 (145.4)
		3	2.175	140.4	115.4	4.8	3.2	996 (144.4)
		4	2.181	141.2	115.7	4.6	3.6	1085 (157.3)
		5	2.176	---	115.8	4.8	3.8	1075 (155.9)
		6	2.183	---	115.5	4.5	3.0	1066 (154.9)
		7	2.175	---	115.3	4.8	3.8	993 (143.9)
		8	2.181	---	115.6	4.6	3.6	1205 (174.8)
		9	2.159	---	115.7	5.5	3.0	1152 (167.0)
		Avg.	**2.174**	**145.8**	**117.4**	**4.8**	**3.5**	**1069 (155.0)**
6.1	2.283	1	2.184	140.6	114.8	4.3	3.2	1148 (166.5)
		2	2.190	140.8	114.9	4.0	3.4	1088 (157.8)
		3	2.198	141.6	115.2	3.7	3.2	1089 (157.9)
		4	2.194	139.5	114.2	3.9	3.4	1108 (160.8)
		5	2.193	140.5	115.0	3.9	3.2	1051 (152.4)
		6	2.198	---	---	3.7	3.2	1078 (156.3)
		Avg.	**2.193**	**140.6**	**114.8**	**3.9**	**3.3**	**1094 (158.6)**
6.2	2.268	1	2.193	139.7	114.9	3.3	3.0	1126 (163.3)
		2	2.189	140.0	114.8	3.5	3.0	1085 (157.3)
		3	2.196	141.3	115.2	3.2	---	---
		4	2.195	140.8	115.1	3.2	3.4	1034 (149.9)
		5	2.197	141.1	114.9	3.1	3.2	1046 (151.8)
		6	2.172	142.4	116.4	4.2	4.0	991 (143.8)
		7	2.196	140.4	115.4	3.2	3.4	1018 (147.7)
		8	2.189	141.2	115.7	3.5	3.4	997 (144.6)
		9	2.193	140.6	115.3	3.3	3.8	1023 (148.4)
		10	2.192	140.8	115.3	3.4	3.4	1053 (152.8)
		Avg.	**2.191**	**140.9**	**115.3**	**3.4**	**3.1**	**937 (135.9)**
6.5	2.269	1	2.200	139.5	115.1	3.0	4.4	1111 (161.2)
		2	2.198	139.8	115.2	3.1	4.0	1117 (161.9)
		Avg.	**2.199**	**139.7**	**115.2**	**3.1**	**4.2**	**1114 (161.6)**

* Aggregate mass was 4400 grams. All other samples were 4100 grams aggregate mass.

1: Initial height of sample measured by SGC

2: Final height of sample measured by SGC

3: Time to peak tensile strength

Table A.4. Suite 1 Compaction Data for Blend 4 for 25 C to 60 C (77 F to 140 F)

Temp C (F)	Rep	H_I[1] mm	H_F[2] mm	G_{mb}	V_a	T[3] sec	S_t kPa (psi)
25 (77)	1	168.0	145.4	---	---	---	---
	2	176.0	153.4	---	---	---	---
	3	171.4	149.8	---	---	---	---
	Avg.	**171.8**	**149.5**	**---**	**---**	**---**	**---**
32 (90)	1	171.2	150.2	---	---	---	---
	2	166.5	144.8	---	---	---	---
	3	169.6	149.8	---	---	---	---
	Avg.	**169.1**	**148.3**	**---**	**---**	**---**	**---**
38 (100)	1	171.7	149.5	---	---	---	---
	2	169.7	148.5	---	---	---	---
	3	171.4	149.5	---	---	---	---
	Avg.	**170.9**	**149.2**	**---**	**---**	**---**	**---**
49 (120)	1	167.6	146.6	---	---	---	---
	2	168.4	147.3	---	---	---	---
	3	167.5	146.6	---	---	---	---
	Avg.	**167.8**	**146.8**	**---**	**---**	**---**	**---**
60 (140)	1	164.9	143.7	---	---	---	---
	2	166.1	144.2	---	---	---	---
	3	165.51	144.0	---	---	---	---
	Avg.	**165.5**	**144.0**	**---**	**---**	**---**	**---**

* All samples were 5000 grams total sample mass.

1: Initial height of sample measured be SGC

2: Final height of sample measured by SGC

Table A.5. Suite 1 Compaction Data for Blend 4 for 71 C to 177 C (160 F 350 F)

Temp C (F)	G_{mm}	Rep	H_I[1] mm	H_F[2] Mm	G_{mb}	V_a	T[3] sec	S_t kPa (psi)
71 (160)	2.380	1	162.6	140.7	2.042	14.2	1.8	277 (40.2)
		2	159.6	139.7	2.052	13.8	1.4	241 (34.9)
		3	161.6	140.3	2.045	14.1	---	---
		Avg.	**161.3**	**140.2**	**2.046**	**14.0**	**1.6**	**259 (37.5)**
82 (180)	2.380	1	158.2	136.6	2.099	11.8	1.2	453 (65.7)
		2	157.8	136.8	2.093	12.1	1.2	554 (80.3)
		3	158.1	136.7	2.093	12.1	1.2	631 (91.5)
		Avg.	**158.0**	**136.7**	**2.095**	**12.0**	**1.2**	**546(79.2)**
93 (200)	2.380	1	157.1	135.5	2.120	10.9	1.6	779 (113.0)
		2	157.8	135.8	2.110	11.3	1.4	757 (109.8)
		3	157.2	135.6	2.114	11.2	1.4	792 (114.8)
		Avg.	**157.4**	**135.6**	**2.115**	**11.1**	**1.5**	**776 (112.5)**
104 (220)	2.380	1	156.4	133.1	2.153	9.5	2.4	978 (141.8)
		2	155.1	133.1	2.105	11.6	1.2	1021 (148.1)
		3	154.3	132.3	2.165	9.0	---	---
		Avg.	**155.3**	**132.8**	**2.141**	**10.0**	**1.8**	**999 (144.9)**
116 (240)	2.380	1	153.6	130.9	2.181	8.4	1.2	1389 (201.5)
		2	158.1	133.4	2.149	9.7	1.4	1253 (181.8)
		3	156.8	132.5	2.163	9.1	1.6	1328 (192.6)
		Avg.	**156.1**	**132.3**	**2.164**	**9.1**	**1.4**	**1324 (192.0)**
127 (260)	2.380	1	155.5	131.3	2.200	7.6	2.0	1661 (240.8)
		2	154.6	130.6	2.193	7.9	---	---
		3	153.1	130.2	2.199	7.6	---	---
		Avg.	**154.4**	**130.7**	**2.197**	**7.7**	**2.0**	**1661 (240.8)**
138 (280)	2.380	1	154.1	130.2	2.214	7.0	---	---
		2	152.6	129.1	2.209	7.2	1.4	2144 (311.0)
		3	152.5	129.1	2.156	9.4	---	---
		Avg.	**153.0**	**129.5**	**2.193**	**7.9**	**1.4**	**2144 (311.0)**
149 (300)	2.380	1	152.0	128.9	2.221	6.7	1.6	2232 (323.7)
		2	152.0	129.0	2.220	6.7	1.2	1913 (277.5)
		3	152.4	129.1	2.237	6.0	----	---
		Avg.	**152.1**	**129.0**	**2.226**	**6.5**	**1.4**	**2072 (300.6)**
163 (325)	2.380	1	153.1	129.5	2.215	6.9	1.4	2075 (301.0)
		2[4]	153.7	129.9	---	---	1.2	1887 (273.7)
		3	151.9	129.0	2.214	7.0	---	---
		Avg.	**152.9**	**129.5**	**2.215**	**7.0**	**1.3**	**1981 (287.4)**
177 (350)	2.380	1	155.0	130.9	2.192	7.9	1.8	1413 (204.9)
		2	156.2	131.8	2.180	8.4	2.2	1287 (186.7)
		3	154.8	131.6	2.174	8.7	1.2	1253 (181.7)
		Avg.	**155.3**	**131.4**	**2.182**	**8.3**	**1.7**	**1318 (191.1)**

* All samples were 5000 grams total sample mass.

1: Initial height of sample measured by SGC

2: Final height of sample measured by SGC

3: Time to peak tensile strength

4: Data point considered erroneous and omitted from analysis.

Table A.6. Suite 2 Compaction Data Blend 5 for 25 C to 60 (77 F to 140 F)

Temp C (F)	Rep	H_I[1] mm	H_F[2] mm	G_{mb}	V_a	T[3] sec	S_t kPa (psi)
25 (77)	1	188.9	164.6	---	---	---	---
	2	190.5	165.3	---	---	---	---
	3	187.3	163.5	---	---	---	---
	Avg.	**188.9**	**164.5**	---	---	---	---
32 (90)	1	182.0	159.3	---	---	---	---
	2	182.5	159.8	---	---	---	---
	3	185.5	161.7	---	---	---	---
	Avg.	**183.3**	**160.3**	---	---	---	---
38 (100)	1	180.4	157.9	---	---	---	---
	2	180.6	157.6	---	---	---	---
	3	181.4	158.1	---	---	---	---
	Avg.	**180.8**	**157.9**	---	---	---	---
49 (120)	1	175.3	152.5	---	---	---	---
	2	177.6	154.1	---	---	---	---
	3	177.4	153.6	---	---	---	---
	Avg.	**176.8**	**153.4**	---	---	---	---
60 (140)	1	171.5	148.4	---	---	---	---
	2	173.1	149.3	---	---	---	---
	3	171.8	148.4	---	---	---	---
	Avg.	**172.1**	**148.7**	---	---	---	---

* All samples were 5000 grams total sample mass.

1: Initial height of sample measured be SGC

2: Final height of sample measured by SGC

Table A.7. Suite 2 Compaction Data for Blend 5 for 71 C to 177 C (160 F to 350 F)

Temp C (F)	G_{mm}	Rep	H_I[1] mm	H_F[2] mm	G_{mb}	V_a	T[3] sec	S_t kPa (psi)
71 (160)	2.341	1	170.5	147.1	1.928	17.6	1.4	199 (28.9)
		2	169.2	146.4	1.954	16.5	2.8	190 (27.5)
		3	169.4	146.4	1.957	16.4	1.6	206 (29.8)
		Avg.	**169.7**	**146.6**	**1.946**	**16.9**	**1.9**	**275 (39.9)**
82 (180)	2.341	1	164.2	141.0	2.026	13.5	1.2	605 (87.8)
		2	167.1	143.1	2.004	14.4	1.4	601 (87.1)
		3	165.2	141.6	2.023	13.6	1.6	556 (80.7)
		Avg.	**165.5**	**141.9**	**2.018**	**13.8**	**1.4**	**587 (85.2)**
93 (200)	2.341	1	164.3	140.1	2.037	13.0	1.4	769 (111.5)
		2	162.8	139.4	2.055	12.2	1.8	812 (117.8)
		3	163.6	139.5	2.055	12.2	1.2	739 (107.2)
		Avg.	**163.6**	**139.7**	**2.049**	**12.5**	**1.5**	**773 (112.2)**
104 (220)	2.341	1	163.0	137.5	2.087	10.9	1.6	1170 (169.6)
		2	160.9	136.1	2.109	9.9	1.6	1251 (181.4)
		3	160.9	135.7	2.112	9.8	2.2	1261 (182.9)
		Avg.	**161.6**	**136.4**	**2.103**	**10.2**	**1.8**	**1227 (178.0)**
116 (240)	2.341	1	158.9	134.4	2.141	8.5	2.0	1704 (247.2)
		2	159.7	135.3	2.128	9.1	1.8	1715 (248.7)
		3	160.7	135.6	2.113	9.7	1.8	1544 (224.0)
		Avg.	**159.8**	**135.1**	**2.127**	**9.1**	**1.9**	**1654 (240.0)**
127 (260)	2.341	1	156.6	131.6	2.169	7.3	1.8	1579 (229.1)
		2	156.6	132.1	2.179	6.9	1.8	2208 (320.3)
		3	158.5	133.1	2.182	6.8	1.8	2258 (327.5)
		Avg.	**157.2**	**132.3**	**2.177**	**7.0**	**1.8**	**2015 (292.3)**
138 (280)	2.341	1	155.4	130.9	2.193	6.3	1.8	2173 (315.2)
		2	154.7	130.3	2.203	5.9	2.0	2395 (347.4)
		3	155.3	130.5	2.205	5.8	1.8	2719 (394.3)
		Avg.	**155.1**	**130.6**	**2.200**	**6.0**	**1.9**	**2429 (352.3)**
149 (300)	2.341	1	155.6	130.5	2.206	5.8	1.8	2435 (353.2)
		2	154.5	129.8	2.216	5.3	1.8	2122 (307.7)
		3	156.0	130.9	2.197	6.2	2.0	2660 (385.8)
		Avg.	**155.4**	**130.4**	**2.206**	**5.8**	**1.9**	**2406 (348.9)**
163 (325)	2.341	1	155.3	130.5	2.206	5.8	2.2	3186 (462.1)
		2	154.8	129.9	2.213	5.5	2.0	2717 (394.1)
		3	155.4	130.1	2.213	5.5	1.6	2394 (347.2)
		Avg.	**155.2**	**130.2**	**2.211**	**5.6**	**1.9**	**2766 (401.1)**
177 (350)	2.341	1	158.6	133.7	2.155	7.9	1.2	1367 (198.3)
		2	159.7	134.3	2.145	8.4	1.4	1393 (202.0)
		3	161.3	135.6	2.121	9.4	1.2	1135 (164.6)
		Avg.	**159.9**	**134.5**	**2.140**	**8.6**	**1.3**	**1298 (188.3)**

* All samples were 5000 grams total sample mass.

1: Initial height of sample measured by SGC

2: Final height of sample measured by SGC

3: Time to peak tensile strength

Table A.8. Suite 3 Compaction Data for Blend 5 for 71 C to 177 C (160 F to 350 F)

Temp C (F)	G_{mm}	Rep	H_I[1] mm	H_F[2] mm	G_{mb}	V_a	T[3] sec	S_t kPa (psi)
71 (160)	2.333	1	171.9	147.7	1.947	16.5	1.4	213 (30.9)
		2	170.6	147.2	1.949	16.5	1.4	205 (29.7)
		3	178.6	145.6	1.962	15.9	1.4	125 (18.1)
		Avg.	**173.7**	**146.8**	**1.953**	**16.3**	**1.4**	**181 (26.2)**
82 (180)	2.333	1	165.6	143.1	1.889	19.0	1.6	410 (59.4)
		2	167.5	144.3	1.919	17.7	1.6	381 (55.3)
		3	166.1	142.8	1.914	18.0	1.6	517 (75.0)
		Avg.	**166.4**	**143.4**	**1.907**	**18.2**	**1.6**	**436 (63.2)**
93 (200)	2.333	1	164.7	140.4	2.045	12.3	1.6	779 (113.0)
		2	163.3	139.5	2.059	11.7	1.6	746 (108.2)
		3	166.4	141.6	2.032	12.9	1.8	752 (109.0)
		Avg.	**164.8**	**140.5**	**2.045**	**12.3**	**1.7**	**759 (110.1)**
104 (220)	2.333	1	163.5	138.5	2.077	11.0	1.8	1074 (155.7)
		2	162.8	138.1	2.081	10.8	2.2	874 (126.7)
		3	159.7	136.3	2.108	9.6	1.8	972 (141.0)
		Avg.	**162.0**	**137.6**	**2.086**	**10.5**	**1.9**	**973 (141.2)**
116 (240)	2.333	1	161.7	137.5	2.085	10.6	1.6	1510 (219.0)
		2	161.4	136.6	2.094	10.2	1.8	1730 (250.8)
		3	160.5	135.7	2.096	10.2	2.6	1472 (213.5)
		Avg.	**161.2**	**136.6**	**2.092**	**10.3**	**2.0**	**1571 (227.8)**
127 (260)	2.333	1	156.9	132.7	2.162	7.3	3.4	1922 (278.8)
		2	156.6	132.4	2.168	7.1	2.0	2099 (304.4)
		3	161.0	135.1	2.096	10.2	2.0	2147 (311.4)
		Avg.	**158.2**	**133.4**	**2.142**	**8.2**	**2.5**	**2056 (298.2)**
138 (280)	2.333	1	156.0	130.9	2.199	5.7	2.2	2414 (350.1)
		2	155.7	130.3	2.200	5.7	2.2	2509 (363.9)
		3	158.7	132.8	2.170	7.0	2.4	1920 (278.4)
		Avg.	**156.8**	**131.3**	**2.190**	**6.1**	**2.3**	**2281 (330.8)**
149 (300)	2.333	1	160.5	133.7	2.079	10.9	2.0	2515 (364.8)
		2	158.7	132.6	2.093	10.3	2.0	2424 (351.5)
		3	156.2	130.2	2.134	8.5	2.2	2674 (387.8)
		Avg.	**158.5**	**132.2**	**2.102**	**9.9**	**2.1**	**2538 (368.0)**
163 (325)	2.333	1	155.5	129.4	2.096	10.2	2.6	3031 (439.7)
		2	156.7	130.3	2.210	5.3	2.2	2702 (391.9)
		3	160.2	133.5	2.145	8.1	2.2	2729 (395.8)
		Avg.	**157.5**	**131.1**	**2.150**	**7.9**	**2.3**	**2821 (409.1)**
177 (350)	2.333	1	154.0	128.2	2.221	4.8	2.4	2848 (413.1)
		2	-	130.5	2.179	6.6	2.6	3202 (464.5)
		3	159.3	132.5	2.168	7.1	2.4	2672 (387.5)
		Avg.	**156.7**	**130.4**	**2.189**	**6.2**	**2.5**	**2907 (421.7)**

* All samples were 5000 grams total sample mass.

1: Initial height of sample measured by SGC

2: Final height of sample measured by SGC

3: Time to peak tensile strength

Table A.9. Suite 4 Compaction Data for Blend 5 for 71 C to 177 C (160 F to 350 F)

Temp C (F)	G_{mm}	Rep	H_I[1] mm	H_F[2] mm	G_{mb}	V_a	T[3] sec	S_t kPa (psi)
71 (160)	2.333	1	167.8	144.6	1.978	15.2	1.6	302 (43.8)
		2	166.7	144.4	1.999	14.3	1.4	258 (37.3)
		3	164.7	144.7	1.985	14.9	1.6	266 (38.6)
		Avg.	**166.4**	**144.6**	**1.987**	**14.8**	**1.5**	**275 (39.9)**
82 (180)	2.333	1	166.4	142.7	2.012	13.8	2.2	411 (59.7)
		2	165.8	142.1	2.022	13.3	1.8	534 (77.5)
		3	166.6	143.0	2.034	12.8	3.2	313 (45.4)
		Avg.	**166.3**	**142.6**	**2.023**	**13.3**	**2.4**	**419 (60.8)**
93 (200)	2.333	1	161.2	137.8	2.086	10.6	1.4	962 (139.6)
		2	161.0	137.4	2.088	10.5	2.2	872 (126.5)
		3	162.8	138.4	2.074	11.1	1.4	837 (121.4)
		Avg.	**161.7**	**137.9**	**2.083**	**10.7**	**1.7**	**891 (129.2)**
104 (220)	2.333	1	159.5	135.5	2.118	9.2	1.6	1179 (171.1)
		2	159.4	135.4	2.123	9.0	1.8	1307 (189.7)
		3	158.4	134.6	2.134	8.5	1.8	1408 (204.2)
		Avg.	**159.1**	**135.2**	**2.125**	**8.9**	**1.7**	**1298 (188.3)**
116 (240)	2.333	1	156.1	132.2	2.167	7.1	1.6	1849 (268.2)
		2	157.1	132.5	2.170	7.0	1.8	1683 (244.1)
		3	158.6	133.3	2.156	7.6	1.8	1837 (266.4)
		Avg.	**157.3**	**132.7**	**2.164**	**7.2**	**1.7**	**1790 (259.6)**
127 (260)	2.333	1	156.9	131.7	2.186	6.3	2.0	2152 (312.2)
		2	156.2	131.5	2.183	6.4	2.0	1650 (239.2)
		3	155.6	130.9	2.195	5.9	1.8	2188 (317.3)
		Avg.	**156.2**	**131.4**	**2.188**	**6.2**	**1.9**	**1997 (289.6)**
138 (280)	2.333	1	154.0	129.5	2.217	5.0	2.0	2445 (354.6)
		2	154.5	129.7	2.215	5.1	2.0	2681 (388.9)
		3	154.2	129.4	2.225	4.6	2.0	2460 (356.8)
		Avg.	**154.2**	**129.5**	**2.219**	**4.9**	**2.0**	**2529 (366.8)**
149 (300)	2.333	1[4]	153.4	128.8	---	---	2.6	2254 (326.9)
		2	152.9	128.5	2.235	4.2	2.2	3021 (438.1)
		3	152.2	128.1	2.246	3.7	2.2	3067 (444.1)
		Avg.	**152.8**	**128.5**	**2.260**	**4.0**	**2.3**	**2779 (403.0)**
163 (325)	2.333	1	154.1	129.5	2.207	5.4	2.0	2416 (350.4)
		2	154.2	129.5	2.225	4.6	2.0	2389 (346.4)
		3	154.9	129.7	2.185	6.3	2.0	2654 (384.9)
		Avg.	**154.4**	**129.6**	**2.206**	**5.5**	**2.0**	**2486 (360.6)**
177 (350)	2.333	1	154.1	128.7	2.237	4.1	2.2	2825 (409.7)
		2	153.3	128.9	2.234	4.2	1.8	2408 (349.2)
		3	156.7	131.1	2.197	5.8	2.0	2425 (351.7)
		Avg.	**154.7**	**129.6**	**2.223**	**4.7**	**2.0**	**2552 (370.2)**

* All samples were 5000 grams total sample mass.
1: Initial height of sample measured by SGC
2: Final height of sample measured by SGC
3: Time to peak tensile strength
4: Data point considered erroneous and omitted from analysis.

Table A.10. Compaction Data for Blend 3 at 116 C (240 F)

Sasobit %	G_{mm}	Rep	G_{mb}	H_I[1] mm	H_F[2] mm	V_a	T[3] sec	S_t kPa (psi)
0	2.287	1	2.179	141.6	115.6	4.7	2.5	940 (136.3)
		2	2.178	142.5	115.8	4.8	2.5	882 (127.9)
		3	2.187	142.0	115.8	4.4	2.7	863 (125.2)
		4	2.184	141.9	115.5	4.5	2.5	890 (129.1)
		5	2.176	142.7	116.3	4.9	2.5	896 (130.0)
		Avg.	**2.181**	**142.1**	**115.8**	**4.7**	**2.5**	**894 (129.7)**
1.0	2.267	1	2.173	141.4	115.4	4.1	3.8	936 (135.7)
		2	2.174	141.3	115.5	4.1	2.8	945 (137.0)
		3	2.191	140.2	114.7	3.4	3.2	963 (139.6)
		4	2.190	141.2	115.3	3.4	3.0	955 (138.5)
		5	2.183	140.7	114.8	3.7	4.0	962 (139.5)
		Avg.	**2.182**	**141.0**	**115.1**	**3.7**	**3.4**	**952 (138.1)**
1.5	2.262	1	2.193	140.2	114.3	3.1	3.0	987 (143.2)
		2	2.182	141.0	115.0	3.5	3.0	981 (142.3)
		3	2.189	140.4	114.5	3.2	3.0	981 (142.2)
		4	2.195	141.5	115.6	3.0	2.8	996 (144.4)
		5	2.196	141.1	115.1	2.9	2.8	1005 (145.7)
		Avg.	**2.191**	**140.8**	**114.9**	**3.1**	**2.9**	**989 (143.5)**

* All samples were 4100 grams aggregate mass.
1: Initial height of sample measured by SGC
2: Final height of sample measured by SGC
3: Time to peak tensile strength

Table A.11. Compaction Data for 50% (*I-55*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$ [1]	G_{mm} [2]	S [3]	Rep	G_{mb}	H_I [4] mm	H_F [5] mm	V_a	T [6] sec	S_t kPa (psi)
0	2.330	1.0	1	2.135	142.8	117.4	8.4	2.2	1627 (235.9)
			2	2.139	142.7	117.2	8.2	2.0	1671 (242.3)
			Avg.	**2.137**	**142.8**	**117.3**	**8.3**	**2.1**	**1649 (239.1)**
		1.5	1	2.143	142.2	116.6	8.0	2.6	1866 (270.6)
			2	2.150	142.2	116.9	7.7	2.6	2024 (293.6)
			Avg.	**2.147**	**142.2**	**116.8**	**7.9**	**2.6**	**1945 (282.1)**
2.0	2.304	1.0	1	2.182	141.3	116.2	5.3	2.8	1885 (273.4)
			2	2.184	142.2	116.8	5.2	3.0	1907 (276.6)
			Avg.	**2.183**	**141.8**	**116.5**	**5.3**	**2.9**	**1896 (275.0)**
		1.5	1	2.181	141.3	116.2	5.3	3.8	1954 (283.4)
			2	2.183	141.4	115.9	5.3	2.8	2010 (291.5)
			Avg.	**2.182**	**141.4**	**116.1**	**5.3**	**3.3**	**1982 (287.4)**
2.5	2.289	1.0	1	2.192	141.6	116.2	4.2	3.2	1953 (283.3)
			2	2.178	141.9	116.5	4.8	3.0	1812 (262.8)
			Avg.	**2.185**	**141.8**	**116.4**	**4.5**	**3.1**	**1883 (273.1)**
		1.5	1	2.194	141.1	115.9	4.2	2.8	2011 (291.7)
			2	2.188	141.9	116.2	4.4	2.8	1970 (285.7)
			Avg.	**2.191**	**141.5**	**116.1**	**4.3**	**2.8**	**1991 (288.7)**
2.8	2.283	0.0	1	2.163	142.9	117.0	5.3	2.5	1733 (251.4)
			2	2.182	142.8	116.6	4.4	2.5	1891 (274.2)
			Avg.	**2.173**	**142.9**	**116.8**	**4.9**	**2.5**	**1812 (274.1)**
		1.0	1	2.164	143.5	117.3	5.2	2.5	1869 (271.0)
			2	2.185	142.2	116.3	4.3	2.5	1829 (265.2)
			Avg.	**2.175**	**142.9**	**116.8**	**4.8**	**2.5**	**1849 (262.8)**
		1.5	1	2.167	142.4	116.5	5.1	2.5	1875 (272.0)
			2	2.188	141.5	115.8	4.2	2.5	1904 (276.2)
			Avg.	**2.178**	**142.0**	**116.2**	**4.7**	**2.5**	**1890 (268.1)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ (V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test

Table A.12. Compaction Data for 75% (*I-55*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$[1]	G_{mm}[2]	S[3]	Rep	G_{mb}	H_I[4] Mm	H_F[5] Mm	V_a	T[6] sec	S_t kPa (psi)
0	2.309	1.0	1	2.162	138.1	115.2	6.4	1.8	2146 (311.3)
			2	2.151	139.8	116.4	6.8	2.0	2219 (321.8)
			Avg.	**2.157**	**139.0**	**115.8**	**6.6**	**1.9**	**2183 (316.6)**
		1.5	1	2.146	139.5	116.1	7.1	2.6	2324 (337.1)
			2	2.151	138.5	115.7	6.8	2.6	1808 (262.2)
			Avg.	**2.149**	**139.0**	**115.9**	**7.0**	**2.6**	**2066 (299.7)**
2.0	2.309	1.0	1	2.205	138.0	115.5	4.5	3.0	2667 (386.8)
			2	2.211	138.2	115.0	4.2	3.0	2531 (367.2)
			Avg.	**2.208**	**138.1**	**115.3**	**4.4**	**3.0**	**2599 (377.0)**
		1.5	1	2.219	137.1	114.5	3.9	2.8	2804 (406.6)
			2	2.209	138.6	115.3	4.3	3.0	2634 (382.0)
			Avg.	**2.214**	**137.9**	**114.9**	**4.1**	**2.9**	**2719 (394.3)**
2.1	2.297	0.0	1	2.202	138.4	115.3	4.1	2.5	2681 (388.8)
			2	2.186	139.5	116.1	4.8	2.5	2279 (330.5)
			Avg.	**2.194**	**139.0**	**115.7**	**4.5**	**2.5**	**2480 (359.7)**
		1.0	1	2.186	138.3	115.5	4.8	2.5	2515 (364.7)
			2	2.190	139.4	115.6	4.7	2.5	2379 (345.0)
			Avg.	**2.188**	**138.9**	**115.6**	**4.7**	**2.5**	**2447 (354.9)**
		1.5	1	2.204	139.2	116.0	4.0	2.5	2127 (308.5)
			2	2.197	139.0	115.6	4.4	2.5	2118 (307.2)
			Avg.	**2.201**	**139.1**	**115.8**	**4.2**	**2.5**	**2123 (307.9)**
2.5	2.275	1.0	1	2.219	138.4	115.2	2.5	2.4	2551 (370.0)
			2	2.206	138.4	115.7	3.0	2.6	2566 (372.1)
			Avg.	**2.213**	**138.4**	**115.5**	**2.8**	**2.5**	**2558 (371.1)**
		1.5	1	2.216	138.8	115.2	2.6	3.4	2312 (335.3)
			2	2.215	138.7	115.1	2.6	2.6	2599 (376.9)
			Avg.	**2.216**	**138.8**	**115.2**	**2.6**	**3.0**	**2455 (356.1)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ ((V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test

Table A.13. Compaction Data for 100% (*I-55*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$ [1]	G_{mm} [2]	S [3]	Rep	G_{mb}	H_I [4] mm	H_F [5] mm	V_a	T [6] sec	S_t kPa (psi)
0	2.333	1.0	1	2.128	138.7	117.6	8.8	1.8	1469 (213.0)
			2	2.115	138.8	117.3	9.3	1.4	1321 (191.6)
			Avg.	**2.122**	**138.8**	**117.5**	**9.1**	**1.6**	**1395 (202.3)**
		1.5	1	2.096	138.2	117.3	10.2	1.8	1245 (180.6)
			2	2.099	138.5	117.5	10.0	1.6	1127 (163.5)
			Avg.	**2.098**	**138.4**	**117.4**	**10.1**	**1.7**	**1187 (172.1)**
1.5	2.320	0.0	1	2.188	138.0	116.1	5.7	1.5	1934 (280.5)
			2	2.199	138.1	116.1	5.2	2.5	2521 (365.6)
			Avg.	**2.194**	**138.1**	**116.1**	**5.5**	**2.0**	**2227 (323.0)**
		1.0	1	2.201	137.6	115.8	5.1	2.5	2630 (381.4)
			2	2.207	137.7	115.9	4.9	2.5	2675 (388.0)
			Avg.	**2.204**	**137.7**	**115.9**	**5.0**	**2.5**	**2653 (384.7)**
		1.5	1	2.193	138.5	116.1	5.5	2.1	2607 (378.1)
			2	2.172	139.9	117.4	6.4	2.3	2484 (360.3)
			Avg.	**2.183**	**139.2**	**116.8**	**6.0**	**2.2**	**2546 (369.2)**
2.0	2.283	1.0	1	2.248	133.9	113.1	1.5	2.8	2863 (415.2)
			2	2.236	136.0	113.9	2.1	2.6	2836 (411.3)
			Avg.	**2.242**	**135.0**	**113.5**	**1.8**	**2.7**	**2849 (413.3)**
		1.5	1	2.231	135.9	113.7	2.3	2.8	2912 (422.3)
			2	2.232	136.1	113.7	2.2	2.6	2824 (409.6)
			Avg.	**2.232**	**136.0**	**113.7**	**2.3**	**2.7**	**2868 (416.0)**
2.5	2.275	1.0	1	2.237	135.3	114.1	1.7	2.6	2973 (431.2)
			2	2.237	136.1	114.4	1.7	2.6	2923 (423.9)
			Avg.	**2.237**	**135.7**	**114.3**	**1.7**	**2.6**	**2948 (427.6)**
		1.5	1	2.228	136.5	114.3	2.1	3.0	2969 (430.6)
			2	2.224	136.9	114.8	2.2	2.6	2976 (431.6)
			Avg.	**2.226**	**136.7**	**114.6**	**2.2**	**2.8**	**2972 (431.1)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ (V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test

Table A.14. Compaction Data for 50% (*MS-25*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$ [1]	G_{mm} [2]	S [3]	Rep	G_{mb}	H_I [4] mm	H_F [5] Mm	V_a	T [6] sec	S_t kPa (psi)
0	2.328	1.0	1	2.200	137.7	114.2	5.5	3.8	1893 (274.5)
			2	2.199	137.9	113.7	5.5	3.2	2190 (317.6)
			Avg.	**2.200**	**137.8**	**114.0**	**5.5**	**3.5**	**2042 (296.1)**
		1.5	1	2.206	136.8	113.5	5.2	3.2	2249 (326.2)
			2	2.214	136.7	113.1	4.9	2.6	2395 (347.4)
			Avg.	**2.210**	**136.8**	**113.3**	**5.1**	**2.9**	**2322 (336.8)**
0.4	2.338	0.0	1	2.191	137.5	113.9	6.3	2.5	2142 (310.7)
			2	2.205	136.8	113.5	5.7	2.5	2126 (308.4)
			Avg.	**2.198**	**137.2**	**113.7**	**6.0**	**2.5**	**2134 (309.6)**
		1.0	1	2.221	136.4	113.1	5.0	2.5	2266 (328.6)
			2	2.230	137.0	113.4	4.6	2.5	2220 (322.0)
			Avg.	**2.226**	**136.7**	**113.3**	**4.8**	**2.5**	**2243 (325.3)**
		1.5	1	2.224	135.9	112.2	4.9	2.5	2319 (336.3)
			2	2.171	137.2	113.3	7.1	2.5	2188 (317.3)
			Avg.	**2.198**	**136.6**	**112.8**	**6.0**	**2.5**	**2254 (326.8)**
0.7	2.297	1.0	1	2.222	137.2	113.2	3.3	2.6	2156 (312.7)
			2	2.220	137.8	113.6	3.4	3.2	2197 (318.7)
			Avg.	**2.221**	**137.5**	**113.4**	**3.4**	**2.9**	**2177 (315.7)**
		1.5	1	2.212	137.7	113.8	3.7	3.0	2125 (308.2)
			2	2.231	135.8	112.7	2.9	2.8	2277 (330.2)
			Avg.	**2.222**	**136.8**	**113.3**	**3.3**	**2.9**	**2201 (319.2)**
2.0	2.285	1.0	1	2.235	135.6	112.7	2.2	3.0	1936 (280.8)
			2	2.233	136.1	112.8	2.3	3.2	1933 (280.4)
			Avg.	**2.234**	**135.9**	**112.8**	**2.3**	**3.1**	**1935 (280.6)**
		1.5	1	2.234	134.2	112.2	2.2	3.0	2091 (303.3)
			2	2.246	136.1	112.9	1.7	3.6	1728 (250.6)
			Avg.	**2.240**	**135.2**	**112.6**	**2.0**	**3.3**	**1910 (277.0)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ (V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test

Table A.15. Compaction Data for 75% (*MS-25*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$[1]	G_{mm}[2]	S[3]	Rep	G_{mb}	H_I[4] mm	H_F[5] mm	V_a	T[6] sec	S_t kPa (psi)
0	2.361	1.0	1	2.226	134.1	112.0	5.7	2.4	2608 (378.2)
			2	2.218	134.0	111.8	6.1	2.2	2681 (388.8)
			Avg.	**2.222**	**134.1**	**111.9**	**5.9**	**2.3**	**2132 (383.5)**
		1.5	1	2.211	134.3	112.3	6.4	2.2	2406 (348.9)
			2	2.225	133.9	111.9	5.8	4.2	1858 (269.4)
			Avg.	**2.218**	**134.1**	**112.1**	**6.1**	**3.2**	**2744 (309.2)**
0.5	2.332	0.0	1	2.233	133.8	111.7	4.2	2.5	2987 (433.2)
			2	2.238	133.3	111.6	4.0	2.5	2821 (409.2)
			Avg.	**2.236**	**133.6**	**111.7**	**4.1**	**2.5**	**2904 (421.2)**
		1.0	1	2.238	132.7	111.2	4.0	2.5	2879 (417.6)
			2	2.244	132.8	111.2	3.8	2.5	2810 (407.6)
			Avg.	**2.241**	**132.8**	**111.2**	**3.9**	**2.5**	**2845 (412.6)**
		1.5	1	2.245	132.8	111.2	3.7	2.5	2845 (412.6)
			2	2.230	133.9	112.0	4.4	2.5	2654 (384.9)
			Avg.	**2.238**	**133.4**	**111.6**	**4.1**	**2.5**	**2750 (398.8)**
0.7	2.307	1.0	1	2.242	133.3	111.8	2.8	2.8	2971 (430.9)
			2	2.241	133.7	111.9	2.9	5.0	2517 (365.0)
			Avg.	**2.242**	**133.5**	**111.9**	**2.9**	**3.9**	**2623 (398.0)**
		1.5	1	2.226	132.9	111.5	3.5	4.8	2902 (420.9)
			2	2.236	132.6	111.3	3.1	3.4	2961 (429.5)
			Avg.	**2.231**	**132.8**	**111.4**	**3.3**	**4.1**	**2932 (425.2)**
2.0	2.297	1.0	1	2.258	132.0	111.9	1.7	3.4	2326 (337.3)
			2	2.243	132.4	112.5	2.4	2.4	2360 (342.3)
			Avg.	**2.251**	**132.2**	**112.2**	**2.0**	**2.9**	**2343 (339.8)**
		1.5	1	2.252	131.7	111.9	2.0	3.0	2551 (369.9)
			2	2.257	132.0	112.0	1.7	3.2	2440 (353.8)
			Avg.	**2.255**	**131.9**	**112.0**	**1.9**	**3.1**	**2495 (361.9)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ (V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test

Table A.16. Compaction Data for 100% (*MS-25*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$[1]	G_{mm}[2]	S[3]	Rep	G_{mb}	H_I[4] mm	H_F[5] mm	V_a	T[6] sec	S_t kPa (psi)
0	2.306	1.0	1	2.196	134.1	113.1	4.8	2.0	2246 (325.8)
			2	2.197	134.8	112.8	4.7	2.0	2289 (331.9)
			Avg.	**2.197**	**134.5**	**113.0**	**4.8**	**2.0**	**2268 (328.9)**
		1.5	1	2.201	134.2	113.2	4.6	2.0	2400 (348.0)
			2	2.187	135.3	114.0	5.2	1.6	2034 (295.0)
			Avg.	**2.194**	**134.8**	**113.6**	**4.9**	**1.8**	**2217 (321.5)**
0.6	2.344	0.0	1	2.244	134.1	112.4	4.3	2.5	3155 (457.5)
			2	2.246	135.1	113.1	4.2	2.5	3006 (436.0)
			Avg.	**2.245**	**134.6**	**112.8**	**4.2**	**2.5**	**3081 (446.8)**
		1.0	1	2.237	134.6	112.7	4.6	2.0	2463 (357.20
			2	2.227	134.8	112.7	5.0	2.5	3131 (454.1)
			Avg.	**2.232**	**134.7**	**112.7**	**4.8**	**2.3**	**2797 (405.7)**
		1.5	1	2.244	134.0	112.4	4.3	2.5	2956 (428.7)
			2	2.245	133.6	112.1	4.2	2.5	2968 (430.5)
			Avg.	**2.245**	**133.8**	**112.3**	**4.2**	**2.5**	**2962 (429.6)**
0.7	2.325	1.0	1	2.222	133.1	111.1	4.4	2.6	3001 (435.3)
			2	2.228	133.9	111.9	4.2	2.4	2978 (431.9)
			Avg.	**2.225**	**133.5**	**111.5**	**4.3**	**2.5**	**2990 (433.6)**
		1.5	1	2.242	132.3	111.0	3.6	3.8	3082 (447.0)
			2	2.243	132.1	110.9	3.5	2.4	3077 (446.2)
			Avg.	**2.243**	**132.2**	**111.0**	**3.6**	**3.1**	**3080 (446.6)**
2.0	2.284	1.0	1	2.278	130.7	110.7	0.3	3.2	2868 (416.0)
			2	2.279	130.8	110.7	0.2	3.2	2790 (404.6)
			Avg.	**2.279**	**130.8**	**110.7**	**0.3**	**3.2**	**2829 (410.3)**
		1.5	1	2.278	131.3	110.8	0.3	3.0	2846 (412.7)
			2	2.276	130.7	110.3	0.4	2.8	2690 (390.2)
			Avg.	**2.277**	**131.0**	**110.6**	**0.4**	**2.9**	**2768 (401.5)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ (V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test

Table A.17. Compaction Data for 50% (*SP*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$ [1]	G_{mm} [2]	S [3]	Rep	G_{mb}	H_I [4] mm	H_F [5] mm	V_a	T [6] sec	S_t kPa (psi)
0	2.375	1.0	1	2.213	135.4	112.5	6.8	3.0	1888 (273.8)
			2	2.210	136.9	113.6	6.9	2.6	2032 (294.7)
			Avg.	**2.212**	**136.2**	**113.1**	**6.9**	**2.8**	**1960 (284.3)**
		1.5	1	2.199	137.0	113.7	7.4	3.0	1758 (255.0)
			2	2.192	137.2	113.9	7.7	3.4	1690 (245.1)
			Avg.	**2.196**	**137.1**	**113.8**	**7.6**	**3.2**	**1724 (250.1)**
1.1	2.343	0.0	1	2.191	137.6	114.2	6.5	2.5	1731 (251.1)
			2	2.186	137.8	114.5	6.7	2.5	1705 (247.3)
			Avg.	**2.189**	**137.7**	**114.4**	**6.6**	**2.5**	**1718 (249.2)**
		1.0	1	2.188	134.1	110.9	6.6	2.5	1802 (261.4)
			2	2.208	136.6	113.5	5.8	2.5	1873 (271.7)
			Avg.	**2.198**	**135.4**	**112.2**	**6.2**	**2.5**	**1838 (266.6)**
		1.5	1	2.185	137.5	114.1	6.7	2.5	1775 (257.4)
			2	2.201	137.0	113.6	6.1	2.5	1917 (278.0)
			Avg.	**2.193**	**137.3**	**113.9**	**6.4**	**2.5**	**1846 (267.7)**
1.3	2.295	1.0	1	2.215	136.1	112.9	3.5	2.4	1926 (279.3)
			2	2.220	136.6	113.3	3.3	2.4	2014 (292.1)
			Avg.	**2.218**	**136.4**	**113.1**	**3.4**	**2.4**	**1970 (285.7)**
		1.5	1	2.220	136.3	113.4	3.3	2.4	1912 (277.3)
			2	2.211	136.3	113.4	3.7	2.6	1961 (284.4)
			Avg.	**2.216**	**136.3**	**113.4**	**3.5**	**2.5**	**1937 (280.9)**
2.0	2.314	1.0	1	2.233	134.1	112.1	3.5	2.8	2009 (291.4)
			2	2.239	135.5	112.9	3.2	2.4	1952 (283.1)
			Avg.	**2.236**	**134.8**	**112.5**	**3.4**	**2.6**	**1981 (287.3)**
		1.5	1	2.226	136.0	113.4	3.8	2.8	1936 (280.8)
			2	2.226	135.3	112.3	3.8	3.0	2010 (291.5)
			Avg.	**2.226**	**135.7**	**112.9**	**3.8**	**2.9**	**1973 (286.2)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ (V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test

Table A.18. Compaction Data for 75% (*SP*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$ [1]	G_{mm} [2]	S [3]	Rep	G_{mb}	H_I [4] mm	H_F [5] mm	V_a	T [6] sec	S_t kPa (psi)
0	2.324	1.0	1	2.192	135.8	114.6	5.7	2.0	1667 (241.8)
			2	2.174	134.9	113.9	6.5	2.6	1533 (222.3)
			Avg.	**2.183**	**135.4**	**114.3**	**6.1**	**2.3**	**1600 (232.1)**
		1.5	1	2.215	132.4	111.6	4.7	2.6	2294 (332.7)
			2	2.228	135.5	114.6	4.1	2.4	2020 (293.0)
			Avg.	**2.222**	**134.0**	**113.1**	**4.4**	**2.5**	**2157 (312.9)**
1.3	2.332	0.0	1	2.241	130.8	110.6	3.9	2.5	2115 (306.7)
			2	2.239	131.9	111.7	4.0	2.5	2437 (353.4)
			Avg.	**2.240**	**131.4**	**111.2**	**3.9**	**2.5**	**2276 (330.1)**
		1.0	1	2.243	132.5	111.7	3.8	2.8	2095 (303.8)
			2	2.236	132.6	112.1	4.1	3.6	2180 (316.1)
			Avg.	**2.240**	**132.6**	**111.9**	**4.0**	**3.2**	**2138 (310.0)**
		1.5	1	2.239	132.1	111.9	4.0	3.0	2555 (370.6)
			2	2.242	130.8	111.0	3.9	3.4	2431 (352.6)
			Avg.	**2.241**	**131.5**	**111.5**	**3.9**	**3.2**	**2493 (361.6)**
2.0	2.310	1.0	1	2.265	129.6	110.8	1.9	2.4	2303 (334.0)
			2	2.248	128.1	108.9	2.7	3.4	2191 (317.7)
			Avg.	**2.257**	**128.9**	**109.9**	**2.3**	**2.9**	**2247 (325.9)**
		1.5	1	2.247	131.6	112.2	2.7	3.0	2291 (332.2)
			2	2.256	129.5	110.9	2.3	2.8	2502 (362.8)
			Avg.	**2.252**	**130.6**	**111.6**	**2.5**	**2.9**	**2397 (347.5)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ (V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test

Table A.19. Compaction Data for 100% (*SP*) RAP Aggregate at 116 C (240 F)

$P_{b\ (V\text{-}s(R))}$ [1]	G_{mm} [2]	S [3]	Rep	G_{mb}	H_I [4] mm	H_F [5] mm	V_a	T [6] sec	S_t kPa (psi)
0	2.267	1.0	1	2.145	136.1	116.1	5.4	1.6	1014 (147.1)
			2	2.131	135.6	116.0	6.0	1.8	1001 (145.1)
			Avg.	**2.138**	**135.9**	**116.1**	**5.7**	**1.7**	**1008 (146.1)**
		1.5	1	2.162	134.9	115.5	4.6	1.4	932 (135.2)
			2	2.158	134.9	115.6	4.8	1.4	925 (134.2)
			Avg.	**2.160**	**134.9**	**115.6**	**4.7**	**1.4**	**929 (134.7)**
0.9	2.369	0.0	1	2.230	129.7	111.6	5.9	2.5	2479 (359.5)
			2	2.248	129.8	111.4	5.1	2.5	2332 (338.2)
			Avg.	**2.239**	**129.8**	**111.5**	**5.5**	**2.5**	**2406 (348.9)**
		1.0	1	2.229	129.9	111.3	5.9	2.0	2491 (361.2)
			2	2.252	129.2	111.0	4.9	2.5	2053 (297.9)
			Avg.	**2.241**	**129.6**	**111.2**	**5.4**	**2.3**	**2272 (329.6)**
		1.5	1	2.233	130.2	111.7	5.7	2.5	2133 (309.4)
			2	2.257	130.1	111.6	4.7	2.4	2286 (331.6)
			Avg.	**2.245**	**130.2**	**111.7**	**5.2**	**2.5**	**2210 (320.5)**
1.3	2.342	1.0	1	2.260	127.9	109.1	3.5	2.2	2761 (400.5)
			2	2.265	128.5	110.1	3.3	2.8	2855 (414.1)
			Avg.	**2.263**	**128.2**	**109.6**	**3.4**	**2.5**	**2808 (407.3)**
		1.5	1	2.265	128.5	109.9	3.3	2.2	2774 (402.3)
			2	2.263	128.3	109.7	3.4	2.2	2559 (371.1)
			Avg.	**2.264**	**128.4**	**109.8**	**3.4**	**2.2**	**2667 (386.7)**
2.0	2.305	1.0	1	2.281	127.1	109.0	1.0	2.8	2810 (407.6)
			2	2.288	129.1	111.1	0.7	2.4	2969 (430.6)
			Avg.	**2.285**	**128.1**	**110.1**	**0.9**	**2.6**	**2890 (419.1)**
		1.5	1	2.282	128.4	110.1	1.0	2.4	2892 (419.4)
			2	2.284	127.2	109.3	0.9	2.8	2753 (399.2)
			Avg.	**2.283**	**128.4**	**110.2**	**1.0**	**2.6**	**2823 (409.3)**

* All samples were 4100 grams aggregate mass.

1: $P_{b\ (V\text{-}s(V))}$ Additional binder added to the RAP portion by total RAP mass

2: G_{mm} did not vary based on Sasobit content

3: % Sasobit added to the binder by total binder mass

4: Initial height of sample measured by SGC

5: Final height of sample measured by SGC

6: Time to peak load in indirect tensile test