TECHNICAL REPORT STANDARD PAGE

1. **Report No.** FHWA/LA.09/465

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

Characterization of HMA Mixtures Containing High Reclaimed Asphalt Pavement Content With Crumb Rubber Additives

5. Report Date March 2013

6. Performing Organization Code

7. Author(s)

Louay N. Mohammad, Ph.D., Samuel B. Cooper, Jr., MSCE., P.E., Bill King, P.E., Amar Raghavendra, P.E.

8. Performing Organization Report No.

9. Performing Organization Name and Address

Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70809

10. Work Unit No.

11. Contract or Grant No.

State Project Number: 736-99-1574
LTRC Project Number: 09-1B

12. Sponsoring Agency Name and Address

Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70809

13. Type of Report and Period Covered

Final Report
Period Covered: September 2008-June 30, 2009

14. Sponsoring Agency Code

15. Supplementary Notes

6. Abstract

As the price of petroleum and material costs escalate and pressures of maintaining the sustainability of our environment, owners must continually find methods to decrease material costs and maximize their benefits. This paper presents the findings of laboratory characterization of HMA mixtures containing high reclaimed asphalt pavement (RAP) content with crumb rubber (CR) additives. Five mixtures were examined in this study. The conventional mixture contained a styrene-butadiene-styrene, polymer-modified asphalt cement, Performance Grade (PG) 76-22M and no RAP. The second mixture utilized 15 percent RAP and PG 76-22M asphalt cement binder. The third mixture contains no RAP, 30 mesh CR additives blended (wet process) with a PG 64-22 binder. The fourth mixture contains 40 percent RAP, 30 mesh CR additives blended (dry process) with a PG 64-22 asphalt cement binder. The final mixture utilized 100 percent RAP with CR additives. Laboratory mixture characterization includes the Asphalt Mixture Performance Tests (Dynamic Modulus, E*, and Flow Number, FN), Semi-Circular Bend test, Dissipated Creep Strain Energy test, and the Modified Lottman test. In addition, Loaded Wheel Tracking, LWT, test was performed. Results indicate that the addition of CR additives as a dry feed to carry rejuvenating agents is promising. Mixtures containing high RAP content and CR additives exhibited similar performance as conventional mixture with PG 76-22M binder.

17. Key Words

Crumb Rubber, HMA, Asphalt Mixture Performance Tests, Materials Characterization

18. Distribution Statement

Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

19. Security Classif. (of this report) N/A	**20. Security Classif. (of this page)** N/A	21. No. of Pages 109	22. Price

Project Review Committee

Each research project has an advisory committee appointed by the LTRC Director. The Project Review Committee (PRC) is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

LTRC appreciates the dedication of the following Project Review Committee members in guiding this research study to fruition.

LTRC Manager

Bill King

Senior Asphalt Research Engineer

Members

Luanna Cambas, LADOTD

Philip Graves, DOTD

Philip Arena, FHWA

Don Weathers, LAPA

Danny Smith, DOTD

Gary Fitts, Asphalt Institute

Directorate Implementation Sponsor

William H. Temple, DOTD Chief Engineer

Characterization of HMA Mixtures Containing High Recycled Asphalt Pavement Content with Crumb Rubber Additives

by

Louay N. Mohammad, Ph.D.
Professor of Civil and Environmental Engineering
Director, Engineering Materials Characterization Research Facility

Samuel B. Cooper, Jr., MSCE, P.E.
Associate Director Technology Transfer and Training

Bill King, P.E.
Senior Asphalt Research Engineer

Amar Raghavendra, P.E.
Application Engineer Manager

Louisiana Transportation Research Center
Research Project No. 09-1B
State Project No. 736-99-1574

Louisiana Transportation Research Center
4101 Gourrier Ave.
Baton Rouge, LA 70808

March 2013

ABSTRACT

This study presents the findings of a laboratory characterization of hot mix asphalt (HMA) mixtures containing high reclaimed asphalt pavement (RAP) content with crumb rubber (CR) additives. Five mixtures were examined in this study. The conventional mixture contained a styrene-butadiene-styrene polymer modified asphalt cement, Performance Grade (PG) 76-22M and no RAP. The second mixture utilized 15 percent RAP and PG 76-22M asphalt cement binder. The third mixture contained no RAP, 30 mesh CR additives blended (wet process) with a PG 64-22 binder. The fourth mixture contained 40 percent RAP, 30 mesh CR additives blended (dry process) with a PG 64-22 asphalt cement binder. The final mixture utilized 100 percent RAP with CR additives. Laboratory mixture characterization included the asphalt mixture simple performance tests (Dynamic Modulus, E*, and flow number, F_N); semi-circular bend test, dissipated creep strain energy test; and the modified Lottman test. In addition, Loaded Wheel Tracking, LWT, test was performed. Results indicate that the addition of CR additives as a dry feed to carry rejuvenating agents is promising. Mixtures containing high RAP content and CR additives exhibited similar performance as conventional mixtures with PG 76-22M binder.

ACKNOWLEDGEMENTS

The research work reported in this paper was sponsored by the Louisiana Department of Transportation and Development (LADOTD) through the Louisiana Transportation Research Center (LTRC). The authors would like to express thanks to all who have provided valuable help in this study especially Greg Tullier, Willie Gueho, Patrick Frazier, and Amar Raghavendra. Also, the authors would like to thank Md Sharear Kabir for providing technical input in this study. Lastly, the authors would like to thank John Osborn of Elastomeric Concentrates, LLC who supplied the crumb rubber additives utilized in this study.

IMPLEMENTATION STATEMENT

The results of this study clearly show the benefits of utilizing the absorptive properties of crumb rubber to carry rejuvenating type products into an HMA mixture that contains a high RAP content. The outcome of this study indicates that crumb rubber additives can be added as part of the aggregate portion (dry feed) during HMA production in lieu of crumb rubber as part of the asphalt cement binder (i.e., wet blending). The use of crumb rubber additives as demonstrated in this study clearly indicates promise. However, since this was a limited study, further investigation utilizing several RAP sources and asphalt cement sources should be conducted. Optimization of the crumb rubber additives is necessary to maximize a mixtures performance, i.e., fatigue resistance or permanent deformation. In addition, a life cycle cost analysis should be included to indicate the economic benefit in utilizing high RAP and recycled products such as crumb rubber.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Background

One of the issues concerning environmental sustainability is determining how to make the production, distribution, and consumption of goods and services last longer and have less impact on our ecological systems consisting of all plants, animals, and micro-organisms in an area functioning together with all non-living physical factors of the environment. One such method of sustainability in the hot mix asphalt (HMA) industry is using recycled materials to replace a percentage of virgin materials used in the manufacturing process such as aggregates and asphalt cement binder, which has a direct impact on cost and the environment.

Agencies and owners must continually find methods to decrease material costs and maximize their benefits as the price of HMA mixtures continually rise because of the increase in material costs such as aggregates and petroleum products. One such method is to increase and/or begin using readily available recycled materials like reclaimed asphalt pavements (RAP) and crumb rubber (CR).

Asphalt pavements are the most recycled product in America. A reclaimed asphalt pavement, which is commonly called RAP, is an HMA mixture containing aggregates and asphalt cement binder that has been removed and reclaimed from an existing pavement. Properly processed RAP consists of well-graded aggregates coated with asphalt cement binder.

Reports from the Federal Highway Administration (FHWA) and the United States Environmental Protection Agency (U.S. EPA) state that approximately 80 percent of removed asphalt pavements are reused as part of new roads, roadbeds, shoulders, and embankments.

Another available recycled material is crumb rubber. Crumb rubber or ground rubber is typically defined as scrap tire rubber that has been reduced to a particle size of 3/8 inch or less. There are approximately 290 million scrap tires generated per year in the United States. In 2004, there were approximately 275 million scrap tires in stockpiles in the United States. About 27 millions scrap tires are estimated to be disposed in landfills annually resulting in major disposal costs, environmental risks related to pests and insect growths that promote the outbreak of diseases, and fires that are hard to distinguish and cause contamination of the soil. The three largest markets for the use of recycled scrap tires are tire derived fuel; civil engineering applications (subgrade fill, embankments, septic system drain fields, etc.); and ground rubber, i.e., crumb rubber applications/rubberized asphalt. Currently there are 30 million tons of scrap tires that are recycled into crumb rubber each year.

The use of crumb-rubber modifiers (CRM) in hot-mix asphalt mixtures can be traced back to the 1840s when natural rubber was introduced into bitumen to increase its engineering performance *[1]*. Since the 1960s, researchers and engineers have used shredded automobile tires in HMA mixtures for pavements. The process of applying crumb rubber in asphalt mixtures can be divided into two broad categories: a dry process and a wet process. In the dry process, crumb rubber is added to the aggregate before the asphalt binder is charged into the mixture. In the wet process, asphalt cement is pre-blended with the rubber at high temperature (177 – 210°C) and specific blending conditions *[1]*.

LADOTD initiated a research project to evaluate different procedures of CRM applications used in HMA mixtures in 1994 in which the long-term pavement performance of CRM asphalt pavements was compared to that of control sections built with conventional asphalt mixtures *[2]*. It is reported that the conventional mixtures exhibited higher laboratory strength characteristics (indirect tensile strength) than CRM mixtures. Also, the pavement sections constructed with CRM asphalt mixtures showed overall better performance indices (rut depth, fatigue cracks, and international roughness index numbers) than the corresponding control sections *[3]*.

In the 1970s, states and paving contractors began making extensive use of RAP in HMA pavements because of the cost savings and the environmentally positive method of recycling. From 1987 through 1993, several research projects were carried out to develop the Superpave method of HMA designs under the Strategic Highway Research Program (SHRP).   One of the distinct shortcomings of this mix design method was that there was no provision for the use of RAP in the mix design process. It was determined that the effect of aged binder from RAP on the performance properties of the virgin binder depends upon the level of RAP used in the HMA mixture. When the percentage of RAP used in the HMA is low (10 – 20 percent), the effect on the asphalt binder properties is minimal. As RAP percentage increases (greater than 20 percent) in the HMA, the aged binder from RAP blends with the virgin asphalt binder in sufficient quantity to significantly affect the asphalt binder performance. The blending of old, hardened asphalt binders from RAP with a virgin asphalt binder will typically result in an asphalt binder that is harder than the original virgin asphalt binder. Usually this binder hardening is counteracted by adding a softer virgin asphalt binder and letting the RAP asphalt binder stiffen the softer binder to achieve a blended asphalt binder of desired properties. In addition to the use of softer asphalt binders, recycling agents or rejuvenators are also used to soften the hardened RAP asphalt binders *[4]*.

This study explored the use of the absorption properties of crumb rubber to carry asphalt cement binder components (light ends) that are typically lost during oxidation of HMA pavements as a dry feed component in the making of hot mix asphalt mixtures. No available literature was found indicating that this method has been evaluated. Laboratory mechanistic performance and mixture characterization evaluations and analysis were performed to determine the effects of crumb rubber additives and RAP on HMA mixtures' performance.

Literature Review

The term "sustainability" is a relatively new concept that has already proved useful. Sustainability relates to "how to make human economic systems (production, distribution and consumption of goods and services in a particular society) last longer and have less impact on ecological systems consisting of all plants, animals and micro-organisms in an area functioning together with all of the non-living physical factors of the environment, and particularly relates to concern over major global problems such as climate change and oil depletion" *[6]*. One such method of sustainability in the HMA industry is using recycled materials to replace a percentage of virgin materials used in the manufacturing process such as aggregates and asphalt cement binder, which has a direct impact on cost and the environment.

Agencies and owners must continually find methods to decrease material costs and maximize their benefits as the price of HMA mixtures continually rise because of the increase in material costs such as aggregates and petroleum products. One such method is to increase and/or begin using readily available recycled materials like RAP and crumb rubber. Therefore it is only logical to try to devise methods to increase the usage of these type products without sacrificing HMA mixture performance. Recycled materials, such as crumb rubber made from scrap tires, and RAP are available to the HMA industry.

Reclaimed asphalt pavement is an HMA mixture containing aggregates and asphalt cement binder that has been removed and reclaimed from an existing roadway. RAP is generated during rehabilitation/reconstruction of existing HMA roadways or from utility cuts across an existing HMA roadway that was necessary to obtain access to underground utilities. When RAP is properly processed, crushed and screened, RAP will consist of well-graded aggregates coated with asphalt cement binder. During reconstruction or rehabilitation, HMA pavements are typically removed by milling machines. This process is commonly referred to as cold planning. The depth of HMA removal by milling varies by the type of reconstruction required. The reconstruction/rehabilitation process may require the removal of an existing wearing course mixture or may require full-depth removal of the entire HMA structure. As the existing HMA pavement is being milled, RAP is deposited directly into haul trucks and then delivered to an HMA hot mix plant for processing. Full-depth removal involves milling the existing HMA structure in several passes depending on the existing depth of the structure or by ripping and breaking the pavement into large pieces using rippers on a bull dozer or by use of a backhoe. When the RAP is broken into large pieces, the broken material is picked up by a front-end loader or backhoe and then loaded into haul trucks and is usually transported to an HMA hot mix plant for processing. At the HMA hot mix plant, the RAP is processed by crushing and screening, and then it is conveyed and stockpiled *[7]*.

It is reported that asphalt pavements are America's most recycled product. More than 73 million tons of reclaimed asphalt pavements are recycled each year as compared to the combined total of 40 million tons of recycled paper, glass, aluminum, and plastic. Reports from the FHWA and the U.S. EPA state that approximately 80 percent of removed asphalt pavements are reused as part of new roads, roadbeds, shoulders, and embankments *[8]*.

In 1994, there were approximately 800 million scrap tires disposed of in stockpiles. Since then, there has been millions of scrap tires removed by aggressive cleanup by state scrap tire management programs. It was reported in 2004 that there were approximately 275 million scrap tires remaining in stockpiles in the United States. There were approximately 290 million scrap tires generated in 2003, which is the typical yearly rate seen in the United States. About 27 million scrap tires are estimated to be disposed in landfills annually resulting in major disposal costs, environmental risks related to pests and insect growths that promote the outbreak of diseases, and fires that are hard to distinguish and cause contamination of the soil. As of 2003, markets existed for the use of 80 percent of the scrap tires that relates to 233 million scrap tires out of 290 million scrap tires available. The three largest markets for the use of recycled scrap tires are tire derived fuel; civil engineering applications (subgrade fill, embankments, septic system drain fields, etc.); and ground rubber, i.e., crumb rubber applications/rubberized asphalt. Currently there are 30 million tons of scrap tires that are recycled into crumb rubber each year *[9]*. The transportation industry still has the potential to escalate its use of disposed scrap tires by increasing the use of crumb rubber in specialty mixes such as CRM HMA mixtures.

Crumb rubber or ground rubber is typically defined as scrap tire rubber that has been reduced to a particle size of 3/8-inch or less. Crumb rubber is described or measured by the mesh screen or sieve size through which it passes in the production process. A 30 mesh means there are 30 openings, per linear inch of screen. There are three processes that are typically used in the making the crumb rubber from scrap tires. First, the scrap tire is reduced to 2 ½-inch to 4-inch size shreds by a slow speed "shear" shredder or shredders. Second, the shreds go through two or three successively narrower blade shredders to further reduce the shreds to 3/8-inch or less. Finally, the particles are processed to even smaller mesh sizes by using cracking or grinding rolling mills. The final mesh size of the crumb rubber product is determined by the number of passes through the mill. Other than shredding, there are other methods for processing scrap tires into crumb rubber: First there are cryogenic systems that utilize sub-zero temperatures to freeze the tires. Then the frozen tires are shattered using a hammer mill which makes it easy to separate the rubber from the steel and fabric. A second alternative method is to use ambient systems that operate at room temperature and literally tear the tire material apart. During the process, screens and gravity separators are used to remove steel, non-ferrous metals, sand, and other unwanted materials, and aspiration equipment is used to remove fibers. One scrap passenger tire can yield between 10-12 lb. of crumb rubber product *[10]*.

The processes of applying crumb rubber in asphalt mixtures can be divided into two broad categories: a dry process and a wet process. In the dry process, crumb rubber is added to the aggregate before the asphalt binder is charged into the mixture. In the wet process, asphalt cement is pre-blended with the rubber at high temperature (177 – 210 ^{o}C) and specific blending conditions. Crumb rubber particles in the dry process are normally coarser than those in the wet process and are considered as part of the aggregate gradations (called "rubber-filler"); whereas, in the wet process, crumb rubber is reacted with asphalt binders (called "asphalt-rubber"). In the wet process, crumb rubber is mixed with asphalt binder at high temperature and is allowed to swell by absorption of the asphalt oil components to form a gel-like material *[1]*. The extent of the swelling process depends on the mixing temperature, the size of the crumb rubber particles, and the concentration of rubber in the blend *[11]*. Researchers have noted that if these variables are not selected properly, the rubber may depolymerize causing a negative impact on the properties of the blend *[12]*. Common dry process methods include the PlusRide™, chunk rubber, and generic dry. Common wet process methods include the Arizona, McDonald, Ecoflex, and Rouse continuous blending methods *[1]*.

The use of CRM in hot mix asphalt mixtures can be traced back to the 1840s when natural rubber was introduced into bitumen to increase its engineering performance *[1]*. The use of ground rubber from scrap tires has long been supported by environmental and government agencies to reduce the disposal problem associated with waste tires. Since the 1960s, researchers and engineers have used shredded automobile tires in HMA mixtures for pavements.

In the 1960s, Charles H. McDonald pioneered the development of the wet process (or reacted) crumb rubber modified asphalt cement binders in the United States. In 1963, McDonald first used CRM asphalt cement binders for a patching material in which he termed the operation as a “band-aid” repair technique in Phoenix, Arizona. The CRM asphalt binder was spray applied using an asphalt distributor and then covered with a “localized chip seal” placed by hand over a small pavement area. The first “large area” spray application was performed in 1967, which became known as stress-absorbing membranes (SAM). In 1972, Arizona DOT placed its first stress–absorbing membrane interlayer (SAMI) as part of a project to evaluate techniques to reduce reflection cracking. Arizona placed its first HMA mixture containing CRM asphalt cement in 1975. Arizona DOT currently uses CRM asphalt binders in SAMIs, gap-graded HMA mixtures, and in open-graded friction courses, which is now the most popular use of CRM binders *[13]*.

Not until the late 1980s did the use of recycled tire crumb rubber in HMA mixtures become popular. In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) specified that all asphalt pavement projects funded by federal agencies must use certain percentages of scrap tires *[14]*. Although this mandate was later suspended from the ISTEA legislation, it has greatly encouraged the research and application of CRM asphalt in HMA pavements.

The National Cooperative Highway Research Programs (NCHRP) “Synthesis of Highway Practice 198 – Uses of Recycled Rubber Tires in Highways” provides a comprehensive review of the use of recycled rubber tires in highways based on a review of nearly 500 references and on information recorded from state highway agencies’ responses to a 1991 survey of current practices *[15]*.

The Florida Department of Transportation (FLDOT) constructed three HMA mixture demonstration projects that utilized CRM wet processes in 1989 for the purpose of evaluating the short term field performance and constructability of these mixtures. It was necessary to construct these projects so that the FLDOT could develop specifications and procedures for CRM use. The mixtures evaluated were two fine-graded and an open-graded Friction Course mixture type. For this study, minus No. 80 mesh crumb rubber was pre-blended ("reacted" or digested") with the asphalt cement binder prior to its incorporation with the aggregates. They concluded that the addition of CRM would increase asphalt film thickness, binder resiliency, viscosity, and shear strength. It was further reported that with the use of CRM the FLDOT was able to increase the asphalt binder content of the mixtures because of the stiffening effect it had on the asphalt cement binder. By increasing the asphalt content, Florida DOT anticipates increased durability of these type mixtures *[16]*.

From 1990 to 1993, Virginia DOT constructed pavements containing CRM asphalt mixtures. The objective was to familiarize the Virginia Department of Transportation and contractors personnel with the construction process and to compare the performance of different types of mixes containing ground tire rubber. Four test sections (dense graded surface mixes, a gap-graded surface mix, a base mix, and a stress-absorbing membrane interlayer) using asphalt rubber hot mix were placed in Virginia utilizing two wet processes, McDonald and Rouse, and then pavement performance was compared to that of conventional asphalt mixtures *[17]*. The McDonald process focuses on reacted asphalt cement/CRM binder in which the time required to "react" these materials is dependent on the size of the crumb rubber particles used in the blending process. The Rouse process blends a 180-micron (80 mesh) sieve CRM with an asphalt cement binder utilizing continuous blending procedures *[1]*. It is reported that the mixes containing asphalt rubber performed at least as well as conventional mixes. In Virginia mixes, the inclusion of asphalt rubber in HMA pavements increased construction costs by 50 to 100 percent as compared to the cost of conventional mixes *[17]*.

Troy et al. *[18]* conducted research on CRM pavements in Nevada. The objective of the study was to test and evaluate CRM binders blended by the wet process using the Superpave performance grading system binder protocols and its applicability to CRM binders. In addition, the CRM HMA mix design was conducted using the Hveem procedure. They concluded that the conventional sample geometry in Superpave binder test protocols cannot be used to test the CRM binders and that the Hveem compaction is inadequate for mixtures containing CRM binders. It was further concluded that Superpave binder testing protocols would not work for CRM binders containing coarse rubber particles. It was recommended that the plate and cup system be used for asphalt cement binders blended with crumb rubber. It was further concluded that the plate and cup system could not replace the bending beam rheometer for low-temperature testing. In addition, a modified Hveem mix design procedure was developed when CRM mixtures are used.

LADOTD initiated a research project to evaluate different procedures of CRM applications used in HMA mixtures in 1994 in which the long-term pavement performance of the CRM asphalt pavements was compared to that of the control sections built with conventional asphalt mixtures *[2]*. There were eight CRM applications evaluated in this study as follows:

- Arizona wet process incorporated into a gap-graded mixture;
- Arizona wet process incorporated into a SAMI;
- Arizona wet process incorporated into an open-graded friction course (OGFC);
- PlusRide™ dry process utilizing a gap-graded aggregate structure;
- Rouse powdered rubber wet process incorporated into a typical dense-graded mixture;
- A terminal-blended material formulated by Neste Wright in a dense-graded mixture;
- Rouse dry-powdered rubber process blended into a dense-graded aggregate structure; and
- Generic CRM dry process incorporated into a gap-graded mixture.

Huang et al. evaluated conventional and CRM asphalt mixtures through laboratory engineering performance tests such as ITS and indirect tensile resilient modulus (M_r) tests *[19]*. Marshall Stability and Flow tests were also conducted during the mixture design. Huang et al. also compared field performance through the pavement structural non-destructive test using Dynaflect and long-term pavement performance measurement, such as roadway core density, International Roughness Index (IRI), rutting, and fatigue cracking. The conventional mixtures exhibited higher laboratory strength characteristics than CRM mixtures. However the pavement sections constructed with CRM asphalt mixtures showed overall better performance indices (rut depth, fatigue cracks, and international roughness index numbers) than the corresponding control sections *[19]*. In addition, Cooper et al. evaluated the long term field performance (10 years) as it relates to random cracking, International Roughness Index, and rutting of asphalt pavements constructed with these eight different CRM applications as opposed to the control sections built with conventional HMA mixtures *[3]*. It is reported that the “pavement sections constructed with CRM asphalt mixtures showed overall better field performance indices (rut depth, random cracks, and IRI numbers) than corresponding control sections. Both CRM modified, wet and dry, and HMA mix types are performing equally well, if not better, than the conventional mix types evaluated.”

LADOTD conducted a study in 2004 to evaluate and characterize HMA mixtures that used recycled polymer-modified asphalt pavements as one of the mixture components *[20]*. According to the study, "the objectives of this research were to (1) analyze the properties of field-aged polymer modified asphalt cement (PMAC) relative to Pressure Aging Vessel (PAV) with aged PMAC; (2) examine the compatibility and feasibility of blending reclaimed PMAC with virgin PMAC based on chemical component analysis methods and Superpave binder specification; and (3) evaluate the fatigue and permanent deformation properties of asphalt mixtures containing various percentages of laboratory-aged and/or field-extracted PMACs based on laboratory fundamental engineering tests." The scope of this study was to develop extraction techniques necessary for the removal of the aged asphalt cement binder from the aggregate components of the HMA mixture. Also the extraction technique would allow for the separation of the polymer additive component from the asphalt cement binder. Asphalt cement binder testing, analysis, and Superpave characterization included (1) differential scanning calorimetric (DSC) measurement, (2) Fourier transform infrared (FTIR) measurement, (3) gel permeation chromatograph (GPC) measurement, (4) rotational viscosity measurement, (5) dynamic shear modulus and phase angle measurement, and (6) beam stiffness and creep slope measurement. In addition, a 19 mm nominal maximum aggregate size (NMAS) high volume HMA mixture that is commonly used by LADOTD was designed using virgin PMAC, meeting LADOTD PAC-40HG and PG 70-22M specifications and then blended with varying percentages (0, 20, 40, and 60 percent) of reclaimed polymer modified asphalt cement (RPMAC) and virgin aggregates. To characterize the HMA mixtures on both lab-aged and field-aged RPMAC mixtures being evaluated, a series of fundamental engineering tests were utilized. These tests included the frequency sweep at constant height (FSCH), repeated shear at constant height (RSCH), simple shear at constant height (SSCH), ITS and strain, indirect tensile modulus (M_r), semi-circular fracture, beam fatigue, and asphalt pavement analyzer (APA) tests. It is reported that as the percentage of RPMAC binder in mixtures increased, the rutting resistance increased and the fatigue resistance decreased. The asphalt cement binder that was extracted from field cores revealed that the binder was quite brittle at low temperatures as measured by the force ductility and bending beam tests. In addition, the extracted RPMAC binder was blended with the virgin PMAC and analyzed. It is reported that the resultant blends had much stiffer properties than those of lab-aged PMAC, which indicates that the PAV procedure did not predict the field aging of PMAC binders. It was stated that the HMA mixture containing 60 percent RPMAC exhibited better fatigue life than those mixtures with 20 and 40 percent RPMAC *[20]*.

In the 1970s, states and paving contractors began making extensive use of RAP in HMA pavements. The use of RAP results in cost savings and an environmentally positive method of recycling. Properly designed HMA containing RAP can perform as well as HMA prepared with 100 percent virgin materials *[4]*. From 1987 through 1993, several research projects were carried out to develop the Superpave method of design based on performance based HMA designs under the SHRP. One of the distinct shortcomings of this mix design method was no provision for the use of RAP in the mix design process. This shortcoming hindered the use of RAP in HMA mixtures by agencies that adopted the Superpave mix design process. In order to temporarily remedy this situation, interim guidelines were developed by a Superpave Mixtures Expert Task Group based on their experience. It was noted that the effect of aged binder from RAP on the performance properties of the virgin binder depends upon the level of RAP used in the HMA mixture. When the percentage of RAP used in the HMA is low (10 – 20 percent), the effect on the asphalt binder properties is minimal. At these low percentages, RAP affects the mix volumetrics and performance through gradation because RAP acts like a "black rock." As RAP percentage in the HMA increases (greater than 20 percent), the aged binder from RAP blends with the virgin asphalt binder in sufficient quantity to significantly affect the asphalt binder performance *[4]*. McDaniel et al. as part of NCHRP Project 9-12, were given the task of developing guidelines for the use of RAP in HMA mixtures *[4]*. RAP materials from three states (Florida, Connecticut, and Arizona) yielded recovered RAP asphalt binders of different stiffness properties in combination with two virgin asphalt binders at RAP contents of 10 and 40 percent. Mixtures properties were evaluated using the Superpave shear tests [AASHTO TP7 - Simple Shear Test at Constant Height) at high temperatures and indirect tensile creep and strength tests (AASHTO TP9 - Standard Test Method for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device] for low temperature properties. The findings confirmed current practice that low amounts of RAP, typically 10 to 20 percent, can be used without determining the recovered asphalt binder properties. This is because there is not enough of the old, hardened RAP asphalt binder present in the final asphalt cement binder blend to change the properties of the asphalt binder, and the RAP may account as an aggregate component of the aggregate. When more than 20 percent RAP is used in an HMA mixture, recovery and testing of its binder is recommended, along with blending charts to determine what performance grade of virgin asphalt binder should be used in the HMA mixture design. The blending of old, hardened asphalt binders from RAP with a virgin asphalt binder will typically result in an asphalt binder that is harder than the virgin asphalt binder properties used. Usually this binder hardening is counteracted by adding a softer virgin asphalt binder and allowing the RAP asphalt binder stiffen the softer binder to achieve a blended asphalt binder of desired properties. In addition to the use of softer asphalt binders, recycling agents are also used to soften the hardened RAP asphalt binders. The recommended binder selection guidelines for RAP mixtures are as follows *[4]*:

- Less than 20 percent RAP used – no change in asphalt binder selection.
- Between 20 – 30 percent RAP used – select one grade softer virgin asphalt binder than normally used (e.g., select a PG 58-28 in lieu of a PG 64-22).
- Greater than 30 percent RAP – develop and use recommendations from blending charts.

Softening of hardened RAP binders when high percentages of RAP content (greater than 25 percent) are used in a HMA mixture is typically achieved by adding rejuvenating agents. The use of rejuvenators changes the composition, physical properties, and performance properties of the rejuvenated aged asphalt binders in RAP *[5]*. Rejuvenators are used to recover the original properties of the aged binders and then reconstitute the chemical compositions of the aged binders that were lost due to the aging and oxidation process over time. An asphalt binder that experiences oxidization aging has a lower concentration of more reactive components, nitrogen base plus first acidaffins, and a higher concentration of less reactive components such as paraffines plus second acidaffins *[5]*.

Many CRM asphalt pavements used in the past are becoming prime candidates for recycling. Shen et al. studied the effects of rejuvenating agents on CRM modified binders by characterizing blended laboratory-aged CRM asphalt binders and rejuvenating agents using gel permeation chromatography (GPC) *[21]*. Results of the study indicated that the compositional changes of the asphalt binder blends with varying percentages of RAP or rejuvenating agents is reflected in the GPC test results. It was shown that the large molecular size (LMS) of blends decreases as the small molecular size (SMS) increases as the percentage of rejuvenators used increases regardless of the type of aged binders or rejuvenating agents. As a result, empirical prediction models were developed for Superpave binder properties for viscosity and high-failure temperature using LMS and SMS. It is stated that the predicted values from these models show a high correlation with viscosity and the high-failure temperature of asphalt binders *[21]*.

Shen et al. studied the effects of rejuvenating agents on Superpave HMA mixtures containing RAP in South Carolina *[5]*. There were three objectives of this study: first, to evaluate the properties of Superpave mixtures containing various RAP sources and a rejuvenator and then comparing to those of the recycled Superpave mixtures utilizing a softer asphalt cement binder; second, to investigate the use of blending charts of aged asphalt cement binders and a rejuvenator for determining the rejuvenator contents for the design of Superpave mixtures containing RAP; and third, to evaluate the properties of virgin Superpave mixtures and

Superpave mixtures containing RAP to ascertain the possibility of incorporating RAP into Superpave mixtures. Two RAPs were incorporated into a 9.5 mm nominal maximum size Superpave mixtures containing either a rejuvenator or a softer binder (control mixture).The HMA mixtures were evaluated in terms of volumetrics, ITS, and rutting potential using the APA. The rejuvenator content was determined from the blending charts of RAP binders containing the rejuvenator. Twelve Superpave mixtures were designed, 10 containing RAP and two with virgin materials. It was reported that for the mixtures tested, ITS and APA properties of the RAP HMA mixtures containing rejuvenator were better than those that contained only the softer binder. In addition, by using a rejuvenator in lieu of a softer binder, one could use 10 percent more RAP in the HMA mixture. It was further reported that there were good relationships between the measured performance parameters and rejuvenator contents utilized, which were determined by the blending charts developed from the extracted aged binders making it possible to determine the design rejuvenator contents necessary for recycling RAP *[5]*.

Problem Statement

Asphalt cement prices, like gasoline and crude oil, are at an all-time high with no relief in sight. With HMA mixtures' prices continuously climbing, highway agencies and owners are continually searching for methods to decrease material costs and maximize their benefits with no compromise in performance. One such method is to develop innovative technology to incorporate waste and recycled materials, such as crumb rubber from waste tires and RAP in HMA mixtures. RAP is currently allowed for use in limited percentages within HMA layers. As HMA pavements age over time, the asphalt binders become hardened and oxidized causing premature cracking in pavements. Thus, the current limiting factor in increasing the percentages of RAP is the excessive stiffness of the resulting HMA mixture. Rejuvenating additives are often used to "soften" the asphalt cement binder of RAP materials. Therefore, the incorporation of these additives into the HMA mixture will enable the use of higher percentages of RAP in the finished product. Furthermore, absorption properties of crumb rubber, from waste tires, may be used to carry those additives to revitalize the properties of the aged binders. Research is needed to evaluate the performance of HMA mixtures containing these additives.

A limited comparative laboratory mechanistic performance evaluation of conventional HMA mixtures and mixtures that contain waste tire crumb rubber, additives, and RAP will be conducted. HMA mixture characterization in terms of fatigue cracking, moisture susceptibility, and rutting will be analyzed and evaluated to determine the effects of the crumb rubber, additives, and RAP on the HMA mixtures' performance.

OBJECTIVE

The main objective of this study was to characterize the laboratory performance of conventional HMA mixtures and mixtures containing high RAP content and waste tire crumb rubber/additives through their fundamental engineering properties.

The second objective was to characterize the laboratory performance of an HMA mixture containing 100% RAP and waste tire crumb rubber/additives. A candidate for this mixture is the asphalt treated base mixture.

SCOPE

A Superpave l9-mm nominal maximum aggregate size (NMAS) Level 2 HMA mixture meeting LADOTD specifications was designed and examined. Siliceous limestone aggregates and coarse natural sand that are commonly used in Louisiana were included in this study. A total of four mixtures were examined in this study to fulfill the main objective. The first mixture was a control mixture, that contains a Styrene-Butadiene (SB) polymer modified asphalt cement meeting Louisiana specifications for PG 76-22M. The second mixture contained no RAP, 30 mesh CR plus additives blended (wet process) with a PG 64-22 asphalt cement binder, which yielded a PG76-22. The third mixture contained 15 percent RAP and PG 76-22M asphalt cement binder. The fourth mixture contained 40 percent RAP, 30 mesh crumb rubber, and additives blended (dry process) with a PG 64-22 asphalt cement binder. In addition, to fulfill the second objective of this study, an asphalt treated base mixture, which utilized 100 percent RAP and 30 mesh CR plus additives, was examined and characterized to determine its fundamental engineering properties. The CR and additives were introduced to the mixture at a rate of 10 percent by total weight of binder. Mixture performance tests conducted included simple performance tests (Dynamic modulus, E*, and flow number, F_N), Semi-circular bend (SCB) test, dissipated creep strain energy (DCSE) test, and modified Lottman test. Triplicate samples were used for each test. In addition, Loaded Wheel Tracking, LWT, test was performed.

METHODOLOGY

Test Factorial Design

Four HMA mixtures and an asphalt treated base mixture were considered in this study. Table 1 presents a summary of the test factorial considered.

Table 1
Test factorial

MIX TYPE	Mixture Variables			Modified Lottman		DCSE	E*	Fn	Jc	LWT
		% RAP	CRM/ Additives	Uncond	Cond				Aged	
19 mm NMAS Superpave Level 2	Conventional	0	----	3	3	3	3	3	3	2
	CRM/additives	0	10%	3	3	3	3	3	3	2
	RAP	15	----	3	3	3	3	3	3	2
	RAP, CRM/additives	40	10%	3	3	3	3	3	3	2
Asphalt Treated Base	RAP CRM/additives	100	10%	3	3	3	3	3	3	2
			TOTAL	15	15	15	15	15	15	10

For this study, mixture designations and their descriptions are as follows:

- 76CO: HMA Mixture/PG 76-22M, Conventional
- 76CRM: HMA Mixture/PG 76-22, Crumb Rubber Modified (Wet Blend) PG 64-22
- 76RAP15: HMA Mixture/PG 76-22M + 15% RAP (No CR Additive)
- 64RAP40: HMA Mixture/PG 64-22 +40% RAP + CR Additives
- 100%RAP: HMA Mixture/100% RAP +CR Additives

Hot Mix Asphalt Mixture Design Development

A Superpave l9-mm NMAS Level 2 HMA mixture meeting LADOTD specifications ($N_{initial}$ = 8-, N_{design} = 100-, N_{final} = 160-gyrations), was designed according to AASHTO TP28, “Standard Practice for Designing Superpave HMA” and Section 502 of the 2000 “Louisiana Standard Specifications for Roads and Bridges” *[22]*. Specifically, the optimum asphalt cement content will be determined based on volumetric (VTM = 2.5 - 4.5 percent, VMA ≥

12%, and VFA = 68% -78%) and densification (%G_{mm} at $N_{initial} \leq$ 89, %G_{mm} at $N_{final} \leq$ 98) requirements. It is noted that the aggregate structure for all the mixtures considered will be similar (i.e., the aggregate proportions for the blend selected will be adjusted to allow for the addition of RAP). Siliceous limestone aggregates and coarse natural sand that are commonly used in Louisiana will be included in this study.

Four HMA mixtures were evaluated to meet the main objective and were as follows: The first mixture was a conventional HMA mix type, as a control mixture, that contained no RAP and no CR additives material type and an SB polymer modified asphalt cement meeting Louisiana specifications for PG 76-22M. The second mixture contained no RAP and 30 mesh CR and additives blended (wet process) with a PG 64-22 asphalt cement binder, which yielded a PG76-22. The third mixture contained 15 percent RAP with PG 76-22M asphalt cement and no CR and additives. The fourth mixture contained 40 percent RAP, 30 mesh CR and additives, and PG 64-22 asphalt cement.

In the making of the 64RAP40 HMA mixture, crumb rubber additives were introduced as a dry feed at 10 percent by total weight of asphalt cement binder. This study explored the use of the absorption properties of crumb rubber to carry asphalt cement binder components that are typically lost during oxidation of HMA pavements as a dry feed component in the making of hot mix asphalt mixtures. There were two distinct CR additive components used as a dry feed in the 64RAP 40 HMA mixtures. The first CR component was comprised of 70 percent 30 mesh crumb rubber that had been pre-swelled, 10 percent long-chain wax, and 20 percent asphaltenes. The second component contained 70 percent 30 mesh pre-swelled crumb rubber, 10 percent long-chain wax, and 20 percent de-metalized motor oil. The two components were blended at a 50/50 ratio before being introduced into the HMA mixture at the specified rate of 10 percent by total weight of binder.

To meet the second objective of this study, an asphalt treated base mixture containing 100% RAP, 30 mesh CR, and additives was selected. This mixture was designed using the methodology developed under ongoing LTRC research study 04-4B *Development of a Design Methodology for Asphalt Treated Base Mixture*.

The job mix formula for the four HMA mixtures considered in this study is summarized in Table 2. The design optimum asphalt cement binder content for the mixtures indicated is similar.

Table 2
Job mix formula

Mixture Designation		76CO	76CRM	76RAP15	64RAP40
Mix Type		19.0 mm (3/4 in.) Superpave			
Aggregate Blend	#67 LS	37%	37%	38.5%	34%
	#78 LS	25%	25%	24. 5%	19.6%
	#11 LS	29%	29%	14%	----
	CS	9%	9%	8%	6%
	RAP	N/A	N/A	15%	40%
	CR	N/A	N/A	N/A	0.4%
Binder type		PG 76-22M	PG 76-22 CRM	PG 76-22M	PG 64-22
% G_{mm} at N_{Ini}		87.0	86.9	87.7	87.6
% G_{mm} at N_{Max}		97.6	97.5	97.3	98.0
Binder content, %		4. 0	4. 0	4. 1	4.0
Design air void, %		3.7	4.2	3.9	3.4
VMA, %		13	12	13	12
VFA, %		68	66	71	72
Metric (U. S.) Sieve		Composite Gradation Blend			
37. 5 mm (1½ in.)		100	100	100	100
25.0 mm (1 in.)		100	100	100	100
19.0 mm (3/4 in.)		98	98	95	95
12. 5 mm (1/2 in.)		77	77	77	79
9. 5 mm (3/8 in.)		61	61	60	61
4. 75 mm (No. 4)		41	41	37	37
2. 36 mm (No. 8)		29	29	28	27
1. 18 mm (No. 16)		21	21	21	19
0. 600 mm (No. 30)		15	15	16	15
0. 300 mm (No. 50)		8	8	9	9
0.150 mm (No. 100)		6	6	6	6
0. 075 mm (No. 200)		4. 6	4. 6	4. 6	4.5

Note: N/A: Not Applicable, LS: Limestone, CR: Crumb Rubber, CS: Coarse Sand
76CO: HMA Mixture/PG 76-22M, Conventional
76CRM: HMA Mixture/PG 76-22, Crumb Rubber Modified (Wet Blend) PG 64-22
76RAP15: HMA Mixture/PG 76-22M + 15% RAP (NO CR Additive)
64RAP40: HMA Mixture/PG 64-22 +40% RAP + CR Additives

Aggregate Tests

Aggregates from each source were tested to determine aggregate properties. The test items included coarse aggregate angularity, fine aggregate angularity (FAA), flat and elongated particles, gradation analysis, and sand equivalency.

For the mixtures considered in this study, RAP, siliceous limestone aggregates (#67 Limestone, #78 Limestone, and #11 Limestone) and coarse sand typically used in Louisiana were included in this study. To determine the aggregate gradation from each source a washed sieve analysis was performed on aggregates in accordance with AASHTO T 27 "Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates." The gradation analysis results of these aggregates obtained from sieve analysis are presented in Appendix A of this document. In addition the measured aggregate consensus properties for the materials used in this study can be found in Appendix A.

Additionally, the #67 Limestone and #78 Limestone aggregates were sieved and materials retained on 3/4 in.,1/2 in., 3/8 in., No. 4 sieves, and passing No. 4 sieves were stored in separate containers. For blending the high RAP content (40 percent) HMA mixture, the RAP aggregate was fractionated between the +8 and -8 sieves and stored in separate containers. The RAP did not require fractionation at the lower percentage (15 percent) evaluated in this study. Separating the aggregates into various sizes was needed so the required aggregate blend gradations could be batched directly from individual sized fractions for the desired HMA mix design. This method allowed for consistent replication of the HMA mixtures' composite aggregate gradation because each sieve size batch weight was mixed at the exact proportions needed for the hot mix job mix formula.

Figure 1 indicates the gradation blend for each mixture evaluated.

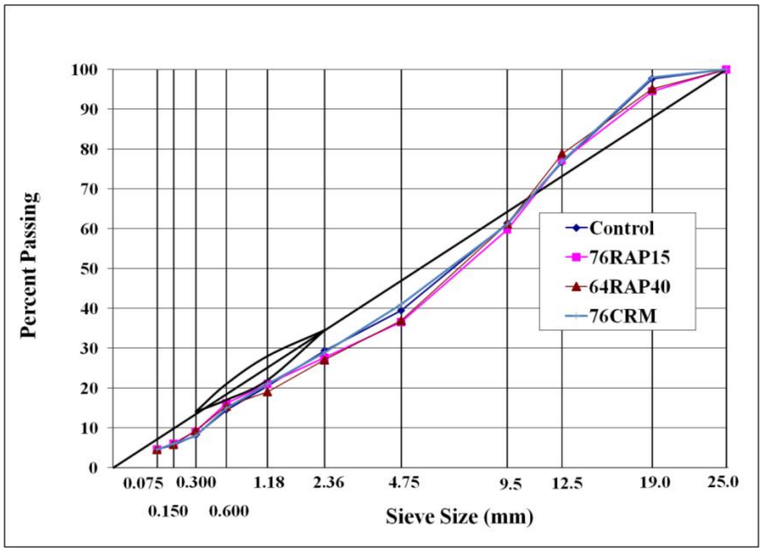

Figure 1
Aggregate gradation curves

Asphalt Binder Tests

Asphalt cement binders are one of man's oldest known engineering materials. The rheological properties of an asphalt cement binder can affect an HMA pavement's performance. An asphalt cement binder's rheological properties change during the production of an HMA mixture and as the AC ages over time due to oxidation and environmental influences. Pavement distresses may result if these changes are not properly addressed before production of a HMA mixture. Some of the specific types of pavement distresses that are contributed to by the rheological properties of an asphalt cement binder are raveling, cracking, stripping, and rutting. To ensure that an asphalt cement binder meets criteria to reduce and/or prevent pavement distresses due to changes in its rheological properties, testing of the asphalt cements binder properties is necessary. Therefore specifications were developed to minimize an asphalt cement binder's contribution for durability, rutting, fatigue cracking, and low temperature cracking.

Asphalt cement binders (virgin binder, RAP binder, and RAP with CR additives) were tested and characterized according to AASHTO PP6, "Practice for Grading or Verifying the Performance Grade of an Asphalt Binder" in order to determine the effect of the CRM/additives on asphalt cements considered in this study.

The asphalt binders included in this study (PG 64-22, PG 76-22M, and PG76-22) were tested and characterized according to the "Louisiana Department of Transportation and Development Performance Graded Asphalt Cement" specifications *[23]*; see Table 3. The asphalt cement binder's rheological properties were measured on unaged binders in accordance with the American Association of State Highway Transportation Officials (AASHTO) test methods. The rolling thin film oven (RTFO) test was performed in accordance with AASHTO T 240-06 "Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)" to simulate the binder aging that occurs during HMA mixture production and construction operations. The RTFO measures an asphalt cement binder's resistance to aging (durability) during construction. In addition, to determine the effect of long-term aging, the pressure aging vessel (PAV) test was conducted in accordance with AASHTO R 28 "Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)" to simulate binder aging (hardening) that takes place during an HMA mixture's service life. The PAV test is used to measure the resistance to aging (durability). The test purpose of the Rotational Viscometer (RV) is to measure the binder properties at high construction temperatures to ensure pumping and handling during production. This test was conducted in accordance with AASHTO T 316-06 "Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer" for determining the viscosity of the asphalt binder at 135°C. The Dynamic Shear Rheometer (DSR) test measures the binder properties at high and intermediate service temperatures to determine its resistance to permanent deformation (rutting) and fatigue cracking. The Dynamic Shear Rheometer test was conducted in accordance with AASHTO T 315-06 "Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)" method. In addition, the Bending Beam Rheometer (BBR) test is used to measure the asphalt cement binder properties at low service temperatures to determine its resistance to thermal cracking. This test was performed in accordance with AASHTO T 313-06 "Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)." Also, additional tests were conducted to determine the elastic properties of the asphalt cements considered in this study, utilizing the force ductility and elastic recovery tests in accordance with AASHTO T 300 "Standard Method of Test for Force Ductility Test of Asphalt Materials" and AASHTO T 301 "Standard Method of Test for Elastic Recovery Test of Asphalt Materials by Means of a Ductilometer," respectively.

Table 3
LADOTD performance graded asphalt cement specification

Property	AASHTO Test Method	Specification	
		PG 64-22	PG 76-22M
Tests on Original Binder			
Rotational Viscosity @ 135°C, Pa.s	T 316	3.0-	3.0-
Dynamic Shear, 10 rad/s, G*/Sin Delta, kPa	T 315	1.30+ @ 64°C	1.00+ @ 76°C
Force Ductility Ratio (F2/F1, 4°C, 5 cm/min, F2 @ 30 cm elongation)	T 300	N/A	0.30+
Force Ductility, (4°C, 5 cm/min, 30 cm elongation, kg)	T 300	N/A	N/A
Tests on RTFO Residue			
Dynamic Shear, 10 rad/s, G*/Sin Delta, kPa	T 315	2.20+ @ 64°C	2.20+ @ 76°C
Elastic Recovery, 25ºC, 10 cm elongation, %	T 301	N/A	60+
% Mass Loss	T 240	1.00-	1.00-
Tests on PAV Residue			
Dynamic Shear, @ 25ºC, 10 rad/s, G*Sin δ, kPa	T 315	5000-	5000-
Bending beam Creep Stiffness, S, Mpa	T 313	300-	300-
Bending beam Creep Slope, m value	T 313	0.300+	0.300+

Note: N/A: Not Applicable
"M" designation indicates modified

HMA Mixture Blending

Upon the completion of the design phase of this study, aggregate blending calculations were performed to determine the weight of each dry aggregate component for a specific batch weight. After determining each aggregate's batch weight, aggregates were weighed and placed in flat pan. After batching, the aggregates were placed in a force draft oven at 163 °C until such time that they reached this temperature. Approximately 1 hour before blending of the aggregate with the asphalt cement (AC) binder, the AC was placed in a force draft oven at 163°C. To ensure uniform mixing, all mixing equipment was also placed in the force draft oven at 163°C prior to blending aggregate and AC components. After all components reached the temperature of 163°C, these materials were placed in a mixing bucket. A crater in the center of the blended aggregate was formed for placement of the AC binder component at the specified batch weight. The mixing operation followed immediately after the AC binder component was added to the aggregate to ensure uniform blending of the materials. After mixing, the final HMA mixture was distributed in a flat pan and then placed back in a force draft oven at 163°C for 1 hour for short term aging. Upon completion of this step, the samples were prepared using the Superpave gyratory compactor to the specified dimensions for each particular test procedure.

When blending RAP as an aggregate component, it was important to add moisture to the pre-dryed RAP. For this study 5 percent moisture was added to the dryed RAP and then sealed prior to use. The virgin aggregates were placed in a force draft oven at 204°C to superheat the aggregate. The superheated aggregate is needed to cause steaming of the RAP (Figure 2), which also helps distribute heat and activate the RAP binder. The superheated aggregate components and moisture laden RAP were placed in the mixing bucket as follows: first the RAP was placed in the heated mixing bucket on the bottom then the superheated aggregate was placed on top of the RAP. The aggregates were then blended until there were no visible signs of steaming. After mixing the blended aggregates were distributed in a flat plan and placed in the oven at 163°C to remove any remaining moisture and bring the aggregate blend to the temperature of 163°C for required incorporation of the asphalt cement. The remaining blending steps were followed as previously described.

It is noted that the addition of crumb rubber at 10 percent by weight of total asphalt cement binder occurred after placement of the RAP and prior to placement of the superheated aggregate in the mixing bucket.

Figure 2 is a pictorial representation of the HMA mixture blending procedure.

Figure 2
HMA mix blending procedure

Fabrication of Mixture Specimens

Laboratory mix specimens were prepared according to the specific requirements of each individual test. According to the test factorials described, cylindrical samples were fabricated. An SGC as shown in Figure 3 was used to compact all cylindrical specimens.

Figure 3
SGC

Laboratory Tests on HMA Mixtures

Laboratory mechanistic performance and material characterization tests were conducted to evaluate the laboratory performance of conventional HMA mixtures and mixtures containing high RAP content and waste tire crumb rubber/additives through their fundamental engineering properties. HMA mixture characterization in terms of fatigue cracking, moisture susceptibility, and rutting were analyzed and evaluated to determine the effects of the crumb rubber, additives, and RAP on the HMA mixtures' performance. Specimens fabricated through various methods at the target air voids (7 ± ½%) were used to conduct laboratory mixture performance tests as outlined in Table 4. A brief description of each test is provided below. With the exception of LWT, triplicate samples were used for each test.

Table 4
Mixture performance tests

Performance Characteristics	Test	Specimen Details	Test Temp.	Protocol
Durability	Modified Lottman*	N150 x 95 mm	—	AASHTO T 283
Permanent Deformation	Complex Modulus	N150 x 100 mm	54 ºC	AASHTO TP7
	Flow Number	N150 x 100 mm	54 ºC	AASHTO TP7
	Loaded Wheel Tracking (LWT)	N150 x 60 mm, 320mm x 260mm x 80mm	54 ºC	AASHTO T 324
Fatigue Cracking	DCSE	N150 x 50 mm	10 ºC	Roque *[24]*
	Semi Circular Bend	N150 x 57 mm	25 ºC	Mohammad *[25]*

*One freeze/thaw cycle only.

Modified Lottman Test

This test evaluates the effect of saturation and accelerated water conditioning on compacted HMA samples utilizing freeze-thaw cycles. This method quantifies HMA mixtures' sensitivity to moisture damage, which is necessary to assure durability and long lasting hot mix asphalt. Numerical values of retained indirect-tensile properties are obtained by comparing conditioned samples, samples subjected to vacuum saturation and freeze-thaw cycles, to unconditioned samples. "Unconditioned" samples are samples that are not saturated nor subjected to freeze-thaw cycles. For each mix used in the study, six 150 x 95-mm diameter samples were compacted with a SGC to an air void content of 7 ± 0.5 percent. After compaction and air void determination, the six SGC samples were subdivided into two groups of three samples, so the average air void contents of the two subsets are approximately equivalent. The "unconditioned" sample subset was stored at room temperature for 24 ± 3 hours. Afterwards the "unconditioned" specimens were wrapped or placed in a heavy duty, leak proof plastic bag and then placed in a 25 ± 0.5 °C water bath for 2 hours ± 10 minutes. The "unconditioned" specimens were then tested to determine the indirect tensile strength for each sample. The "conditioned" samples were placed in a freezer at -17 °C for 16 to 18 hours. After the freezing cycle, the conditioned samples were placed in a 60°C water bath for 24 hours. Upon completion of the freeze/thaw cycle, the indirect tensile strength for the conditioned samples was determined. The average indirect tensile strength was determined for both conditioned and unconditioned samples by summing the test values and then determining the average value. The tensile strength ratio (TSR) is defined as the ratio of the conditioned to the unconditioned indirect tensile strength (AASHTO T-283, 2003) *[26]*.

Dissipated Creep Strain Energy Test

Fatigue cracking is a major asphalt pavement distress that concerns the owners of asphalt pavement highways. Fatigue cracking begins as microcracks that later coalesce to form macrocracks that propagate due to either tensile or shear stress or a combination of both. Research has indicated that a threshold concept is a good indicator of the cracking mechanism of asphalt pavements, and DCSE is the most reliable criterion to be used as this threshold *[27]*. The DCSE threshold represents the energy that the mixture can tolerate before it fractures. Two laboratory tests, the indirect resilient modulus (M_R) test and the ITS tests, were conducted at 10°C on the same specimen to calculate the dissipated strain energy*[28, 29]* . Triplicate specimens of 150 mm in diameter and 50 mm in thickness were used. Sample instrumentations as shown in Figure 4 were used in order to accurately capture the small deformations resulting from the repeated load applied in the M_R test. Two units of single integral, bi-axial extensometers model 3910 from epsilon technology that measure both lateral and vertical deformations were clipped onto gage points mounted on each face of the specimen. The gage length (i.e., the distance between two gage points) was maintained at 3 inches, which is one half of the sample diameter *[28]*. The test specimens were conditioned at 10°C for four hours before a 200-cycle haversine load with 0.1-second loading period and 0.4-second rest period in each loading cycle was applied along the diametrical plane on the specimen. A conditioning loading sequence was applied before the actual test in order to obtain uniform measurements in load and deformation. Then, a four-cycle haversine compressive load was applied and load and deformation data were recorded continuously. The magnitude of the applied load should result in a deformation as close as possible to 100 microstrains. After one test was complete, the specimen was rotated 90 degrees and tested again. The resilient modulus was then calculated from the average value of the two test results. Once the M_R test was finished, the ITS test was performed on the same specimen. Both tests, M_R and ITS, were performed using a Materials Testing System (MTS) hydraulic loading system, which was also be the same system used for the SCB test.

Figure 4
DCSE test sample instrumentation

The DCSE calculation used in this study was introduced by Roque et al. and later used by Alshamsi *[24]*, *[30]*, *[31]*. As indicated in Figure 5, DCSE is defined as the fracture energy (FE) minus the elastic energy (EE). The fracture energy is defined as the area under the stress-strain curve up to the point where the specimen begins to fracture. As shown in Figure 5 the area within the curve OA and x-axis (i.e., area OAB) is the fracture energy. The elastic energy is the energy resulting in elastic deformation. Therefore, M_R, calculated from the resilient modulus test, is selected as the slope of the line AC and the area of triangle ABC is taken as the EE. The failure strain (ε_f), peak tensile strength (S_t), and fracture energy are determined from the ITS test. A rather clear picture of DCSE calculation is described below:

$$M_r = \frac{S_t}{\varepsilon_f - \varepsilon_0} \tag{1}$$

$$\text{Therefore, } \varepsilon_0 = \frac{(M_R \times \varepsilon_f - S_t)}{M_R} \tag{2}$$

$$EE = \frac{1}{2} \times S_t \times (\varepsilon_f - \varepsilon_0) \tag{3}$$

$$DCSE = FE - EE \tag{4}$$

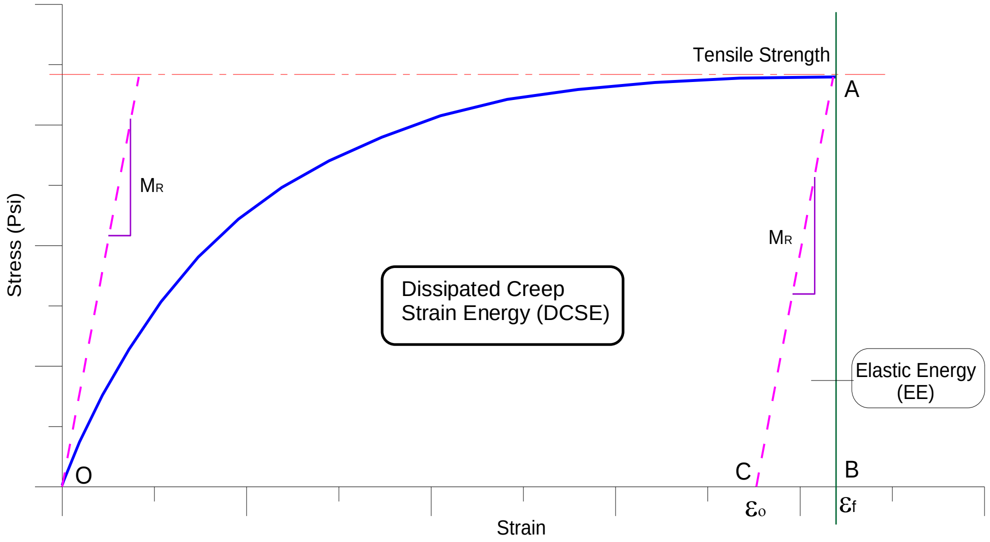

Figure 5
Dissipated creep strain energy determination

SCB Test

This test characterizes the fracture resistance of asphalt mixtures based on a fracture mechanics concept, the critical strain energy release rate, also called the critical value of J-integral, or J_c *[32]*, *[33]*, *[27]*. To determine the critical value of J-integral, semi-circular specimens with three notch depths (25.4, 31.8, and 38.0 mm) were tested. The test was conducted at 25°C. A semi-circular specimen was loaded monotonically till fracture under a constant cross-head deformation rate of 0.5 mm/min in a three-point bend load configuration (Figure 6).

The load and deformation were continuously recorded and the critical value of J-integral was determined based on the following equation:

$$JC = -\left(\frac{1}{b}\right)\frac{dU}{da} \tag{5}$$

where,
b = sample thickness,
a = the notch depth, and
U = the strain energy to failure.

Aged samples were prepared and tested to examine the influence of CR additives and high RAP contents mixtures performance. Mixture aging was performed according to AASHTO PP2 by placing compacted specimens in a forced draft oven for five days at 85°C *[34]*.

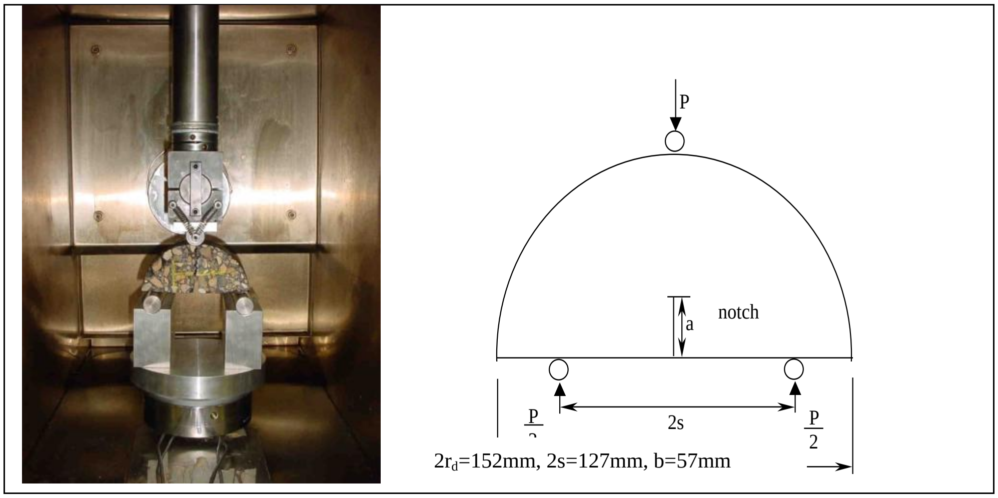

Figure 6
Set-up of semi-circular bending test

Simple Performance Tests (SPTs)

Simple SPTs were performed to characterize the laboratory performance of mixtures evaluated in this study with respect to resistance to permanent deformation as measured by the dynamic modulus and flow number tests. Using the measured dynamic modulus and phase angles obtained from the simple performance tests, a rutting factor and a fatigue factor can be developed, which is an indication of a HMA mixtures ability to resist permanent deformation (i.e., rutting).

Dynamic Modulus, |E*|. The dynamic modulus test is a triaxial compression test, which was standardized in 1979 as ASTM D3497, “Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures” *[35]*. This test consists of applying a uniaxial sinusoidal (i.e., haversine) compressive stress to an unconfined or confined HMA cylindrical test specimen as shown in Figure 7. The stress to strain relationship under a continuous sinusoidal loading for linear viscoelastic materials is defined by a complex number called the “complex modulus” (E*). The absolute value of the complex modulus |E* | is defined as the dynamic modulus. The dynamic modulus is mathematically defined as the maximum (i.e., peak) dynamic stress (σ_o) divided by the peak recoverable strain (ε_o).

$$|E^*| = \frac{\sigma_o}{\varepsilon_o} \tag{6}$$

This test is conducted at -10, 4, 20, 38.8, and 54.4°C at loading frequencies of 0.1, 0.5, 1.0, 5, 10, 25 Hz at each temperature *[36]*.

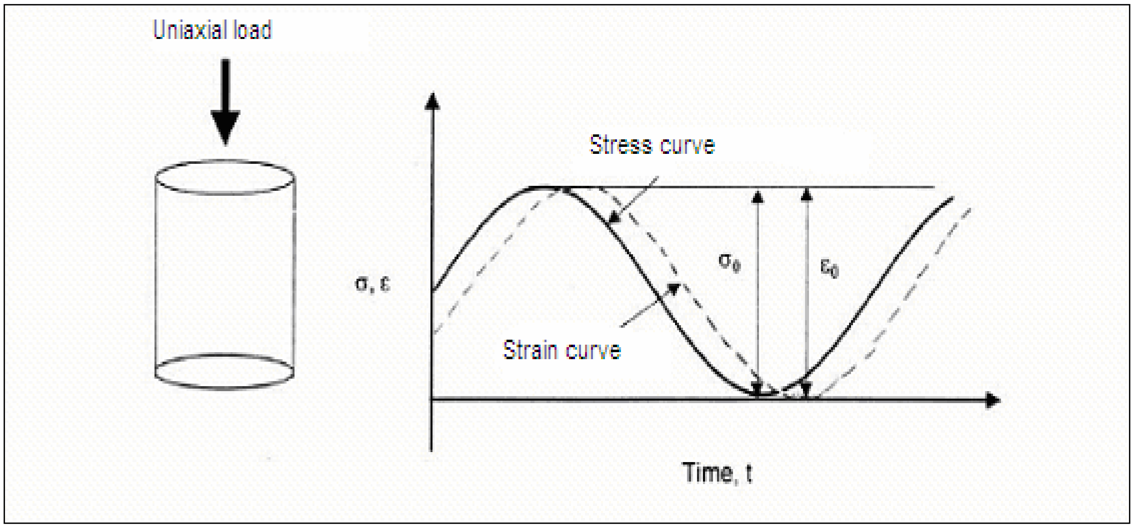

Figure 7
Mixture stress-strain response under sinusoidal load

Repeated Loading Test/Flow Number Test. The flow number test is used to determine the permanent deformation characteristic of hot mix asphalt mixtures by applying a repeated haversine load for several thousand cycles on a cylindrical asphalt sample. The load is applied for 0.1 second with a rest period of 0.9 second in one cycle as shown in Figure 8.

In this study, the test was conducted for 10,000 cycles at 54°C, and a stress level of 30 psi was used. This test was conducted on specimens 100 mm in diameter and 150 mm tall for mixtures with nominal maximum size aggregates less than or equal to 37.5 mm (1.5 in.). The flow number is defined as the number of repetitions corresponding to the minimum rate of change in permanent strain under repeated loading conditions. It is determined by differentiation of the permanent strain versus the number of load cycles curve. Figure 8 represents an example of a typical permanent axial strain response and the computation of flow number.

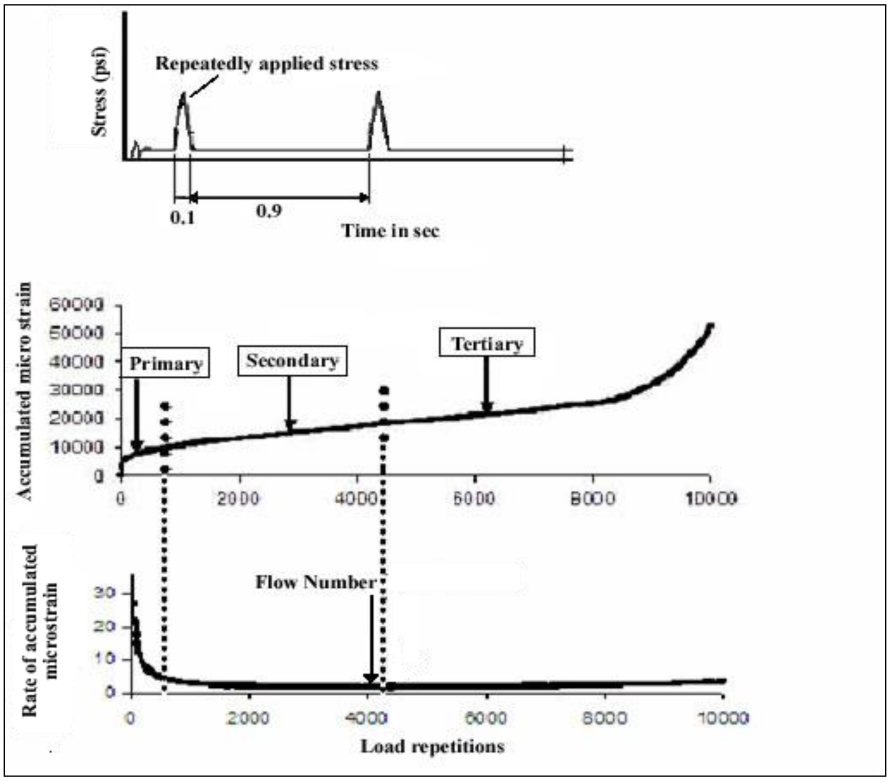

Figure 8
Stages of accumulated permanent strain and flow number computation

Loaded Wheel Tracking Device Test

One of the major distresses in asphalt pavements is its inability to resist permanent deformation due to traffic loading. To determine the rutting characteristics of the HMA mixtures considered in this study, a loaded wheel tracking test was conducted in accordance with AASHTO T 324-04 “Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA).” In this test, specimens are subjected to a steel wheel weighing 703 N, which is repeatedly rolled across its surface while being submerged in 50°C hot water. The test completion time is predicated upon test specimens being subjected to a maximum of 20,000 cycles or attainment of 20 mm deformation, whichever is reached first. Upon completion of the test, the average rut depth for the samples tested are recorded.

The Hamburg type LWT manufactured by PMW, Inc. of Salina, Kansas was used in this study (Figure 9). The Hamburg LWT can test two specimens simultaneously. The test specimens are subject to two reciprocating solid-steel wheels of 203.5 mm in diameter and

47 mm in width while being submerged in hot water at the specified temperature of 50°C which was utilized in this study. Before actual testing of the laboratory specimens, they were conditioned at 50°C, for 90 minutes. After conditioning, a fixed load of 703 N with a rolling speed of 1.1 km/h at the rate of 56 passes/min was implied. Each wheel rolls 230 mm before reversing direction.

In order to accurately measure permanent deformation, two Linear Variable Displacement Transducers (LVDTs) were utilized and the subsequent test results (rut depths, number of passes, and water bath temperature) were collected and recorded in an automatic data recording system associated with the Hamburg Wheel Tracking Device used in this study. Figure 10 represents a typical LWT test output.

Figure 9
Hamburg loaded wheel tracking device

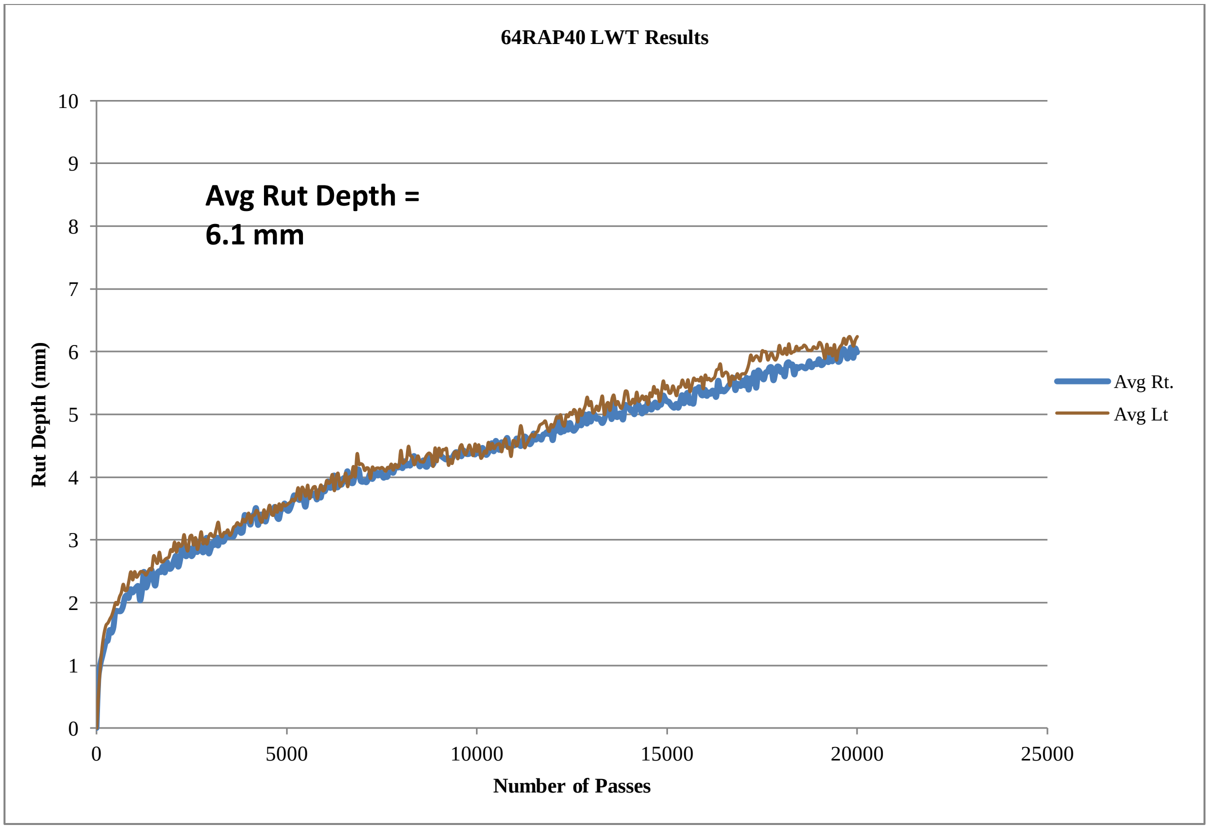

Figure 10
Typical LWT test output

Conduct Data Analysis

Laboratory test data were statistically analyzed using the analysis of variance (ANOVA) procedure provided in the Statistical Analysis System (SAS) program from SAS Institute, Inc. A multiple comparison procedure with a risk level of 5 percent was performed on the means. The groupings represent the mean for the test results reported by mixture type. The results of the statistical grouping were reported with the letters A, B, C, D, and so forth. The letter A was assigned to the highest mean followed by the other letters in appropriate order. A double (or more) letter designation, such as A/B (or A/B/C), will indicate that in the analysis the difference in the means is not clear-cut, and the mean is close to either group.

DISCUSSION OF RESULTS

Asphalt Binder Test Results

It is important to realize that an asphalt cement binder's rheological properties have an effect on the performance of an HMA pavement. Changes in the AC rheological properties due to production and aging that result from oxidation and environmental influences must be addressed to reduce asphalt binder related pavement distresses such as raveling, cracking, stripping, and rutting. It is essential that the asphalt cement binders are tested to ensure that the binder rheology meets specified criteria necessary to reduce pavement distresses. Therefore specifications were developed to characterize an asphalt cement binder's rheology, which is necessary to minimize the AC's contribution to durability issues, rutting, fatigue cracking, and low temperature cracking.

Table 5 presents the physical and rheological asphalt cement binder test results for the asphalt cement binders considered in this study. The PG 76-22 designated material as shown in Table 5 utilized unmodified asphalt cement (PG 64-22) that had been wet blended with CR to yield PG 76-22 asphalt cement binder. The PG 76-22 asphalt cement binder had a CR total content of 9 percent crumb rubber additive, 8 percent 30 mesh crumb rubber, and 1 percent Gilsonite. The 64RAP40 extraction sample is the extracted asphalt cement binder taken from the 64RAP40 HMA mixtures and subsequently tested for specification compliance. Table 5 shows the final test results for the conventional and crumb rubber modified (wet blend) virgin asphalt cement binders used in this study. Also shown in Table 5 is the asphalt binder rheology test results for the extracted asphalt cement binder from 64RAP40 HMA mixture. The rotational viscosity measured at 135°C for all ACs considered in this study passed the specified criteria of 3.0 Pa·s (maximum value) with the exception of the PG 76-22 binder, 3.1 Pa·s. The conventional asphalt cement binders (PG 64-22 and PG 76-22M) utilized in this study passed all specification requirements for their appropriate grading as observed in Table 5. In regards to the extracted 64RAP40 binder, research has shown that when high percentages of RAP are incorporated (i.e., 40 percent as in the 64RAP40 HMA mixture) into an HMA mixture, the blended asphalt cement (RAP AC plus virgin AC) will be stiffer and will grade out as high as three temperature grades, high and low temperature specification parameters, above the original virgin AC used *[4]*. For example, the virgin AC grading is PG 64-22, then 40 percent RAP is added to the mixture, and RAP AC blends with the virgin AC during production. The asphalt cement is extracted from the HMA mixture and then tested to determine it grading. The final grading could be as much as three temperature grades higher (high temperature and low temperature) than original grading, i.e., PG 82-4. Table 5 shows that this was not the case in the 64RAP40 extraction. The actual final performance grade of this material was a PG 70-28. The addition of the CR additives softened the RAP binder such that the final blended material stiffness was not increased. In fact, on the high temperature side, there was an increase in one temperature grade from PG 64 to PG 70, and there was a decrease in the low temperature properties of one grade, from -22 to -28. It must be noted that the extracted binder material did not go through the PAV process that provides for long-term service aging. Aging the 64RAP40 extracted binder with this process would have additionally stiffened the G*Sinδ and bending beam results. Nevertheless, the 64RAP40 extracted binder generally should be more rut and fatigue resistant than the PG 64-22, while also being more resistant to low temperature cracking (thermal cracking). In addition, in regards to pavement performance based on the asphalt cement binder rheology presented in Table 5, the 64RAP40 HMA mixture could possibly be comparable to the conventional PG 76-22M HMA mixture (76CO) with respect to pavement deformation, especially since the G*/Sinδ rutting factor on the original binder test parameter passed at the temperature of 76°C. Also the 64RAP40 HMA mixture resistance to fatigue cracking should be better than the conventional mixture (64CO) utilizing the PG 64-22. Table 5 indicates that the addition of a crumb rubber as a dry feed for the purpose of carrying rejuvenating type additives without sacrificing performance is viable.

Table 5
LADOTD performance graded asphalt cement test results

	Spec	**PG 64-22**	**PG 76-22M**	**PG 76-22 Wet Blend (CRM)**	**Extraction from 64RAP40 HMA Mixture**
Dynamic Shear, G*/Sin(δ), (kPa)	1.30^{+} @ 64°C	1.92	—	—	6.65
Dynamic Shear, G*/Sin(δ), (kPa)	1.00^{+} @ 70°C	0.88	—	—	3.35
Dynamic Shear, G*/Sin(δ), (kPa)	1.00^{+} @ 76°C	—	1.82	2.71	1.56
Dynamic Shear, G*/Sin(δ), (kPa)	1.00^{+} @ 82°C	—	1.29	1.54	—
Dynamic Shear, G*/Sin(δ), (kPa)	1.00^{+} @ 88°C	—	—	1.29	—
Force Ductility Ratio (F2/F1, 4°C, 5 cm/min, F2 @ 30 cm elongation	0.30+ (PG 76-22m)	N/A	0.49	N/A	N/A
Rotational Viscosity @ 135°C (Pa·s)	3.0^{+}	0.5	1.7	3.1	1.3
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 64°C	3.25	—	—	5.56
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 70°C	1.61	—	4.72	3.07
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 76°C	—	2.48	5.97	1.68
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 82°C	—	1.67	3.25	—
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 88°C	—	—	1.89	—
Elastic Recovery, 25ºC, 10 cm elongation, %	60+ (PG 76-22m)	N/A	70	75	N/A
Dynamic Shear, @ 25°C, G*Sin(δ), (kPa)	5000^{-}	2774	2297	2166	1463
Bending Beam Creep Stiffness @ -12°C, (MPa)	300^{-}	234	152	104	53
Bending Beam m-value@ -12°C	0.300^{+}	0.312	0.327	0.320	0.421
Bending Beam Creep Stiffness @ -18°C, (MPa)	300^{-}	—	—	—	151
Bending Beam m-value@ -18°C	0.300^{+}	—	—	—	0.342
Actual PG Grading		**PG 64-22**	**PG 76-22M**	**PG 76-22**	**PG 70-28**

Note: “ — ” *Test was not performed*
N/A: Not applicable

It is shown in Table 5 that the addition of crumb rubber as a wet blend (PG 76-22CRM) increased the dynamic shear G*/Sinδ rutting factor properties and rotational viscosity of the asphalt cement binder while improving the fatigue rutting factor G*(Sinδ) as indicated by the dynamic shear results at the 25°C testing temperature. The addition of the wet blended crumb rubber appears to have also improved the elastic properties of the asphalt cement binder tested as shown by the bending beam test results.

In order to determine if the CR additives had an effect on the recycled asphalt pavement used in this study, it was necessary to blend the crumb rubber additives with the RAP and then extract the asphalt cement binder from the HMA mixture. Table 6 presents the extracted RAP asphalt cement binder test results for the 100 percent RAP and the 100 percent RAP with CR additive blend. It is noted that the asphalt cement materials characterized in Table 6 did not go through the RTFO and PAV aging methods since the RAP utilized in this study was from a roadway previously constructed 15 years earlier and this material had been through the short term and long term aging process naturally throughout its life on the roadway. However this material was tested as if they had been aged through RTFO and PAV. It is shown that both materials graded out as a PG 82-16; however, in review of each test parameter, the addition of the crumb rubber to the RAP had a positive effect. The actual test results showed a significant improvement in regards to G*/Sinδ, rutting factor, tested as the original asphalt cement binder and as tested as a RTFO material. In addition, the G*(Sinδ), fatigue factor, as tested on the PAV material exhibited a substantial improvement over the extracted 100 percent RAP material.

Table 6
Extracted RAP asphalt cement binder rest results

	Spec	Extracted 100% RAP	Extracted 100% RAP w/ CR
Test on Original Binder			
Dynamic Shear, G*/Sin(δ), (kPa)	1.00^{+} @ 70°C	32.23	13.82
Dynamic Shear, G*/Sin(δ), (kPa)	1.00^{+} @ 76°C	14.25	6.41
Dynamic Shear, G*/Sin(δ), (kPa)	1.00^{+} @ 82°C	6.41	3.08
Dynamic Shear, G*/Sin(δ), (kPa)	1.00^{+} @ 88°C	3.18	1.53
Rotational Viscosity @ 135°C (Pa·s)	3.0^{+}	3.9	3.1
Tests on RTFO			
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 70°C	24.94	14.40
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 76°C	8.53	7.03
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 82°C	4.07 pass	3.25 pass
Dynamic Shear, G*/Sin(δ), (kPa)	2.20^{+} @ 88°C	1.90	1.63
Tests on (RTFO+ PAV)			
Dynamic Shear, @ 25°C, G*Sin(δ), (kPa)	5000^{-}	8616	4149
Dynamic Shear, @ 28°C, G*Sin(δ), (kPa)	5000^{-}	6135	2748
Dynamic Shear, @ 31°C, G*Sin(δ), (kPa)	5000^{-}	4329	1899
Bending Beam Creep Stiffness @ -12°C, (MPa)	300^{-}	200	275
Bending Beam m-value@ -12°C	0.300^{+}	0.299	0.238
Bending Beam Creep Stiffness @ -18°C, (MPa)	300^{-}	397	423
Bending Beam m-value@ -18°C	0.300^{+}	0.236	0.191
Actual PG Grading		**PG 82-16**	**PG 82-16**

Figure 11 is a graphical illustration of the dynamic shear rutting factor results of the 100 percent RAP and 100 percent RAP with crumb rubber additives. It is shown that throughout the temperature ranges tested the 100 percent RAP and crumb rubbers were substantially improved over the 100 percent RAP only material. It is shown that both materials passed the required specification of 1.1 kPa at 88°C.

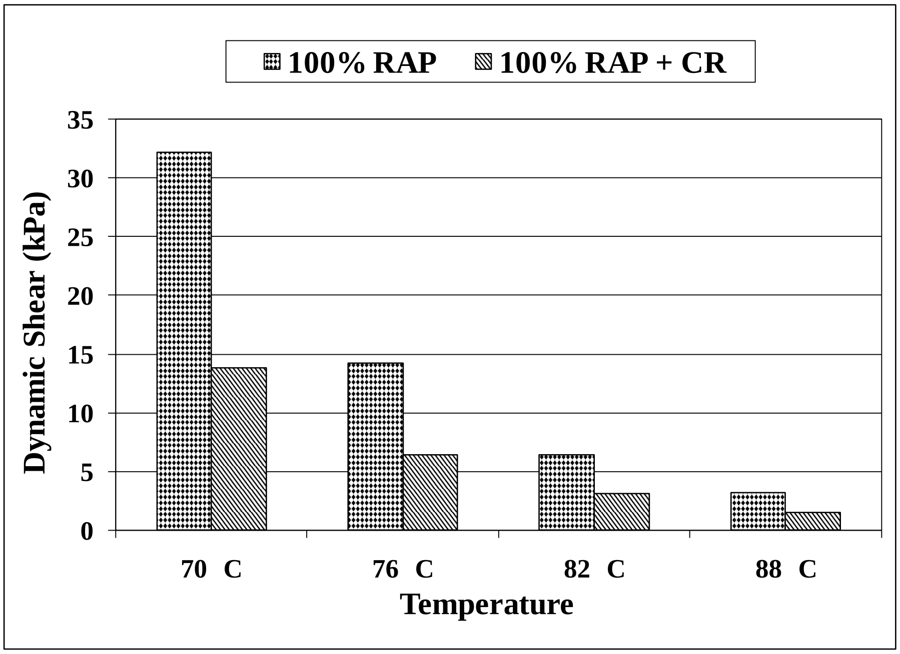

Figure 11
Dynamic Shear, G*/Sin(δ) (RAP binder tested as original)

Figure 12 illustrates the rutting factor, G*/Sinδ, dynamic shear test results on both extracted materials tested as an RTFO material. This figure also shows a benefit in the addition of crumb rubber additives as can be seen by the lower values for each test temperature tested. It is noted that these materials passed the specification requirement of 2.2 kPa at 82°C yet failed this criteria at the 88°C test temperature. Therefore these materials grade out as a PG 82 material on the high temperature side of the performance graded binder specification.

Figure 13 presents the graphical representation of the fatigue factor, G*(Sinδ), dynamic shear test results for the 100 percent RAP and 100 percent RAP and crumb rubber additives tested as a PAV material. It is shown that there was an improvement in the binder characterization when the crumb rubber additives were blended with the 100 percent RAP as indicated by the decrease in actual test values. This improvement can be seen at all test temperatures conducted for fatigue factor determination. The specification criterion for this material is a maximum value of 5000 kPa tested at 25°C. In Table 6, it is indicated that the 100 percent RAP and crumb rubber additives passed this criteria at the required specification test temperature of 25°C and that the 100 percent RAP binder had a failing test value of 8616 kPa at this temperature. It is shown that the 100 percent RAP binder attained a passing test value of 4329 kPa at the test temperature of 31°C; whereas, the 100 percent RAP and crumb rubber additive binder decreased to a test value of 1899 kPa.

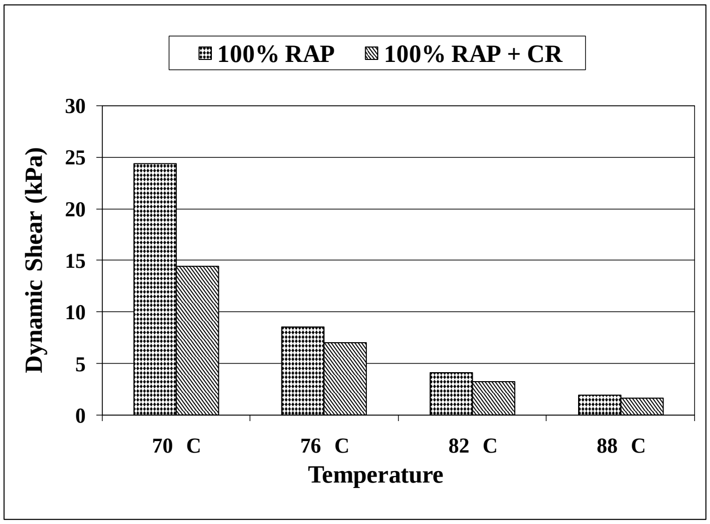

Figure 12
Dynamic Shear, G*/Sin(δ) (RAP binder tested as RTFO)

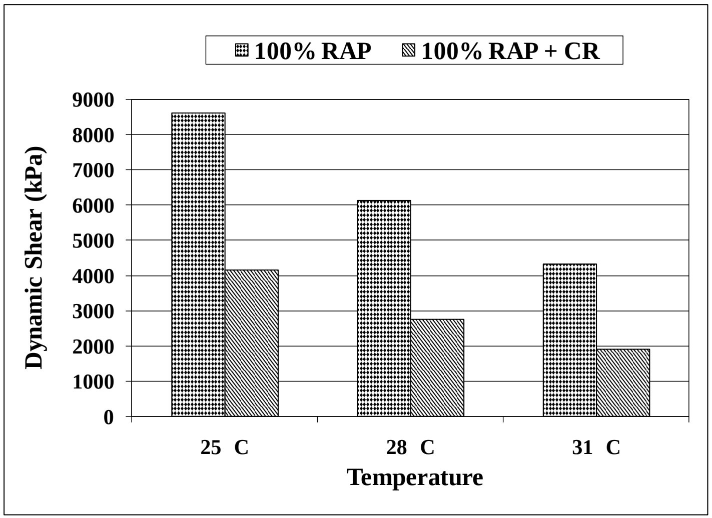

Figure 13
Dynamic Shear, G*Sin(δ) (RAP binder tested as PAV)

Figure 14 shows the rotational viscosity test results for both extracted RAP binders. It is indicated that both materials failed specification criteria of 3.0 Pa·s at the test temperature of 135°C. However the addition of the CR clearly illustrates a reduction in viscosity as indicated.

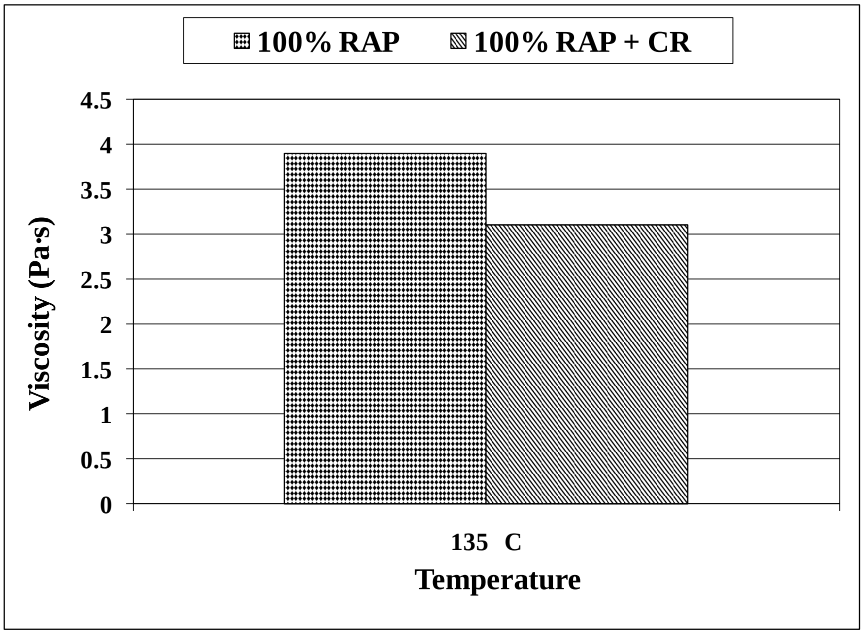

Figure 14
RAP binder rotational viscosity

HMA Mixture Characterization Test Results

Several laboratory tests were conducted and evaluated to measure the performance characteristics of the HMA mixtures considered in this study. The pavement performance characteristics were analyzed for the HMA mixtures' durability as measured by the modified Lottman test. The HMA mixtures' performance in terms of resistance to fatigue cracking was evaluated from results obtained from the SCB, DCSE, and dynamic modulus [i.e., fatigue factor, E*(Sinδ)] tests. Furthermore, dynamic modulus (i.e., rutting factor, E*/Sinδ) and flow number were used to determine the mixtures resistance to permanent deformation. In addition, a simulative type test was performed, LWT. Triplicate samples were prepared and tested for each laboratory test. The detailed analysis for these test results is included in the following sections of this chapter.

Modified Lottman Test Results

The modified Lottman test evaluates the effect of saturation and accelerated water conditioning on compacted HMA samples utilizing freeze-thaw cycles. This test quantifies

HMA mixtures' sensitivity to moisture damage, which is necessary to assure durability and long lasting hot mix asphalt pavements. Moisture sensitivity is measured by the percentage of retained tensile strength ratio of the conditioned samples compared to the control samples. The conditioned samples are samples that have been subjected to the required freeze/thaw cycle. Louisiana requires that the retained tensile strength be equal or greater than 80 percent to be considered as a passing result. Table 7 presents the measured modified Lottman test results and Figure 15 is the graphical presentation of the test results as shown in Table 7 for the five mixtures evaluated in this study. It is noted that no liquid anti-strips that facilitate adhesion of the asphalt cement binder to the aggregates were used in this study. In doing so, the test results specifically indicate the asphalt cement binders effect on adhesion to the aggregate by the measure of the percent retained tensile strength ratio. As expected the 100% RAP mixture failed the modified Lottman test. In addition, HMA mixtures 76CO and 76RAP15, which contain SBS modified asphalt cement binder (PG 76-22M), had passing results. It is shown in Table 7 that the HMA mixture 76RAP15 had the highest percent tensile strength ratio followed by the 76CO mixture. In addition, the HMA mixture 64RAP40 that contains an unmodified AC (PG 64-22), 40 percent RAP, and CR additives passed the modified Lottman test. However the mixture 76CRM failed this test. The AC used in the 76CRM HMA mixture is unmodified asphalt cement (PG 64-22) that has been wet blended with CR to yield PG 76-22 asphalt cement. The CR modified asphalt had a total of 9 percent crumb rubber and additive (8 percent 30 mesh crumb rubber, and 1 percent Gilsonite). It is suspected that the percentage of Gilsonite, which is used to increase resistance to water susceptibility (stripping), was insufficient to increase the retained tensile strength to passing level at the percentage incorporated into the total blend of 9% utilized to make the PG 76-22 CR modified asphalt cement binder.

Table 7
Modified Lottman test results

Mix Type		Tensile Strength (PSI)		Mix Type		Tensile Strength (PSI)	
		Control	Conditioned			Control	Conditioned
76CO	Average	188.44	160.83	76CRM	Average	155.99	107.37
	Stdev	9.27	28.11		Stdev	6.82	7.48
	CV	4.92	17.48		CV	4.37	6.97
	%TSR	85.3			%TSR	68.8	
76RAP15	Average	160.64	140.22	64RAP40	Average	185.91	150.34
	Stdev	4.01	8.35		Stdev	17.57	9.04
	CV	2.49	5.95		CV	9.45	6.01
	%TSR	87.3			%TSR	80.9	
100%RAP	Average	138.47	70.66				
	Stdev	23.15	32.78				
	CV	16.72	46.39				
	%TSR	51.0					

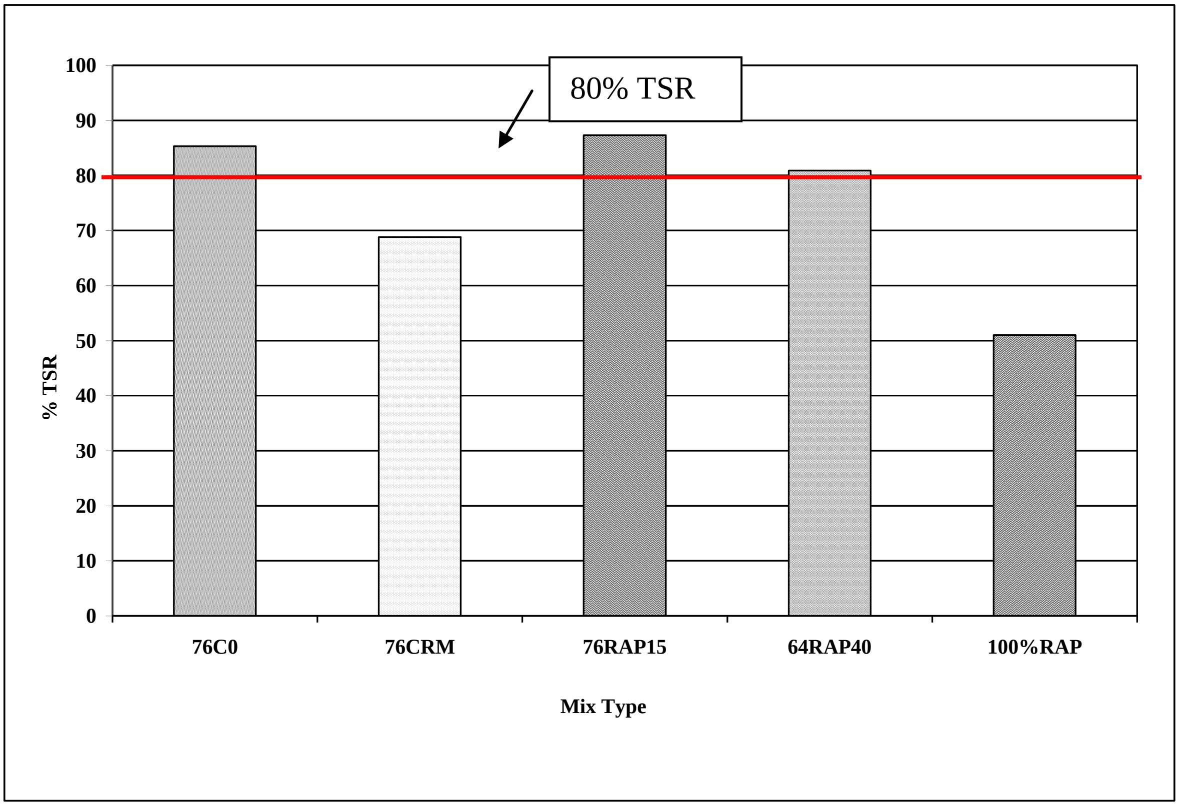

Figure 15
Modified Lottman retained tensile strength

DCSE Test Results

The calculated DCSE threshold values represent the energy that the mixture can tolerate before it fractures. Roque et al. reported that a DCSE minimum value of 0.75 Kj/m^3 as the limiting criterion *[30]*. HMA mixtures having a DCSE value greater than 0.75 Kj/m^3 are not as susceptible to cracking. Figure 16 represents the calculated DCSE mean values for the HMA mixtures analyzed in this study. The coefficient of variation (CV) of the samples tested ranged from 6 to 18 percent. It is shown that the 76CO mixture has the highest DCSE values of all mixtures tested and therefore is less prone to crack. In addition, three out of the five mixtures meet the 0.75 KJ/m3 criteria for resistance to cracking. The 64RAP40 and the 100%RAP mixtures had less than the limiting criterion necessary for fracture resistance.

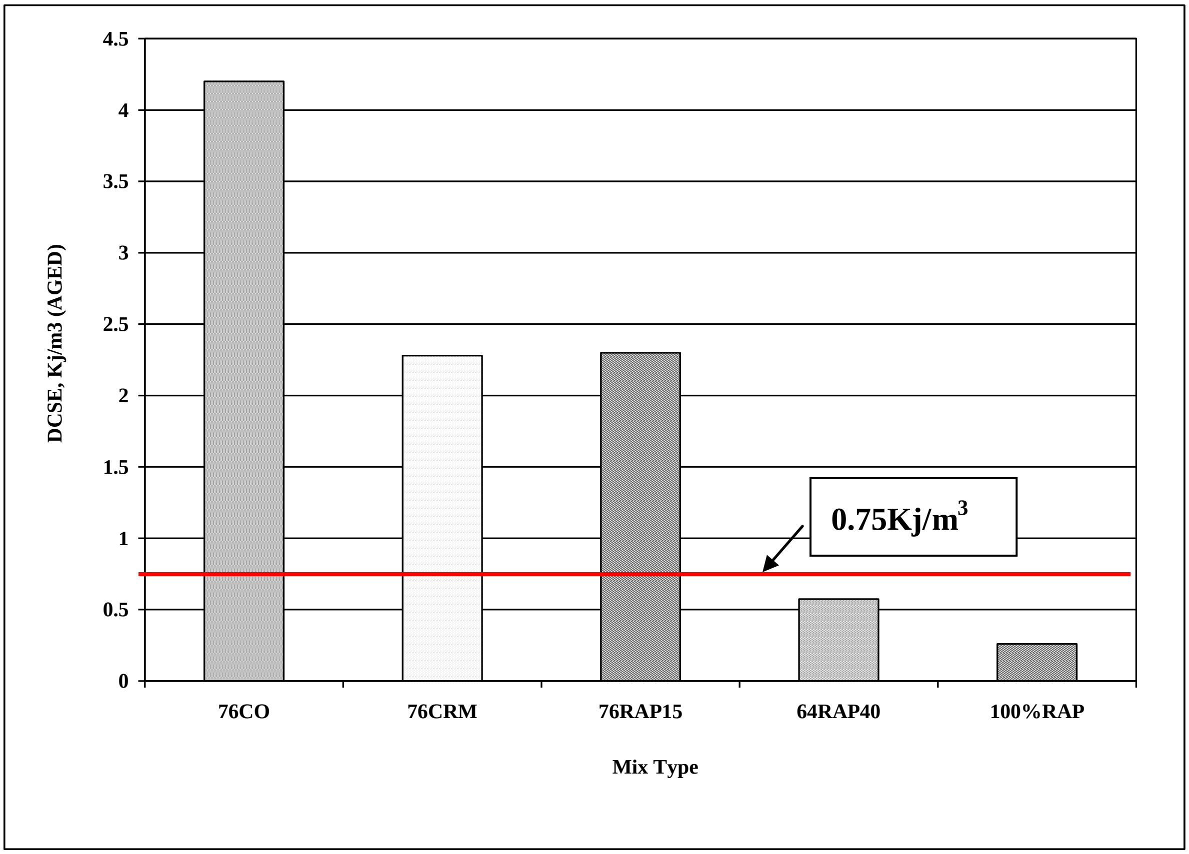

Figure 16

Dissipated Creep Strain Energy test results

Semi-Circular Bend (SCB) Test Results

Table 8 indicates the average peak load during testing that was required to cause cracking to begin at the tip of the sample notches, which were previously cut as part of the sample preparation. It is shown in this table that there is a decrease in peak load as the notch depths are increased for all mix types. This is consistent since it would take lower peak loads to propagate cracking as the effective depth of the sample above the notch decreases due to the increased sample notch depth. In addition, Table 8 indicates that in general for the mixtures studied, the mixtures containing RAP had the highest SCB peak loads. It is noted that the 76RAP15 followed by the 100% RAP mixture had the highest peak loads necessary to propagate cracking as shown in Table 8. It is noted that the 76RAP15 has the highest peak load followed by the 100%RAP and 64RAP40 HMA mixtures, respectively.

Figure 17 presents the calculated critical fracture resistance (J_c) values for the six HMA mixture types evaluated. In terms of fracture resistance, the higher the J_c value the greater the fracture resistance the HMA mixtures possess. It is shown that the 76RAP15 HMA mixture had the highest J_c value and, therefore, has the greatest fracture resistance of all mixtures evaluated in this study. The 100%RAP mixture attained the lowest J_c and has the highest propensity for fatigue cracking.

Table 8
SCB peak load test results

Mix Type	Peak Load (KN)		
	Aged		
	Notch Depths (mm)		
	25.4	31.8	38.0
64CO	0.75	0.62	0.37
76CO	1.11	0.77	0.45
76CRM	1.18	0.92	0.64
76RAP15	1.77	1.03	0.85
64RAP40	1.17	1.11	0.65
100%RAP	1.28	0.97	0.78

In a previous study, Mohammad et al. indicates that any mixture achieving a J_c value greater than 0.65 Kj/m^2 is expected to exhibit good fracture resistance *[33]*. Figure 17 indicates that with the exception of the 100%RAP and 64RAP40 mixtures all other mixtures passed this criterion.

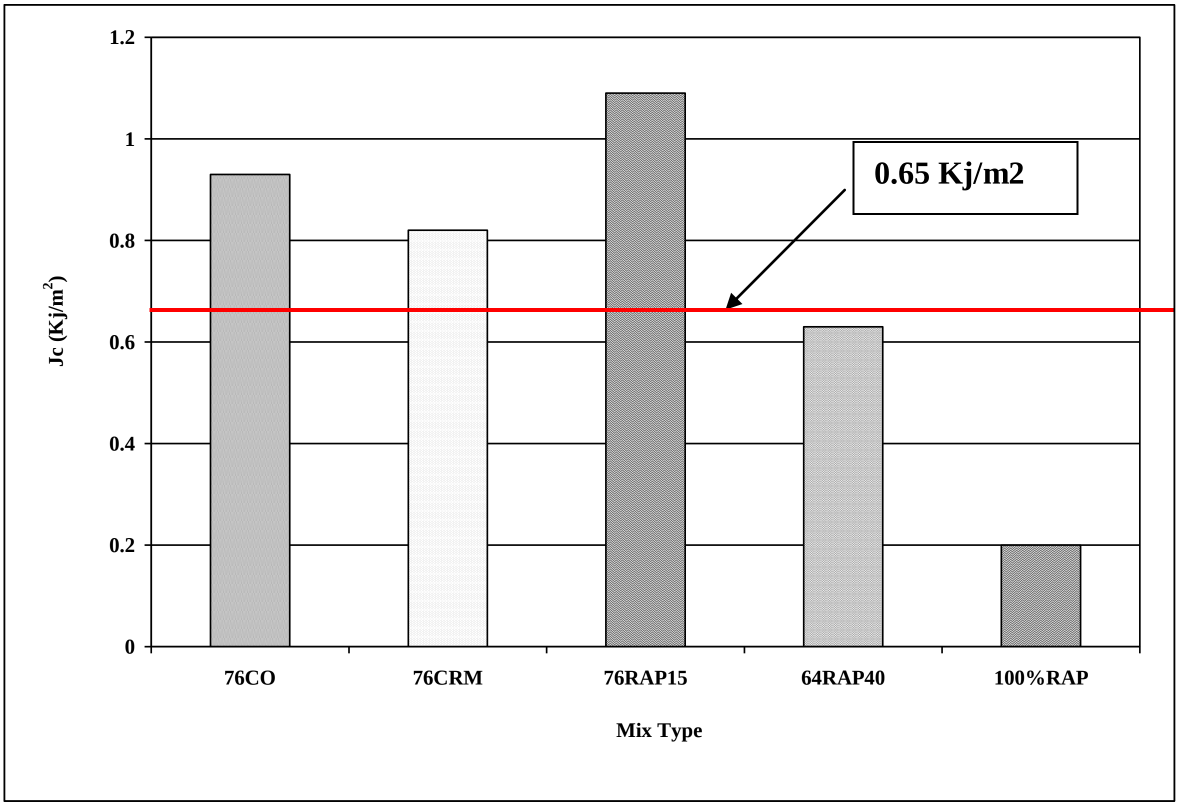

Figure 17
Semi-circular bend test results

Dynamic Modulus (E*) Test Results

The purpose of the dynamic modulus test is to evaluate the visco-elastic response characteristics of HMA mixtures over a given range of temperatures and frequencies. Figure 18 and 19 present the dynamic modulus isotherms at various temperatures and frequencies for all mixtures considered in this study. The values indicated are the average E* results for three laboratory specimens evaluated per HMA mixture type. The CV of the samples tested ranged from 1 to 18 percent. As shown in Figure 18 and Figure 19, the E* values increase as the frequency increases. Furthermore the E* values decrease with increased temperatures. Figure 19 indicates that, at low temperatures (4.4°C), the isotherms are inclined in a straight line direction. This indicates that the HMA mixture behavior is in the visco-elastic region and is predominately affected by the asphalt cement binders. The E* isotherms became concave at the intermediate and high temperature levels, 25°C, 37.8°C, and 54°C, respectively. This change in the isotherm shape represents the non-linear behavior in HMA mixtures during compression. This non-linear behavior reveals the mechanical response that is caused by the aggregate skeleton of the HMA mixture overwhelming the viscous influence of the asphalt cement binder materials within the HMA materials at these high temperatures. In Figure 18, it is shown that at any given temperature for any given HMA mixture that the E* values decrease with decreased frequency.

Analysis of the phase angle results, which is determined from the dynamic modulus test, was performed to further confirm the findings as shown by the E* isotherms. These results are discussed further within this section.

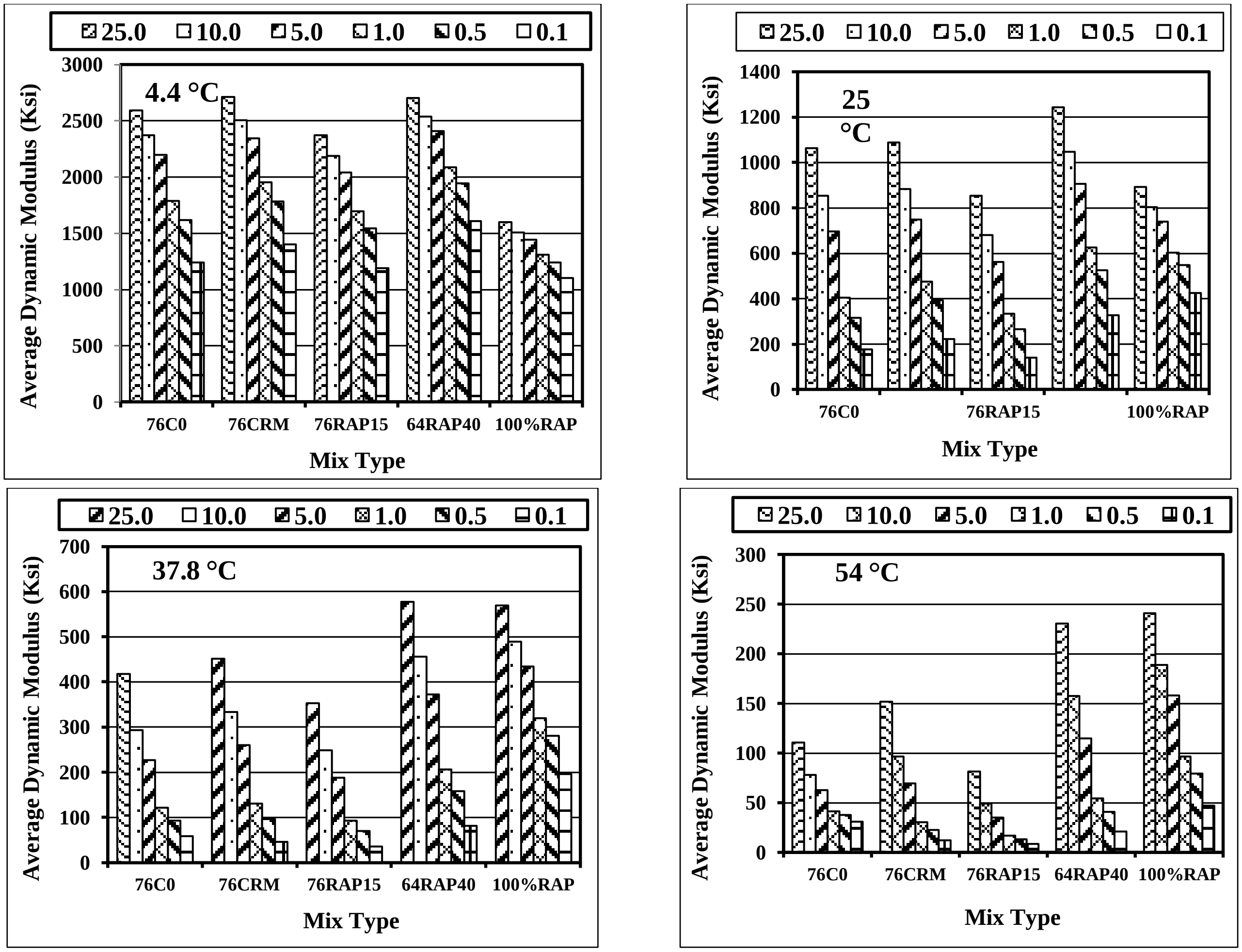

Figure 18
Dynamic modulus test results

Dynamic Modulus (E*) Ratio

Figure 20 indicates the comparison between all HMA mixtures evaluated in this study based on the dynamic modulus (E*) at the various test temperatures computed at 5 Hz. For the purpose of comparison, the E* values calculated at various test temperatures for the 76CO HMA mixture was considered as the unit value (i.e., E* = 1.0). To illustrate this concept, the E* values for the 64RAP40 and 76CO mixtures at 54.4°C and 5 Hz were 109.5 ksi and 62.4 ksi, respectively.

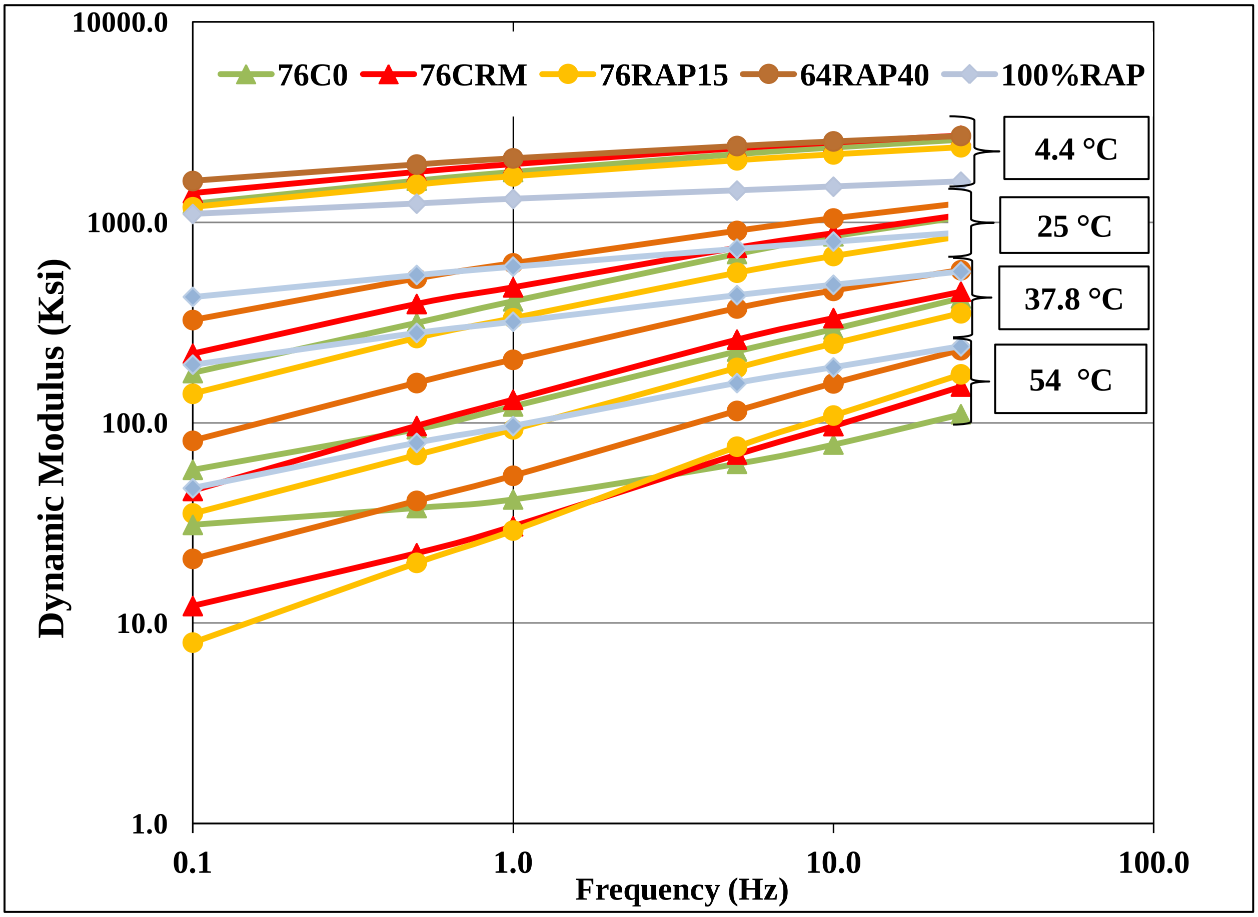

Figure 19

Dynamic modulus isotherms

The E* ratio is calculated as 109.5 ÷ 62.4 = 1.75 for the 64RAP40 HMA mixture. Any mixtures exhibiting an E* ratio greater than 1.0 has greater stiffness than the 76CO mixture. It is shown in Figure 20 that the E* ratio at the low and service temperature ranges (4.4°C and 25°C) the 76RAP15 has an E* value less than 1.0. This could be attributed to the PG76-22M binder utilized in this HMA mixture having a greater affect than the percentage of RAP incorporated in the blend. Also shown at the high and intermediate temperatures the 76RAP values are greater than the E* values for the 76CO mixture. This indicates that this mixture is more susceptible to permanent deformation than the 76CO HMA mixture at these temperatures tested. The 100%RAP mixture at the low temperature (4.4°C) is more susceptible to rutting (i.e., permanent deformation) than the 76CO mixture as can be seen by the reported E* ratio. The 76CRM and 64RAP40 mixtures exhibit greater stiffness at all temperature ranges as compared to the 76CO HMA mixture. Figure 20 shows that at the intermediate and high temperature levels that the final ranking of the mixtures is as one would expect for the asphalt cement binders used in this study. At these higher temperatures, the asphalt cement binders are leaving the visco-elastic range of their respective material and are becoming more viscous. At these high temperatures, the final outcome is predominantly based on the stiffness of the asphalt binders at these temperatures as shown by the E* values.

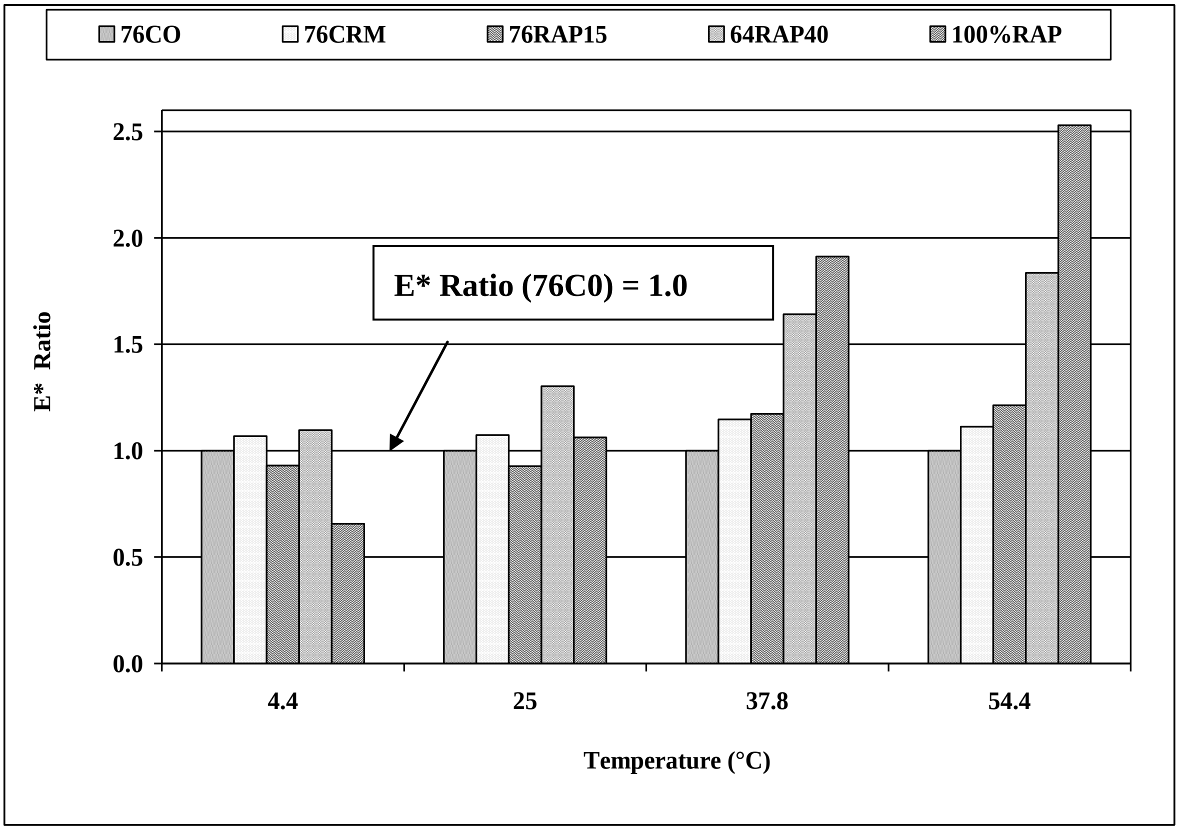

Figure 20
Dynamic modulus ratio comparison (E* ratio)

Phase Angle Test Results

Figure 21 indicates the graphical representation of the phase angle mean results with respect to the dynamic modulus values for all six HMA mixtures considered in this study. The CV of the samples tested ranged from 1 to 14 percent. As shown in this figure, the phase angle for the various materials tested are plotted in the arithmetic scales, while the E* values are plotted in the logarithmic scale. This figure shows the phase angle for all HMA materials (76CO, 76CRM, 76RAP15, and 64RAP40) evaluated in this study increases with an increase in temperature and a decrease in frequency. Then at some point the phase angle peaks and then declines as the temperature increases further and the frequency continually decreases. It can be noticed from Figure 21 that the phase angle values for the HMA mixtures initially increased with an increase in the temperature, reached a peak, and afterwards started to decrease as the temperature further increased. However Figure 21 shows that as the temperature and frequency decreases, so does the phase angle for the 100%RAP mixture.

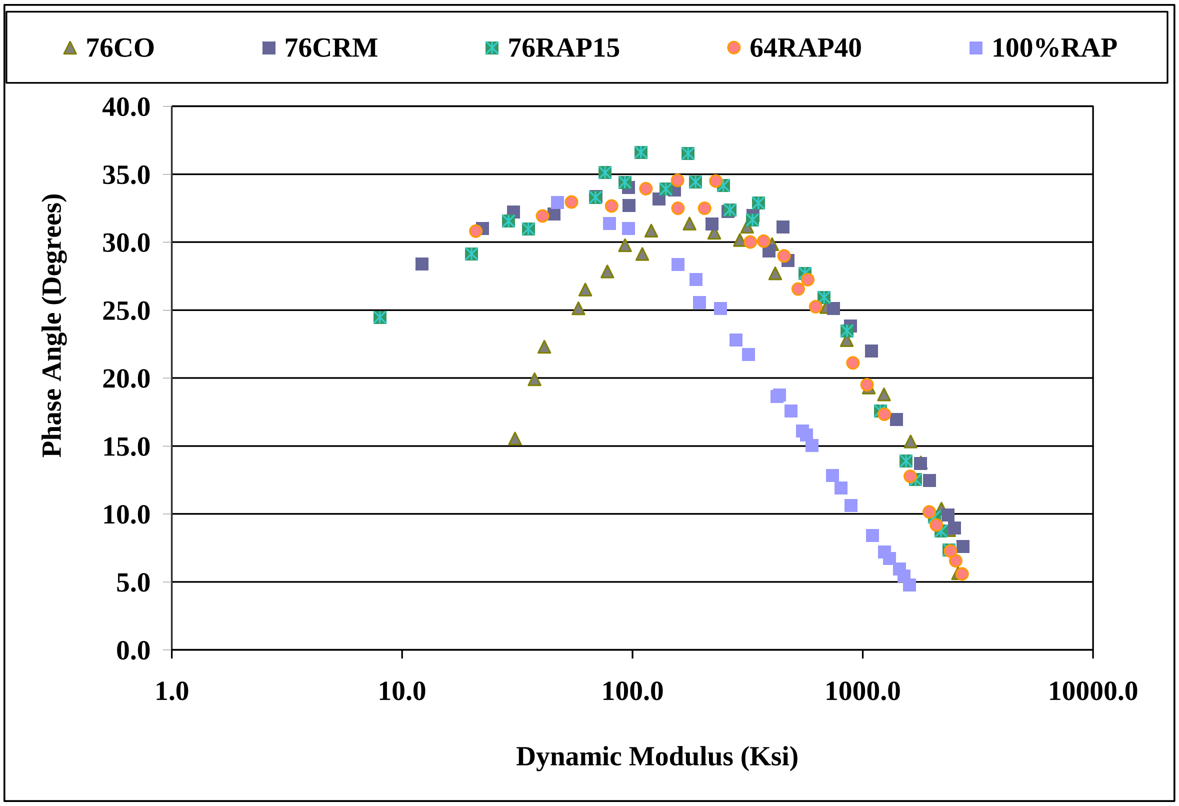

Figure 21
Dynamic modulus and phase angle relationships

Figure 22 presents the phase angle test results at the various temperatures and frequencies for all HMA mixtures considered in this study. This figure indicates that at low temperatures (4.4°C) the phase angle increases as the frequency decreases. In addition, as the temperature increases so does the measured phase angle. At 4.4°C, the phase angles are inclined, which indicate that the asphalt cement binder is predominately affecting the characteristics of the HMA mixtures. As can be seen for the test temperature 37.8°C, the 76CO, 76CRM, and

76RAP15 HMA mixtures start to increase and reach a peak but then decrease as the frequency continues to decrease. It is noted that the phase angle for the other HMA mixture type (64RAP40) and the 100%RAP mixture at this temperature is still predominately being affected by the asphalt cement binders used. At the test temperature 37.8 °C, Figure 22 shows that all HMA mixtures with the exception of the 64RAP40 and the 100%RAP mixtures has reached a peak phase angle at 5 Hz before making the downward trend. The 64RAP40 HMA mixture and the 100%RAP mixture phase angle is still being affected by the asphalt cement binder. With the exception of the 100%RAP mixture at 54°C, the phase angle for all mixtures decreases with a decrease in frequency. This trend is opposite of the behavior noted at the low temperature of 4.4°C. This behavior characteristic indicates that the phase angle is predominately affected by the aggregate structure. It is noted that the shift in this behavior was observed at 37.8°C.

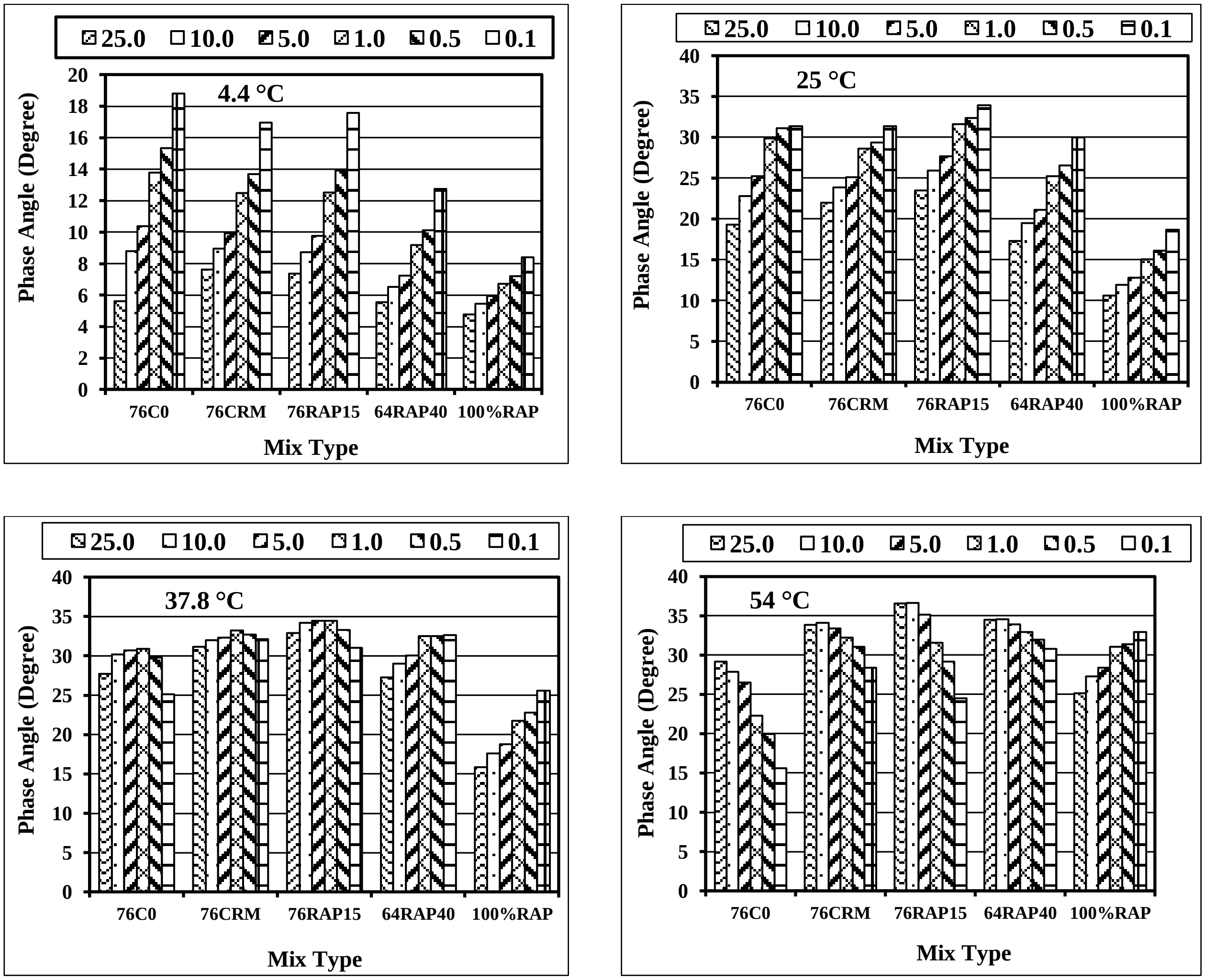

Figure 22
Phase angle vs. mix type relationship

Flow Number Test (Repeated Load Permanent Deformation Test) Results

The flow number test is used to determine the permanent deformation characteristic of hot mix asphalt mixtures. The flow number is defined as the number of repetitions corresponding to the minimum rate of change in permanent strain under repeated loading conditions. It is the starting point, or cycle number, at which tertiary flow occurs on a cumulative permanent strain curve generated during the test. Therefore, the higher the flow number value, the better the mixture resists permanent deformation.

Figure 23 presents the flow number test results for the five mixtures considered in this study. It is shown that the 100%RAP mixture had the highest flow number values and, therefore, was the most rut resistant for the mix types evaluated by this test. The second grouping was the 76CO and the 76RAP15 HMA mixtures, which contain a SBS modified asphalt cement binder. The last grouping as shown in Figure 23 is the 64RAP40 and 76CRM HMA mixtures, which utilized PG64-22 base asphalt cement binder. The 64RAP40 and 76 CRM was the least resistant to permanent deformation for the mixtures evaluated.

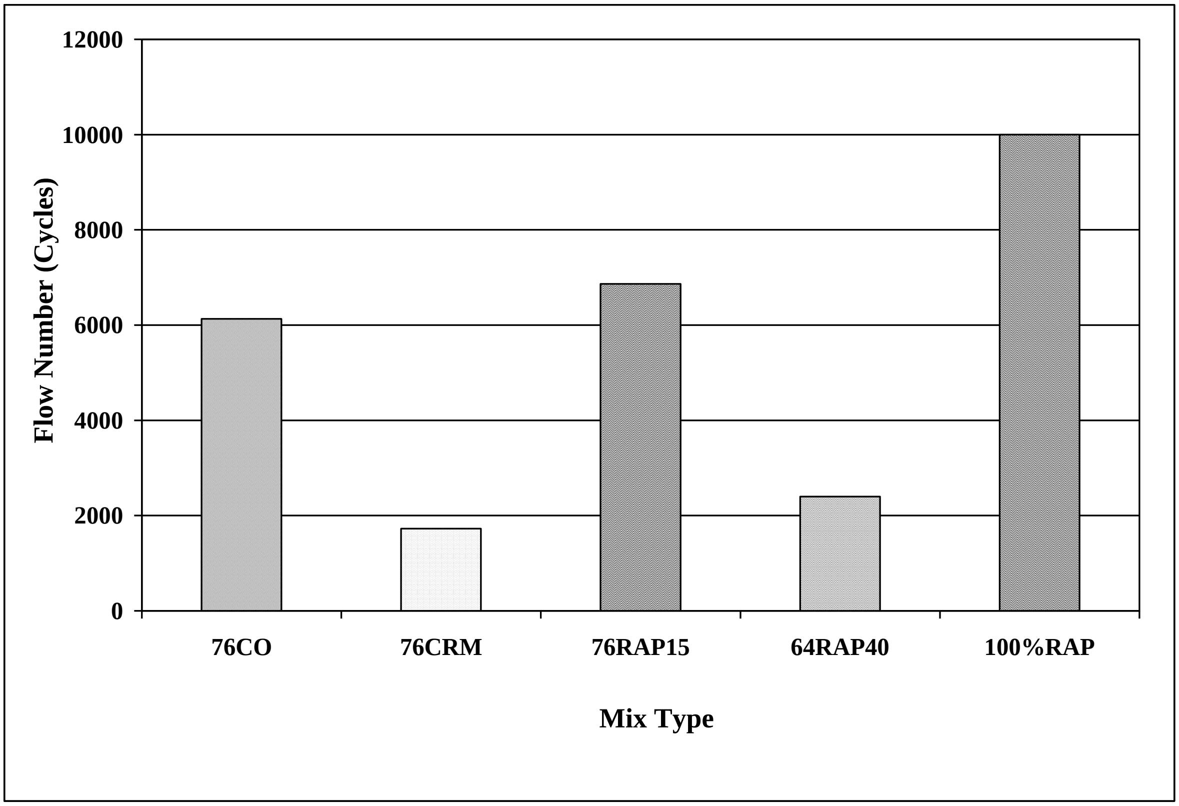

Figure 23
Flow number vs. mix type

Evaluation of Rutting and Fatigue Factors from E* Tests

An HMA mixture propensity to resist permanent deformation (rutting) and fatigue cracking can be characterized by using the dynamic modulus test results from various temperatures and frequency. The rutting factor is defined as E*/Sinδ, where δ is the phase angle at a particular temperature and frequency. A loading frequency of 5Hz and test temperature of 54.4ºC was used for computation of the rutting factor, E*/Sinδ in this study *[37]*. For mixtures to be rut resistant and exhibit higher stiffness, a higher E* value and a lower phase angle is necessary. The higher the rutting factor value indicates a mixture greater resistance to permanent deformation.

Figure 24 shows the rutting factor values for all mix types evaluated in this study. It clearly indicates that the 100%RAP mixture followed by the 64RAP40 HMA mixture has the greatest resistance to rutting. This can be contributed to the high RAP content used in these mixture types. It is noted that there is a grouping of similar results for the 76CO, 76CRM, and 76RAP15 HMA mixture types.

To determine a mixture's resistance to fatigue cracking, a parameter termed fatigue factor is calculated from dynamic modulus test results at a given frequency and test temperature. The test temperature of 25ºC and a loading frequency of 5 Hz were selected for this study *[37]*. By definition the fatigue factor is calculated as E*(Sinδ), where δ is the phase angle at the selected temperature and frequency. For a mixture to resist fatigue cracking, its corresponding E* value should be lower as well as the phase angle at the in-service temperature of 25ºC. The lower the fatigue factor value indicates the mixture's performance against fatigue cracking.

Figure 25 indicates the fatigue factor values for all mix types evaluated in this study. There are two distinct groups as shown in Figure 25. The first grouping showing similar test results is the four HMA mixtures (76CO, 76CRM, 76RAP15, and 64RAP40) that indicate these mixtures as being the best in fatigue cracking resistance of the five mixtures evaluated in this study. The second group (100%RAP mixture) exhibited the highest fatigue factor value and, therefore, was the least resistant to fatigue cracking.

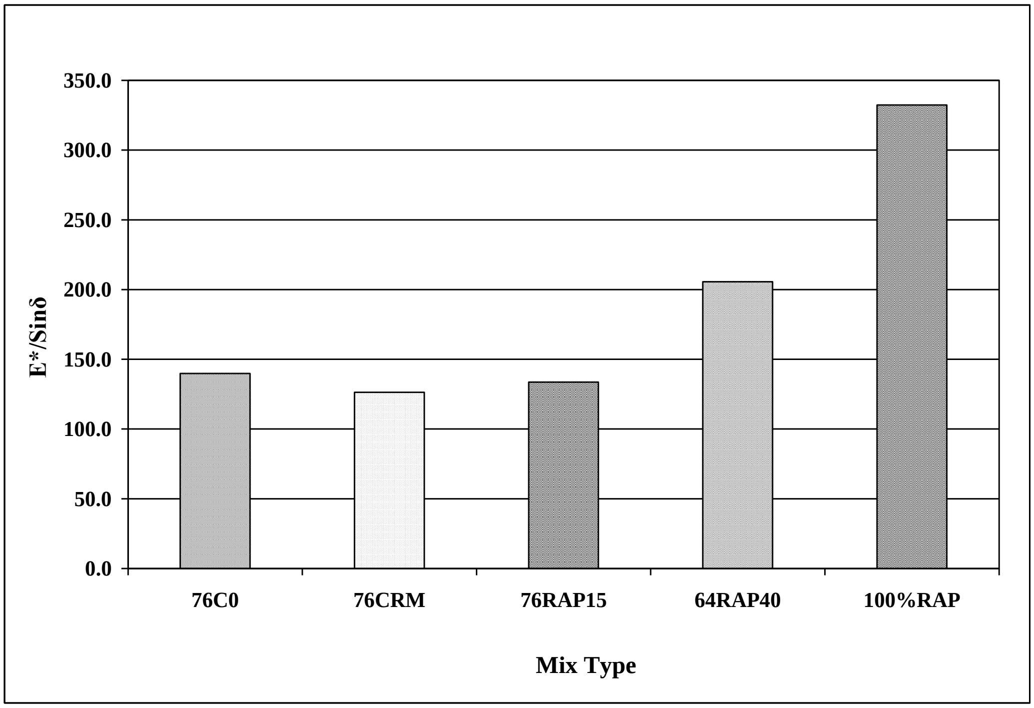

Figure 24
Rutting factor, E*/Sinδ @ 5Hz, 54.4°C

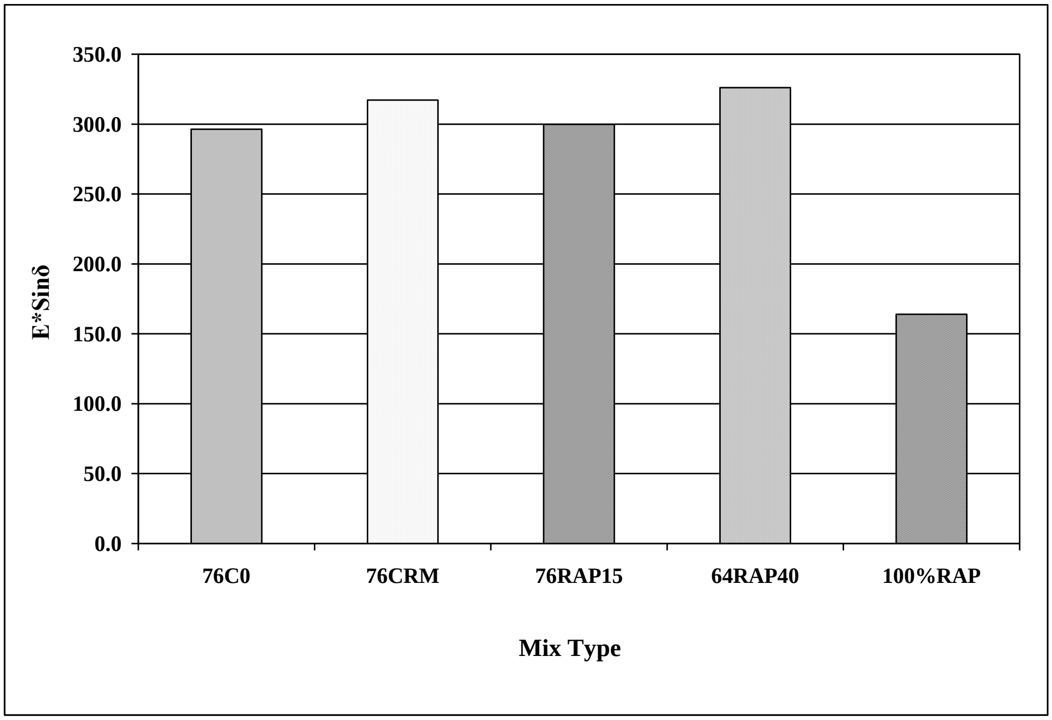

Figure 25
Fatigue factor, E*(Sinδ) @ 5Hz, 25.0°C

Loaded Wheel Tracking Test Results

Figure 26 indicates the average rut depth of the five mixtures evaluated in this study. The specimens rut depth is continuously measured and recorded for 20,000 passes unless the specimen attains more than 20.0 mm of rutting in which the testing is then terminated. The average rut depth reported in Figure 26 is the mean rut depth after 20,000 passes of the LWT. Mixtures with an average rut depth less than 6.0 mm after 20,000 passes are considered acceptable. As shown in Figure 26, the 64RAP40 HMA mixtures that utilize PG 64-22 asphalt cement failed the acceptable rutting criterion. However, it is noted that the 64RAP40 mixture was borderline failing with a measured rut depth of 6.1 mm. As expected, the 100%RAP mixture failed this test due to stripping, which confirms this mixtures propensity to moisture damage based on the modified Lottman test results as previously shown in Table 7 and Figure 15. All other mixtures tested passed the maximum rut depth requirement (6.0 mm).

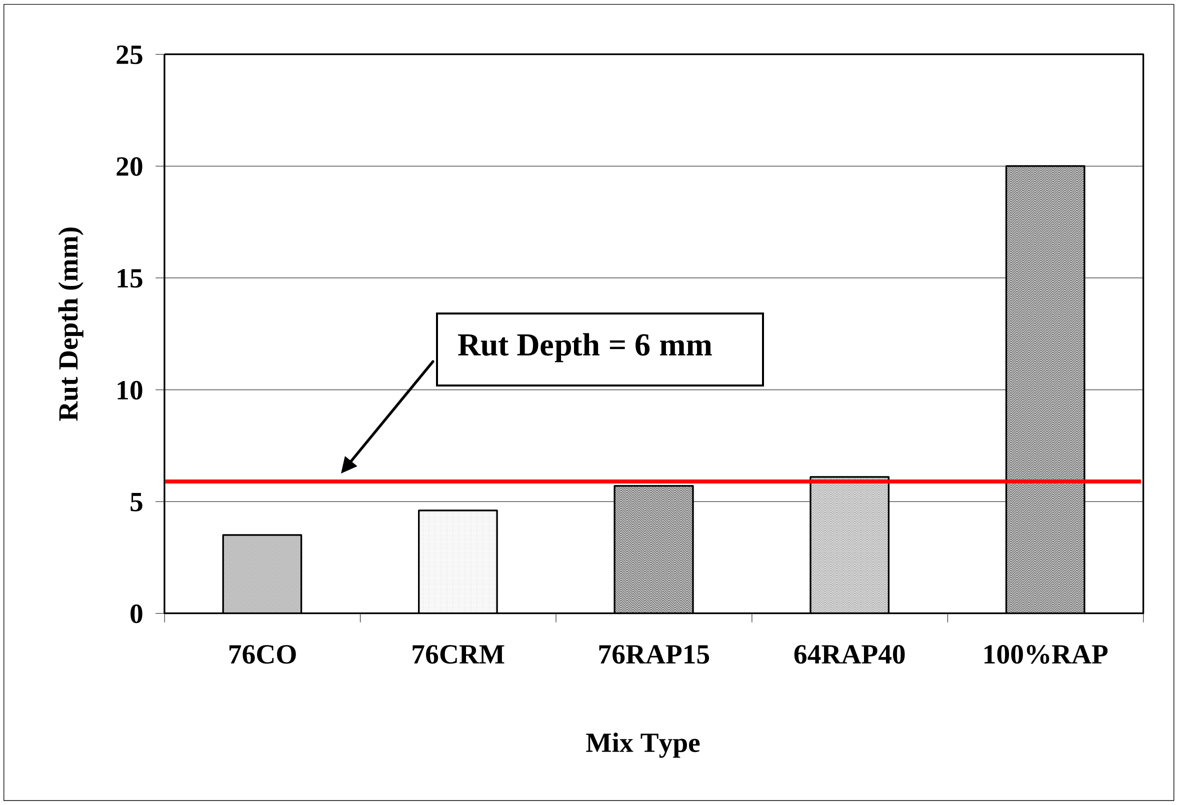

Figure 26
LWT rutting results

Correlation between Laboratory Test Results

This section presents the correlation of the HMA mixture test results from various laboratory tests evaluated in this study. In this section, 76CO, 76CRM, 76RAP15, and the 64RAP40 HMA mixtures are compared. The 100%RAP mixture is not included in the evaluation because it is not a true HMA mixture that is based on mix design principles and the inclusion of virgin aggregates and asphalt cement binder. A linear regression statistical analysis was applied to determine the level of relationships between laboratory test parameters. In addition, the coefficient of determination, R^2, was computed to measure the goodness of fit.

Correlation between J_c and DCSE Test Results

Figure 27 indicates the correlation between the semi-circular bend test and the dissipated creep strain energy test results. As expected, there is a fair correlation between the dissipated creep strain energy and semi-circular bend test parameters as noted by the coefficient of determination, R^2, value of 0.70. It is also shown in Figure 27 by the linear regression line that as the DCSE values increase, the J_C values also increase.

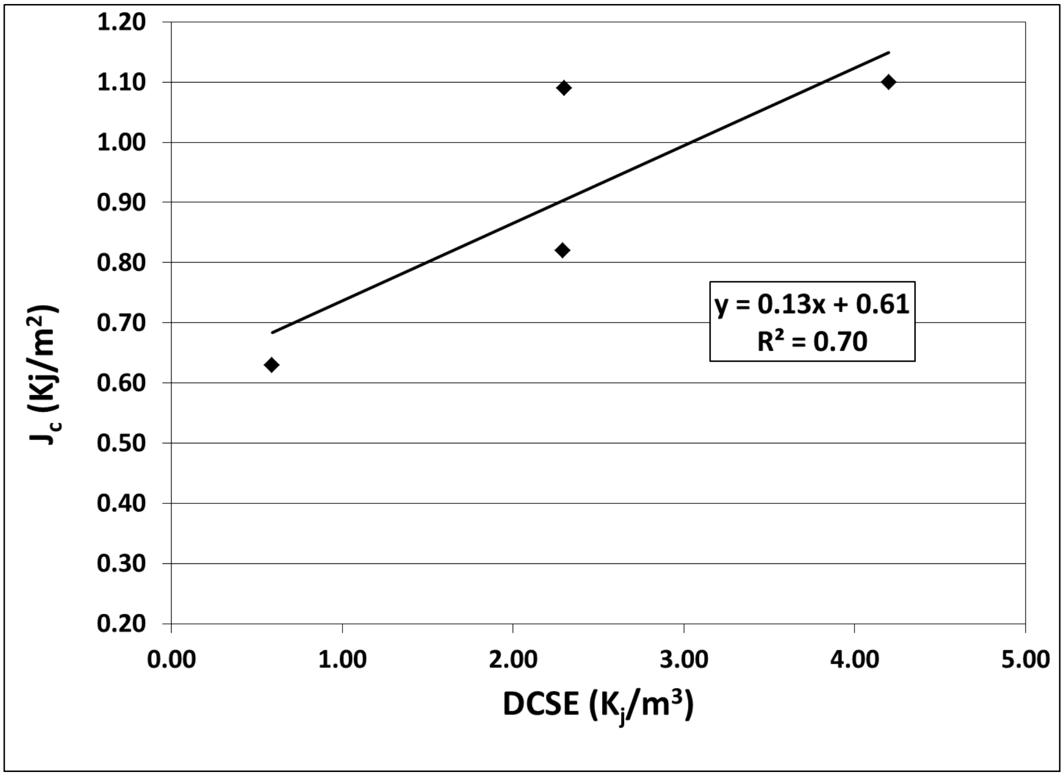

Figure 27

Correlations between J_c and DCSE test parameters

Correlation between Modified Lottman and Semi-Circular Bend Test Results

Figure 28 illustrates the correlations between the modified Lottman test and the semi-circular bend test as measured by %TSR and J_c, respectively. As shown in Figure 28, there appears that there was not a fair correlation as indicated by the R^2 value between the modified Lottman test results as measured by %TSR and the semi-circular bend test, J_C results. It is indicated that as the %TSR increases, the J_C values also increase. This would appear to be logical since the Modified Lottman test is a measure of a mixture's susceptiblility to moisture damage that is highly dependent upon the HMA mixtures adhesion and cohesive properties, which is also the case of the semi-circular bend test.

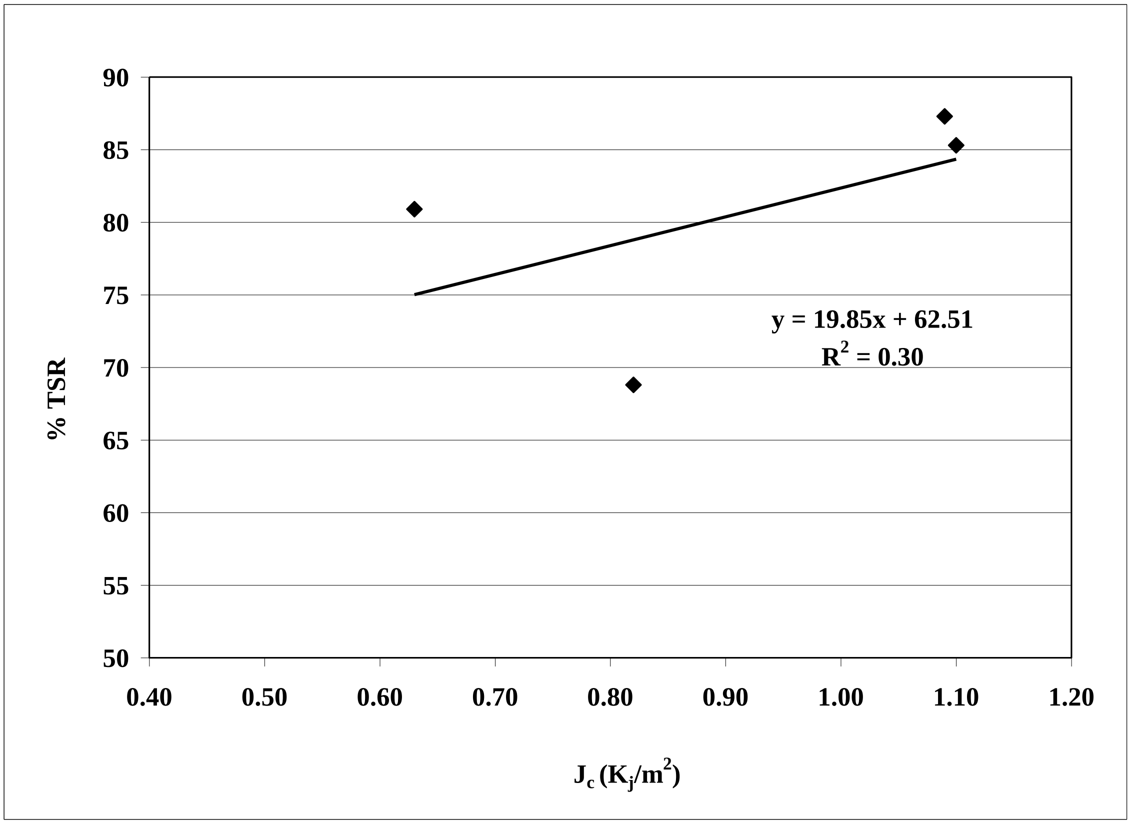

Figure 28

Correlations between %TSR and J_c test results

Correlation between Fatigue Factor and DCSE Test Results

Figure 29 shows the correlation between the fatigue factor and dissipated creep strain energy laboratory test results. This figure indicates that there was fair correlation between these performance characteristics for the mixtures evaluated in this study. However Figure 29 does show a trend in these properties. It is illustrated that as the DCSE increases the fatigue factor decreases. This is logical since higher DCSE values are desirable for crack resistance; whereas, lower fatigue factor values are desirable.

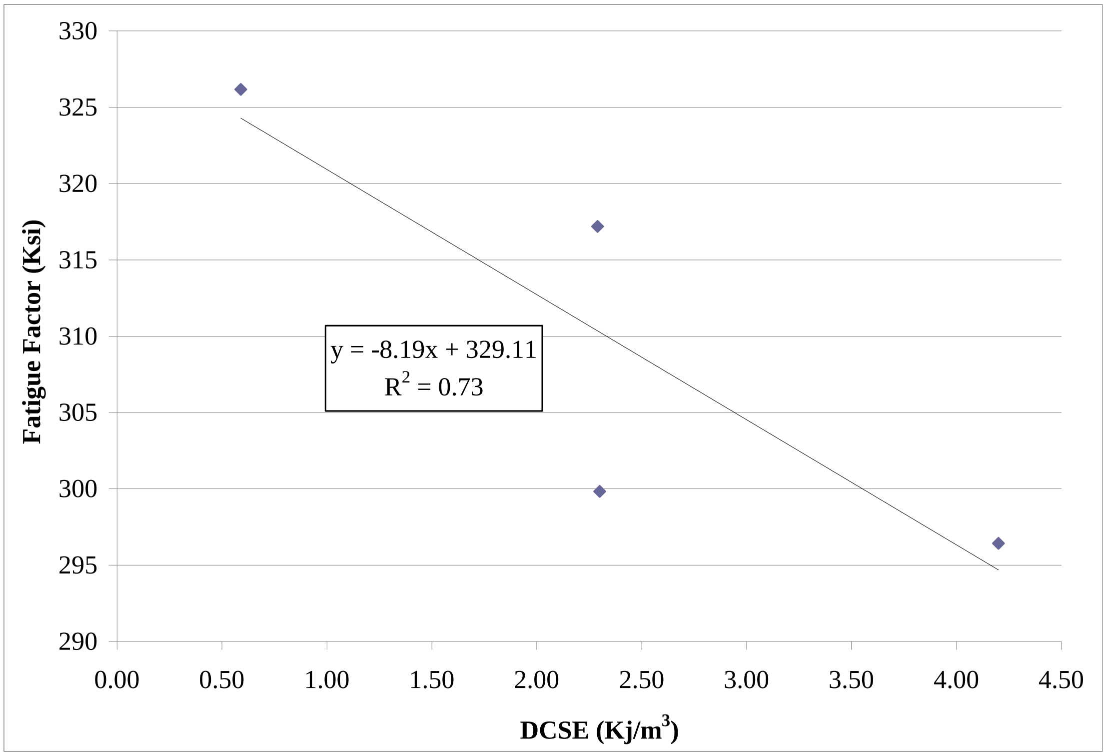

Figure 29

Correlations between fatigue factor and DCSE test results

Correlation between Fatigue Factor and Semi-Circular Bend Test Results

Figure 30 indicates the correlation between the fatigue factor and the semi-circular bend test performance characterization laboratory test results for the HMA mixtures evaluated in this study. This figure shows that there is a strong correlation between the fatigue factor and SCB test results. It is noted that Figure 30 does indicate a trend in these parameters. It is illustrated in Figure 30 that as the J_c increases the fatigue factor decreases. This is desirable trend since higher J_c values indicate an HMA mixture's stronger propensity for crack resistance; whereas, lower fatigue factor values are desirable for resistance to cracking.

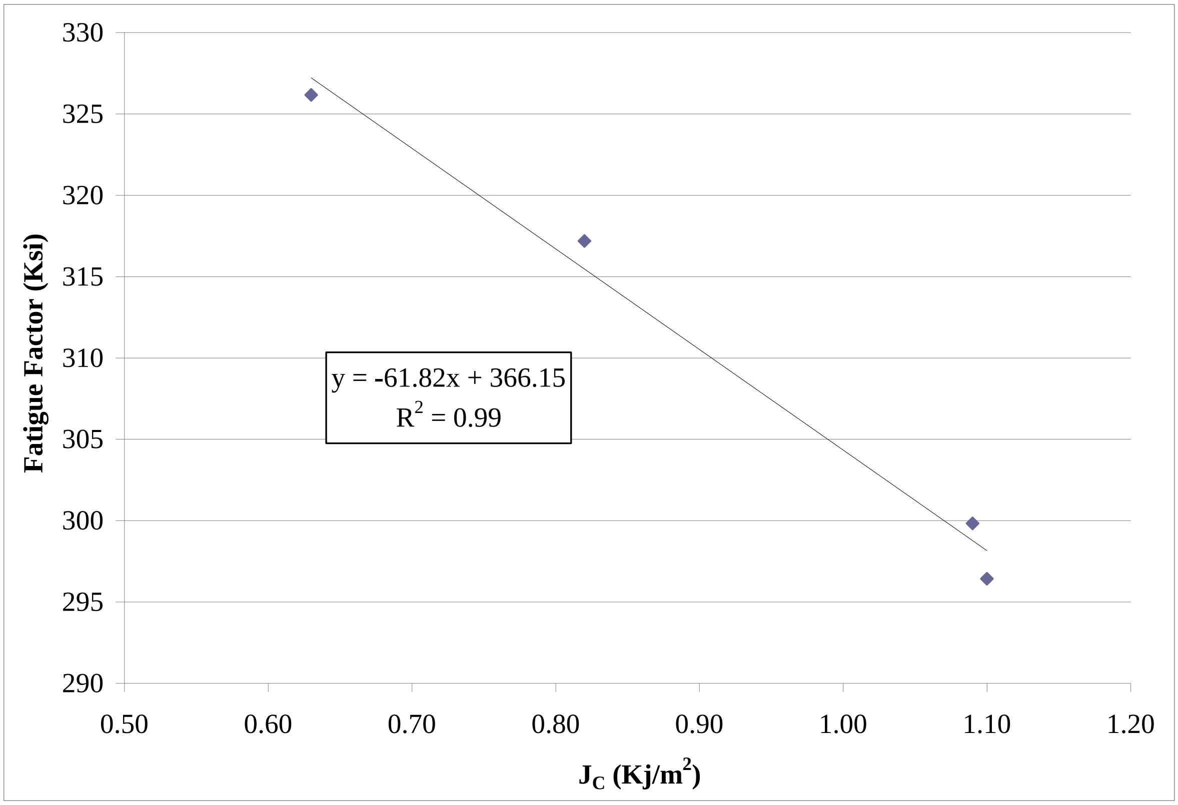

Figure 30
Correlations between fatigue factor and J_c test results

Comparison of Statistical Ranking of HMA Mixtures

Tables 9 summarizes the statistical ranking of several of the laboratory performance test results for the HMA mixture types considered in this study. In this section, 76CO, 76CRM, 76RAP15, and the 64RAP40 HMA mixtures are statistically analyzed to determine any statistical difference between mixture types. The evaluation of the HMA mixtures' laboratory performance in this study included durability, permanent deformation, and fatigue resistance. The durability performance characteristic was measured by the modified Lottman test. The mixture's ability to resist deformation was characterized by the flow number and dynamic modulus test as measured by the rutting factor. The mixtures fatigue resistance was measured through the DCSE, SCB, and dynamic modulus test as reported by the fatigue factor calculation. However, statistical analysis was based only on two mixture performance criteria namely: (1) fatigue resistance and (2) permanent deformation. In addition the results reported in this analysis are the DCSE, fatigue factor, rutting factor, and flow number tests because the SCB and modified Lottman tests numbers were limited and did not lend themselves to statistical analysis for this study.

The laboratory performance data were statistically analyzed using the analysis of variance (ANOVA) procedure.   More specifically a multiple comparison procedure with a risk level of 5 percent was performed on the laboratory test results. The statistical results of each grouping is reported with the letters A, B, C, D, and so forth. The letter A is assigned to the HMA mixtures performance having the highest mean followed by the other letters in appropriate order. A double (or more) letter designation, such as A/B (or A/B/C), indicates that in the analysis the difference in the mixture performance is not clear-cut, and the mixture performance is close to either group.

It is indicated in Table 9 that all HMA ranked similar in fatigue resistance as measured by the fatigue factor. In addition, the DCSE analysis shows three distinct groupings. The first group is the 76CO mixture. The second group is the 76CRM and 76RAP15 HMA mixtures followed by the 64RAP40 mixture group.

Table 9 indicates that there was not an agreement on permanent deformation. It is shown that for the rutting factor there were two groupings. The 64RAP40 mixture had the highest resistance to rutting followed by the 76CO, 76CRM, and 76RAP15 HMA mixture grouping. In regards to permanent deformation as measured by flow number, the 76CO and 76RAP HMA mixtures, which had similar rankings, had the highest propensity to resist rutting followed by the grouping of the 76CRM and 64RAP40 HMA mixtures.

The tests evaluated and presented were selected to capture the laboratory performance of the HMA mixtures studied. However the test results were not consistent and did not clearly rank the mixtures. The LWT and FN tests, which are used for checking a mixtures resistance for permanent deformation, were not clear cut. This may be due to the fact that the LWT samples are tested in confinement; whereas, the FN test is tested in an unconfined mode. In addition the modified Lottman and J_C tests were inconsistent. A mixture’s adhesion and cohesive behavior is important in both of these tests. In one test, modified Lottman, the 64RAP40 shows good properties. However in the J_C test, the mean values are low for this mixture type. If the modified Lottman indicated good adhesive and cohesion properties, then the J_C values should have been higher than the reported value. It is noted that in general the 76CO HMA mixture ranked highest in all tests evaluated.

Table 9
Statistical ranking of mixtures fatigue and rutting characteristics

	Fatigue Performance Characteristic				Permanent Deformation Performance Characteristic			
Property	Fatigue Factor (E*Sinδ)		DCSE		Rutting Factor (E*/Sinδ)		Flow Number	
Aging Criterion	Un-aged		Aged		Un-aged		Un-aged	
Mixture Type	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
76CO	296.5	A	4.20	A	141.0	B	6132.0	A
76CRM	316.8	A	2.29	B	126.5	B	1325.3	B
76RAP15	300.4	A	2.30	B	133.7	B	6867.0	A
64RAP40	330.2	A	0.57	C	197.4	A	2397.0	B

CONCLUSIONS

This study characterized the laboratory performance of conventional HMA mixtures and mixtures containing high RAP content and waste tire crumb rubber/additives through their fundamental engineering properties. A comparative laboratory evaluation of six 19-mm NMAS Level 2 Superpave HMA mixtures meeting LADOTD specifications was considered in this study. Four HMA mixtures were evaluated as follows: The first mixture was a conventional HMA mix type, as a control mixture, that contained no RAP and no CR additives material type and an SB polymer modified asphalt cement meeting Louisiana specifications for PG 76-22M. The second mixture contained no RAP and 30 mesh CR and additives blended (wet process) with a PG 64-22 asphalt cement binder, which yielded a PG76-22. The third mixture contained 15 percent RAP with PG 76-22M asphalt cement and no CR and additives. The fourth mixture contained 40 percent RAP, 30 mesh CR and additives, and PG 64-22 asphalt cement. The CR and additives were introduced to the mixture at a rate of 10 percent by total weight of asphalt cement binder. In addition an asphalt treated base mixture containing 100% RAP, 30 mesh CR, and additives were selected for mixture characterization.

To evaluate performance, physical and rheological tests were evaluated on asphalt binders and HMA mixtures. A simulative permanent deformation test, LWT, was performed on mixtures evaluated in this study. The RTFO test, PAV test, RV test, DSR test, and BBR test were performed on the asphalt cement binders to characterize their physical and rheological properties. In addition to asphalt cement rheology characterization, HMA mixture performance and characterization tests namely, the SCB test, DCSE test, LWT test, simple performance tests (dynamic modulus, E*, flow number, F_N), and modified Lottman test were conducted to define permanent deformation (stability) and the fatigue life (durability) of HMA mixtures considered in this study. A statistical analysis was performed on the results of these tests to determine if there were any significant differences in the fundamental material characterization properties of the HMA mixtures considered in this study. Based on the results of this study, the following conclusions are drawn:

- The addition of the crumb rubber additives softened the blended AC for the 64RAP40 HMA mixture as determined by rheology testing of the asphalt cement extracted from the mixture. The blended AC for the 64RAP40 HMA mixture that contained PG 64-22, high RAP content (40 percent), and crumb rubber additives graded as a PG 70-28 asphalt cement.
- The addition of the crumb rubber additives with RAP had a positive influence in the asphalt cement binder rheology. This can be attributed to the use of the absorptive

properties of crumb rubber carrying rejuvenating products back into the HMA mixture allowing the RAP binders to be softened in lieu of the original binders being stiffened by the effect of the aged RAP binders.

- The asphalt mixtures considered in this study were subjected to the Modified Lottman test, which quantifies the mixtures sensitivity to moisture damage. The mixtures containing 100%RAP failed this test. The 64RAP40 mixture that contained unmodified PG 64-22 asphalt cement binder passed the modified Lottman test. This indicates the CR additives had a positive influence in the asphalt cement binder's ability to increase adherence to the aggregate structure.
- Fracture resistance as measured by the dissipated creep strain energy test indicates that the 64RAP40 HMA mixture ranked last in its ability to resist fracture while the 76CO mixture had the highest fracture resistance. This is attributable to the binder types utilized in the respective HMA mixtures. The 76CO HMA mixture utilized PG 76-22M polymer modified asphalt cement; whereas, the 64RAP40 contained unmodified PG 64-22 AC, which is less stiff than the PG 76-22M material and does not have the elastic properties as does a SBS modified asphalt cement. The elastic properties of a SBS modified binder increases a mixtures resistance to the initiation of fatigue cracking.
- Fracture resistance as measured by the semi-circular bend test confirmed the DCSE results in regards to the fracture resistance of the 64RAP40 mixture.
- Dynamic modulus tests used to evaluate the visco-elastic response of HMA mixtures indicate that as the frequency increases the E* values also increase, and as the temperatures increase the E* values decrease. In addition, at 4.4°C, the E* isotherms show that the HMA mixtures are in the visco-elastic range and are primarily affected by the asphalt cement. As the temperatures increase, the isotherms shape changes to a non-linear shape that represents the non-linear response, which is indicative of the mechanical response caused by the aggregate structure of the HMA mixture, overwhelming the viscous influence of the asphalt cement binder.
- Analysis of the phase angle test results as determined from the dynamic modulus test confirms the E* isotherm findings. The phase angle results indicate that at 4.4°C all mixtures tested were in the visco-elastic range. At 37.8°C, the 76CO, 76CRM, and the 76RAP HMA mixtures show the non-linear response indicating the aggregate structure has taken control of these mixtures properties. At the test temperature of 37.8°C, all mixtures with the exception of the 64RAP40 and 100%RAP mixtures exhibit the non-linear response. It was shown that the 64RAP40 HMA mixtures characteristic was still in the visco-elastic range indicating that the asphalt cement binder was still the contributing factor and that the non-linear response did not occur

until the 54°C test temperature. It is noted that the 100%RAP mixture did not indicate the non-linear response at any temperature tested.

- The HMA mixtures' resistance to permanent deformation (i.e., rutting) as determined by the E* ratio and rutting factor, E*/Sinδ, as measured from the dynamic modulus test indicate that the 100%RAP mixture followed by the 64RAP40 HMA mixture has the greatest propensity to resist rutting.
- Results of the LWT test showed that mixtures evaluated in this study passed the maximum rut depth requirement of 6.0 mm, except 100% RAP mixture.
- In regard to fatigue resistance as determined from the fatigue factor, E*(Sinδ), the 100%RAP mixture had the least resistance to fatigue cracking. All other HMA mixtures evaluated in this study were ranked similarly.

RECOMMENDATIONS

The results of this study illustrated the benefits of utilizing the absorptive properties of crumb rubber to carry engineered additives into asphalt mixtures containing high levels of RAP content. Optimization of crumb rubber and engineered additives for the various types of RAP sources should be performed. Further, it is recommended that the use of crumb rubber and engineered additives in a dry process be investigated to ascertain its utilization in applications such as warm mix additives and anti-strip additives. In addition, life cycle cost analysis should be performed to indicate the economic benefits in utilizing high RAP and recycled products such as crumb rubber in flexible pavement construction and rehabilitation.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt cement
ANOVA	analysis of variance
APA	asphalt pavement analyzer
BBR	Bending Beam Rheometer
cm	centimeter(s)
CR	crumb rubber
CRM	crumb-rubber modifiers
CV	coefficient of variance
DCSE	dissipated creep strain energy
DSC	differential scanning calorimetric
DSR	Dynamic Shear Rheometer
EE	elastic energy
FAA	fine aggregate angularity
FE	fracture energy
FHWA	Federal Highway Administration
FLDOT	Florida Department of Transportation
F_n	flow number
FSCH	frequency sweep at constant height
ft.	foot (feet)
FTIR	Fourier transform infrared
GPC	gel permeation chromatograph
HMA	hot mix asphalt
in.	inch(es)
IRI	International Roughness Index
ISTEA	Intermodal Surface Transportation Efficiency Act
ITS	indirect tensile strength
LADOTD	Louisiana Department of Transportation and Development
lb.	pound(s)
LMS	large molecular size
LTRC	Louisiana Transportation Research Center
LVDT	Linear Variable Displacement Transducer
m	meter(s)
NMAS	nominal maximum aggregate size
NCHRP	National Cooperative Highway Research Program

OGFC	open-graded friction course
PAV	Pressure Aging Vessel
PG	Performance Grade
PMAC	polymer modified asphalt cement
RAP	reclaimed asphalt pavement
RPMAC	reclaimed polymer modified asphalt cement
RSCH	repeated shear at constant height
RV	Rotational Viscometer
SAM	stress-absorbing membranes
SAMI	stress–absorbing membrane interlayer
SAS	Statistical Analysis System
SCB	semi-circular bend
SGC	Superpave gyratory compactor
SHRP	Strategic Highway Research Program
SMS	small molecular size
SPTs	Simple Performance Tests
SSCH	simple shear at constant height
TSR	tensile strength ratio
U.S. EPA	United States Environmental Protection Agency

REFERENCES

1. Heitzman, M., “State of the Practice – Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier,” Research Report No. FHWA-SA-92-022, Federal Highway Administration, Washington, D.C., May, 1992.

2. “LTRC Annual Research Program,” Louisiana Transportation Research Center (LTRC), Baton Rouge, LA, June 1996, pp. 23.

3. Cooper, Jr., S.B., Mohammad, L.N., and Abadie, C., “Evaluation of Field Projects Using Crumb Rubber Modified Asphaltic Concrete,” Louisiana Transportation Research Center, Report No. FHWA/LA.04/393, March 2007.

4. McDaniel, R., and Anderson, R.M., “Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician’s Manual,” NCHRP Report 452, 2001.

5. Shen, J., Amirkhanian, S.N., and Miller, J.A., “Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement,” *Journal of Material in Civil Engineering,* ASCE, Vol. 19, No. 5, May 1, 2007.

6. Wikipedia, http://en.wikipedia.org/wiki/Sustainablility, Accessed September 2008.

7. Turner- Fairbank Highway Research Center, www.tfhrc.gov/hnr20/recycle/waste/rap131.htm, Accessed June 2006.

8. NAPA, National Asphalt Pavement Association, http://www.hotmix.org/allaboutasphalt.php, Accessed 2008.

9. US EPA, United States Environmental Protection Agency, http://www.epa.gov/, Accessed 2008.

10. TNRCC Information, “The Many Uses of Crumb Rubber,” Waste Tire Recycling Program, Office of Permitting, September 1999.

11. Jensen, W., and Abdelrahman, M. “Use of Crumb Rubber in Performance Graded Binder,” Nebraska Department of Roads, Lincoln, NE, 2006.

12. Chehovits, J., and Hicks, R. “Mix Design Procedures.” Session 10.0, Crumb Rubber Modifier Workshop Notes, Federal Highway Administration, Office of Technology Applications, March 1993.

13. Hicks, R., and Epps, J., “Life Cycle Cost Analysis of Asphalt-Rubber Paving Materials,” RPA Reports, htpp://www.rubberpavements.org/library/lcca_australia/history.html, Accessed 2000.

14. Public Law, “Intermodal Surface Transportation Efficiency Act of 1991,” Public Law 102 – 240, December 18, 1991.

15. Epps, J., “Use of Recycled Rubber Tires in Highways – A Synthesis of Highway Practice,” NCHRP Synthesis 198, National Cooperative Highway Research Program, TRB, National Research Council, Washington, D.C., 1994.

16. Page, G., “Florida’s Initial Experience Utilizing Ground Tire Rubber in Asphalt Concrete Mixes,” Research Report FL/DOT/MO89-366, Florida Department of Transportation, Materials Office, September 1989.

17. Maupin, G., Jr., “Hot Mix Asphalt Rubber Applications in Virginia,” Transportation Research Record, No. 1530, TRB, National Research Council, Washington, D.C., 1996.

18. Troy, K., Sebaaly, P., and Epps, J., “Evaluation Systems for Crumb Rubber Modified Binders and Mixtures,” Transportation Research Record, No. 1530, TRB, National Research Council, Washington, D.C., 1996.

19. Huang, B., Mohammad, L.N., Graves, P.S., and Abadie, C., “Louisiana Experience with Crumb Rubber-Modified Hot-Mix Asphalt Pavement,” Transportation Research Record, No. 1789, TRB, National Research Council, Washington, D.C., 2002.

20. Mohammad, L.N., Daly, W.H., Negulescu, I.I., Wu, Z., and Daranga, C., “Investigation of the Use of Recycled Polymer-Modified Asphalt in Asphaltic Concrete Pavements,” Louisiana Transportation Research Center, Report No. FHWA/LA04/391, June 2004.

21. Shen, J., Amirkhanian, S.N., and Lee, S.J., “HP-GPC Characterization of Rejuvenated Aged CRM Binders,” *Journal of Material in Civil Engineering*, ASCE, June 2007.

22. Louisiana Standard Specifications for Roads and Bridges, Louisiana Department of Transportation and Development, Baton Rouge, Louisiana, 2000.

23. Louisiana Standard Specifications for Roads and Bridges, Louisiana Department of Transportation and Development, Baton Rouge, Louisiana, 2006.

24. Roque, R., Birgisson, B., Zhang, Z., Sangpetngam, B., and Grant, T., "Implementation of SHRPP Indirect Tension Tester to Mitigate Cracking in Asphalt Pavements and Overlays," Final Report Submitted to Florida Department of Transportation, University of Florida, Gainesville, FL, May 2002.

25. Mohammad, L., Wu, Z., and Mull, M.A. "Characterization of Fracture Resistance of Superpave Mixture using the Semi-Circular Bending Test." *Journal of ASTM International (JAI)*, Vol. 2, No.3, March 2005.

26. AASHTO, American Association of State Highways and Transportation Officials, "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage," AASHTO T 283-03, Washington D.C., 2003.

27. Mull, M.A., Stuart, K., and Yehia, A., "Fracture Resistance Characterization of Chemically Modified Crumb Rubber Asphalt Pavement," Journal of Materials Science, Vol. 37, 2002, pp. 557-566.

28. Witczak, M.W., "Laboratory Determination of resilient Modulus for Flexible Pavement Design," Research Results Digest, National Cooperative Highway Research Program (NCHRP) Report 1-28A, Transportation Research Board of the National Academies, No. 285, 2004.

29. AASHTO, American Association of State Highways and Transportation Officials, "Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device," AASHTO Designation: TP 322-03, Washington D.C., 2006.

30. Roque, R., Birgisson, B., Drakos, C. and Dietrich, B., "Development and Field Evaluation of Energy-Based Criteria for Top-Down Cracking Performance of Hot-Mix Asphalt," *Journal of the Association of Asphalt Paving Technologists*, Vol. 73, Baton Rouge, LA, 2004.

31. Alshamsi, K.S., “Development of Mix Design Methodology for Asphalt Mixtures with Analytically Formulated Aggregate Structures,” Ph.D. Dissertation, Louisiana State University and Agricultural and Mechanical College, Baton Rouge, Louisiana, May, 2006.

32. Mohammad, L.N., and Paul, H.R., “Evaluation of a New Indirect Tension Test Apparatus,” Transportation Research Record No. 1353, pp.62-68, 1992.

33. Mohammad, L.N., Wu, Z., and Aglan, M., “Characterization of Fracture and Fatigue Resistance on Recycled Polymer-Modified Asphalt Pavements,” The 5th RILEM conference on Pavement Cracking, France, 2004.

34. AASHTO, American Association of State Highways and Transportation Officials, “Practice for Short and Long Term Aging of Hot Mix Asphalt.” AASHTO Designation PP2, Washington D.C., 1994.

35. ASTM D3497, “Standard Test Method for Dynamic Modulus of Asphalt Mixtures,” ASTM International, West Conshohocken, PA, 1979.

36. Witczak, M.W., Kaloush, K., Pellinen, T., and El-Basyouny, M., “Appendix A –Test Method for Dynamic Modulus of Asphalt Concrete Mixtures for Permanent Deformation,” National Cooperative Highway Research Program (NCHRP) Report 465, Transportation Research Board, National Research Council, Washington, D.C., 2002.

37. Witczak, M.W., Kaloush, K., Pellinen, T., El-Basyouny, M., and Quintus, H.V., “Simple Performance Test for Superpave Mix Design,” *National Cooperative Highway Research Program (NCHRP) Report 465*, Transportation Research Board, National Research Council, Washington, D.C., 2002.

APPENDIX A

Aggregate Gradations and Material Properties

Table 10
Sieve analysis of aggregates (percent passing)

Metric (U.S.) Sieve	Aggregate Type				
	# 67 LS	# 78 LS	# 11 LS	Coarse Sand	RAP
37.5 mm (1½ in)	100.0	100.0	100.0	100.0	100.0
25 mm (1 in)	100.0	100.0	100.0	100.0	100.0
19 mm (¾ in)	85.8	100.0	100.0	100.0	100.0
12.5 mm (½ in)	45.3	94.1	100.0	100.0	97.7
9.5 mm (⅜ in)	24.5	62.1	100.0	100.0	87.5
4.75 mm (No. 4)	7.0	10.3	94.6	95.7	69.8
2.36 mm (No. 8)	4.1	4.8	68.8	87.4	55.2
1.18 mm (No.16)	3.0	3.3	42.7	78.8	45.4
0.6 mm (No. 30)	2.4	2.7	27.9	62.9	37.9
0.3 mm (No. 50)	2.2	2.4	19.8	16.8	24.0
0.15 mm (No. 100)	1.9	2.2	14.8	1.6	17.2
0.075 mm (No. 200)	1.8	2.1	12.2	0.6	10.8

Table 11
Aggregate consensus properties

Property	Test Protocol	Specification	HMA Mixtures
CAA, %	ASTM D 5821	95+, 2 face	100
FAA, %	AASHTO T 304	45+	46
F&E, %	ASTM D 4791	10-, 5:1 ratio	0
SE,%	AASHTO T 176	45+	62

Note: CAA: Coarse Aggregate Angularity, FAA: Fine Aggregate Angularity
F&E: Flat and Elongated Particles, SE: Sand Equivalent

Table 12:
Tire crumb rubber certificate of analysis

Screen Size	Sieve Analysis (% passing)	Chemical Analysis	
30 mesh*	100.0	Acetone Extract	12.09%
40 mesh	87.0	RHC	49.03%
50 mesh	45.7	Carbon Black	31.85%
60 mesh	31.5	Ash	7.021%
80 mesh	16.2	Moisture Content	0.65%
Pan	0.0		

Reference: PolyVulc, Lot 236-A, 6-06-08
*Trace retained on 30 Mesh

APPENDIX B

Simple Performance Test Results for Asphalt Mixtures

Table 13
Dynamic modulus (E*) test results, 76CO HMA

Temperature	Sample ID	Air Voids (%)	E* (Ksi) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0. 5 Hz	0. 1 Hz
4.4 ºC	1	7.4	2637	2421	2241	1801	1618	1213
	2	6.5	2577	2401	2242	1827	1663	1305
	9	7.3	2558	2286	2098	1730	1565	1196
	Average	7.1	2591	2369	2194	1786	1615	1238
	Stdev	0.5	41.5	72.8	82.8	50.4	48.9	58.8
	CV%	6.9	1.6	3.1	3.8	2.8	3.0	4.7
25.0 ºC	1	7.4	1084	864	696	391	292	152
	2	6.5	1124	904	739	423	342	190
	9	7.3	983	789	652	398	310	189
	Average	7.1	1064	852	696	404	315	177
	Stdev	0.5	72.6	58.5	43.8	17.1	25.5	21.4
	CV%	6.9	6.8	6.9	6.3	4.2	8.1	12.1
37.8 ºC	1	7.4	439	303	231	114	89	55
	2	6.5	459	323	247	128	97	57
	9	7.3	354	251	202	120	92	63
	Average	7.1	417	292	227	121	93	58
	Stdev	0.5	55.8	37.2	22.5	6.9	4.3	3.9
	CV%	6.9	13.4	12.7	9.9	5.7	4.6	6.6
54.4 ºC	1	7.4	105	74	58	37	34	27
	2	6.5	111	76	61	40	37	32
	9	7.3	115	84	69	47	42	34
	Average	7.1	110	78	62	41	38	31
	Stdev	0.5	5.2	5.2	5.8	5.4	4.3	3.8
	CV%	6.9	4.7	6.7	9.3	13.1	11.5	12.2

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 14
Dynamic modulus (E*) test results, 76CRM HMA

Temperature	Sample ID	Air Voids (%)	E* (Ksi) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0. 5 Hz	0. 1 Hz
4.4 ºC	8	7.7	2855	2633	2461	2049	1872	1471
	9	7.6	2514	2330	2189	1835	1688	1327
	10	7.1	2769	2544	2379	1969	1791	1398
	Average	7.5	2713	2503	2343	1951	1784	1398
	Stdev	0.3	177.4	155.8	139.6	108.4	92.1	71.7
	CV%	4.3	6.5	6.2	6.0	5.6	5.2	5.1
25.0 ºC	8	7.7	1119	903	771	495	414	235
	9	7.6	1044	872	747	472	382	213
	10	7.1	1103	873	723	454	379	216
	Average	7.5	1089	883	747	474	392	221
	Stdev	0.3	39.6	17.7	23.6	20.7	19.5	11.7
	CV%	4.3	3.6	2.0	3.2	4.4	5.0	5.3
37.8 ºC	8	7.7	451	337	266	131	95	45
	9	7.6	437	319	248	124	92	44
	10	7.1	465	343	265	135	102	49
	Average	7.5	451	333	260	130	96	46
	Stdev	0.3	14.1	12.2	10.0	5.3	5.2	2.7
	CV%	4.3	3.1	3.7	3.9	4.1	5.4	5.8
54.4 ºC	8	7.7	152	98	70	30	22	12
	9	7.6	136	85	60	27	20	10
	10	7.1	167	107	78	35	26	14
	Average	7.5	152	96	69	30	22	12
	Stdev	0.3	15.1	11.2	8.9	3.9	3.1	1.7
	CV%	4.3	10.0	11.6	12.9	12.8	13.7	13.8

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 15
Dynamic modulus (E*) test results, 76RAP15 HMA

Temperature	Sample ID	Air Voids (%)	E* (Ksi) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0. 5 Hz	0. 1 Hz
4.4 ºC	1	7.7	2246	2068	1925	1586	1430	1086
	2	7.6	2537	2331	2179	1806	1639	1260
	4	7.2	2333	2157	2021	1698	1557	1225
	Average	7.5	2372	2185	2041	1697	1542	1190
	Stdev	0.3	149.2	133.7	128.3	109.7	105.3	92.1
	CV%	3.5	6.3	6.1	6.3	6.5	6.8	7.7
25.0 ºC	1	7.7	772	618	510	291	222	113
	2	7.6	900	720	597	353	276	144
	4	7.2	889	703	577	354	296	162
	Average	7.5	854	680	561	333	265	140
	Stdev	0.3	71.3	54.6	45.2	35.8	38.2	24.9
	CV%	3.5	8.3	8.0	8.0	10.8	14.4	17.9
37.8 ºC	1	7.7	319	227	172	84	62	31
	2	7.6	349	243	184	90	68	36
	4	7.2	388	275	208	104	77	39
	Average	7.5	352	248	188	93	69	35
	Stdev	0.3	34.9	24.2	18.1	10.2	7.6	4.0
	CV%	3.5	9.9	9.8	9.6	11.0	11.0	11.2
54.4 ºC	2	7.6	159	103	75	33	24	12
	3	7.7	144	97	73	37	28	17
	4	7.2	175	109	76	29	20	8
	Average	7.5	159	103	75	33	24	12
	Stdev	0.3	15.5	6.0	1.5	4.0	4.0	4.5
	CV%	3.5	9.7	5.8	2.0	12.1	16.7	36.7

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 16
Dynamic modulus (E*) test results, 64RAP40 HMA

Temperature	Sample ID	Air Voids (%)	E* (Ksi) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0. 5 Hz	0. 1 Hz
4.4 ºC	1	7.3	2741	2583	2457	2147	2017	1704
	3	7.4	2574	2420	2298	2005	1871	1556
	5	7.1	2846	2662	2514	2170	2007	1652
	Average	7.3	2720	2555	2423	2107	1965	1637
	Stdev	0.15	137	123	112	89	81	75
	CV%	2.1	5.0	4.8	4.6	4.2	4.1	4.6
25.0 ºC	1	7.3	1295	1103	971	686	587	383
	3	7.4	1219	1031	893	621	519	320
	5	7.1	1278	1074	948	654	554	327
	Average	7.3	1264	1070	937	654	553	343
	Stdev	0.15	39.8	36.3	40.1	32.8	33.9	34.5
	CV%	2.1	3.1	3.4	4.3	5.0	6.1	10.0
37.8 ºC	1	7.3	605	482	397	227	179	98
	3	7.4	554	448	370	208	157	79
	5	7.1	609	469	379	207	158	80
	Average	7.3	589	466	382	214	165	86
	Stdev	0.15	30.6	17.1	13.6	11.5	12.4	10.9
	CV%	2.1	5.2	3.7	3.6	5.4	7.5	12.7
54.4 ºC	1	7.3	218	148	105	54	30	19
	3	7.4	243	167	120	55	42	23
	5	7.1	203	136	99	47	35	18
	Average	7.3	221	150	109	52	39	20
	Stdev	0.15	20.0	15.5	10.4	4.3	3.9	2.3
	CV%	2.1	9.0	10.3	9.5	8.3	10.1	11.7

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 17
Dynamic modulus (E*) test results, 100%RAP

Temperature	Sample ID	Air Voids (%)	E* (Ksi) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0. 5 Hz	0. 1 Hz
4.4 ºC	1	7.1	1765	1678	1613	1481	1402	1254
	2	7.5	1457	1377	1315	1191	1131	998
	6	7.5	1569	1466	1395	1256	1187	1052
	Average	7.4	1597	1507	1441	1309	1240	1101
	Stdev	0.23	156.2	154.4	154.3	152.2	143.0	134.8
	CV%	3.1	9.8	10.2	10.7	11.6	11.5	12.2
25.0 ºC	1	7.1	1046	944	871	709	643	494
	2	7.5	806	720	658	530	479	368
	6	7.5	822	745	689	566	518	411
	Average	7.4	891	803	739	602	547	425
	Stdev	0.23	134.2	122.5	114.8	94.2	85.6	64.1
	CV%	3.1	15.1	15.3	15.5	15.7	15.7	15.1
37.8 ºC	1	7.1	647	556	494	361	317	216
	2	7.5	488	413	364	264	229	158
	6	7.5	570	495	442	333	296	211
	Average	7.4	569	488	434	319	281	195
	Stdev	0.23	79.5	71.7	65.6	49.9	45.7	32.4
	CV%	3.1	14.0	14.7	15.1	15.6	16.3	16.6
54.4 ºC	1	7.1	286	221	183	107	86	48
	2	7.5	211	164	137	84	69	41
	6	7.5	225	181	153	98	83	52
	Average	7.4	241	189	158	96	79	47
	Stdev	0.23	39.6	29.4	23.5	11.5	9.0	5.3
	CV%	3.1	16.5	15.6	14.9	12.0	11.4	11.2

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 18
Phase angle test results, 76CO HMA

Temperature	Sample ID	Air Voids (%)	Phase Angle values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4.4 ºC	1	7.4	6.1	9.0	10.6	14.1	15.8	19.1
	2	6.5	6.0	8.9	10.6	14.1	15.7	19.4
	9	7.3	4.7	8.5	10.0	13.1	14.5	17.9
	Average	7.1	5.6	8.8	10.4	13.8	15.3	18.8
	Stdev	0.5	0.8	0.3	0.4	0.6	0.7	0.8
	CV%	6.9	14.0	3.0	3.4	4.2	4.5	4.0
25.0 ºC	1	7.4	20.2	23.5	26.2	31.2	32.8	33.2
	2	6.5	19.3	22.6	25.0	29.7	30.4	30.8
	9	7.3	18.5	22.3	24.43	28.6	30.2	30.1
	Average	7.1	19.3	22.8	25.2	29.9	31.1	31.4
	Stdev	0.5	0.8	0.6	0.9	1.3	1.4	1.6
	CV%	6.9	4.4	2.8	3.6	4.4	4.5	5.2
37.8 ºC	1	7.4	28.2	31.0	31.8	32.8	30.9	25.6
	2	6.5	28.2	30.6	31.6	32.4	31.4	27.3
	9	7.3	26.6	28.8	28.7	27.4	27.0	22.5
	Average	7.1	27.7	30.2	30.7	30.8	29.8	25.1
	Stdev	0.5	0.9	1.2	1.7	3.0	2.4	2.4
	CV%	6.9	3.3	3.9	5.6	9.7	8.2	9.7
54.4 ºC	1	7.4	31.1	29.8	28.3	23.9	21.2	16.5
	2	6.5	29.7	28.4	26.9	22.1	19.1	14.2
	9	7.3	26.6	25.3	24.4	20.8	19.5	16.0
	Average	7.1	29.1	27.8	26.5	22.3	19.9	15.6
	Stdev	0.5	2.3	2.3	2.0	1.6	1.1	1.2
	CV%	6.9	7.9	8.2	7.5	7.0	5.5	7.6

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 19
Phase angle test results, 76CRM HMA

Temperature	Sample ID	Air Voids (%)	Phase Angle (Degrees) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4.4 ºC	8	7.7	7.5	8.8	9.8	12.3	13.4	16.5
	9	7.6	7.5	8.8	9.8	12.3	13.6	16.8
	10	7.1	7.8	9.2	10.2	12.9	14.1	17.5
	Average	7.5	7.6	9.0	9.9	12.5	13.7	17.0
	Stdev	0.3	0.2	0.2	0.2	0.3	0.4	0.5
	CV%	4.3	2.2	2.3	2.4	2.8	2.6	3.0
25.0 ºC	8	7.7	21.6	23.2	24.3	27.8	28.7	30.9
	9	7.6	21.4	23.1	24.3	27.5	28.2	30.2
	10	7.1	22.9	25.3	26.8	30.6	31.2	33.0
	Average	7.5	22.0	23.8	25.1	28.6	29.4	31.4
	Stdev	0.3	0.8	1.2	1.4	1.7	1.6	1.5
	CV%	4.3	3.8	5.1	5.7	6.0	5.5	4.7
37.8 ºC	8	7.7	31.1	32.0	32.4	33.5	33.3	33.0
	9	7.6	30.7	31.6	31.9	32.9	32.4	31.5
	10	7.1	31.5	32.3	32.5	33.2	32.5	31.7
	Average	7.5	31.1	32.0	32.3	33.2	32.7	32.1
	Stdev	0.3	0.4	0.4	0.3	0.3	0.5	0.8
	CV%	4.3	1.3	1.1	0.9	0.9	1.5	2.5
54.4 ºC	8	7.7	34.2	34.4	33.8	32.2	31.1	28.8
	9	7.6	34.2	34.5	33.8	32.6	31.2	28.6
	10	7.1	33.1	33.2	32.5	31.9	30.8	27.8
	Average	7.5	33.8	34.1	33.4	32.2	31.0	28.4
	Stdev	0.3	0.6	0.7	0.7	0.4	0.2	0.5
	CV%	4.3	1.8	2.1	2.2	1.1	0.7	1.9

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 20
Phase angle test results, 76RAP15 HMA

Temperature	Sample ID	Air Voids (%)	Phase Angle (Degrees) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4.4 ºC	1	7.7	7.5	8.9	10.0	12.9	14.4	18.5
	2	7.6	7.5	9.0	10.1	12.9	14.4	18.1
	4	7.2	7.1	8.3	9.2	11.7	13.0	16.2
	Average	7.5	7.4	8.7	9.8	12.5	13.9	17.6
	Stdev	0.3	0.3	0.4	0.5	0.7	0.8	1.2
	CV%	3.5	3.7	4.4	5.0	5.6	5.9	6.8
25.0 ºC	1	7.7	24.6	27.2	28.9	32.5	33.2	34.6
	2	7.6	23.4	25.7	27.5	31.4	32.2	33.4
	4	7.2	22.4	24.9	26.7	31.0	31.8	33.7
	Average	7.5	23.5	25.9	27.7	31.6	32.4	33.9
	Stdev	0.3	1.1	1.2	1.1	0.8	0.7	0.6
	CV%	3.5	4.9	4.5	4.1	2.6	2.3	1.8
37.8 ºC	1	7.7	33.4	34.6	34.7	34.5	33.5	31.0
	2	7.6	33.8	35.1	35.3	34.9	33.4	30.5
	4	7.2	31.4	32.8	33.3	33.8	33.0	31.5
	Average	7.5	32.9	34.2	34.4	34.4	33.3	31.0
	Stdev	0.3	1.3	1.2	1.0	0.5	0.3	0.5
	CV%	3.5	4.0	3.6	2.9	1.6	0.8	1.6
54.4 ºC**	2	7.6	34.0	34.0	33.3	31.9	30.4	27.4
	3	7.7	36.6	36.6	35.0	31.4	28.8	24.1
	4	7.2	36.4	36.6	35.2	31.7	29.5	24.9
	Average	7.5	35.7	35.7	34.5	31.7	29.6	25.4
	Stdev	0.3	1.4	1.5	1.0	0.3	0.8	1.7
	CV%	3.5	4.0	4.2	3.0	0.8	2.7	6.8

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 21
Phase angle test results, 64RAP40

Temperature	Sample ID	Air Voids (%)	Phase Angle (Degrees) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4.4 ºC	1	7.3	5.1	6.0	6.6	8.3	9.2	11.5
	3	7.4	5.5	6.5	7.2	9.1	10.0	12.5
	5	7.1	5.4	6.4	7.1	9.1	10.0	12.7
	Average	7.3	5.3	6.3	6.9	8.7	9.6	12.0
	Stdev	0.15	0.3	0.4	0.4	0.5	0.6	0.7
	CV%	2.1	5.3	6.1	6.4	6.0	6.1	6.1
25.0 ºC	1	7.3	16.2	18.2	19.8	23.6	24.8	28.0
	3	7.4	16.9	19.2	20.9	25.1	26.4	29.9
	5	7.1	17.2	19.6	21.3	25.5	26.7	29.8
	Average	7.3	16.8	19.0	20.6	24.7	26.0	29.2
	Stdev	0.15	0.5	0.7	0.8	1.0	1.0	1.1
	CV%	2.1	3.3	3.8	3.8	4.0	3.8	3.8
37.8 ºC	1	7.3	26.3	28.1	29.1	31.3	31.2	31.4
	3	7.4	26.8	28.5	29.6	32.4	32.6	33.0
	5	7.1	27.6	29.4	30.4	32.7	32.6	32.5
	Average	7.3	26.9	28.6	29.7	32.1	32.1	32.3
	Stdev	0.15	0.7	0.7	0.7	0.7	0.8	0.8
	CV%	2.1	2.5	2.4	2.2	2.2	2.4	2.6
54.4 ºC	1	7.3	32.7	32.6	32.0	31.6	30.8	29.8
	3	7.4	36.0	36.0	35.0	33.1	31.8	28.9
	5	7.1	34.9	34.9	34.1	32.3	31.0	27.9
	Average	7.3	34.5	34.5	33.7	32.3	31.2	28.9
	Stdev	0.15	1.7	1.7	1.5	0.8	0.5	0.9
	CV%	2.1	4.8	5.0	4.5	2.4	1.8	3.3

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 22
Phase angle test results, 100%RAP

Temperature	Sample ID	Air Voids (%)	Phase Angle (Degrees) values at different frequencies (Hz)					
			25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4.4 ºC	1	7.1	4.4	5.0	5.4	6.3	6.9	8.0
	2	7.5	5.1	6.0	6.7	7.3	7.7	9.0
	6	7.5	4.8	5.4	5.8	6.7	7.1	8.2
	Average	7.4	4.8	4.4	5.9	6.7	7.2	8.4
	Stdev	0.23	0.4	0.4	0.6	0.5	0.4	0.5
	CV%	3.1	8.3	9.1	10.8	7.9	6.1	6.4
25.0 ºC	1	7.1	10.9	12.2	13.1	15.6	16.6	29.5
	2	7.5	11.0	12.4	13.4	15.8	16.9	19.6
	6	7.5	10.0	11.2	11.9	13.8	14.8	16.9
	Average	7.4	10.6	11.9	12.8	15.1	16.1	18.7
	Stdev	0.23	0.6	0.6	0.8	1.1	1.2	1.5
	CV%	3.1	5.6	5.3	6.1	7.1	7.2	8.1
37.8 ºC	1	7.1	16.0	17.9	19.2	22.5	23.5	26.4
	2	7.5	16.4	18.3	19.4	22.4	23.5	26.4
	6	7.5	15.1	16.6	17.7	20.4	21.3	23.9
	Average	7.4	15.8	17.6	18.8	21.8	22.8	25.6
	Stdev	0.23	0.6	0.9	1.0	1.2	1.3	1.5
	CV%	3.1	4.0	5.0	5.1	5.5	5.7	5.7
54.4 ºC	1	7.1	25.8	28.1	29.2	32.0	32.3	34.0
	2	7.5	25.4	27.6	28.8	31.4	31.9	33.3
	6	7.5	24.2	26.1	27.1	29.6	30.0	31.4
	Average	7.4	25.1	27.2	28.4	31.0	31.4	32.9
	Stdev	0.23	0.8	1.1	1.1	1.3	1.3	1.3
	CV%	3.1	3.3	3.9	4.0	4.1	4.0	4.0

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)

Table 23
Flow number test results

Mix Type	Sample ID	Air Void (%)	Flow Number (Cycles)	Mean Flow Number (Cycles)	St Dev	CV (%)
76CO	1	7.3	5493	6132	851.0	13.9
	8	6.7	5805			
	11	7.2	7098			
76CRM	6	7.0	1975	1725	411.6	23.9
	11	6.5	1950			
	14	6.6	1250			
76RAP15	1	7.7	6450	6867	520.4	7.6
	2	7.7	6700			
	3	6.8	7450			
64RAP40	1	7.3	1992	2397	404.0	16.8
	2	7.1	2400			
	3	7.5	2800			
100%RAP	4	7.5	10000	10000	0.0	0.0
	7	7.2	10000			
	8	7.2	10000			

Note: Stdev: Standard Deviation
%CV: Coefficient of Variance (%)