Performance Evaluation of Recycled Asphalt Shingles (RAS) in Hot Mix Asphalt (HMA): An Ontario Perspective

by

Riyad-UL-Islam

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Today, a large quantity of waste is generated from the replacement of residential and commercial roofs. Many of the roofs being upgraded with previously constructed from asphalt shingles. Recycled Asphalt Shingles (RAS) contain nearly 30% of asphalt cement by mass, which can be a useful additive to asphalt pavements. In addition, shingles can offer significant potential savings through recycling and recovery as a construction material in flexible pavement. Currently, one and a half million tons of roofing shingle waste is generated each year in Canada related to the replacement of residential and commercial roofs and 90% of this valuable material is sent to landfills. If engineered properly, the addition of RAS into Hot-Mix Asphalt (HMA) can provide significant benefits. The University of Waterloo's Centre for Pavement and Transportation Technology (CPATT) is committed to working with public and private sector partners to develop sustainable technologies for the pavement industry. Using RAS in HMA can lead to economical, environmental and social benefits. Examples of which are reduced waste going to landfills and a reduction in the quantity of virgin material required.

This research has involved the Ontario Centres of Excellence (OCE) and Miller Paving Limited. It was conducted to evaluate the performance of HMA containing RAS in both field and laboratory tests. A varying percentage of RAS was added to six common Ontario surface and binder layer of asphalt mixes. The intent was to determine if RAS could be added to improve performance and provide longer term cost savings. Laboratory testing was performed to evaluate the mix behavior. The elastic properties, fatigue life and resistance to thermal cracking were all evaluated at the CPATT laboratory. The characteristics of the mixes were evaluated by carrying out Dynamic Modulus, Resilient Modulus, Flexural Fatigue and Thermal Stress Restrained Specimen Test (TSRST) tests following American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM) standards. Field test sections were constructed from HMA containing RAS to monitor the pavement behavior under natural environmental and traffic loading conditions. Evaluation of the field sites was performed using a Portable Falling Weight Deflectometer (PFWD) and carrying out distress surveys following the

Ministry of Transportation Ontario (MTO) guidelines. The results to date show the sections performing very well with minimal to no distress developing.

The results of the laboratory testing and field performance evaluations have shown encouraging results for the future use of RAS in HMA. If RAS can properly be engineered into HMA it can be a useful additive in both the surface and binder layers of the flexible pavement structure. Ultimately, the use of RAS in HMA can provide both an environmentally friendly and cost effective solution to the Ontario paving industry.

Acknowledgements

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I would like to acknowledge the Ontario Centre of Excellence (OCE) and Miller Paving Limited for funding this research. In addition, the technical help and support was provided by Miller Paving Limited, Stead and Evans Limited and McAsphalt have been greatly appreciated. The support from the Centre for Pavement and Transportation Technology (CPATT), Town of Markham and Regional Municipality of Waterloo is also appreciated.

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My special thanks goes to CPATT members Mohab El Hakim, Mohammed Adnan, Antonin du Tartre, Shirley Ddhamba and Peter Chan for their effort and patience in mixing and preparing the samples for this research. Special thanks to Jodi Norris, Vimy Henderson and Rabiah Rizvi who assisted me with laboratory testing and solving technical problem during research progress.

Last but not least, I would like to give my deepest thanks to my wife, Arafat, for her understanding and endless patience. Without her encouragement and support this work would not have been possible.

Dedication

I would like to dedicate this thesis to my parents, family and friends for supporting me throughout the years of my academic study and professional career.

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Chapter 1
Introduction

1.1 Background

The quality and accessibility of a road network has a large impact on the economic activities of the country. According to Transport Canada (2009), Canada has a road network of close to 900,000 km of road. Within the network 39.9% are paved roads, constructed of either rigid or flexible pavement. Up to 1970 and since the construction of the first road in North America in 1870 the focus of the industry was to develop asphalt pavements that performed “better”. Following the energy crisis in the 1970’s, it became more important to consider environmental impacts and recycling of materials became common in pavement industry which includes Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS) and other recycled materials.

Virgin aggregates and asphalt cement (AC) are the major components of Hot-Mix Asphalt (HMA). AC is a product of the distillation process of crude petroleum and it is the most costly component of HMA. Therefore, the oil sector plays a vital role in the current practices of the pavement industry as the cost of AC follows the cost of oil. In addition, large amounts of natural aggregate are mined from quarries for the construction of pavements.

Currently, one and a half million tons of roofing shingles waste is generated each year in Canada related to the replacement of residential and commercial roofs and 90% of this valuable material is dumped in landfills. Recycled Asphalt Shingles (RAS) contain nearly 30% asphalt cement by mass, which can be a useful additive to asphalt pavements. If engineered properly, the addition of RAS into HMA can provide significant benefits.

The incorporation of RAS in conventional mixes can be green and environmentally friendly. Over the last ten years in the United States, there has been a significant increase in the use of RAS in HMA but limited use in Canada. In Canada, the use of RAS in HMA is still at the experimental stages. This research is directed at quantifying the feasible percentages of RAS in HMA.

According to a Natural Resources of Canada study in 2007 entitled "Enhancing the Recovery of End-of-Life Roofing Materials", the use of 5% (by mass) of the annual waste asphalt shingles in HMA can save 900,000 tons of Green House Gas (GHG) emissions.

With diminishing natural resources and growing environmental concerns in many regions of Ontario, the use of recycled materials such as RAS can provide alternative solutions.

In 2006, the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo in cooperation with the Ministry of Transportation Ontario (MTO), Miller Paving Ltd, the Ontario Centre of Excellence (OCE), Materials Manufacturing Ontario (MMO) and École de Technologie Superieure (ETS) in Montreal carried out a project to investigate the effects of RAS in a Hot Laid 8 (HL 8) binder course mix. The findings recommended that 1.4% RAS and 20 % RAP in the HL 8 performed the best in Dynamic Modulus, Resilient Modulus, Thermal Stress Restrained Specimen Tensile Strength Test (TSRST) and French Wheel Rutting testing. After getting a very encouraging test results in Phase 1 and inspecting several field placements in the Town of Markham, Ontario it was decided that Phase 2 (this project) should evaluate the performance of other HMA mixes containing RAS.

1.2 Purpose/Motivation

The purpose of this research was to evaluate the performance of HMA mixes composed of various portions of RAS, RAP and virgin material. The mixes that were included in this study are the following: Hot Laid 3 (HL 3), Superpave 19 (SP19), Superpave 12.5 Friction Course 1 (SP12.5 FC1) and Superpave 12.5 Friction Course 2 (SP12.5 FC2). This research involved laboratory testing including Dynamic Modulus, Resilient Modulus, Thermal Stress Restrained Specimen Test (TSRST) and Flexural Fatigue. All of the mixes listed above were tested. The details of the laboratory testing procedures and interpretation of the data are presented and explained in Chapter 3 and Chapter 4.

Furthermore, this study included a comparison between laboratory test results and a field performance of three streets which were paved in 2007 with SP 12.5 FC1 in the Town of Markham, ON and a new test section was paved in 2009 with HL 3 at the Region of Waterloo Waste Management Facility.

The test section at the Region of Waterloo Waste Management Facility is HL 3 containing 1.5% RAS and 13.5% RAP. It was placed over a conventional HL 8 mix which contained 20% RAP.

Overall, this research aims to optimize the percentage of RAS that can be used in typical Ontario HMA and maintain the performance of conventional mixes.

1.3 Scope and Objectives

The objectives of this thesis are the following:

1. Literature review on the use of RAS in asphalt pavements.
2. Finalization of mix designs with varying percentages of RAP and RAS in typical Ontario HMA mixes which will include HL 3, SP19, SP12.5 FC1 and SP12.5 FC2.
3. Construction and evaluation of CPATT test section constructed with HL 3 containing 1.5% RAS and 13.5% RAP.
4. Analysis of laboratory testing results involving Dynamic Modulus, Resilient Modulus, Thermal Stress Restrained Specimen Test (TSRST) and Flexural Fatigue for the selected typical Ontario HMA mixes with RAS.
5. Evaluation of the performance of the test sections, at the CPATT Test Track paved with HL 3 RAS and three roads in the Town of Markham, ON each paved with SP 12.5 FC1 containing RAS and RAP.

1.4 Research Methodology

Figure 1-1 shows the methodology that was followed in this research project. The methodology is described below:

1. Literature review on the use of RAS in flexible pavements in the USA and its performance over time. In addition, an overview of the structural and functional performance of the HMA pavements following the addition of varying percentages of RAS and RAP.
2. Review of literature related to laboratory testing of flexible pavement materials including Dynamic Modulus, Resilient Modulus, Thermal Stress Restrained Specimen Test (TSRST) and Flexural Fatigue tests.

3. Laboratory testing of Ontario HMA mixes containing various percentages of RAP and RAS to demonstrate the properties of mixes containing these recycled materials.

4. An evaluation of the performance of field test sections in Ontario.

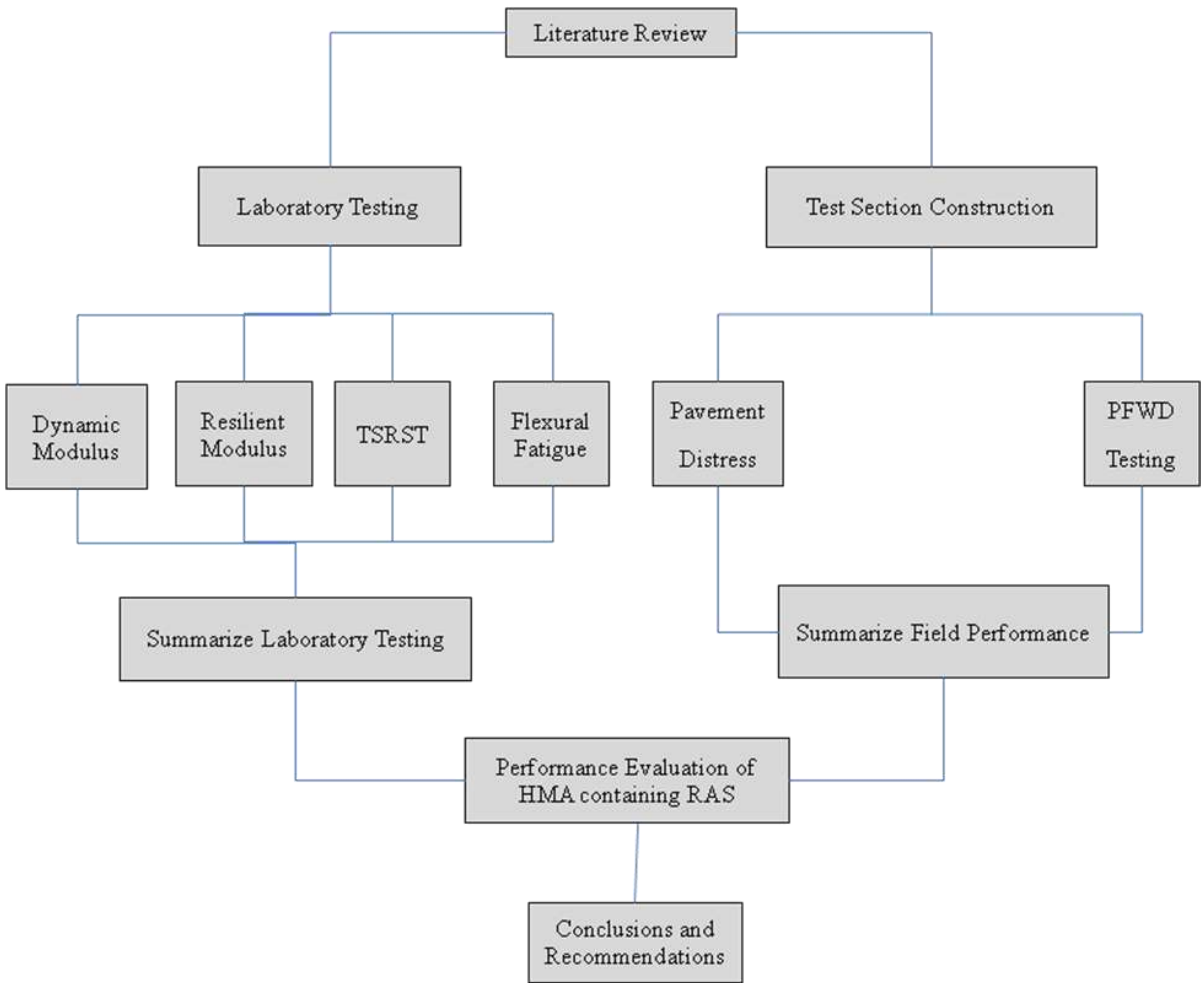

Figure 1-1 : Research Methodology

1.5 Organization of Thesis

Chapter One provides an introduction to the research project. A general overview of the thesis scope and objectives is also provided. The research methodology is explained.

Chapter Two is a review of the current literature related to experiences with the using of RAP and RAS in HMA. This chapter also includes the laboratory testing procedures by which mix properties can be described.

Chapter Three describes the selected HMA mixes that were used in this research.

Chapter Four describes the details of laboratory tests and discus the test results.

Chapter Five includes a brief illustration of the construction work of the test sections and the performance of the test sections to date.

Chapter Six presents the conclusions of the research and recommendations for future work.

Chapter 2
Literature Review

This aim of this chapter is to introduce the RAS as a construction material for usage in asphalt pavements. Some previous applications of RAS in HMA in the United States pavement industries are discussed in this chapter. An overview of the laboratory testing from Phase 1 of this project is included in this chapter. A thorough literature review is also included regarding the laboratory testing which was performed in this research.

2.1 Recycled Asphalt Shingles (RAS)

Shingles are intended for 15–20 years of service. AC, fine aggregates, filler and fibers are the primary components of shingles. Since asphalt shingles contain approximately 30% AC by mass [Foo 1999], using RAS in HMA decreases the amount of virgin AC required, and thus decreasing input costs to produce HMA. Studies have found that the properties of HMA may improve when small amounts of RAS are incorporated; however, this improvement may be dependent upon the source and quality of the RAS. The roofing application of shingles and the demolition are shown in Figure 2-1 and Figure 2-2.

Figure 2-1 : Asphalt Shingles on a Residential Roof

Figure 2-2 : Tear-off Shingles after Service Life

The granular material in the asphalt shingles is composed of crushed rock coated with ceramic metal oxides, and coal slag. It is generally uniform in size, ranging from 0.3mm - 2.36 mm and is hard and angular [Newcomb 1993 Ross 1997]. Powdered limestone (70% passing the No. 200 sieve) is also added as a stabilizer.

2.1.1 Typical Shingle Composition

Based on composition, shingles can be divided in two groups: organic and fiberglass.

2.1.1.1 Organic Shingles

Organic shingles are made of paper (felt) saturated asphalt cement (AC). These types of shingles are heavier and contain more AC. In cold regions, such as the northern USA and Canada, these shingles are used due to the higher flexibility from the large AC content. The increased flexibility makes them less likely to crack in cold weather.

2.1.1.2 Fiberglass Shingles

Fiberglass shingles contain a base layer (mat) of fiberglass coating. These types of shingles are easier to work with and install as the fiberglass base makes the shingles lighter in weight. Fiberglass shingles also provide greater resistance to moisture and fire than organic shingles.

The typical composition of the roofing shingles is shown in Table 2-1 [Grodinsky 2002]

Table 2-1: Composition of Shingles [Grodinsky 2002]

Component	Organic Shingles	Fiberglass Shingles
Asphalt Cement	30-35%	15-20%
Felt	5-15%	5-15%
Mineral Filler	10-20%	15-20%
Fine Aggregate	30-50%	30-50%

2.1.2 Asphalt Cement in Tear-off Shingles

Weathering of a portion of surface granules from roofing shingles results in a greater percentage of AC as compared to new shingles. Oxidation and volatilization of the lighter organic compounds in the roofing shingles makes the AC in tear-off shingles stiffer. As a result, using higher percentages of RAS in HMA can lead to the mix being stiffer than a virgin mix would be. Tear off shingles tend to include nails, paper, wood and other debris which makes recycling a longer process [Mallick 2000]. Care and consideration should be taken when RAS is added to HMA to avoid this potential contamination.

2.1.3 Benefits of RAS in HMA

Benefits of using shingles in HMA include economical savings, environmental preservation, and potential for improved performance. Recycling RAS in HMA avoids the expense associated with the disposal of shingle waste and reduces the amount of material entering landfill sites, which benefits the environment. The amount of virgin AC required in HMA mixes can be reduced by incorporating RAS; this reduces costs. A relatively small percentage of shingles can displace a large percentage of AC [Foo 1999]. Studies have also found increased resistance to high temperature rutting in HMA that contain factory waste shingles or RAS [Foo 1999].

2.2 Roofing Shingle Use in HMA: USA Experiences

Several laboratory and field research projects have been carried out on the use of roofing shingle in HMA in the United States since 1990. The Department of Transportation (DOT) of Minnesota [Newcomb 1993] and North Carolina [Ross 1997], the University of Maryland [Witczak 1994], the National Asphalt Pavement Association [Hughes 1994], asphalt plant manufacturer Astec Plant Industries Inc. [Brock 1996] and others have characterized the composition and properties of asphalt shingles in their studies. Laboratory testing and field performance evaluations have been carried out on HMA containing RAS in Florida, Georgia, Maine, Massachusetts, Missouri, Minnesota, Nevada, New Jersey, New York, Pennsylvania, Maryland, North Carolina, Indiana, Michigan, Tennessee and Texas [Button 1997]. An overview of that research is presented in this section.

- Two test sections of RAS-HMA were constructed by the Minnesota Department of Transportation (Mn/DOT) in 1990 [Janisch 1996]. A portion of a recreational trail in St. Paul was paved with HMA incorporating 6% shingle scrap and 9% shingle scrap by weight of aggregate. All sections were in service as of October 1996 and performed well.
- A portion of a town highway in Mayer, Minnesota using RAS-HMA made with factory scrap shingles was constructed in 1991 by the Minnesota Department of Transportation (Mn/DOT) [Janisch 1996]. The original road was constructed in 1974 and exhibited severe oxidation and longitudinal cracking. The road was paved with a 38 mm leveling course and a 25 mm wearing surface. Using various amounts (5% and 7%) of RAS in both the binder and wearing courses, seven different sections of the road were repaved. Conventional HMA was used to construct the control section. In 1995, after four years of service, Mn/DOT reported that there were no observable differences noticed in the performance between the shingle sections and the control section.
- Scott County in Minnesota reconstructed an 800 meter long section of County State Aid Highway 17 in 1991 [Janisch 1996]. On that project RAS-HMA were used in the

base course of the pavement. After four years in service Mn/DOT reported that the section was in excellent condition.

- The Georgia Department of Transportation paved a test section using RAS-HMA in 1994. The project consisted of widening and reconstructing the Chatham Parkway in Savannah [Watson 1998]. The northbound lane was 477 meter in length and was repaved with a 60 mm RAS-HMA base course and a 50 mm RAS-HMA wearing course. No significant problems were encountered while RAS-HMA was placed by conventional techniques of paving. When compared to the conventional mix, RAS-HMA that was sampled on site indicated that the material properties were similar or slightly improved. After one year in service, six core samples (two from the control section, four from the RAS-HMA section) were obtained; and four additional RAS-HMA cores were also collected after two years. It was revealed in laboratory testing that the RAS-HMA cores showed good compliance with the job mix formulas and plant mix testing. The RAS-HMA, did however, show higher viscosity which may indicate that mix hardened at a faster rate than conventional HMA due to the stiff AC. Field performance evaluation showed that the RAS-HMA section was comparable to the control sections with minimal distress.
- The University of Minnesota conducted research in 1993 on the use of roofing shingles in a number of different HMA mixes [Newcomb 1993]. The project conclusions noted that a stiffer paving mix may have been produced due to the increased hardness of the AC in the RAS. There was also concern that the higher stiffness could be problematic in cold climates such as Minnesota due to an increase in the tendency of cracking. Focusing on cold temperature properties of RAS-HMA, the study concluded the following:

    - Moisture sensitivity of the mixes was not influenced by the inclusion of shingles.

- Large deformations were observed in cold temperatures before thermal cracking occurred in the mix that contained organic shingles. Similar behavior was not evident in the performance of the fiberglass-backed shingles.

- It was observed in creep compliance testing that RAS added to softer (120/150 penetration) AC reduced deformation. When shingles were added to mixtures using harder (85/100 penetration) asphalt cements, opposite results were found.

2.3 Evaluating RAS as Aggregate in Cold Climate

In Canada the use of RAS in HMA has been limited. In 2006, the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo partnered with Miller Group Inc, Ontario Centre of Excellence (OCE) and Materials Manufacturing Ontario (MMO) as well as École de Technologie Superieure (ETS) in Montreal undertook an investigation of the behavior of a HL 8 binder course mix containing RAS [Tighe 2008]. In Phase 1 of the study, five HMA mix designs were considered, incorporating varying quantities of RAP and RAS. Mix designs were compared using the results of Dynamic Modulus and Resilient Modulus testing, which were both performed at the CPATT laboratory. The Thermal Stress Restrained Specimen Test (TSRST) and French Wheel Rutting tests were also performed at ETS [Tighe 2008]. The following five HMA mix designs were considered:

1. Mix 1 (control) –SP19C, Virgin Material
2. Mix 2 - SP19C, 20% RAP
3. Mix 3 - SP19C, 20% RAP, 1.4% RAS
4. Mix 4 - SP19C, 20% RAP, 3.0% RAS
5. Mix 5 - SP19C, 3.0% RAS

2.3.1 Phase 1 Test Methodology

To compare the various mix designs, Dynamic Modulus, Resilient Modulus, TSRST and French Wheel Rutting tests were run for all five mixes. The test procedures are described later in this chapter. The summary of the test purpose are below:

- The Dynamic Modulus test was used to measure the elastic properties of the mixtures and used as an indicator of how a mix will perform over a range of loading and temperature scenarios.
- The Resilient Modulus test provides an indication of the fatigue and thermal cracking potential as well as the quality of materials incorporated in the HMA.
- The TSRST assesses the thermal cracking resistance of a mix.
- The French Wheel Rutting test evaluates the rutting susceptibility of a mix.

2.3.2 Phase 1 Laboratory Test Results

By analyzing the various laboratory test results it was found that the performance of the mixes varied between tests. Mix 1 and Mix 2 were found to have the lowest susceptibility to fatigue, while Mix 3, Mix 4 and Mix 5 were found to have the lowest susceptibility to rutting, Mix 4 being the best in terms of rutting resistance. Mix 1 performed the best in the resilient modulus testing, followed by Mix 2 and Mix 3. The TSRST test results showed Mix 3 to be the most resistant to thermal cracking followed by Mix 1 and Mix 2. In rut testing, Mix 4 had the best overall performance, while Mix 2 had the worst. Overall, all mixes performed relatively well in the various laboratory tests. It was expected that there would be limited rutting in the field as all of the mixes displayed less than 4 mm of permanent deformation in the French Wheel Rutting test.

The laboratory analysis indicated that Mix 3 was the optimum mix based on all test results [Tighe 2008] when compared to Mix 4 or Mix 5 also containing RAS.

The results of the CPATT testing noted proper care should be taken during the addition of RAS in to the mix and also proper engineering should be carried out prior to adding RAS. It was suggested that the RAS and RAP blend needed to be optimized to ensure both thermal and rutting resistance.

2.4 HMA Performance Testing

2.4.1 Dynamic Modulus

The dynamic modulus of an asphalt mix can be measured by applying a cyclic compressive sinusoidal load on an asphalt sample and monitoring the sample's response at different temperatures [Pellin 2006].

In dynamic modulus testing a test specimen is subjected to a repeated axial cyclic load with fixed magnitude and cycle duration. As per test specifications, specimens are prepared with a 1.5 height to diameter (H/D) ratio, which means that a 100 mm diameter test specimens must have a height of 150 mm. A comprehensive study was conducted to evaluate the specimen's size and the resulting material characteristics [Witczak 1994]. It also investigated the effect of different nominal aggregate sizes and specimens with varying height to diameter ratios.

A sinusoidal loading is applied to the specimen for a minimum of 30 seconds and a maximum of 45 seconds for each load application in dynamic modulus testing [Brown 2001]. Test specimens are tested at six temperatures (-10 °C, 4.4 °C, 21.2 °C, 37.8 °C and 54 °C) and six loading frequencies (0.1 Hz, 0.5 Hz, 1.0 Hz, 5.0 Hz, 10.0 Hz and 25.0 Hz) [Brown 2001]. The applied load varies, and is usually applied in a haversine wave. A haversine wave is an inverted cosine offset by half its amplitude. A continuous haversine wave looks like a sine wave where the positive peak is at zero. Figure 2-3 is a schematic of a typical dynamic modulus test plotting [Pavementinteractive 2010].

In dynamic modulus testing the stress-strain relationship of the materials is measured under a continuous sinusoidal loading. This relationship for linear (stress-strain ratio is independent of the loading stress applied) visco-elastic materials is defined by a complex number E* shown in Equation 2.1[Witczak 2002].

$$E^* = |E^*|\cos\varphi + i|E^*|\sin\varphi \qquad (2.1)$$

Where:

E* is the Complex modulus

|E*| is the Dynamic modulus

φ is the Phase angle

i is the Imaginary number

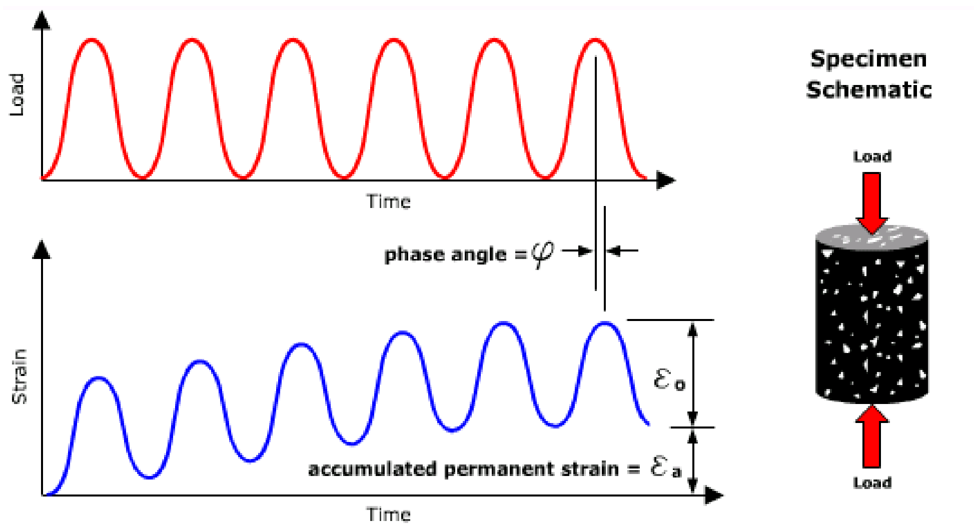

Figure 2-3 : Schematic Diagram of Dynamic Modulus Testing [Pavementinteractive 2010]

For a pure elastic material, φ = 0, and the complex modulus (E*) is equal to the absolute value, or dynamic modulus. For pure viscous materials, φ = 90°).

The absolute value of the complex modulus, |E*|, is defined as the dynamic modulus and is calculated based on Equation 2.2 [Witczak 2002]

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \tag{2.2}$$

Where:

|E*| is the Dynamic Modulus

σ_o is the peak stress amplitude(applied load / sample cross sectional area)

ε_0 is the peak amplitude of recoverable axial strain = Δ L/L (either measured directly with strain gauges or calculated from the displacement measured with linear variable displacement transducers (LVDTs))

L is the gauge length over which the sample deformation is measured

ΔL is the recoverable portion of the change in sample length due to the load

The complex modulus, E*, is the summation of two components:

1. The storage or elastic modulus component

2. The loss or viscous modulus which is the indicator of the viscous properties of the material being evaluated.

2.4.2 Resilient Modulus Testing

The fatigue and thermal cracking susceptibility of a pavement and the quality of the materials in the asphalt mix can be evaluated using the results of resilient modulus testing [Tighe 2008]. Energy absorbed by different materials results in elastic deformation that is recovered by unloading the sample. This phenomenon is measured through resilient modulus testing. In mechanistic empirical pavement design the resilient modulus test results is an important parameter which is used as an input to the multi elastic theory to compute the pavement response under traffic loading [Jahoromi 2009].

Pavement construction materials including surface and binder HMA are under a variety of temperature and stress states, which can be characterized by resilient modulus testing. The results of resilient modulus testing simulate the behavior of the pavement when it is subjected to moving wheel loads. The ratio of the deviator stress to the recoverable strain is defined as the resilient modulus. The stiffness of HMA is determined by the resilient modulus testing where diametrical repeated loading is applied to the compacted cylindrical asphalt cement specimens [Kandhal 1996].

AC experiences some permanent strain after each load application as it is not a purely elastic material. However, AC can be considered as elastic if the material strength is higher than the applied repetitive load and if the deformation due to the load is nearly recoverable and proportional to the load [Huang 1993].

Strains can be generally classified as plastic or elastic. Under repeated loads, plastic strains are noticeable in the initial stage of loading. As the number of load cycles increases, the plastic strain portion decreases while the elastic strain starts to be the dominant factor. The plastic strain almost vanishes or becomes unnoticeable after 100 to 200 cycles of loading [Jahromi 2009].

The resilient modulus represents the stiffness of the pavement mix. A pavement mix having high resilient modulus at low temperatures would be subject to a higher risk of cracking [Michael 2002]. This phenomenon occurs due to the inflexibility of the pavement mixture, which is essential in resisting low temperature cracking.

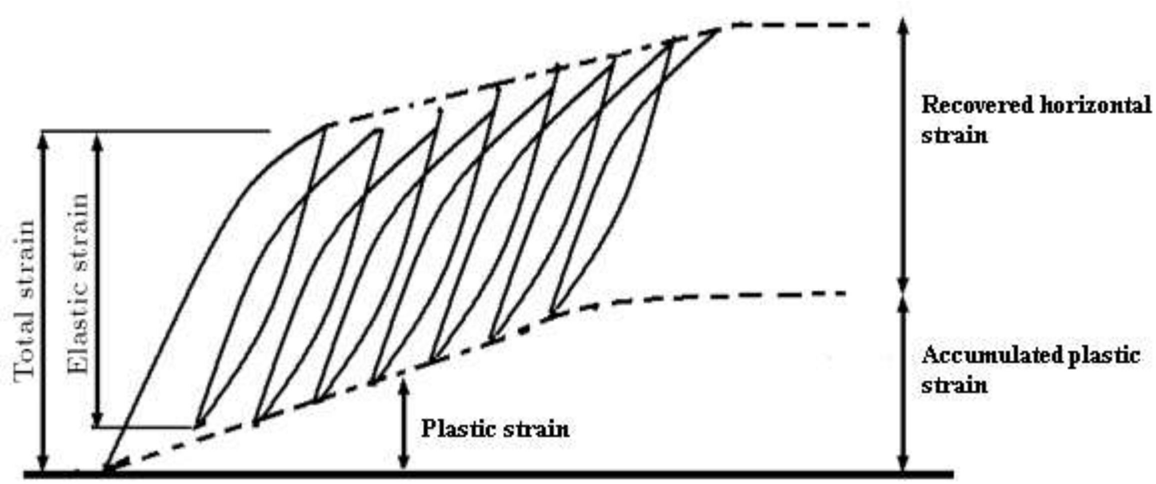

Figure 2-4 : Strain Under Repetitive Load [Jahromi 2009]

In this research, the resilient modulus of the mixes was determined by following AASHTO TP31-96, "Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension".

In resilient modulus testing the test specimen is subjected to a repeated cyclic stress of fixed magnitude with cycle duration of 1.0 second. A dynamic cycle stress (90 % of the total load) is applied to the specimens during testing. The instantaneous and total resilient (recoverable) vertical and horizontal deformation responses of the specimens are measured. The instantaneous and total resilient modulus (M_{ri} and M_{rt} respectively) are calculated by the following equations [AASHTO TP 31-96]

$$M_{ri} = \frac{P(\mu_{Ri}+0.27)}{t\,\Delta H_t} \quad (2.3)$$

$$M_{rt} = \frac{P(\mu_{Ri}+0.27)}{t\,\Delta H_t} \quad (2.4)$$

Where:

P is the repeated load, N
t is the thickness of specimens, mm
M_{ri} is the instantaneous resilient modulus
M_{rt} is the total resilient modulus
μ_{Ri} is the instantaneous resilient poison's ratio
μ_{Rt} is the total resilient poison's ratio
ΔH_t is the total recoverable horizontal deformation, mm

2.4.3 Flexural Bending Beam Testing

The capability of the material to withstand the repeated bending without failure is considered as its fatigue resistance [Akhtarhusein 1996]. A correlation exists between the measured repeated deflection and the fatigue of the asphalt pavement [Hveem 1955].

The factors such as pavement thickness, age of the pavement and the materials used in the mix influence the fatigue resistance of the pavement. Usually thicker asphalt lifts or those with a strong support structure are less likely to show fatigue cracking than thin pavements or those that do not have strong underlying layers. Fatigue cracking is the phenomena that occurs due to the strain development at the bottom of the HMA and grows towards the surface. This is known to be directly proportional to the tensile strain level [Carpenter 2003].

A significant change was observed at lower strain levels (in the vicinity of 70 microstrain) between the strain at the bottom of the HMA layer and the number of cycles to failure relationship [Monismith 1970]. In another study at low levels of strain (less than 70 microstrain), the HMA mixtures were shown to have an infinite fatigue life. After a certain loading period, the plot is essentially horizontal - indicating an infinite fatigue life. The theory suggested that, at low strain levels a continuous physical-chemical healing reaction occurs that gives ability to recover some constant amount of damage or its "healing potential" even during continuous loading. Therefore, at lower strain levels, damage accumulation is virtually non-existent if loading falls below this "healing potential" [Carpenter 2003].

Fatigue should not be a problem in a well designed pavement where strains are low enough to avoid propagation of crack. However, for under-designed pavements, fatigue failures take place under repeated loads due to higher tensile strains. If the pavement is not maintained in time, these failures ultimately result in fatigue cracking which will cause pavement deterioration. Research has been done and models have been developed on the basis of aggregate properties and response to load in order to predict the fatigue resistance of HMA [Minner 1945, Rowe 2000, Abojaradeh 2007]. Such research is based on the concept of an energy ratio to define fatigue failure for the stress-controlled and the strain-controlled modes as well as the microcracks in asphalt concrete.

Fatigue life of HMA is expressed in Equation 2.5 and Equation 2.6 [SHRP Project A003A, Pell 1998]. Tensile strain at the bottom of the HMA and the number of load applications to crack appearance in the pavement is used to develop the model.

$$N_f = K_1 \, (1/\varepsilon_t)^{K2} \qquad (2.5)$$

$$N_f = K_1 \, (1/\sigma_o)^{K2} \qquad (2.6)$$

Where:

N_f is fatigue life (cycles)

ε_t is the tensile strain at bottom of specimen (in./in.)

σ_0 is the applied tensile stress (psi

K_1 and K_2 are the experimentally determined coefficients

The coefficients K_1 and K_2 are determined by regression functions developed with the testing data plotted on a log scale. Usually, K_2 value varies in a range between 3 and 6 while K_1 may vary by several magnitudes.

Another model suggested that fatigue behavior is affected not only by strain but also by the dynamic modulus of the HMA [Finn 1977]. The following equation was proposed by this theory.

$$N_f = K \, (\varepsilon)^a \, (E^*)^b \qquad (2.7)$$

Where:

N_f is fatigue life (cycles)

K, a and b are the laboratory regression coefficient

E* is the dynamic stiffness modulus of the HMA

ε is the tensile strain at bottom of specimen (in./in.)

The Mechanistic–Empirical Pavement Design Guide (MEPDG) has also developed a fatigue model [Adhikari 2009]. Tensile strains at a given location and stiffness of the HMA layer are the basis of the MEPDG model shown in Equation 2.8.

$$N_f = C\, K_1\, (1/\varepsilon_t)^{k2}\, (1/E)^{k3} \qquad (2.8)$$

Where:

N_f is fatigue life (cycles)

ε_t is the tensile strain at critical location (in./in.)

K_1, k2 and k3 are the laboratory regression coefficients

E is the stiffness of material (psi)

C is laboratory adjustment factor

The standard flexural fatigue beam test is performed according to AASHTO T 321 07 [AASHTO 07] and this was performed in the CPATT laboratory.

In the flexural bending test, four clamps are used to hold the beam in place and a repeated haversine (sinusoidal) load is applied to the beam which is shown in Figure 2-5 [Pavementinteractive 2010].

The beam is loaded at a rate of 10 Hz. Due to a four point setup a constant bending moment is produced over the centre portion of the beam (between the two inside clamps) and the deflection at the centre of the beam is kept constant during the test.

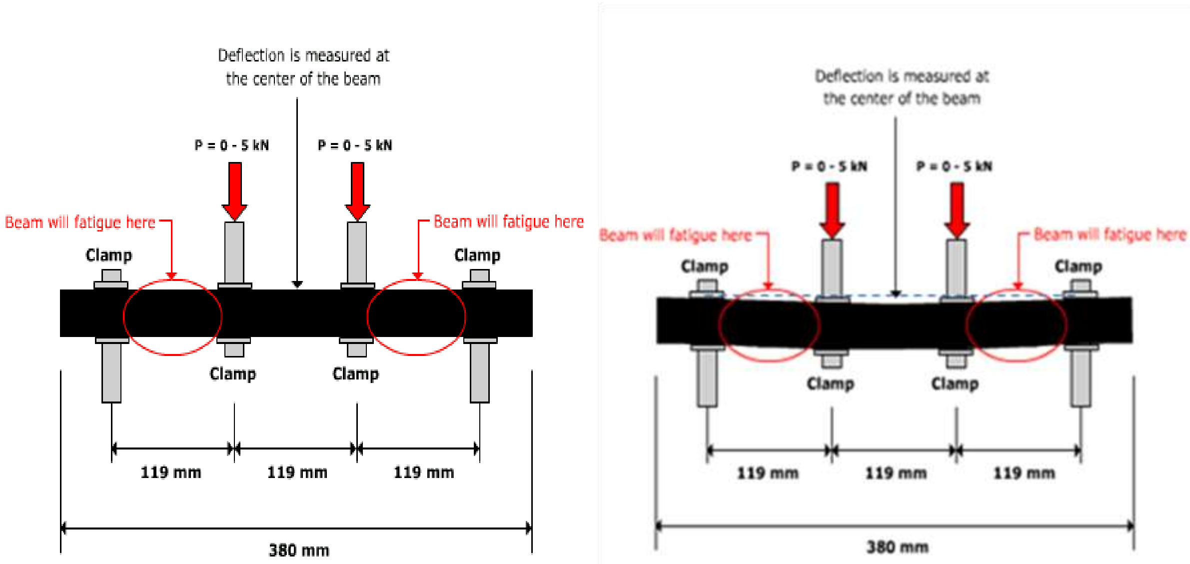

Figure 2-5 : Fatigue Deformation Before and After Applying Load [Pavementinteractive 2010]

A closed loop control system regulates the deflection at the mid-length position of the beam. Fatigue life of a particular HMA mix can be estimated from the number of loading cycles to failure. Equations 2.9 to 2.12 are used to calculate the maximum tensile stress, maximum tensile strength and phase angle.

Maximum Tensile Stress

$$\sigma_t = \frac{3aP}{bh^2} \tag{2.9}$$

Where:

σ_t is the maximum tensile stress (Pa)
a is the space between inside clamps (0.119 m)

P is the applied load (N)
b is the average beam width (m)
h is the average beam height (m)

Maximum Tensile Strain

$$\varepsilon_t = \frac{12\delta h}{3L^2 - 4a^2} \tag{2.10}$$

Where:

ε_t is the maximum tensile strain (m/m)
δ is the applied load (N)
h is the average beam height (m)
L is the beam length between outside clamps (0.357 m)
a is the space between inside clamps (0.119 m)

Flexural Stiffness

$$S = \frac{\sigma_t}{\varepsilon_t} \tag{2.11}$$

Where:

S is stiffness (Pa)
σ_t is the maximum tensile stress (Pa)
ε_t is the maximum tensile strain (m/m)

Normalized Modulus X Cycles

$$NM = \frac{Si\ X\ Ni}{So\ X\ No} \tag{2.12}$$

Where:

NM is the normalized modulus X cycles
S_i is the flexural beam stiffness at cycle i (Pa)
N_i is the cycle i
S_o is the initial flexural beam stiffness (Pa), estimated at 40 cycles
N_o is the actual cycle number where initial flexural beam stiffness is estimated

2.4.4 Thermal Stress Restrained Specimen Test (TSRST)

Low temperature cracking occurs in pavements constructed in the cold regions of the world. Without compromising other performance characteristics, such as resistance to rutting, design engineers have been working to identify the requirements to minimize low-temperature cracking of asphalt concrete pavements [Kanerva 1994].

To identify the low-temperature cracking resistance of the asphalt concrete mixes three methods were employed: (1) regression equations (2) mechanistic prediction and (3) laboratory testing.

2.4.4.1 Regression Equations

A regression equation was established by Dr Haas in 1987 following the analysis of data from 26 airfields in Canada [Haas 1987] . The regression equation was developed to predict the average transverse crack spacing of an asphalt pavement.

$$TCRACK = 218+1.28\ ACTH+2.52\ MTEMP+30\ PVN-60\ COFX \qquad (2.13)$$

Where:

TCRACK is the transverse crack average spacing in millimeters

MTEMP is the minimum temperature recorded on site in °C

PVN is the McLeod's dimensionless pen-vis number (PVN)

COFX is the coefficient of thermal contraction in mm/1000 mm/°C

CTH is the thickness of the asphalt concrete layer in centimeters

The PVN, which is an indicator of temperature susceptibility of the asphalt cement [McLeod 1972 and 1987] is determined from the penetration at 25°C and the kinematic viscosity at 135°C.

2.4.4.2 Mechanistic Prediction

In the surface layer of an asphalt pavement, low temperature cracking occurs when the thermally induced tensile stress exceeds the tensile strength of the asphalt mix. By using the pseudo-elastic beam-analysis equation of the following form, Equation 2.14 the thermally induced tensile stress can be calculated [Hills 1966].

$$\delta(T) = \alpha \sum_{To}^{Tf} s(t,T)\Delta T \qquad (2.14)$$

Where:

$\delta(T)$ is the accumulated, thermal stress for a particular cooling rate

α is the coefficient of thermal contraction

T_o is the initial temperature

T_f is the final temperature

S (t,T) is the HMA mix stiffness

ΔT is the temperature increment over which S (t, T) is applicable.

2.4.4.3 Simulation Measurement

The field condition at which an asphalt pavement fails due to thermal stress, strength and temperature can be measured in the laboratory by cold climate condition simulation [Monismith 1966]. Maintaining the specimen's constant length during cooling is the basic requirement during testing. During the early stage of TSRST test system development, fixed frames were used which were constructed from invar steel [Monismith 1965, Fabb 1974, Janoo 1989, Kanerva and Nurmi 1991]. Performances of these systems were not generally satisfactory as the frame would deflect before the specimen failed. By inserting a displacement feedback loop the test system was improved substantially [Arand 1987]. Under the Strategic Highway Research Program (SHRP) the Thermal Stress Restrained Specimen Test (TSRST) was identified as an accelerated performance test which simulates low-temperature cracking of asphalt concrete mixtures. A typical result from a TSRST is shown in Figure 2-6 [Kanerva 1994].

In the load frame a beam is mounted and the entire frame is enclosed in an environmental chamber [AASHTO TP 10-93]. In the TSRST simulation test system, a beam or cylindrical asphalt concrete sample is subjected to a thermal stress. During testing the specimens are cooled at a constant rate and a computerized hydraulic feedback system is used to keep the specimen length constant. A data acquisition system records the elapsed time, temperature, deformation and tensile load. As temperature decreases gradually (-10°C/hr) in the cabinet the thermal stress in the specimen increases until the specimen fails [Zubeck 1992].

In Figure 2-6 dS/dT, is the slope of the stress-temperature curve. It increases until a maximum value is reached. The stress-temperature curve becomes linear when dS/dT becomes constant at colder temperatures and this transition temperature divides the curve into two parts: relaxation and no relaxation. The asphalt cement becomes stiffer when the temperature approaches the transition temperature and for a specified rate of cooling the thermally induced stresses are not relaxed beyond this temperature.

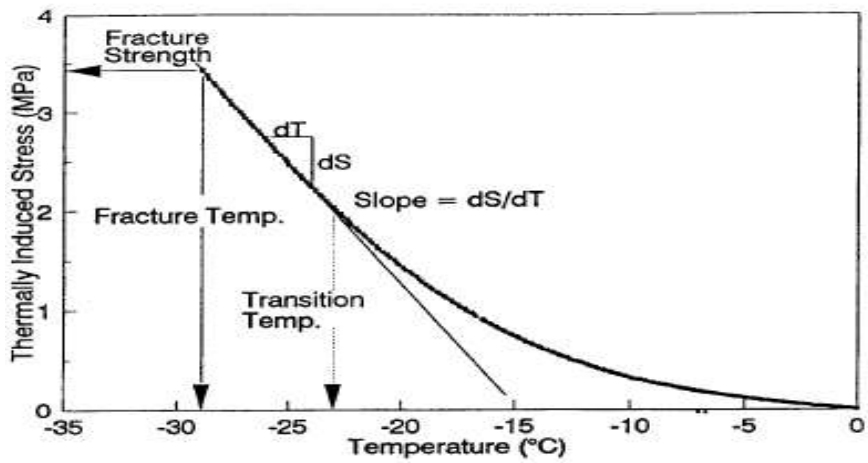

Figure 2-6 : Typical TSRST Results for Monotonic Cooling [Kanerva 1994]

The maximum stress at which the specimen fails is called the fracture strength with a corresponding fracture temperature. Equations 2.15 and 2.16 are used to calculate the fracture stress and slope of the thermally induced stress curve [AASHTO TP 10-93].

$$\text{Fracture stress} = P_{ult}/A \qquad (2.15)$$

Where:

P_{ult} is the ultimate tensile load at fracture in Newton's (pounds)

A is the average cross sectional area of the specimens mm^2

$$\text{Slope} = dS/dT \qquad (2.16)$$

Where:

dS is the average change in stress along the linear portion of the curve just prior to failure, pascal(psi)

dTis the average change in temperature along the linear portion of the curve just prior to failure, in °C.

2.5 Summary

This chapter describes the potential of including RAS in HMA. From the experience in the United States, it is evident that the performance of HMA containing RAS can be similar to that of the conventional HMA. In addition, a thorough literature review is included in this chapter regarding the laboratory tests which are used to evaluate the performance of HMA.

Chapter 3
Mix Designs

The purpose of this chapter is to describe the mixes which are used in this research. A comprehensive description on the preparation of the various HMA mixes containing RAS and details of the various important material proportions are included. Mix Types

Six asphalt mix types were included in this study. The selected mixes are Ontario HMA mixes which are used as two major construction layers of pavement: the surface layer and the binder layer. Normally these mixes do not include RAS. Thus this research attempts to evaluate the effect of the use of RAS in these six HMA mixes. These mixes were selected to represent a wide range of applications from medium to low volume municipal roads. The following mixes were tested and RAP and RAS contents are determined by mass.

- Surface Layer HMA

  1. Mix 1 – HL 3, 13.5% RAP, 1.4% RAS
  2. Mix 2 - SP12.5 FC1, 17% RAP, 3% RAS
  3. Mix 3 - SP12.5 FC2, 12% RAP, 3% RAS
  4. Mix 4 - SP12.5 FC2, 6% RAS

- Binder Layer HMA

  1. Mix 5 - SP19 E, 25% RAP, 3% RAS
  2. Mix 6 - SP19 E, 6% RAS

It should be noted that different PG grade AC used for the different mixes. The details of mix designs are included in this chapter. CPATT worked with Miller Paving Ltd to design the six mix designs. All material for the laboratory testing was obtained from Miller Paving Ltd. All the material in this study meets the Ontario Provincial Standards and Specifications (OPSS) requirements. Mix 1, HL 3 RAS was used to pave the CPATT test track. For the laboratory testing, Mix 1 was obtained from Stead and Evans Ltd's Heidelberg plant. The other five Superpave mixes were prepared at the CPATT laboratory. Approximately one and a half tons of asphalt material were used in this research and were prepared for the laboratory testing in the CPATT laboratory.

The HL 3 mix is a relatively low cost mix which is used in Ontario on low to medium volume roads. The mix gradation, volumetric, stability and flow requirements all met appropriate and relevant Ontario Provincial Standard Specification (OPSS) requirements.

All of the Superpave mixes were designed for category E (more than 30 million ESAL's) traffic loading. In addition, all the Superpave mixes (Mix 2 to Mix 6) have met the Superpave gyratory compaction requirements at the $N_{initial}$ and N_{max} number of gyrations. The gradation and the volumetric requirements have also been met for both the surface and binder course mixes.

The following standards were used in this research:

AASHTO TP 62-07[AASHTO 2007]; AASHTO TP 31-96 [AASHTO 1996]; ASTM D 6931-07[ASTM 2007]; AASHTO TP 10-93[AASHTO 1993] and AASHTO T 321 [AASHTO T 321 07] for the specimens that were prepared for Dynamic Modulus, Resilient Modulus, Indirect Tensile Strength, TSRST and Flexural Fatigue test respectively. The Superpave Gyratory Compactor (SGC) and Asphalt Vibratory Compactor (AVC) were used at the CPATT laboratory to prepare the test specimens. Figure 3-1 and Figure 3-2 shown the SGC and AVC which were used to make test specimens.

3.1 Mix Designs

To meet the Ontario Provincial Standard Specification (OPSS) PROV 1151 requirements all SP19 and SP12.5 mix designs were prepared by following Superpave methodology [MTO 2007]. The HL 3 mix was designed according to Marshall Methodology to meet the requirements of OPSS 1150 [MTO 2008].

Figure 3-1 : CPATT Superpave Gyratory Compactor (SGC)

Figure 3-2 : CPATT Asphalt Vibratory Compactor (AVC)

3.2 Source of Aggregates

For this research, different aggregate sources were used to prepare the mixes according to the mix design. Tables 3-1 to Table 3-6 provide a general overview of the aggregate and AC types and sources used in the mixes.

Table 3-1 : Mix 1 Summary

Mix1-HL 3, 1.5 % RAS, 13.5% RAP			
Name of Aggregates	**Types**	**Percentage (%)**	**Source**
CA #1	Coarse	40.3	Heidelberg(HL 3 Stone)
FA #1	Fine	8.0	Heidelberg(Screenings)
FA #2	Fine	36.7	Heidelberg(Asphalt Sand)
RAP		13.5	Heidelberg(16mm)
RAS		1.5	Miller Paving Ltd(Markham)
New AC	PG 58-28	3.9	McAsphalt Industries

Table 3-2 : Mix 2 Summary

Mix 2- SP 12.5FC1, 17% RAP , 3% RAS			
Name of Aggregates	**Types**	**Percentage (%)**	**Source**
CA #1	Coarse	26.5	MRT (HL1 Stone)
CA #2	Coarse	20.0	MRT (1/8”x1/4” Chip)
FA #1	Fine	8.0	MRT(1/4”x0 Screening)
FA #2	Fine	25.5	CBM (VFA Sand)
RAP		17.0	Miller Paving Ltd (Markham)
RAS		3.0	Miller Paving Ltd (Markham)
New AC	PG 52-34	3.27	McAsphalt Industries

Table 3-3 : Mix 3 Summary

Mix 3-SP 12.5FC2, 12% RAP , 3% RAS			
Name of Aggregates	**Types**	**Percentage (%)**	**Source**
CA #1	Coarse	25.7	MRT (HL1 Stone)
CA #2	Coarse	20.0	MRT (1/8”x1/4” Chip)
FA #1	Fine	14.0	MRT(1/4”x0 Screening)
FA #2	Fine	25.3	MRT (Mfg Sand)
RAP		12.0	Miller Paving Ltd (Markham)
RAS		3.0	Miller Paving Ltd(Markham)
New AC	PG 52-40	3.67	McAsphalt Industries

Table 3-4 : Mix 4 Summary

Mix 4- SP 12.5FC2 , 6% RAS			
Name of Aggregates	**Types**	**Percentage (%)**	**Source**
CA #1	Coarse	35.6	MRT (HL1 Stone)
CA #2	Coarse	20.0	MRT (1/8”x1/4” Chip)
FA #1	Fine	14.0	MRT(1/4”x0 Screening)
FA #2	Fine	29.4	MRT (Mfg Sand)
RAS		6.0	Miller Paving Ltd (Markham)
New AC	PG 52-34	3.58	McAsphalt Industries

Table 3-5 : Mix 5 Summary

Mix 5-SP 19E , 3% RAS , 25% RAP			
Name of Aggregates	**Types**	**Percentage (%)**	**Source**
CA #1	Coarse	25.1	Carden (HL8 Stone)
CA #2	Coarse	17.1	Carden (1/4" Chip)
FA #1	Fine	16.1	Dufferin (Mfg Sand)
FA #2	Fine	13.7	IKO (Iko Sand)
RAP		25.0	Miller Paving Ltd Markham
RAS		3.0	Miller Paving Ltd(Markham)
New AC	PG52-34	2.89	McAsphalt Industries

Table 3-6 : Mix 6 Summary

Mix 6- SP 19E ,6% RAS			
Name of Aggregates	**Types**	**Percentage (%)**	**Source**
CA #1	Coarse	39.5	Carden (HL8 Stone)
CA #2	Coarse	25.5	Carden (1/4" Chip)
FA #1	Fine	28.8	Dufferin (Mfg Sand)
FA #2	Fine	11.9	IKO (Iko Sand)
RAS		6.0	Miller Paving Ltd(Markham)
New AC	PG 52-40	3.28	McAsphalt Industries

3.3 Volumetric Properties

Volumetric properties of the six mixes are shown in Table 3-7. Design air void content, design gyrations, voids in mineral aggregates (VMA), voids filled with asphalt (VFA), AC content and other general features of the mixes are included in this Table.

Table 3-7 : Volumetric Properties of the Mixes

Property	Mix #1	Mix #2	Mix #3	Mix #4	Mix #5	Mix #6
Air Voids,%	4.0	4.0	4.0	4.0	4.0	4.0
N_{design} - Gyrations	N/A	125	125	125	125	125
VFA (%)	73.2	74.2	74.9	75.1	70.3	64.4
VMA (%)	15.0	15.5	16.0	16.0	13.3	12.9
Tensile Strength Ratio (%)	N/A	>=80	>=80	>=80	>=80	>=80
Stability	16750	N/A	N/A	N/A	N/A	N/A
Flow(0.25mm)	10.5	N/A	N/A	N/A	N/A	N/A
Total AC Content(%)	5.0	5.1	5.2	5.2	4.9	4.9
New AC(%)	3.97	3.3	3.3	3.6	2.9	3.3
Total Recycled AC (%)*	1.03	1.83	1.93	1.62	2.01	1.62

* AC from RAP and RAS,N/A -Not Applicable

3.4 Mix Gradation

Gradation plots and the specified gradation envelope for Mix 1 which is the Marshall mix are shown in Figure 3-3. Individual gradation plots for the mixes that were designed with the Superpave methodology and the control points are shown in Figure 3-4 and Figure 3-5 respectively. The mix gradations of all the mixes are given in Table 3-8.

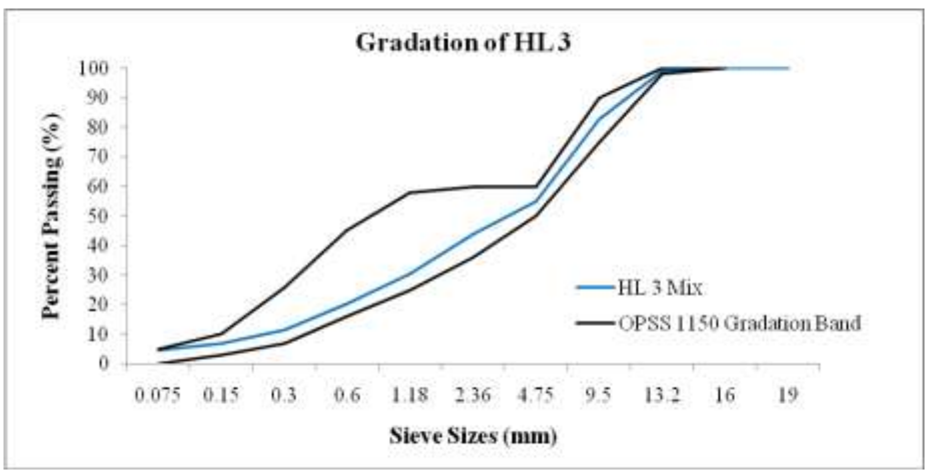

Figure 3-3 : Gradation of Mix1

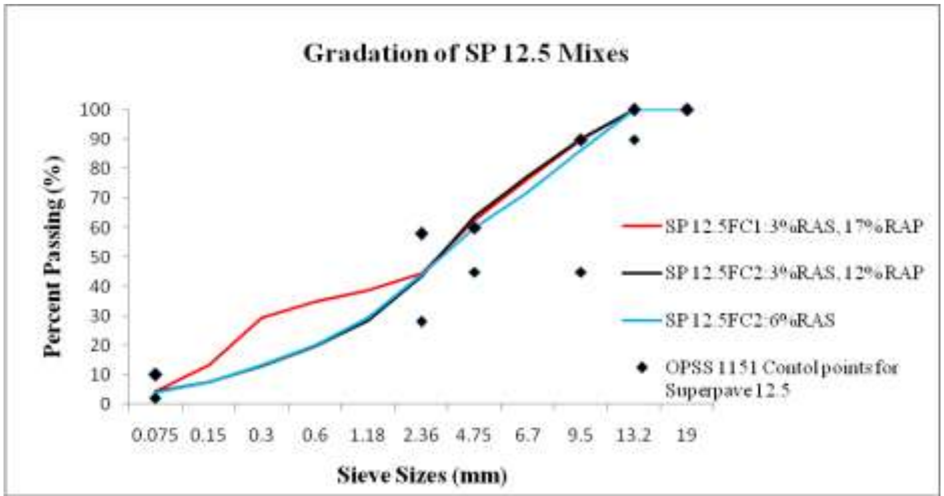

Figure 3-4 : Gradation of Superpave Mixes for Surface Course (Mix 2, Mix 3 and Mix 4)

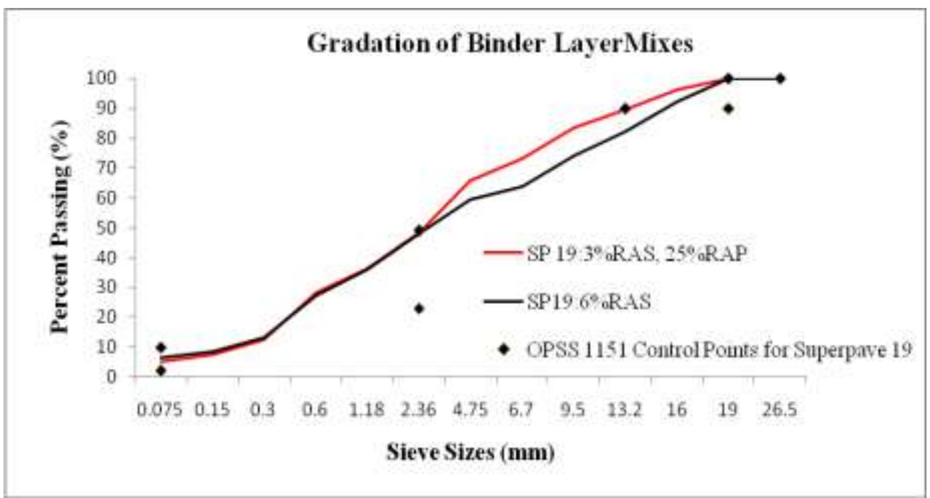

Figure 3-5 : Gradation of Superpave Mix for Binder Course (Mix 5 and Mix 6)

The gradation plots of the mixes shows that all the mixes are within the design specifications. Mix 1 which is a Marshall Mix is within the OPSS 1150 gradation band for HL 3 design. Superpave surface course mixes (SP12.5 FC1 and SP12.5 FC2) also satisfy the control points of OPSS 1151. A similar conclusion can be made for the Superpave binder layer mix SP 19.

Table 3-8 : Gradation of Aggregates

	Mix 1 HL3, 1.5% RAS, 13.5% RAP	Mix 2 SP 12.5 FC1, 3% RAS, 17% RAP	Mix 3 SP12.5 FC2 3% RAS , 12% RAP	Mix 4 SP 12.5 FC2 6% RAS	Mix 5 SP 19E 3 % RAS, 25% RAP	Mix 6 SP 19E 6% RAS
Sieve Size(mm)	**Cumulative Percent Passing**					
26.5	100.0	100.0	100.0	100.0	100.0	100.0
19	100.0	100.0	100.0	100.0	100.0	99.8
16	100.0	100.0	100.0	100.0	96.1	92.4
13.2	99.0	100.0	100.0	100.0	89.7	82.3
9.5	82.7	90.0	90.2	86.4	83.6	74.1
6.7	64.8	76.6	77.7	72.1	73.1	63.7
4.75	55.0	62.6	64.0	60.0	65.9	59.3
2.36	43.7	44.6	43.4	44.3	48.3	48.0
1.18	30.3	38.7	28.6	29.5	36.2	36.0
0.6	20.2	35.0	19.6	20.1	28.1	27.3
0.3	11.5	29.4	13.1	13.4	12.5	13.2
0.15	6.8	13.2	7.6	7.5	7.5	8.4
0.075	4.6	4.4	4.2	4.0	5.2	6.4

3.5 Antistriping Additives

Polymer Antistripping Treatment (PAT) was applied to all coarse and fine aggregates of Mix 2, Mix 3 and Mix 4 except FA # 2(VFA sand) of Mix 2 [OPSS 313 2007]. Ultracote UP 5000 which is a latex polymer antistrip material was applied to the aggregate of the mix prior to coating with asphalt. Ultracote UP 5000 emulsion was received with 65% latex solids. Mixing and coating the emulsion involved diluting to 5% solids by adding 1200 grams of water to 100 grams of 65% UP-5000. Prior to the application of the 5% UP 5000, aggregates were oven dried. During the application, 15 grams of 5% UP 5000 were added slowly to the 1000 grams of aggregate and aggregates were mixed until coated thoroughly. After mixing the latex emulsion the aggregate was placed back in the oven and heated to the appropriate mixing temperature. Figure 3-6 shown with the Ultracote UP 5000 and its applications.

Figure 3-6: Application of UP5000 to Aggregates

3.6 Mix Preparation

Mixes 2, 3, 4, 5 and 6 were prepared in the CPATT laboratory at the University of Waterloo. The aggregate which was collected from Miller Paving Ltd's Markham plant was dried and sieved in the laboratory. For ease of mixing 15 kg batches were prepared according to the mix designs. Table 3-9 shows a sample calculation of a 15 kg batch of Mix 3. The aggregates were kept in the oven for 16 hours at the mixing temperature and the AC which was preheated to the mixing temperature was added in a mixing bowl. Figure 3-8 to Figure 3-13 show the mixing being carried out at the CPATT laboratory. The mixing was continued until the aggregates were thoroughly coated with AC. Approximately 2 to 3 minutes were required to complete the mixing and it was confirmed by visual inspection. The prepared asphalt mixes were then put in boxes to be preserved at room temperature. For quality control (QC) testing samples were collected from random batches.

Table 3-9 : Preparation of 15 Kg Batch - Mix 3 -SP 12.5 FC2, 6% RAS

Sieve Size (mm)	**Materials Retained (gm)**				
	HL1 Stone MRT	**1/8" x ¼" Chips MRT**	**¼" x 0 Screenings MRT**	**Mfg. Sand MRT**	**RAS Markham**
RET 25	0.0	0.0	0.0	0.0	
RET 19.0	0.0	0.0	0.0	0.0	
RET 16.0	0.0	0.0	0.0	0.0	
RET 12.5	117.5	0.0	0.0	0.0	
RET 9.5	2120.0	2.1	0.0	0.0	
RET 6.7	1966.0	107.1	33.8	0.0	
RET 4.75	907.0	630.0	231.8	0.0	
RET 2.36	139.0	1188.6	600.8	352.8	
PASS 2.36	91.0	172.2	1383.7	4057.2	900.0
Total	5340.0	2100.0	2250.0	4410.0	900.0
Total	**15000.0**				

Figure 3-7 : Batch Preparation

Figure 3-8 : Mixing of Aggregates with Additives

Figure 3-9 : Addition of AC to Aggregates

Figure 3-10 : Mixing of Aggregates and AC

Figure 3-11 : Mixing of Aggregates and AC

Figure 3-12 : Transferring Asphalt to Boxes

3.7 Summary

Six mixes were evaluated in this research. The mixes are typical Ontario HMA mixes which are used on low to high volume roads. Among the mixes, four were surface layer mixes and two were binder layer mixes. Different performance graded asphalt cements ranging from PG 58-28 to PG 52-40 were used in the mixes. Marshall Mix HL 3 contains 1.5% RAS and 13.5% RAP was used to pave the CPATT test track. Additionally, five Superpave mixes were prepared at the CPATT laboratory following the MTO guidelines. Ultracote UP 5000 was used as an antistripping agent for surface layer mixes SP 12.5 FC1 containing 3% RAS and 17% RAP, SP12.5 FC2 containing 3% RAS and 12% RAP and SP12.5 FC2 containing 6% RAS. All the mixes met the Ontario Provincial Standards and Specifications (OPSS) requirements.

Chapter 4

Laboratory Testing and Result Analysis

This chapter describes the comprehensive laboratory testing that was performed at the CPATT laboratory to determine the characteristics of the various mixes. The results of the laboratory testing were analyzed and are presented in this chapter.

4.1 Laboratory Testing

4.1.1 Material Testing System (MTS)

Both of the CPATT Material Testing Systems (MTS) were used to test the HMA mixes by performing dynamic modulus, resilient modulus, TSRST and flexural fatigue Beam testing. CPATT has two MTS devices, both of which include an integrated load frame containing a hydraulic power supply and a control panel. In addition, there is an environmental chamber. Figure 4-1 shows a one of the MTS with the environmental chamber.

Figure 4-1 : Material Testing System (MTS) with Environmental Chamber

Figure 4-2 shows CPATT MTS asphalt testing equipment which is used to carry out the flexural fatigue test. This test does not require an environmental chamber.

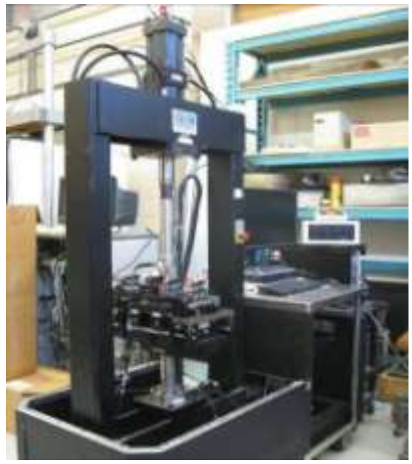

Figure 4-2: MTS used for Flexural Bending Beam Testing

4.2 Dynamic Modulus Testing

Dynamic modulus result indicate how a mix will perform over a over a range of loading (i.e. traffic) and temperature scenarios. The test was performed in accordance with the AASHTO TP 62-07 "Standard Test Method for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures" [AASHTO 2007]. The dynamic modulus testing involved preparation of 150 mm diameter specimens using the CPATT Superpave Gyratory Compactor (SGC). The specimens were then cored from the 150 mm samples to produce a cylindrical sample 100 mm in diameter with an average air void content of 7.0 ±1% as specified by the specification.

4.2.1 Sample Preparation

A number of trials were involved to obtain test specimens with the desired characteristics, mainly void content. Depending on the mix type, it was a challenging to get the target air void level of 7 ± 1.0 % as the air voids of the cores taken from the centre of the cylinder were significantly lower than those measured in the entire cylinder. A number of trials with different number of gyrations were performed to get the target air voids from the different mixes. Table 4-1 summarizes the number of trials, number of gyrations and the quantity of air voids that were produced for each mix during compaction by gyratory compaction process. Table 4-2 summarizes the air voids of the cored specimens for each mix that were tested for dynamic modulus Testing. A testing specimen which was cored from a gyratory cylinder is shown in Figure 4-3.

Table 4-1: Trials for Achieving 7±1% Air Voids

AV(%)= Air Voids (%)

Mix 1		**Mix 2**		**Mix 3**		**Mix 4**		**Mix 5**		**Mix 6**	
Number of Gyration	AV (%)	Number of Gyration	AV (%)	Number of Gyration	AV (%)	Number of Gyration	AV (%)	Number of Gyration	AV (%)	Number of Gyration	AV (%)
50	4.1	40	5.0	30	5.1	20	5.3	40	5.8	**35**	**7.8**
45	4.1	30	5.8	25	6.6	17	5.5	35	7.8	33	8.6
30	5.4	25	6.4	**20**	**7.0**	**14**	**7.5**	33	7.8	30	8.5
20	6.3	20	6.7	18	8.3	13	6.1	**30**	**6.4**		
15	**7.3**	**17**	**7.3**	17	7.4			34	7.8		
10	8.0	14	7.9	15	9.5			33	7.8		

Table 4-2: Dynamic Modulus Testing Specimen Air Voids Content

Specimens	**Air Voids (%)**					
	Mix 1	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**	**Mix 6**
1	7.5	6.9	6.4	6.1	6.8	6.1
2	7.4	7	6.4	6.7	7.1	6.6
3	7.4	7.2	6.5	6.1	7.3	7.3

Figure 4-3 : Dynamic Modulus Test Specimen

4.2.2 Dynamic Modulus Test Result

The dynamic modulus of each specimen was calculated following the AASHTO TP 62-07 specification and using the “Report Generator” feature within the asphalt testing system of the CPATT MTS. Figure 4-4 shows the testing configuration in the environmental chamber of the MTS-810. Two 75 mm Linear Variable Differential Transducers (LVDT's) were used to measure the deformations of each specimen. The specimens were tested in the environmental chamber as shown in Figure 4-4.

Each test specimen was tested at five temperatures (-10 °C, 4.4 °C, 21.1 °C, 37.8 °C, and 54.4 °C) and at six loading frequencies (0.1 Hz, 0.5 Hz, 1.0 Hz, 5.0 Hz, 10.0 Hz, and 25.0 Hz). The test specimen was placed in the environmental chamber to allow the sample to reach the specified test temperature within ±0.3°C. Depending upon the test temperature, a cyclical load was applied to the specimen following the AASHTO TP 62-07 suggested range [AASHTO 2007]. Table 4-3 summarizes the average dynamic modulus test results at different temperatures for all mixes. Figure 4-5 and Figure 4-6 show the typical Dynamic Modulus results at varying temperature and frequency for Mix 1 HL 3 containing 1.5% RAS and 13.5 % RAP.

Figure 4-4 : A Test Specimen in the Environmental Chamber for Dynamic Modulus Test

To compare the mix performance of various HMA mixes containing RAS, dynamic modulus testing results were used to prepare two master curves: one for the surface layer and one for the binder layer. As an example a master curve for Mix 1 is presented in Figure 4-5. A Second order polynomial equation was used to develop the master curve of the mixes AASHTO PP 62-09 standard [AASHTO 2009]. Figure 4-6 shows the master curves for the surface layer mixes and Figure 4-7 shows the master curve for the binder layer mixes.

Table 4-3: Average Dynamic Modulus Test Results

Mix	**Frequency (Hz)**	**Average Dynamic Modulus (MPa)**				
		-10°C	4.4°C	21.1°C	37.8°C	54.4°C
Mix 1	25	16,294	12,003	5,985	3,016	826
	10	16,133	11,579	5,343	2,473	643
	5	15,739	11,157	4,812	2,095	550
	1	14,098	9,111	3,603	1,494	409
	0.5	13,435	8,381	3,223	1,323	370
	0.1	11,838	6,652	2,398	1,038	309

Mix	Frequency (Hz)	Average Dynamic Modulus (MPa)				
		-10°C	4.4°C	21.1°C	37.8°C	54.4°C
Mix 2	25	24,373	14,985	7,088	2,413	868
	10	23,041	13,380	5,999	2,045	702
	5	21,893	11,977	5,355	1,779	613
	1	19,071	9,294	4,117	1,414	498
	0.5	17,827	8,234	3,737	1,295	463
	0.1	15,180	6,472	2,924	1,074	403
Mix 3	25	26,599	14,749	7,405	2,345	868
	10	25,392	13,288	6,381	2,159	685
	5	24,125	12,316	5,608	1,892	601
	1	21,045	9,634	4,198	1,423	458
	0.5	19,927	8,721	3,737	1,288	418
	0.1	17,012	6,941	1,316	1,067	356
Mix 4	25	25,387	14,459	7,071	2,650	1044
	10	24,382	13,310	6,272	2,313	850
	5	22,784	12440	5,619	2,023	721
	1	20,701	9,639	4,199	1,504	548
	0.5	18,767	8,902	3,790	1,330	503
	0.1	16,782	7,019	2,973	1,140	413
Mix 5	25	24,888	16,700	9,272	4,045	1339
	10	24,106	14,412	8,188	3,431	1119
	5	23,278	13,879	7,584	3,054	957
	1	20,764	12,789	5,735	2,978	710
	0.5	19,665	10,598	5,118	2,074	645
	0.1	17,412	9,023	4,060	1,565	527
Mix 6	25	29,006	20,157	7,721	5,558	2203
	10	27,600	19,557	6,272	4,890	1822
	5	26,453	18,621	5,619	4,298	1500

Mix	Frequency	Average Dynamic Modulus (MPa)				
	(Hz)	-10°C	4.4°C	21.1°C	37.8°C	54.4°C
	1	23,787	15,293	4,199	3,211	1075
	0.5	22,730	13,818	3,790	2,783	988
	0.1	20,136	12,012	2,973	2,169	748

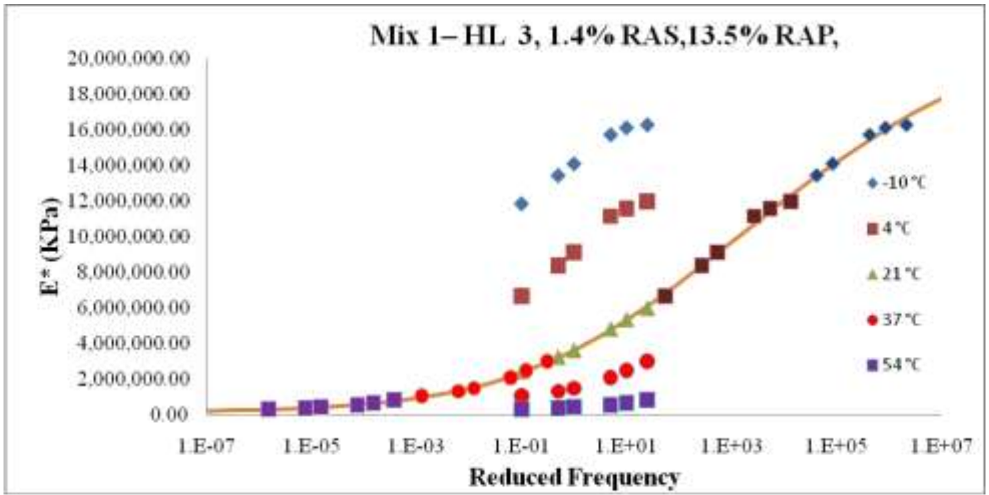

Figure 4-5: Master Curves of the Mix 1-HL 3, 13.5% RAP, 1.5% RAS

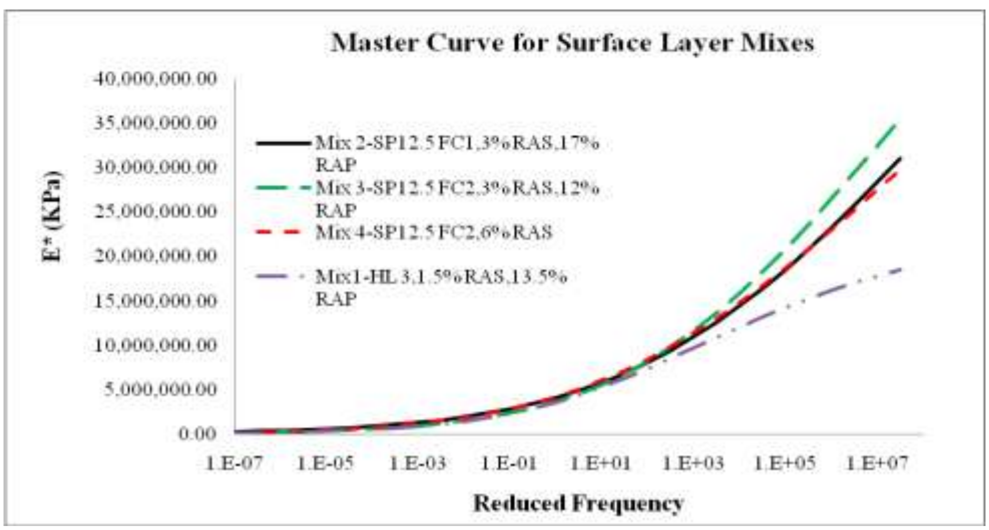

Figure 4-6: Master Curves for Surface Layer Mixes

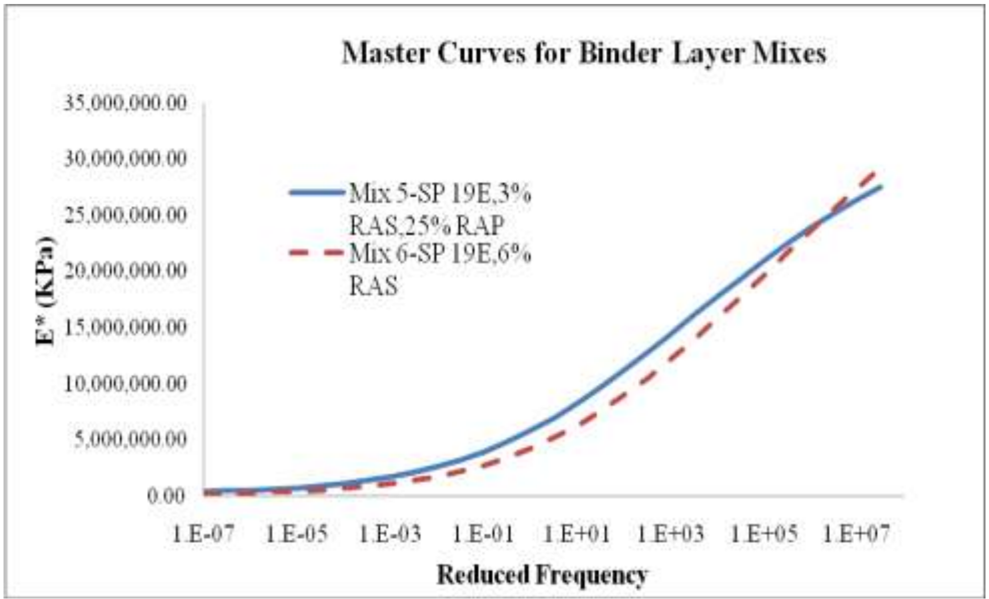

Figure 4-7 : Master Curves for Binder Layer Mixes

To reduce rutting potential, a higher dynamic modulus at high temperatures is desirable, while a lower dynamic modulus at low temperatures is desirable to reduce fatigue cracking potential. At low temperatures Mix 3 (SP12.5 FC2 containing 3% RAS and 12 % RAP) a surface layer mix and Mix 6 (SP 19E containing 6% RAS) a binder layer mix, had the highest dynamic modulus relative to the comparable mixes, indicating higher fatigue cracking susceptibility. At high temperatures Mix 1(HL 3 containing 1.5 % RAS and 13.5 % RAP) a surface layer mix and Mix 5 (SP19 E containing 3% RAS and 25 % RAP) a binder layer mix had the lowest dynamic modulus relative to the comparable mixes, indicative of lower resistance to rutting.

4.2.3 Comparison of Test Results

The dynamic modulus test results for Mix 1(HL 3 containing 1.5% RAS and 13.5% RAP) were compared with results of a conventional HL 3 mix from Uzarowski in 2006 at CPATT [Uzarowski 2006]. The test results are summarized in Table 4-4.

Table 4-4: HL 3 Dynamic Modulus Test Results [Uzarowski 2006]

Loading Frequency (Hz)	Dynamic Modulus (MPa)				
	-10°C	4.4°C	21.1°C	37.8°C	54.4°C
25	29,035	18,234	8,517	3,677	1,772
10	26,141	15,782	6,724.	2,531	1,241
5	23,758	14,155	5,632	2,001	1,062
1	19,464	8,970	3,567	1,324	789
0.5	17,024	8,410	2,903	1,139	723
0.1	12,462	5,904	1,923	876	543

4.2.4 Statistical Analysis of Dynamic Modulus for HL 3 RAS and Conventional HL 3 Mix

The t-test has been performed for comparing the dynamic modulus of HL 3 containing RAS and a conventional HL3 mix. The hypothesis of the t-test is given below:

Ho : $\mu_D = 0$

Ho : $\mu_D \neq 0$

Where μ_D is the difference between the dynamic modulus results for HL 3 containing RAS and conventional HL 3 mix. The results from the t- test are summarized in Table 4-5.

For the highest and lowest temperature hypothesis, H_0 is rejected as $t_{observed} > t_{critical}$. This indicates that the two mixes are statistically different at the high (54.4 °C) and low (-10°C) temperatures. However, at 4.4°C, 21.1°C and 37.8 °C they are statistically the same. This indicates that addition of RAS at the high and low temperature ranges need to be carefully monitored and evaluated to ensure it performs well in the field. The results of the dynamic modulus testing at -10°C and 54.4°C indicate that both mixes are adequate and will perform well. In addition, it should be noted that the mix design, air voids, testing equipment and testing procedures are the major factors that influence the dynamic modulus testing and the two mixes, composed of different materials, both met the respective requirements for HL 3. In short, different aggregates and slightly different gradations were used in the conventional HL 3 and HL 3 containing RAS [Uzarowski 2006].

Table 4-5: t-Test results for Dynamic Modulus |E*| comparison

Loading Frequency (Hz)	Differences in Dynamic Modulus (MPa)				
	-10°C	4.4°C	21.1°C	37.8°C	54.4°C
25	9846	3778	739	-484	415
10	10007	4202	1381	58	597
5	8019	2997	819	-93	512
1	5365	-141	-35	-170	380
0.5	3589	28	-319	-184	352
0.1	624	-747	-475	-161	233
Mean, $\mu_{1-}\ \mu_2$	6242	1686	351	-172	415
SD	3733	2210	736	177	127
Var	139,40,098	48,88,431	5,42,699	31,475	16,192
$t_{observed}$	4.1	1.9	1.2	-2.4	7.9
$T_{Critical}$: $t_{(5,0.025)}$	2.57				

4.3 Resilient Modulus Test

Resilient Modulus test results describe fatigue and thermal cracking susceptibility of a pavement and the quality of the materials in the asphalt mix. This test was performed at the University of Waterloo's CPATT laboratory following AASHTO TP 31-96, "Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension" [AASHTO 1996]. Test specimens were 150 mm in diameter and prepared using the CPATT Superpave Gyratory Compactor (SGC).

4.3.1 Sample Preparation

The findings related to achieving desired air void contents in the preparation of dynamic modulus samples were applied to the preparation of the resilient modulus sample. This being that the optimum number of gyrations required to get 7%±1% air voids were used.

Depending on the maximum size of aggregate in the mix, the test specimen thickness was determined from AASHTO TP 31-96 requirements and samples were obtained by cutting a 150 mm diameter gyratory prepared cylinder. Figure 4-8 shows an example of a test specimen which was tested for resilient modulus. Table 4-6 summarizes the air void content of the specimens after they were cut to size for resilient modulus testing.

Table 4-6: Specimen Air Voids content for Resilient Modulus Testing

Specimens	Air Voids (%)					
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
1	6.2	7.8	6.9	6.7	6.9	6.7
2	6.4	7.7	6.6	6.8	6.8	7.1
3	6.3	7.9	6.5	7.1	7.2	7.2

Figure 4-8 : Resilient Modulus Sample for Mix 5-SP 19, 6% RAS

4.3.2 Resilient Modulus Testing Results

4.3.2.1 Indirect Tensile Test Results

To establish the load level for the resilient modulus testing, a destructive Indirect Tensile Test (IDT) was performed at 25°C. The IDT strength of the mix was determined in accordance with the ASTM D 6391-07 “Standard Test Method for Indirect Tensile Strength of Bituminous Mixtures" [ASTM D 6391-07]. Figure 4-9 shows the IDT testing system using the Master Loader HM 3000 at the CPATT laboratory. Table 4-7 summarizes the IDT values of the mixes. The IDT results of the mixes were determined by the Equation 4.1.

$$S_t = (2 \times P) / (\pi \times t \times D) \tag{4.1}$$

Where:

S_t is the indirect tensile strength, KPa

P is the maximum load, N

t is the specimen height before test, mm

D is the specimen diameter, mm

Table 4-7: Indirect Tensile (IDT) Results

Mix	**Avg. Load (kN)**	**Std Deviation of Load(kN)**	**Avg. IDT(kPa)**	**Std Deviation of IDT(kPa)**
Mix 1	11.12	0.27	1.31	0.27
Mix 2	6.80	0.14	0.83	0.02
Mix 3	6.58	0.007	1.13	0.003
Mix 4	6.26	0.09	0.75	0.02
Mix 5	6.93	0.46	0.83	0.25
Mix 6	10.50	0.48	1.29	0.03

4.3.3 Resilient Modulus Testing System

The resilient modulus of each specimen was calculated following the AASHTO TP 31-96 specification and using the "Report Generator" feature within the asphalt testing system of the CPATT MTS. Figure 4-10 shows the testing configuration in the MTS 810 for resilient modulus testing. The system is fully computer controlled. Two LVDT's were used on each sample to measure vertical deformation. Two extensometers were used to measure the horizontal deformation

Figure 4-9: IDT Testing in Master Loader HM-3000

Figure 4-10 : Resilient Modulus Testing in MTS

4.3.4 Resilient Modulus Testing Results

To start the testing the actuator shaft was lowered carefully such that it touched the surface of the specimen. The testing was started and loading was 10% of the load which was determined by the IDT test result as presented earlier. Table 4-8 summarizes the test results. The resilient modulus test results showed that for the surface layer mixes, Mix 1(HL 3 containing 1.5% RAS and 13.5 % RAP) had the highest total and instantaneous resilient modulus result. A higher resilient modulus result represents an indication of increased potential for thermal cracking. Mix 4 (SP 12.5 FC2 containing 6% RAS) was the lowest resilient modulus result among the surface mixes.

Table 4-8: Resilient Modulus (MPa) Test Result

Mix	Average Total Resilient Modulus (MPa)	Average Instantaneous Resilient Modulus (MPa)	Total Poisson Ratio	Instantaneous Poisson Ratio
Mix 1	2,889	2,728	0.28	0.30
Mix 2	1,376	1,374	0.32	0.32
Mix 3	1,162	1,157	0.34	0.34
Mix 4	1,013	1,049	0.34	0.34
Mix 5	1,482	1,472	0.29	0.25
Mix 6	1,709	1,728	0.25	0.30

For the binder layer mixes, Mix 6 which has the highest RAS content 6% RAS, showed the higher resilient modulus result, therefore greater than Mix 5. An average Poisson Ratio from 0.25 to 0.35 was observed among the mixes. In determining the quality of asphalt materials the Poisson Ratio is not influential parameter but it is commonly accepted to be about 0.3.

4.3.5 Comparison of Resilient Modulus Results for the Binder Layer

Binder layer mixes, Mix 5 and Mix 6, can be compared with previous test, which were performed at the CPATT laboratory in 2006 [Tighe 2008]. In 2006 resilient modulus was tested for the mixes SP 19C (control), SP 19C containing 20% RAP and SP 19C containing 1.4% RAS and 20% RAP at the CPATT laboratory. The results show that Mix 6 (SP 19E containing 6% RAS) has a higher resilient modulus value as compared to the SP 19C control mix. Mix 5 (SP 19E containing 3% RAS and 25% RAP) also showed similar resilient modulus values of SP 19C control mix which was tested in 2006. Figure 4-11 compare the resilient modulus results of the binder layer mixes which were tested in 2006 and 2010.

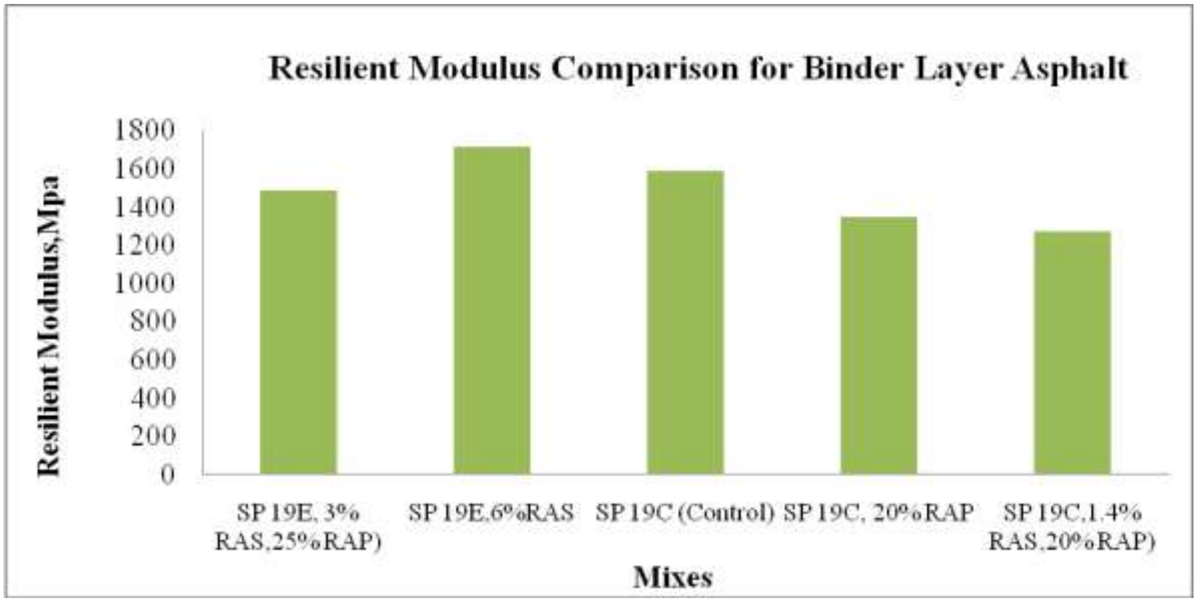

Figure 4-11: Resilient Modulus Results of Binder Layer Mix

4.4 Flexural Bending Beam Test

Flexural fatigue resistance of the HMA is an indication of its resistance to fracturing or failure under a repeated bending load. This test was performed for the for surface layer mix at the University of Waterloo's CPATT laboratory following ASTM D 7460-08 "Standard Test Method for Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending" [ASTM 2008]. Samples were prepared in an asphalt vibratory compactor (AVC) and then cut to dimension of 380 mm by 50 mm by 63 mm. During the testing the beams were subjected to a cyclic haversine load in a four point bending frame.

4.4.1 Sample Preparation

The AVC at the CPATT laboratory was used to make beams (390 mm x73 mm x 70 mm) for Flexural Bending Beam testing. The AVC applies vibration at 110 kPa of pressure for 25 seconds to create a beam that meets the air void content of 7 ± 1.0%. The beam was then cut to 380 mm x 63 mm x 50 mm for testing. Figure 4-12 shows a beam being cut in preparation for testing. Table 4-9 provides a summary of air voids of test specimens. Mix 5 and Mix 6 which were the binder layer mixes consistently had air void contents above the desire 7 ±

1.0% and it was not possible to achieve further compression in the AVC. This was possibly due to the larger aggregate in the mix. Several trials were performed by changing the AVC compaction pressure from 110 kPa to 120 kPa and also increasing the vibration time from 25 seconds to 45 seconds. After several trials the minimum air void content that was achieved for this two mixes was about 10%. Therefore, the results of fatigue testing for the binder layer mixes could be lower due to the high air voids in the samples.

Table 4-9: Air Void Content of Specimens Tested for Flexural Fatigue

Specimens	Air voids (%)					
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
1	7.8	8.2	7.7	7.3	10.3	10.1
2	8.1	7.9	7.6	6.8	10.0	9.7
3	7.1	7.1	7.9	7.2	9.8	10.6

Figure 4-12: Saw Cutting of Fatigue Beams

4.4.2 Test Instrumentation

The general configuration for the test setup of the four point bending beam in the CPATT MTS is shown in Figure 4-13. The system is fully computer controlled and it consists of a load frame, a closed loop control and data acquisition system. Three beams of each mix were tested according to ASTM D 7460-08 specifications at room temperature, 21°C [ASTM 2008].

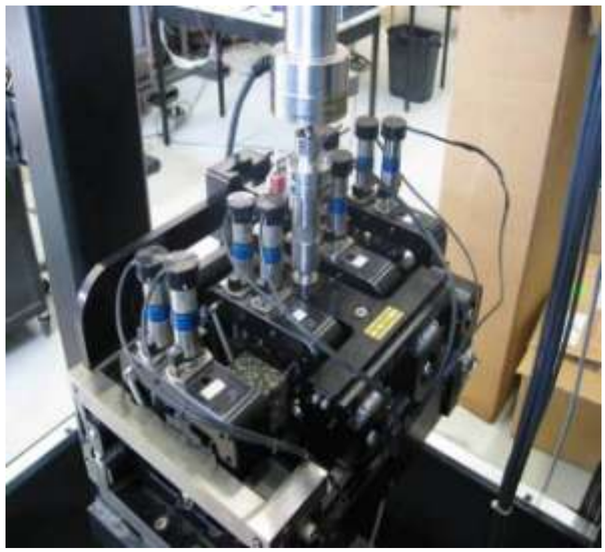

Figure 4-13 : Typical Set up for Fatigue Failure Testing in MTS

4.4.3 Flexural Bending Testing

The test beam was put in to position in the bending apparatus and the horizontal spacing of the clamps (119 mm) was completed with the assistance of the alignment bar. When the specimens and clamps were in position, side and top clamps were closed around the sampled. Adequate clamping pressure was applied. It was finally confirmed that all clamps were seated properly and laid flat against the beam.

Following ASTM D 7460-08 the microstrain level that the test would run at was selected to ensure that samples were loaded for at least 10,000 cycles. After a few trial and error run it was determined that testing the samples at 800 microstrains would ensure testing past 10,000 cycles without tests running for too long. After selecting all the testing parameter, the control and the data acquisition systems were activated. The test was terminated automatically when the stiffness of the beam reduced 40 % of the initial stiffness.

4.4.3.1 Test Results

Maximum tensile stress, flexural beam stiffness, and normalized modulus x cycles were calculated using the Equations 2-9, 2-11 and 2-12. A sample calculation is given in Table 4-10 for Mix 2. Figure 4-14 shows the normalized modulus x cycles versus cycle number to determine the failure point from a best fit polynomial. The peak of the plot was found by taking the first order differential of the curve equation is equal to zero. Table 4-11 shows the summary of the failure point for each mix that was tested.

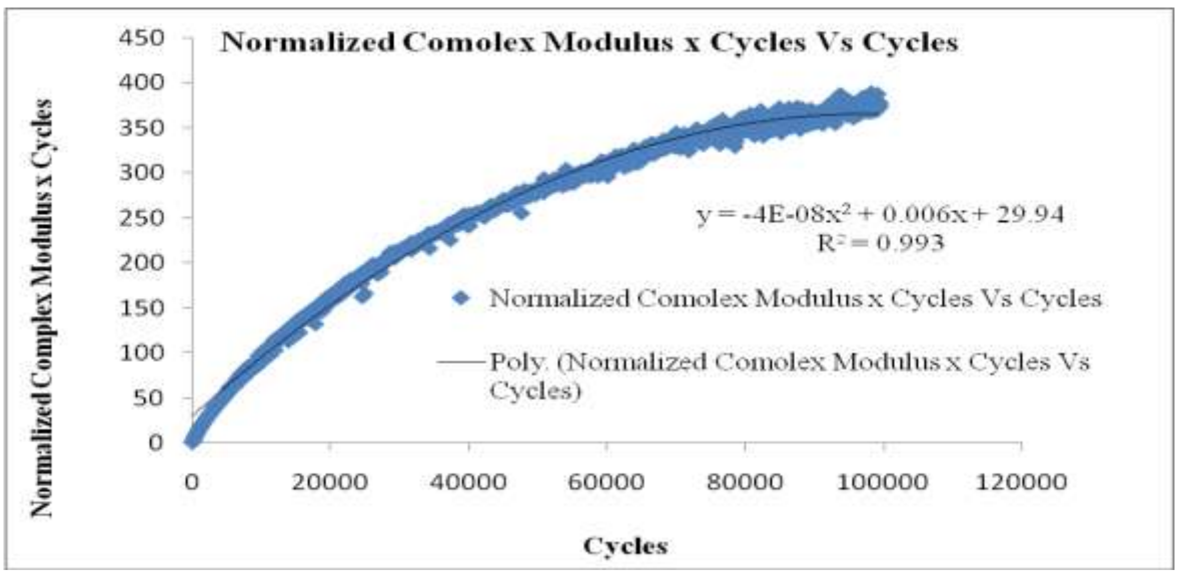

Figure 4-14: Fatigue Failure Test Results of Mix 2

Table 4-10: Typical Fatigue Testing Data for Mix 2

Force(N)	Cycle	Stress(Pa)	Stiffness(Ksi)	NM
-210.3	39	476,647	595,809,313	1.0
-185.4	99	420,218	525,272,743	2.2
-166.2	199	376,789	470,986,813	4.0
-156.6	299	354,882	443,602,788	5.7
-149.4	399	338,569	423,210,892	7.3
-143.5	499	325,351	406,688,393	8.7
-139.4	599	316,006	395,007,892	10.2
-135.7	699	307,491	384,363,483	11.6
-132.8	799	300,981	376,226,518	12.9
-129.4	899	293,213	366,516,062	14.2
-127.1	999	288,158	360,196,935	15.5
-124.6	1099	282,355	352,943,857	16.7
-122.6	1199	277,977	347,471,557	17.9
-120.8	1299	273,707	342,133,868	19.1
-	-	-	-	-
-94.1	4099	213,340	266,674,487	47.0
-94.1	5299	213,322	266,652,503	60.8
-93.9	5399	212,880	266,099,938	61.8
-93.9	4199	212,836	266,044,580	48.1
-93.0	5699	210,757	263,446,240	64.6
-92.6	5499	209,801	262,251,815	62.1
-92.5	4399	209,620	262,025,335	49.6
-65.5	18599	148,387	185,483,745	148.5
-65.4	18499	148,159	185,199,272	147.4
-65.3	21299	148,018	185,022,535	169.6
-65.2	20699	147,888	184,859,782	164.7
-	-	-	-	-
-30.6	97699	69,267	86,583,887	364.0
-30.3	98999	68,764	85,954,870	366.2
-29.9	97399	67,771	84,714,131	355.1
-29.8	97099	67,592	84,489,946	353.1
-29.7	97999	67,388	84,234,858	355.3
-29.5	98699	66,946	83,682,809	355.4

Table 4-11: Flexural Fatigue Test Results

Mix	Air Voids (%)	Failure Point	Mean	Std Deviation

		(Cycles)	(Cycles)	
Mix 1	7.8	24,399	23,899	707
	7.1	23,399		
Mix 2	7.9	88,199	79,849	11,809
	7.1	71,499		
Mix 3	8.2	38,999	37,549	10,865
	7.6	36,099		
Mix 4	6.9	70,699	70,299	2,051
	7.2	69,899		
Mix 5	10.2	19,999	20,999	141
	10.0	20,199		
Mix 6	9.8	7,199	9,899	3,818
	10.6	12,599		

When comparing the surface layer mixes, Mix 1 (HL 3 containing 1.5 % RAS and 13% RAP) had the lowest susceptibility to fatigue failure where as Mix 2 (SP 12.5 FC1 containing 3% RAS and 17 % RAP) had the highest resistance for fatigue failure. Mix 4 (SP 12.5 FC2 containing 6% RAS) performed better than Mix 3 (SP12.5 FC2 containing 3% RAS and 12% RAP). For the binder layer mixes, the results are lower than expected. This is likely because of the higher air void and lower AC content. Given the scope of this research, it was not possible to examine this further. However, future research into improved sample preparation techniques for binder layer mixes should be explored.

4.5 Thermal Stress Restrained Specimen Testing (TSRST)

The stress behavior of asphalt materials at various cold temperatures can be calculated from the data that obtained from thermal stress restrained specimen testing. The TSRST test data can be used in pavement design and structural analysis to reduce thermal cracking potential and improve life cycle performance of asphalt pavements. The TSRST test was performed at University of Waterloo’s CPATT laboratory following AASHTO TP 10-93 “Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength” [AASHTO 93]. Multiple 250 mm long by 50 mm thick by 50 mm wide asphalt concrete beam specimens were then cooled at a rate of 10°C per hour in the MTS-810 environmental chamber.

4.5.1 Sample Preparation

The AVC at the CPATT laboratory was used to make beams (300 mm x 125 mm x 78 mm) for the TSRST testing. The AVC applied vibration to the samples with 110 kPa for 25 seconds to achieve the target air void content of 7 ± 1.0%. The test samples were then saw cut to 250 mm x 50 mm x 50 mm for testing. Figure 4-16 shows a test beam for TSRST testing which was obtained by cut the larger beam produced in the AVC. Table 4-12 summarizes the air void contents of the test beams produced. Mix 5 and Mix 6 which were binder layer mixes, did not achieve the designed air void content in the AVC, likely due to the larger aggregates in the mix. Several trials were performed by changing the AVC compaction pressure from 110 kPa to 120 kPa and also increase the vibration time from 25 seconds to 45 seconds. Minimum air void content that could be achieved for these two mixes was approximately 10%.

4.5.2 TSRST Instrumentation

The TSRST of each specimen was calculated following the AASHTO TP 10-93 specification. Figure 4-16 shows the TSRST testing configuration in the environmental chamber.

Figure 4-15: TSRST Beam Sample

Table 4-12: Air Void Content of Beams for TSRST

Specimens	Air Voids (%)

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
1	6.7	6.9	7.4	7.5	9.7	9.9
2	7.0	6.9	7.9	7.6	10.5	10.0
3	7.6	7.0	7.1	7.8	9.6	10.3

Figure 4-16: TSRST Instrumentation in the Environmental Chamber and MTS-810

4.5.2.1 Epoxy Preparation

Loctite 608 Hysol Epoxy was used to attach the test specimens to the platents. Epoxy resin and epoxy hardener was taken in and mixed thoroughly until a uniform color and consistent texture was achieved. A thick film of epoxy of 3 to 6 mm was placed over both ends of the specimen. The specimen was then placed in the platents and the top platen was carefully lowered so that the specimen's ends epoxy and the platents were in contact. Care was taken to make sure that the specimen was not displaced.

The specimen setup was then left for four hours at room temperature to allow the epoxy to harden. After curing the epoxy, the assembly was conditioned 5±2°C in environmental chamber for six hours prior to testing.

4.5.3 TSRST Testing

The environmental chamber was cooled at a rate of 10°C per hour during the test. As the test progressed, elapsed time, displacement of specimens, load and the temperature of the environmental chamber was recorded automatically. Test was continued until the specimen was failed or the chamber temperature reached -40°C.

The fracture stress was calculated as per Equation 2-15. Table 4-13 summarizes the TSRST results.

The tensile load and temperature were recorded at failure point, as shown in Table 4-13. The mean and standard deviation of the stress at the failure temperature for each mix are also shown. The temperature versus stress relationship for the Mix 2 throughout the duration of the test is shown in Figure 4- 17.

Table 4-13: Summary of TSRST Results

Mix	Specimen	Fracture Stress (MPa)	Mean Stress (MPa)	Std Dev of Fracture Stress (MPa)	Failure Temp (°C)	Mean of Failure Temp (°C)	Std Dev of Failure Temp (°C)
Mix 1	1	1.40	1.17	0.33	-21.60	-18.90	3.82
	2	0.93			-16.20		
Mix 2	1	2.19	1.79	0.36	-29.50	-28.43	1.05
	2	1.49			-27.40		
	3	1.68			-28.40		
Mix 3	1	2.07	2.27	0.42	-35.50	-33.90	3.86
	2	1.99			-36.70		
	3	2.76			-29.50		
Mix 4	1	3.17	2.71	0.65	-29.50	-31.80	3.25
	2	2.25			-34.10		
Mix 5	1	2.05	1.87	0.51	-33.10	-32.80	4.66
	2	1.30			-28.00		
	3	2.27			-37.30		
Mix 6	1	1.41	1.31	0.14	-29.56	-25.88	5.20
	2	1.21			-22.20		

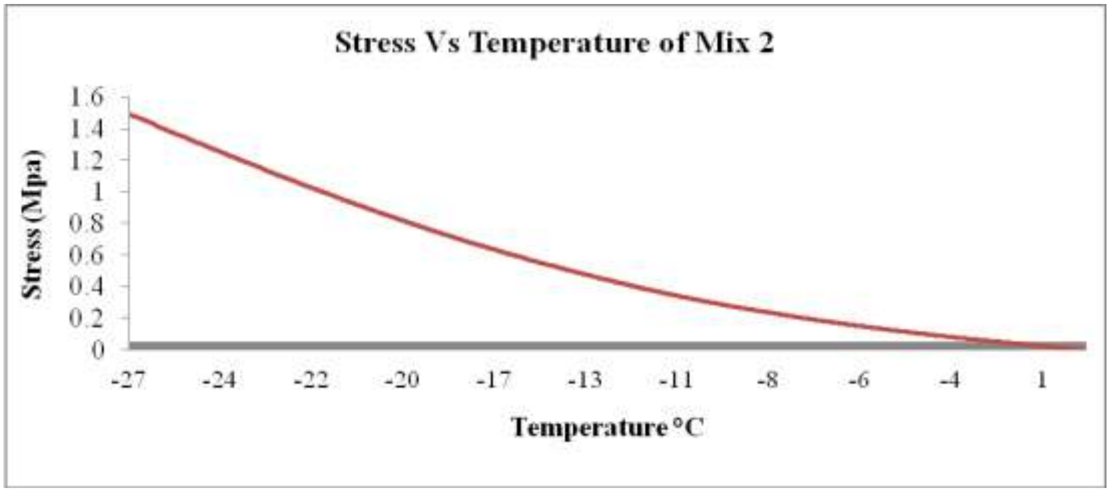

Figure 4-17: Stress during TSRST Testing of Mix 2

For the surface layer mixes, Mix 3 (SP 12.5 FC 2 containing 3 % RAS and 12 % RAP) reached the lowest temperature prior to failure. The temperature and stress value reached by Mix 1 (HL 3 containing 1.5 % RAS and 13.5 % RAP) prior to failure were significantly higher than the temperature and stress values reached by Mix 2 (SP 12.5 FC1 containing 3% RAS and 17 % RAP), Mix 3 (SP 12.5 FC 2 containing 3 % RAP and 12 % RAP) and Mix 4 (SP 12.5 FC 2 containing 6 % RAS). For binder layer mixes, Mix 5 (SP 19E containing 3% RAS and 25 % RAP) reached lowest temperature prior to failure. Generally, it is assumed that the addition RAS in HMA produces a stiffer mix which leads to an increase in the susceptibility to thermal cracking. By comparing the TSRST results for the same applications such as Mix 3 and Mix 4 for the surface layer, the failure temperature was higher for mixes with a higher percentage of RAS. Similar results have been found for binder layer mixes, Mix 5 and Mix 6, based on the testing results. Though the other two surface layer mixes, Mix 1 and Mix 2, are showing higher failure temperature, it should be noted that mix designs and aggregate sources are a major parameter that could be contributing to the overall performance. Incorporating a large quantity of RAS into a mix, such as 6%, can reduce resistance to thermal cracking and would likely require a softer asphalt binder to improve resistance to that of a virgin mix. However, a small quantity of shingles, such as 3%, in combination with RAP, lead to performance expected from conventional mixes.

4.6 Summary

Testing and data collection procedures that were used in this research have been presented in this chapter. The dynamic modulus, resilient modulus, flexural fatigue and thermal stress restrained specimen test were performed for this research to compare six different asphalt mixes. Testing methods, test results and the statistical analysis of the test results were also included in this chapter. The results of the laboratory tastings are summarized as below:

- In dynamic modulus testing, for the surface layer mixes Mix 3-SP12.5 FC2 containing 3% RAS and 12% RAP showed highest number in low temperature (-10°C) which is indicative of lowest resistance to fatigue cracking where as Mix 1-HL 3 containing 1.5% RAS and 13.5% RAP gave the lowest resistance to rutting at high temperatures. In the binder layer mixes, Mix 6-SP 19E containing 6% RAS performed better at the low temperature where as Mix 5-SP 19E containing 3% RAS and 25% RAP performed better at the high temperature.
- Mix 1-HL 3 containing 1.5% RAS and 13.5 % RAP, showed the highest resilient modulus result from all of the surface layer mixes and of the binder layer mixes Mix 6-SP19E which contains 6% RAS, performed better than Mix 5 which contains 3% RAS and 25% RAP.
- With the fatigue tests, Mix 2-SP12.5 FC1 with 3% RAS and 17% RAP showed the highest fatigue resistance of the surface layer mixes, however for the binder layer mixes the fatigue results were too low to make a conclusion.
- In TSRST testing, Mix 3-SP12.5 FC2 containing 3% RAS and 12% RAP had best performance amongst the surface layer mix and Mix 5-SP 19E contains 3% RAS and 25% RAP reached to the lowest temperature prior failure.

Chapter 5
Construction and Performance of Test Sections

To evaluate the field performance of HMA where RAS is incorporated as an additive, a few test sections were paved in the Region of Waterloo and the Town of Markham, ON. This chapter elaborates on these project locations and the construction procedure of the test sections.

5.1 CPATT Test Track

5.1.1 Project Location

The CPATT Test Track is located in the south-east corner of the Regional Municipality of Waterloo's Waste Management Facility. The test track was constructed as an access road to the various landfill cells. The first portion is various flexible sections containing two control sections and three flexible test sections constructed in 2002. The rigid section contains one control section and three sections with varying percentages of Recycled Concrete Aggregate (RCA). This rigid section was constructed in 2007. Also in 2007, three interlocking concrete paver crosswalks were installed in the flexible pavement section. An additional crosswalk section was installed in July 2009. The location of the CPATT test track is shown in Figure 5-1.

Figure 5-1 : CPATT Test Track Satellite View (Google Maps)

5.1.2 RAS Test Section

The total length of the CPATT test track prior to placing the RAS section was 880 metres and it was 8 metres wide. The new section started from 0+880 and extends south 210 metres and then turns west and continues another 214 metres. A shoulder parking pad was also constructed at 0+997 to 0+1018 on the west shoulder of the southbound lane. The complete CPATT test track layout is shown in Figure 4-2.

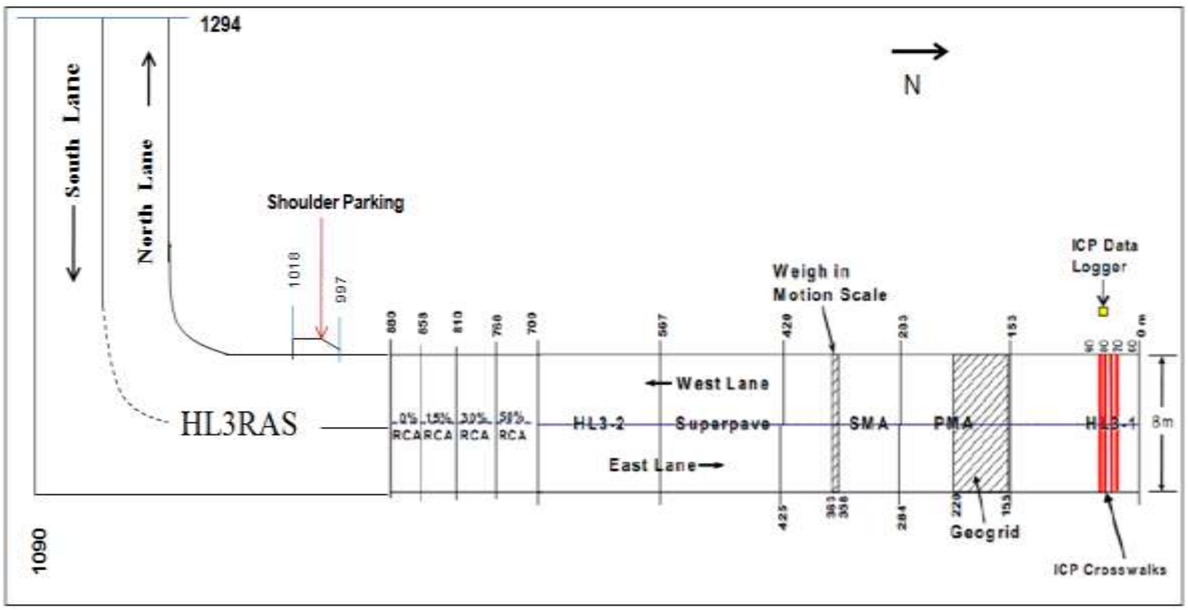

Figure 5-2 : CPATT Test Track Layout

5.2 Pavement Design

The mix design of the surface course of the RAS test section is HL 3 containing 1.5% RAS and 13.5% RAP. The mix design and RAS were provided by Miller Paving Ltd. The binder layer is 90 mm of a conventional HL 8 with 20% RAP. There is 150 mm of Granular A over 450 mm of Granular B below the HMA layers. A geotextile was placed directly on top of the subgrade. On October 20, 2009, 50 mm of HL 3 RAS mix was placed directly over the HL 8. There was no tack coat used between the HL 8 and HL 3 RAS. Figure 5-3 shows the cross section of the RAS test track section.

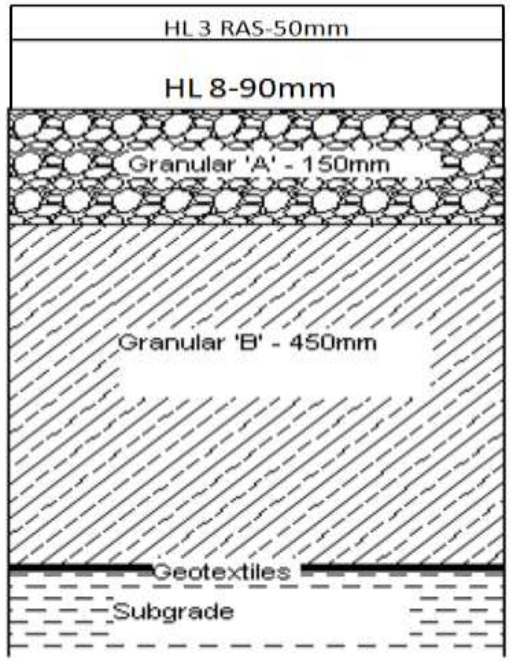

Figure 5-3: Cross Section of RAS Section

5.2.1 Mix Design of HL 3 RAS

The Job Mix Formula (JMF) and other design features of the HL 3 RAS mix are presented below in Table 4-1. Complete mix design information is found in Table 4-2.

Table 5-1 : Gradation of the HL 3 RAS mix

JOB MIX FORMULA—GRADATION PERCENT PASSING														
% AC/Sieve size (mm)	%AC	26.5	19.0	16.0	13.2	9.5	6.7	4.75	2.36	1.18	0.60	0.30	0.15	0.075
JMF	5.0*	100	100	100	99	82.7	64.8	55	43.7	30.3	20.2	11.5	6.8	4.6

*AC from RAS and RAP=1.31; New AC=3.97%

Table 5-2 : Design Features of HL 3 RAS

Marshall Test Result		**Requirements**	**Selected**
Percentage Air Voids		4.0+/-0.5	4.0
Flow (min)[0.25mm]@ 3.5% Air Voids		8	10.5
Stability(min) N		8900	16750
Percentage Voids in Mineral Aggregates		15.0	15
Aggregate Types	**Percentage**	**Mix Properties**	**Percentage**
Coarse Aggregate #1	40.3	Asphalt Cement (A.C) in RAP	6.87
Coarse Aggregate #2	-	RAP PEN	N/A
Coarse Aggregate #3	-	Bulk Relative Density, BRD	2.412
Fine Aggregate # 1	8.0	Maximum Relative Density ,MRD	2.513
Fine Aggregate # 2	36.7	Specific Gravity, Gb	2.696
RAP	15.0**		
Aggregate Types		**Source**	
Coarse Aggregate # 1		Hiedelberg (HL3 stone)	
Fine Aggregate # 1		Hiedelberg (Screening)	
Fine Aggregate # 2		Hiedelberg (Asphalt Sand)	
RAP # 1		Hiedelberg (16 mm RAP)	
RAS		Miller Paving Ltd	
Asphalt Cement		McAsphalt (PG 58-28)	

**% RAP indicated contains 13.5% RAP and 1.5% RAS

5.3 Schedule of Construction

Steed and Evans Ltd carried out the construction work over a two day period on October 19 and 20, 2009. Steed and Evans Limited was the subcontractor on the job while the prime contractor was Gateway Milloy. Steed and Evans Limited worked closely with Miller Paving Limited on the development of the HL 3 RAS mix. The weather was sunny and windy (4 °C at 9 AM and 12 °C at 12 PM). This was considered to be cold weather paving and not ideal conditions. It was necessary to place the section prior to winter shutdown of asphalt plant.

5.4 Production of Asphalt

Two different plants were used to produce each of the HL 8 and HL 3 RAS mixes. In total, 828 tons of HL 8 and 404 tons of HL 3 RAS were placed. Steed and Evans Limited used Kitchener Asphalt Limited (KAL) and their Heidelberg Plant to produce HL 8 and HL 3 RAS mixes respectively. Both plants were close to the construction site. On average, the travel time was 25 to 30 minutes to the site.

The locations of the asphalt plants were very important for maintaining the temperature of the asphalt mixes, given the air temperature. The temperature of the HMA was measured at the site for each truck and it ranged from 125°C - 160°C which is deemed to be acceptable in accordance with the OPSS specifications.

5.4.1 Construction Progress

For the ease of unloading the asphalt truck and paving operation, paving crews divided the track to four sections for paving. Figure 5-4 shows the approximate sectioning of the site. It was assumed that the north and south lanes would be Section 1 and Section 2 while the west and east lanes were Section 3 and Section 4.

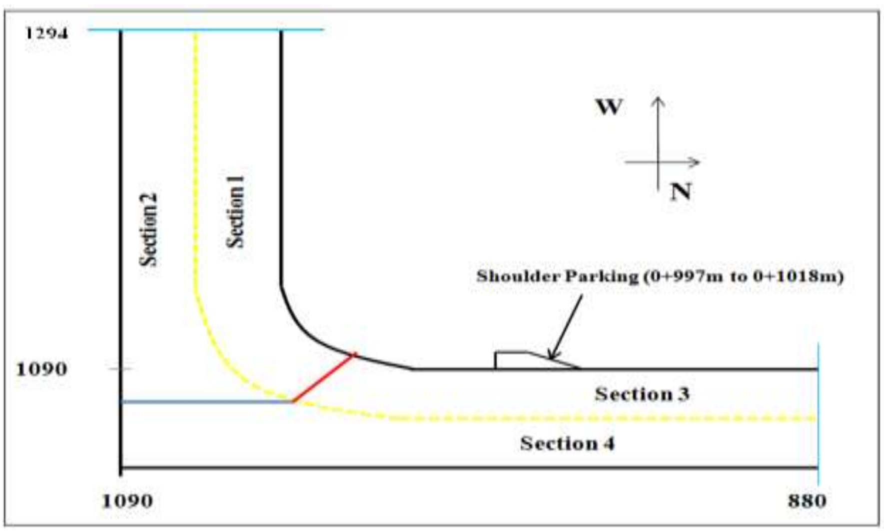

Figure 5-4 : Sections of HL 3 RAS Portion of the CPATT Test Track

5.4.2 Placement of HL 3 RAS

The 50 mm surface course consisting of HL 3 RAS was placed over the HL 8 on October 20 2009. The paving began at 7:45 AM from station 0+1294 in Section 2 and continued until station 0+1090. The paver then backed up to station 0+1294 at Section 1 and continued until station 0+880 of Section 3. After completing Section 3 the paver moved to station 0+1090 of Section 4 and progressed until 0+880. Figure 5-5 and Figure 5-6 show the compaction of the asphalt at station 0+1100.

Figure 5-5 : Compaction of the Asphalt with Steel Wheel Roller at Station 0+1100

Figure 5-6 : Compaction of Asphalt with Pneumatic Tire Compactor at Station 0+1100

5.5 Town of Markham, ON Test Sections

In 2007, Miller Paving Ltd paved three residential streets to test the performance of the overlays that incorporated RAS in the Town of Markham, ON. All three streets had low volumes of traffic with no parking lanes or sidewalks. These three streets are dead-end streets, two of the three have wide semi cul-de-sacs at the end and the third one has a full cul-de-sac. Figure 5-7 shows Town of Markham RAS test sections.

Figure 5-7 : Test Sites in the Town of Markham, ON

5.5.1 Site 1: Ida Street

On November 14, 2007 the first site, Ida Street, was paved with 241 tons of SP12.5 FC1 surface course containing 3.5% of RAS. Quality control test results for this mix were generally within the design mix parameters, with the exception of the material passing the 9.5 mm and 2.36 mm sieves, which were lower than the lower limit specified [Eyers 2007]. The length and the width of the street was 187.5 metres and 8 metres respectively.

5.5.2 Site 2: Paul Street and Vintage Lane

On November 7, 2007 the second site, Paul Street and Vintage Lane were paved with 718 tons of SP 12.5 surface course containing 13.5% RAP and 1.5% of RAS. The material passing the larger sieves (9.5 mm, 6.7 mm and 4.75 mm)was lower than the lower limit specified, while the material passing the smaller sieve (0.075 mm) was more than the upper design limit [Eyers 2007]. The length and the width of the street is 508 metres by 8 metres respectively.

5.5.3 Site 3: Thornhill Summit Drive

On November 8, 2007 the third site, Thornhill Summit Drive, was paved with 292 tons of SP12.5 surface course containing 13.5% RAP and 1.5% of RAS. The material passing through the larger sieves (9.5 mm, 6.7 mm and 4.75 mm) was lower than the lower limit specified, while the material passing through the smaller sieve (0.075 mm) was more than the design limit. The length and the width of the street is 197 metres by 8 metres respectively.

Miller Paving Ltd was responsible for the construction of all three test sections and confirmed that the mix characteristics in terms of blending, compaction and workability were achieved. The QA/QC test also showed the paved products met the requirements of the contract [Eyers 2007].

5.6 Pavement Performance to Date

5.6.1 Deflection Measurement

The CPATT Light Weight Deflectometer (LWD) Dynatest 3031 was used to measure the deflection at the CPATT test track RAS section. The LWD is a dynamic impact device. In order to simulate a load impulse similar to traffic loading, a weight is dropped on a loading plate in contact with the road. Figure 5-8 shows the CPATT LWD.

Four sets of deflection data were collected at the CPATT test track. For each location, six measurements were performed. The deflection was measured on the right and left wheel paths on the South-West lane at 25 m intervals. Similarly, the deflection was measured on the

North-East lane on both wheel paths. The test could not be carried out at one location (1025m) due to the slope of the lane.

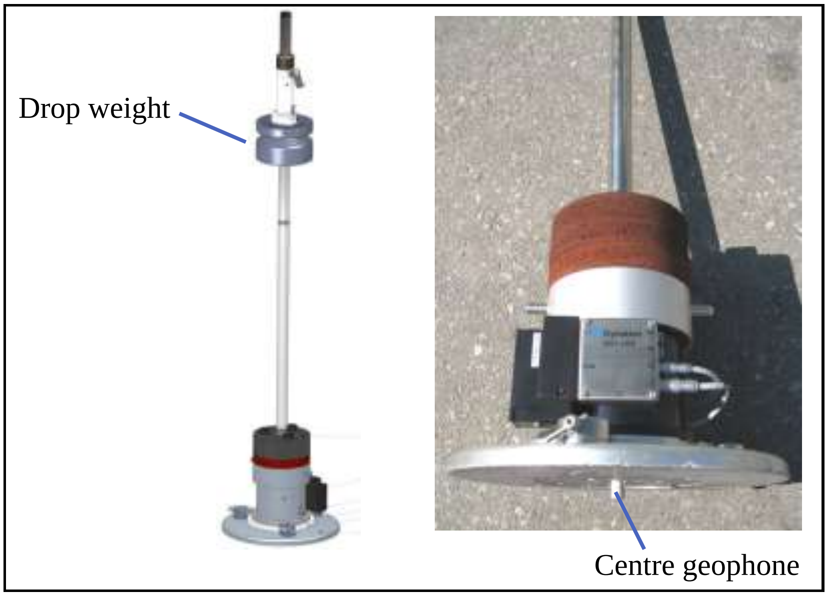

Figure 5-8 : Light Weight Deflectometer (LWD) Dynatest 3031

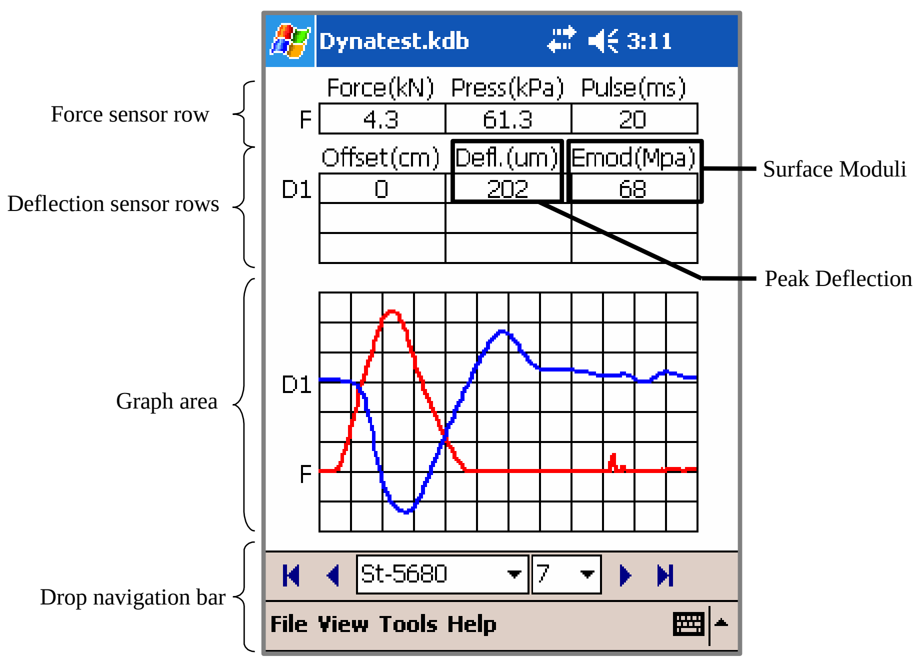

Figure 5-9 : Dynatest 3031 LWD – PDA Display [Dynatest 3031 LWD Owner's Manual]

A personal digital assistant (PDA) was used to record the stress and deflection that occurred during each drop. Figure 5-9 shows a typical PDA data while test was performed. To calculate the surface modulus for a homogeneous, isotropic, linear-elastic half-space, and a static loading condition, the following Equation 5.1 was used [Ryden 2009]

$$E_0 = \frac{f \cdot (1 - \nu^2) \cdot \sigma_0 \cdot a}{d_0} \tag{5.1}$$

Where:

f is the stress distribution factor

ν is the Poisson's ratio of the material

σ_0 is the applied stress at surface

a is the radius of the loading plate

d_0 is the centre deflection.

For a uniform stress distribution, f is 2. A typical assumed value of Poisson's ratio is 0.35 for bituminous asphalt concrete [MEPDG 2009].

For comparison purposes, all deflections were normalized to a 150 kPa stress. During the analysis, the points presenting unexpected stress values (deviation higher than 30%) or unexpected deflection values (deviation higher than 80%) were deleted. An average was then calculated for the centre deflection at each location. Figure 5-10 and Figure 5-11 represent the deflection pattern and the elastic modulus of the surface on the respective wheel path.

The surface was paved in October 2009 and it was expected that the performance would be the same over the entire HL 3 RAS test section. The deflection data showed that the deflection was consistent with 10 to 15% deviation except at Location 1 where the deviation was slighlty higher than other points.

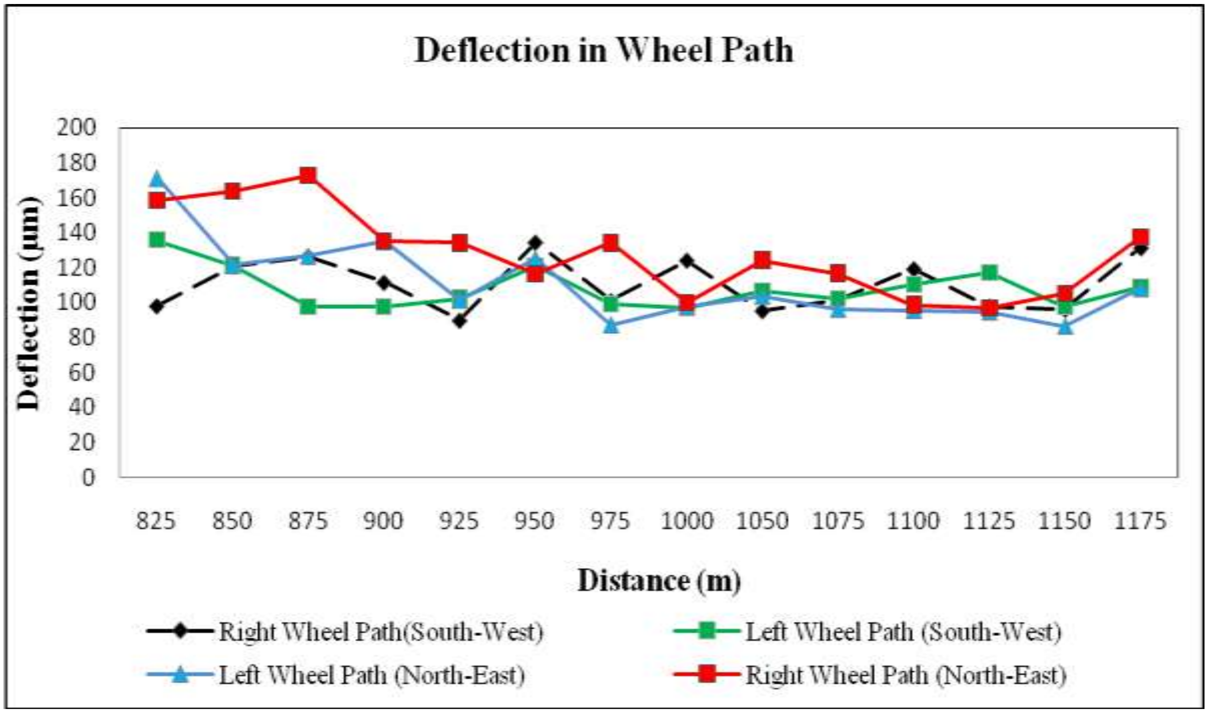

Figure 5-10 : Deflection on Wheel Paths

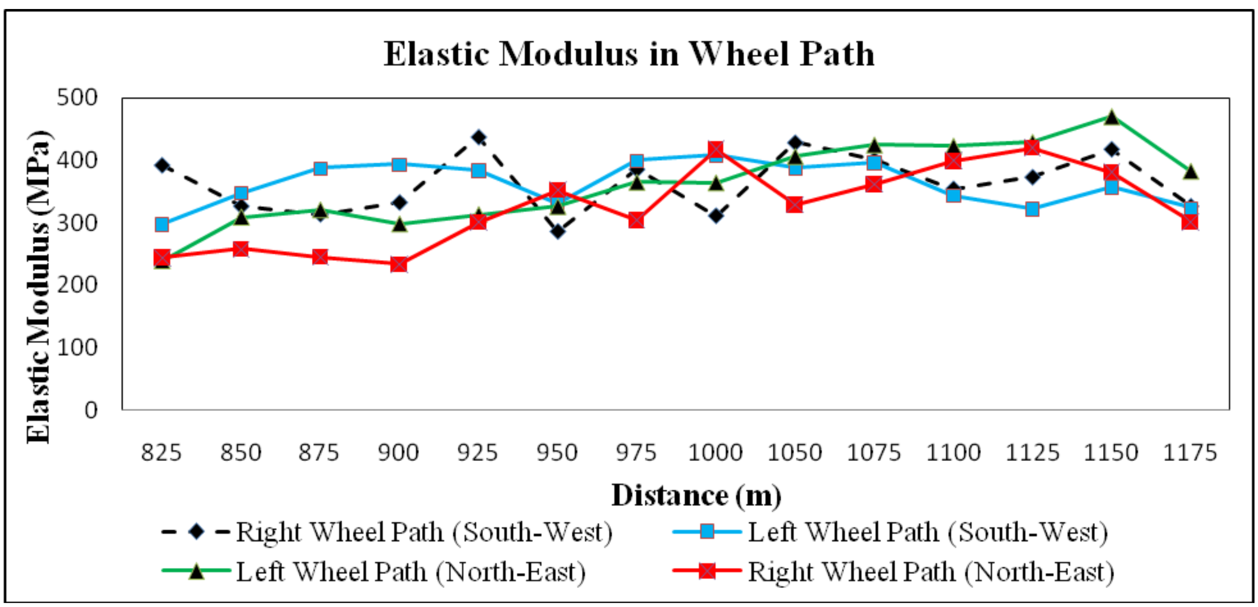

Figure 5-11 : Elastic Modulus on Wheel Paths

5.6.2 Distress Survey

On June 1, 2010, a condition survey was carried out to evaluate the overall condition of the pavements at all the field sites. For the surveys the Ministry of Transportation Ontario (MTO) flexible pavement condition evaluation form was used.

5.6.2.1 Performance Evaluation of CPATT Test Track

After one winter, the RAS section at the CPATT test track was performing very well. No noticeable surface distresses or cracks were observed. Only in a few places, segregation was observed. Figure 5-12 and Figure 5-13 show the condition of the sections before and after winter 2010.

Figure 5-12 : CPATT Test Track November 2009

Figure 5-13 : CPATT Test Track June 2010

5.6.2.2 Performance Evaluation of Town of Markham Sections

The Ida Street section showed slight coarse aggregate loss as shown in Figure 5-15 during the evaluation in June 2010. These pop outs are small (largest is approximately 10 mm to 15 mm) and less than those noticed on neighboring sections that do not contain RAS. In addition, a few transverse and longitudinal cracks were observed and were 3 mm to 5 mm in width. At the end of cul-de-sac, a few longitudinal cracks were observed. These cracks are slight, 5 mm to 7 mm in width. The quantity of slight aggregate loss and the cracking showed slight increases from the 2009 observations as shown in Figure 5-14. Overall the section is still in good condition as there were no major cracks or distresses observed.

Figure 5-14 : Ida Street 2009

Figure 5-15 : Ida Street 2010

Figure 5-16 : Paul St and Vintage Lane 2009

Figure 5-17 : Paul St and Vintage Lane 2010

Figure 5-18 : Thornhill Summit Drive 2009

Figure 5-19 : Thornhill Summit Drive 2010

The Paul Street and Vintage Lane Section are performing very well as shown in Figure 5-16 and Figure 17. Overall the performance of Paul Street is better as compared to Ida Street as no transverse or longitudinal cracks have been observed. A few ravelled areas were noted and slight depressions were found in between the two maintenance holes, likely related to poor compaction. Since the 2009 observation, there have been no significant surface distresses or cracks develop. In one location very slight rutting was noted which was not found in the 2009 observations. Otherwise the section was in excellent condition.

The Thornhill Summit Drive section was also paved with the same mix, SP12.5, with 1.5% RAS and 13.5% RAP so the performance of this road would be expected to be similar to the Paul Street and Vintage Lane given it has similar traffic and subgrade conditions. The rutting which was noted near the curve and the catch basin during the 2009 observations still remains in the same condition. The slight depression that was noted near the drainage outlet and pavement edge in the 2009 observation is still in the same condition. Figure 5-18 and Figure 5-19 shows the overall excellent condition of this street and it is in the same condition as 2009.

5.7 Summary

Field performance of the test sections has been very encouraging. The inclusion of 1.5% to 3% RAS proved to result in similar performance of HMA. Unlike HMA RAP mixes, HMA RAS mixes can be placed in a conventional way where no additional techniques or instrumentation are required. The CPATT test track has experienced one winter season and is performing very well. The Town of Markham test sections which were paved in 2007 are performing well without any minor or major maintenance. Overall it can be concluded that the addition of RAS in HMA can lead to a useful pavement material which has environmental and economical benefits.

Chapter 6
Summary, Conclusions and Recommendations

This chapter summarizes the major findings that were achieved from this research and provides recommendations for future study.

6.1 Summary of Research

This research has involved evaluating the performance of HMA where RAS was used as an additive. Six mixes which are commonly used in Ontario were considered for this research. Among the six mixes, four were surface course mixes and the other two were binder layer mixes. A varying percentage of RAS and RAP were added to the mixes to quantify the mix behavior. The characteristics of the asphalt mixes containing RAS were evaluated by laboratory testing. All the testing was performed at the CPATT laboratory. In addition, four test sections were constructed in this research to evaluate the field performance of HMA containing RAS in the field. One test section, which was designed for heavily loaded vehicles, was placed at the CPATT test track during this research which is located at the Region of Waterloo's Waste Management Facility. Three other test sections were designed for low volume use and were placed in the Town of Markham. These were placed prior to the start of this thesis but monitored in this research.

To evaluate the elastic properties of the mixes, dynamic modulus testing was performed. Fatigue and thermal cracking susceptibility of the mixes was assessed through resilient modulus and flexural fatigue testing. TSRST testing was performed to determine the thermal cracking tendencies of HMA at low temperatures. A comprehensive statistical comparison of the test results is presented in this research.

Field performance evaluation of the test sections was a significant portion of this research. Regular pavement distress surveys were performed on the Town of Markham's three year old pavements following Ministry of Transportation Ontario (MTO) guidelines [MTO 1989]. A similar survey was conducted at the flied site of the CPATT test track. Testing was also carried out with the LED at the CPATT test section.

6.2 Conclusions

Based on the research findings, the summary of the surface mix is as follows: Mix 3-SP12.5 FC2 which contains 3% RAS and 12 % RAP performed best according to the dynamic modulus and TSRST testing. Mix 1-HL 3 containing 1.5% RAS and 13.5 % RAP had the highest resilient number while Mix 2-SP12.5 FC1 containing 3% RAS and 17 % RAP performed the best under the flexural fatigue test. For binder layer mixes, Mix 5-SP 19E containing 3% RAS and 25% RAP and Mix 6-SP19E containing 6% RAS showed similar performance in laboratory. The high air void content of the specimens prepared in the AVC resulted in very low flexural fatigue bending beam results for both mixes. It is expected that if the laboratory specimens can be prepared with a lower air void content, these results would improve and be more reflective of the field performance. A statistical comparison of the dynamic modulus test results for the Mix 1 (HL 3 containing 1.5% RAS and 13.5 % RAP) and a conventional HL 3 mix showed that Mix 1 performed statistically the same at 4.4°C, 21.1 °C and 37.8°C . Also, at extreme temperatures, both the high (54 °C) and low (-10°C) temperature had slightly different performance.

The field performance evaluation involved deflection measurements at test section at the CPATT test track. The RAS section performed well in both wheel paths which was expected as the test section was less than one year old at the time of testing. The CPATT test section continue to perform very well under heavily loaded traffic as no noticeable distresses have been observed. The Town of Markham test sections are also performing well to date without any major or minor maintenance over the last there years. Overall, the laboratory test results and field performance of the test sites are very encouraging, indicating that RAS can be a useful additive to asphalt mixes in low to medium volume roads as long as it is engineered properly into the mix.

6.3 Recommendations

The following best describes recommendations for future research examining the use of RAS in HMA. The recommendations presented below were developed from the conclusions and findings of this research project.

1. Continue to work towards optimizing RAS and RAP quantities into typical Ontario HMA through combined field and laboratory research. Additional test sections can be included to further understand the designs and performance of these mixes.

2. For base layer asphalt mixes, which contain larger sized aggregates, the development of a specimen preparation protocol which produces samples with air void contents of 7% needs to be developed.

3. Further research is required to evaluate the rutting resistance of the mixes. In addition, skid resistance testing of the surface layer mixes should be carried out.

4. Core sampling of the paved test sections at the CPATT test track and at the Town of Markham should be carried out in a few years to investigate the in situ condition of the paved sections.

5. A Comprehensive Life Cycle Cost Analysis (LCCA) and Environmental Cost Benefits (ECB) model that considers HMA containing RAS should be developed.

6. Construction of additional test sections using RAS in binder layer could allow for monitoring of the pavement performance in medium and high traffic scenarios.

7. Continued monitoring field sections to quantify long term performance and develop a numerical model that can simulate the deterioration of HMA containing RAS.

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Appendix

Mix Designs

HOT MIX ASPHALT DESIGN BLEND SHEET

Supplier: Research | RAP AC: 27.00 | 5.99

Project	Various	Product No				Traffic Categroy	
Project No	M2010	% RAP	20.0	Stability	8000		
Client	Research	%AC-RAP	9.14	Flow	8	E	
Mix No	4-1E	DP (Spec)	0.6-1.2	VMA	14	Estmd for AV=4	
Mix Type	SP12.5FC1 / Surface Course	Nini (Spec)	9	VFA	65-75	Gmb	2.493
Date	20-Jul-09	Ndes (Spec)	125	TSR	>=80%	Gmm	2.597
%AC	5.1	Nmax (Spec)	205	VCA_{max}		VMA	15.51
AC Grade	PG 52-34 - Conventiona	% Fines	0.0	VCA_{dry}		DP	0.94
Supplier	McAsphalt	FF Ratio	0.34	Voids %	4.0+/-0.5	Pbe	4.732
Comp. Gst	2.800	Anti-Stripp.		Min AC	4.7	Gse	2.830

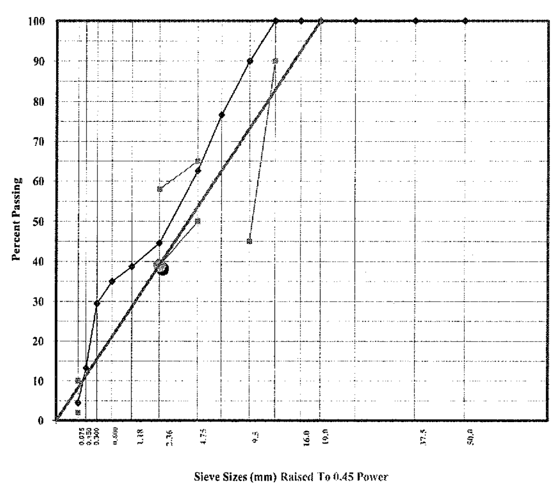
	MATERIAL	SOURCE	INV. #	% AGG	% VOL	Gsb	Gsa	Abs
CA1	HL-1 Stone	MRT		26.5	27.4	2.899	2.928	0.346
CA2	1/8 x 1/4 Chips	MRT		20.0	20.6	2.892	2.937	0.533
CA3				0.0	0.0	1.000	1.000	0.000
FA1	/4 x 0 Screening	MRT		8.0	8.2	2.885	2.906	0.256
FA2	VFA Sand	CBM	N02-075	25.5	24.6	2.702	2.720	0.251
FA3				0.0	0.0	1.000	1.000	0.000
RAP1	Shingles	Markham		3.0	2.5	2.300	2.300	0.000
RAP2	3/8" RAP	Markham		17.0	16.8	2.768	2.768	0.000
Film Thick	#REF!		Total:	100.0	100.0			

Sieve Sizes (mm)	COARSE AGGREGATES CA1	CA2	CA3	FINE AGGREGATES FA1	FA2	FA3	RAP RAP1	RAP2
	HL-1 Stone MRT	1/8 x 1/4 Chips MRT		1/4 x 0 Screenings MRT	VFA Sand CBM		Shingles Markham	3/8" RAP Markham
Lab No.	Pat treated	Pat treated		Pat treated				
50.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
37.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
25.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	97.8	100.0	100.0	100.0	100.0	100.0	99.5	100.0
9.5	58.1	99.9	100.0	100.0	100.0	100.0	99.2	96.8
6.7	21.3	94.8	100.0	98.5	100.0	100.0	98.0	84.0
4.75	4.3	64.8	100.0	88.2	100.0	100.0	96.2	70.0
2.36	1.7	8.2	100.0	61.5	99.9	100.0	92.0	50.1
1.18	1.5	2.2	100.0	43.4	99.7	100.0	75.3	35.2
0.600	1.0	1.5	100.0	32.8	99.0	100.0	52.7	25.6
0.300	0.8	1.2	100.0	24.3	87.0	100.0	41.7	18.1
0.150	0.6	1.0	100.0	16.8	32.2	100.0	29.2	12.8
0.075	0.4	0.8	100.0	10.5	4.0	100.0	22.6	9.2

Please Select a Specification: Superpave | SP12.5FC1 | Re-Calculate

Sieve Sizes (mm)	BLEND	LOW	HIGH	FINAL BLEND	Aggregate	%	Agg. Proportion
50.0	100.0			100.0	% Total CA		
37.5	100.0			100.0	% Total FA		
25.0	100.0			100.0	CA1		26.5
19.0	100.0	100.0	100.0	100.0	CA2		20.0
16.0	100.0			100.0	CA3		0.0
12.5	99.4	90.0	100.0	100.0	FA1		8.0
9.5	88.3	45.0	90.0	90.0	FA2		25.5
6.7	75.2			76.6	FA3		0.0
4.75	61.4	50.0	65.0	62.6	Total FA	100.0	
2.36	43.8	39.0	58.0	44.6	RAP1	27.00	3.0
1.18	38.0			38.7	RAP2	5.99	17.0
0.600	34.4			35.0		Aggs. Total	100.0
0.300	28.9			29.4	Total CA	100.0	
0.150	13.0			13.2	Total AC		5.10
0.075	4.4	2.0	10.0	4.4	New AC		3.27

Notes:



Bailey's Method	
Blend Characteristics	
NMAS	12.5mm
PCS	2.36mm
SCS	0.600mm
TCS	0.150mm
Half Sieve	6.7mm
CA Ratio	0.64
Range	0.50-0.65
FAc Ratio	0.58
Range	0.35-0.50
FAf Ratio	0.19
Range	0.35-0.50
LUW_{CA}	1.0
RUW_{CA}	1.0
LUW_{FA}	1.0
RUW_{FA}	1.0
Programmer	Narayan

HOT MIX ASPHALTIC CONCRETE WEIGH CARD

Mix: SP12.5FC1 / Surface Course 'Superpave Method' | Date: 20-Jul-09 | Project: Various | Mix No.: 4-1E

SIEVE SIZES (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP 1	RAP 2				
	HL-1 Stone MRT	1/8 x 1/4 Chips MRT		1/4 x 0 Screenings MRT	VFA Sand CBM		Shingles Markham	3/8" RAP Markham	%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
Lab No	Pat treated	Pat treated		Pat treated								
RET 25	0.0						0.0	0.0				
RET 19.0	0.0						0.0	0.0	2.8	4.6	43	43
RET 16.0	0.0						0.0	0.0	3.3	5.1	51	51
RET 12.5	8.7						0.2	0.0	3.8	5.6	59	59
RET 9.5	166.6	397.8					0.4	8.2	4.3	6.1	67	67
RET 6.7	312.9	413.1		699.3			0.9	40.8				
RET 4.75	380.4	503.1		711.7			1.7	76.5				
RET 2.36	390.7	672.9		743.7	817.9		3.6	127.2				
PASS 2.36	**397.5**	**697.5**		**817.5**	**1200.0**		**45.0**	255.0	**1500.0**			

FINES =	0		RAS / RAP	45	255	Total Weight:	**1500.0**	
MRDs @ AC	5.1	5.6		AC Grade		PG 52-34		
Nini (Spec)	9			Supplier		McAsphalt		
Ndes (Spec)	125			Mixing Temp		145 °C		
Nmax (Spec)	205			Compaction Temp		131 °C +3		
Gsb	**2.800**							

SIEVE SIZES (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP 1	RAP 2	AC Grade	Mixing Temp	Compaction Temp	Ndes (Spec)
	HL-1 Stone MRT	1/8 x 1/4 Chips MRT		1/4 x 0 Screenings MRT	VFA Sand CBM		Shingles Markham	3/8" RAP Markham	PG 52-34	145 °C	131 °C +3+3	125
Lab No	Pat treated	Pat treated		Pat treated					%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
RET 25	0.0						0.0	0.0				
RET 19.0	0.0						0.0	0.0				
RET 16.0	0.0						0.0	0.0				
RET 12.5	30.0						0.8	0.0				
RET 9.5	570.7	1363.1					1.2	28.0	2.8	4.6	147	147
RET 6.7	1072.1	1415.6		2396.3			3.1	139.8	3.3	5.1	174	174
RET 4.75	1303.5	1724.0		2438.6			5.9	262.1	3.8	5.6	201	201
RET 2.36	1338.9	2305.8		2548.4	2802.6		12.3	436.0	4.3	6.1	229	229
PASS 2.36	**1362.1**	**2390.1**		**2801.3**	**4112.0**		**154.2**	873.8	**5140.0**			
	FINES =	0.0		RAS / RAP	154.2	873.8	Total Weight:	**5140.0**	5313.9	5286.5		

Notes: *Weight of Mixture for 115 +/-5 mm Ht/ 150mm Dia, g =* 5275.0 Total Wt. without RAP/RAS: 4112.0 **Mix No.: 4-1E**

Approx. Weight of Mixture for TSR Specimen 95 +/-5 mm Ht/ 150mm Dia, g = 3893.8

HOT MIX ASPHALT DESIGN BLEND SHEET

Project	Various	Product No				Traffic Categroy	
Project No	M2010	% RAP	15.0	Stability	8900		
Client	Research	%AC-RAP	10.19	Flow	8	E	
Mix No	3-1B	DP (Spec)	0.6-1.2	VMA	14	Estmd for AV=4	
Mix Type	SP12.5FC2 / Surface Course	Nini (Spec)	9	VFA	65-75	Gmb	2.539
Date	27-Jan-10	Ndes (Spec)	125	TSR	>=80%	Gmm	2.645
%AC	5.2	Nmax (Spec)	205	VCA_{max}		VMA	16.01
AC Grade	PG 52-34 - Conventional	% Fines	0.0	VCA_{dry}		DP	0.86
Supplier	McAsphalt	FF Ratio	1.18	Voids %	4.0+/-0.5	Pbe	4.849
Comp. Gsb	2.866	Anti-Stripp.		Min AC	5.0	Gse	2.896

	MATERIAL	SOURCE	INV. #	% AGG	% VOL	Gsb	Gsa	Abs
CA1	HL1 Stone	MRT		25.7	26.0	2.899	2.928	0.346
CA2	1/8 x 1/4 Chips	MRT		20.0	20.1	2.892	2.937	0.533
CA3				0.0	0.0	1.000	1.000	0.000
FA1	/4 x 0 Screening	MRT		14.0	14.1	2.885	2.906	0.256
FA2	Mfg. Sand	MRT		25.3	25.9	2.934	2.969	0.402
FA3				0.0	0.0	1.000	1.000	0.000
RAP1	Shingles	Carden		3.0	2.4	2.300	2.300	0.000
RAP2	3/8" RAP	Markham		12.0	11.6	2.768	2.768	0.000
Film Thick	#REF!		Total:	100.0	100.0			

Supplier Research — RAP AC 27.00 5.99

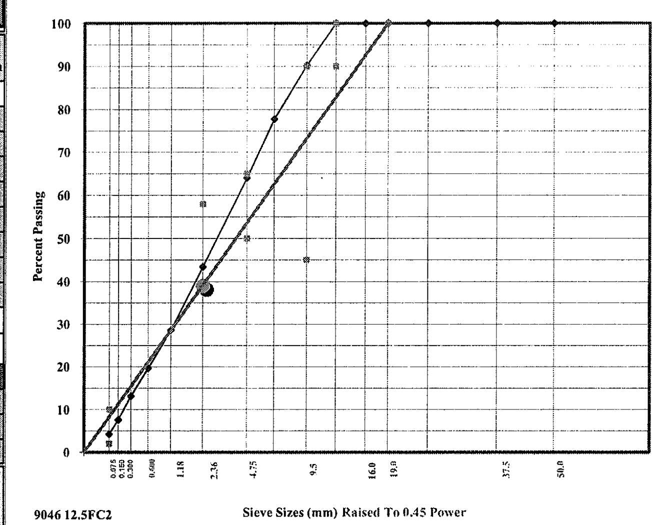
	COARSE AGGREGATES			FINE AGGREGATES			RAP	
	CA1	CA2	CA3	FA1	FA2	FA3	RAP1	RAP2
Sieve Sizes (mm)	HL1 Stone MRT	1/8 x 1/4 Chips MRT		1/4 x 0 Screenings MRT	Mfg. Sand MRT		Shingles Carden	3/8" RAP Markham
Lab No.	Pat treated	Pat treated		Pat treated	Pat treated			
50.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
37.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
25.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	97.8	100.0	100.0	100.0	100.0	100.0	99.5	100.0
9.5	58.1	99.9	100.0	100.0	100.0	100.0	99.2	96.8
6.7	21.3	94.8	100.0	98.5	100.0	100.0	98.0	84.0
4.75	4.3	64.8	100.0	88.2	100.0	100.0	96.2	70.0
2.36	1.7	8.2	100.0	61.5	92.0	100.0	92.0	50.1
1.18	1.5	2.2	100.0	43.4	58.4	100.0	75.3	35.2
0.600	1.0	1.5	100.0	32.8	37.7	100.0	52.7	25.6
0.300	0.8	1.2	100.0	24.3	22.3	100.0	41.7	18.1
0.150	0.6	1.0	100.0	16.8	9.3	100.0	29.2	12.8
0.075	0.4	0.8	100.0	10.5	2.4	100.0	22.6	9.2

Please Select a Specification — Superpave — SP12.5FC2 — Re-Calculate

Sieve Sizes (mm)	BLEND	LOW	HIGH	FINAL BLEND
50.0	100.0			100.0
37.5	100.0			100.0
25.0	100.0			100.0
19.0	100.0	100.0	100.0	100.0
16.0	100.0			100.0
12.5	99.4	90.0	100.0	100.0
9.5	88.8	45.0	90.0	90.2
6.7	76.5			77.7
4.75	63.0	50.0	65.0	64.0
2.36	42.7	39.0	58.0	43.4
1.18	28.2			28.6
0.600	19.3			19.6
0.300	12.9			13.1
0.150	7.5			7.6
0.075	4.1	2.0	10.0	4.2

Aggregate	%	Agg. Proportion
% Total CA		
% Total FA		
CA1		25.7
CA2		20.0
CA3		0.0
FA1		14.0
FA2		25.3
FA3		0.0
Total FA	100.0	
RAP1	27.00	3.0
RAP2	5.99	12.0
	Aggs. Total	100.0
Total CA	100.0	
Total AC		5.20
New AC		3.67

Notes:



Bailey's Method	
Blend Characteristics	
NMAS	12.5mm
PCS	2.36mm
SCS	0.600mm
TCS	0.150mm
Half Sieve	6.7mm
CA Ratio	2.80
Range	0.50-0.65
FAc Ratio	0.65
Range	0.35-0.50
FAf Ratio	0.48
Range	0.35-0.50
LUW_{CA}	1.0
RUW_{CA}	1.0
LUW_{FA}	1.0
RUW_{FA}	1.0
Programmer	Narayan

HOT MIX ASPHALTIC CONCRETE WEIGH CARD

Mix: SP12.5FC2 / Surface Course 'Superpave Method' | Date: 27-Jan-10 | Project: Various | Mix No.: 3-1B

SIEVE SIZES (mm)	CA1 HL1 Stone MRT	CA2 1/8 x 1/4 Chips MRT	CA3	FA1 1/4 x 0 Screenings MRT	FA2 Mfg. Sand MRT	FA3	RAP 1 Shingles Carden	RAP 2 3/8" RAP Markham	%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
Lab No	Pat treated	Pat treated		Pat treated	Pat treated							
RET 25	0.0						0.0	0.0				
RET 19.0	0.0						0.0	0.0	3.2	4.7	49	49
RET 16.0	0.0						0.0	0.0	3.7	5.2	57	57
RET 12.5	8.5						0.2	0.0	4.2	5.7	65	65
RET 9.5	161.5	385.8					0.4	5.8	4.7	6.2	74	74
RET 6.7	303.4	401.1		688.7			0.9	28.8				
RET 4.75	368.9	491.1		710.3			1.7	54.0				
RET 2.36	378.9	660.9		766.4	925.9		3.6	89.8				
PASS 2.36	**385.5**	**685.5**		**895.5**	**1275.0**		**45.0**	180.0	**1500.0**			

FINES =	0		RAS / RAP	45	180	Total Weight:	**1500.0**
MRDs @ AC	5.2	5.7					
Nini (Spec)	9						
Ndes (Spec)	125						
Nmax (Spec)	205						
Gsb	**2.866**						

AC Grade	PG 52-34
Supplier	McAsphalt
Mixing Temp	145 °C
Compaction Temp	131 °C

SIEVE SIZES (mm)	CA1 HL1 Stone MRT	CA2 1/8 x 1/4 Chips MRT	CA3	FA1 1/4 x 0 Screenings MRT	FA2 Mfg. Sand MRT	FA3	RAP 1 Shingles Carden	RAP 2 3/8" RAP Markham	AC Grade PG 52-34	Mixing Temp 145 °C	Compaction Temp 131 °C	Ndes (Spec) 125
Lab No	Pat treated	Pat treated		Pat treated	Pat treated				%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
RET 25	0.0						0.0	0.0				
RET 19.0	0.0						0.0	0.0				
RET 16.0	0.0						0.0	0.0				
RET 12.5	29.0						0.8	0.0				
RET 9.5	551.9	1318.2					1.2	19.7	3.2	4.7	168	168
RET 6.7	1036.7	1370.4		2352.9			3.1	98.4	3.7	5.2	195	195
RET 4.75	1260.5	1677.9		2426.8			5.8	184.5	4.2	5.7	223	223
RET 2.36	1294.7	2258.1		2618.4	3163.4		12.3	306.9	4.7	6.2	251	251
PASS 2.36	**1317.1**	**2342.1**		**3059.6**	**4356.3**		**153.8**	**615.0**	**5125.0**			

FINES =	0.0	RAS / RAP	153.8	615.0	Total Weight:	**5125.0**	5320.3	5292.8	

Notes: *Weight of Mixture for 115 +/-5 mm Ht/ 150mm Dia, g =* **5300.0** Total Wt. without RAP/RAS: 4356.3

Mix No.: 3-1B

Approx. Weight of Mixture for TSR Specimen 95 +/-5 mm Ht/ 150mm Dia, g = 3965.5

HOT MIX ASPHALT DESIGN BLEND SHEET

Project	Various	Product No				Traffic Categroy	
Project No	M2010	% RAP	6.0	Stability	8900		
Client	Research	%AC-RAP	27.00	Flow	8	E	
Mix No	18-1A	DP (Spec)	0.6-1.2	VMA	14	Estmd for AV=4	
Mix Type	SP12.5FC2 / Surface Course	Nini (Spec)	9	VFA	65-75	Gmb	2.536
Date	27-Jan-10	Ndes (Spec)	125	TSR	>=80%	Gmm	2.641
%AC	5.2	Nmax (Spec)	205	VCA_{max}		VMA	15.99
AC Grade	PG 52-40 - Conventiona	% Fines	0.0	VCA_{dry}		DP	0.82
Supplier	McAsphalt	FF Ratio	1.13	Voids %	4.0+/-0.5	Pbe	4.848
Comp. Gsb	2.861	Anti-Stripp.		Min AC	5.0	Gse	2.891

	MATERIAL	SOURCE	INV. #	% AGG	% VOL	Gsb	Gsa	Abs
CA1	HL1 Stone	MRT		35.6	36.0	2.899	2.928	0.346
CA2	1/8 x 1/4 Chips	MRT		14.0	14.1	2.892	2.937	0.533
CA3				0.0	0.0	1.000	1.000	0.000
FA1	/4 x 0 Screening	MRT		15.0	15.1	2.885	2.906	0.256
FA2	Mfg. Sand	MRT		29.4	30.1	2.934	2.969	0.402
FA3				0.0	0.0	1.000	1.000	0.000
RAP1	Shingles	Markham		6.0	4.8	2.300	2.300	0.000
RAP2	3/8" RAP	Markham		0.0	0.0	2.790	2.790	0.000
Film Thick	#REF!		Total:	100.0	100.0			

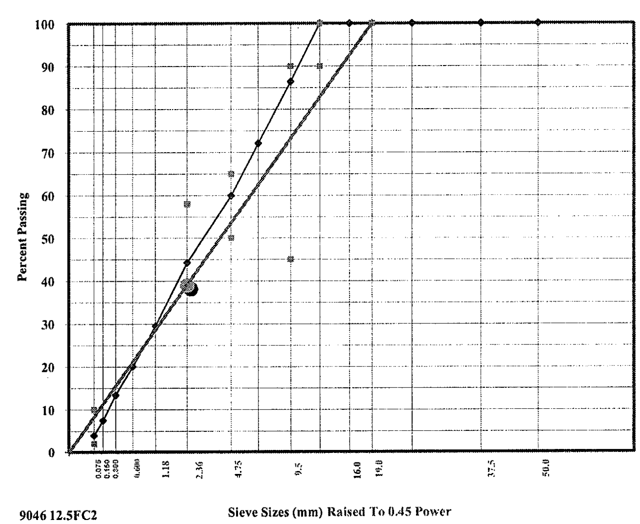
Supplier Research — RAP AC: 27.00 | 5.99

	COARSE AGGREGATES			FINE AGGREGATES			RAP	
	CA1	CA2	CA3	FA1	FA2	FA3	RAP1	RAP2
Sieve Sizes (mm)	HL1 Stone MRT	1/8 x 1/4 Chips MRT		1/4 x 0 Screenings MRT	Mfg. Sand MRT		Shingles Markham	3/8" RAP Markham
Lab No.	Pat treated	Pat treated		Pat treated	Pat treated			
50.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
37.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
25.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	97.8	100.0	100.0	100.0	100.0	100.0	99.5	100.0
9.5	58.1	99.9	100.0	100.0	100.0	100.0	99.2	96.8
6.7	21.3	94.8	100.0	98.5	100.0	100.0	98.0	84.0
4.75	4.3	64.8	100.0	88.2	100.0	100.0	96.2	70.0
2.36	1.7	8.2	100.0	61.5	92.0	100.0	92.0	50.1
1.18	1.5	2.2	100.0	43.4	58.4	100.0	75.3	35.2
0.600	1.0	1.5	100.0	32.8	37.7	100.0	52.7	25.6
0.300	0.8	1.2	100.0	24.3	22.3	100.0	41.7	18.1
0.150	0.6	1.0	100.0	16.8	9.3	100.0	29.2	12.8
0.075	0.4	0.8	100.0	10.5	2.4	100.0	22.6	9.2

Please Select a Specification: Superpave — SP12.5FC2 — Re-Calculate

Sieve Sizes (mm)	BLEND	LOW	HIGH	FINAL BLEND	Aggregate	%	Agg. Proportion
50.0	100.0			100.0	% Total CA		
37.5	100.0			100.0	% Total FA		
25.0	100.0			100.0	CA1		35.6
19.0	100.0	100.0	100.0	100.0	CA2		14.0
16.0	100.0			100.0	CA3		0.0
12.5	99.2	90.0	100.0	100.0	FA1		15.0
9.5	85.0	45.0	90.0	86.4	FA2		29.4
6.7	70.9			72.1	FA3		0.0
4.75	59.0	50.0	65.0	60.0	Total FA	100.0	
2.36	43.5	39.0	58.0	44.3	RAP1	27.00	6.0
1.18	29.0			29.5	RAP2	5.99	0.0
0.600	19.7			20.1		Aggs. Total	100.0
0.300	13.2			13.4	Total CA	100.0	
0.150	7.4			7.5	Total AC		5.20
0.075	3.9	2.0	10.0	4.0	New AC		3.58

Notes:



Bailey's Method	
Blend Characteristics	
NMAS	12.5mm
PCS	2.36mm
SCS	0.600mm
TCS	0.150mm
Half Sieve	6.7mm
CA Ratio	2.80
Range	0.50-0.65
FAc Ratio	0.65
Range	0.35-0.50
FAf Ratio	0.48
Range	0.35-0.50
LUW_{CA}	1.0
RUW_{CA}	1.0
LUW_{FA}	1.0
RUW_{FA}	1.0
Programmer	Narayan

HOT MIX ASPHALTIC CONCRETE WEIGH CARD

Mix: SP12.5FC2 / Surface Course 'Superpave Method' | Date: 27-Jan-10 | Project: Various | Mix No.: 18-1A

SIEVE SIZES (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP 1	RAP 2	%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
	HL1 Stone MRT	1/8 x 1/4 Chips MRT		1/4 x 0 Screenings MRT	Mfg. Sand MRT		Shingles Markham	3/8" RAP Markham				
Lab No	Pat treated	Pat treated		Pat treated	Pat treated							
RET 25	0.0							0.0				
RET 19.0	0.0							0.0	3.1	4.7	477	477
RET 16.0	0.0							0.0	3.6	5.2	557	557
RET 12.5	117.5						4.5	0.0	4.1	5.7	638	638
RET 9.5	2237.5	5342.1					7.2	0.0	4.6	6.2	720	720
RET 6.7	4203.1	5449.2		7473.8			18.0	0.0				
RET 4.75	5110.4	6079.2		7705.5			34.2	0.0				
RET 2.36	5249.2	7267.8		8306.3	10042.8		72.0	0.0				
PASS 2.36	**5340.0**	**7440.0**		**9690.0**	**14100.0**		**900.0**	**0.0**	**15000.0**			

TSR Wt. (g): 4040

FINES =	0	
MRDs @ AC	5.2	5.7
Nini (Spec)	9	
Ndes (Spec)	125	
Nmax (Spec)	205	
Gsb	**2.861**	

RAS / RAP 900 0 **Total Weight: 15000.0** 15556.9

AC Grade	PG 52-40
Supplier	McAsphalt
Mixing Temp	150 °C
Compaction Temp	140 °C

SIEVE SIZES (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP 1	RAP 2	AC Grade	Mixing Temp	Compaction Temp	Ndes (Spec)
	HL1 Stone MRT	1/8 x 1/4 Chips MRT		1/4 x 0 Screenings MRT	Mfg. Sand MRT		Shingles Markham	3/8" RAP Markham	PG 52-40	150 °C	140 °C	125
Lab No	Pat treated	Pat treated		Pat treated	Pat treated				%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
RET 25	0.0						0.0	0.0				
RET 19.0	0.0							0.0				
RET 16.0	0.0							0.0				
RET 12.5	39.9						1.5	0.0				
RET 9.5	760.7	1816.3					2.4	0.0	3.1	4.7	162	162
RET 6.7	1429.1	1852.7		2541.1			6.1	0.0	3.6	5.2	189	189
RET 4.75	1737.5	2066.9		2619.9			11.6	0.0	4.1	5.7	217	217
RET 2.36	1784.7	2471.1		2824.1	3414.6		24.5	0.0	4.6	6.2	245	245
PASS 2.36	**1815.6**	**2529.6**		**3294.6**	**4794.0**		**306.0**	**0.0**	**5100.0**			

FINES = 0.0 RAS / RAP 306.0 0.0 **Total Weight: 5100.0** 5289.4 5262.1

Notes: ***Weight of Mixture for 115 +/-5 mm Ht/ 150mm Dia, g = 5250.0*** Total Wt. without RAP/RAS: 4794.0 **Mix No.: 18-1A**

Approx. Weight of Mixture for TSR Specimen 95 +/-5 mm Ht/ 150mm Dia, g = 3960.3

HOT MIX ASPHALT DESIGN BLEND SHEET

Supplier Research

RAP AC	4.80	27.00

Project	Various	Product No				Traffic Categroy	
Project No	M2010	% RAP	28.0	Stability			
Client	Research	%AC-RAP	7.18	Flow		E	
Mix No	1009B	DP (Spec)	0.6-1.2	VMA	13	Estmd for AV=4	
Mix Type	SP19.0 / Base Course	Nini (Spec)	9	VFA	65-75	Gmb	2.455
Date	20-Jan-10	Ndes (Spec)	125	TSR	>=80%	Gmm	2.556
%AC	4.9	Nmax (Spec	205	VCA_{max}		VMA	13.29
AC Grade	PG 52-34 - Conventiona	% Fines	0.5	VCA_{dry}		DP	1.32
Supplier	McAsphalt	FF Ratio	3.12	Voids %	4.0+/-0.5	Pbe	3.898
Comp. Gsb	2.692	Anti-Stripp.		Min AC	5.0	Gse	2.769

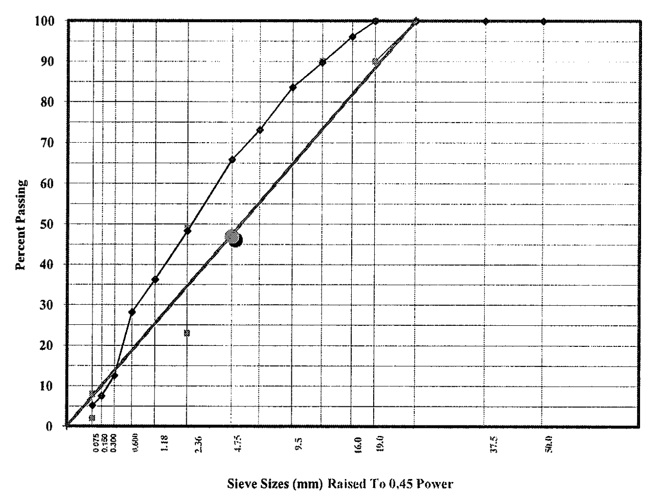
	MATERIAL	SOURCE	INV. #	% AGG	% VOL	Gsb	Gsa	Abs
CA1	HL8 Stone	Carden	O11-123	25.1	24.8	2.658	2.718	0.830
CA2	1/4" Chips	Carden	O11-123	17.1	16.9	2.670	2.706	0.500
CA3				0.0	0.0	1.000	1.000	0.000
FA1	Mfg. Sand	Dufferin	B12-127	16.1	16.7	2.788	2.835	0.592
FA2	IKO Sand	IKO	C01-148	13.7	14.0	2.750	2.788	0.500
FA3				0.0	0.0	1.000	1.000	0.000
RAP1	1/2" RAP	Markham		25.0	25.1	2.708	2.708	0.000
RAP2	Shingles	Markham		3.0	2.6	2.300	2.300	0.000
Film Thick	#REF!		Total:	100.0	100.0			

	COARSE AGGREGATES			FINE AGGREGATES			RAP	
	CA1	CA2	CA3	FA1	FA2	FA3	RAP1	RAP2
Sieve Sizes (mm)	HL8 Stone Carden	1/4" Chips Carden		Mfg. Sand Dufferin	IKO Sand IKO		1/2" RAP Markham	Shingles Markham
Lab No.								
50.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
37.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
25.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	95.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16.0	76.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	51.8	100.0	100.0	100.0	100.0	100.0	100.0	99.5
9.5	31.4	100.0	100.0	100.0	100.0	100.0	96.8	99.2
6.7	10.1	90.0	100.0	100.0	100.0	100.0	84.0	98.0
4.75	1.6	82.0	100.0	99.8	99.8	100.0	70.0	96.2
2.36	0.7	24.6	100.0	85.6	99.5	100.0	50.1	92.0
1.18	0.7	9.6	100.0	54.3	98.9	100.0	35.2	75.3
0.600	0.6	4.7	100.0	31.8	96.1	100.0	25.6	52.7
0.300	0.6	3.2	100.0	17.4	18.5	100.0	18.1	41.7
0.150	0.6	2.6	100.0	8.6	5.9	100.0	12.8	29.2
0.075	0.5	2.3	100.0	3.7	3.4	100.0	9.2	22.6

Please Select a Specification Superpave SP19.0 Re-Calculate

Sieve Sizes (mm)	BLEND	LOW	HIGH	FINAL BLEND	Aggregate	%	Agg. Proportion
50.0	100.0			100.0	% Total CA		
37.5	100.0			100.0	% Total FA		
25.0	100.0	100.0	100.0	100.0	CA1		25.1
19.0	98.9	90.0	100.0	100.0	CA2		17.1
16.0	94.2			96.1	CA3		0.0
12.5	87.9		90.0	89.7	FA1		16.1
9.5	82.0			83.6	FA2		13.7
6.7	71.7			73.1	FA3		0.0
4.75	64.6			65.9	Total FA	0.0	
2.36	47.1	23.0	49.0	48.3	RAP1	4.80	25.0
1.18	35.2			36.2	RAP2	27.00	3.0
0.600	27.2			28.1		Aggs. Total	100.0
0.300	11.8			12.5	Total CA	0.0	
0.150	6.9			7.5	Total AC		4.90
0.075	4.6	2.0	8.0	5.2	New AC		2.89

Notes:



Bailey's Method

Blend Characteristics	
NMAS	19.0mm
PCS	4.75mm
SCS	1.18mm
TCS	0.300mm
Half Sieve	9.5mm
CA Ratio	0.52
Range	0.60-0.75
FAc Ratio	0.55
Range	0.35-0.50
FAf Ratio	0.42
Range	0.35-0.50
LUW_{CA}	1.0
RUW_{CA}	1.0
LUW_{FA}	1.0
RUW_{FA}	1.0

HOT MIX ASPHALTIC CONCRETE WEIGH CARD

Mix: SP19.0 / Base Course 'Superpave Method' **Date: 20-Jan-10** **Project: Various** **Mix No.: 1009B**

SIEVE SIZES (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP 1	RAP 2	%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
	HL8 Stone Carden	1/4" Chips Carden		Mfg. Sand Dufferin	IKO Sand IKO		1/2" RAP Markham	Shingles Markham				
Lab No												
RET 25	0.0						0.0					
RET 19.0	22.6						0.0					
RET 16.0	116.0						0.0		2.4	4.4	49	49
RET 12.5	242.0						0.0	500.3	2.9	4.9	60	60
RET 9.5	344.4						16.0	500.5	3.4	5.4	70	71
RET 6.7	451.3	536.2					80.0	501.2	3.9	5.9	81	81
RET 4.75	494.0	563.6		844.6	1166.5		150.0	502.3				
RET 2.36	498.5	759.9		890.4	1167.4		249.5	504.8				
PASS 2.36	**502.0**	**844.0**		**1166.0**	**1440.0**		**500.0**	**2000.0**				

FINES =	10	
MRDs @ AC	4.9	5.4
Nini (Spec)	9	
Ndes (Spec)	125	
Nmax (Spec)	205	
Gsb	**2.692**	

RAP 500 **Total Weight: 2010.0** 2069.8

AC Grade	PG 52-34
Supplier	McAsphalt
Mixing Temp	145 °C
Compaction Temp	131 °C

SIEVE SIZES (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP 1	RAP 2	AC Grade	Mixing Temp	Compaction T...	Ndes (Spec)
	HL8 Stone Carden	1/4" Chips Carden		Mfg. Sand Dufferin	IKO Sand IKO		1/2" RAP Markham	Shingles Markham	PG 52-34	145 °C	131 °C	125
Lab No									%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
RET 25	0.0						0.0					
RET 19.0	54.6						0.0					
RET 16.0	280.3						0.0					
RET 12.5	584.9						0.0	1209.5				
RET 9.5	832.5						38.7	1209.9				
RET 6.7	1091.0	1296.3					193.4	1211.7	2.4	4.4	118	119
RET 4.75	1194.2	1362.4		2041.9	2820.1		362.6	1214.3	2.9	4.9	144	145
RET 2.36	1205.1	1837.0		2152.5	2822.1		603.2	1220.4	3.4	5.4	170	171
PASS 2.36	**1213.6**	**2040.4**		**2818.8**	**3481.2**		**1208.8**	**4835.0**	3.9	5.9	196	197

FINES = **24.2** RAP 1208.8 **Total Weight: 4859.2** 5003.8 4978.2

Notes: ***Weight of Mixture for 115 +/-5 mm Ht/ 150mm Dia, g = 5000.0***

Approx. Weight of Mixture for TSR Specimen 95 +/-5 mm Ht/ 150mm Dia, g = 3834.5

HOT MIX ASPHALT DESIGN BLEND SHEET

Project	Various	Product No				Traffic Categroy	
Project No	M2010	% RAP	6.0	Stability			
Client	Research	%AC-RAP	27.00	Flow		E	
Mix No	1019B	DP (Spec)	0.6-1.2	VMA	13	Estmd for AV=4	
Mix Type	SP19.0 / Base Course	Nini (Spec)	9	VFA	65-75	Gmb	2.455
Date	25-Jan-10	Ndes (Spec)	125	TSR	>=80%	Gmm	2.556
%AC	4.9	Nmax (Spec)	205	VCA_{max}		VMA	12.93
AC Grade	PG 52-40 - Conventiona	% Fines	3.0	VCA_{dry}		DP	1.72
Supplier	McAsphalt	FF Ratio	2.93	Voids %	4.0+/-0.5	Pbe	3.747
Comp. Gst	2.681	Anti-Stripp.		Min AC	5.0	Gse	2.769

	MATERIAL	SOURCE	INV. #	% AGG	% VOL	Gsb	Gsa	Abs
CA1	HL8 Stone	Carden	O11-123	39.5	39.1	2.658	2.718	0.830
CA2	1/4" Chips	Carden	O11-123	13.8	13.7	2.670	2.706	0.500
CA3				0.0	0.0	1.000	1.000	0.000
FA1	Mfg. Sand	Dufferin	B12-127	28.8	29.9	2.788	2.835	0.592
FA2	IKO Sand	IKO	C01-148	11.9	12.2	2.750	2.788	0.500
FA3				0.0	0.0	1.000	1.000	0.000
RAP1	1/2" RAP	Markham		0.0	0.0	2.708	2.708	0.000
RAP2	Shingles	Markham		6.0	5.1	2.300	2.300	0.000
Film Thick	#REF!		Total:	100.0	100.0			

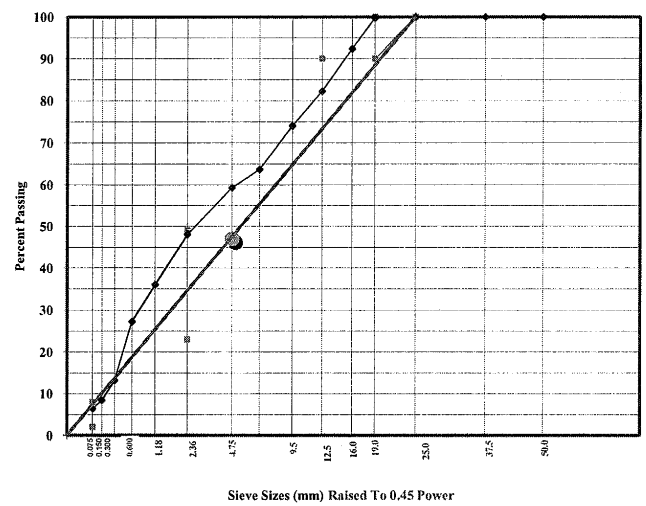
Supplier Research

						RAP AC	4.80	27.00
	COARSE AGGREGATES			FINE AGGREGATES			RAP	
Sieve Sizes (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP1	RAP2
	HL8 Stone Carden	1/4" Chips Carden		Mfg. Sand Dufferin	IKO Sand IKO		1/2" RAP Markham	Shingles Markham
Lab No.								
50.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
37.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
25.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	95.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0
16.0	76.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5	51.8	100.0	100.0	100.0	100.0	100.0	100.0	99.5
9.5	31.4	100.0	100.0	100.0	100.0	100.0	96.8	99.2
6.7	10.1	87.7	100.0	100.0	99.9	100.0	84.0	98.0
4.75	1.6	82.0	100.0	99.8	99.8	100.0	70.0	96.2
2.36	0.7	24.6	100.0	85.6	99.5	100.0	50.1	92.0
1.18	0.7	9.6	100.0	54.3	98.9	100.0	35.2	75.3
0.600	0.6	4.7	100.0	31.8	96.1	100.0	25.6	52.7
0.300	0.6	3.2	100.0	17.4	18.5	100.0	18.1	41.7
0.150	0.6	2.6	100.0	8.6	5.9	100.0	12.8	29.2
0.075	0.5	2.3	100.0	3.7	3.4	100.0	9.2	22.6

Please Select a Specification | Superpave | SP19.0 | Re-Calculate

Sieve Sizes (mm)	BLEND	LOW	HIGH	FINAL BLEND	Aggregate	%	Agg. Proportion
50.0	100.0			100.0	% Total CA		
37.5	100.0			100.0	% Total FA		
25.0	100.0	100.0	100.0	100.0	CA1	74.5	39.5
19.0	98.2	90.0	100.0	99.8	CA2	25.5	13.8
16.0	90.9			92.4	CA3		0.0
12.5	80.9		90.0	82.3	FA1	71.4	28.8
9.5	72.9			74.1	FA2	28.6	11.9
6.7	62.7			63.7	FA3		0.0
4.75	58.3			59.3	Total FA	100.0	
2.36	45.7	23.0	49.0	48.0	RAP1	4.80	0.0
1.18	33.5			36.0	RAP2	27.00	6.0
0.600	24.6			27.3		Aggs. Total	100.0
0.300	10.4			13.2	Total CA	100.0	
0.150	5.5			8.4	Total AC		4.90
0.075	3.3	2.0	8.0	6.4	New AC		3.28

Notes:



Bailey's Method	
Blend Characteristics	
NMAS	19.0mm
PCS	4.75mm
SCS	1.18mm
TCS	0.300mm
Half Sieve	9.5mm
CA Ratio	0.52
Range	0.60-0.75
FAc Ratio	0.55
Range	0.35-0.50
FAf Ratio	0.42
Range	0.35-0.50
LUW_{CA}	1.0
RUW_{CA}	1.0
LUW_{FA}	1.0
RUW_{FA}	1.0

HOT MIX ASPHALTIC CONCRETE WEIGH CARD

Mix: SP19.0 / Base Course 'Superpave Method' **Date: 25-Jan-10** **Project: Various** **Mix No.: 1019B**

SIEVE SIZES (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP 1	RAP 2				
	HL8 Stone Carden	1/4" Chips Carden		Mfg. Sand Dufferin	IKO Sand IKO		1/2" RAP Markham	Shingles Markham	%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
Lab No												
RET 25	0.0											
RET 19.0	35.6								2.8	4.4	57	59
RET 16.0	182.5								3.3	4.9	68	70
RET 12.5	380.8							0.6	3.8	5.4	79	81
RET 9.5	541.9							1.0	4.3	5.9	89	92
RET 6.7	710.2	824.0			1642.3			2.4				
RET 4.75	777.4	839.7		1067.2	1642.5			4.6				
RET 2.36	784.5	998.1		1148.9	1643.2			9.6				
PASS 2.36	**790.0**	**1066.0**		**1642.0**	**1880.0**		**0.0**	**2000.0**				

FINES =	60	
MRDs @ AC	4.9	5.4
Nini (Spec)	9	
Ndes (Spec)	125	
Nmax (Spec)	205	
Gsb	**2.681**	

RAP 0 **Total Weight: 2060.0**

AC Grade	PG 52-40
Supplier	McAsphalt
Mixing Temp	150 °C
Compaction Temp	140 °C

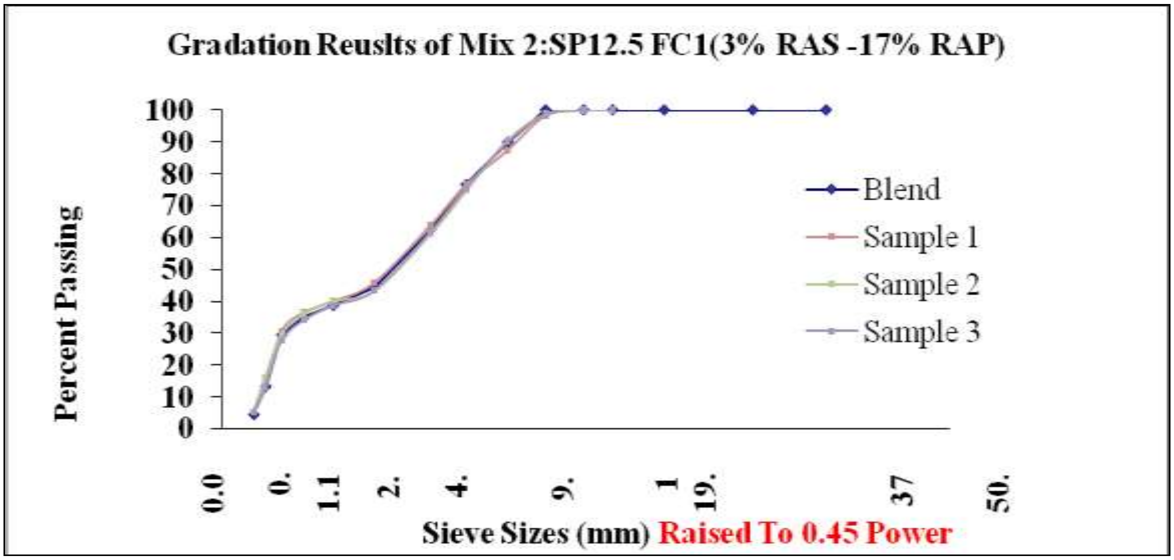
SIEVE SIZES (mm)	CA1	CA2	CA3	FA1	FA2	FA3	RAP 1	RAP 2	AC Grade	Mixing Temp	Compaction Temp	Ndes (Spec)
	HL8 Stone Carden	1/4" Chips Carden		Mfg. Sand Dufferin	IKO Sand IKO		1/2" RAP Markham	Shingles Markham	PG 52-40	150 °C	140 °C	125
Lab No									%AC NEW	TOT.%AC	AC GRAMS	ADJ. AC GRAMS
RET 25	0.0											
RET 19.0	82.8											
RET 16.0	425.2											
RET 12.5	887.2							1.4				
RET 9.5	1262.7							2.2	2.8	4.4	133	137
RET 6.7	1654.8	1919.9			3826.6			5.6	3.3	4.9	158	163
RET 4.75	1811.2	1956.5		2486.5	3827.0			10.6	3.8	5.4	183	189
RET 2.36	1827.8	2325.6		2677.0	3828.6			22.4	4.3	5.9	208	215
PASS 2.36	**1840.7**	**2483.8**		**3825.9**	**4380.4**		**0.0**	**4660.0**				

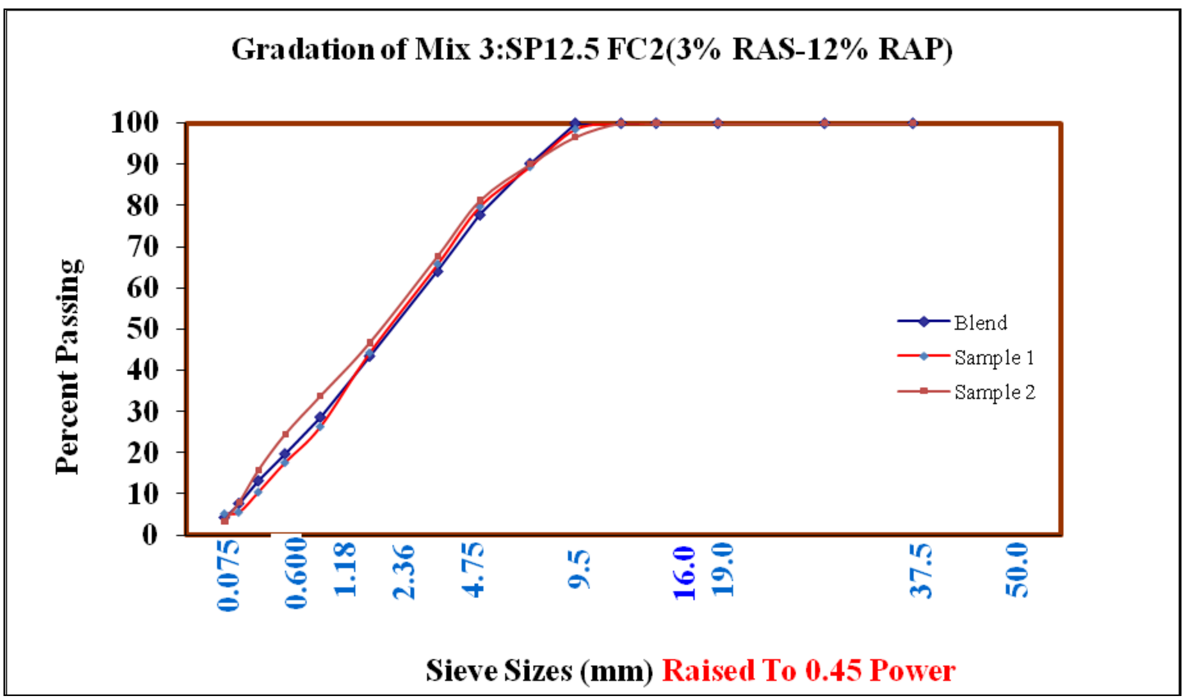
FINES = 139.8 RAP 0.0 **Total Weight: 4799.8** 4962.6 4937.0

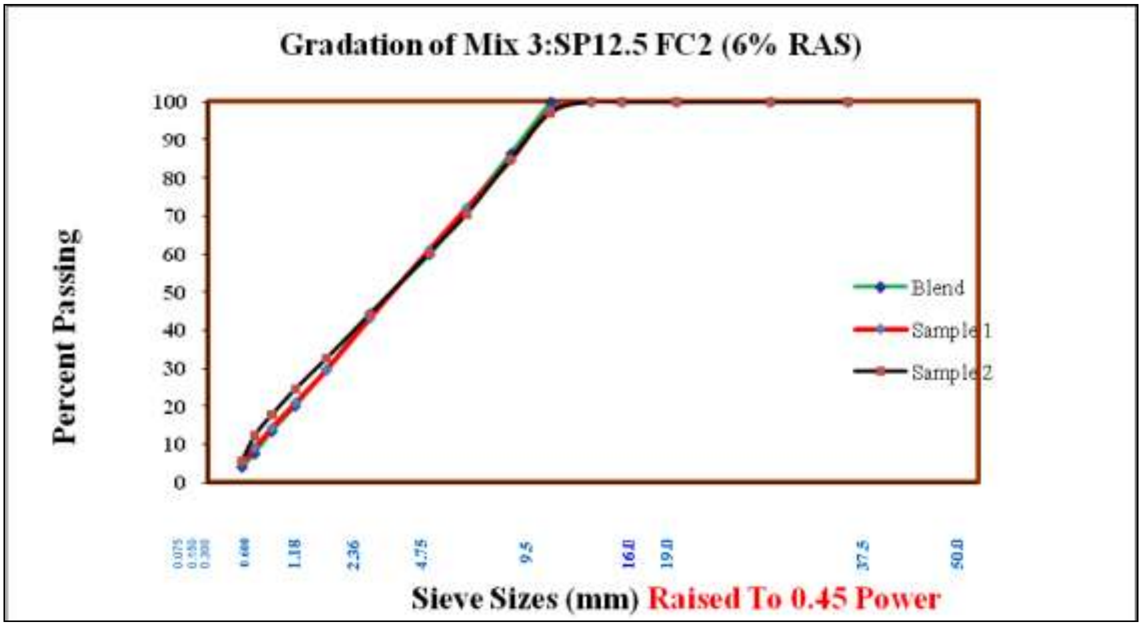
Notes: ***Weight of Mixture for 115 +/-5 mm Ht/ 150mm Dia, g = 4900.0***

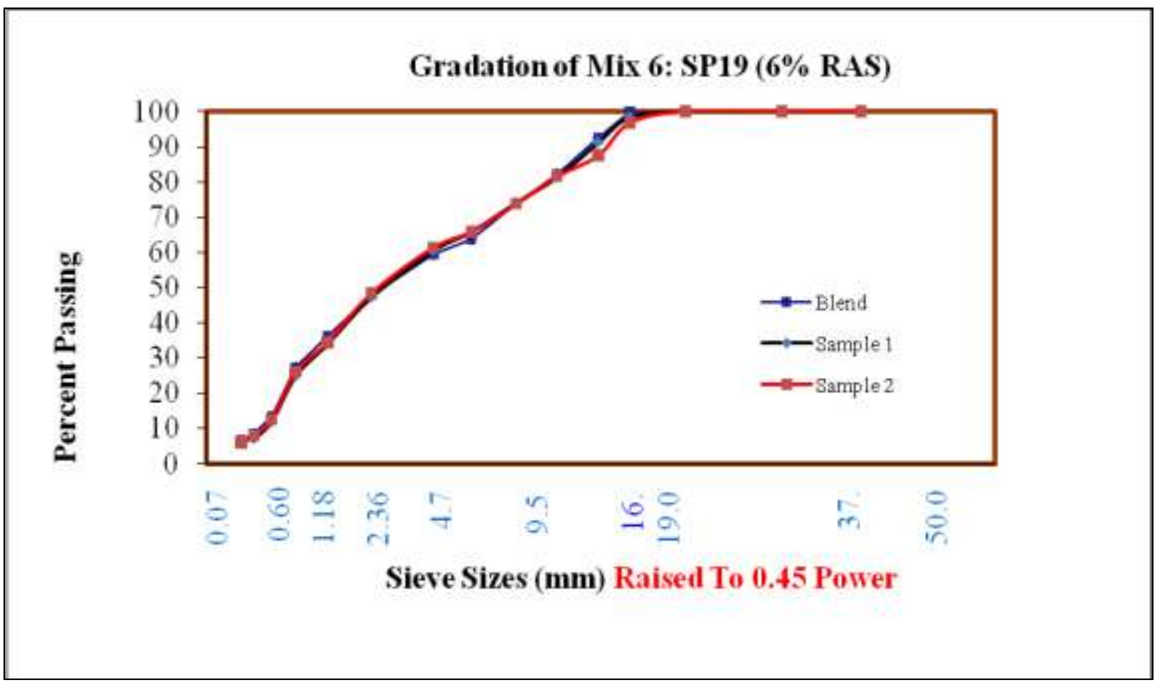
Approx. Weight of Mixture for TSR Specimen 95 +/-5 mm Ht/ 150mm Dia, g = 3834.5

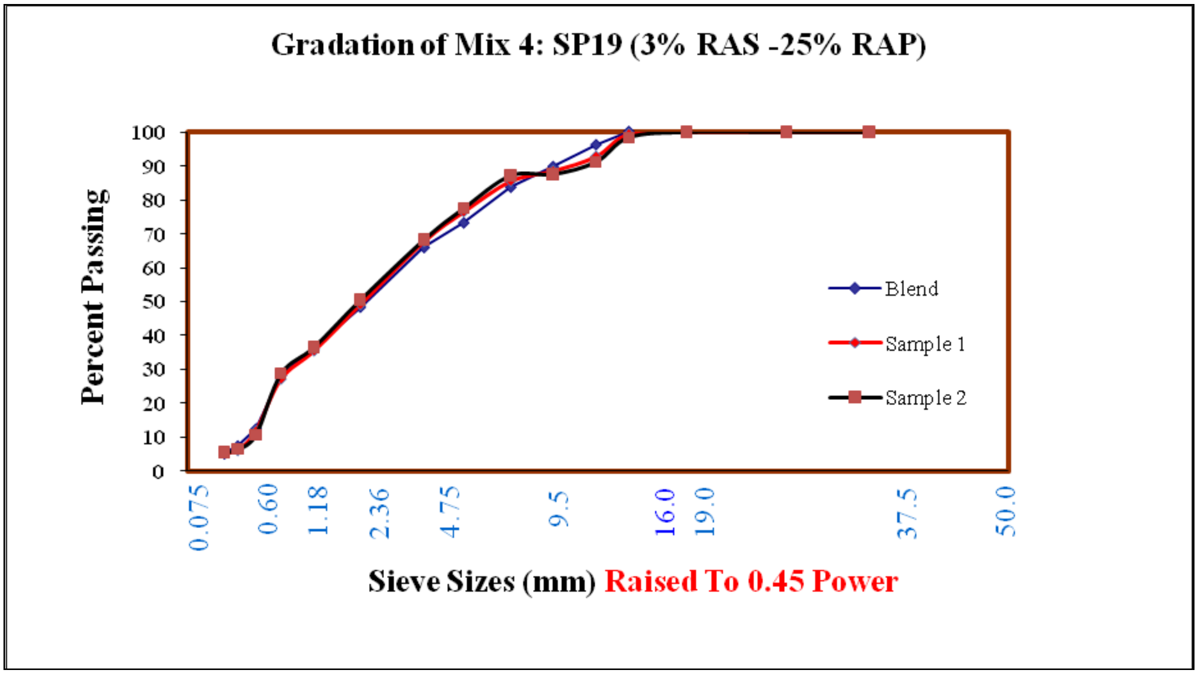
Extraction/Gradation Test



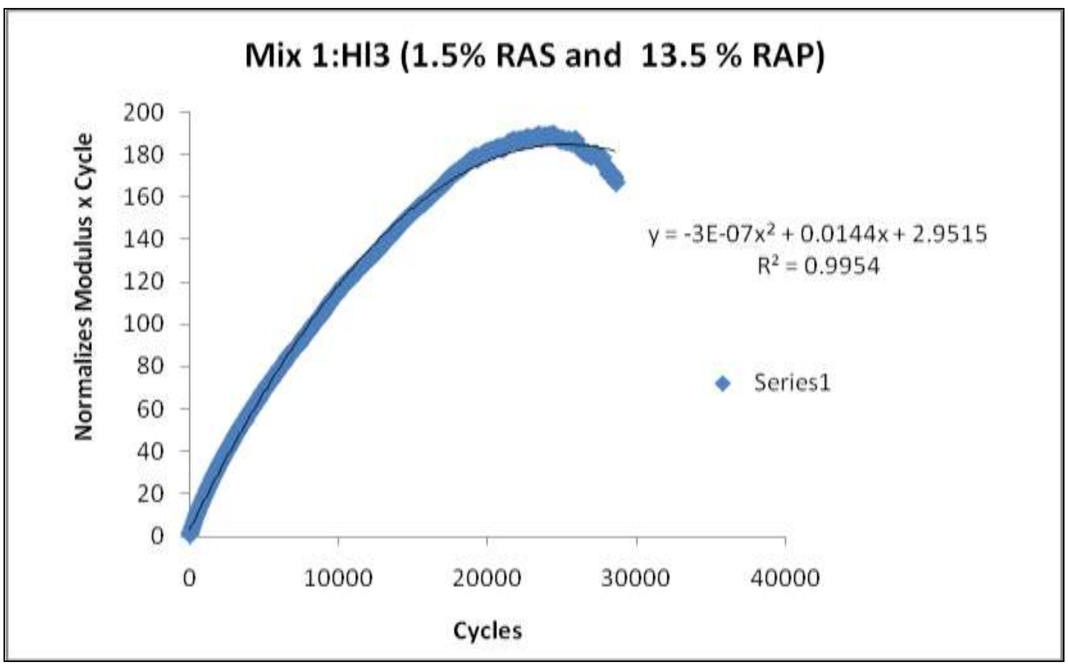


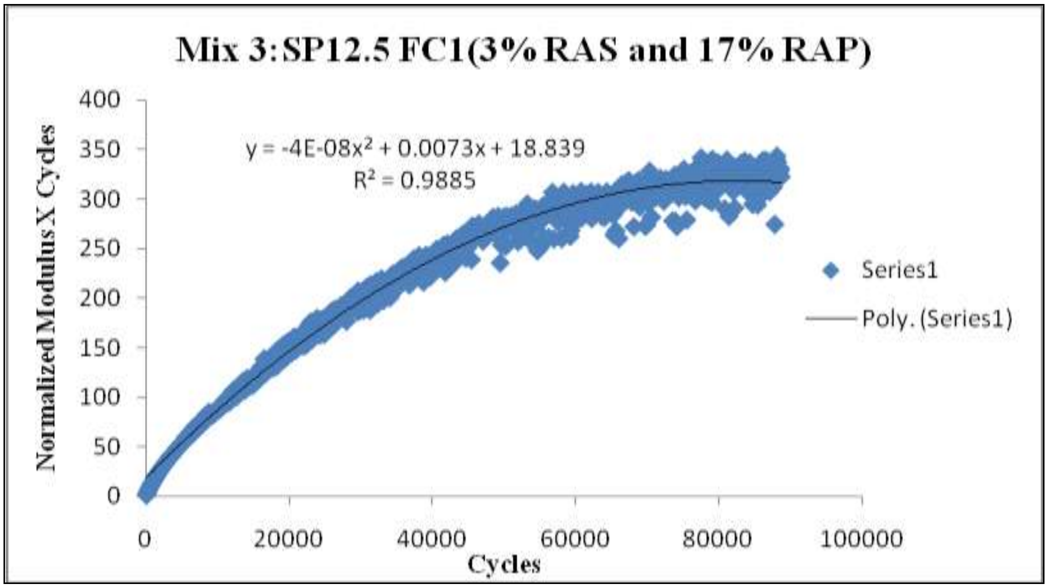

Gradation of Mix 3:SP12.5 FC2 (6% RAS)
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
Blend
Sample 1
Sample 2
0.600
1.18
2.36
4.75
9.5
16.0
19.0
37.5
50.0
Sieve Sizes (mm) Raised To 0.45 Power

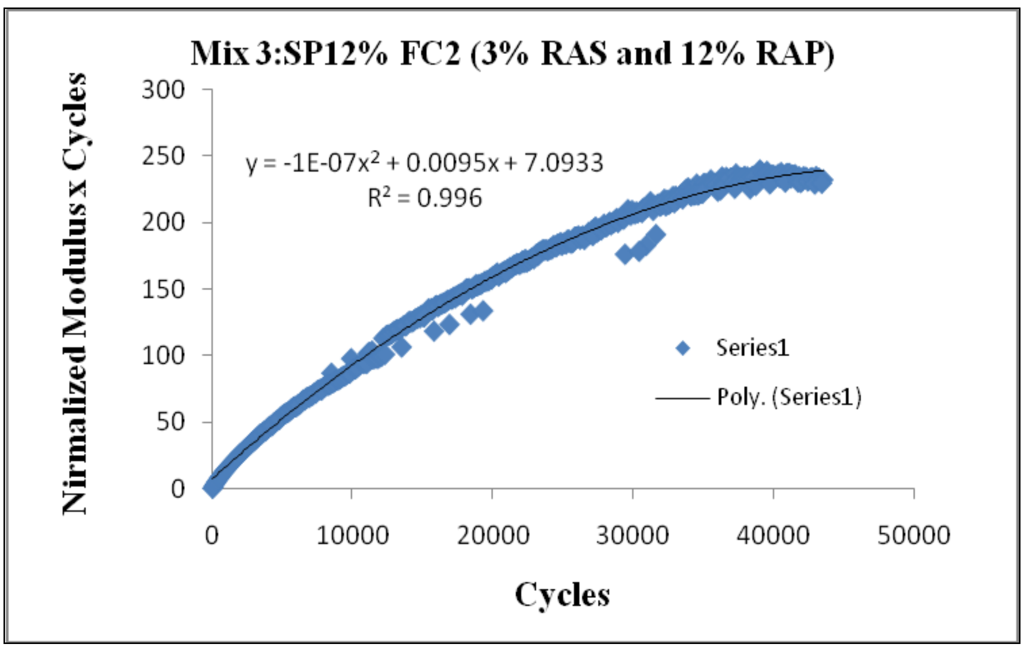

Gradation of Mix 6: SP19 (6% RAS)
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
Blend
Sample 1
Sample 2
0.07
0.60
1.18
2.36
4.7
9.5
16.
19.0
37.
50.0
Sieve Sizes (mm) Raised To 0.45 Power



Fatigue Test




Mix 3:SP12.5 FC1(3% RAS and 17% RAP)
y = -4E-08x² + 0.0073x + 18.839
R² = 0.9885
Normalized Modulus X Cycles
400
350
300
250
200
150
100
50
0
0
20000
40000
60000
80000
100000
Cycles
Series1
Poly. (Series1)


Mix 3:SP12% FC2 (3% RAS and 12% RAP)
y = -1E-07x² + 0.0095x + 7.0933
R² = 0.996
Nirmalized Modulus x Cycles
300
250
200
150
100
50
0
0
10000
20000
30000
40000
50000
Cycles
Series1
Poly. (Series1)

t Table

t Table

cum. prob	$t_{.50}$	$t_{.75}$	$t_{.80}$	$t_{.85}$	$t_{.90}$	$t_{.95}$	$t_{.975}$	$t_{.99}$	$t_{.995}$	$t_{.999}$	$t_{.9995}$
one-tail	0.50	0.25	0.20	0.15	0.10	0.05	0.025	0.01	0.005	0.001	0.0005
two-tails	1.00	0.50	0.40	0.30	0.20	0.10	0.05	0.02	0.01	0.002	0.001
df											
1	0.000	1.000	1.376	1.963	3.078	6.314	12.71	31.82	63.66	318.31	636.62
2	0.000	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	22.327	31.599
3	0.000	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841	10.215	12.924
4	0.000	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	0.000	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	5.893	6.869
6	0.000	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	0.000	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	4.785	5.408
8	0.000	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	0.000	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	0.000	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	0.000	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	0.000	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	0.000	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	0.000	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	0.000	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	0.000	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	0.000	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	0.000	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	0.000	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	0.000	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	0.000	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	0.000	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	0.000	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	3.485	3.768
24	0.000	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	0.000	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	0.000	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	0.000	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28	0.000	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	0.000	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.396	3.659
30	0.000	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	0.000	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704	3.307	3.551
60	0.000	0.679	0.848	1.045	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80	0.000	0.678	0.846	1.043	1.292	1.664	1.990	2.374	2.639	3.195	3.416
100	0.000	0.677	0.845	1.042	1.290	1.660	1.984	2.364	2.626	3.174	3.390
1000	0.000	0.675	0.842	1.037	1.282	1.646	1.962	2.330	2.581	3.098	3.300
z	0.000	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	3.090	3.291
	0%	50%	60%	70%	80%	90%	95%	98%	99%	99.8%	99.9%
	Confidence Level										