Effect of Reclaimed Asphalt Pavement on Ontario Hot Mix Asphalt Performance

by

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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

The use of Reclaimed Asphalt Pavement (RAP), sometimes called Recycled Asphalt Pavement, in Hot Mix Asphalt (HMA) provides many benefits and has been successfully used in Ontario for several years. The production and usage of this material results in numerous environmental and economic advantages. Using RAP in HMA has various proven benefits including: reuse of high quality materials, saves on dwindling non-renewable aggregate resources, diverts large volumes of materials from overloaded landfills, reduces road building costs and contributes significantly to provincial and municipal recycling obligations. However, the usage of this material is still very conservative.

Several challenges can be faced when introducing RAP in HMA, particularly in higher amounts. The characteristics of the RAP, particularly the aged (stiffer) asphalt cement (AC) in the recycled material, can affect the performance of the mix. The primary concern with increasing RAP percentages in HMA mixes are its effects on endurance against fatigue and thermal cracking. The common question in many agencies within the pavement industry is whether RAP acts as a “black rock” or the aged AC in RAP blends with the new AC in the mix.

Accordingly, this research evaluated the impact that RAP in varying percentages has on a conventional Ontario mix, Superpave (SP) 12.5mm, and provided some new guidelines on the usage of RAP. Using virgin aggregates and RAP collected from a local contractor, twelve mixtures were modelled in the laboratory, with 0%, 20%, and 40% RAP contents and AC with different Performance Grade (PG).

The research also examined how the addition of RAP to HMA alters the performance of the mix, and how HMA can be tested to determine the RAP content.

This research intended to answer the following questions: First, can the RAP percentage be determined from the recycled hot mix asphalt characteristics or performance? And second, can the blended binder PG be deduced from performance testing of recycled hot mix?

This research demonstrated that is possible to design Superpave mixes incorporating 20% RAP and 40% RAP without compromising the specified consensus properties and volumetric characteristics.

Based on the results, it was determined that the performance of the recycled hot mixes regarding low temperature cracking, rutting and stiffness, which is related to the fatigue susceptibility of the mix, was simultaneously influenced by the RAP content and the virgin asphalt PG. The effect of the RAP addition was more dramatic for the mixes with virgin binder PG 52-xx than for the mixes with PG 58-xx.

A method to determine the presence and quantity of RAP was formulated, and also an estimation of the performance grade of the resulting blended binder without extraction and recovery of the asphalt was possible.

Acknowledgements

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This research would not be possible without the continuous support from Prof. Susan Tighe, who is my mentor and encouraged me to grow not only professionally but personally. I want to acknowledge all the help that I received from the entire Centre of Pavement and Transportation Technology (CPATT) group, including the students who already finished their degree, those who are just starting, the co-op students and visiting students. They have all helped and I am grateful.

Dedication

To my parents, Oswaldo and Maria, who cultured in me the value of perseverance. To my husband Fernando and my daughter Luciana for giving me the motivation and love that I need every day. To my grandma Elena, who is the angel that prays for me from heaven.

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Chapter 1
Introduction

The Ministry of Transportation Ontario is committed to having the greenest roads in North America (MTO, 2011). Ontario has one of the maximum allowances of Reclaimed Asphalt Pavement (RAP) content for new Hot Mix Asphalt (HMA) (O'Reilly, 2012). Currently, up to 20% RAP by mass is allowed for Superpave surface courses and 40% for binder courses. The use of RAP in HMA is a common practice in Ontario. Increased use of RAP is also being promoted because of its environmental and economic advantages. Using RAP in HMA has many proven benefits including: the reuse of high quality materials, the saving of dwindling non-renewable aggregate and asphalt resources, the diversion of large volumes of materials from overloaded landfills, and the reduction of road building costs (OHMPA, 2007a).

The Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, DBA Engineering Limited, the Ontario Hot Mix Producers Association (OHMPA) and the Ministry of Transportation Ontario (MTO) initiated a partnership in spring 2011 to examine the impact of RAP on conventional Ontario HMA. Various material characterization tests were conducted at both the CPATT laboratory and DBA Engineering laboratory to provide the most comprehensive information to the MTO and OHMPA. In addition, the research was aimed to assist Departments of Transportation (DOT's) throughout Canada.

In short, the intent of the research was to provide DOT's, and more specifically the MTO, with the ability to assess the impact that RAP has on the Performance Graded Asphalt Cement (PGAC) and determine the actual percentage of RAP material in a HMA when it is plant mixed. The research described herein was directed at providing the characterization of a typical Superpave surface course, SP12.5, with different percentages of RAP. The PGAC for the mixtures was representative of the typical asphalt binders used in Ontario. Finally, the mixtures were evaluated with different tests for long term performance evaluation.

The research was practical and focused on providing recommendations that could be easily implemented in Ontario. In essence, there are a couple of fundamental questions that were addressed: How does RAP affect mix properties? What kind of testing is appropriate to predict long term field performance? There are several benefits to using RAP in HMA and the findings of this research are expected to contribute to understanding the role that RAP has on HMA performance.

The gap identified in the existing quality assurance practice related to RAP mixtures is the lack of a procedure to accurately determine the percentage of recycled material in an existing recycled hot mix.

More specifically, it is very difficult to accurately determine the percentage of RAP in HMA. That represents a challenge because the aging, the origin and quality of the RAP aggregates and binder, can introduce variability and ultimately result in a reduced life cycle of the pavement. RAP in HMA could potentially result in an increased life cycle as well but currently its impact is not fully understood. However, when the properties of the RAP and its associated impact on the new HMA are identified, engineers and designers can better utilize the material.

The other challenge that currently exists is the need to determine the overall Performance Grade (PG) for the recycled hot mix. Considering that the aged binder from the RAP affects the performance of the virgin binder, it is important to determine the final PG that is achieved. If this could be determined by the performance tests on plant mix, that would represent a significant advancement in the state-of-the-art practice.

Consequently, plant mixed recycled hot mix not only needs to be characterized, but also evaluated to predict its long term field performance. Considering the shortage of resources for conducting a complete performance investigation, it is necessary to determine a protocol for testing and the associated guidance for interpreting how these results relate to field performance of the recycled hot mix.

1.1 Research Hypothesis

The hypotheses of this research are as follows:

- The percentage of recycled asphalt material in HMA containing RAP can be determined from mixture characterization performance tests.
- The RAP does not behave completely as a black rock as it appears some degree of blending occurs.
- The RAP percentage is related to the PG of the blended binder and the PG of the binder can be estimated through the analysis of performance tests conducted on the recycled hot mix asphalt.

1.2 Scope and Objectives

This research evaluates the quality of recycled hot mix by developing a method to determine the percentage of RAP contained in a HMA. The analysis of the variation of the properties of the HMA combined with the mechanical response of the material when adding different known quantities of RAP for laboratory prepared samples represent the foundation of this research.

The purpose of this research was to evaluate the impact that RAP has on surface layer asphalt material in the Superpave 12.5 (SP12.5) mixtures and provide some new guidelines on the usage of RAP. In order to evaluate this, an extensive laboratory evaluation was conducted that involved evaluation of both basic properties as well as the usage of performance tests such as dynamic modulus testing, thermal stress restrained specimen test (TSRST), and Hamburg wheel rutting test. Different PG grades were also selected for each percentage of RAP mix to represent typical Ontario conditions.

The objectives were as follows:

1. Determination of the percentage of RAP in recycled HMA and description of how mixes can be tested for this purpose.
2. Discussion on how the RAP percentage impacts the PGAC and the performance tests that could be used to back-calculate this property.
3. Analysis of the differences of the recycled hot mix properties with different PG binders.
4. Determination of the relationship between basic properties of the mix and performance.

1.3 Research Methodology

The research methodology considered seven primary tasks as presented in Figure 1-1. These tasks are described in detail below.

Task 1: Carry out a comprehensive literature review on the state-of-the-art of RAP usage. Various Initial documentation from the National Center for Asphalt Technology (NCAT), National Highway Cooperative Research Program (NCHRP), North Central Superpave Centre (NCSC), Transportation Research Board (TRB), Asphalt Institute (AI) and the International Society of Asphalt Pavements (ISAP) were identified as a starting point for this research.

Task 2: This task focused primarily on the RAP characterization. It involved the fundamental evaluation of the basic RAP properties. This included recovery AC in the RAP, recovery gradation of the RAP and the PG of the RAP. RAP samples were collected with the assistance of OHMPA. Capital Paving Inc. donated RAP and virgin aggregate for a typical SP12.5. In addition, McAsphalt Industries Ltd., Canadian Asphalt Industries Inc., Bitumar Inc. and Coco Paving Inc. also donated PGAC to the project.

Task 3: This task involved a preliminary analysis of the results from the designs provided by DBA Engineering Ltd. The consensus properties, gradation, and Superpave design parameters were evaluated to determine if they met the specified requirements and their variation with the increase of RAP.

Task 4: This task involved performance testing of the SP12.5 mixes for the varying percentages of RAP (control 0% RAP, 20% RAP, and 40% RAP). As noted in Figure 1-1, to properly assess these mixes for Ontario, four PG binders were used for each mix. Overall, the identified performance tests included: dynamic modulus, TSRST, and Hamburg wheel rutting test. The various test results for each of the mixes were evaluated and compared. This task attempted to benchmark the mixes through the performance testing.

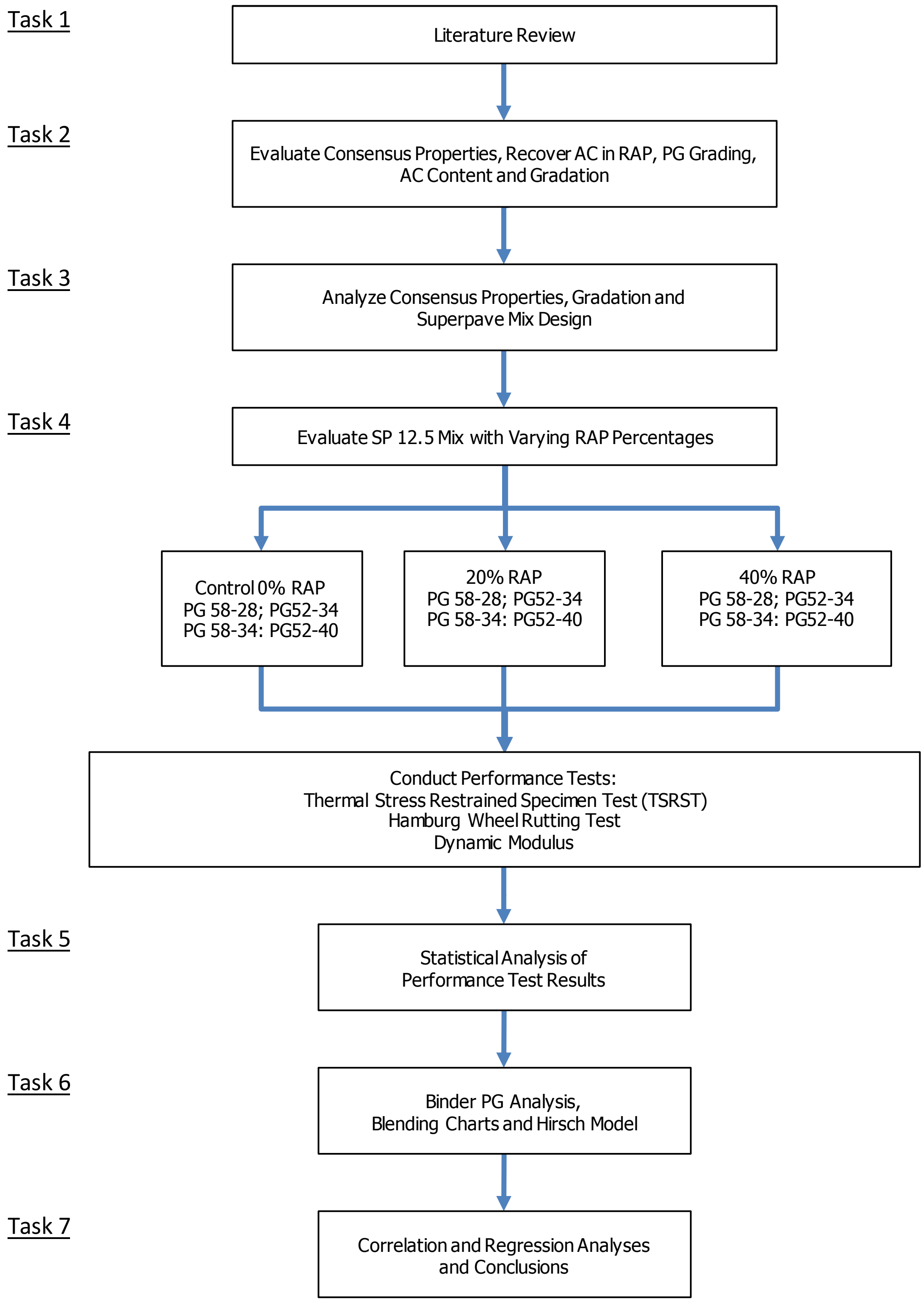

Figure 1-1 Research Methodology

Task 5: The main intent of this task was to analyze the results obtained from the performance testing as outlined in Task 4. The significance of the differences between the samples was verified, using statistical testing including ANOVA analysis and t-tests. Statistical analyses were used to determine similarities and differences as RAP percentages were increased. This task also involved the development of master curves from the dynamic modulus results and yielded the performance characterization of the different mixtures.

Task 6: This task focused on the study of the effect of RAP on the binder PG. This involved three main sub-tasks.

- Study the relationship between the RAP percentage and the blended binder PG.
- Use the findings from NCHRP Project 9-12 (McDaniel & Anderson, 2001a) to obtain an estimation of the RAP binder ratio from the blending charts and compare this estimation with the actual percentage of RAP binder in the mix.
- Use the Hirsch model to determine the properties of the blended binder and compare them with the results obtained from the extracted and recovered AC characterization.

Task 7: Finally, correlation analyses were performed to study the existing relationships in the design properties and the performance tests. When the correlation was found significant, an appropriate regression model for the RAP content estimation was determined. At the end, a method was proposed for future research in the detection of RAP and the pertaining conclusions were obtained.

Only one source of RAP was considered in this research. The material was donated by an active asphalt plant in Southern Ontario. Table 1-1 provides a summary of the different mixtures studied identified by the RAP content and the PG of the virgin binder used. The highlighted cells denote the selected mixtures for the design phase. DBA Engineering Ltd. was responsible for the mix design of the HMA, and determination of the consensus properties as well as the AC recovery and characterization.

Table 1-1 Proposed Matrix for Mixes to be Evaluated

RAP Content	**Virgin Binder PG Grade** (Mixture ID: % RAP – PG Grade)			
	PG 58 -28	**PG 58-34**	**PG 52-34**	**PG 52-40***
0%	0-58-28	0-58-34	0-52-34	0-52-40
20%	20-58-28	20-58-34	20-52-34	20-52-40
40%	40-58-28	40-58-34	40-52-34	40-52-40

Notes: *Polymer Modified Binder

The following activities were conducted as part of this research in the CPATT laboratory:

- Sieve virgin aggregates and RAP aggregates.
- Batch according to blend cards provided by DBA Engineering Ltd.

- Mix 18 batches of approximately 15kg of HMA for each mix type.
- Monitor the Maximum Relative Density (MRD) for each day.
- Prepare the samples for the performance tests.
- Conduct the performance tests according to Table 1-2.

The disk-shaped compact tension test was also conducted by the Asphalt Institute in accordance with ASTM D7313-07a Standard, on the design cells with the samples manufacture in the CPATT. The complete test plan is shown in Table 1-3.

All laboratory-produced loose mixtures were subjected to short-term aging during four hours at 135ºC in a forced-draft oven in accordance with AASHTO R 30-02 Standard, in order to simulate the plant-mixing and construction effects on the mixture.

Table 1-2 Performance Tests Conditions

Laboratory Test	**Performance Indicator**	**Test Temperature**	**Test Protocol**
Dynamic Modulus	Elastic modulus and phase angle	-10°C, 4°C, 21°C, 37°C, 54°C	AASHTO TP 62-07
Thermal Stress Restrained Specimen	Fracture stress and temperature	from 5°C to failure temperature	AASHTO TP 10-93
Hamburg Wheel Rutting Test	Rut depth and creep slope	50°C	AASHTO T 324-04

Table 1-3 Complete Test Plan

<table>
<tr><th></th><th>12 mixtures</th><th>6 mixtures</th></tr>
<tr><td rowspan="5">Tests on Mixtures</td><td>Thermal Stress Restrained Specimen
AASHTO TP 10-93</td><td>Fracture Energy
ASTM D7313-07</td></tr>
<tr><td rowspan="2">Hamburg Wheel Rutting
AASHTO T 324-04</td><td>Flow Number
AASHTO TP 79-12</td></tr>
<tr><td>Tensile Strength Ratio
AASHTO T 283-07</td></tr>
<tr><td>Dynamic Modulus (MTS)
AASHTO T 342-11</td><td>Dynamic Modulus (AMPT)
AASHTO TP 79-12</td></tr>
<tr><td rowspan="2">Tests on Binders</td><td>Extraction and Recovery
AASHTO T 164</td><td rowspan="2">Shear Modulus (DSR)
ASTM D7175-08</td></tr>
<tr><td>PG Grading
ASTM D7643-10</td></tr>
</table>

As a first stage in the research, the consensus properties of all the mixes were evaluated in order to identify how the percentage of RAP affected those physical properties. Each variable was examined for how sensitive its impact was to an increase in the percentage of RAP. Also, an analysis of the design gradation using the Power-Law method was conducted.

Secondly, the research involved studying the performance tests results and the associated effect of addition of RAP on the performance indicators. Using the ANOVA and t-test, the significance of the differences from the data obtained was assessed.

The blending charts were used to determine the allowable RAP content for comparison to the real RAP content added. In addition, correlation and regression analyses were used to examine RAP content impacts.

For the determination of the blended binder performance grade, the following procedure was followed in this research (after Mogawer et al. 2010):

1. Perform dynamic modulus testing on at least three replicate specimens.
2. Estimate high temperature PG grade:
   a. Obtain |E*| master curve for virgin mixture and RAP mixture.
   b. Obtain |E*| master curve for recycled hot mix.
   c. Back-calculate |G*| using the measured dynamic modulus and the Hirsch model.
   d. Compare back-calculated |G*| to virgin and RAP values to estimate the effective high temperature PG grade.
3. Estimate low temperature PG grade for fatigue:
   a. Back-calculate |G*| using the measured dynamic modulus and the Hirsch model.
   b. Using the RHEA software, determine the phase angles from the back-calculated |G*| master curve.
   c. Shift master curves to determine temperature at which $|G^*| \sin\delta = 5000$ kPa.
4. Estimate low temperature PG grade for thermal cracking:
   a. Back-calculate |G*| using the measured dynamic modulus and the Hirsch model.
   b. Use the RHEA software to calculate creep stiffness of binder.
   c. Calculate S-value and m-value for each mixture as a function of temperature.
   d. Calculate temperature at which S=300 MPa and m=0.300.
   e. Determine effective low temperature PG grade.

The estimated performance grade of the blended binder was also examined through the linear blending charts. The deviations between the critical temperatures determined from the linear blending charts and from actual testing were also quantified to determine if they were significant.

1.4 Organization of Thesis

Chapter 2 presents a background with the basic concepts required to understand the research conducted and the results obtained, also the literature review (Task 1) on the state-of-the-art of recycled hot mixtures in Ontario and the experience on performance testing on the same are summarized. Chapter 3 describes the properties of the materials used and the results and analysis from the design stage (Task 2 and Task 3). Task 4 and Task 5, covering the performance testing results and analyses, are presented in Chapter 4. Chapter 5 is dedicated to Task 6 where the estimations with Hirsch model and blending charts are explained. In Chapter 6 the evaluation of the RAP binder ratio is described. Chapter 7 provides the conclusions and recommendations from the research.

Chapter 2
Literature Review

2.1 General Background

2.1.1 Asphalt Cement (AC)

Asphalt is a by-product of the petroleum distillation process. It is a combination of heavy molecules, namely asphaltenes, suspended in a less dense matrix of maltenes. The asphalt also includes volatile elements that are lost during mixing and placement and is affected by the oxidation due to the chemical reactions with air and water through time under the environmental conditions which contribute with the stiffening of the material (Hernández Noguera, Rondón Quintana, & Fernández Gómez, 2014). The properties of AC vary with temperature. At high temperatures the asphalt is liquid, but at room temperature it is semi-solid while at low temperatures it becomes solid.

2.1.2 Hot Mix Asphalt (HMA)

Asphalt concrete is a composite material made by the mixing of natural and crushed aggregates, and asphalt cement. The asphalt mix has three phases: aggregates, asphalt binder and air voids, as shown in Figure 2-1.

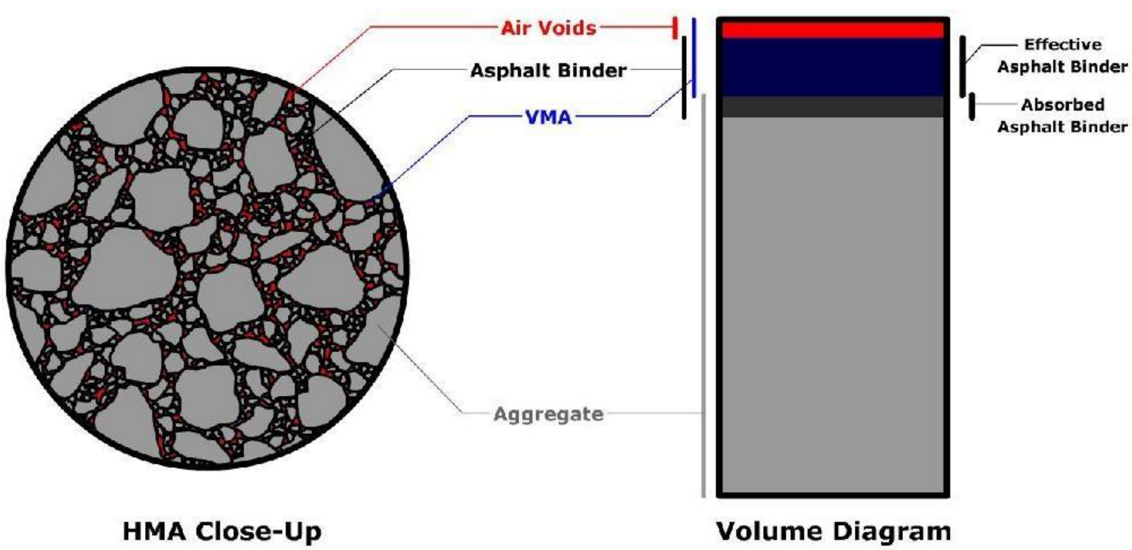

Figure 2-1 Asphalt Concrete Parts (Pavement Interactive, 2010)

The term hot mix asphalt term refers to the materials that are mixed, transported, extended and compacted in a hot state, in order to work with the desired viscosity of the asphalt. The viscosity of asphalt decreases with the increase of temperature. To determine the mixing and the compaction temperatures, a viscosity-temperature chart is required.

Based on the known weight and volume of the different phases, important relations can be drawn. The most commonly used of these are the volume of air voids (Va), voids in mineral aggregate (VMA) and voids filled with asphalt (VFA).

According to the distribution of the sizes of the aggregates, a mix can be open graded, gap graded or dense graded. A dense graded mix is achieved when the aggregates have a good size distribution, meaning a similar amount of particles of each size, that allows filling more voids with the smaller aggregates and then getting a more dense structure.

2.1.3 Reclaimed Asphalt Pavement (RAP)

Reclaimed Asphalt Pavement is the result of milling an existing HMA layer that was removed for preservation of rehabilitation on a road. The milled material is transported to a stockpile for future use. Usually, this material has to be classified, crushed and sieved to remove any oversized particles and fractionated to the required nominal maximum aggregate size. The correct handling of the stockpiles is critical to avoid clumping, segregation and contamination. By its characteristics, RAP is a heterogeneous material, and is different from site to site. Special consideration should be taken when mixing RAP from different sources.

2.1.4 Recycled Hot Mix (RHM)

According to Ontario Provincial Standard Specification OPSS 313 (MTO, 2007a), recycled hot mix is the product of mixing reclaimed asphalt pavement, virgin aggregate and new asphalt cement in a hot mix plant (MTO, 2007b). Recycled hot mix may be used in any paving course except in surface courses carrying in excess of 5000 AADT/2 Lanes. Figure 2-2 shows the different components of a RHM, and Figure 2-3 shows an example of the weight relations of a RHM compared to a conventional HMA.

Figure 2-2 Recycled Hot Mix Components

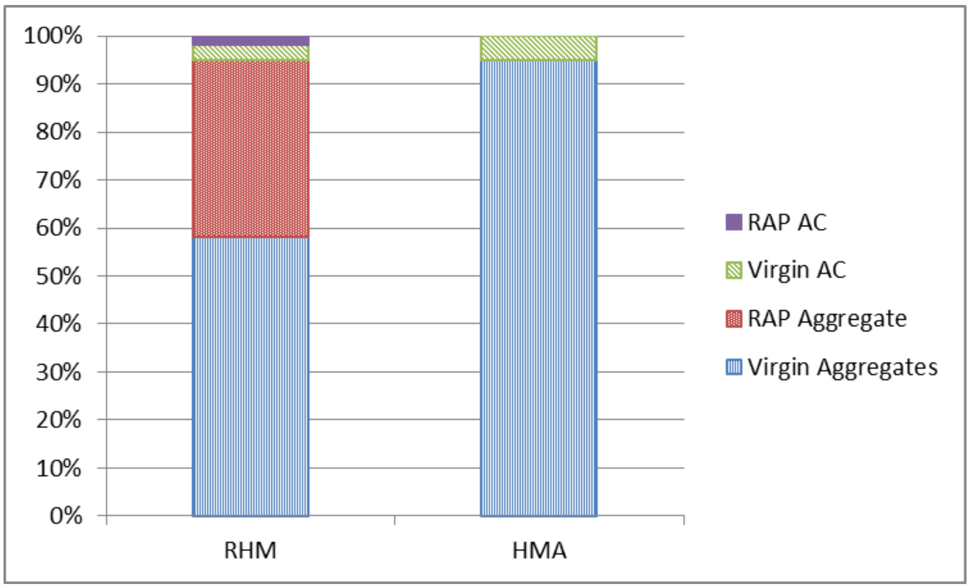

Figure 2-3 Weight Diagram RHM vs HMA

The current Ontario Specification OPSS 1151 for Superpave Mixtures permits the use of up to 20% by mass of RAP for surface course mixes, and up to 40% for binder mixes (MTO, 2007b).

According to Kriz et al., blending between the virgin asphalt and the aged asphalt in the RAP occurs via two main mechanisms: contact and diffusion (Kriz et al., 2014). Kriz et al. also identified several scenarios for the blending process as shown in Figure 2-4. Two main scenarios can be identified. One scenario is that there is contact between the RAP and the virgin materials, but there is no blending between the aged asphalt in the RAP and the new asphalt. The second scenario is when there is contact, and also blending, meaning that the molecules in the aged binder combines with the molecules in the new asphalt, creating a new blended binder. Obtaining one or other of the mentioned scenarios depends on the relative stiffness of the two binders, the temperature of the mix and the mixing time.

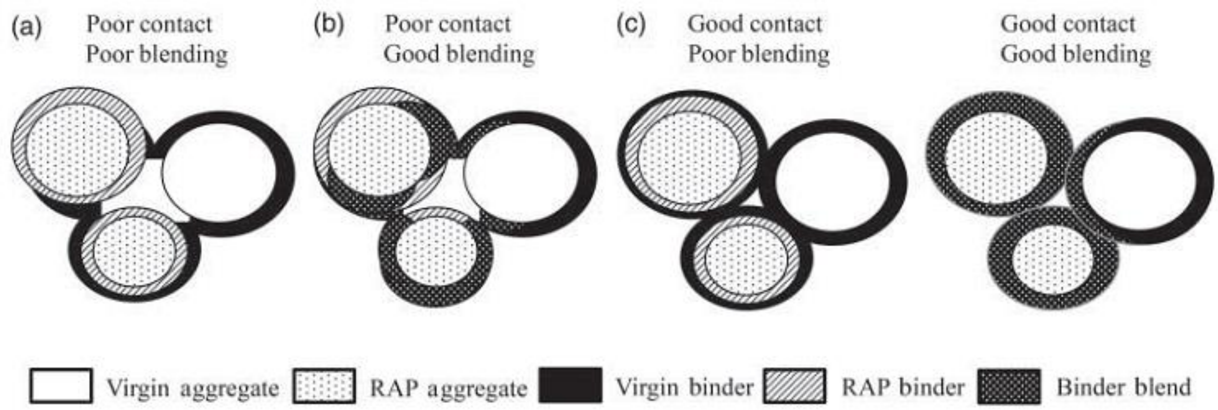

Figure 2-4 RAP-Virgin Blending Options (Kriz et al., 2014)

2.2 Mechanical Properties

Viscoelastic materials are characterized by their behavior under load in terms of stress and strain. When asphalt binders and asphalt mixtures are under dynamic load, the response of the material is dependent on the frequency of the load application and temperature. When a sinusoidal load is applied to an elastic material, the reaction occurs immediately. The material deforms immediately, while for a perfectly viscous material, the moment when the deformation occurs have a lag of 90° from the moment when the load was applied. For a viscoelastic material the difference is determined to be between the moment when the load is applied and the moment when the deformation starts is between 0° and 90, a graphical explanation is shown in Figure 2-5.

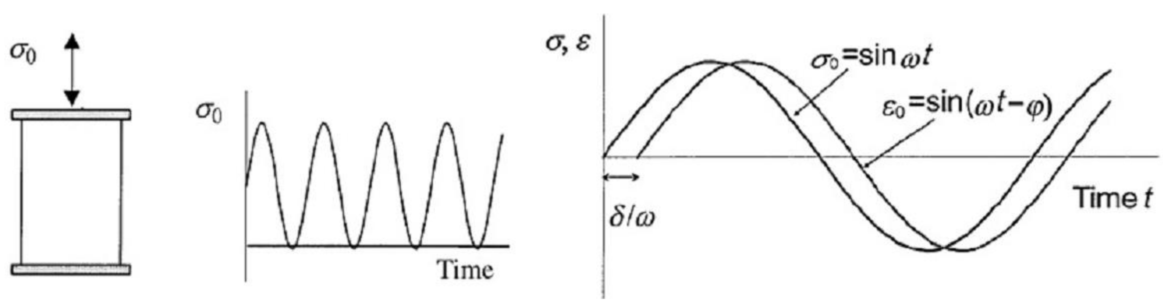

Figure 2-5 Sinusoidal Stress and Strain in Cyclic Loading (Kim, 2009)

Then, the response of a viscoelastic material under cyclic loading has two components; an elastic component and a viscous component. The modulus of the material is best represented by a complex number, with a real portion including the storage or elastic modulus, and an imaginary portion with the loss or viscous modulus, as show in Figure 2-6. The angle shown represents the lag between the stress and the strain.

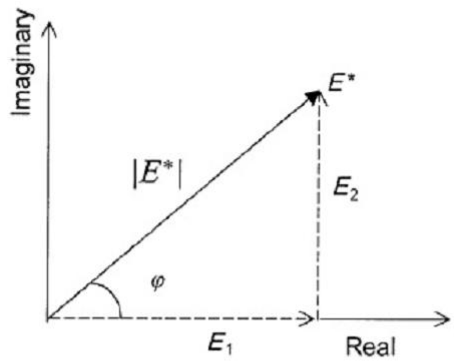

Figure 2-6 Complex Plane (Kim, 2009)

When a sample is subjected to uniaxial compressive stress, the complex modulus is represented by E*, but when the sample is under shear stress then the complex modulus is defined as the relation of shear stress and shear strain and is represented as G*.

2.3 Performance Grade (PG)

The Performance Grade indicates the range of pavement temperatures in which the asphalt cement meets all the intended performance criteria. It is composed by two numbers; the first one indicates the average 7-day maximum pavement temperature in degrees Celsius, e.g. 58°C, and the second number is the minimum pavement temperature e.g. -28°C. The PG is given by increments of 6°C however, the exact critical temperature can be also determined and it is known as continuous grade.

To define the pavement design temperatures, Ontario is divided in three zones, according to the geographic and climatic information, as shown in Figure 2-7. The Ontario Specification for Asphalt Cement OPSS 1101 suggests guidelines when selecting the asphalt cement performance grade as shown in Table 2-1.

When RAP is added in HMA, the change of the PG of the virgin binder for a softer PG is known as binder bump. If either the high or low grade is decreased, it is called a single bump. If both the high and the low PG temperatures are reduced, it is referred as double bump.

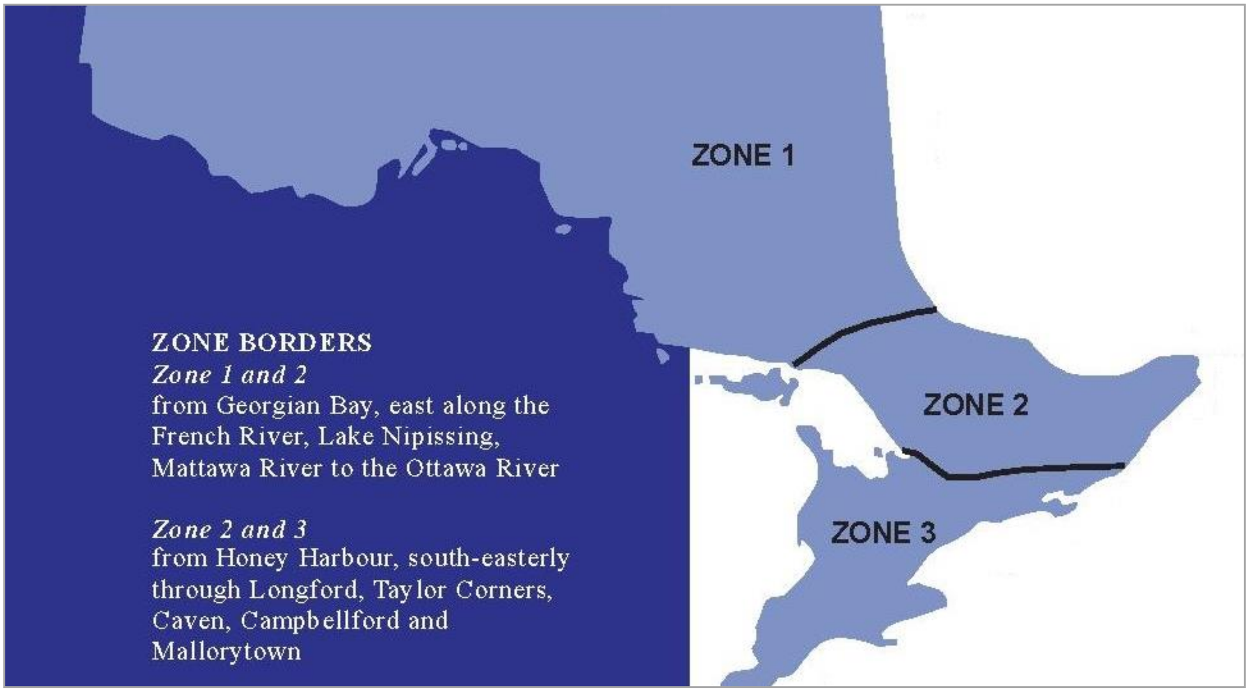

Figure 2-7 Ontario PGAC Zones (OHMPA, 1999)

Table 2-1 Grade Selection for Ontario (MTO, 2002)

	PGAC Zones		
	Zone 1	**Zone 2**	**Zone 3**
New Hot Mix or up to 20% RAP	52-34	58-34	58-28
21 to 40% RAP	52-40	52-40	52-34

2.4 Superpave

Superior Performing Asphalt Pavement or Superpave is an asphalt design methodology that was developed in the United States in the 1990s which is used to design and evaluate asphalt mixtures. It considers the material selection, mix design, mix performance testing and pavement performance prediction (OHMPA, 2007b). Prior to this the asphalt cement was characterized in terms penetration and viscosity, rather that its performance in terms of stress and strain. The Superpave methodology considers climate and loading conditions which greatly improves the evaluation of materials (Asphalt Institute, 2007).

2.4.1 Mix Design

Asphalt mixture design examines the optimum amount of asphalt in the mixture to meet the required volumetric properties at the desired compaction level. The gyratory compactor is used to compact 150mm diameter cylinders. It compacts the asphalt mixture by applying a pressure of 600kPa while the mold rotates at 30 revolutions per minute and the number of gyrations is related to the number of passes necessary to get the desired air voids content. Additionally an angle of 1.25° is applied to simulate the kneading effect of roller compactor equipment in the field.

At the end, the purpose of the mix design is to control the appearance of distresses on the pavement surface. There are three common distresses associated with the asphalt concrete performance: permanent deformation (rutting), fatigue cracking and thermal cracking as shown in Figure 2-8. Rutting is the deformation of the pavement under slow moving vehicles and/or high temperatures. Fatigue occurs after numerous load repetitions as the tension stress is higher than the strength of the material. Thermal cracking is the result of the brittleness of the material at low temperatures. To control rutting and fatigue it is convenient that the material is elastic but to resist thermal cracking, the material should be able to flow and release the stresses.

Figure 2-8 Pavement Distresses: a) Rutting (Pavement Interactive, 2008), b) Fatigue Cracking (Pavement Interactive, 2009), c) Thermal Cracking (FHWA, 2011)

2.4.2 Consensus Properties

Given that the aggregates comprise the majority of the volume in the mix, their quality is a critical consideration in the mix design. The consensus properties relate to the desirable characteristics of the aggregates in the mixture, and for the Superpave design method, the following tests are considered:

- Coarse Aggregate Angularity (ASTM, 2006a)

This test involves the determination of the percentage of particles with at least one crushed face in the aggregates retained on the No. 4 (4.75mm) sieve. More crushed faces means better interlock between the aggregates, given the increased friction as the particles do not slip easily enhancing the endurance to permanent deformation.

- Uncompacted Void Content of Fine Aggregate (ASTM, 2006b)

This test measures the angularity in the portion of aggregates that passes the Sieve No. 8 (2.36mm), by means of the determination of the air voids in the loose state. The more air voids, the more angularity.

- Flat or Elongated Particles in Coarse Aggregate (ASTM, 2010b)

The shape of the particles is also a parameter that affects the behavior of the mix, flat and elongated aggregates are usually fragile and breaks easily when subjected to load, and that is undesirable in the aggregates for an asphalt mixture. Less percentage of flat and elongated particles is preferable. The test is conducted on particles retained on the 9.5mm sieve.

- Sand Equivalent Test (ASTM, 2009b)

The Sand Equivalent is the proportion of clay in the aggregate passing the Sieve No. 4 (4.75 mm). If the sand equivalent is high, there are less clay-like materials that might affect the adhesion of the asphalt to the stones. It is important to consider that the test is conducted on the bared aggregates, and given that the asphalt in RAP is usually removed with solvents, the loss of fines during the process might affect the resulting sand equivalent.

2.4.3 Binders Characterization

The Superpave binder characterization and grading of the asphalt cement is described in Figure 2-9. Asphalt Cement is tested under a range conditions to predict performance. The first drawing in the figure shows the Direct Tension Test (DTT) and Bending Beam Rheometer (BBR) to predict at what temperature Thermal Cracking would occur. The Dynamic Shear Rheometer (DSR) has 8mm plates and is tested at an intermediate temperature for Fatigue Cracking. The DSR is also used to evaluate high temperature performance with 25mm plates for permanent deformation (rutting). Lastly the Rotational

Viscosity (RV) is used to evaluate the workability during construction. The reason for this testing is to select a binder that is sufficiently stiff to resist rutting, but not too stiff to contribute to fatigue cracking.

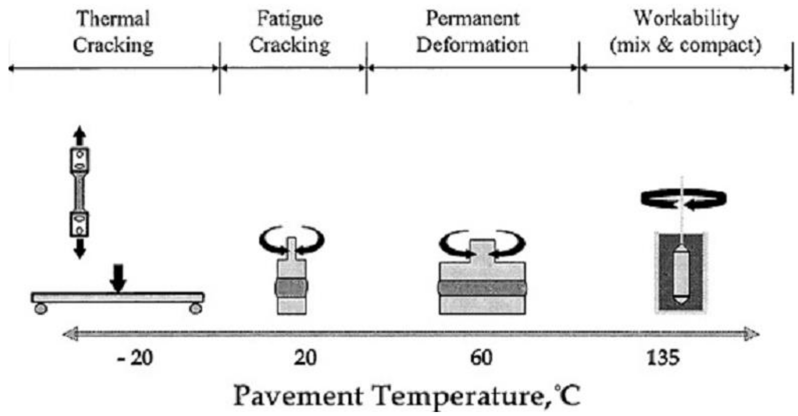

Figure 2-9 Binders Characterization (Kim, 2009)

- Aging (PAV and RTFO)

The effect of oxidation of the asphalt due to the exposure to the environment can be simulated in the laboratory. The Rolling Thin-Film Oven (RTFO) simulates the short term aging of the asphalt; it is the aging during occurring to the mixing and compaction process by subjecting small quantities of asphalt poured in glass containers to elevated temperatures while they rotate during 85 minutes.

The Pressure Aging Vessel (PAV) is able to simulate the long term aging of the asphalt during the operation of the road over an in-service period of 7 to 10 years. After RTFO has taken place, the asphalt is placed on flat circular steel containers, and taken to a heated pressurized chamber for 20 hours.

- Dynamic Shear Rheometer (DSR)

The DSR is used to test the binder at high and intermediate temperatures. It is used to determine the PG of the binder, and the dynamic properties of the same in terms of shear modulus G* and phase angle (δ). There are two parameters controlled: the rutting parameter for high temperatures on the virgin binder ($G^*/\sin\delta$ > 1kPa) and on the RTFO aged binder ($G^*/\sin\delta$ > 2.2kPa) and the fatigue parameter at intermediate temperatures on the RTFO and PAV aged binder ($G^*\sin\delta \leq$ 5000kPa) given that fatigue cracking occurs after the pavement have been in service for several years, when a number of load cycles or vehicle passes has been reached.

- Bending Beam Rheometer (BBR)

The BBR is used to test the RTFO and PAV aged binder. It subjects a small beam made with the binder to three point bending test at cold temperatures. The parameters controlled in this test are the creep stiffness $S(t) \leq 300MPa$ and the slope of the stiffness curve $m \geq 0.3$.

2.5 Quality Assurance in HMA

According to the Ontario provincial standard specification for Superpave and stone mastic asphalt mixtures, the quality of the mix is assured by the verification of the following parameters (MTO, 2007b):

Aggregate gradation: The job mix formula gradation must meet the control points specified for the corresponding HMA type. Table 2-2 presents the requirements for SP 12.5 mixtures.

Table 2-2 Superpave Aggregate Gradation Control Points

Percentage Passing byDryMass of Aggregates									
Sieve Size (mm)									
50.0	37.5	25	19.0	12.5	9.5	4.75	2.36	1.18	0.075
-	-	-	100	90-100	90	-	28-58	-	2-10

Volumetric properties: The mix must meet the Superpave HMA volumetric properties for the corresponding traffic category. The assessed properties are: percentage of theoretical maximum gravity; voids in mineral aggregate (VMA) voids filled with asphalt (VFA) and dust to binder ratio. For a SP 12.5 and traffic category C the requirements are summarized in Table 2-3.

Table 2-3 Superpave HMA Volumetric Properties

%of Theoretical Maximum Specific Gravity			Voids in Mineral Aggregate (VMA) %minimum	Voids Filled with Asphalt (VFA) %	Dust to Binder Ratio
$N_{initial}$	N_{design}	N_{max}			
≤89.0	96.0	≤98.0	14.0	65-75	0.6-1.2

Notes: N – Compactive effort in number of revolution of the Superpave gyratory compactor

Adjustment to job mix formula (JMF): In the field, the mix is sampled in order to verify that it meets with the specified tolerance with respect to the approved JMF. The parameters evaluated are shown in Table 2-4. The general procedure for quality assurance consists in taking samples of the loose mix in the field for the extraction and quantification of the asphalt cement in the laboratory, and the gradation of the recovered aggregates. For the mix design monitoring, samples of asphalt cement, aggregates, RAP and mineral filler are taken to replicate the design, and obtain mixes that are fabricated with the gyratory compactor to verify the volumetric properties. The determination of the quantity of RAP plays and important role, given that if RAP is incorporated in higher amount than the approved without a proper design can affect the integrity of the mix and can compromise the performance and lifespan on the pavement. However, a test protocol to determine the quantity of RAP in the completed mixtures does not exist yet.

Table 2-4 Permitted Field Adjustments for HMA

JMF Property	Maximum Field Adjustment
Percent asphalt cement content	±0.2
Percent RAP	-5.0
Percent passing 26.5 mm, 25.0 mm, 19.0 mm, and 16.0 mm sieves	±5.0
Percent passing 13.2 mm, 12.5 mm, and 9.5 mm sieves	±4.0
Percent passing 4.75 mm, 2.36 mm, and 1.18 mm sieves	±3.0
Percent passing 600 µm, 300 µm, and 150 µm sieves	No limits
Percent passing 75 µm sieve	±1.0

2.6 Overview to RAP addition in HMA

The use of RAP in HMA is a technique well known in Ontario. RAP usage is encouraged because of its environmental and economic advantages.

In order to maximize the potential benefits of using RAP in new asphalt mixes, it is critical to understand the behavior of RAP. RAP can be considered as simply a “black rock”, therefore assuming that the aged asphalt cement does not interact with the virgin asphalt cement in the mix. The opposite scenario can also be considered where it is assumed that 100 percent of the aged asphalt cement blends with the new, virgin asphalt cement (Al-Qadi, Elseifi, & Carpenter, 2007). It is unclear to industry which of these cases is actually happening and it is anticipated that it is more complex than being either extreme.

The results of the 2010 Recycle Survey conducted by the American Association of State Highway and Transportation Officials (AASHTO) subcommittee on materials and the TAC Pavement Asset Design and Management Guide (PADMG) survey demonstrate the interest throughout industry to recycle RAP into pavements including surface, binder, base and shoulder HMA mixes (AASHTO, 2010b; Tighe & Bland, 2010). The widespread use of RAP indicates that agencies consider it a benefit, whether it be in performance, economically, environmentally, or a combination of all. The recycling of RAP into pavements reduces the consumption of virgin aggregate and asphalt cement and also decreases the volume of waste material going to landfills. In 1997 Kandhal and Mallick estimated that the inclusion of 20 to 50 percent of RAP in pavements can reduce costs by 14 to 34 percent (Kandhal & Mallick, 1998). In a study conducted for the United States Environmental Protection Agency (US EPA) and the Federal Highway Administration (FHWA) in 1993, it was found that in excess of 80 percent of the asphalt pavements removed are reused in various highway applications and less than 20 percent are discarded (Bloomquist, Diamond, Oden, Ruth, & Tia, 1993). It can be expected that with advancements in the knowledge of recycling, the percentage being discarded is lower today and has the potential to decrease even further.

2.7 Historical Usage of RAP in Ontario

The Ministry of Transportation of Ontario (MTO) began their recycling program in 1978 when a task force was assembled to study the recycling practices in the United States. Based on the information gathered by the task force, 20 percent of MTO's paving program in 1980 involved recycling at various percentages. Also, during 1979 and 1980, the Ontario road builders acquired a total of 15 pugmill and drum-mix plants that were equipped to incorporate RAP into new HMA. The maximum recycling material percentage used on selected projects at that time was in the order of 70 percent. Overall, the 1980 recycling program in Ontario was considered to be a success. In 1981 another 800,000 tonnes of the HMA including RAP was specified (Lynch & Evers, 1981).

An economic analysis was undertaken by Wrong and Oliver (Wrong & Oliver, 1981) in 1980 for four of the recycling projects that were constructed in the 1980 paving season in Ontario. They found that for those four projects MTO had an initial cost savings of 14.5 percent. In addition, economic benefits were also achieved through the conservation of approximately 126,000 tonnes of virgin aggregate that would have been used if RAP was not included in the same projects.

In the early days of RAP incorporation into new HMA, it was believed that the maximum benefit from RAP can be achieved with high RAP incorporation percentages (>50 percent). As a result, a number of the early projects had RAP contents that were as high as 70 percent, as this is the maximum that could be used with the existing drum-mix plants. McLukie et al. (McLukie, Korgemagi, & Villneff, 1987) described the field performance of four pavement sections that were placed in 1980 in Northern Ontario. They found that the performance of HMA containing RAP is directly related to the penetration of the recovered binder. The higher the penetration of the recovered asphalt, the better will be the in-field performance of the pavement. However, flushing could also be a problem if a very soft virgin binder is used in the mix. At higher RAP contents, under-asphalting of the mix was a common problem for the pavement sections evaluated.

In 1988, the MTO commissioned two pavement sections where design-penetration recycled HMA was utilized. This procedure for designing HMA containing RAP is based on the premise that the penetration of the blended asphalt (virgin and RAP binder) proportionally varies with the logarithm of each of their individual penetrations. The two sections that were placed with the mixes using the aforementioned design method, in 1989, were performing similar to recycled mixes designed with the conventional methodology at the time (Hadipour, Kazmierowski, & Cheng, 1989).

In 1991, the usage of RAP in new HMA had become common practice in the Canadian pavement industry. Based on the performance and economics of existing pavement sections containing RAP, Emery (Emery, 1993) found that there was no justification for HMA containing RAP to be considered as inferior to conventional HMA. At the time, the use of HMA containing RAP was not considered for pavements requiring high rutting resistance.

2.8 Current Usage of RAP in Ontario

The Transportation Association of Canada (TAC) commissioned a project for the development of a Pavement Asset Design and Management Guide (PADMG) in 2009. Five cities in the Province of Ontario responded to the PADMG survey and all indicated that they actively consider sustainability in their pavement design and management practices. This is further evidence that the use of RAP in Ontario and in other Canadian provinces is now common practice approximately 30 years after the first trial sections were placed of HMA mixes containing RAP (Tighe, 2013). In 2005, a maximum of 15 percent of RAP in surface course mixes and 30 percent in binder course mixes was permitted in Ontario. Up to 50 percent of RAP could also be used in certain situations provided testing results indicated that the recycled mix met specifications (Federation of Canadian Municipalities & National Research Council of Canada, 2005). According to a 2010 survey by the AASHTO Subcommittee on Materials, Ontario had the highest maximum allowable RAP percentage at 40 percent. Texas also allows for 40 percent RAP inclusion; however, only for mixes that are at least 200 mm below the riding surface. Figure 2-10 shows the 2010 AASHTO survey results for the maximum allowable RAP replacement (AASHTO, 2010b).

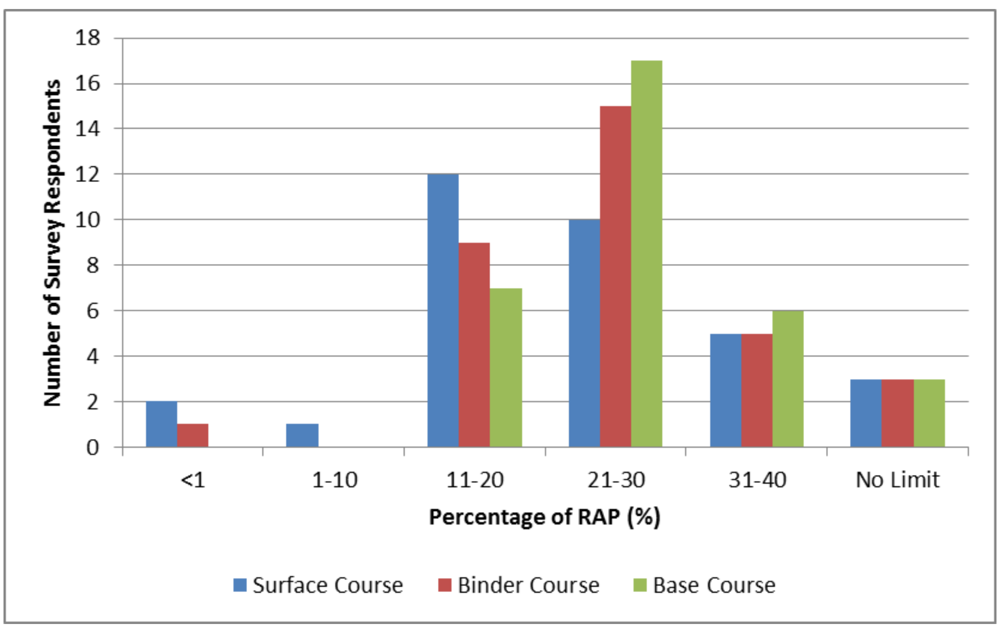

Figure 2-10 Maximum Allowable RAP Replacement for Surface, Binder and Base Course

In addition, the AASHTO survey determined the average percentage of RAP replacement implemented by contractors in comparison with the maximum allowable in the state or province. For Ontario, the average contractor replacement of RAP was found to be approximately 20 percent. The average percent replacement was approximately 50 percent lower than the average maximum allowable. Figure 2-11 shows the 2010 AASHTO survey results for the maximum allowable and contractor average use of RAP in base course mixes (AASHTO, 2010b).

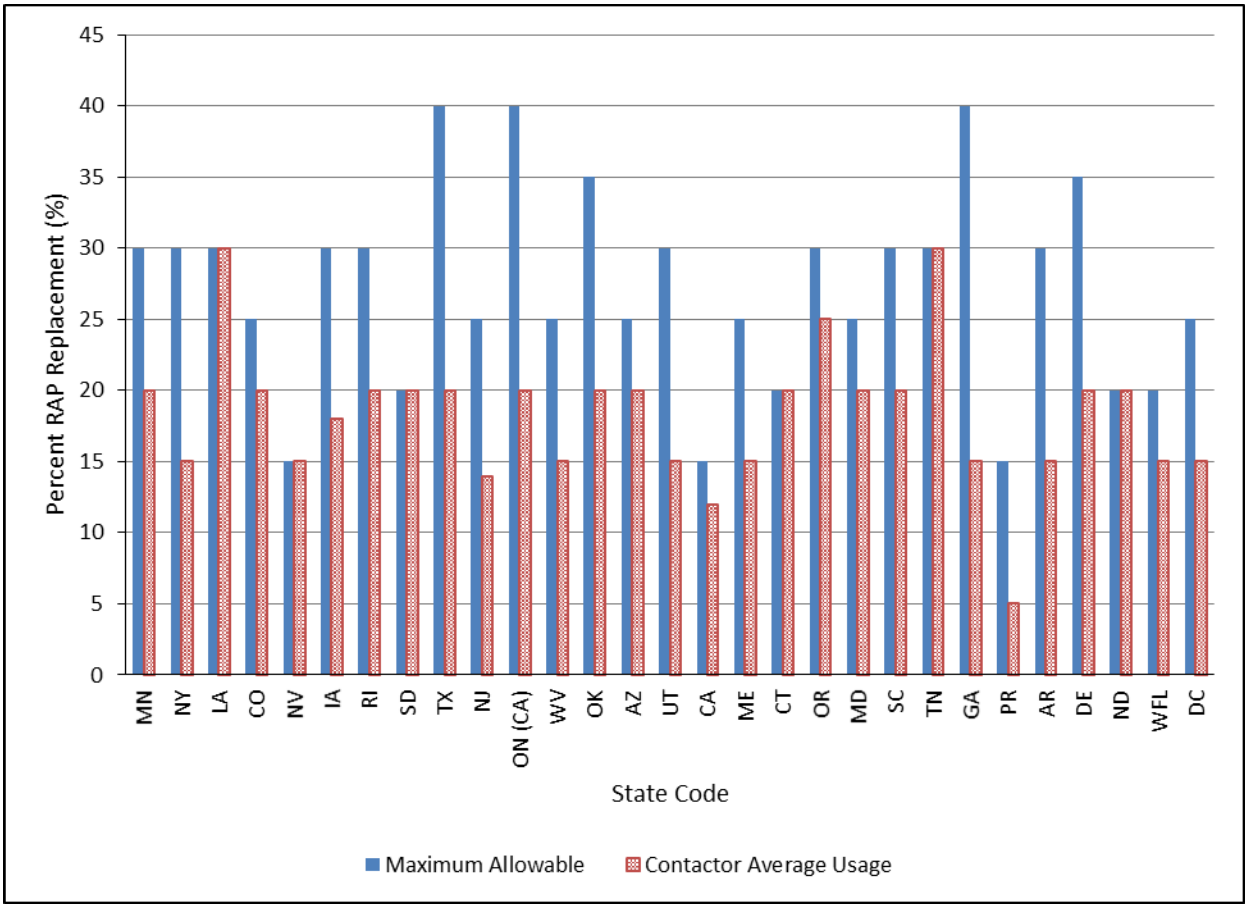

Figure 2-11 Maximum Allowable and Average Contractor RAP in the Base Course

2.9 Primary Concerns with RAP

The limitations of increasing the maximum allowable percentage of RAP in HMA mixes are primarily due to pavement performance rather than a lack of availability of RAP. The challenges associated with using higher RAP contents in mixes will have to be overcome in order to continue to advance and be sustainable as an industry (Al-Qadi et al., 2007). The primary concerns with increasing the RAP percentage in HMA mixes are its effects on moisture susceptibility of the mix and on resistance against fatigue and thermal cracking. Durability of high content RAP mixes is primarily of concern due to the complex and poorly understood interaction between the aged and the virgin asphalt binder (Al-Qadi et al., 2007).

AASHTO, in their 2010 survey of the North American state and provincial transportation agencies, identified the primary concerns that these agencies had with increasing the percentage of RAP in their HMA mixes. Some of the more prominent responses from the survey are the following: long-term performance, durability and increased thermal cracking, adjustment of binder grade or “binder bumping”, inability to meet consensus properties and losing desired performance grade of binder, mix stiffening, reduced workability and “compactability” in the field, and premature aging of the HMA.

An additional challenge with increasing the RAP contents to greater than 40 percent would be the need for new plant technologies such as indirect heating to be able to produce such HMA mixes (Loria et al., 2011).

A common challenge with recycled material of any type is the variability in the RAP due to the fact that sometimes all the RAP sources regardless of the age and previous use of the pavement are placed in the same stockpile without sorting. To avoid this situation, some agencies require separate piles. Variability can be a significant hindrance to increasing the proportion of RAP as the methods used to predict performance would not always be indicative of in-field performance. The variability would also make it difficult to establish a mix design procedure that could be utilized to design HMA mixes having high RAP content. The following are best practice recommendations for managing RAP stockpiles (Johnson & Olson, 2009):

- RAP should be free of debris and sorted based on source;
- Avoid compacting stockpiles by pushing them with a loader or driving on them as it can make it challenging to remove material from the stockpile in the future and re-crushing may be necessary;
- Avoid segregation of the stockpiles and blend in order to create and maintain uniformity;
- During crushing, perform extraction to determine asphalt cement content and performance grade; and
- Consider drainage and use a solid surface or pad underneath the stockpile when possible.

Aguiar-Moya et al. (Aguiar-Moya, Hong, & Prozzi, 2011) cautioned against the use of RAP without fully considering the life cycle cost of its use. Short term benefits of using RAP, such as less pavement deterioration in early years and lower capital costs can lead to long term expenses for repairs and maintenance being overlooked. A small sample of Long Term Pavement Performance (LTPP) sites in Texas demonstrated that RAP sections showed the initiation of cracking earlier and the progression rate of the cracks was higher. This work notes that RAP has several benefits and technology is continually being improved but there is a need within industry to understand the long-term effects of using RAP in new mixes in order to fully benefit from its use.

2.10 Overall Performance of HMA with RAP

Significant amounts of laboratory testing and field evaluation of HMA mixes containing varying percentages of RAP have been completed and are documented in the literature. The results indicate that the addition of RAP into HMA mixes increases the stiffness of the mix. This was shown through dynamic and resilient modulus testing done by Sondag et al. (Sondag, Chadbourn, & Drescher, 2002) in which both the resilient and dynamic (complex) modulus values increased with increasing the RAP percentages. It is important to note that the phase angle of the mix decreased with increasing RAP percentages. The reduction in the phase angle corresponds to an increase in the elastic properties and a reduction in the viscous properties of the mix.

In a study examining effects of RAP percentages and sources, Li et al. (Li, Clyne, & Marasteanu, 2004) found that as the percentage of RAP in a mix increased, there was increased variability in the dynamic modulus values at lower temperatures. Daniel and Lachance (Daniel & Lachance, 2005) found that the creep flow time increased with increasing RAP content in the HMA mixes and that mixes containing RAP had improved resistance to permanent deformation and decreased resistance to fatigue and thermal cracking. The study also found that there is an optimal pre-heating time for RAP to enable the aged binder to become viscous and blend with the virgin binder.

The cracking performance of HMA mixes containing RAP has been the topic of numerous studies; however, the results of these studies have been contradictory in whether the addition of RAP results in diminished performance in regard to thermal and fatigue cracking. Tam et al. (Tam, Joseph, & Lynch, 1992) found that addition of RAP resulted in the mix being more susceptible to thermal cracking than conventional HMA for five recycled hot mix sites constructed during 1981 and 1983 in Ontario, within different regions, asphalt cements and recycling ratios (60/40, 30/70, 50/50, 70/30 and 25/75). On the other hand, Kandhal et al. (Kandhal, Rao, Watson, & Young, 1995) found that there was no significant difference between the performance of mixes containing recycled materials when compared to just virgin materials for five projects in Georgia with 10 to 25 percent RAP. Finally, a study by Sargious and Mushule (Sargious & Mushule, 1991) found that mixes that included RAP showed improved cracking performance for a mix with recycling ratio of 45.2/54.8 as compared with a virgin mix both designed at the University of Calgary. It should be noted that the mix design process and selecting the correct asphalt binder grade is critical to the cracking performance of mixes that do and do not contain RAP.

The source of the RAP can have an effect on the performance of the final mix. Pavements that were extensively damaged before being removed often contain binders which have experienced more aging than a pavement in better condition. A pavement in fair condition when reclaimed could be less susceptible to oxidation and therefore may offer better performance when recycled into a new pavement (Al-Qadi et al., 2007). The degree to which the binder in the RAP has aged can affect the performance of the final mix. When up to 20 percent of RAP is used in a mix, it has been noted that the age or stiffness of the binder does not contribute to the performance of the new mix (Kennedy, Tam, & Solaimanian, 1998).

The type of aggregate in the RAP can play a significant role in the performance of the HMA mix. McDaniel et al. (McDaniel, Soleymani, & Shah, 2002) found that when the RAP content was increased, the performance of the mixes decreased when tested using repeated shear testing. They concluded that the decreased performance could be attributed to change in the aggregate structure in the mix, which was playing a more significant role than the binder stiffening that would normally result in increased performance for the repeated shear test. Therefore, significant care needs to be taken in regard to the quality and structure of the RAP.

Laboratory testing of both the aged and virgin binder and the final HMA mix containing RAP is critical to determine the effects that addition of RAP has on HMA performance. By developing an understanding of these affects, procedures can be developed for incorporation of higher percentages of RAP into HMA mixes.

The majority of performance tests have been done on mixes containing less than 40 percent RAP. Dynamic modulus testing can be done to evaluate the stiffness of HMA mixes containing RAP. This is a critical test since previous literature has shown that complex modulus of the mix is sensitive to the changes in mixture volumetric properties and binder stiffness (Shah, McDaniel, & Gallivan, 2005). Additionally, shear tests and indirect tensile tests can be done to determine mixture stiffness at high and low temperatures. Resilient modulus testing can also be done to characterize mix stiffness; however, this testing was found to be extremely variable and therefore previously mentioned alternatives should be used (McDaniel et al., 2002). Rutting resistance of HMA mixes containing RAP can be inferred from stiffness tests. An Asphalt Pavement Analyzer (APA) or a Hamburg Wheel Rut Tester can also be used to determine rut depths. A four point bending beam test can be done on beam samples to determine the fatigue resistance of samples. Finally, resistance to thermal cracking can be evaluated by performing the Thermal Stress Restrained Specimen Test (TSRST).

One of the few studies conducted on HMA mixes containing greater than 40 percent RAP was conducted by Loria et al. (Loria et al., 2011). The study evaluated the performance of field and laboratory produced HMA mixes containing 0, 15 and 50 percent RAP in terms of their resistance to moisture damage and thermal cracking. Moisture sensitivity was evaluated by conducting indirect tensile strength tests on conditioned and unconditioned samples. Resistance to thermal cracking of the mixes was determined by conducting TSRST on conditioned and unconditioned asphalt specimens. The conditioning process involved subjecting the asphalt specimens to numerous freeze-thaw cycles. For the 50 percent RAP content, two sets of samples were prepared, one without a performance grade bump and one with a low-end performance grade bump.

Some of the key findings of this study were that regardless of the AC grade used, the samples with 50 percent RAP did not meet low temperature performance grade of -28°C. For the 15 percent RAP samples, it was determined that no change in binder grade would be required as both the high and low temperature performance grades were either met or exceeded (Loria et al., 2011).

For the TSRST, the fracture temperatures of all mixes except one were -28°C or colder. The mix that did not reach -28°C before failure was the laboratory prepared 50 percent RAP with PG 58-28 and it failed at -27°C. The difference in fracture temperature between samples that were and were not exposed to freeze-thaw cycles for the same mix was between 0 and 1°C. The fracture temperatures across all mixes were consistent, ranging from -27 to -34°C. The TSRST fracture temperatures for the 0 and 15 percent RAP contents were similar to the critical low temperature for the recovered asphalt binder. For the 50 percent RAP content, the fracture temperatures were between 5 to 8°C lower than the critical low temperature for recovered binder (Loria et al., 2011).

In the case of both field and laboratory samples, fracture stress generally increased as RAP content increased. Fracture stress in the TSRST is believed to control the spacing of thermal cracks in the field, with a higher fracture stress corresponding to a larger spacing between thermal cracks. When the samples were exposed to freeze-thaw cycles, the fracture stress decreased by up to half of that of the corresponding samples that had not been conditioned. Results of the testing indicate that although conditioning the samples did not affect the temperature at which thermal cracks would develop, the spacing of cracks is significantly reduced for pavements that have undergone numerous freeze-thaw cycles (Loria et al., 2011).

The tensile strength testing showed that the addition of 50 percent RAP in the mix did not result in a larger reduction in tensile strength after moisture conditioning, as compared to the virgin mix. The Tensile Strength Ratio (TSR) for the samples containing 50 percent RAP and a softer binder was the same as that of the virgin mix. This indicates that the moisture susceptibility of the mix is not further increased due to the addition of higher percentages of RAP in the mix.

A study conducted by Shah, et al. (Shah, McDaniel, Huber, & Gallivan, 2007), evaluated the effects on the complex moduli of adding 15, 25 and 40 percent of RAP to HMA with PG 64-22, as well as 25 and 40 percent of RAP to HMA with PG 58-28. According to the results, some differences were observed for 40 percent RAP content and the virgin mix, but only at high temperatures thereby indicating that the properties of the mixture remain almost unchanged with the addition of RAP.

Regarding the dynamic modulus of mixtures containing RAP and different PG binders, Li et al. (Li, Marasteanu, Williams, & Clyne, 2008) found that the addition of RAP impacted the dynamic modulus of the mixtures, giving higher results than the control mixtures, but the dynamic modulus for 20% RAP mixtures was the highest for high frequencies. With respect to thermal cracking, they found that the addition of 40% RAP significantly decreases the fracture resistance measured with Semi-circular Bending Test.

Al-Qadi et al. (Al-Qadi, Aurangzeb, Carpenter, Pine, & Trepanier, 2012) evaluated the performance of HMA with RAP with no binder grade bumping, with single binder grade bumping (one grade softer upper temperature) and double binder grade bumping (one grade softer for both upper and lower temperatures), concluding that the effect of binder grade bumping was less significant for higher RAP contents. This research also showed that thermal cracking susceptibility increases when increasing the RAP content, but in general double binder-grade bumping improved the resistance compared to the no bumping.

2.11 Asphalt Cement Performance Grade with RAP Addition

Research into the blending behavior of virgin binder and aged binder in RAP is a continued area of interest. In general, researchers try to examine if RAP acts as a “black rock” or the aged AC in RAP blends fully with the new AC in the mix. The NCHRP Project 9-12 was designed to address this question (McDaniel & Anderson, 2001a). The study was conducted with RAP contents of 10%, 20% and 40% in the HMA. Three blending cases were considered: actual practice, “black rock” and total blending At the lower RAP content, it was found that there was no difference in AC test results for the different blending cases. However, at the higher RAP contents, the “black rock” blending scenario had lower mix stiffness and higher deformation than the other two blending scenarios. The study concluded that although complete blending likely does not occur, significant blending does occur such that the properties of the binder in the mix are a combination of the virgin and aged binders. However, at lower RAP contents, there is not enough RAP binder to affect significantly the results.

Understanding the interaction between asphalt cement in RAP and virgin asphalt cement in hot mix asphalt is of particular interest as it assists in determining which performance grade of asphalt cement is appropriate. Both McDaniel et al. (2002) and Loria et al. (2011) have tested this and found similar results. Loria et al. compared mixes prepared in the field and in the lab. McDaniel et al. tested the virgin, RAP and blended binders from plant mixes in Indiana, Michigan and Missouri. The results show that for RAP contents greater than 20% there is a change in the behavior of asphalt cement in the new mix.

In the case of Loria et al. (2011), a softer virgin binder grade was used in the 50% RAP mix as compared to the mix with only virgin materials. This was done with the goal of meeting the design high and low temperature for the mix once the aged and virgin binders combined. For both the lab and field samples, when a softer virgin binder was used, the extracted binder had a critical low temperature that was closer to the desired value; however, in both cases the critical low temperature was not met. When high percentages of RAP were included in the mix, the critical high temperature for the blended binder is seen to increase from the virgin binder by one grade (6°C) showing the stiffening effect of RAP.

The McDaniel et al. (2002) study showed that for the Michigan and Missouri RAP sources, the critical low temperature of the blended binder did not change from the virgin binder. However, in the case of the Indiana RAP, the critical low temperature increased by one grade. This could be attributed to the quality of the RAP in each of the three states. In the case of Indiana, the increased stiffness of the blended binder could occur if the pavement from which the RAP was obtained was significantly more aged and deteriorated than in the other two states. The high temperature grade increased by one grade for all three cases.

2.12 Current Design Procedures for HMA Mixes Containing RAP

The Research Results Digest 253, a publication as part of the NCHRP 9-12 study, summarizes the findings of the study and includes details regarding the following points (McDaniel & Anderson, 2001b):

- Determining the properties of RAP.
- Determining RAP binder properties.
- Developing Superpave mix designs that include RAP.
- Additional QC and QA tests for asphalt mixes containing RAP.

Based on the results of the NCHRP 9-12 study, a tiered approach was recommended for the addition of RAP in to HMA mixes. If less than 15% RAP is to be included in the HMA mix, this can be done by direct replacement without any changes to the binder. For RAP contents between 15% and 25%, the high and low temperatures of the virgin binder should be bumped to one grade softer. This is done due to the higher concentration on RAP binder. This can result in the recovered binder not meeting the critical low temperature if a softer virgin binder is not used. For the case when greater than 25% RAP in included in the HMA mix, blending charts need to be made to determine either the virgin binder grade required or the amount of RAP that can be included with the selected virgin binder grade.

To construct a blending chart, the information that is required includes the final binder grade required, the physical properties and critical high and low temperatures for the extracted RAP binder, and either the RAP percentage to be included in the mix or the virgin binder grade to be used in the mix. Figure 2-12 and Figure 2-13 show the two proposed design methods for mixes containing RAP as a result of the NCHRP Project 9-12 findings (McDaniel & Anderson, 2001b).

The NCHRP 9-12 study reported that for HMA which contains over 40% RAP content, some non-linearity in the behavior of the blended binder begins to appear and therefore the linear blending equation may not necessarily be applicable (McDaniel et al., 2001). The use of blending charts is a regular practice for designing recycled hot mixtures. The comparison with the critical temperatures of the blended binder measured directly from the extracted binder has drawn interesting conclusions. In the research conducted by Horton et al. (Horton, Wielinski, Huber, Wissel, & McGaughey, 2011), on high RAP plant mixtures for the low temperature grade, the measured properties of the blended asphalt binder had a lower grade than predicted by the blending charts equation, suggesting that low temperature performance would be expected to be better than the calculated lower PG. In the research conducted by Hajj et al. (Hajj et al., 2011), was found that at high RAP content the recovered binders' temperatures were higher from the thermal stress restrained specimen test (TSRST) fracture temperature but overall field-produced and laboratory-produced mixtures ranking was similar for dynamic modulus and TSRST. According to Daniel and Mogawer (Daniel & Mogawer, 2010) the linear blending prediction is a simple and straight forward method, but is not representative of the reality of the mix in the field. They found that the Hirsch Model offers a good method to determine the effective PG of the mixture.

In the research conducted by Daniel and Mogawer (Daniel & Mogawer, 2010), the Hirsch Model was used to back-calculate the shear modulus of the asphalt binder in the recycled mix. Also, the binder was extracted to determine the shear modulus |G*| directly; in this case, this binder represents total blending of the virgin asphalt and the RAP binder. The research showed that the recovered |G*| from the mix is consistently higher than the values back-calculated from the dynamic modulus of the mix, which would indicate that the RAP binder in the mix is not fully blended with the virgin asphalt, resulting in an effective binder that is softer than the fully blended condition. The research also showed that the back-calculated |G*| for mixes containing highly aged RAP is softer than mixes containing moderately aged RAP due to less blending. This leads to a more fundamental question that needs to be answered. That is: whether there is total blending in the mix or is the RAP simply a "black rock". The real answer is that blending is occurring to some degree but the amount of blending is dependent on several factors such as the age of the RAP, RAP content, stiffness of the RAP and virgin binders, etc. The research determined that the recovered (fully blended) |G*| increased with increasing RAP content.

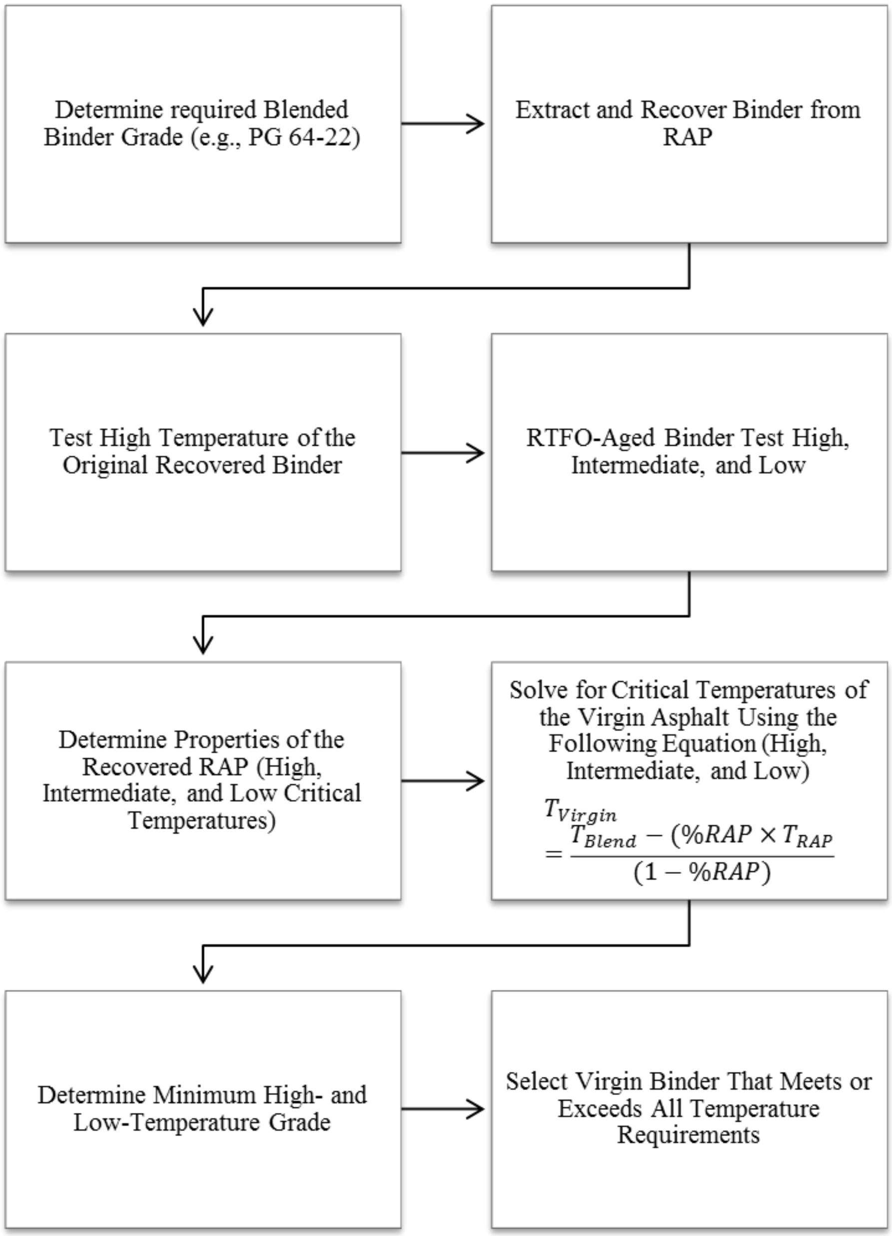

Figure 2-12 Blending at a Known RAP Percentage - Virgin Binder Grade Unknown

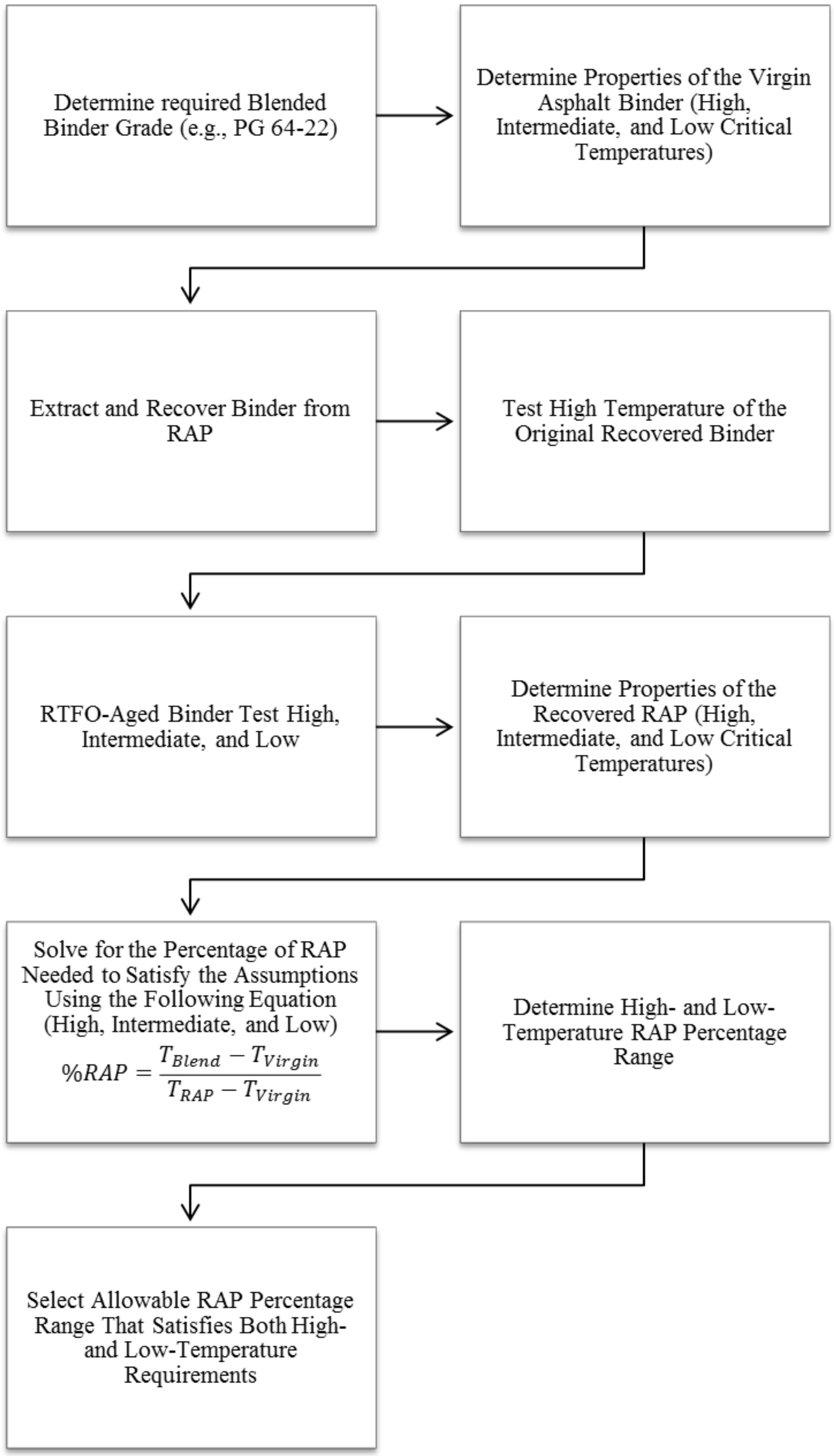

Figure 2-13 Blending with a Known Virgin Binder - RAP Percentage Unknown

The applicability of the linear blending charts was also evaluated by Loria et al. (2011) and they found that even for high RAP contents the critical temperatures estimated from the linear blending charts were in agreement with the measured critical temperature. They also found that regardless of the percentage of RAP included in the mix, the linear blending charts on some occasions underestimated or overestimated the critical temperature by up to 2°C. The overall consensus is that for even higher RAP contents, the linear blending charts still seem to be applicable; however, it should be noted that they should be used with caution.

Even though RAP has been successfully used in North America since the early 1970s there is still a need to continue to research the performance of recycled hot mixes. The current focus seems to be on the evaluation of mixes with higher percentages of RAP. The key question becomes: what effect does the hardened asphalt in the RAP have on the binder in the recycled mix?

2.13 Summary and Conclusions

From the aforementioned discussion it can be seen that significant amounts of work have been completed in developing mix design procedures for incorporating RAP in to HMA and testing the effects that inclusion of RAP has on the virgin binder, as well as the HMA performance. However, all these tests have been primarily completed for lower RAP contents and limited research has been conducted on higher RAP contents.

Some work has been conducted to address the question of how virgin binder blends with the binder in RAP; however, additional work could be done to fully characterize the extent of blending between the two binders at different RAP percentages. Furthermore, research needs to be conducted on how different sources of RAP and their quality affect the performance of the HMA in to which they are incorporated.

Numerous studies have been completed on how the aged binder in RAP affects the HMA in to which they are incorporated; however, it has also been identified that the quality of aggregate in the RAP also plays a significant role in the performance of the mix. At greater proportions of replacement, the RAP aggregate itself can be expected to play a greater role in the final performance of the mix and therefore greater efforts need to be made to completely characterize its effects on HMA performance.

Extensive laboratory tests have been completed to predict the performance of HMA containing RAP. These tests have primarily been conducted at RAP contents of less than 20 percent, and it is possible that at higher RAP contents the effects may be significantly different. Even at lower RAP contents, test results regarding thermal and fatigue cracking have been contradictory between different studies. Extensive and thorough research needs to be done to evaluate the changes in resistance to cracking when higher percentages of RAP are added to HMA.

Chapter 3
Raw Materials Properties and Mix Designs

3.1 Introduction

The raw materials for this research were collected from different suppliers across southern Ontario. Approximately 8.8 tons of aggregates and 520 litres of asphalt were collected in total for design and performance testing purposes. The asphalt cement was supplied by four suppliers including Bitumar, Canadian Asphalt Inc., Coco Paving and Mc Asphalt Industries. The aggregate and RAP were supplied by Capital Paving Inc. One third of the materials were designated for design and the remaining two thirds for performance testing. The design process was completed by DBA Engineering Ltd. in partnership with CPATT.

Once the materials were obtained, the design and characterization of the aggregates and the bitumen were completed at DBA Engineering Ltd. laboratory. The asphalt from the RAP was extracted and recovered, in order to determine the amount of usable binder, and also obtain its continuous grade. The four different virgin asphalts were also graded. The suitable combination of the aggregates was determined and its corresponding consensus properties were assessed. The preliminary results for the literature review and the analyses from the designs were presented in the 2012 Canadian Technical Asphalt Association Annual Conference (Sanchez, Tighe, Aurilio, & Tabib, 2012).

3.2 Aggregates

Four aggregate types were gathered from Capital Paving Inc. plant in Guelph, Ontario, as described in Table 3-1. Additionally, a small amount of mineral filler (Baghouse Dust) was needed, and it was provided by DBA Engineering Ltd. The gradation for each of the aggregates is shown in Table 3-2.

Table 3-1 Aggregates Sources

Material	Supplier	Source
HL3 Stone	Capital Paving Inc.	Pit No. 2 – Waynco Pit
HS Sand	Lafarge Canada	Dundas Quarry
Blend Sand	WSMI	Top of the Hill Aggregates
1/4” Chip	Capital Paving Inc.	Pit No. 5 – Wellington Pit

Table 3-2 Aggregates Gradation

Sieve opening (mm)	% Passing				
	HL-3 Stone	High Stability Sand	Blend Sand	1/4" Chip	RAP
50	100	100	100	100	100
37.5	100	100	100	100	100
25	100	100	100	100	100
19	100	100	100	100	100
16	100	100	100	100	100
12.5	96.2	100	100	100	99.8
9.5	67	100	100	100	92.2
4.75	4.7	100	98.9	69.2	65.3
2.36	1.6	96.4	95.3	5.6	53.6
1.18	1.1	55.1	84.3	2.6	41.5
0.6	1	30.8	58.9	1.7	31.5
0.3	0.9	15.3	22.9	1.4	19.8
0.15	0.8	7.9	3.3	1.2	13
0.08	0.6	3.5	2.6	0.9	8.7

3.3 Reclaimed Asphalt Pavement

The RAP used for this study has a nominal maximum aggregate size of 12.5mm. The RAP was fractionated on the ½" sieve at the plant and stockpiled as shown in Figure 3-1.

Figure 3-1 Capital Paving Inc. RAP Stockpile during Collection

For design purposes, the AC content of the RAP was determined as 4.5%. Table 3-3 shows the temperatures for which the Superpave requirement for rutting, fatigue and thermal cracking are met, indicating that the Performance Grade of the RAP binder is PG76-22.

Table 3-3 RAP Binder Tests Results

Condition	Criteria	Specification	Results	Test Temperature (°C)
Abson Recovered	G*/sin δ, kPa	>= 2.20	2.32	76
PAV	G* sin δ, kPa	<= 5000	4810	25
	S, MPa	<= 300	147	-12
	m-value	>= 0.30	0.305	-12

3.4 Binders

The binders described in Table 3-4 were collected for the research. All of the companies provided the MSDS and the temperature-viscosity chart from which the mixing and compaction temperatures were taken. The continuous grade of all the binders was determined and summarized in Table 3-5.

Table 3-4 Binders Sources

Virgin Binder PG	Provider	Mixing Temp (°C)	Compaction Temp (°C)
58-28	Canadian Asphalt	145	134
52-34	Bitumar	140	129
58-34	Coco Paving	151	139
52-40*	Mc Asphalt	150	140

*polymer modified asphalt

Table 3-5 Virgin Binders Continuous Grade

Virgin Binder PG	High Grade (°C)	Low Grade (°C)	Comments
58-28	60.9	-30.0	Meet high temp + 2.9°C & Low Temp -2.0°C
58-34	62.7	-35.1	Meet high temp + 4.7°C & Low Temp -1.1°C
52-34	54.7	-34.7	Meet high temp + 2.7°C & Low Temp -0.7°C
52-40	56.4	-40.6	Meet high temp + 4.4°C & Low Temp -0.6°C

3.5 Mix Designs

The summary of the relative proportions of aggregates is shown in Table 3-6. The complete designs can be seen in Appendix A. These three main design, form the skeleton of the mix and the combination of those materials have the appropriate gradation that meets the Superpave specification with 0% RAP, 20% RAP and 40% RAP as presented in Table 3-7 and Figure 3-2. All of the mixtures contain HL-3 Stone as coarse aggregate and High Stability Sand as fine aggregate as seen in Figure 3-3. Additionally, the 0% RAP mixtures incorporated the typical raw materials used by Capital Paving Inc., which are the Blend Sand as a fine aggregate and the 1/4”Chip as an intermediate size aggregate. It can be observed that when more RAP is added less HL-3 stone and less sand are required.

Table 3-6 Aggregates Proportions

RAP Content	HL-3 Stone	High Stability Sand	Blend Sand	1/4" Chip	Total
0%	46%	26%	18%	10%	100%
20%	42%	38%			100%
40%	35%	25%			100%

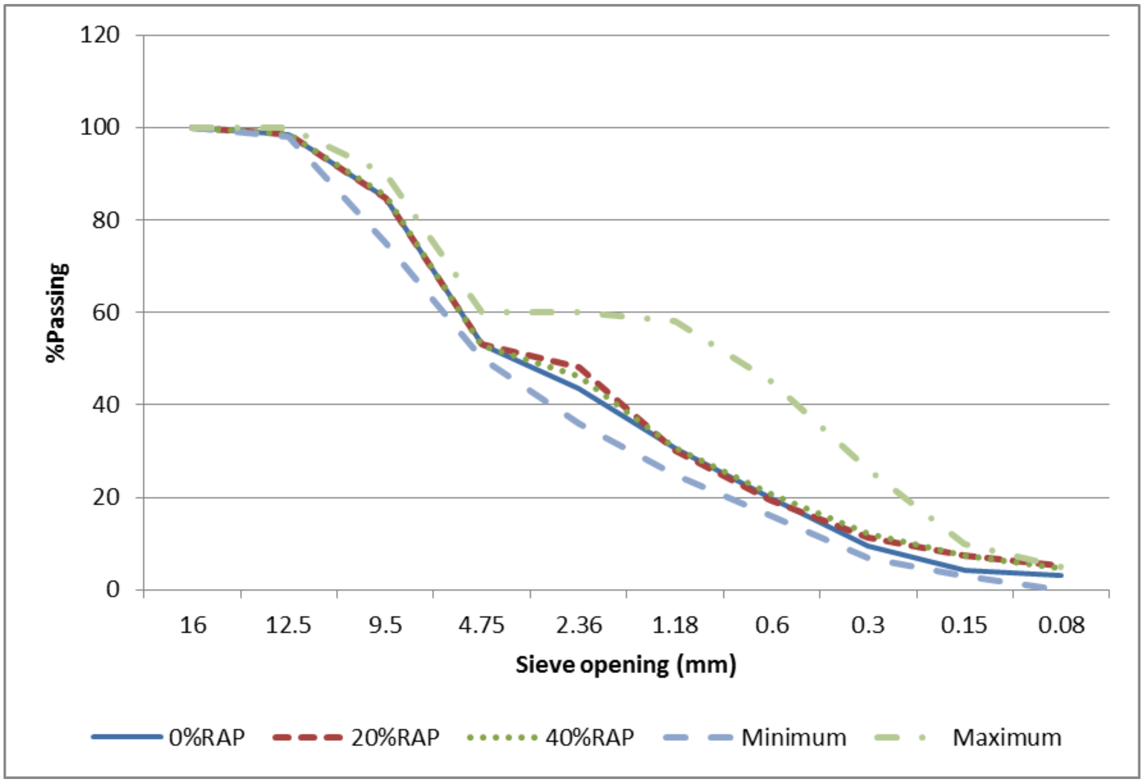

Figure 3-2 Job Mix Formula Gradation

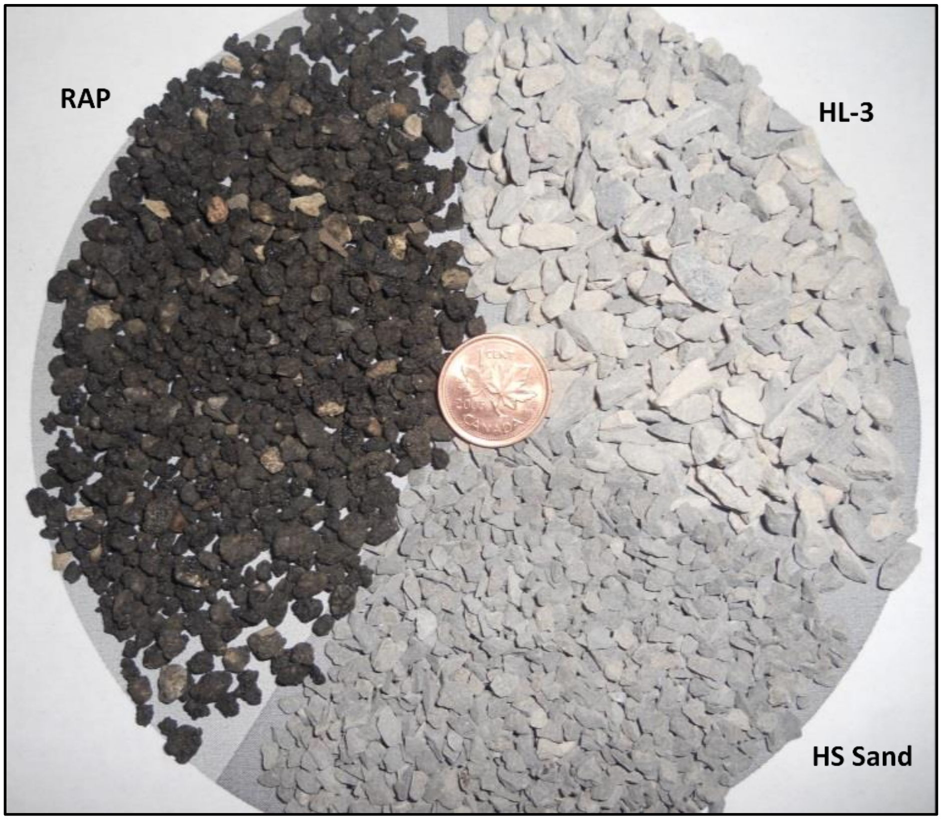

Figure 3-3 Proportions for 40% RAP Mix

Table 3-7 Job Mix Formula Gradation

RAP content (%)	Sieve opening (mm)/ Percent Passing									
	16	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.2**	**0.1**
0	100	98.3	84.8	52.9	43.5	30.6	19.8	9.5	4.3	3.2
20	100	98.4	84.6	53.0	48.0	30.1	19.2	11.4	7.5	5.3
40	100	98.6	85.3	52.8	46.1	30.8	20.7	12.1	7.4	4.6
Minimum	*100*	*98*	*75*	*50*	*36*	*25*	*16*	*7*	*3*	*0*
Maximum	*100*	*100*	*90*	*60*	*60*	*58*	*45*	*26*	*10*	*5*

Mineral filler was required for the 0% RAP mixtures, the proportion of dust added was 1.5% of the weight of the aggregates. To make the mixtures similar, 2.0% dust was required for the 20% RAP mixtures; but the 40% RAP mixtures did not require the incorporation of additional dust.

Two asphalt binder grades were selected per RAP percentage, to determine the asphalt cement content and the volumetric properties. Table 3-8 presents the summary of the design for the six mixtures selected. From the previous results it is possible to notice that all the designs met the specifications, and the volumetric properties of the mixtures were similar to each other.

Table 3-8 Summary of the Designs

RAP content (%)	Virgin Asphalt PG	AC (%)	AC from RAP (%)	Virgin AC (%)	BRD g/cm³	MRD g/cm³	Air Voids (%)	VMA (%)	VFA (%)	Dust Proportion (%)
0	52-34	5.2	0.0	5.2	2.433	2.534	4.0	15.0	73.4	0.7
0	58-28	5.2	0.0	5.2	2.44	2.541	4.0	14.8	73.1	0.7
20	52-40	5.2	0.9	4.3	2.449	2.551	4.0	14.3	72.1	1.2
20	58-34	5.2	0.9	4.3	2.446	2.547	4.0	14.7	73.1	1.2
40	52-40	4.9	1.8	3.1	2.451	2.554	4.0	14.2	71.5	1.1
40	58-28	5.1	1.8	3.3	2.451	2.553	4.0	14.3	72.1	1.1
Min.							4.0	14.0	65.0	0.6
Max.									75.0	1.2

Notes: BRD=Bulk Relative Density, MRD=Maximum Relative Density, VMA=Void in Mineral Aggregate, VFA=Voids Filled with Asphalt

3.5.1 Consensus Properties

For the evaluation of the consensus properties of the aggregate combination, the asphalt from the RAP was extracted and the recovered aggregates were used. Two replicates were considered for each test. The angularity of the coarse aggregates, in terms of crushed faces, slightly decreases as the percentage of RAP added increases. Statistical analyses using the analysis of variance (ANOVA) presented in Table 3-9 and Table 3-10 show however that there is no significant difference with $F_{calculated}$ (0.28) < $F_{critical}$ (9.55) for 1 face crushed and $F_{calculated}$ (1.17) < $F_{critical}$ (9.55) for 2 faces crushed. All the values are kept above the lower limit (85% for 1 face and 80% for 2 faces). Figure 3-4 shows the crushed faces results.

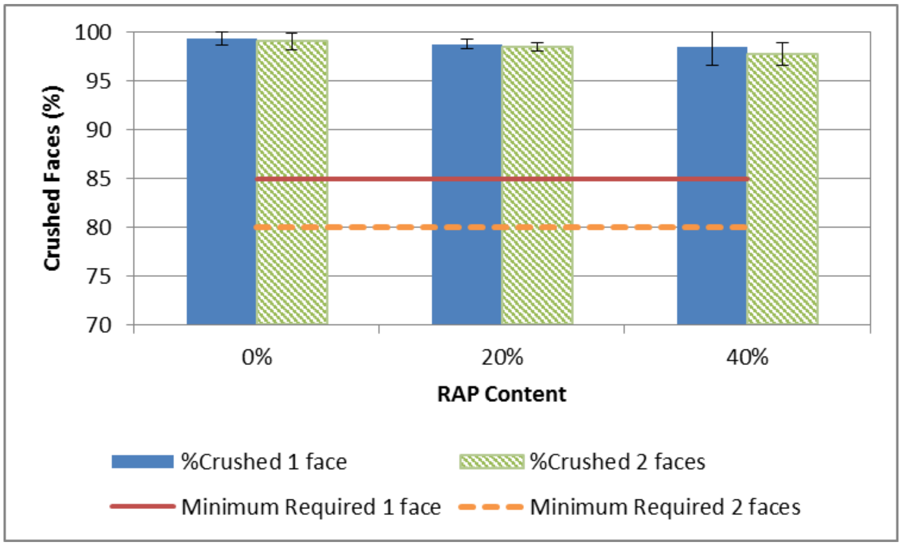

Figure 3-4 Crushed Faces vs. RAP Content

Table 3-9 ANOVA Crushed 1 Face

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
Between Groups	0.76	2	0.38	0.28	0.77	9.55
Within Groups	4.03	3	1.34			
Total	4.79	5				

Table 3-10 ANOVA Crushed 2 Faces

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
Between Groups	1.83	2	0.92	1.17	0.42	9.55
Within Groups	2.34	3	0.78			
Total	4.17	5				

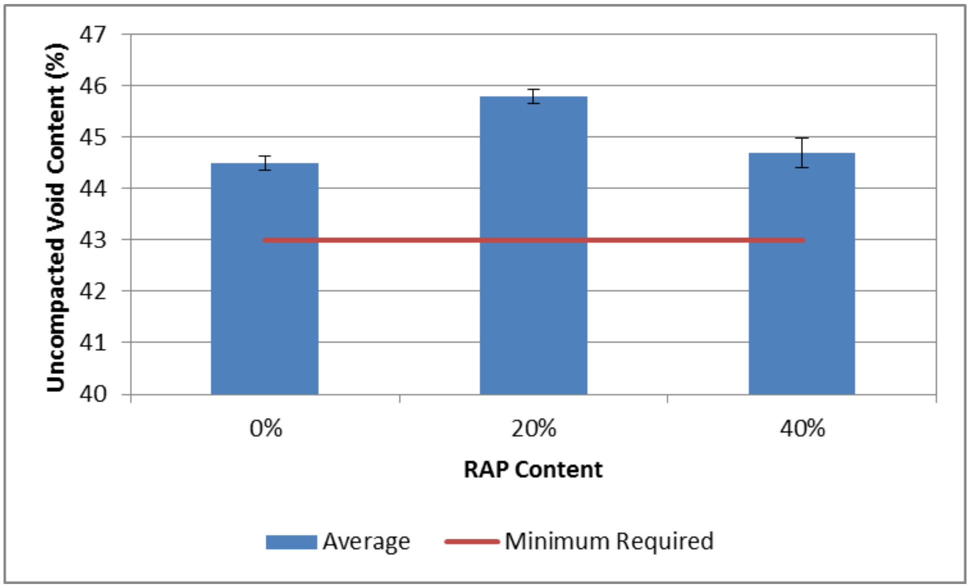

Figure 3-5 Uncompacted Void Content vs. RAP Content

Table 3-11 ANOVA Uncompacted Voids

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
Between Groups	1.96	2	0.98	24.50	0.01	9.55
Within Groups	0.12	3	0.04			
Total	2.08	5				

As shown in Figure 3-5, the uncompacted voids increase for the 20 percent RAP but for the 40 percent they return to a value closer to the virgin mix (minimum required 43). The ANOVA analysis shown in Table 3-11 allowed concluding that the difference is significant with $F_{calculated}$ (24.50) > $F_{critical}$ (9.55), and that 20% RAP has higher uncompacted voids than 0% RAP or 40% RAP mixes.

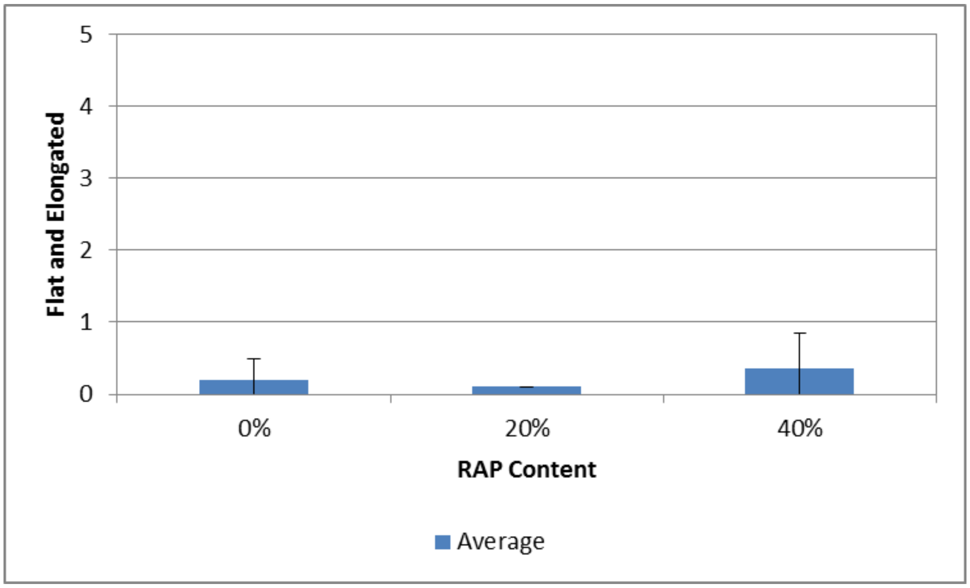

Figure 3-6 Flat and Elongated Particles vs. RAP Content

Table 3-12 ANOVA Flat and Elongated Particles

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
Between Groups	0.06	2	0.03	0.29	0.77	9.55
Within Groups	0.33	3	0.11			
Total	0.39	5				

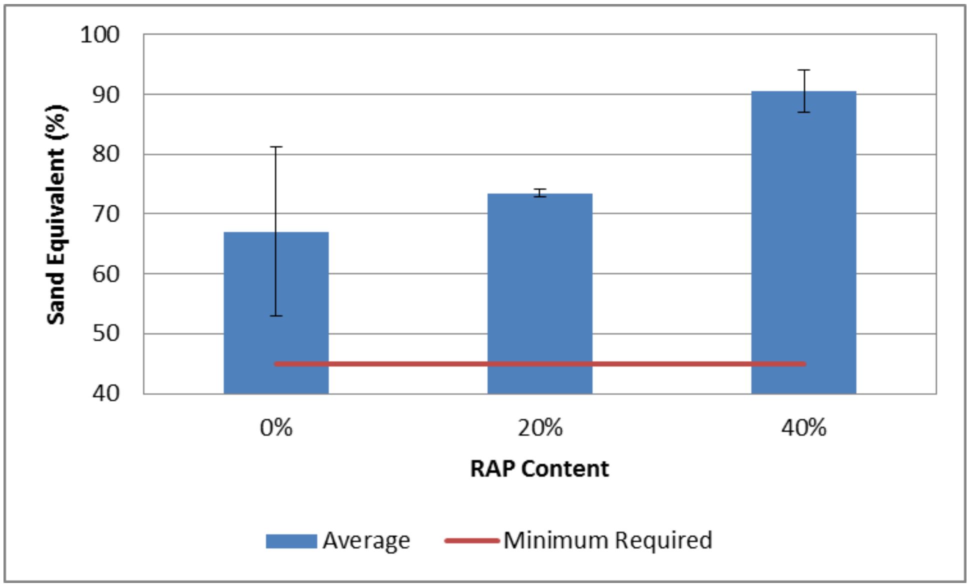

Figure 3-7 Sand Equivalent vs. RAP Content

Table 3-13 ANOVA Sand Equivalent

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
Between Groups	589.00	2	294.50	4.15	0.14	9.55
Within Groups	213.00	3	71.00			
Total	802.00	5				

Figure 3-6 shows the flat and elongated particles. With a maximum admissible value of 10, this parameter is not a concern. The statistical analysis with ANOVA in Table 3-12 showed that the mixes did not have a significant difference with $F_{calculated}$ (0.29) < $F_{critical}$ (9.55).

For the sand equivalent, observed in Figure 3-7, the value increases as the percent of RAP increases, so the sand equivalent will move away from the minimum acceptable (45) when more RAP is added. This means that the RAP mixtures have a lower proportion of clay-like materials, which benefit the bonding of AC with the aggregate. However, given the variability of the 0% RAP or control mixtures, this parameter did not show statistical difference with $F_{calculated}$ (4.15) < $F_{critical}$ (9.55) as seen in Table 3-13.

3.5.2 Gradation

The gradation was analyzed using the Power-law method. As an example of the use of the method, Figure 3-8 shows the application of the procedure for the 0% RAP mix. In the power regression model equations shown in Figure 3-8 'y' is the percent by weight passing a given sieve that has an opening of width 'x'. The results are shown in Table 3-14. The power law method, suggested by Ruth et al (2002), characterize the slope and the intercept constants of the coarse and fine aggregate portions using a power law regression analysis, with the following form (Ruth, Roque, & Nukunya, 2002):

$$P_{CA} = a_{CA}(d)^{n_{CA}} \quad (3.1)$$

$$P_{FA} = a_{FA}(d)^{n_{FA}} \quad (3.2)$$

Where:

P_{CA} and P_{FA}: percent by weight passing a given sieve that has an opening of width d

a_{CA}: intercept constant for the coarse aggregate

a_{FA}: intercept constant for the fine aggregate

d: sieve opening width, mm

n_{CA}: slope (exponent) for the coarse aggregate

n_{FA}: slope (exponent) for the fine aggregates

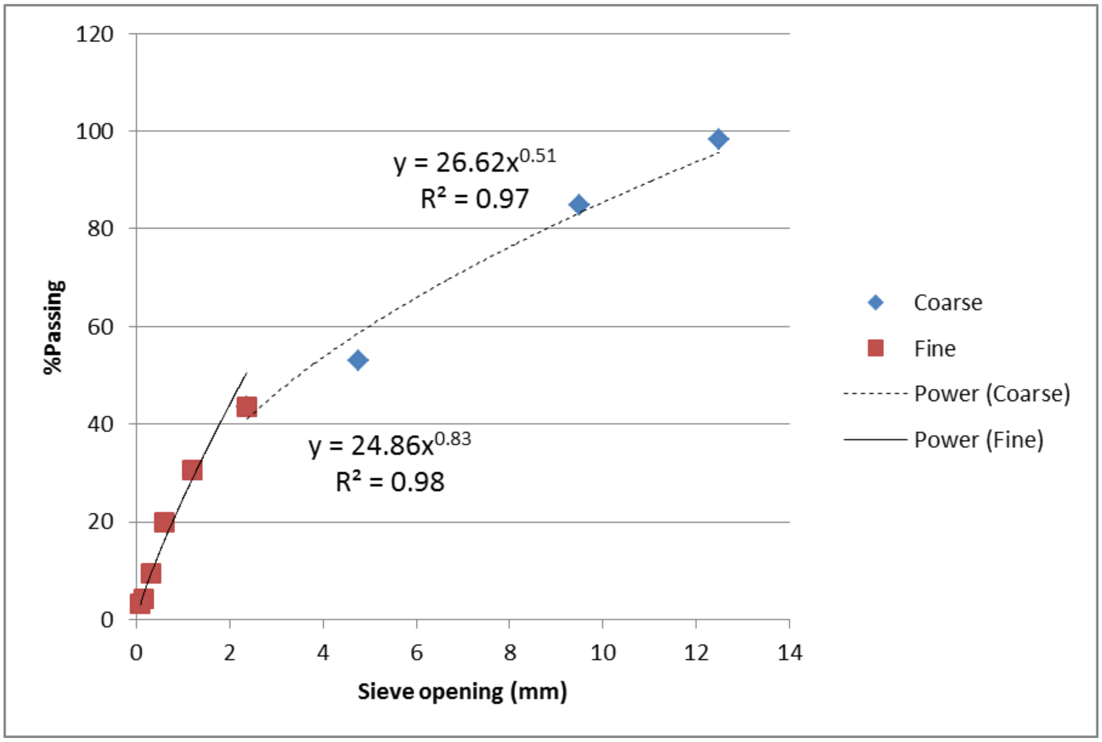

Figure 3-8 Power-Law Gradation 0% RAP

The divider sieve between coarse and fine aggregate is given by the NMAS of the mixture. In this case for 12.5mm, the dividing sieve suggested is 2.36mm (No. 8).

Table 3-14 Power-Law Gradation Analysis

RAP Content (%)	a_{CA}	n_{CA}	a_{FA}	n_{FA}
0	26.6	0.5	24.9	0.8
20	30.2	0.5	26.8	0.7
40	28.5	0.5	27.2	0.7

The method stated that the higher the slope value, the coarser or finer the portion. Then it can be concluded that the FA portion in 0% RAP mixes aggregate gradation is finer. Figure 3-9 shows the relation between the Dust Proportion (DP), also known as dust to binder ratio, and the RAP content. It can be noticed a higher DP for the RAP mixtures as compared with the virgin mixtures, which might be related to a lower effective binder content for the RAP mixtures.

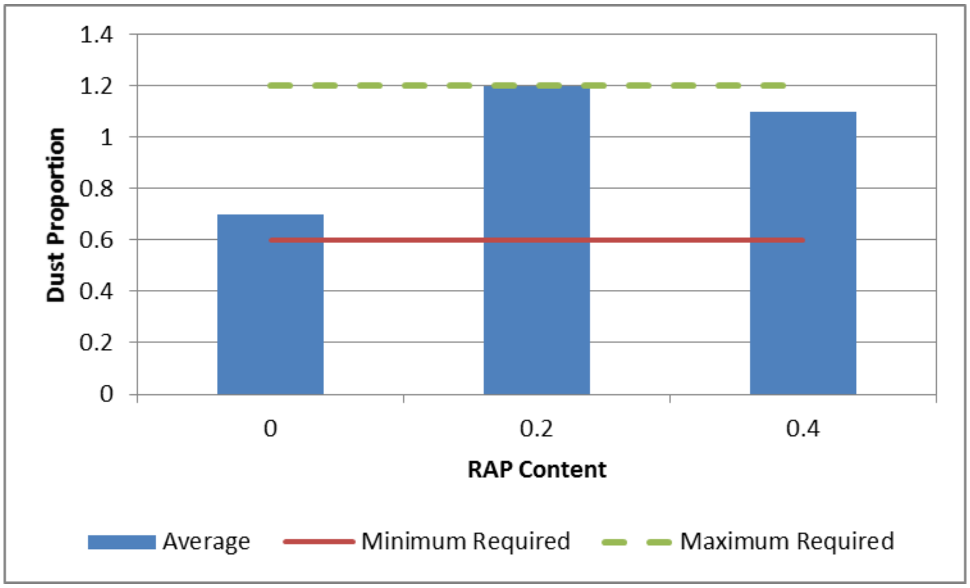

Figure 3-9 Dust Proportion vs. RAP Content

3.5.3 Superpave Requirements

For the volumetric properties, it was observed that the Voids in the Mineral Aggregate (VMA) and Voids Filled with Asphalt (VFA) apparently decrease as the RAP content increases, as shown in Figure 3-10 and Figure 3-11. That could be explained, because the percentage of virgin asphalt added decreases, but more fines from the RAP fill the spaces between particles, as the RAP percentage increases. It is worthwhile to mention that the results are within the allowable limits. The mixes meet the minimum 14% for VMA and the VFA is between 65% and 75% requirement.

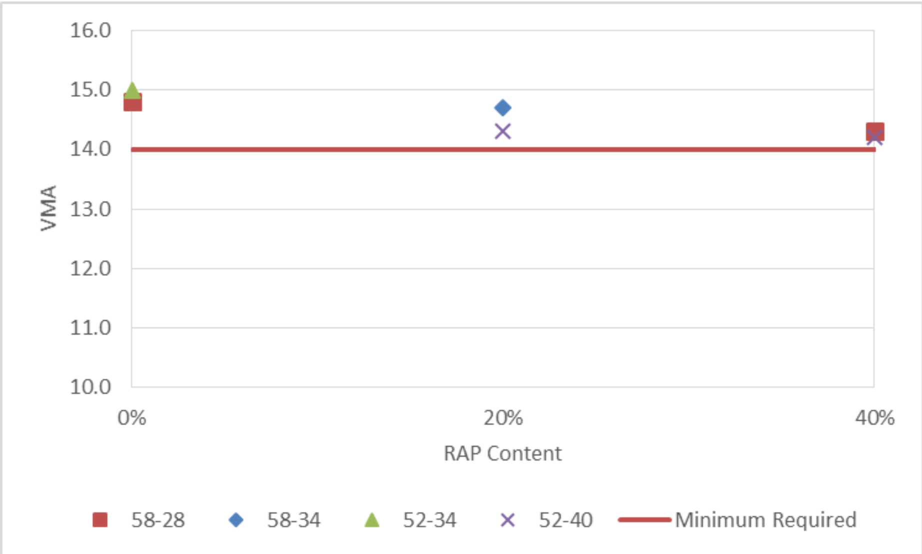

Figure 3-10 VMA vs. RAP Content

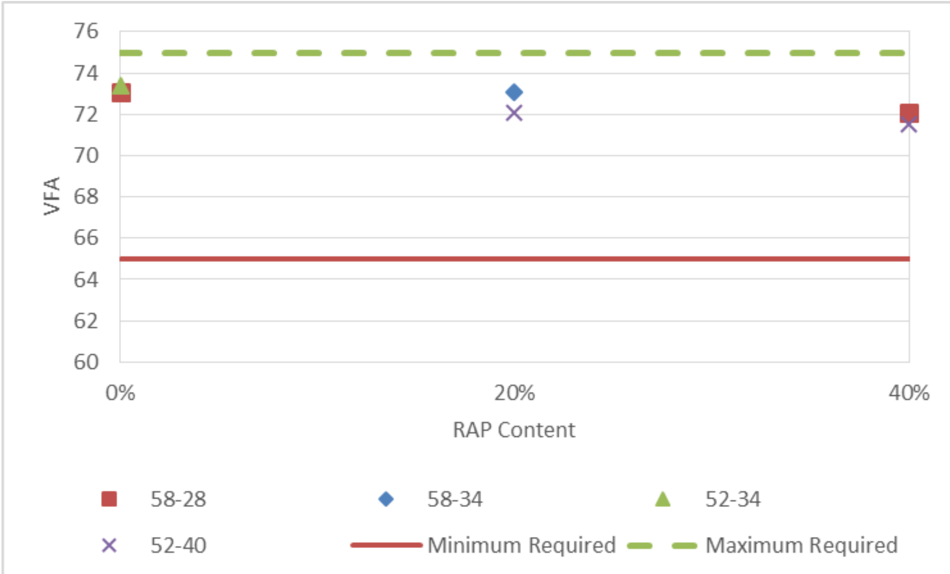

Figure 3-11 VFA vs. RAP Content

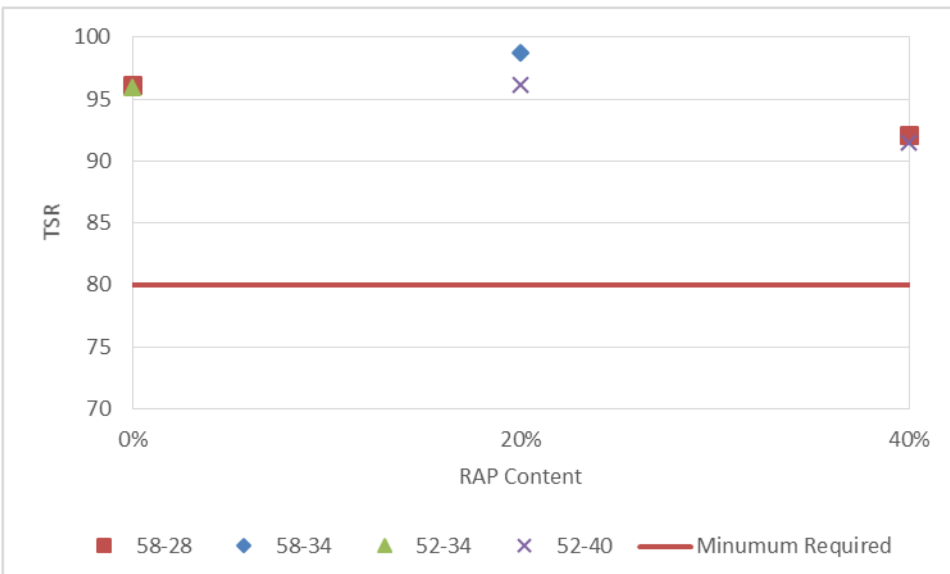

Figure 3-12 TSR vs. RAP Content

The Tensile Strength Ratio (TSR) characterizes the resistance of compacted asphalt mixtures to moisture-induced damage (AASHTO, 2003). In this test, the tensile strength of compacted samples subjected to moisture conditioning is compared to the tensile strength of un-conditioned specimens. All the TSR values were above the minimum 80 percent required; however, in Figure 3-12 it can be seen that the lowest results were obtained from the 40 percent RAP mixes, which are about 4% below the result obtained for the virgin mix.

3.6 Laboratory Mixing Procedure

All the mixtures for the performance testing were prepared in the CPATT laboratory as part of this research. For that purpose the following procedure was followed:

Sieve all the aggregates by the appropriate sizes: 16mm, 12.5mm, 9.5mm, 4.75mm and 2.36mm as shown in Figure 3-13. For this purpose the shaker shown in Figure 3-14 was used in this research.

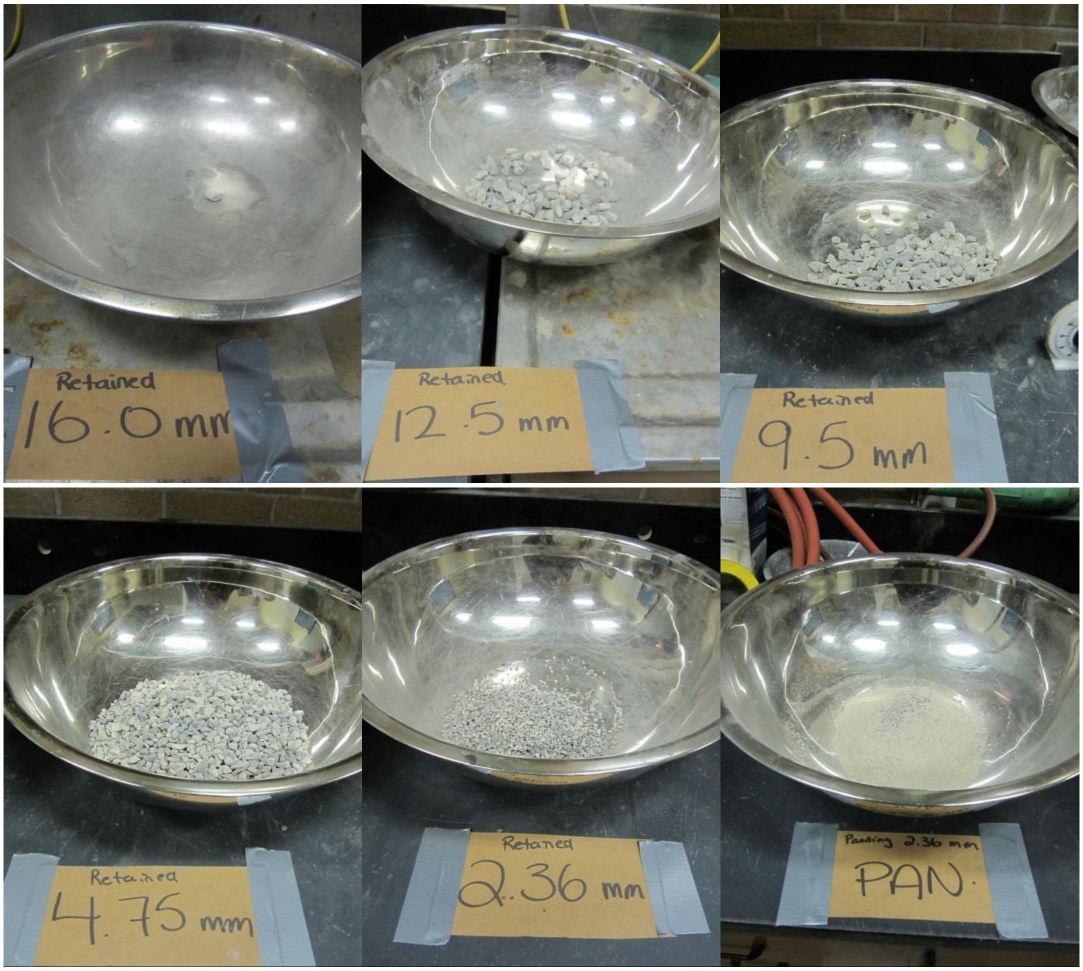

Figure 3-13 Sieved Aggregates

Figure 3-14 CPATT Sieving Equipment

The aggregates were dried overnight in the oven at 110°C until constant weight was obtained. The RAP was dried at room temperature.

The aggregates were then batched according to the proportions established in the design as shown in Figure 3-15 and Figure 3-16.

Figure 3-15 Batching Procedures

Figure 3-16 Resulting 15kg Batches for 0% RAP Mixes

The aggregates were heated to 160°C and they were not allowed to exceed the mixing temperature plus 28°C for a minimum of 16 hours. When RAP was used, the RAP was heated at 60°C.

Figure 3-17 Heating Asphalt and Aggregates

The asphalt was heated to the mixing temperature as shown in Figure 3-17. Special care was taken to ensure the asphalt was not overheated.

Batches of 15kg of dried aggregate were mixed. The aggregates and RAP were mixed for 15 seconds, as seen in Figure 3-18 and then the asphalt was added carefully as shown in Figure 3-19 and mixed for 1.5 minutes. For this research six batches were mixed per day.

Figure 3-18 Mixing RAP and Virgin Aggregates

Figure 3-19 Adding Hot Asphalt Binder

Figure 3-20 Preparing Samples for Evaluation of Maximum Relative Density

Samples for maximum relative density (MRD) were taken every 45kg and conditioned according to AASHTO R 30-02 Specification for 2 hours in a force draft oven at the compaction temperature (AASHTO, 2006). The MRD samples preparation is seen in Figure 3-20 and Figure 3-21 shows the equipment used for this test. The MRD was determined in accordance with AASHTO T 209.

Figure 3-21 MRD Equipment

Figure 3-22 Samples during Conditioning Procedure

Short term aging for performance testing was conducted as required by the AASHTO R30-02 Specification 4 hours at 135°C in the force draft oven as shown in Figure 3-22. The preparation of the beams for TSRST was done using the AVC (Asphalt Vibratory Compactor) to obtain beams of 39.0 x 12.5 x 10.0 cm as shown in Figure 3-23, to get two specimens of the desired dimensions from each.

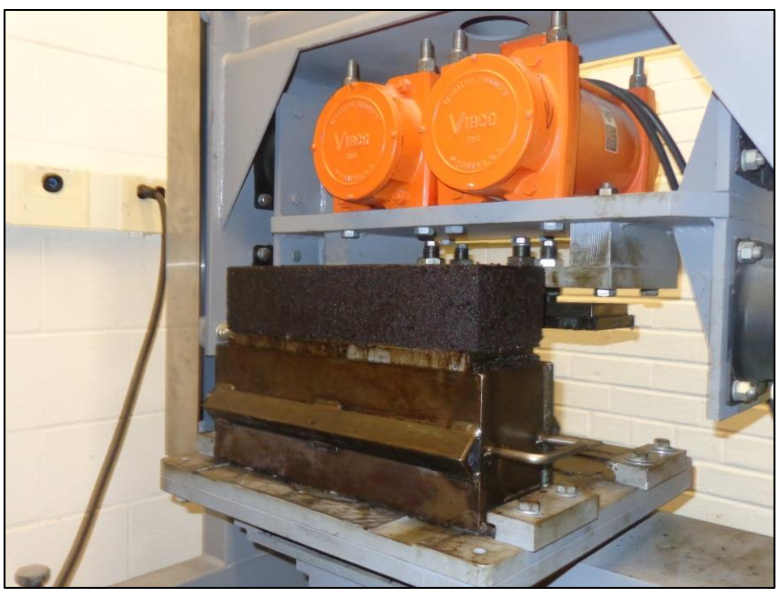

Figure 3-23 Asphalt Vibratory Compacted Beam

The samples for disk-shaped compact tension, Hamburg wheel rutting and dynamic modulus were obtained by means of the Superpave gyratory compactor following the AASHTO T 312 standard (AASHTO, 2009), as seen in Figure 3-24, to a target air void content of 7% after coring, cutting and end grinding. The BRD was determined using saturated surface-dry specimens as described in the AASHTO T 166 standard (AASHTO, 2010a). The equipment used for coring is shown in Figure 3-25 and the cutting machine in Figure 3-26.

Figure 3-24 Superpave Gyratory Compacted Cylinder

Figure 3-25 Coring Equipment

Figure 3-26 Cutting TSRST Samples

3.1 Summary and Conclusions

Based on the raw material properties and mix design, it is apparent that HMA with RAP can be designed to meet all the specified properties for the Superpave design requirements, as well as all the consensus properties required for the aggregates. The angularity of the coarse aggregate could affect the rutting of recycled hot mix. Also, the differences in the dust proportion would dictate the performance of the mastic in the mix and could have a potential impact on its performance.

The statistical analyses indicated that the addition of RAP did not significantly affect the consensus properties or the volumetric properties of the mixtures, except for the fine aggregate angularity and the TSR results.

A careful mixing procedure was followed that tried to resemble the plant mixing environment. Also conditioning of the mixtures was considered to simulate the aging of the material during production, transport and placement.

Chapter 4
Mixtures Performance Evaluation

4.1 Introduction

Considering the different demands that the surface asphalt mixtures have to meet, a series of material characterization tests were conducted to evaluate the performance of the RHM. Thermal stress restrained specimen (TSRST), Hamburg wheel rutting device (HWRD) and dynamic modulus using the materials testing system (MTS) were completed for all mixes. The TSRST is oriented to evaluate thermal cracking; the HWRD, permanent deformation; and the dynamic modulus, permanent deformation and fatigue cracking. In addition, all of these tests were conducted for manufactured 100% RAP mixtures.

Additionally, disk-shaped compact tension (DC(T)), flow number (FN) and dynamic modulus with the Asphalt Mixture Performance Tester (AMPT) were conducted for half of the matrix in order to verify and compare the susceptibility to thermal cracking, permanent deformation and stiffness characterization.

According to the test results, the mixtures were ranked in ascending order; the first mix exhibits the best performance while the last mix, the weakest performance.

The information collected from the different tests is accompanied with the respective statistical analysis to verify the significance of the results.

The ANOVA analysis was the selected method for comparing three or more means. For the case when there is only information available for six cells, the t-test was used for testing the statistical difference between the groups. In general, the method for hypothesis testing described by Montgomery (Montgomery, 2013) was used.

ANOVA single factor was conducted grouping the cells by RAP content and by asphalt PG. For example the group 20% RAP encompasses the following mixes: 20% RAP PG 58-28, 20% RAP PG 58-34, 20% RAP PG 52-34 and 20% RAP PG 52-40; and the group PG 58-28 is comprised by the 0% RAP PG 58-28, 20% RAP PG 58-28 and 40% RAP PG 58-28 mixes. Also ANOVA Two-Factor was conducted to complement the analysis.

It is necessary to prove that the measured means of the parameters are different, and that this difference is statistically significant. For that purpose the following hypothesis is tested:

$$H_0: \mu_1 = \mu_2 = \mu_n \tag{4.1}$$

$$H_1: \mu_1 \neq \mu_2 \neq \mu_n \tag{4.2}$$

Where:

H_0= Null hypothesis

H_1= Alternate hypothesis

μ_n= mean for cell n

In the case of ANOVA, the null hypothesis is rejected when $F_{calculated} > F_{critical}$. The P-value provides the statistical significance of the findings. Considering a level of significance α=0.05, it is determined that the difference is statistically significant when P-value<0.05. When the P-value is higher than the selected level of significance, it is consistent with null hypothesis.

For t-test, when $|t_{calculated}| > t_{critical\ two\text{-}tail}$ the null hypothesis is rejected, that is, the results are statistically different. The probability that the $t_{calculated}$ is less that $t_{critical\ two\text{-}tail}$, P(T<=t) < 0.05 supports the rejection of the null hypothesis with 95% confidence level.

4.2 Low Temperature Cracking

4.2.1 Thermal Stress Restrained Specimen Test

The TSRST measures the resistance to thermal cracking of compacted bituminous mixtures at extremely low temperatures. This test is conducted in accordance with the AASHTO TP 10-93 standard (AASHTO, 1993).

Figure 4-1 CPATT TSRST Frame and Environmental Chamber

The specimen test is shown in Figure 4-1. The TSRST system applies an initial tensile load to the compacted beam specimens measuring 250 mm x 50 mm x 50 mm whilst being simultaneously subjected to a constant cooling rate of -10ºC hourly; as well as restraining it from contracting by re-establishing the initial length of the specimen.

The beam fails as the stress generated exceeds the tensile strength, when the failure temperature and fracture stress are recorded. The failure temperature represents the temperature at which the asphalt pavement will develop a transverse thermal crack and the fracture stress controls the spacing between those cracks. A higher fracture stress results in wider spacing between cracks in the field, so fewer distresses would be observed (Loria et al., 2011) . A typical stress temperature curve is shown in Figure 4-2. The preliminary results and analyses for the first four mixtures examined were presented in the 2013 Transportation Association Canada Annual Meeting (Ambaiowei, Sanchez, Safiuddin, Aurilio, & Tighe, 2013).

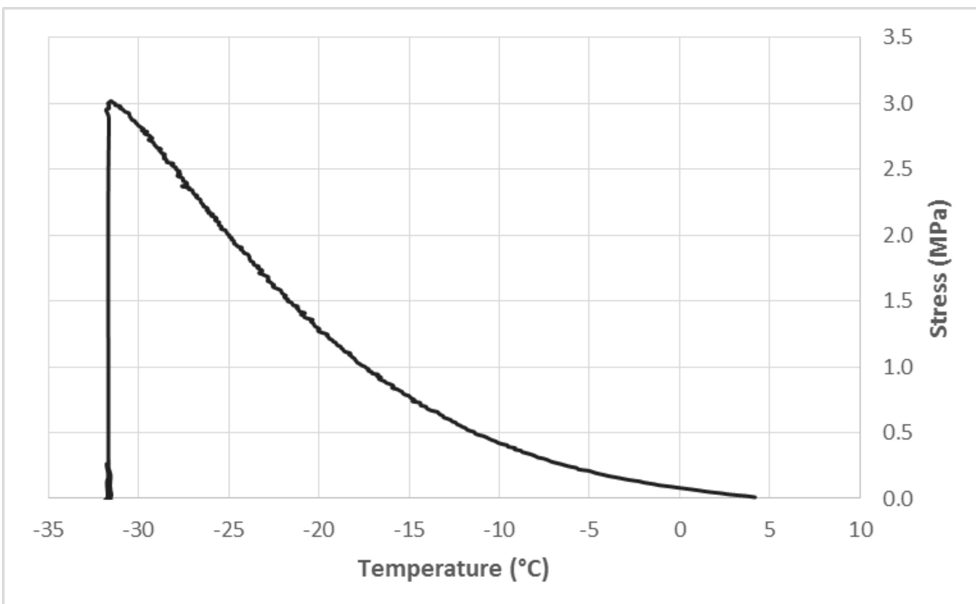

Figure 4-2 TSRST Stress Temperature Curve

Failure Temperature

The failure temperature is deemed to be the minimum temperature that the mix can tolerate before cracking. It is at the point where the binder becomes brittle and allows for crack propagation. In general it is expected that the use of a softer binder makes the failure temperature lower, while adding RAP to the mix would make the failure temperature higher. The average and standard deviation results from three test replicates are shown in Table 4-1. As can be observed, the highest variations in the failure temperature were obtained for the 40% RAP PG 58-28 and 20% RAP PG 52-40. For most cases, less variation in the failure temperature was obtained for the virgin mixtures compared to the RAP added. The mix with best resistance to thermal cracking, in terms of the lower failure temperature, is the 0% RAP PG 52-40.

Table 4-1 TSRST Failure Temperature Results

Mix Type	TSRST Failure Temperature (°C)		Ranking	Comments
	Average	StDev		
0-58-28	-30.1	0.5	9	Meet -28°C
20-58-28	-28.2	1.0	11	Meet -28°C
40-58-28	-29.2	2.9	10	Meet -28°C
0-58-34	-34.3	1.1	2	Meet -34°C
20-58-34	-33.6	0.8	4	0.4°C warmer than-34°C
40-58-34	-31.1	1.3	8	Meet -28°C
0-52-34	-33.9	0.1	3	0.1°C warmer than -34°C
20-52-34	-31.9	0.7	7	2.1°C warmer than -34°C
40-52-34	-27.7	0.9	12	0.3°C warmer than -28°C
0-52-40	-42.7	0.3	1	Meet -40°C
20-52-40	-32.5	2.9	6	1.5°C warmer than -34°C
40-52-40	-32.6	0.8	5	1.4°C warmer than -34°C

A target temperature was defined according to the Ontario specification, a minimum of -28°C is required for the provincial Zone 3 and a minimum of -34°C is required for the two other provincial zones, Zone 1 and Zone 2. The minimum of -28°C was met for all 12 mixtures, except for the 40% RAP PG 52-34 where the specimens failed at -27.7°C. The -34°C failure temperature was not met for any of the RAP mixtures, even when a modified binder was used.

Figure 4-3 shows the comparison of the critical temperatures. In this figure it is observed that the addition of RAP results in increases in the failure temperature, meaning they are less resistant to colder temperatures. It also shows that the PG 58-28 is less affected by the addition of RAP than the PG 52-40.

From Figure 4-3 it is noticeable that the difference between adding 20% or 40% did not have much influence for the PG 58-28 and PG 52-40. For the PG 58-34 and PG 52-34, the 40% RAP mixtures were shown to have a warmer failure temperature than the 20% RAP mixtures.

An ANOVA Two-Factor with replication was conducted to evaluate the significance of the obtained outcomes. The results are summarized in Table 4-2.

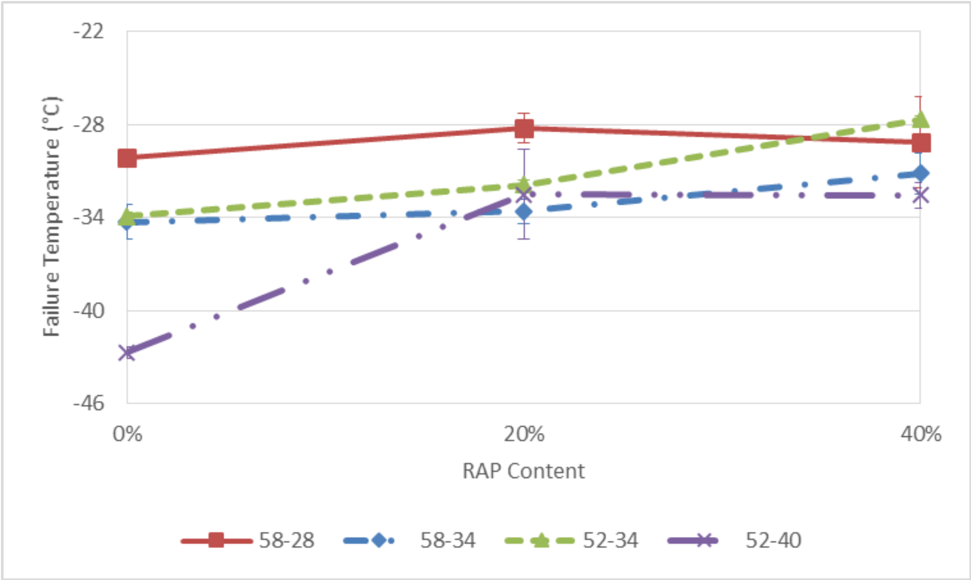

Figure 4-3 Critical Temperatures Comparison

Table 4-2 ANOVA Two-Factor with Replication for Failure Temperature

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
RAP Content	169.8	2	84.9	43.0	<0.01	3.4
Asphalt PG	222.6	3	74.2	37.6	<0.01	3.0
Interaction	121.9	6	20.3	10.3	<0.01	2.5
Within	47.3	24	2.0			
Total	561.6	35				

From Table 4-2 it is notable that the addition of RAP has a significant impact on the failure temperature with $F_{calculated}=43.0>F_{critical}=3.4$. The results are also affected by the change in the asphalt PG with $F_{calculated}=37.6>F_{critical}=3.0$. The interaction between the two factors is not negligible with $F_{calculated}=10.3>F_{critical}=2.5$. That means that the failure temperature is a result of the combined effect of the RAP content and the virgin asphalt PG, but looking at the sum of squares results, the effect on the asphalt PG in the variability of the results is more significant.

From the results in Table 4-1 it is observed that the failure temperature for the PG 58-28 mixes was not affected by the addition of RAP.

It can also be observed that the change in asphalt PG affect the failure temperature for the 0% RAP, 20% RAP and 40% RAP mixes. However, it can be concluded that the change of asphalt PG has a lower impact in the failure temperature for the 40% RAP mixtures. The addition of RAP also affected the failure temperature of the PG 58-34, PG 52-34 and PG 52-40.

Table 4-1 Results ANOVA Single Factor Failure Temperature

Group	$F_{calculated}$	*P-value*	$F_{critical}$	Statistically Different	Significant at α=0.05
0% RAP	217.4	<0.01	4.1	Yes	Yes
20% RAP	6.3	0.02	4.1	Yes	Yes
40% RAP	4.7	0.04	4.1	Yes	Yes
PG 58-28	0.8	0.48	5.1	No	
PG 58-34	73.2	<0.01	5.1	Yes	Yes
PG 52-34	6.9	0.03	5.1	Yes	Yes
PG 52-40	34.4	<0.01	5.1	Yes	Yes

Fracture Stress

The fracture stress is related to the distance between thermal cracks. The higher the fracture stress, the greater the distance between the cracks. Based on the material properties, it would be expected that as the percentage of RAP increases, because RAP is stiffer, these mixes may be more prone to cracking. In short, it would be expected to result in a lower fracture stress. This does not however appear to be the case in this research. Instead, the use of a softer binder seems to provide higher fracture stress. The mix with the highest observed fracture stress was the 40% RAP PG 52-40.

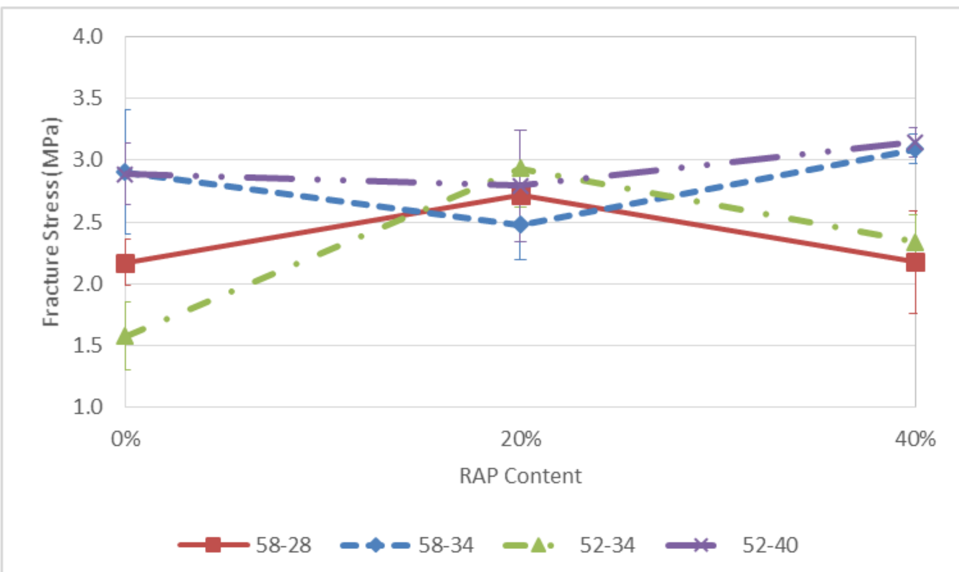

Figure 4-4 Fracture Stress for Different RAP Contents

In general, more variability was observed for this parameter than for the failure temperature; however, the standard deviation remains in the same range for all the mixtures at less than 0.5MPa as seen in Table 4-3.

A graphical representation of the fracture stress results is shown in Figure 4-4. In this figure, the 40% RAP PG 52-40 developed a higher average fracture stress in comparison with the other mixtures. For the PG 58-28 and PG 52-34 the average fracture stress is higher with 20% RAP.

Table 4-3 TSRST Fracture Stress Results

Mix Type	TSRST Fracture Stress (MPa)		Ranking
	Average	StDev	
0-58-28	2.2	0.2	11
20-58-28	2.7	0.0	7
40-58-28	2.2	0.4	10
0-58-34	2.9	0.5	4
20-58-34	2.5	0.3	8
40-58-34	3.1	0.1	2
0-52-34	1.6	0.3	12
20-52-34	2.9	0.3	3
40-52-34	2.3	0.2	9
0-52-40	2.9	0.2	5
20-52-40	2.8	0.4	6
40-52-40	3.1	0.1	1

An ANOVA two-factor with replication was conducted for the fracture stress. As shown in Table 4-4, the effect of the RAP addition is significant, as well as the effect of the change in the virgin binder performance grade. The interaction between both factors was also shown to be significant, meaning that the fracture stress result is a combined effect of the RAP content and the asphalt PG used. However, the asphalt PG has a greater influence in the variability of the results.

Table 4-4 ANOVA Two-Factor with Replication for Fracture Stress

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
RAP content	0.8	2	0.4	4.9	0.02	3.4
Asphalt PG	2.9	3	1.0	11.3	<0.01	3.0
Interaction	3.3	6	0.6	6.3	<0.01	2.5
Within	2.1	24	0.1			
Total	9.2	35				

An ANOVA single factor was also conducted, as shown in Table 4-5. It can be observed that the fracture stress was not significantly affected by the use of a softer binder for the 20% RAP mixes. Also, the addition of RAP did not significantly affect the fracture stress for the PG 58-28, PG 58-34 and PG 52-40, and then the cracking density in the field would be similar for those mixes.

The change in asphalt PG affected the fracture stress of the 0% RAP and 40% RAP mixes. Also, the addition of RAP impacted the fracture stress of the PG 52-34 mixes.

Table 4-5 Results ANOVA Single Factor Fracture Stress

Group	$F_{calculated}$	*P-value*	$F_{critical}$	Statistically Different?	Significant at α=0.05
0% RAP	11.6	<0.01	4.1	Yes	Yes
20% RAP	1.2	0.38	4.1	No	
40% RAP	12.1	<0.01	4.1	Yes	Yes
PG 58-28	4.2	0.07	5.1	No	
PG 58-34	2.6	0.15	5.1	No	
PG 52-34	19.1	<0.01	5.1	Yes	Yes
PG 52-40	1.1	0.40	5.1	No	

4.2.2 Disk-Shaped Compact Tension Test

This test was conducted for six of the twelve mixtures studied. Through this test, the determination of the fracture energy of asphalt-aggregate mixtures is possible. The fracture energy is a fundamental property of the materials and is defined as the energy required to create a new unit of area; it is measured in J/m^2. The higher the fracture energy, the more stress the specimen is able to withstand which means the material has a better resistance to thermal cracking.

The disk-shaped compact tension test was conducted in accordance with ASTM D7313-07a Standard (ASTM, 2013) . In this test a notch and two loading holes are placed on a 150mm diameter and 50mm thick circular sample, that is subjected to tension and the crack mouth opening displacement (CMOD) is measured. The test set up, and geometry of the sample are shown in Figure 4-5.

This test was conducted by the Asphalt Institute at a test temperature of 10°C above the low temperature performance grade of the asphalt binder, as suggested by the specification.

It is expected that the addition of RAP would decrease the fracture energy, and that the use of softer asphalt would increase this property.

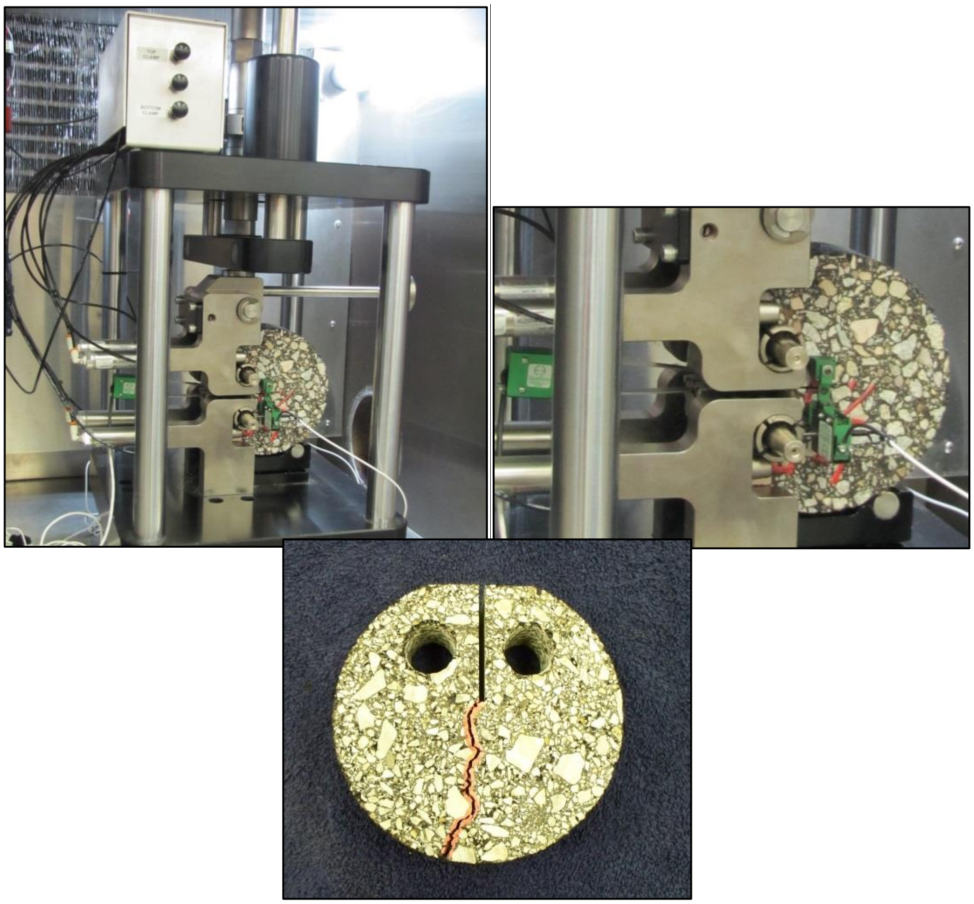

Figure 4-5 Disk-Shaped Compact Tension Test

The results for the disk-shaped compact tension test are shown in Table 4-6. A maximum coefficient of variation of 25% is observed in every test. The highest variations were obtained for the 0% RAP PG 58-28 and 20% RAP PG 58-34 for -18°C, whereas for -24°C the highest variation was found for the 20% RAP PG 52-40 mixture. For -18°C, the Fracture Energy range is from 398.5 to 598.1 J/m^2 for -18°C, obtaining the highest results for the virgin mixtures. For -24°C, a decrease between 18% and 27% was obtained, comparing to the -18°C results, except for the 0% RAP 58-28, where the Fracture Energy decreased almost 50% of the obtained with -24°C. The mix with better fracture energy is the 0% RAP PG 52-34.

The fracture energy at -24°C is less than the results obtained at -18°C, which is expected, as the temperature decrease, the endurance of the mixture is reduced. However, the fracture energy for the control mixtures drops more from -18°C to -24°C compared to the recycled mixtures. Figure 4-6 shows the results of the average fracture energy at -18°C and Figure 4-7 the results of the average fracture energy at -24°C.

Table 4-6 DC(T) Results

Mix Type	Fracture Energy (J/m²) at -18°C		Ranking	Fracture Energy (J/m²) at -24°C		Ranking
	Average	StDev		Average	StDev	
0-58-28	513.1	41.5	2	255.2	15.0	6
40-58-28	424.1	122.0	4	321.6	12.0	5
20-58-34	398.5	66.2	6	325.0	86.7	4
0-52-34	598.1	100.6	1	437.9	28.5	1
20-52-40	478.7	68.1	3	368.3	57.8	2
40-52-40	406.6	74.6	5	334.8	28.1	3

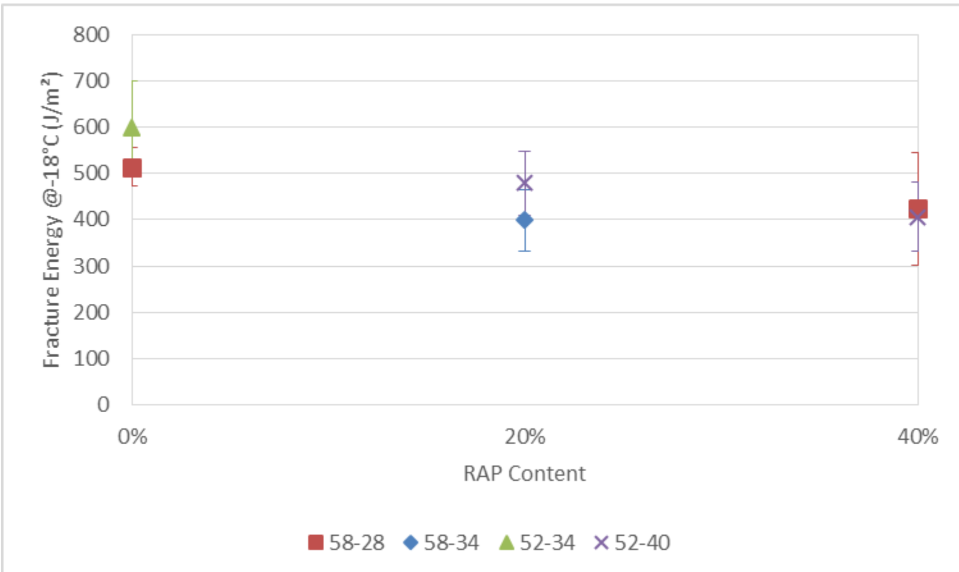

Figure 4-6 Fracture Energy Results at -18°C

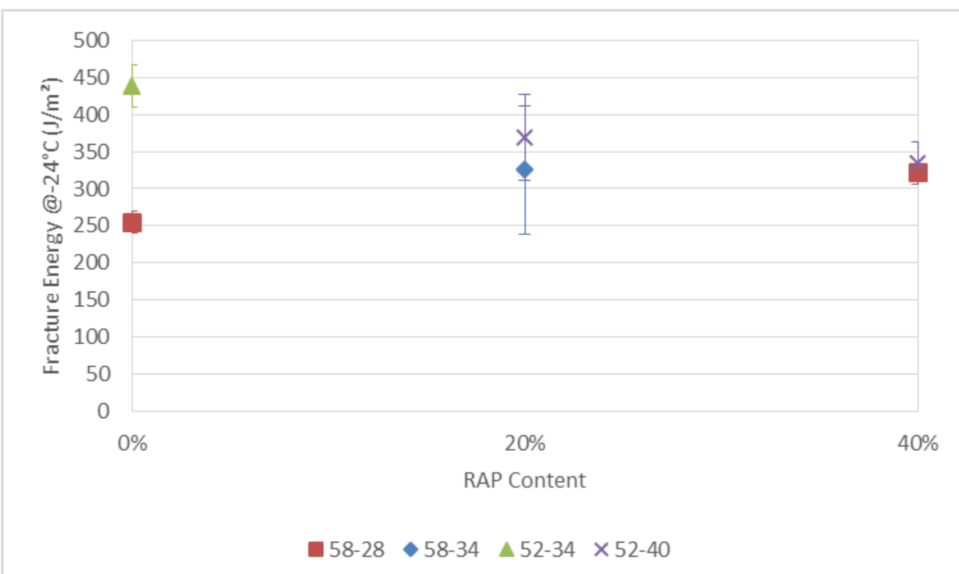

Figure 4-7 Fracture Energy Results at -24°C

A t-test was conducted to determine the statistical difference between the samples; the results are shown in Table 4-7 to Table 4-10.

Table 4-7 DC(T) Fracture Energy at -18°C $t_{calculated}$

Mix Type	0-58-28	40-58-28	0-52-34	20-58-34	20-52-40	40-52-40
0-58-28		1.1	-1.1	1.3	0.4	1.3
40-58-28			-3.5	0.4	-0.9	0.3
0-52-34				3.2	2.6	4.2
20-58-34					-1.2	-0.1
20-52-40						1.3
40-52-40						

Notes: t Critical two-tail = 2.78 / t Critical one-tail = 2.13

Table 4-8 DC(T) Fracture Energy at -18°C P(T<=t) two-tail

Mix Type	0-58-28	40-58-28	0-52-34	20-58-34	20-52-40	40-52-40
0-58-28		0.34	0.32	0.28	0.69	0.26
40-58-28			0.02	0.74	0.40	0.78
0-52-34				0.03	0.06	0.01
20-58-34					0.31	0.91
20-52-40						0.26
40-52-40						

Table 4-9 DC(T) Fracture Energy at -24°C $t_{calculated}$

Mix Type	0-58-28	40-58-28	0-52-34	20-58-34	20-52-40	40-52-40
0-58-28		-3.8	-16.4	-3.9	-2.2	-2.3
40-58-28			-6.3	-0.1	-0.9	-0.4
0-52-34				6.1	1.4	3.0
20-58-34					-0.8	-0.3
20-52-40						0.6
40-52-40						

Notes: t Critical two-tail = 2.78 / t Critical one-tail = 2.13

Table 4-10 DC(T) Fracture Energy at -24°C P(T<=t) two-tail

Mix Type	0-58-28	40-58-28	0-52-34	20-58-34	20-52-40	40-52-40
0-58-28		0.02	<0.01	0.02	0.09	0.08
40-58-28			<0.01	0.89	0.42	0.74
0-52-34				<0.01	0.24	0.04
20-58-34					0.46	0.81
20-52-40						0.61
40-52-40						

The following conclusions can be drawn from Table 4-7 and Table 4-9:

- 0% RAP PG 58-28 is not statistically different to 20% RAP PG 58-34 (Single Bump) at -18°C; but 0% RAP PG 58-28 is lower than 20% RAP PG 58-34 (Single Bump) at -24°C.
- 0% RAP PG 58-28 is not statistically different to 40% RAP PG 58-28 (No Bump) at -18°C; but 0% RAP PG 58-28 is lower than 40% RAP PG 58-28 (Single Bump) at -24°C.
- 0% RAP PG 52-34 is not statistically different to 20% RAP PG 52-40 (Single Bump)
- 0% RAP PG 52-34 higher than 40% RAP PG 52-40 (Single Bump)
- 20% RAP PG 58-34 is not statistically different to 20% RAP PG 52-40(Double Bump)

That means that in terms of fracture energy, the performance of some of the RAP mixtures is comparable to the control mixtures. However, for the 40% RAP PG 52-40 it was noticed a decrease in the fracture energy compared to the control mix, meaning that the addition of RAP would make this mixture be more prone to thermal cracking despite the use of a modified binder.

4.3 Rutting and Moisture Damage

4.3.1 Hamburg Wheel Rutting Test

The CPATT Hamburg wheel rutting device (HWRD) was used to determine the potential for rutting and moisture damage of the different mixtures. This test was conducted following the standard procedure AASHTO T324-04 (AASHTO, 2008a). The test setup in shown in Figure 4-8.

Figure 4-8 Hamburg Wheel Rutting Test

The Superpave Gyratory Compactor was used to compact the cylinders, and then the samples were cut to the required height, to ensure similar air voids content. This equipment uses two samples of the same mix with 6.32cm height and 15.24cm diameter submerged in a water bath at 50°C and placed in parallel under the repeated pass of a steel wheel. The machine records the average impression made by the wheel on the asphalt until 20,000 passes (10,000 cycles) or 12.5mm whatever happens first. The air voids of the samples should be 7%±2%

Figure 4-9 shows a typical rut depth vs number of passes based on the HWRD. This figure shows the three features measured: the creep slope, the stripping slope and the Stripping Inflection Point (SIP). The creep slope is the slope for the first steady state portion of the curve, and it defines the rate of permanent deformation at constant load. Stripping is the phenomenon of loss of material due to the action of water, in other words, when the aggregates detach from the mix surface. When stripping occurs, the slope becomes steeper. The SIP marks the transition from one state to the other and is defined as the point where the two slopes intercepts, or the number of passes when stripping starts.

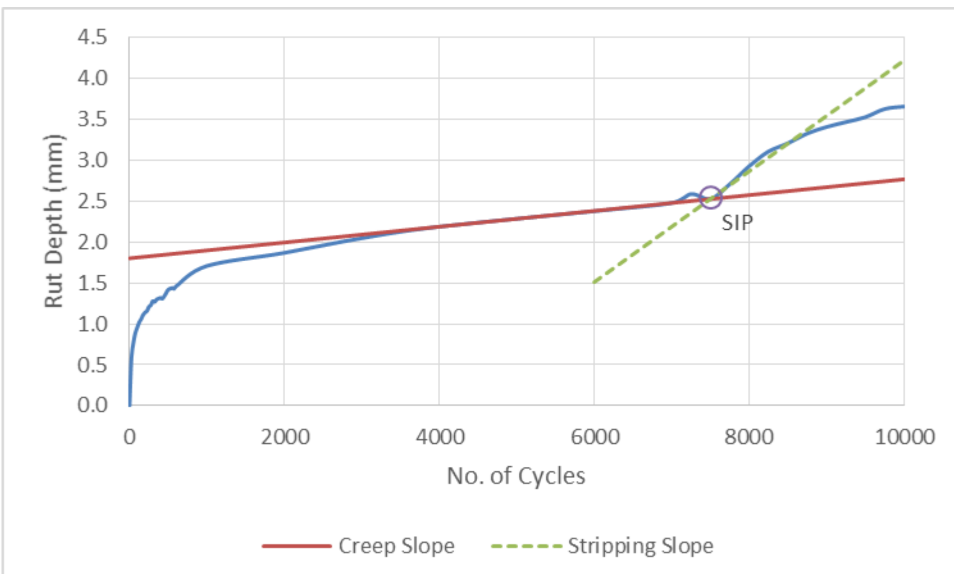

Figure 4-9 HWRD Rut Depth vs Number of Passes

The two steady state portions are visually detected and the slope can be determined given any two points in those lines. Two tests were conducted per mixture.

Rut Depth

The maximum observed rutting after 20,000 passes of the wheel provides an indication of the rutting potential of the mixture, and it is shown in Table 4-11 and Figure 4-10. In general, it can be expected that the use of softer binders would make the mix produce a higher rut, and the addition of RAP would have the opposite effect. The results do not show any generalized trend with the increase in the RAP content. The highest rutting was noticed for the 20% RAP PG 58-34, and the minimum for the 40% RAP PG 52-40. In general all of the rutting results are below 7mm which is an acceptable value according to the Ontario Pavement Evaluation Standards (Chong, Phang, & Wrong, 1989).

Table 4-11 Rut Depth Results

Mix Type	Rut Depth (mm)		Ranking
	Average	StDev	
0-58-28	3.2	0.2	2
20-58-28	4.1	1.1	8
40-58-28	3.5	0.9	4
0-58-34	4.1	1.1	9
20-58-34	6.7	0.4	12
40-58-34	3.8	0.8	7
0-52-34	5.8	1.0	10
20-52-34	6.0	0.5	11
40-52-34	3.6	0.6	5
0-52-40	3.7	0.1	6
20-52-40	3.4	0.2	3
40-52-40	2.6	0.3	1

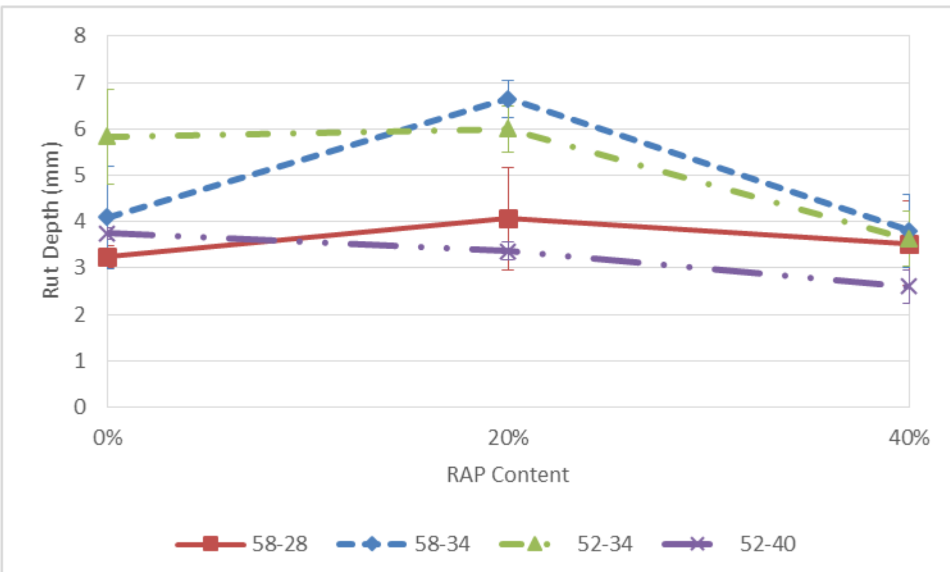

Figure 4-10 Average Rut Depth

The ANOVA two-factor with replication for the rut depth is shown in Table 4-12. From this table, it can be seen that the source of variation in the results is within the different RAP contents and the different asphalt PG, but the interaction is not having a significant effect. The sums of squares results suggest that the effect of the asphalt PG is higher.

Table 4-12 ANOVA Two-Factor with Replication for Rut Depth

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
RAP Content	10.6	2	5.3	10.8	<0.01	3.9
Asphalt PG	15.6	3	5.2	10.6	<0.01	3.5
Interaction	8.3	6	1.4	2.8	0.06	3.0
Within	5.9	12	0.5			
Total	40.4	23				

The ANOVA single factor for rut depth is shown in Table 4-13. In most cases, the use of softer binders or the addition of RAP did not have a significant difference in the creation of ruts on the mixes.

Table 4-13 Results ANOVA Single Factor Rut Depth

Group	$F_{calculated}$	***P-value***	$F_{critical}$	**Statistically Different**	**Significant at α=0.05**
0% RAP	4.4	0.09	6.6	No	
20% RAP	11.7	0.02	6.6	Yes	Yes
40% RAP	1.2	0.41	6.6	No	
PG 58-28	0.5	0.65	9.6	No	
PG 58-34	7.5	0.07	9.6	No	
PG 52-34	6.4	0.08	9.6	No	
PG 52-40	11.8	0.04	9.6	Yes	Yes

The rut depth is affected by the asphalt PG for the 20% RAP mixes, but not for the 40% RAP mixes. Also the content of RAP impacted the rut depth for the mixes with PG 52-40.

Creep Slope

The creep slope is another indication of the rutting susceptibility of the mixture. The higher the creep slope, the more susceptible the mix is to rutting. It could be expected that the addition of RAP would decrease the creep slope, and that the use of softer binders would increase it.

The results in Table 4-14 are consistent with the rut depth behavior, and here it is possible to notice that the 40% RAP mixtures seems to have less rutting potential, and interestingly the 20% RAP mixtures have a higher rutting potential compared to the control mixtures. However, the variability in this parameter is considerable given the small order of magnitude of the same.

Table 4-14 Creep Slope Results

Mix Type	Creep Slope		Ranking
	Average	StDev	
0-58-28	6.8E-5	5.4E-6	4
20-58-28	1.1E-4	1.4E-5	9
40-58-28	2.9E-5	3.8E-5	1
0-58-34	1.0E-4	4.1E-5	8
20-58-34	1.3E-4	9.8E-5	10
40-58-34	8.2E-5	7.5E-5	7
0-52-34	1.8E-4	2.6E-5	11
20-52-34	2.4E-4	3.0E-5	12
40-52-34	6.0E-5	5.7E-5	2
0-52-40	6.8E-5	4.0E-5	5
20-52-40	7.2E-5	3.3E-5	6
40-52-40	6.3E-5	1.9E-5	3

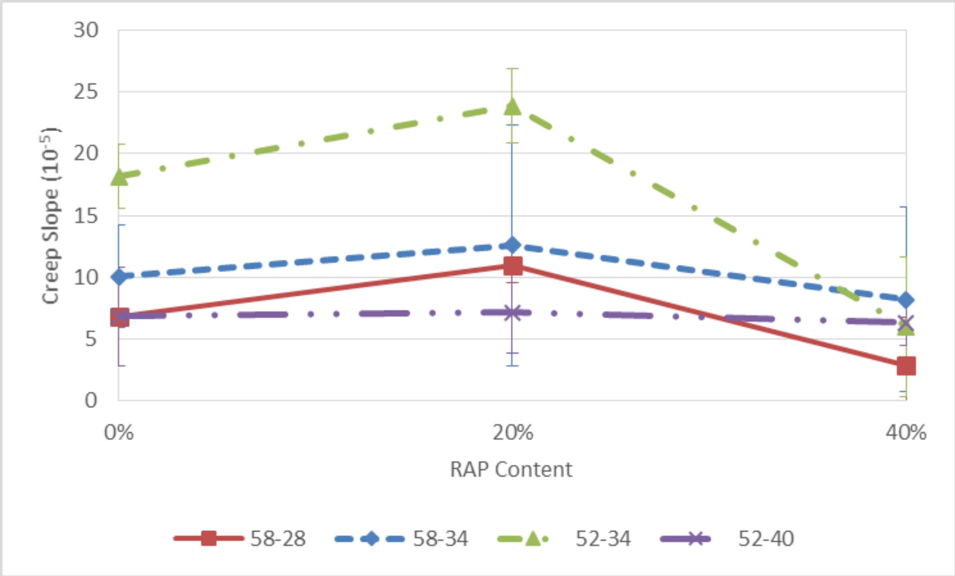

Figure 4-11 Creep Slope Results

In this case, the higher slope among all the mixtures was obtained for the 20% RAP PG 52-34 and the smaller for the 40% RAP PG 58-28 as seen in Figure 4-11.

Similarly to the rut depth, it is observed in Table 4-15 that the RAP content is showing a significant effect, as well as the change in the asphalt PG. The interaction between both factors was not found significant, so the effect of the addition of RAP is acting independently to the asphalt PG on the rutting potential. According to the sum of squares results, the asphalt PG would have a higher influence on the variability of the results.

Table 4-15 ANOVA Two Factor with Replication for Creep Slope

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
RAP Content	2.5E-8	2	1.2E-8	5.6	0.02	3.9
Asphalt PG	3.4E-8	3	1.1E-8	5.1	0.02	3.5
Interaction	1.7E-8	6	2.9E-9	1.3	0.32	3.0
Within	2.6E-8	12	2.2E-9			
Total	1.0E-07	23				

The single factor ANOVA in Table 4-16 shows that in general the creep slope is not significantly affected by the addition of RAP or the change in the PG binder, except for the PG 52-34, where the RAP content seems to impact the creep slope result.

Table 4-16 Results ANOVA Single Factor Creep Slope

Group	$F_{calculated}$	***P-value***	$F_{critical}$	**Statistically Different?**	**Significant at α=0.05**
0% RAP	5.7	0.06	6.6	No	
20% RAP	3.5	0.13	6.6	No	
40% RAP	0.4	0.78	6.6	No	
PG 58-28	5.8	0.09	9.6	No	
PG 58-34	0.2	0.85	9.6	No	
PG 52-34	10.5	0.04	9.6	Yes	Yes
PG 52-40	0.0	0.97	9.6	No	

Stripping Slope and Stripping Inflection Point

Stripping phenomenon was not observed for all of the mixtures. In fact in some cases it was reported only for one of the replicates. The 40% RAP PG 58-34 mixture seems susceptible to moisture damage according to the Hamburg Wheel Test. The point where the stripping begins was detected in all cases above 6,000 cycles.

In Table 4-17, the blank cells indicate no stripping. In can be observed that for most of the mixtures tested no signs of striping were detected during the test execution at a number of passes lower than 20000. Given that the stripping slope was observed for only one of the mixtures test for the 0% RAP PG 58-34, 40% RAP PG 52-34 and 0% RAP PG 52-40, this observations are not conclusive on the susceptibility of the mix to the stripping phenomenon. However, the 40% RAP PG 58-34 seems to be prone to striping damage.

Table 4-17 Stripping Results from HWRD

Mix Type	Test 1		Test 2	
	Stripping Slope	SIP (cycles)	Stripping Slope	SIP (cycles)
0-58-28				
20-58-28				
40-58-28				
0-58-34			4.7E-4	6643
20-58-34				
40-58-34	3.4E-4	8686	5.0E-4	6822
0-52-34				
20-52-34				
40-52-34	5.9E-4	6421		
0-52-40	6.8E-4	7497		
20-52-40				
40-52-40				

4.3.2 Flow Number

The flow number (FN) is a destructive test that measures the point (number of axial load cycles) where the rate of permanent deformation is a minimum, which is the point where the strain starts increasing at a high rate (FHWA, 2013). This test was conducted on the same samples from dynamic modulus with the Asphalt Mixture Performance Tester (AMPT) by DBA Engineering Ltd. The test temperature is 52°C and the test standard followed is AASHTO TP 79 (AASHTO, 2012) . The criteria used for the evaluation is provided in the NCHRP Project 9-33 (Advanced Asphalt Technologies, 2011) and corresponds to the minimum value for HMA for the traffic category in question (FN>53).

Table 4-18 Flow Number AMPT

Mix Type	Flow Number (Cycles)		Ranking
	Average	StDev	
0-58-28	171.3	21.2	5
40-58-28	397.3	72.3	4
20-58-34	428.7	22.3	3
0-52-34	56.7	3.8	6
20-52-40	681.0	180.4	2
40-52-40	915.3	241.9	1

The test was conducted for six of the twelve mixtures, and the results are shown in Table 4-18 and Figure 4-12. It could be assumed that increasing the RAP content would increase the flow number while using a softer binder might decrease the number of cycles before flow. The results for flow number are consistent with the results from the Hamburg wheel rutting device. The lower rut depth was obtained for the 40% RAP PG 52-40 mix which is where the highest flow number occurs while the lower flow number occurs for the control mix or 0% RAP PG 52-34 which has a high rut depth. From Figure 4-12 it seems that the addition of RAP resulted in an increase in Flow Number. The virgin mixtures exhibited the smaller results. This parameter is related to the rutting resistance of the pavement, when the flow number is low, the mixture is more susceptible to rutting. The flow numbers for the 0% RAP PG 58-28 and the 40% RAP PG 58-28 are very different despite both of them having very similar rut depths. Consequently, the flow number could be an appropriate test to detect the presence of RAP in a mixture. The results from t-test are shown in Table 4-19 and Table 4-20. It can be seen that most of the results are statistically different, and that the P(T<=t) is consistent with those findings.

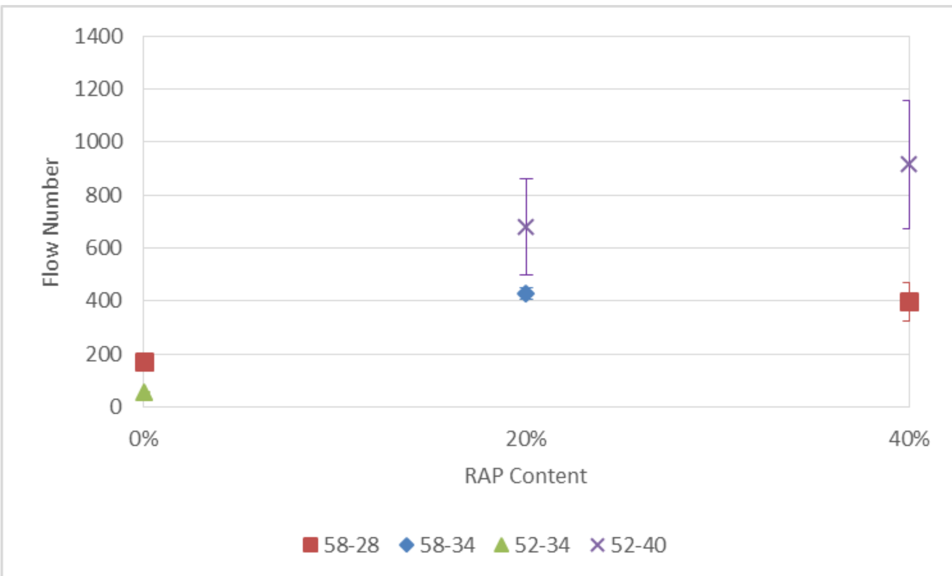

Figure 4-12 Flow Number Test Results

Table 4-19 Flow Number $t_{calculated}$

Mix Type	0-58-28	40-58-28	0-52-34	20-58-34	20-52-40	40-52-40
0-58-28		-6.1	9.0	-15.6	-5.8	-6.3
40-58-28			8.2	-0.7	-2.5	-3.6
0-52-34				-28.5	-6.0	-6.1
20-58-34					-2.4	-3.5
20-52-40						-1.3
40-52-40						

Notes: t Critical two-tail = 2.78 / t Critical one-tail = 2.13

Table 4-20 Flow number P(T<=t) two-tail

Mix Type	0-58-28	40-58-28	0-52-34	20-58-34	20-52-40	40-52-40
0-58-28		<0.01	<0.01	<0.01	<0.01	<0.01
40-58-28			<0.01	0.51	0.06	0.02
0-52-34				<0.01	<0.01	<0.01
20-58-34					0.07	0.03
20-52-40						0.25
40-52-40						

From Table 4-19, the following can be observed:

- 0% RAP PG 58-28 lower than 20% RAP PG 58-34 (Single Bump)
- 0% RAP PG 58-28 lower than 40% RAP PG 58-28(No Bump)
- 0% RAP PG 52-34 lower than 20% RAP PG 52-40 (Single Bump)
- 0% RAP PG 52-34 lower than to 40% RAP PG 52-40 (Single Bump)
- 20% RAP PG 58-34 is not statistically different to 20% RAP PG 52-40(Double Bump)

That means that the rutting potential in terms of flow number is higher for the control mixtures and that the use of a softer binder might not have a negative effect in the rutting behavior for RAP mixtures.

4.4 Dynamic Modulus

4.4.1 Testing with MTS810

Given the viscoelastic nature of HMA, the performance of asphalt mixtures depends on the frequency and the temperature. In order to measure the response of the mixtures to different loading rates and weather condition the dynamic modulus test was conducted. For this purpose the standard procedure in AASHTO TP 62 (AASHTO, 2007) was used. For this test a 100mm diameter and 150mm height specimen was cored from the SGC cylinder. The ends were cut and the ends grinded to assure a leveled surface. Steel pins were glued equally spaced on the perimeter of the sample. The vertical distance between the pins was 100mm. Three extensometers Epsilon Model 3910 with 100mm gauge length were attached magnetically to the pins. The range of the transducer was ±1mm, with 0.0001mm resolution. The test set up is shown in Figure 4-13. Three replicates were tested per mixture. A Material Testing System (MTS) frame was used, in conjunction with an environmental chamber capable of achieving and maintaining the test temperatures. MTS Model 793.67 System Software was used for creating and running the test routine (MTS, 2003). Five test temperatures were tested: -10, 4, 21, 37 and 54°C. For each temperature six frequencies were applied: 25, 10, 5, 1, 0.5 and 0.1 Hz.

Figure 4-13 Dynamic Modulus Test

Low frequencies and high temperatures are related to slow moving traffic, which is the condition for rutting. At moderate temperatures the mixtures are evaluated for permanent deformation and fatigue cracking, while the low temperatures are related to thermal cracking. With the information collected, the dynamic modulus (E*) and phase angle are then calculated for each temperature and frequency. Even when the dynamic modulus is not a fatigue test, the results from the stiffness at intermediate temperatures and frequency corresponding to the standard vehicle operation speed, can be an indication of the susceptibility to fatigue of the material. For higher stiffness values and lower phase angles, the material would be more prone to fatigue cracking.

Complex Modulus E*

The complex modulus (E*) describes the relationship between stress and strain of the material. When the complex modulus is higher, the material is stiffer. It is expected that the use of softer binders would decrease the stiffness of the mix, while the addition of RAP would make the mix stiffer in terms of complex modulus. Each temperature and frequency yield a different stress vs strain curve. In order to properly present the information, isotherms are constructed. An isotherm describes the dynamic modulus at the different frequencies for only one temperature. When all the isotherms are available, the master curves can be built. A master curve characterize the response of the material at a given reference temperature. The frequency shown in the graph is known as the reduced frequency. To convert this reduced frequency to the real frequency for a given temperature, a shifting equation is required. There are several methods available for shifting the isotherms and fitting them to a master curve through mathematical models (Booshehrian, Mogawer, & Bonaquist, 2012). In this research, the software RHEA™ - Rheology Analysis by Abatech Inc. was used (Abatech Inc., 2011). Figure 4-14 shows the master curves grouped by asphalt PG. For the PG 58-28 the curves for 0% RAP and 40% are very similar, almost overlapping, while the stiffness for the 20% RAP was higher for all the frequencies. For the PG 58-34, the 0% RAP was less stiff than the 40% RAP. However, the 20% RAP was slightly higher than the 40% for most of the frequencies. For the PG 52-34, the 0% RAP was less stiff while the 20% was the stiffest for the slower reduced frequencies (<1E-4Hz) or low temperatures, and for the remaining specimens, the 40% RAP seems to be the stiffest however the curves for 20% and 40% are very close. For the PG 52-40 the difference between RAP contents is clearly defined, with the 20% RAP being the stiffest. In summary it is possible to observe that the gap between the control mixtures and the RAP mixtures is more marked when the asphalt PG is softer.

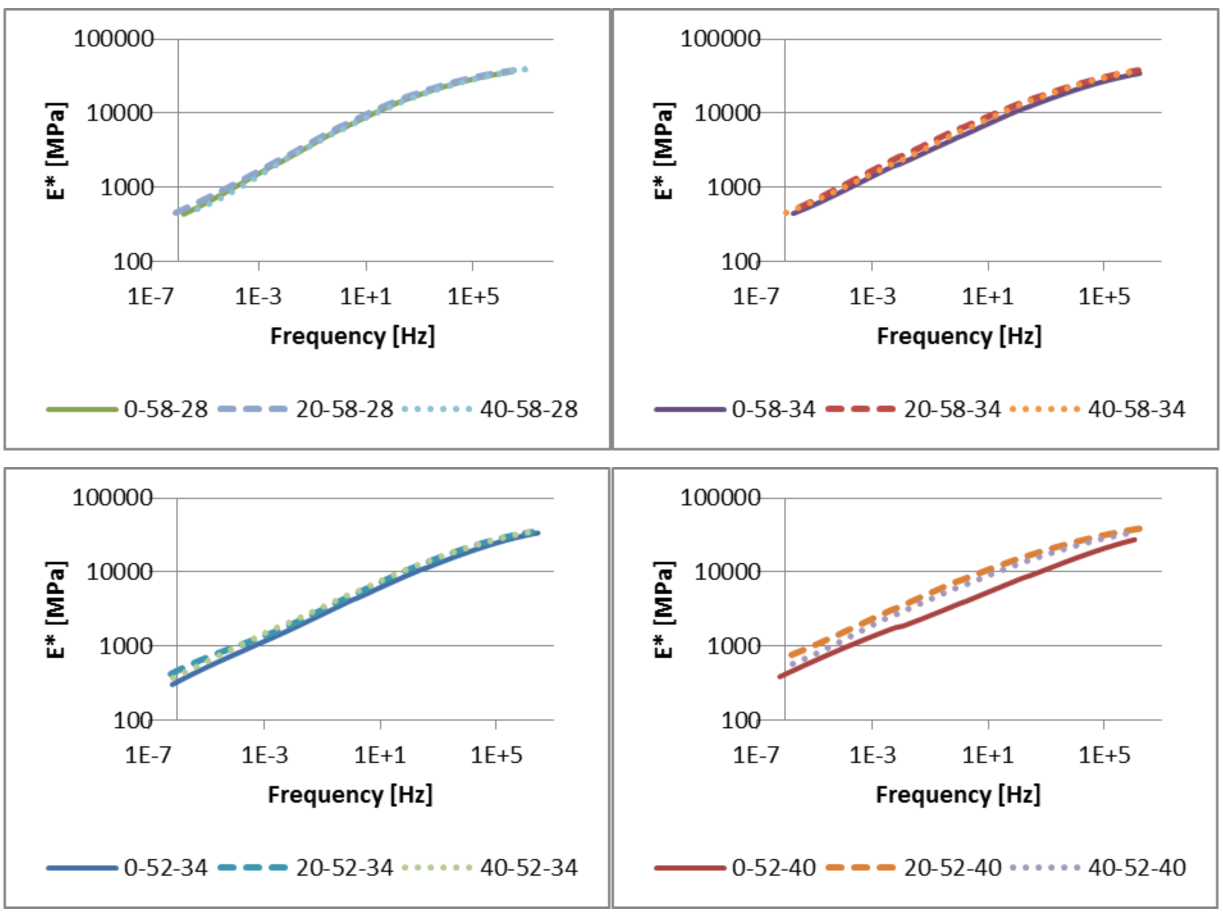

Figure 4-14 Master Curves by Asphalt PG

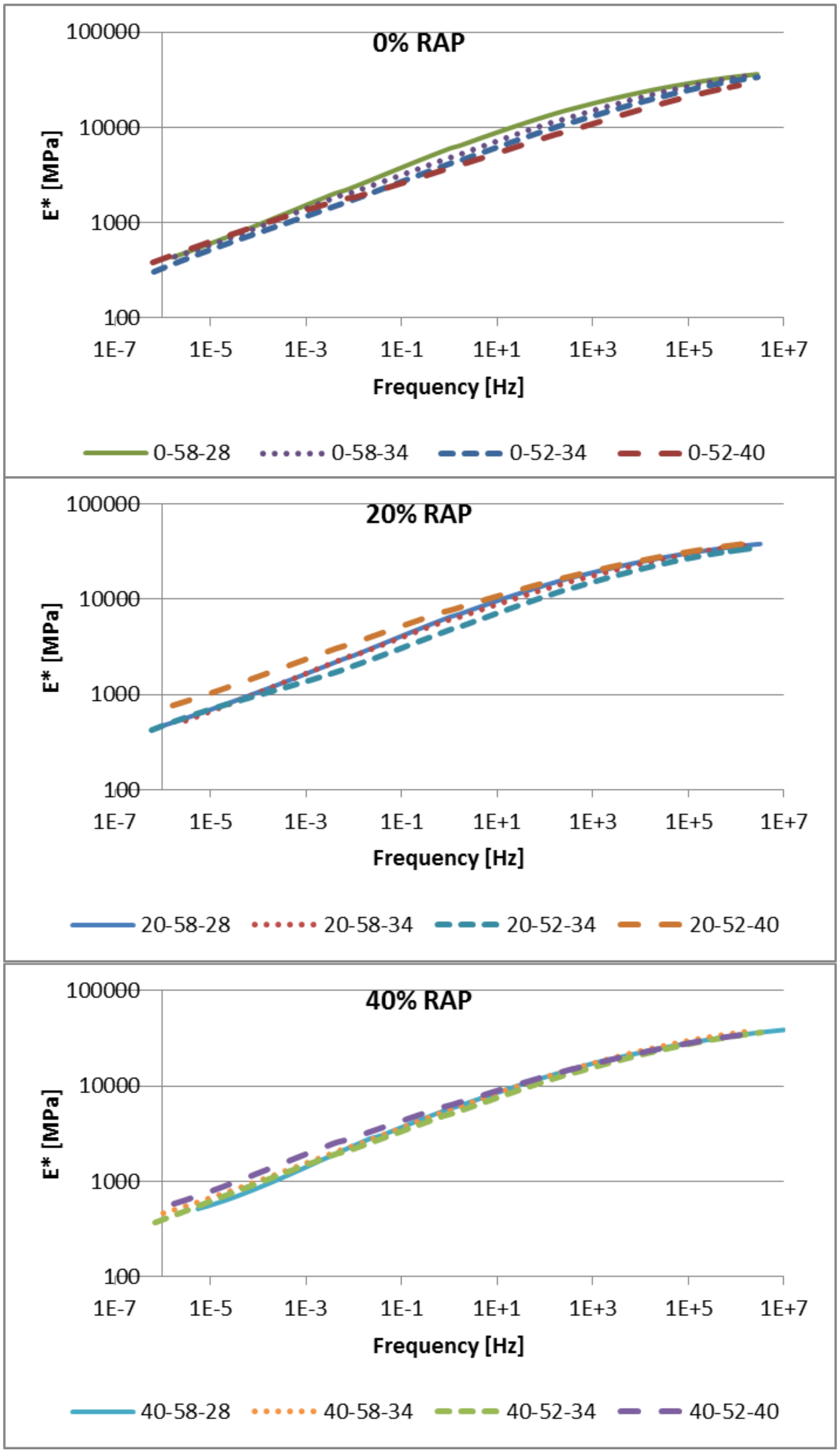

Figure 4-15 Master Curves by RAP Content

The comparison of the stiffness for the different PG binders is easily observed when the curves are grouped by RAP content as shown in Figure 4-15. Given that the gradation is the same for all the mixtures with the same RAP content, the stiffness of the mixtures varies basically only depending on the stiffness of the binder. In the original condition, without RAP, the stiffness of the PG 52-40 is higher for slow frequencies (<1E-2Hz) or low temperatures. After this point, the PG 52-40 is the less stiff followed by the PG 52-34, then the PG 58-34 and last the PG 58-28 is shown to be the stiffest. For the 20% RAP, the PG 52-34 mixes is the least stiff, while the PG 58-28 and PG 58-34 have a similar behavior, with the PG 52-40 observed as the stiffest.

For 40% RAP, the different curves are comparable between each other. However the PG 52-40 seems to be again the stiffest until faster frequencies (>1E2Hz) or higher temperatures are reached when the curves seem to start converging. In order to study the susceptibility to fatigue, the data for 21°C and 10 Hz was extracted, as seen in Table 4-21. From this table, it can be observed that the least stiff mix is the 0% RAP PG 52-40. A graphical representation of the results is shown in Figure 4-16. It is observed that the addition of RAP has a marked negative effect in the fatigue resistance of the mixes with PG 52-40.

To verify the statistical significance of the test results from the triplicated specimens, an ANOVA two-factor with replication was conducted on the original data for the complex modulus at 21°C and 10Hz.

Table 4-21 Complex Modulus MTS at 21°C & 10Hz

Mix Type	Complex Modulus (MPa)		Ranking
	Average	StDev	
0-58-28	8850.9	503.0	9
20-58-28	9531.4	96.2	11
40-58-28	8362.2	1701.2	7
0-58-34	7088.1	1259.1	3
20-58-34	8738.4	1131.2	8
40-58-34	8169.0	65.0	6
0-52-34	6132.8	309.4	2
20-52-34	7131.0	622.6	4
40-52-34	7490.3	554.0	5
0-52-40	5222.3	382.2	1
20-52-40	10561.5	1747.9	12
40-52-40	8881.4	972.9	10

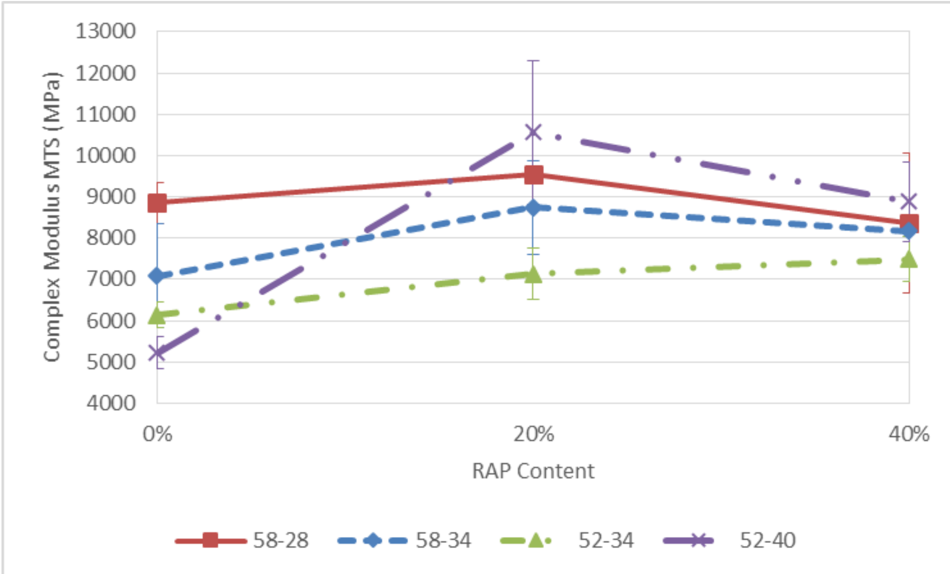

Figure 4-16 Complex Modulus MTS at 21°C & 10Hz

Table 4-22 ANOVA Two-Factor with Replication MTS E*

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
RAP Content	28989702	2	14494851	15.9	<0.01	3.4
Asphalt PG	18503500	3	6167833	6.8	<0.01	3.0
Interaction	24982795	6	4163799	4.6	<0.01	2.5
Within	21926369	24	913598.7			
Total	94402366	35				

Table 4-23 ANOVA Single Factor for E* at 21°C & 10Hz

Group	$F_{calculated}$	***P-value***	$F_{critical}$	**Statistically Different**	**Significant at α=0.05**
0% RAP	13.9	<0.01	4.1	Yes	Yes
20% RAP	5.3	0.03	4.1	Yes	Yes
40% RAP	1.0	0.46	4.1	No	
PG 58-28	1.0	0.43	5.1	No	
PG 58-34	2.2	0.19	5.1	No	
PG 52-34	5.6	0.04	5.1	Yes	Yes
PG 52-40	16.2	<0.01	5.1	Yes	Yes

The results presented in Table 4-22, show that the variation derives from the RAP content and also from the different PG. The interaction between the two variables also impacts the results. In the case of the complex modulus, the RAP content is the factor with a more significant effect on the variability of the results according to the sum of squares. As shown in Table 4-23, the ANOVA single factor did not detect significant differences for the 40% RAP mixtures. Also the PG 58-28 and the PG 58-34 were not found to be significantly affected by the addition of RAP.

The complex modulus of the 0% RAP and the 20% RAP mixes is impacted by the change in asphalt PG. The effect of the change of asphalt PG is less with the addition of RAP. Also, the addition of RAP affects the complex modulus of the PG 52-34 and PG 52-40. The results from the estimated complex modulus given by the master curves obtained with RHEA were also assessed. The ANOVA two-factor without replication on the complex modulus at the reference temperature 20°C and 10Hz indicated that in this case, the null hypothesis is accepted and the difference is not significant as shown in Table 4-24. That means that the susceptibility to fatigue would not be significantly different regardless of the different PG and RAP content, then the expected behavior in the field would be comparable for the twelve mixtures.

Table 4-24 ANOVA Two-Factor Without Replication RHEA Results

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	$F_{calculated}$	*P-value*	$F_{critical}$
RAP Content	10213677.5	2	5106838.7	3.98	0.08	5.14
Asphalt PG	6673105.6	3	2224368.5	1.73	0.26	4.76
Error	7698097.6	6	1283016.3			
Total	24584880.7	11				

Phase Angle

The phase angle characterizes the viscoelastic behavior of the mix. A higher angle indicates a lower elastic component, while a smaller angle indicates a lower viscous component of the complex modulus.

Table 4-25 Phase angle MTS at 21°C & 10Hz

Mix Type	Phase Angle (°)		Ranking
	Average	StDev	
0-58-28	19.0	1.3	5
20-58-28	18.3	0.7	9
40-58-28	18.6	0.9	6
0-58-34	19.2	1.3	2
20-58-34	18.4	0.4	8
40-58-34	18.6	1.0	7
0-52-34	19.7	1.5	1
20-52-34	19.2	0.2	3
40-52-34	19.1	0.7	4
0-52-40	17.4	0.4	10
20-52-40	15.1	1.2	12
40-52-40	15.8	0.1	11

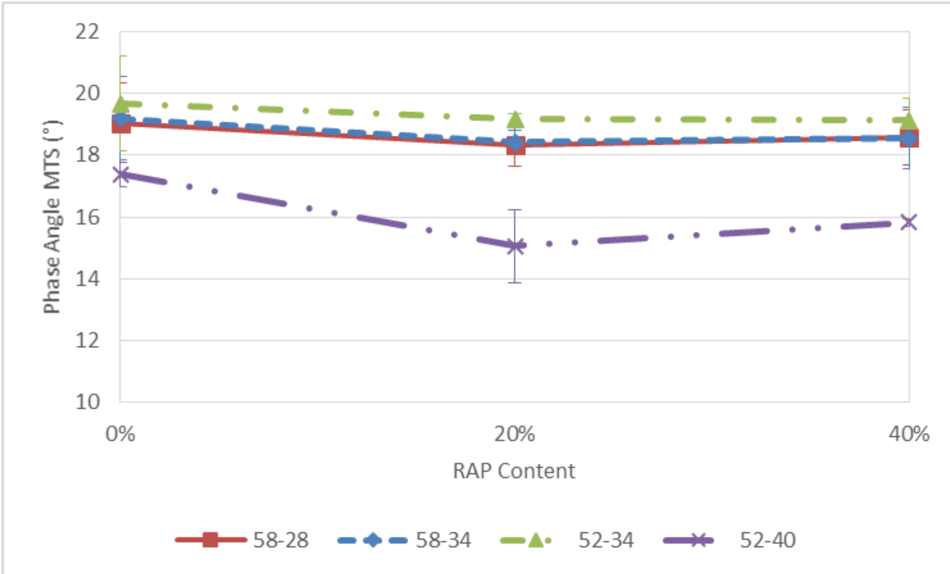

Figure 4-17 Phase Angle MTS at 21°C & 10Hz

Table 4-26 ANOVA Two-Factor with Replication MTS Phase Angle

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	*$F_{calculated}$*	*P-value*	*$F_{critical}$*
RAP Content	7.6	2	3.8	4.4	0.02	3.4
Asphalt PG	55.5	3	18.5	21.6	<0.01	3.0
Interaction	3.2	6	0.5	0.6	0.71	2.5
Within	20.6	24	0.9			
Total	86.86	35				

Table 4-27 ANOVA Single Factor for Phase Angle at 21°C & 10Hz

Group	***$F_{calculated}$***	***P-value***	***$F_{critical}$***	**Statistically Different**	**Significant at α=0.05**
0% RAP	2.0	0.19	4.1	No	
20% RAP	19.5	<0.01	4.1	Yes	Yes
40% RAP	11.6	<0.01	4.1	Yes	Yes
PG 58-28	0.4	0.67	5.1	No	
PG 58-34	0.5	0.61	5.1	No	
PG 52-34	0.3	0.77	5.1	No	
PG 52-40	8.1	0.02	5.1	Yes	Yes

It would be expected that when RAP is added, the phase angle decreases, given the loss of the viscous properties of the aged binder present in RAP. The results for the phase angle are shown Table 4-25 and in Figure 4-17. It can be noticed that the higher values were obtained for the virgin mixtures. From the ANOVA two factor with replication shown in Table 4-26 it can be observed that the interaction between the RAP content and the asphalt PG is not significant, and that the main effect in the phase angle is given by the PG of the virgin asphalt. From Table 4-27 it is noticed that the effect of adding RAP is not significant for all the mixtures, except for the PG 52-40. It can also be concluded that the phase angle of the mixes with PG 52-40 is significantly lower.

4.4.2 Testing with AMPT

Some samples were sent to DBA Engineering Ltd for dynamic modulus testing with the asphalt mixture performance test (AMPT). In this case, three temperatures (4, 20 and 35°C) and three frequencies (0.1, 1, 10 Hz) were tested. For 35°C, an additional frequency (0.01Hz) was included. Triplicates were tested from six of the twelve mixtures.

Complex Modulus E*

The resulting master curves obtained with RHEA are shown in Figure 4-18. As seen in Table 4-28, the less stiff mixture is the 0% RAP PG 52-34 which is consistent with the finding obtained with the MTS. However, the stiffer mix in this case was the 40% RAP PG 58-28.

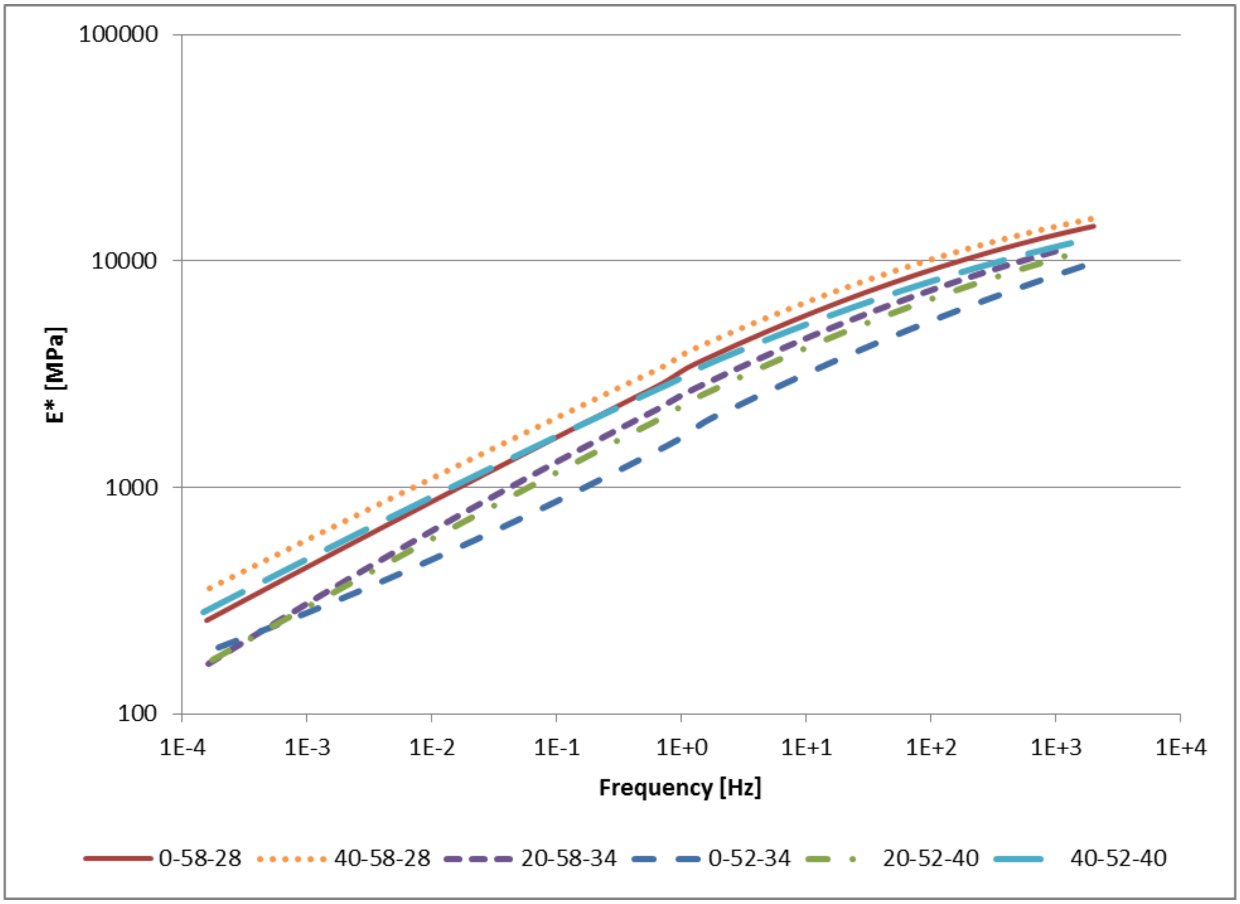

Figure 4-18 Master Curves AMPT

The 20% RAP mixtures had similar trend, but the result for the 0% RAP PG 58-28 is surprising as it seems stiffer than the 20% RAP mixtures and with comparable results to the 40% RAP PG 52-40. Figure 4-19 shows a graphical representation of the results.

Table 4-28 Complex Modulus AMPT at 20°C & 10Hz

Mix Type	Complex Modulus (MPa)		Ranking
	Average	StDev	
0-58-28	5806.0	132.4	5
40-58-28	6629.8	274.2	6
20-58-34	4582.7	361.2	3
0-52-34	3184.5	92.6	1
20-52-40	4187.0	82.4	2
40-52-40	5256.8	328.8	4

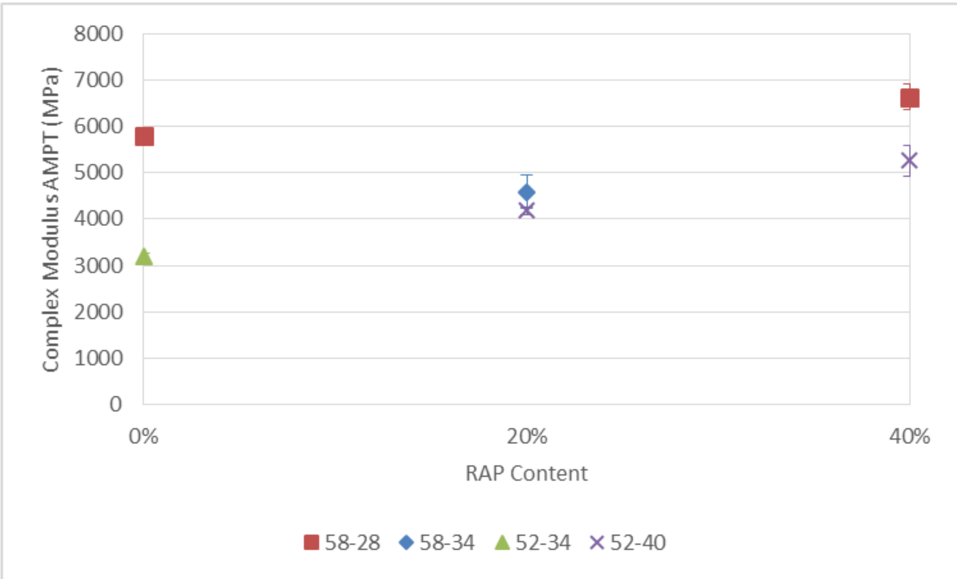

Figure 4-19 Complex Modulus AMPT at 20°C & 10 Hz

Table 4-29 Complex Modulus AMPT $t_{calculated}$

Mix Type	0-58-28	40-58-28	20-58-34	0-52-34	20-52-40	40-52-40
0-58-28		-4.7	5.5	28.1	18.0	2.7
40-58-28			7.8	20.6	14.8	5.6
20-58-34				6.5	1.9	-2.4
0-52-34					-14.0	-10.5
20-52-40						-5.5
40-52-40						

Notes: t Critical two-tail = 2.78 / t Critical one-tail = 2.13

Table 4-30 Complex Modulus AMPT P(T<=t) two-tail

Mix Type	0-58-28	40-58-28	20-58-34	0-52-34	20-52-40	40-52-40
0-58-28		0.01	0.01	<0.01	<0.01	0.06
40-58-28			<0.01	<0.01	<0.01	0.01
20-58-34				<0.01	0.14	0.08
0-52-34					<0.01	<0.01
20-52-40						0.01
40-52-40						

The statistical significance of the results was checked using a t-test. It can be seen in Table 4-29 and Table 4-30 that the estimated complex modulus with RHEA at 20°C and 10Hz is significantly different for the majority of the mixtures. From Table 4-29, the following can be observed:

- 0% RAP PG 58-28 is higher than 20% RAP PG 58-34 (Single Bump)
- 0% RAP PG 58-28 is lower than 40% RAP PG 58-28(No Bump)
- 0% RAP PG 52-34 is lower than 20% RAP PG 52-40 (Single Bump)
- 0% RAP PG 52-34 is lower than 40% RAP PG 52-40 (Single Bump)
- 20% RAP PG 58-34 is not statistically different to 20% RAP PG 52-40 (Double Bump)

The virgin mixes have a lower complex modulus which suggests that the RAP mixtures would be more prone to fatigue cracking; however, the combination of 20% RAP with PG 58-34 had better performance than the control mix with PG 58-28. Also, the change in binder grade does not always ensure that the mixture would perform significantly better, as is the case for the 20% RAP PG 58-34 compared to the 20% RAP PG 52-40.

Phase Angle

The results for the phase angle measured with AMPT are shown in Table 4-31 and Figure 4-20. It is observed that the 40% RAP mixes developed a smaller phase angle.

Table 4-31 Phase Angle AMPT at 20°C & 10Hz

Mix Type	Phase angle (°)		Ranking
	Average	StDev	
0-58-28	23.5	0.9	4
40-58-28	22.1	1.3	5
20-58-34	24.6	1.0	3
0-52-34	28.3	0.5	1
20-52-40	25.6	0.4	2
40-52-40	22.0	0.7	6

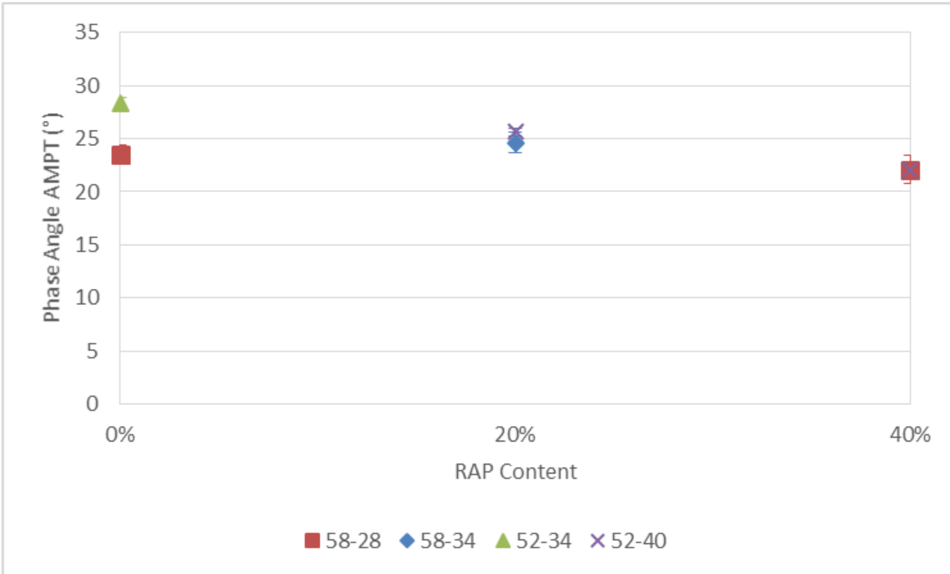

Figure 4-20 Phase Angle AMPT at 20°C & 10 Hz

Table 4-32 Phase Angle AMPT $t_{calculated}$

Mix Type	**0-58-28**	**40-58-28**	**20-58-34**	**0-52-34**	**20-52-40**	**40-52-40**
0-58-28		1.5	-1.4	-8.0	-3.7	2.2
40-58-28			-2.7	-7.6	-4.5	0.0
20-58-34				-5.7	-1.6	3.7
0-52-34					7.3	12.5
20-52-40						7.8
40-52-40						

Notes: t Critical two-tail = 2.78 / t Critical one-tail = 2.13

Table 4-33 Phase Angle AMPT P(T<=t) two-tail

Mix Type	**0-58-28**	**40-58-28**	**20-58-34**	**0-52-34**	**20-52-40**	**40-52-40**
0-58-28		0.20	0.22	<0.01	0.02	0.09
40-58-28			0.06	<0.01	0.01	0.97
20-58-34				<0.01	0.18	0.02
0-52-34					<0.01	<0.01
20-52-40						<0.01
40-52-40						

Table 4-32 and Table 4-33 shows the statistical analysis performed for the phase angle. The following can be observed:

- 0% RAP PG 58-28 is not statistically different than 20% RAP PG 58-34 (Single Bump)
- 0% RAP PG 58-28 is not statistically different than 40% RAP PG 58-28(No Bump)

- 0% RAP PG 52-34 is higher than 20% RAP PG 52-40 (Single Bump)
- 0% RAP PG 52-34 is higher than 40% RAP PG 52-40 (Single Bump)
- 20% RAP PG 58-34 is not statistically different to 20% RAP PG 52-40 (Double Bump)

4.4.3 Comparison AMPT and MTS

As shown in Table 4 34, the variability with the AMPT or with the MTS is less than 20% in all cases.

Table 4-34 Coefficient of Variation per Test System

Mix Type	Complex Modulus		Phase angle	
	MTS	AMPT	MTS	AMPT
0-58-28	5.7%	2.3%	6.8%	3.9%
20-58-28	1.0%		3.8%	
40-58-28	20.3%	4.1%	4.7%	6.0%
0-58-34	17.8%		7.0%	
20-58-34	12.9%	7.9%	2.0%	4.1%
40-58-34	0.8%		5.3%	
0-52-34	5.0%	2.9%	7.8%	1.8%
20-52-34	8.7%		1.0%	
40-52-34	7.4%		3.7%	
0-52-40	7.3%		2.2%	
20-52-40	16.5%	2.0%	7.9%	1.5%
40-52-40	11.0%	6.3%	0.8%	3.2%

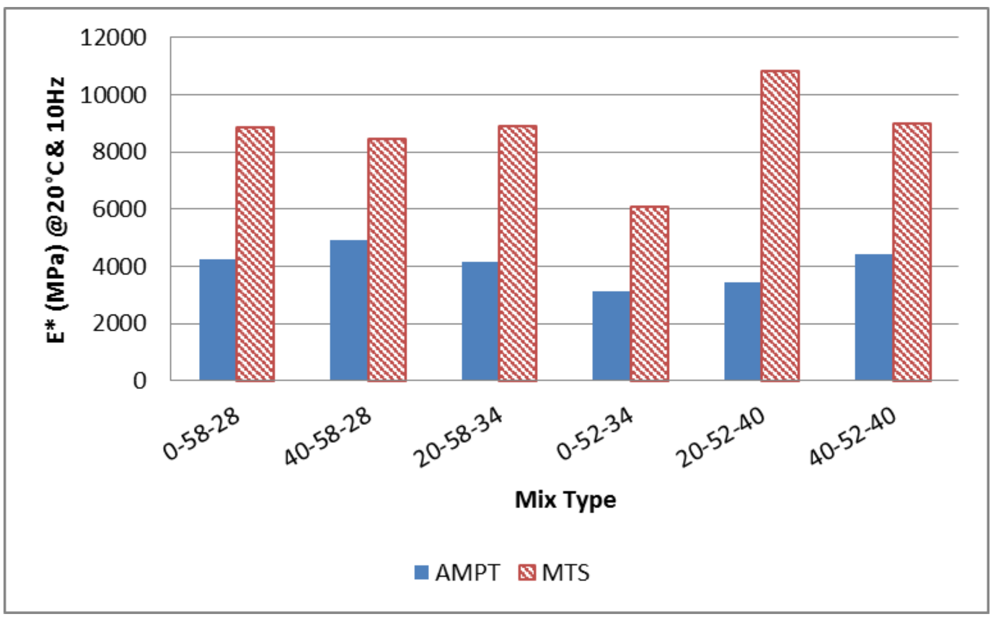

Figure 4-21 Comparison MTS and AMPT RHEA Results

The average coefficient of variation for the complex modulus of the different mixtures is less than 20%. The highest variability was noticed for the 40% RAP PG 58-28 which explains the differences in the results. That suggests that it is not easy obtaining homogeneous samples with this combination.

The complex modulus results obtained with the AMPT are in general lower than those measured with MTS, while the AMPT phase angle is higher than the MTS phase angle. The results at the reference temperature (20°C) and 10 Hz, obtained through RHEA are shown in Figure 4-21.

4.5 RAP Performance

As part of the experimentation, RAP samples were manufactured and tested. It is important to clarify that the gradation of the RAP is finer and does not meet the required SP12.5mm specification. For that reason achieving the 7% target air voids was not possible. The samples were compacted using the same parameters used for the designed mixtures, but the air voids contents were always less than 4%. Given that the viscosity-temperature charts are not available for the RAP binder, a compaction temperature of 140°C was used, which corresponds to the maximum temperature of the virgin binders studied. The results are shown in Table 4-35.

Table 4-35 Performance 100% RAP Mix

TSRST Failure Temperature (°C)	-20.9
TSRST Fracture Stress (MPa)	3.8
Rut Depth (mm)	1.3
Creep Slope	9.2E-5
Complex Modulus (MPa)*	19517.2

* at 21°C & 10Hz

The results obtained make sense given the characteristics of the RAP. It can be seen that the failure temperature is the warmest and the fracture stress is the highest compared to the results for the twelve mixtures. Also the rut depth is the lowest and the complex modulus the highest as expected considering the stiffness of the aged binder.

Additionally a 70% RAP mix was compacted; regardless of the Superpave mix design parameters, and its complex modulus tested for comparison purposes, with an average complex modulus of 10779 MPa.

4.6 Summary and Conclusions

A color map was drawn to identify the ranking of the different mixtures. In Table 4-36, the ranking one is shown in the color green which indicates the best performance for the given parameter, yellow is an acceptable performance and the color red or the highest number represent the lowest performance. The ranking for the parameters measured for half of the matrix is shown in Table 4-37. From the results shown in the tables, it is possible to see that some of the RAP mixtures ranked similar to or better than the virgin mixtures. It can also be concluded that the effect of the addition of RAP is not always having a negative impact on the performance of the asphalt mixtures, but the effect of the addition of RAP does not seem to be easily predicted.

Table 4-36 Ranking Full-Matrix Experiments

Mix Type	TSRST Failure Temp.	TSRST Fracture Stress	Rut Depth	Creep Slope	Dynamic Modulus MTS	Phase angle MTS	Average
0-58-28	9	11	2	4	9	5	7
20-58-28	11	7	8	9	11	9	9
40-58-28	10	10	4	1	7	6	6
0-58-34	2	4	9	8	3	2	5
20-58-34	4	8	12	10	8	8	8
40-58-34	8	2	7	7	6	7	6
0-52-34	3	12	10	11	2	1	7
20-52-34	7	3	11	12	4	3	7
40-52-34	12	9	5	2	5	4	6
0-52-40	1	5	6	5	1	10	5
20-52-40	6	6	3	6	12	12	8
40-52-40	5	1	1	3	10	11	5

Table 4-37 Ranking Half-Matrix Experiments

Mix Type	Fracture Energy at -18°C	Fracture Energy at -24°C	Dynamic Modulus AMPT	Phase Angle AMPT	Flow Number	Average
0-58-28	2	6	5	4	5	4
40-58-28	4	5	6	5	4	5
20-58-34	6	4	3	3	3	4
0-52-34	1	1	1	1	6	2
20-52-40	3	2	2	2	2	2
40-52-40	5	3	4	6	1	4

Regarding the predicted performance for thermal cracking, the TSRST failure temperature was warmer for the RAP mixtures when compared to the virgin mixtures. Overall, all the mixtures pass the -28°C threshold, however, none of them reached -34°C. The mixtures more affected by the addition of RAP were the mixtures with asphalt binder PG 52-40 where the increase in the failure temperature was more evident. The fracture stress results showed a higher variability. The fracture energy appears to be a reliable measure of the cracking susceptibility. One interesting finding in this parameter is that the reduction in fracture energy is controlled by the RAP addition, which means that when the low temperature decreases the RAP mixes showed a lower drop in the fracture energy.

For rutting, it was observed that the results from Hamburg Wheel and flow number were consistent, however the flow number gives an advanced indication of the rutting susceptibility of the mixtures, while for the HWRD a difference in rut depth from 3mm to 6mm is not considered substantial. The results confirm that permanent deformation is not a concern for RAP mixtures.

The dynamic modulus provided an indication of the fatigue susceptibility of the mixtures through the analysis of the relative stiffness of the different mixtures; however a direct measurement of this parameter would be valuable. The results indicated that in general the RAP mixtures are stiffer than the virgin mixtures; however, the mixtures with 20% RAP are either higher than or comparable to the 40% RAP mixtures in terms of stiffness.

From the ANOVA two-factor analyses, it was observed that the interaction between RAP content and PG binder was significant for most of the performance variables. However, it is possible to conclude that for the rutting and the phase angle the main effect is the PG binder; while for the TSRST and the complex modulus the most significant factor was the asphalt PG, and for the dynamic modulus the most significant factor in the variability of the results is the RAP content.

The parameter than seems to be consistently affected by the RAP addition, regardless of the asphalt PG, is the low temperature cracking. However, in general, the RAP content did not have a significant effect in the performance for the PG 58-28 mixtures.

One encouraging finding is that samples with 100% RAP material can be produced and those performance results could potentially be used to evaluate PG of the blended binder of the mixtures as described in the following chapter.

Chapter 5
Binder Characteristics Evaluation

5.1 Introduction

This chapter explains the research which was conducted to evaluate the blended binder characteristics and the continuous Performance Grade. From the different virgin binders and the varying RAP percentages, it is possible to use blending charts to estimate the critical temperature of the resulting blended binder. The results were compared with the extracted and recovered critical temperature. A procedure in this research was proposed to determine the critical temperatures from the dynamic modulus testing.

5.2 Hirsch Model

According to the literature review, various methods have been evaluated to determine or estimate the binder grade from mixes containing RAP. One method that appears to be promising involves using the Hirsch model to back-calculate the shear modulus |G*| of the binder from the measured dynamic modulus (Christensen Jr, Pellinen, & Bonaquist, 2003). The model was refined by Christensen to predict |E*| using the shear modulus and the volumetrics of the mix.

With the results from dynamic modulus and the volumetric properties of the mix, the Hirsch model can be applied to obtain the complex modulus G* of the binder without extraction. The suggested model is expressed below (Christensen Jr et al., 2003):

$$|E^*| = Pc \cdot \left[4{,}200{,}000 \cdot \left(1 - \frac{VMA}{100}\right) + 3 \cdot |G^*|_{binder} \left(\frac{VFA \cdot VMA}{10{,}000}\right)\right] + (1 - Pc) \cdot \left[\frac{1 - \frac{VMA}{100}}{4{,}200{,}000} + \frac{VMA}{3 \cdot VFA \cdot |G^*|_{binder}}\right]^{-1} \tag{5.1}$$

$$Pc = \frac{\left[20 + \frac{VFA \cdot 3 \cdot |G^*|_{binder}}{VMA}\right]^{0.58}}{650 + \left[\frac{VFA \cdot 3 \cdot |G^*|_{binder}}{VMA}\right]^{0.58}} \tag{5.2}$$

Where:

$|E^*|$: Mixture complex modulus (psi), $|G^*|_{binder}$: Binder complex modulus (psi)

VMA: Voids in the mineral aggregate (%), VFA: Voids filled with asphalt cement (%)

Pc: Aggregate contact factor

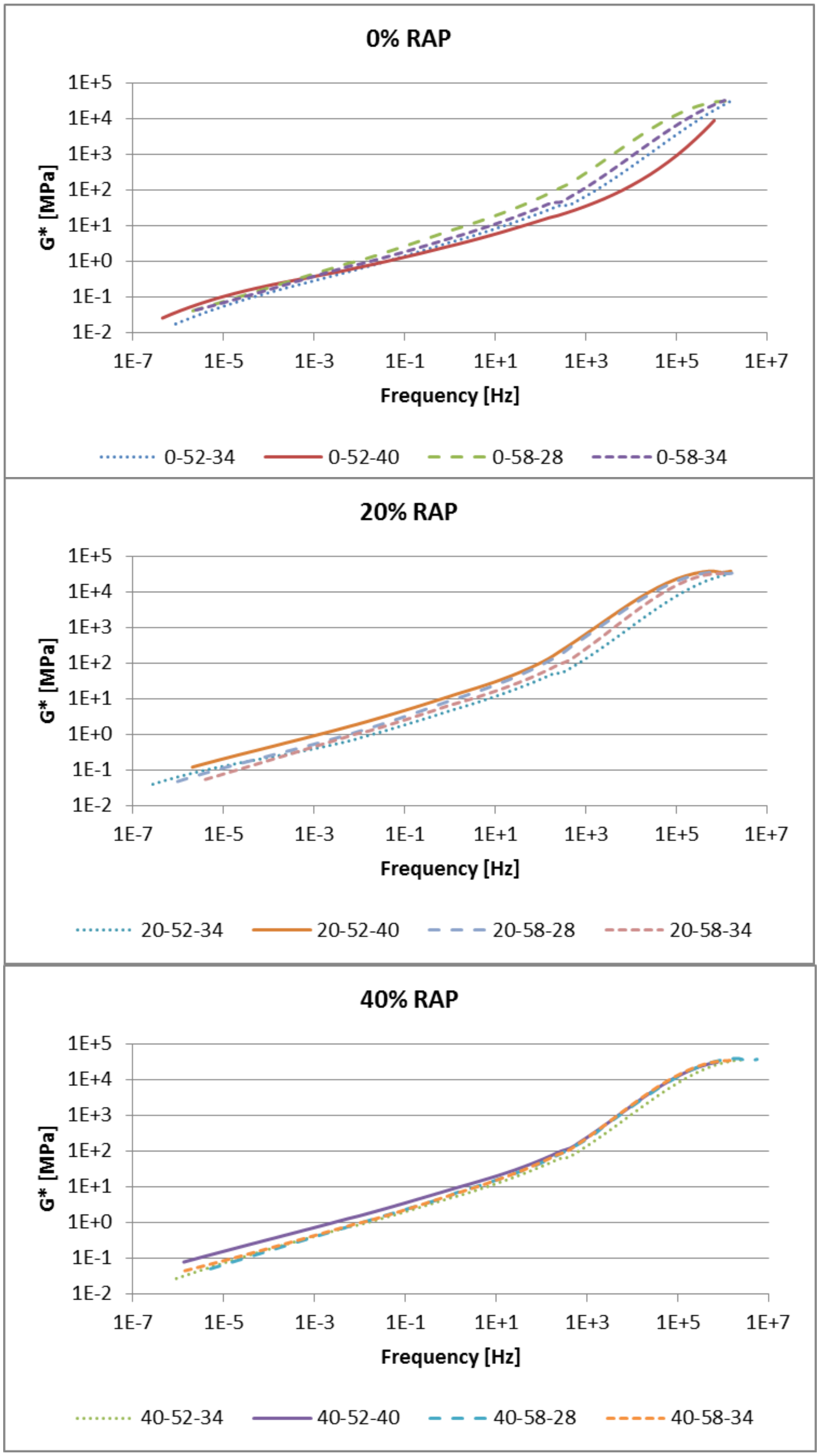

Figure 5-1 Binder Master Curves Hirsch Model

The data obtained with the dynamic modulus test using the MTS was used to obtain the G* from the measured E* for each of the twelve mixtures. Then those results were processed using the RHEA software and the corresponding master curves are shown in Figure 5-1. The results of the estimation of G* at 10Hz and 21°C are shown in Figure 5-2.

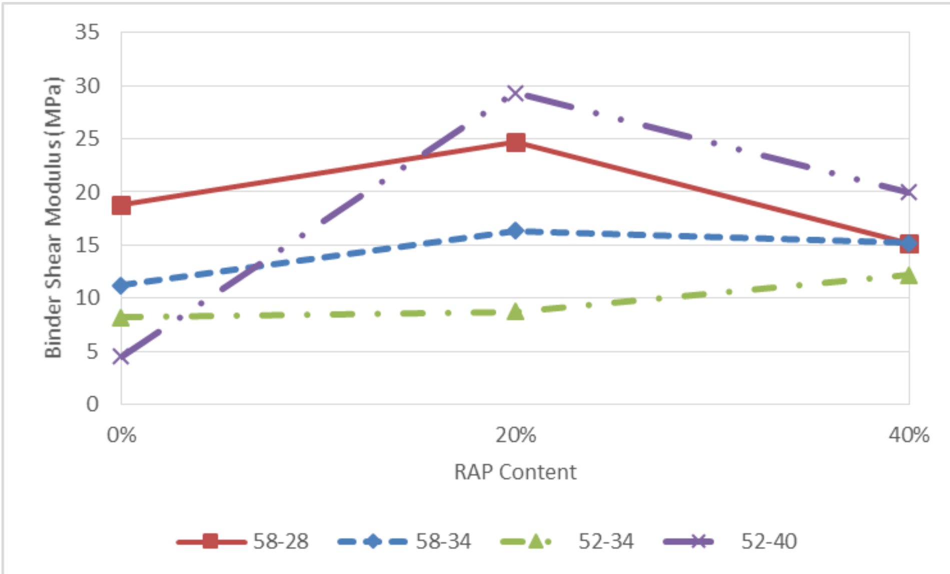

Figure 5-2 Binder Shear Modulus Obtained with Hirsch Model

In general, the results follow the same trend as the complex modulus E* for the mixtures. The stiffest binder was in the 20% RAP PG 52-40, while the least stiff is the 0% RAP PG 52-40, thus, mixtures containing the PG 52-40 appear to be more affected by the RAP addition.

5.3 Complex Modulus of Extracted Binder

From the samples used to evaluate the dynamic modulus and flow number with AMPT, the binder was extracted with trichloroethylene (TCE) following the AASHTO T 164 standard, method A (AASHTO, 2008b) and recovered using the Abson method (ASTM, 2009a) by DBA Engineering Ltd, in order to conduct the required testing using the DSR to obtain the corresponding master curves and compare the results obtained with the Hirsch Model.

The results obtained with a DSR Bohlin Instruments Ltd, were analyzed with RHEA to obtain the corresponding master curves shown in Figure 5-3.

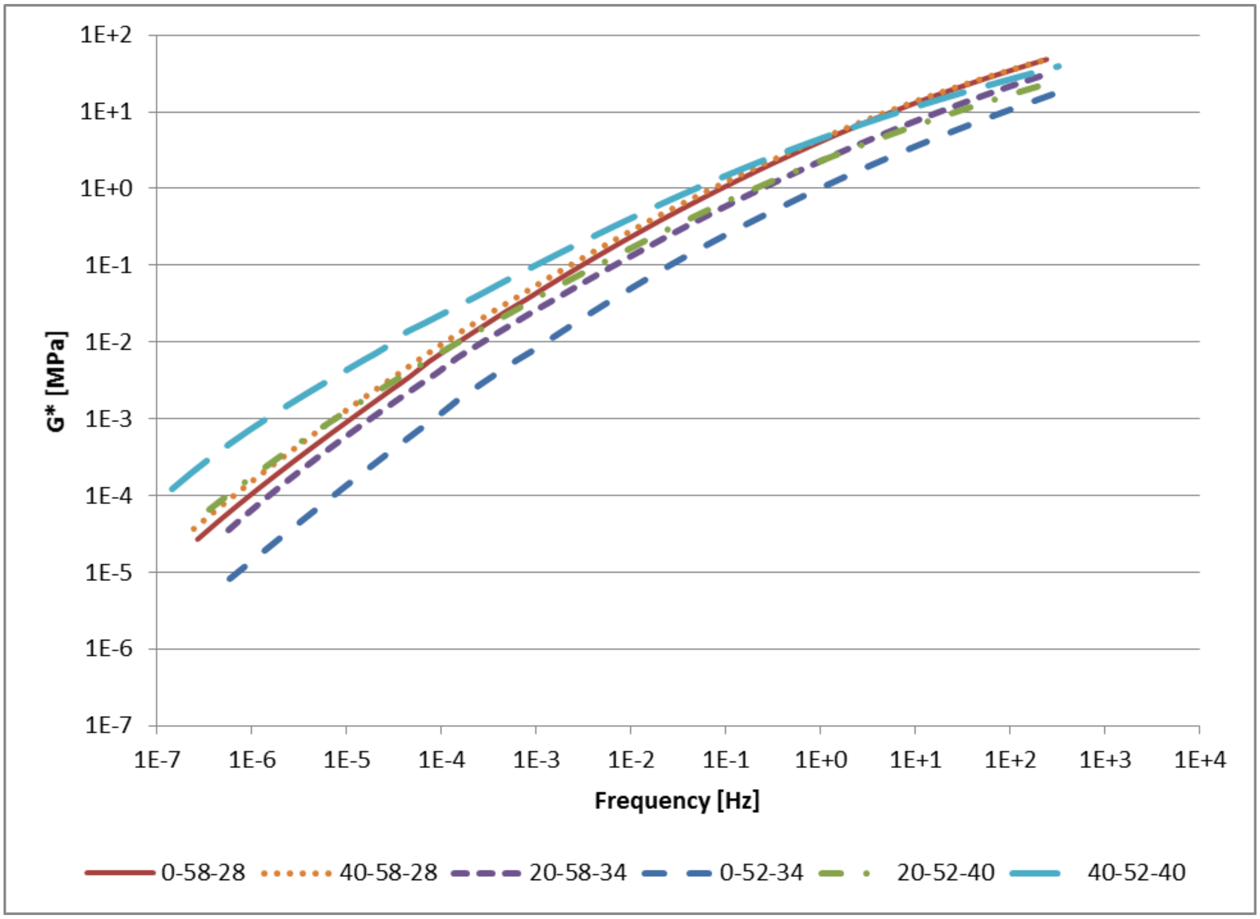

Figure 5-3 Master Curves Extracted and Recovered Binders

The Hirsch Model was applied to the results obtained with AMPT by DBA Engineering Ltd. to compare with the results from the extracted and recovered binders as shown in Figure 5-4.

From Figure 5-4 it is possible to see that the G* on the extracted and recovered binders is higher than that back-calculated from the mixtures' E*. However, given that the same behavior is observed for the virgin mixes, it is not clear that the extracted and recovered binders for the RAP mixes are stiffer given the full blend of the virgin and the aged binder, while through blending is not achieved in the mix.

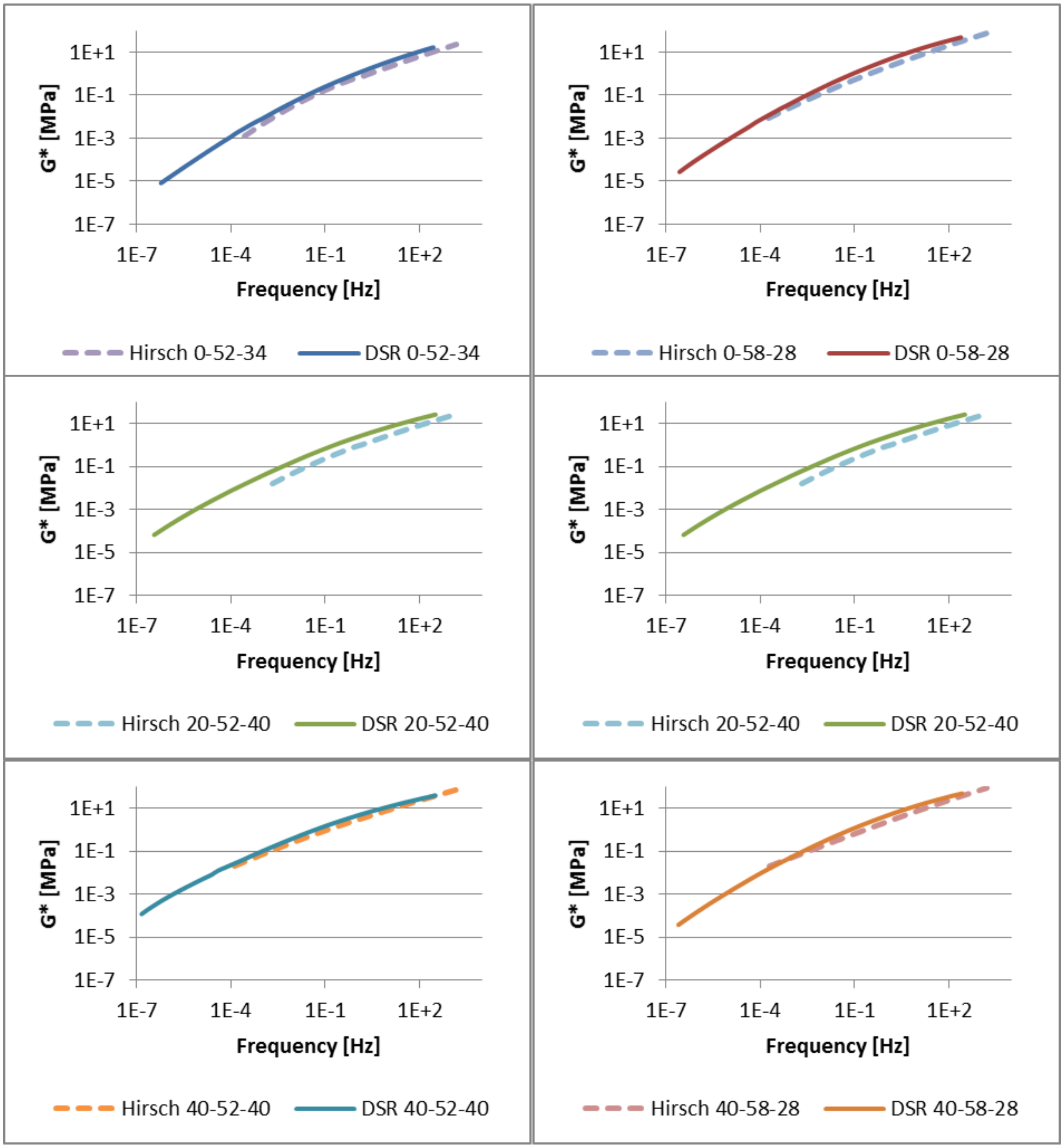

Figure 5-4 Comparison Hirsch AMPT and DSR Master Curves

As shown in Figure 5-5, the G* values obtained through the MTS results are higher than those obtained through AMPT or from the extracted and recovered binder. An example of this trend can be seen in Figure 5-6. The complex modulus seems to diverge for the highest and the lowest frequencies according to the measures from the MTS. The different shape for the MTS and AMPT curves suggests the need of a calibration between those two methods.

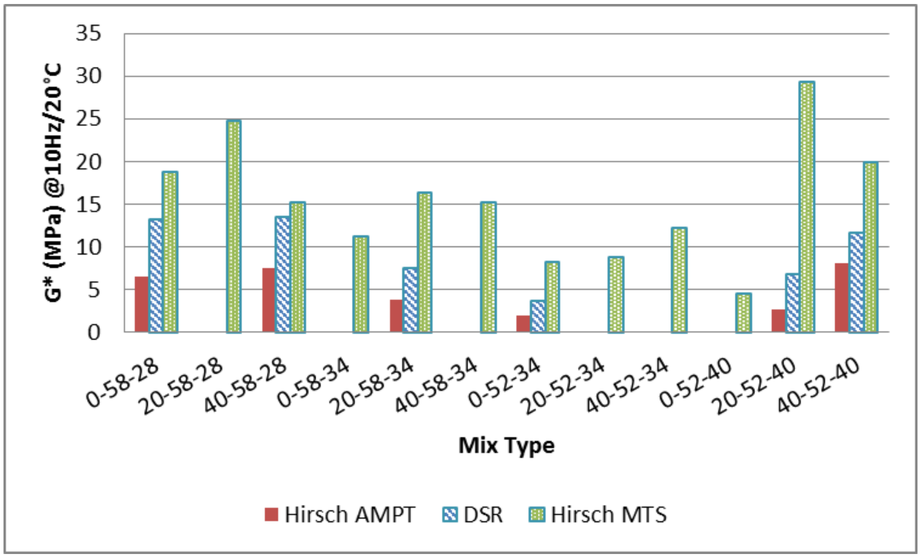

Figure 5-5 Binder Complex Modulus Comparison

In order to verify the results obtained with the DSR, the Hirsch Model was used directly to obtain the estimated E* of the mixture as seen in Figure 5-7.

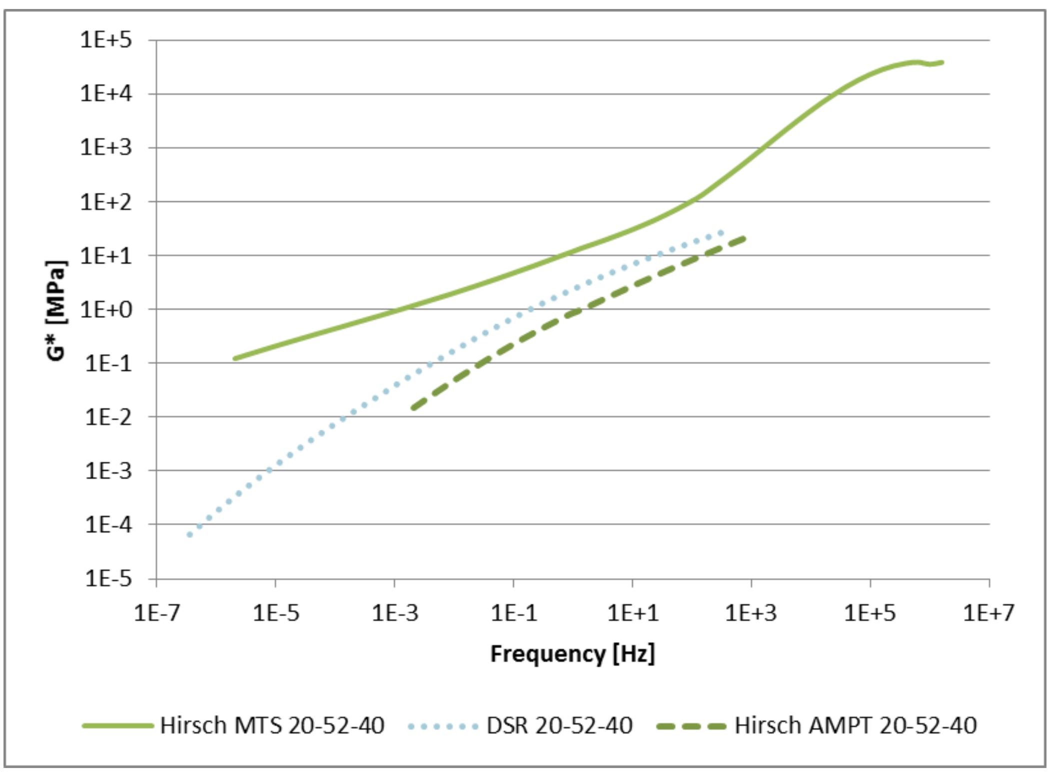

Figure 5-6 Comparison of Master Curves 20% RAP PG 52-40

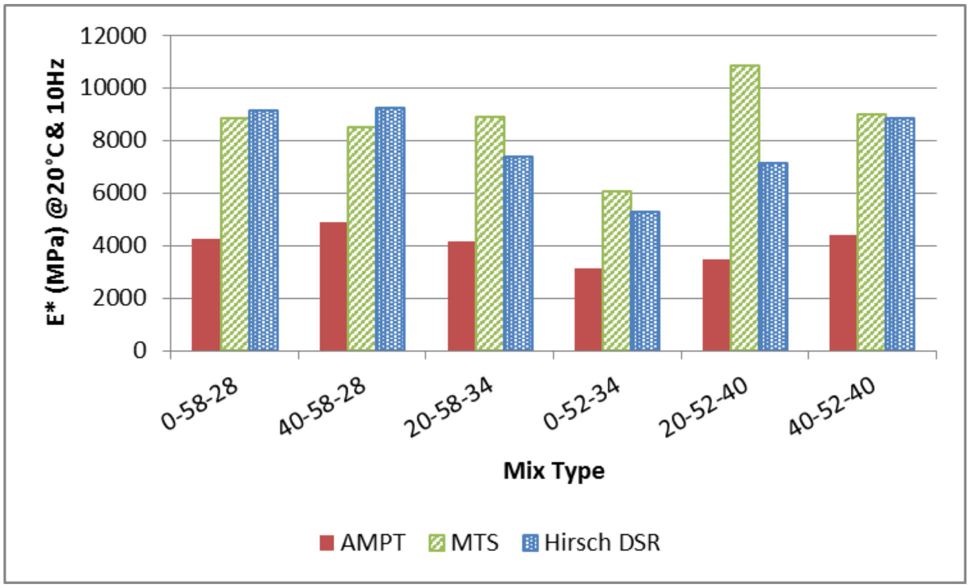

Figure 5-7 Mixture Complex Modulus Comparison

From Figure 5-7 it can be noticed that the MTS and the Hirsch Model estimation are closer to each other than the AMPT results, which supports the need for calibrating the results between the two test systems.

5.4 Blended Binder Characterization

Loose samples were sent to Golder Associates Ltd in order to extract and recover the resulting blended binder from the prepared RAP mixtures. The extraction was conducted using normal propyl bromide (nPb) as solvent and the Rotavapor to recover asphalt (ASTM, 2012). MTO discontinued the use of chlorinated solvents for extraction testing in quality assurance and referee laboratories (MTO, 2009), and the nPb could replace directly the TCE (Stroup-Gardiner & Nelson, 2000) From those extracted binders the Continuous Performance Grade and the AC content were determined on one sample per mix following the ASTM D7643 standard (ASTM, 2010a) and the results are shown in Table 5-1. The virgin binder continuous grades can be found in Table 3-5. It can be observed that the results for the 100% RAP obtained with nPb are similar when compared to the values obtained during the design phase using trichloroethylene which were PG76.6-22.9 and 4.5% AC Content. A preliminary analysis on the blended binder testing results was presented in the 2014 Transportation Association Canada Annual Meeting (Varamini, Ambaiowei, Sanchez, & Tighe, 2014).

Table 5-1 Extraction and Recovery Results

RAP Content (%)	*Virgin Binder PG*	*High Grade (°C)*	*Low Grade (°C)*	*%AC*	*Blended PG Comments*
20	58-28	58.9	-33.5	5.19	Same PG as virgin binder
40	58-28	64.3	-33.2	5.25	High temperature one PG grade higher. Same low temperature PG
20	58-34	56.9	-34.6	5.31	High temperature one PG grade lower. Same low temperature PG
40	58-34	64.9	-33.4	5.49	High temperature one PG grade higher. Low temperature one PG grade higher
20	52-34	58.9	-34.1	5.20	High temperature one PG grade higher. Same low temperature PG
40	52-34	65.0	-35.9	5.30	High temperature two PG grades higher. Same low temperature PG
20	52-40	60.7	-32.0	5.24	High temperature one PG grade higher. Low temperature two PG grades higher
40	52-40	61.9	-33.0	5.06	High temperature one PG grade higher. Low temperature two PG grades higher
100	RAP	76.8	-22.6	4.46	RAP binder PG 76-22

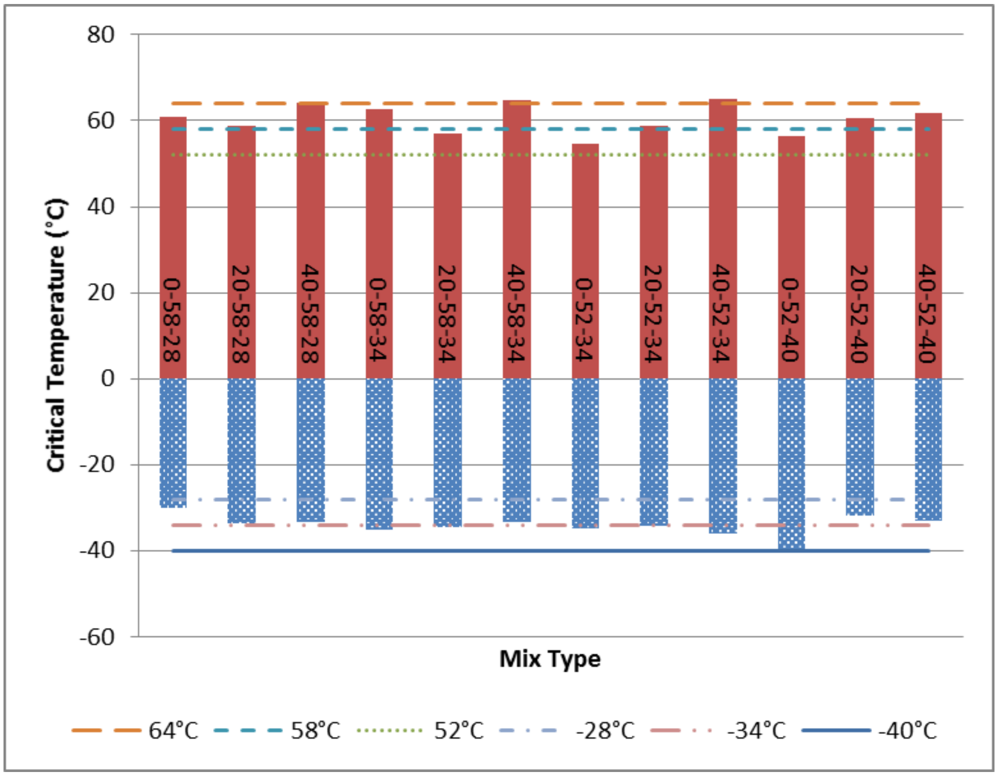

Figure 5-8 Critical Temperatures from Extracted Binder

There are several concerns associated with extracting and recovering the binders. One of them is the softening effect that the solvent can have on the extracted binder. The procedure attempts the removal of all the solvent in the sample; however it is possible that traces of solvent remains in the binder making it appear softer (Ma, Mahmoud, & Bahia, 2010). The use of dangerous chemicals is also a concern for the health and the environment. For those reasons, the pavement industry is looking for alternatives to estimate those parameters. Figure 5-8 shows the comparison of the critical temperatures of the virgin with the RAP mixtures.

In Figure 5-8 it is possible to see how the addition of RAP seems to have a greater impact for the high temperatures as compared to the lower temperatures. However, for the high temperatures, the effect for the 58-xx mixtures is different from the PG 52-xx. The assumed behavior is that the binder would get stiffer with the addition of RAP, which means that when adding more RAP the high and low critical temperatures would increase.

When comparing the results to the virgin binder continuous grade, the following observations can be made:

High Temperature

- For the PG 58-28, the temperature was 2°C lower with 20% RAP and increased 3.4°C higher with 40% RAP.
- For the PG 58-34, the temperature is 5.8°C lower with 20% RAP and 2.2°C higher with 40% RAP. The apparent decrease in the 20% RAP might be associated with the softening effect of the solvent; however the critical temperature is closer to 58°C than 52°C.
- For the PG 52-34, the temperature increased by 4.2°C with 20% RAP and by 10.3°C with 40% RAP.
- For the PG 52-40, the temperature increased by 4.3°C with 20% RAP and by 5.5°C with 40% RAP.

Low Temperature

- For the PG 58-28 the temperature decreased by 3.5°C with 20% RAP and by 3.2°C with 40% RAP addition.
- For the PG 58-34, the temperature was 0.5°C higher with 20% RAP and 1.5°C higher with 40% RAP.
- For the PG 52-34 the temperature increased by 0.6°C with 20% RAP but decreased by 1.2°C with 40% RAP addition.
- For the PG 52-40, the temperature was 8.6°C higher with 20% RAP and 7.6°C higher with 40% RAP.
- Considering that those mixtures were to be applied in southern Ontario where the critical low temperature is -28, all of the mixtures would meet this requirement.

Regarding the asphalt content, a difference of ±0.3% with the design is considered acceptable (MTO, 2012).

5.5 Blending Charts

The blending charts that were developed in the NCHRP Project D9-12 (McDaniel & Anderson, 2001b) research establish a methodology to obtain the required binder PG through the RAP binder and the virgin binder information assuming full blending, and knowing the RAP content incorporated in the mix. The most recent NCHRP Report 752 (West, Willis, & Marasteanu, 2013) recommends applying the following relationship:

$$Tc_{Virgin} = \frac{Tc_{need} - (RBR \times Tc_{RAP})}{1 - RBR} \tag{5.3}$$

Where:

Tc_{need}: Critical Temperature needed for the climate and pavement layer

T_{Virgin}: Critical Temperature of the virgin binder

RBR: RAP Binder Ratio

T_{RAP}: Critical Temperature of the RAP Binder

For evaluation purposes, from the Equation (5.3), the critical temperature of the blended binder can be estimated as follows:

$$Tc_{blend} = Tc_{virgin} \times (1 - RBR) + (RBR \times Tc_{RAP}) \tag{5.4}$$

Where:

Tc_{blend}: Critical Temperature of the resulting blended binder

Tc_{Virgin}: Critical Temperature of the virgin binder

RBR: RAP Binder Ratio

Tc_{RAP}: Critical Temperature of the RAP Binder

The RAP binder for the resulting mixture can be obtained through the following expression:

$$RBR = \frac{Pb_{RAP} \times P_{RAP}}{Pb_{Total}} \tag{5.5}$$

Where:

RBR: RAP binder ratio

Pb_{RAP}: Binder content of the RAP

P_{RAP}: RAP percentage by weight of mixture

Pb_{Total}: Total binder content in the mixture

In order to use Equation 5.5 the RAP content as a percentage by weight of the mixture is required. Provided that the 20% and 40% RAP content were given as a percent by weight of the aggregates, the RAP content as a percent of the total weigh of the mix was calculated as 18.8% and 38.7% respectively. Table 5-2 shows the critical temperatures from the estimation based on blending charts.

Table 5-2 Blending Charts Critical Temperature

Mix Type	RBR (%)	High Temperature (°C)	Intermediate Temperature (°C)	Low Temperature (°C)
20-58-28	16.1	63.4	18.6	-28.9
40-58-28	32.9	66.1	19.4	-27.7
20-58-34	15.8	64.9	15.8	-33.2
40-58-34	31.4	67.1	17.1	-31.3
20-52-34	16.1	58.2	12.8	-32.8
40-52-34	32.5	61.8	14.8	-30.9
20-52-40	16.0	59.6	9.2	-37.8
40-52-40	34.2	63.3	12.2	-34.6

The proposed method to estimate the critical temperatures involves different steps as defined in the methodology for this research, and will be developed in the following paragraphs. The results are going to be compared with the values obtained through the blending charts Equation 5.4.

5.6 Critical Temperatures from Performance Testing

5.6.1 High Critical Temperature

The high critical temperature is established to control the rutting in the asphalt mixture. It is expected that rutting is not a concern for RHM given the higher stiffness provided by the aged binder in the RAP (Rahman & Hossain, 2014). However, having an estimation of the effective critical temperature is often required.

Provided that the G* were not directly measured from the virgin binders or the extracted and recovered RAP binder, the results from the E* were used to determine the high critical temperature. Note that the G* can be obtained using the Hirsch Model, however, given that they are directly related with E*, the estimation would not be significantly different. If the E* of the virgin mixes were not available, it could be obtained through the Hirsch Model with the G* measured directly on the virgin binder.

Given the E* of the different mixtures, and the known critical temperatures for the RAP and the virgin binders from the design phase, the critical temperature of the mix can be assessed using the following equation:

$$Tc_{blend} = Tc_{RAP} + \frac{(E^*{}_{RAP} - E^*{}_{Mix})(Tc_{RAP} - Tc_{Virgin})}{(E^*{}_{RAP} - E^*{}_{Virgin})} \tag{5.6}$$

Where:

Tc_{blend}: Critical Temperature of the resulting blended binder

Tc_{RAP}: Critical Temperature of the RAP Binder

Tc_{Virgin}: Critical Temperature of the virgin binder

$E^*{}_{RAP}$: Dynamic Modulus if the 100% RAP mix

$E^*{}_{Mix}$: Dynamic Modulus of the RHM

$E^*{}_{Virgin}$: Dynamic Modulus of the 0% RAP mix

Since it is uncertain that the critical temperature is directly proportional with the RAP content, a method is proposed assuming a linear relationship between the complex modulus and the critical temperature. The assumption of linearity can be confirmed with the results shown in Table 5-3 and in Figure 5-9. The estimation of the critical high temperature for the 40% RAP PG 58-28 mix is presented as an example in Figure 5-10. This method, compared to the proposed by Daniel and Mogawer (Daniel & Mogawer, 2010), does not use the back-calculated complex modulus G* or the critical temperature of the extracted and recovered binder.

Table 5-3 Complex Modulus Virgin Mixes and RAP

Mix Type	E* [MPa] at 37°C	E* [MPa] at 21°C	E* [MPa] at 4°C	High Grade (°C)
0-58-28	3521.6	8850.9	19021.6	60.9
0-58-34	3056.8	7088.1	15110.8	62.7
0-52-34	2439.5	6132.8	14573.6	54.7
0-52-40	2455.1	5222.3	11267.8	56.4
RAP 100%	9490.8	19517.2	34486.7	76.6

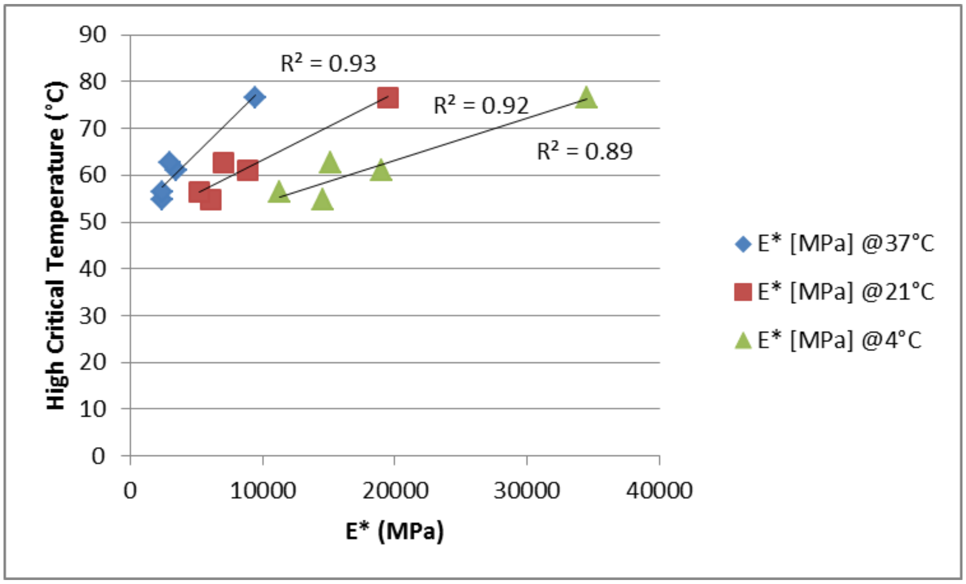

Figure 5-9 High Critical Temperature vs E*

For the high critical temperature, the results for the complex modulus at 37°C and 10 Hz are considered. Even when the results for 54°C were available, they were not considered given that this temperature is not regularly tested in practice, and also because the variability observed for these results was higher. Table 5-4 summarizes the estimated High Critical Temperature.

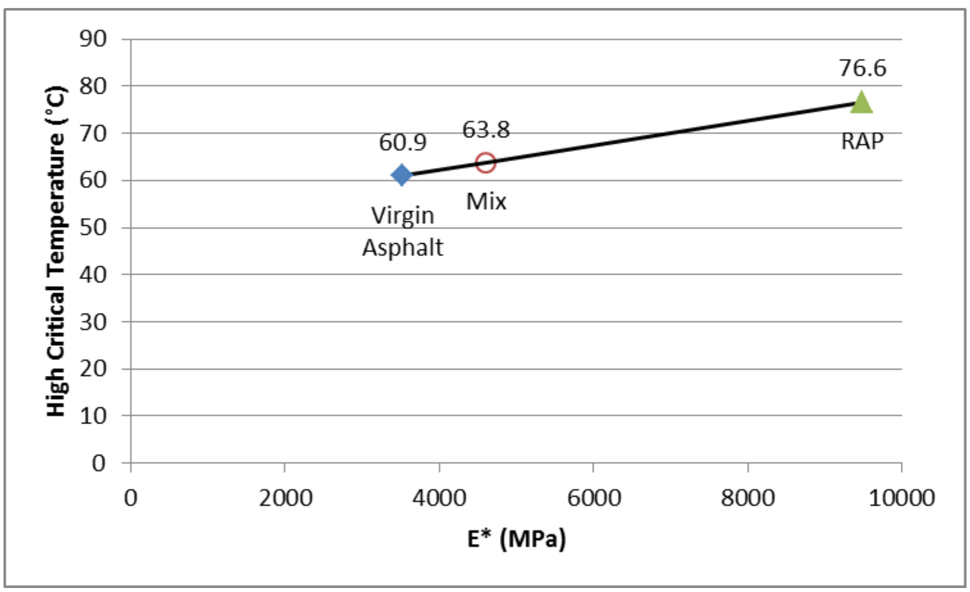

Figure 5-10 Estimation High Critical Temperature 40% RAP PG 58-28

Table 5-4 High Critical Temperatures Estimation with E*Results

Mix Type	High Temperature (°C)
20-58-28	62.0
40-58-28	63.8
20-58-34	64.7
40-58-34	63.6
20-52-34	56.3
40-52-34	57.2
20-52-40	63.1
40-52-40	61.3

The estimation achieved through this method offers a suitable option for obtaining the critical temperatures of the blended binder without previous knowledge of the RAP Binder Ratio in the mixture. The continuous grades were compared with the results obtained with the blending charts and are summarized in Figure 5-11. The difference with the estimation with blending charts is within ±5°C, being the estimation with blending charts slightly conservative in most cases.

From Figure 5-11, it is observed that for most of the RAP mixtures, the continuous grade from the extracted and recovered binder is below that estimated through the blending charts. The higher difference is observed for the 20% RAP PG 58-34 (14%), while the remaining RAP mixtures yielded a difference under 8%.

In general for all of the mixtures, it is possible to see an increase of the high temperature with the addition of RAP compared to the virgin binder. However, a small difference is observed between the 20% RAP and the 40% RAP.

The estimation of the high critical temperature obtained through the complex modulus was within ±5°C difference with the results from blending charts. The importance of the proposed method relies on avoiding the extraction and recovery process to get the critical temperature of the resulting blended binder. Furthermore, this research affirms blending charts as a suitable method to estimate the critical temperature of the blended binder when the RAP Binder Ratio in known.

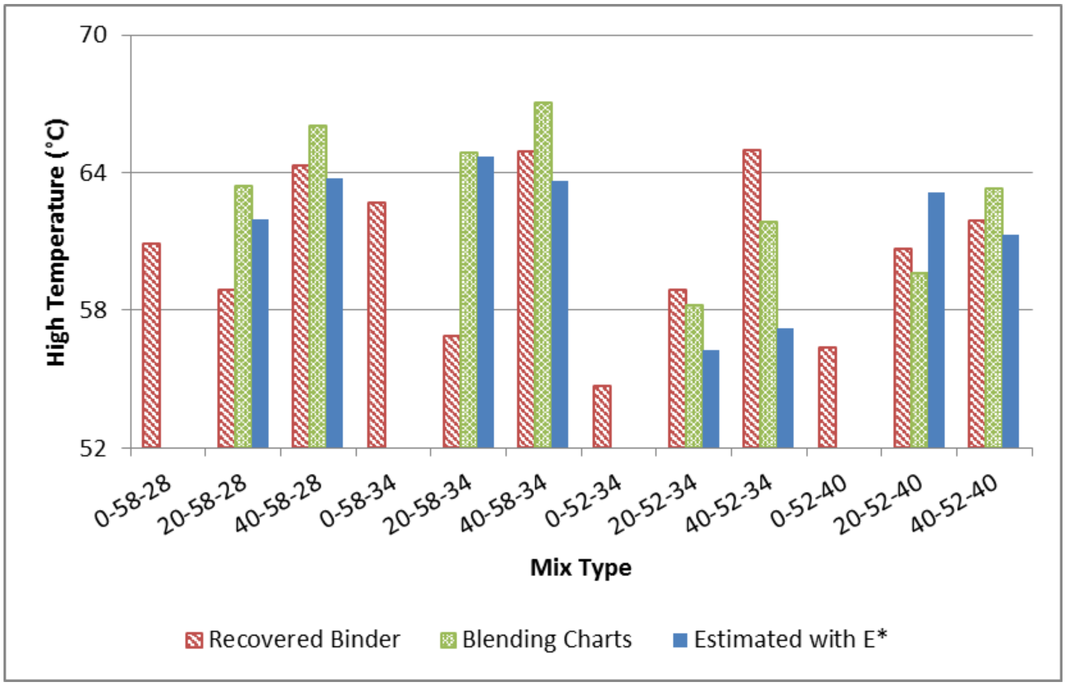

Figure 5-11 High Critical Temperatures

5.6.2 Intermediate Critical Temperature

Fatigue cracking is the distress controlled at intermediate temperatures. The critical binder intermediate temperature is the temperature for which G*sinδ = 5000kPa. The RHEA Software was used to determine the critical intermediate temperature from the back-calculated G* obtained through the Hirsch Model at 10rad/s frequency. Given that the intermediate temperature is between the temperatures tested, the result can be found with the function for calculating the properties from the master curves included in the RHEA software as shown in Figure 5-12. It is a trial an error process until finding the best approximation, which results are shown in Table 5-5. The results were compared with the blending charts estimation and the extracted and recovered binders' intermediate temperatures in Figure 5-13. The complex modulus at 21°C and 10Hz was used to estimate the intermediate critical temperature similarly as described for the high critical temperature. The estimation through the fatigue parameter yields higher temperatures compared to the blending charts and the continuous grade as shown in Figure 5-11.

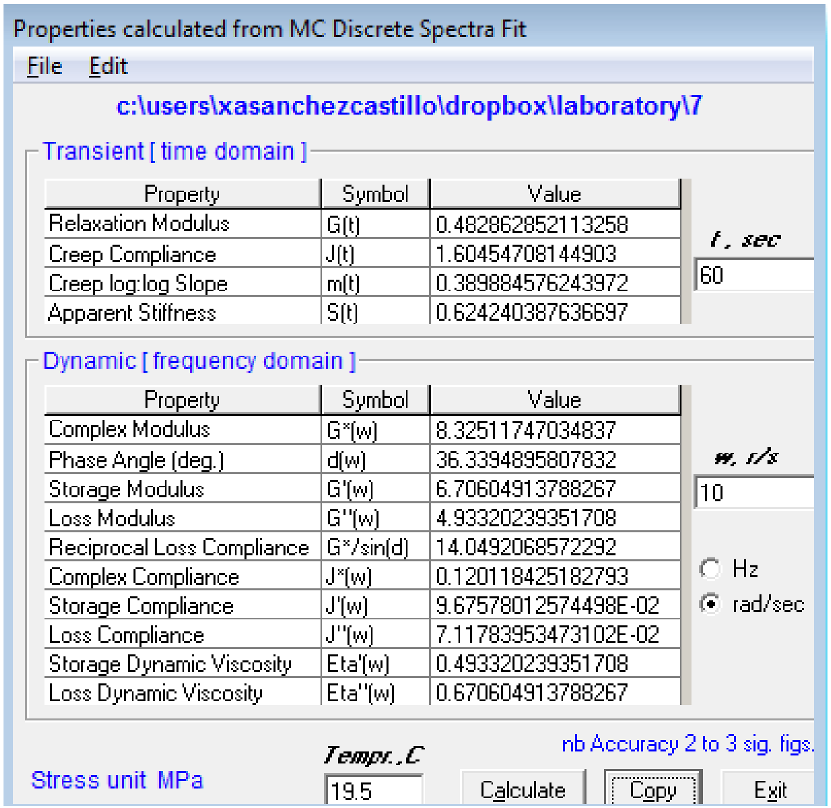

Figure 5-12 RHEA Properties Calculator

The results with E* are closer to those obtained with blending charts except for the PG 52-40 where the RAP appears to significantly impact the intermediate critical temperature. It is expected that the intermediate critical temperatures is higher for RAP mixtures as compared to virgin mixtures.

Table 5-5 Intermediate Critical Temperatures

Mix Type	G*sinδ (kPa)	Intermediate Temperature (°C)
0-58-28	4995.6	20.5
20-58-28	4995.4	22.3
40-58-28	4974.3	19.5
0-58-34	4941.8	16.5
20-58-34	4933.2	19.5
40-58-34	4940.3	19.0
0-52-34	4973.1	14.7
20-52-34	4912.5	15.4
40-52-34	4928.9	17.5
0-52-40	4965.8	9.2
20-52-40	4960.6	24.2
40-52-40	4962.9	21.0

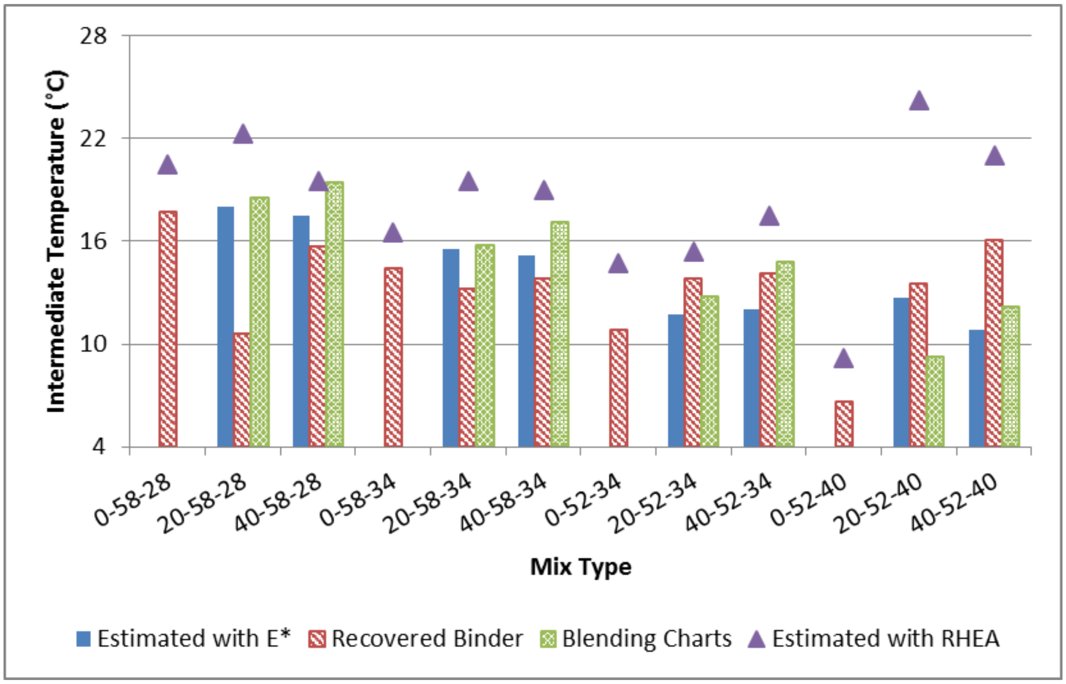

Figure 5-13 Intermediate Critical Temperatures

5.6.3 Low Critical Temperature

The low critical temperature is the temperature for which the creep stiffness S=300MPa at 60 seconds or the creep rate m=0.3 which are the parameters defined for the Superpave method to control thermal cracking. Given that the lower temperature tested with the dynamic modulus is -10°C, there is no information available at the critical low temperature. However, the S(t) and m-value could be modelled from the results obtained with the RHEA. For each mix, the results at different negative temperatures were obtained and the suitable regression was made. The creep stiffness, summarized in Figure 5-14, was successfully fit to a logarithmic equation, with $R^2 \geq 0.99$ in all cases. It was not possible to identify a relevant trend for the m-value as shown in Figure 5-15.

Figure 5-16 shows the low critical temperatures obtained with the creep stiffness approach compared with the blending charts estimation and the extracted and recovered critical low temperature. For the low critical temperature the results from the dynamic modulus at 4°C and 10Hz were used for the estimation of this parameter.

For the majority of the mixtures, the estimation of the low critical temperature through the creep stiffness is warmer than the continuous grade from the extracted and recovered binder and the blending charts estimation. The difference between the estimation with S(t) and the blending charts is higher for the PG 58-28 mixtures and the 20% RAP PG 52-40.

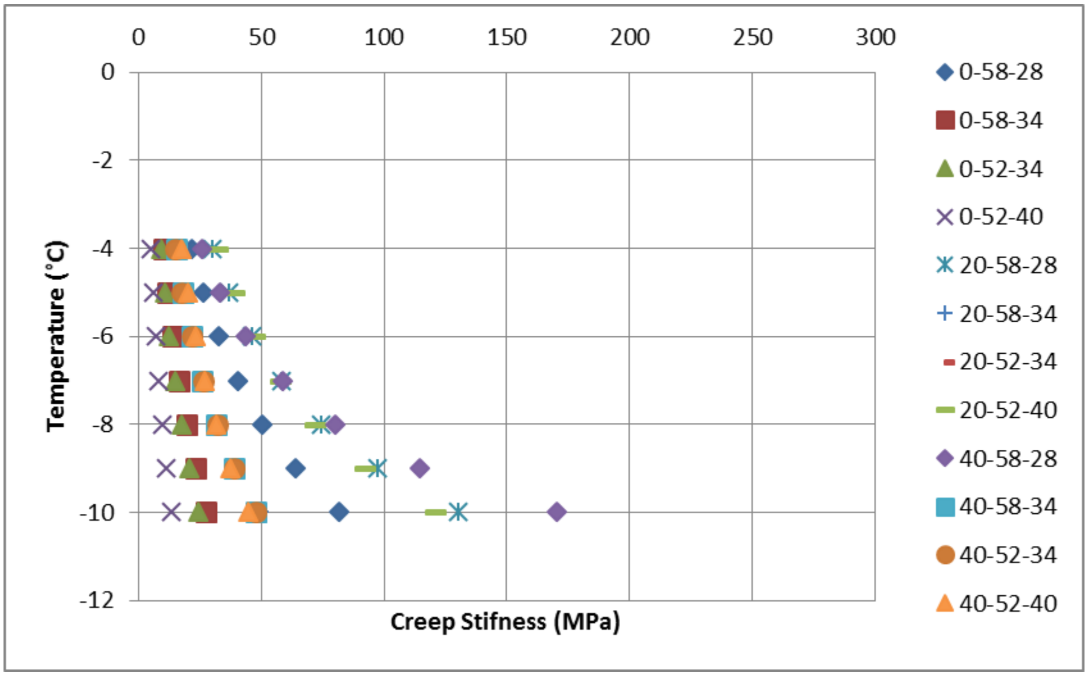

Figure 5-14 Estimated Creep Stiffness

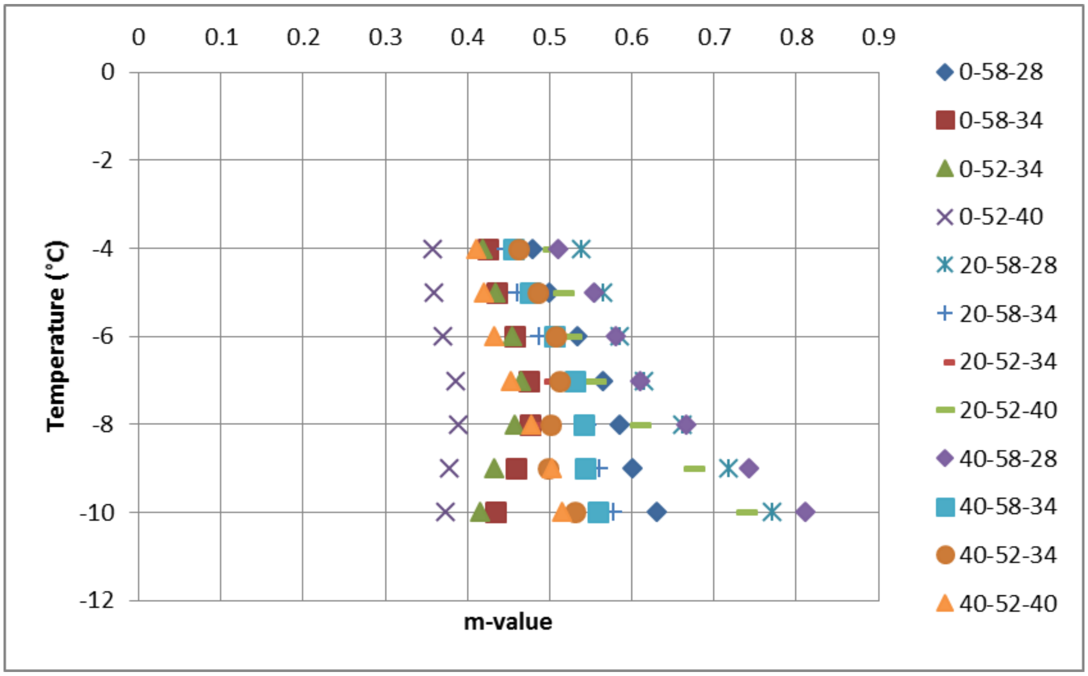

Figure 5-15 Estimated m-value

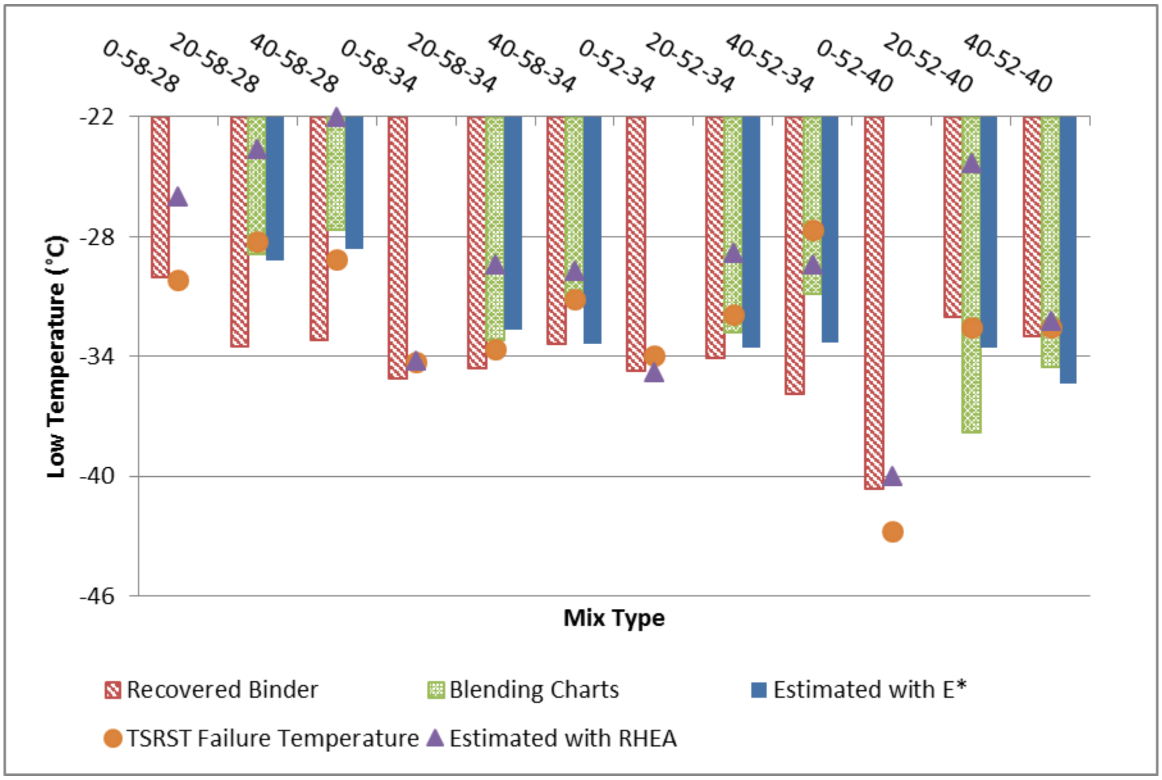

Figure 5-16 Low Critical Temperatures

It can be seen that the estimation with RHEA is accurate for three of the virgin binders critical temperature, however for the PG 58-28 the estimated temperature is 4°C under the true grade.

The comparison with the TSRST indicates that the failure temperature is either colder or relatively close to the critical temperature in most cases. The continuous grade of the mixtures 20% RAP PG 58-28, 40% RAP PG 58-28 and 40% RAP PG 52-34 exhibited the opposite behavior.

5.7 Summary and Conclusions

For high temperatures, the extraction and recovery of the asphalt binder resulted in lower PG grades for the 20% RAP PG 58-28 and 20% RAP PG 58-34 than the corresponding virgin binders, which might be an indication of the softening effect of the solvent.

The effect of the addition of RAP seems more dramatic for the high than the low critical temperature and the PG 52-xx seems to have a higher increase in the critical temperatures.

Blending charts offer a good estimation for the critical temperatures when the RBR is known. However, the estimation for the PG 52-40 should be further investigated as the results were slightly more variable.

The Hirsch model was used to estimate the G* master curves from the E* results. The curves seem to converge for 40% RAP content. The comparison of the extracted binder master curves obtained with DSR vs the master curves obtained with Hirsch Model indicate that full blending is not occurring in the mix.

A need for calibration between the MTS E* and the AMPT E* was identified; however the results with AMPT seem to be conservative compared to the MTS.

It is possible to obtain the critical temperatures from the dynamic modulus testing. In general of the estimation with the complex modulus differ between ±5°C from the blending charts estimation.

Chapter 6
RAP Content Determination

6.1 Introduction

This chapter explains the efforts made to determine the RAP content from an existing recycled hot mix. Given the critical temperatures, the blending charts were used to obtain an estimate of the RAP Binder Ratio. Also, statistical tools were used to determine the performance parameter most affected by the addition of RAP. Other techniques were also utilized to examine the presence and quantity of RAP in completed RHM.

6.2 Blending Charts

According to the NCHRP Report 752 (West et al., 2013), the allowable RAP Binder Ratio of the mix, or the maximum amount of RAP binder to achieve a required critical temperature, can be estimated by the following equation:

$$\mathrm{RBR}_{max} = \frac{Tc_{need} - Tc_{virgin}}{Tc_{RAP} - Tc_{Virgin}} \tag{6.1}$$

Where:

RBR_{max}: Maximum RAP binder ratio

Tc_{need}: Critical Temperature needed for the climate zone

Tc_{virgin}: Critical Temperature of the Virgin Binder

Tc_{RAP}: Critical Temperature of the RAP Binder

The observed RAP Binder Ratio (RBR) was assessed using the Equation 5.5 and the data from the extraction and recovery as explained in the previous chapter.

6.2.1 Back-calculation with TSRST

One of the objectives of this research was to study the ability to determine the RAP content from a RHM when the critical temperature or the performance characteristics are known.

Using the continuous grade for the different virgin binders and the RAP, and assuming that the failure temperature obtained with TSRST represents the blended binder low critical temperature, the blending charts were tested for determining the RAP Binder Ratio in the mixture using the following equation:

$$\mathrm{RBR}_{TSRST} = \frac{Tc_{TSRST} - Tc_{virgin}}{Tc_{RAP} - Tc_{Virgin}} \tag{6.2}$$

Where:

RBR_{TSRST}: RAP binder ratio estimated with TSRST

Tc_{TSRST}: Failure temperature from TSRST results

Tc_{virgin}: Critical Temperature of the Virgin Binder

Tc_{RAP}: Critical Temperature of the RAP Binder

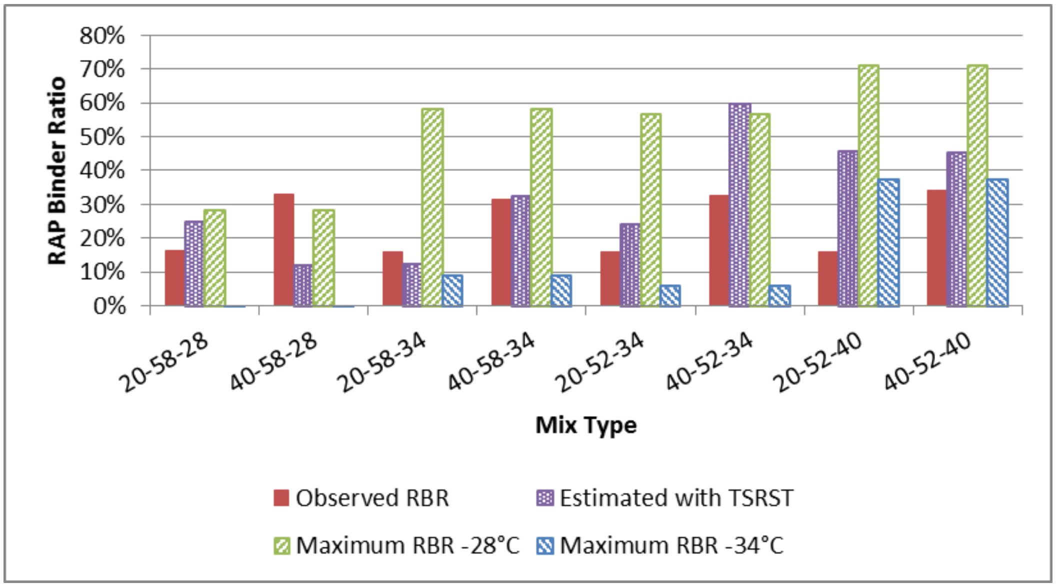

Figure 6-1 RBR Estimation

From the results shown in Figure 6-1, it can be noticed that for the PG 58-34, the estimated RBR was only 3% below for 20% RAP and 1% above for 40% RAP, resulting in the most accurate result. However for the rest of the mixtures, the results are mostly higher than expected, and might be associated with the effect of RAP in the mixture performance. A suitable interpretation of the results is that when the RBR estimated with the TSRST failure temperature is higher than the observed RBR, the influence of the RAP is more marked for the mixture. Considering that, the results for the PG 40% RAP PG 58-28 are consistent with the observed similar performance to the virgin mixture indicating that the effect of RAP in this mix is not having a considerable negative effect. Considering that the critical temperature needed for the climate zone was -28°C, it is possible to see that most of the mixtures contained a lower RBR than the maximum recommended except for the 40% RAP PG 58-28. It is important to notice that for some of the mixtures more RAP could be allowed from the design criterion, however, according to the TSRST results, the critical temperature might not be achieved.

This research showed that the percentage of RAP has an important variation with the critical temperature. The rate of change is as high as 17.7% RAP per each degree Celsius decrease for the PG 52-40. When using the critical temperature results from the extracted and recovered binders, the results were inconsistent. Given the sensitivity of the RBR with the critical temperature, this approach was shown to provide inconsistent results.

The next step involved determining which of the performance parameters measured is most influenced by the RAP addition. For that purpose, a correlation analysis was conducted. The results of the correlation coefficients are shown in Table 6-1 to Table 6-4. The correlation coefficients range from -1.0 to +1.0, where -1.0 represents perfect negative correlation, +1.0 represents perfect positive correlation and 0.0 represent absolute no linear relationship between the variables. In this research, the values above +0.7 and below -0.7 are considered to be a strong relationship. From Table 6-1 it can be inferred that from the design consensus properties and gradation, the RAP content is more related with the results for angularity of the coarse aggregate, and the sand equivalent. It was also found that the RAP content also explains the dust proportion and the power law results from the gradation analysis.

Table 6-1 Coefficients of Correlation for Consensus Properties

	RAP	*%Crushed 1 face*	*%Crushed 2 faces*	*Flat and Elongated*	*Uncompacted void*	*Sand Equivalent*
RAP	1.0					
%Crushed 1 face	**-1.0**	1.0				
%Crushed 2 faces	**-1.0**	1.0	1.0			
Flat and Elongated	0.6	-0.4	-0.6	1.0		
Uncompacted void	0.1	-0.4	-0.1	-0.7	1.0	
Sand Equivalent	**1.0**	***-0.9***	**-1.0**	0.8	-0.1	1.0
aCA	0.5	-0.7	-0.5	-0.4	0.9	0.3
nCA	-0.5	0.7	0.5	0.4	-0.9	-0.3
aFA	**0.9**	-1.0	-0.9	0.3	0.5	**0.8**
nFA	**-0.8**	0.9	0.7	0.0	-0.7	-0.6
DP	**0.8**	-0.9	-0.7	-0.1	0.8	0.6

Table 6-2 Coefficients of Correlation for Gradation Features

	aCA	*nCA*	*aFA*	*nFA*	*DP*
aCA	1.0				
nCA	-1.0	1.0			
aFA	0.8	-0.8	1.0		
nFA	-0.9	0.9	-0.9	1.0	
DP	1.0	-1.0	**0.9**	-1.0	1.0

Table 6-3 Coefficients of Correlation for the Performance Tests (1)

	% RAP	*Virgin Binder High PG*	*Virgin Binder Low PG*	*TSRST Failure Temp.*	*TSRST Fracture Stress*	*Rut Depth*	*Creep Slope*	*Complex Modulus MTS*	*Phase angle MTS*
% RAP	1.0								
Virgin Binder High PG	0.0	1.0							
Virgin Binder Low PG	0.0	0.7	1.0						
TSRST Failure Temperature	0.6	0.3	0.6	1.0					
TSRST Fracture Stress	0.3	0.0	-0.5	-0.2	1.0				
Rut Depth	-0.3	0.0	0.1	-0.1	-0.3	1.0			
Creep Slope	-0.3	-0.2	0.0	-0.1	-0.1	0.8	1.0		
Complex Modulus MTS	0.4	0.3	0.2	0.6	0.2	-0.3	-0.3	1.0	
Phase angle MTS	-0.2	0.4	0.7	0.2	-0.5	0.5	0.4	-0.5	1.0
Blended Binder High Grade	**0.7**	0.3	0.2	0.6	0.3	-0.6	-0.6	0.3	0.0
Blended Binder Low Grade	0.2	0.4	0.4	0.7	-0.1	-0.2	-0.1	0.8	-0.1
Fracture Energy at -18°C	**-0.8**	-0.4	0.2	-0.2	-0.7	0.2	0.6	-0.6	0.4
Fracture Energy at -24°C	-0.1	-0.7	-0.5	-0.7	-0.3	0.4	0.7	-0.5	0.0
Complex Modulus AMPT	0.5	0.7	0.5	0.9	0.2	-0.6	-0.9	0.3	0.0
Phase Angle AMPT	**-0.7**	-0.4	-0.2	-0.7	-0.6	0.6	0.9	-0.4	0.3
DSR G*	0.5	0.6	0.5	0.9	0.3	-0.7	-0.9	0.3	0.0
Flow Number	**0.8**	-0.4	-0.7	-0.1	1.0	-0.5	-0.5	0.7	-0.9
TSR	**-0.7**	0.2	0.0	-0.5	-0.3	0.7	0.6	0.0	0.3

Table 6-3 shows that from the performance testing, the parameters most related with the RAP content are the fracture energy at-18°C, the flow number, the phase angle, the TSR and the high critical temperature from the extracted and recovered blended binders. The fracture energy at -24°C yielded a very low coefficient of correlation. It is important to recall that none of the recycled mixtures reach a failure temperature lower than -34°C.

Table 6-4 Coefficients of Correlation for the Performance Tests (2)

	Blended Binder High Grade	*Blended Binder Low Grade*	*Fracture Energy at -18°C*	*Fracture Energy at -24°C*	*Complex Modulus AMPT*	*Phase Angle AMPT*	*DSR G**	*Flow Number*	*TSR*
Blended Binder High Grade	1.0								
Blended Binder Low Grade	0.3	1.0							
Fracture Energy at -18°C	-0.5	0.1	1.0						
Fracture Energy at -24°C	-0.6	-0.7	0.5	1.0					
Complex Modulus AMPT	0.9	0.5	-0.6	-0.8	1.0				
Phase Angle AMPT	**-0.9**	-0.4	**0.8**	0.8	-0.9	1.0			
DSR G*	0.9	0.6	-0.5	-0.8	1.0	-0.9	1.0		
Flow Number	0.5	0.0	**-0.7**	-0.1	0.2	-0.5	0.2	1.0	
TSR	**-0.7**	-0.1	0.3	0.1	-0.5	0.6	-0.6	-0.5	1.0

It can be said that the increase in the RAP content is strongly related to a decrease in the fracture energy at -18°C, with a coefficient of correlation of -0.82. Considering the results from the correlation, a regression analysis was performed for the fracture energy. From the performance test analysis, it is known that the performance of the mixtures is a result of the combined effect of the RAP content and the virgin asphalt performance grade, consequently, the high and the low critical temperatures of the virgin binder were both included. The results for the multiple regression are shown in Table 6-5 to Table 6-7.

Table 6-5 Regression Statistics

Multiple R	0.98
R Square	0.97
Adjusted R Square	0.93
Standard Error	0.05
Observations	6

Table 6-6 ANOVA Regression

	Sum of Squares	*Degrees of Freedom*	*Mean Square*	*F*	*Significance F*
Regression	3	0.16	0.05	21.63	0.04
Residual	2	0.005	0.002		
Total	5	0.16			

Table 6-7 Coefficients of Regression

	Coefficients	*Standard Error*	$t_{calculated}$	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	8.49	1.73	4.89	0.04	1.02	15.95	1.02	15.95
High Grade (°C)	-0.09	0.02	-4.39	0.05	-0.18	-0.002	-0.18	-0.002
Low Grade (°C)	0.05	0.01	3.77	0.06	-0.01	0.10	-0.01	0.10
Fracture Energy (J/m²) at -18°C	-0.004	0.001	-7.24	0.02	-0.01	-0.002	-0.01	-0.002

The regression equation is presented below:

$$\%RAP = 8.49 - 0.09HPG_{Virgin} + 0.05LPG_{Virgin} - 0.004FE \qquad (6.3)$$

Where:

$\%RAP$: RAP content as percentage weight of aggregates

HPG_{Virgin}: Virgin Binder PG high temperature

LPG_{Virgin}: Virgin Binder PG low temperature

FE: Fracture energy at -18°C (J/m^2)

In Figure 6-2, the estimated RAP content for the six mixes is presented. According to this regression, the RAP content could be estimated with approximately ±4% difference as seen in Table 6-8. It is important to note that the coefficient of determination, R square, in Table 6-5It can be said that the increase in the RAP content is strongly related to a decrease in the fracture energy at -18°C, with a coefficient of correlation of -0.82. Considering the results from the correlation, a regression analysis was performed for the fracture energy. From the performance test analysis, it is known that the performance of the mixtures is a result of the combined effect of the RAP content and the virgin asphalt performance grade, consequently, the high and the low critical temperatures of the virgin binder were both included. The results for the multiple regression are shown in Table 6-5 to Table 6-7.

is 0.97, which is very close to 1 and the significance in Table 6-6 is less than 0.05, which provides good reliability. Also, assuming a $t_{critical}$ of 2.57, for 5 degrees of freedom at 95% reliability, all the coefficients are significant.

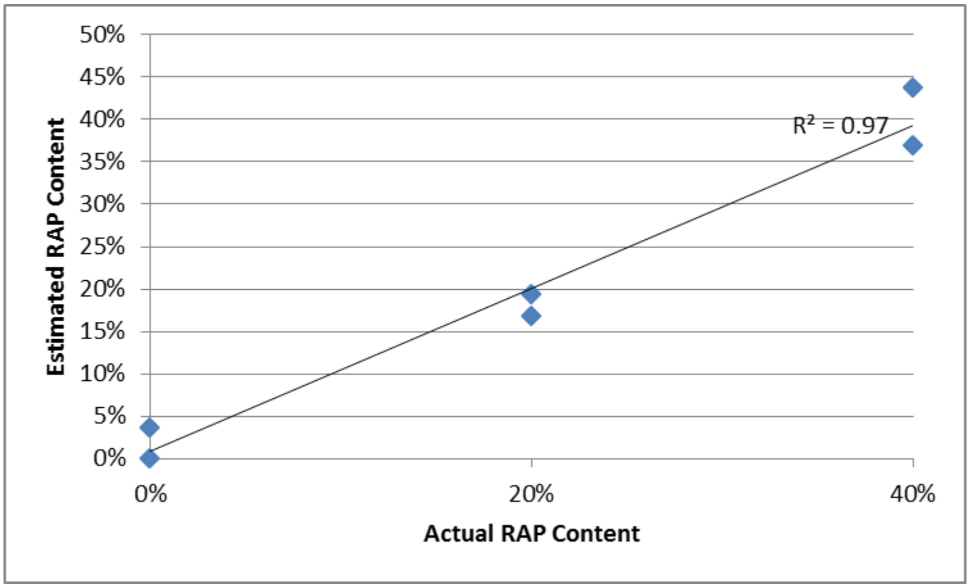

Figure 6-2 Actual RAP Content and Estimated from Fracture Energy

Table 6-8 Regression Results

Mix Type	Actual RAP Content	Estimated RAP Content	Difference
0-58-28	0%	3.7%	3.7%
40-58-28	40%	36.9%	-3.1%
20-58-34	20%	19.4%	-0.6%
0-52-34	0%	-0.6%	-0.6%
20-52-40	20%	16.9%	-3.1%
40-52-40	40%	43.8%	3.8%

6.3 Partial Extraction

The method of partial extraction was used as described by Buttlar et al. (Buttlar, Rebholz, & Nassar, 2004). In this procedure, a loose sample of mix, is subjected to two cycles of soaking in a solution on methylene chloride and ethyl alcohol, in order to remove the virgin binder from the aggregates. This procedure can be used to determine the presence of RAP in a mixture and also to estimate the approximate amount of RAP when compared to the control mixtures of known RAP content, in this case the virgin and the 100% RAP mixtures. The method is summarized below:

- Get 400g of loose mix (in this research, the remaining hollow cylinder from the cored specimens was used).

- Put the sample in a rectangular stainless steel container, as shown in Figure 6-3, and move constantly with a spatula to avoid clumps while it cools down.
- When it is cold submerge in a solution of 50% methylene chloride (200ml) and 50% of ethyl alcohol (200ml) for 2 hours, as shown in Figure 6-4.

Figure 6-3 Samples before Soaking

Figure 6-4 Samples during Soaking

- Strain the mix over the No. 8 sieve, as seen in Figure 6-5, and wash for 30 seconds with Mineral Spirits (200ml). Rinse with ethyl alcohol (200ml).

- Put the sample in the container again and add a solution of 85% methylene chloride (320ml) and 15% ethyl alcohol (80ml), and mix vigorously for one minute.
- Strain the mix on the No. 8 sieve and wash with ethyl alcohol (400ml), as seen in Figure 6-6.
- Let the sample air dry for 24 hours in the fume hood as shown in Figure 6-7.

Figure 6-5 Samples after First Soaking

Figure 6-6 Samples after Second Soaking

Figure 6-7 Samples after Completed Procedure

The method indicates that the remaining asphalt in the particles corresponds to the original binder present in the RAP. The more RAP, the more particles covered by this product. Figure 6-8 shows how the RAP aggregates look after the partial extraction. The same procedure was conducted for the 12 mixtures of the research matrix as shown in Figure 6-9 arranged by RAP content being in the bottom the 40% RAP mixes. Figure 6-10 shows the comparison of the mixtures with PG 58-34 as an example.

Figure 6-8 RAP Sample after Partial Extraction

From the Figure 6-9 and Figure 6-10 it is not clearly identified the difference between the mixtures at simple sight. The control mixtures also presented some small traces of asphalt after the partial extraction and the difference between the 20% RAP and the 40% RAP is not significant. This test might allow for identifying the presence of RAP when accompanied by a petrographic analysis, however, the amount of RAP cannot be easily determined.

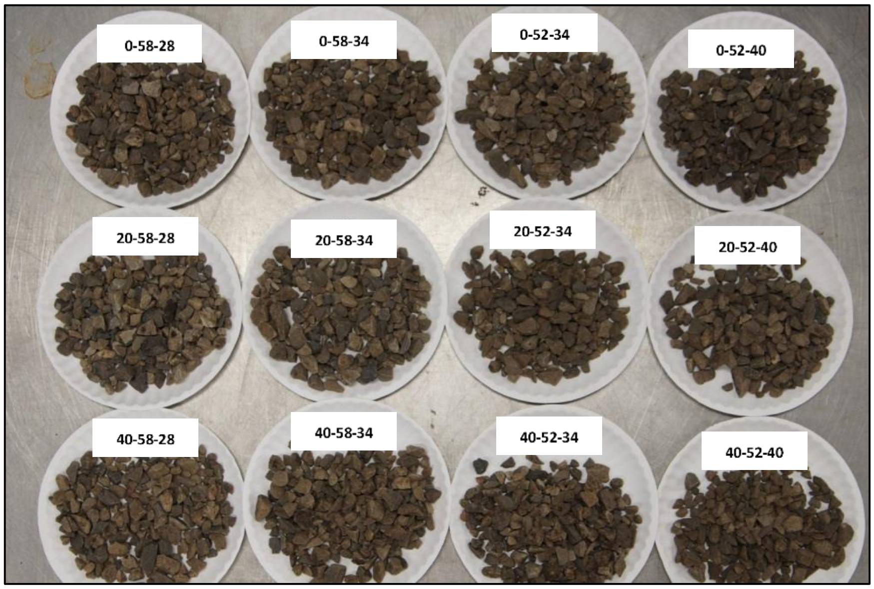

Figure 6-9 Mixtures after Partial Extraction

Figure 6-10 Comparison of Extracted Aggregates

6.4 Microscopy

The samples used for the dynamic modulus with MTS were cut to obtain a thin slice of approximately 1cm of the middle third. Those slices were then examined with an optical microscope to take pictures at micro-scale and study some suitable differences with the addition of RAP. Again the samples with the PG 58-34 are taken as example and shown in Figure 6-11.

It can be seen that some pockets of darker and brighter areas characterize the virgin binder. An interesting feature observed is that the density of these pockets in the images is less with increasing percentages of RAP. Thus, differences between the mixes, with the human eye are not easily detected between the entire blend of new and aged materials. This initial evaluation which detected differences could be continued in the future research on the RAP detection and RAP content determination.

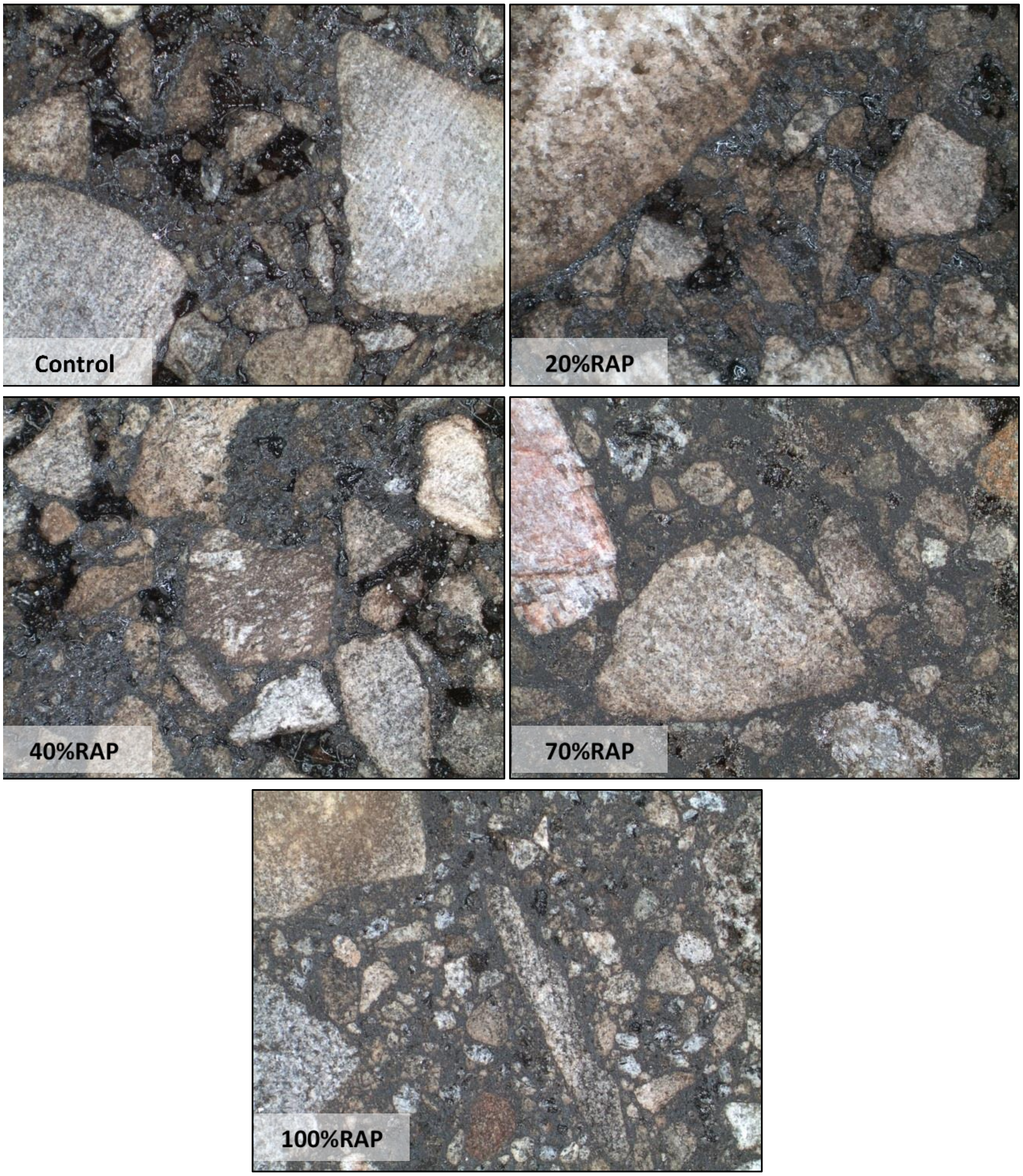

Figure 6-11 Optical Microscope Images

6.5 Summary and Conclusions

The RAP binder ratio estimated through the volumetric properties of the mixtures is higher than the maximum allowable RBR obtained with the blending charts, except for the 20% RAP PG 58-28, 20% RAP PG 52-40 and 40% RAP PG 52-40 where this condition was not exceeded.

The estimation of the RAP content, in terms of RAP Binder Ratio, is highly variable using the blending charts. The estimation using the TSRST failure temperature does not approach to the designed RBR in all cases.

Interestingly, a strong correlation was observed between the RAP percentage and the crushed faces, and the RAP percentage and the sand equivalent. Also, the analysis of the gradation yielded a strong correlation with the intercept of the fine portion, determined by the power-law method. This would likely vary depending on the RAP aggregates properties.

In terms of performance, it was observed that the RAP content explains the results for the flow number and the phase angle. However, the highest correlation was achieved for the fracture energy, for which a suitable correlation was obtained.

The quantification of RAP by partial extraction did not provide successful results. Given the mineralogy of the materials used, it appears that the physical characteristics of the RAP are similar to the virgin aggregates and did not allow identifying at simple sight the particles with traces of aged binder.

The microscopic techniques seem to be promising for the detection and quantification of RAP. The detection of RAP through image analysis would be an interesting research topic.

Based on the finding for this chapter Figure 6-12 summarizes the parameters more affected by the addition of RAP that could potentially be subject of further research.

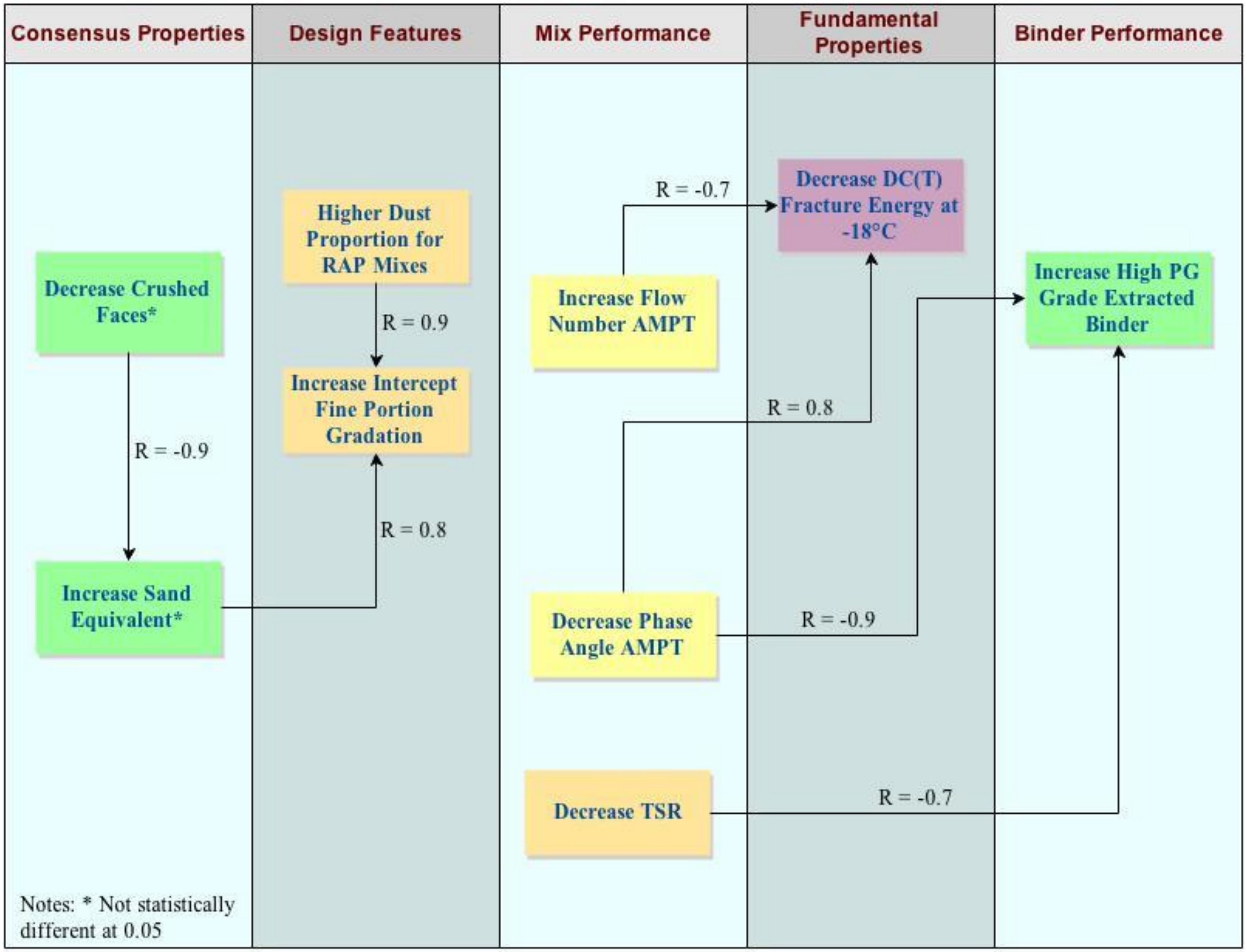

Figure 6-12 Flow Chart RAP Content Effect

Chapter 7
Conclusions and Recommendations

The major findings of this research are summarized in this chapter. Also the future research and recommendations based on those findings are further discussed. The conclusions are formulated based on the research hypothesis and specific objectives indicated in the introduction chapter.

7.1 Impact of RAP Addition in HMA

The purpose of this research was to evaluate the impact that RAP has on the SP12.5 mixture. From the designs, it was possible to observe that the addition of RAP affected the angularity of the fine aggregates and the resistance to moisture damage of the mixtures, where statistical differences were detected, however in practical terms the consensus properties of the aggregates were not dramatically affected by the addition of RAP.

The failure temperature for the PG 58-28 mixtures was not significantly affected, while for the rest of the mixtures, the analysis suggested that the failure temperature for the RAP mixtures is warmer than the control, which means that they would endure less cold. The addition of RAP did not affect significantly the fracture stress except for the mixes with PG 52-34. The addition of RAP seems to decrease the fracture energy.

The rut depth was not significantly affected by the addition of RAP except for the PG 52-40 where an improvement in the rutting potential was detected with the presence of RAP. In terms of creep slope, the addition of RAP did not have a significant effect with exception of the mixes with PG 52-34. The flow number allowed identifying a significant difference between the control and the RAP mixtures, indicating that the RAP mixtures are more resistant to rutting than the control mixtures.

The dynamic modulus results showed that the effect of RAP would not significantly impact the susceptibility to fatigue for the PG 58-xx. However for the PG 52-xx the stiffness of the RAP mixtures was evidently higher than the control mix, indicating that those mixtures might present more fatigue cracking.

7.2 RAP Content Detection

The intent of the research was primarily to formulate a method to determine the percentage of RAP in an already completed HMA. The research questions were: Can the RAP content be determine from the performance of the RHM? Which of the parameter was consistently affected by the addition of RAP?

Those questions were not easily answered, once the research showed that the performance depends simultaneously on the PG of the virgin binder and the content of RAP so this effect cannot be isolated. However it should be noted that the mixtures were carefully designed to meet the Superpave requirements, and for some of the performance tests the differences were not significant between the control mixtures and the RAP mixtures, or between the 20% RAP or the 40% RAP.

It can be concluded that the amount of RAP cannot be quantified from the performance tests, but the presence of RAP might be detected. Samples manufactured under the controlled conditions of the laboratory, under a careful design that meet the Superpave requirements, did not result in a method of detecting the RAP in the RHM. This may be associated with the degree of blending achieved in the laboratory. Given that the performance tests did not clearly identify the percentage of RAP, some physical methods were studied, from which the microscopic techniques seem to have promising future in this field.

From the design phase it was noticed that the RAP content could be related to a decrease in the crushed faces, and increases in the sand equivalent and an increase in the intercept of the fine portion of the gradation. However, the differences were not found to be significant, and obtaining a regression with those parameters was not possible. Similarly, the fracture energy and the flow number seem to exhibit a linear trend with the increase of the RAP content. A regression model for the estimation of the RAP content as a function of the fracture energy and the PG of the virgin asphalt was obtained.

It seems that the RAP source had similar characteristics with the minerals in the aggregates used, and this was the primary reason why the consensus properties and the physical characteristics of the combined aggregates did not show significant differences.

7.3 Blended Binder Critical Temperatures

The second module of this research focused on determining the characteristics of the resulting binder in the RHM. The research question was: Can the Performance Grade of the blended binder be determined?

The extracted and recovered binder from the mixtures shows the flaws of this method, given that in some mixtures, the critical temperature was even below what was obtained for the virgin binder, which might be attributed to the softening effect that the solvent might have or the variability of this test. One option to eliminate this confounding factor is to study the extracted and recovered binder from the virgin mixes as well.

In most cases, the blending charts allowed having an accurate estimate of the low critical temperature when compared to the actual failure temperature from the thermal stress restrained test (TSRST). The only case when the blending charts have results that could overestimate the critical temperature was for the PG 52-40, which is a modified binder.

It was possible to apply the Hirsch Model to the results from the dynamic modulus to obtain the complex modulus G* of the blended binder. The corresponding master curves were obtained with RHEA software, and the Superpave parameters for fatigue and thermal parameters were back-calculated. An improved method was proposed to obtain an estimation of the critical temperatures through the E* results.

7.4 Impact of Virgin Binder Performance Grade

The results obtained with the ANOVA two-factor analyses indicated that the performance of the mixtures was dependent on the PG of the virgin binder used; the impact of the use of softer binders in the performance is summarized as follows:

The PG had a significant effect on the TSRST failure temperature for all the RAP contents. The results indicated that using a softer binder would improve the thermal cracking susceptibility of the mixtures. The effect of changing the PG binder was significant for the 0% RAP and the 40% RAP mixes fracture stress.

The use of a different binder PG had a significant effect in the rut depth for the 20% RAP. The rutting potential seemed to be unaffected for the change of binder PG for the 0% RAP and 40% RAP mixes. The use of softer binders did not affect the creep slope.

The susceptibility to fatigue cracking was significantly affected by the PG of the virgin binder used except for the 40% RAP where the results were not statistically different. The use of softer binders improved or lowered the stiffness of the mixes; however, this improvement was not seen by the RAP mixes with PG 52-40 which had the opposite behavior.

The performance of the PG 52-40 mixtures was different than expected in all the tests and seems to be related to this type of binder as it was more affected by the addition of RAP. The effect that RAP has on this kind of mixes might be associated to the interaction and blending between the aged binder and the polymer modifiers used for this special type of binder. However, it would be suggested that further work on the PG 52-40 should be carried out.

7.5 Significant Contributions

This research studied the effect of the amount of RAP in the performance of typical SP12.5 HMA in Ontario. Also the effect of change in the binder grade have on the behavior of the recycled hot mix was analyzed.

This research detected the properties that are significantly affected by the addition of RAP when all the Superpave requirements are met. This narrowed the spectrum of testing effort for the determination of the presence and/or the quantity of RAP incorporated in a complete mixture.

As a result of this investigation, a multiple linear regression model to determine the quantity of RAP in the mix using the fracture energy of the material and the performance grade of the virgin binder was obtained for this research.

A method to obtain the performance grade of the blended binder through the results of the complex modulus of the mix was proposed. This method avoids the extraction and recovery of the binder and also can be applied in samples which RAP content is unknown.

The use of the blending charts to estimate the performance grade of the binder was validated. The similarity of the resulting low critical temperature with the failure temperature measured directly from the mixture with the TSRST confirms the reliability of this design method. However, the use of polymer modified binder requires special attention.

Considering that the most of the result of the mixtures with 40% RAP seems to converge, it can be concluded that the use of binder bump for mixes with RAP content above 20% might not necessarily improve significantly the performance of the recycled hot mix. This suggests the incorporation of a performance test during the design of the mix to select the most adequate virgin binder.

7.6 Recommendations

From the two different design approaches provided by the NCHRP Report 752, determining the critical temperature of the binder yielded a more consistent approximation to the results obtained through performance testing of the mixtures. The RAP binder ratio (RBR) did not seem to reflect the RAP content allowance.

The performance test that would allow a better characterization of RAP added mixtures is the dynamic modulus. This is a comprehensive test from which considerable information can be obtained and estimated. The TSRST test, specifically the failure temperature, was the only test that allows detecting differences for both factors: performance grade and RAP content for all the different mixes.

Considering that the extraction and recovery of the blended binder could not be always reliable, the Hirsch model can be applied to obtain the dynamic response of the blended binder from the results of the complex modulus and the volumetric properties of the mixtures.

The use of blending charts to estimate the performance grade of the blended binder is encouraged. The estimation obtained with the blending charts is consistent with the results from performance testing.

7.7 Future Research

The four point fatigue test would complement the conclusions obtained in this research. It is anticipated that the possible differences would not greatly impact the overall performance of the mix. However having a direct measure of this parameter would be valuable.

The correlation and regression analysis complements the conclusions drawn in this research. Future research should consider at least another two additional RAP contents, such as 15% and 30% RAP, to provide more information.

The preparation of samples was carefully controlled in the laboratory; but the effect of blending times and blending temperatures in the plant can play an important role in the interaction process between the aged binder in the RAP and the new materials. The study of plant produced mixtures, and field compacted specimens are necessary to validate the suggestions presented in this document.

Given that the performance and characteristics of the studied mixtures were similar, the detection and determination of the RAP content was not possible using qualitative techniques. In the future, the use of test at micro-scale or even nanoscale to study in detail the possible physical and chemical variations of the recycled hot mixtures should be considered. Also the petrographic analysis of the virgin and the RAP aggregates could provide useful information.

This research used only one source of RAP material. Given the high variability of the RAP from different locations with the age, the pavement type, and the environmental conditions; future research could incorporate the effect of the RAP source in the determination of the RAP content.

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Appendix A

Mix Designs

0% RAP PG 58-28

DBA ENGINEERING LTD.

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SUPERPAVE MIX DESIGN REPORT

Mix Number: 2119 **Project No.: 11-2115-01**
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering and University of Waterloo

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A

Test Data Certified By: Vince Aurilio, P.Eng.,

Date Sampled: 7-Dec-11
Date Completed: 7-Feb-12

Mix Type: 12.5 mm
Traffic Category: C
Asphalt Cement Type: 58-28
Asph. Cement Supplier: Canadian Asphalt
Mixing Temperature: 145 °C
Compaction Temperature: 134 °C

JOB MIX FORMULA GRADATION PERCENT PASSING

%AC / Sieves	% AC	50	37.5	25	19	16	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.08
JMF	5.2	100.0	100.0	100.0	100.0	100.0	98.3	84.8	52.9	43.5	30.6	19.8	9.5	4.3	3.2
	Percent	**Aggregate Gradation**													
CA 1	46	100.0	100.0	100.0	100.0	100.0	96.2	67.0	4.7	1.6	1.1	1.0	0.9	0.8	0.6
CA 2															
CA 3															
FA 1	26	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	96.4	55.1	30.8	15.3	7.9	3.5
FA 2	18	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.9	95.3	84.3	58.9	22.9	3.3	2.6
FA 3	10	100.0	100.0	100.0	100.0	100.0	100.0	100.0	69.2	5.6	2.6	1.7	1.4	1.2	0.9
FA 4															
RAP 1															
RAP 2															

	Selected	Specification	
BRD (Gmb)	2.440		
MRD(Gmm)	2.541		
% Air Voids (Va)	4.0	4	
% VMA	14.8	14	
% VFA	73.1	65	75
D/P	0.7	0.6	1.2
% Gmm @ ini	88.7	89	
% Gmm @ des	96	96	
% Gmm @ max	96.7	98	

% RAP	0.0
% AC From RAP	0.0
Virgin AC	5.2
Nini	7
Ndes	75
Nmax	115
Dust Returned	1.5
TSR	96.2 Spec. Min 80
Additive Supplier	N / A
Additive Type	N / A
% Additive	N / A
Briquette Wt.	4915
Recomp Temp	134
Water Absorp.	0.3

	Aggregate Name	Aggregate Source	Aggregate Inventory #
CA 1	HL-3 Stone	Capital Paving - Waynco Pit	Not Provided
CA 2			
CA 3			
FA 1	High Stability Sand	Lafarge - Dundas Quarry	H03-033
FA 2	Blend Sand	WSMI Pit	S11-050
FA 3	1/4" Chip	Capital Paving - Wellington Pit	C44-352
FA 4			
RAP 1			
RAP 2			

Coarse Specific Gravity	2.694
Coarse Absorption	1.44
Fine Specific Gravity	2.733
Fine Absorption	0.71
Combined Specific Gravity	2.714

1 The pass 4.75mm portion of the blend gradation has been adjusted for fines returned to mix.
2 No SSD air voids correction is required.
3 Gradation is based on Process control and sample results.

Professional Engineers Ontario CCIL Certified Concrete Testing Laboratory ohmpa ISO 9001

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SUPERPAVE MIX SUMMARY REPORT

Mix Number: 2119 **Project No.:** 11-2115-01 **Date:** 7-Feb-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering and University of Waterloo

Mix Type: 12.5 mm
Category: C
Mixing Temp: 145 °C
Compaction Temp: 134 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 7-Dec-11
Date Completed: 7-Feb-12

					N max		
Asphalt Cement	**4.7**	**5.2**	**5.7**	**6.2**	**5.2**	**Criteria**	
Bulk Specific Gravity (Gmb)	2.427	2.440	2.459	2.474	2.460		
Maximum Specific Gravity(Gmm)	2.563	2.541	2.525	2.504	2.543		
% Air Voids (Va)	5.3	4.0	2.6	1.2		4.0	4.0
% VMA	14.8	14.8	14.6	14.5		14.0	
% VFA	64.0	73.1	82.0	91.8		65.0	75.0
Dust / Asphalt Ratio	0.7	0.7	0.7	0.7		0.6	1.2
% Gmm @ ini	87.7	88.7	89.6	91.1	88.1		89.0
% Gmm @ des	94.7	96.0	97.4	98.8	95.6		96.0
% Gmm @ max					96.7		98.0

Specific Gravity of Aggregate (GSb) 2.714
Specific Gravity of Binder (Gb) 1.02

Input By: ____________

Verified By: ____________

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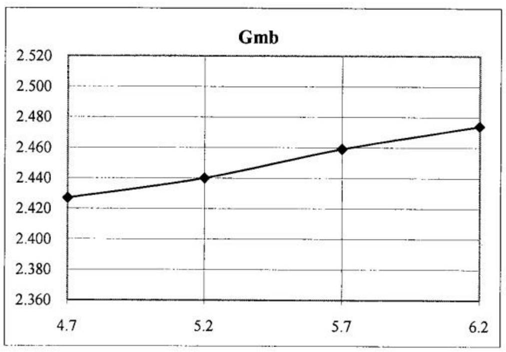

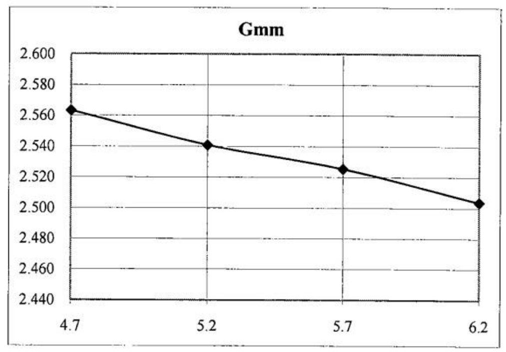

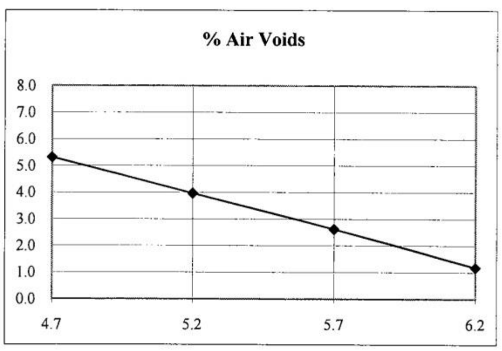

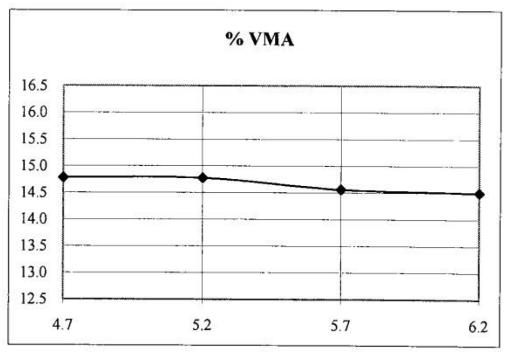

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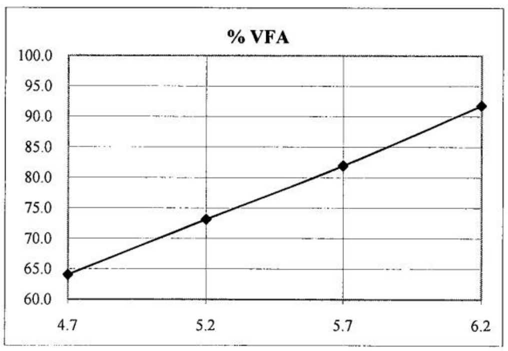
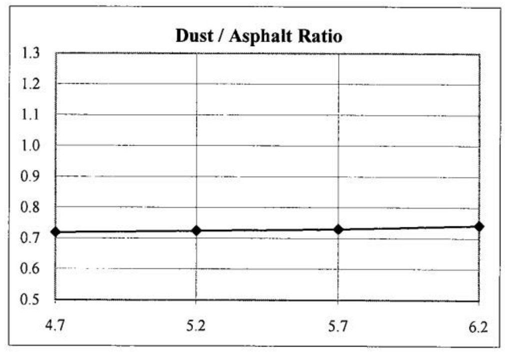
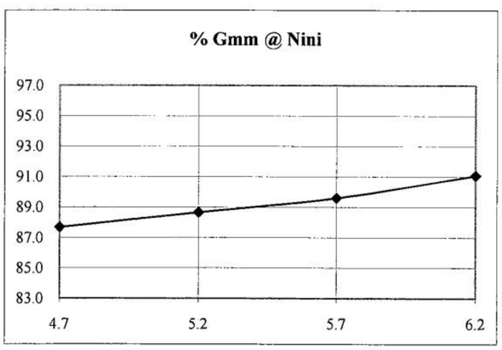
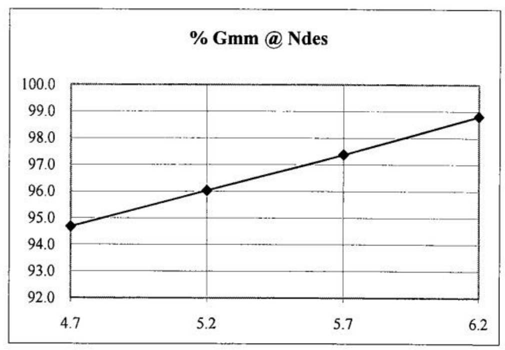
Mix Type: 12.5 mm
Category: C
Mixing Tempeture: 145 °C
Compaction Temp: 134 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 7-Dec-11
Date Completed: 7-Feb-12









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SUPERPAVE LABORATORY WORKSHEET

Mix Number: 2119
Mix Type: 12.5 mm
Category: C

Project No.: 11-2115-01
Contractor: University of Waterloo

Date: 7-Feb-12

										Nmax	
% Asphalt Cement		4.7		5.2		5.7		6.2		5.2	
Briquette Number		1	2	3	4	5	6	7	8	9	10
N ini	7	125.1	125.2	124.6	124.5	124.6	123.9	123	122.4	124.9	126.1
N des	75	115.8	116	115.1	114.9	114.7	114	113.3	112.9	115.4	115.9
Nmax	115									114.1	114.6
Wt in Air		4877.7	4876.1	4873.2	4875.6	4875.2	4873.3	4865.7	4855.6	4876.8	4874.1
SSD		4888.5	4886.4	4878.3	4880.6	4877.5	4875.2	4867.2	4856.7	4880.3	4877.6
Wt in water		2881.6	2874.5	2883.8	2879.8	2892.7	2895.8	2897.1	2897.4	2899.7	2894.3
Volume		2006.9	2011.9	1994.5	2000.8	1984.8	1979.4	1970.1	1959.3	1980.6	1983.3
BRD (Gmb)		**2.430**	**2.424**	**2.443**	**2.437**	**2.456**	**2.462**	**2.470**	**2.478**	**2.462**	**2.458**
Water Absorption		0.54	0.51	0.26	0.25	0.12	0.10	0.08	0.06	0.18	0.18

Flask Number	9	10	11	12
Flask & Mix air	2729	2607.9	2632	2694.6
Flask in air	646.5	636.8	644.4	604.1
Mix in air	2082.5	1971.1	1987.6	2090.5
Flask & Mix Water	1828.5	1751	1763	1791.2
Flask in Water	564.8	556.4	563	527.9
Mix in Water	1263.7	1194.6	1200	1263.3
Volume	818.8	776.5	787.6	827.2
MRD (Gmm)	**2.543**	**2.538**	**2.524**	**2.527**

Input By: ______________

Verified By: ______________

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Fax: (905) 851-0091

CONSENSUS PROPERTIES

Mix Number: 2119 **Project No.:** 11-2115-01 **Date:** 7-Feb-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering and University of Waterloo **Mix Type:** 12.5 mm
Category: C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 7-Dec-11
Date Completed: 7-Feb-12

COARSE AGGREGATE

	Min	Max	Blend
% Crushed 1 Face	85		99.8
% Crushed 2 Face	80		99.7
Flat and Elogated		10	0.0

FINE AGGREGATE

	Min	Max	Blend
Uncompacted Void	45		44.6
Sand Equivalent	45		57.0

Notes 1 As per SP No. 110F12M, uncompacted void content of 43 % is acceptable as long as the selected mix satisfies the mix volumetrics

Input By: ____________

Verified By: ____________

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Ontario

Ministry of Transportation

AGGREGATE TEST DATA – HOT MIX ASPHALT
Superpave - Consensus Properties (SSP 110S12)

Contract No.: MTO/OHMPA RAP Study	Contractor: University of Waterloo	Contract Location: DBA Engineering Ltd. & University of Waterloo	
Testing Laboratory: DBA Engineering Ltd.		Telephone No.: 905-851-0090	Fax No.: 905-851-0091
Sampled by (Print Name): University of Waterloo		Date Sampled: (YY/MM/DD) 11/12/07	2119
Mix Type: 12.5mm	Lot No.:	Quantity (tonnes):	

FINE AGGREGATE(S)

Source Name & Location	Aggregate Inventory Number (AIN)	Pit (P) or Quarry (Q)	% of Mix
Mix # 2119			

Laboratory Test and Number		Requirement: Traffic Level Category A	B	C	D	E	Test Result: Sample	Meets Requirement (Y / N)
LS-629 Uncompacted Void Content, % Minimum	≤100 mm (Note 1)	–	40	45 (Note 3)	45 (Note 3)	45 (Note 3)	44.6	Y
	>100 mm (Note 1)	–	40	40	40	45 (Note 3)	-	-
AASHTO T176 Sand Equivalent Method 1, % minimum, (Note 2)		40	40	45	45	50	57	Y

COARSE AGGREGATE(S)

Source Name & Location	Aggregate Inventory Number (AIN)	Pit (P) or Quarry (Q)	% of Mix
Mix # 2119			

Laboratory Test and Number		Requirement: Traffic Level Category A	B	C	D	E	Test Result: Sample	Meets Requirement (Y / N)
ASTM D 5821 Fractured Particles in Coarse Aggregate, % minimum, (Note 4)	≤100 mm (Note 1)	55/-	75/-	85/80	95/90	100/100	99.8/99.7	Y
	>100 mm (Note 1)	–	50/-	60/-	80/75	100/100	-	-
ASTM D 4791 Flat and Elongated Particles (5:1), % maximum		–	10				0	Y

Notes:
1. Denotes the depth of the top of lift below the final pavement surface. If less than 25% of a layer is within 100 mm of the surface, the layer may be considered to be below 100 mm.
2. Where the total combined fine aggregate includes aggregate derived from RAP or RST or both, this requirement shall be met prior to blending with RAP or RST or both.
3. A minimum uncompacted void content of 43% is acceptable provided that the selected mix satisfies the mix volumetrics specified elsewhere in the Contract Documents.
4. 85/80 denotes that 85% of the coarse aggregate has one fractured face and 80% has two or more fractured faces.

Issued by (Testing Laboratory Representative):

Kevin Jackson (PRINT NAME) — Kevin Jackson (SIGNATURE) — Feb. 7/12 (DATE)

Received by (Contract Administrator Representative):

PRINT NAME — SIGNATURE — DATE

Copies to: ☐ Contract Administrator; ☐ Contractor; ☐ Regional Quality Assurance; ☐ Regional Geotechnical; ☐ MERO (Soils and Aggregates)

PH-CC-449c June-11

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ASPHALTIC CONCRETE MOISTURE SUSCEPTIBILITY TEST REPORT

AASHTO Designation: T283-07

Project No.:	11-2115-01	**Mix Type:**	12.5 mm
Contract No.:	MTO / OHMPA RAP Study	**Mix No.:**	2119
Location:	DBA and University of Waterloo	**Additive**	N / A
Client:	University of Waterloo	**Dose:**	0.0
Date:	February 7, 2012	**A.C. Type:**	58-28

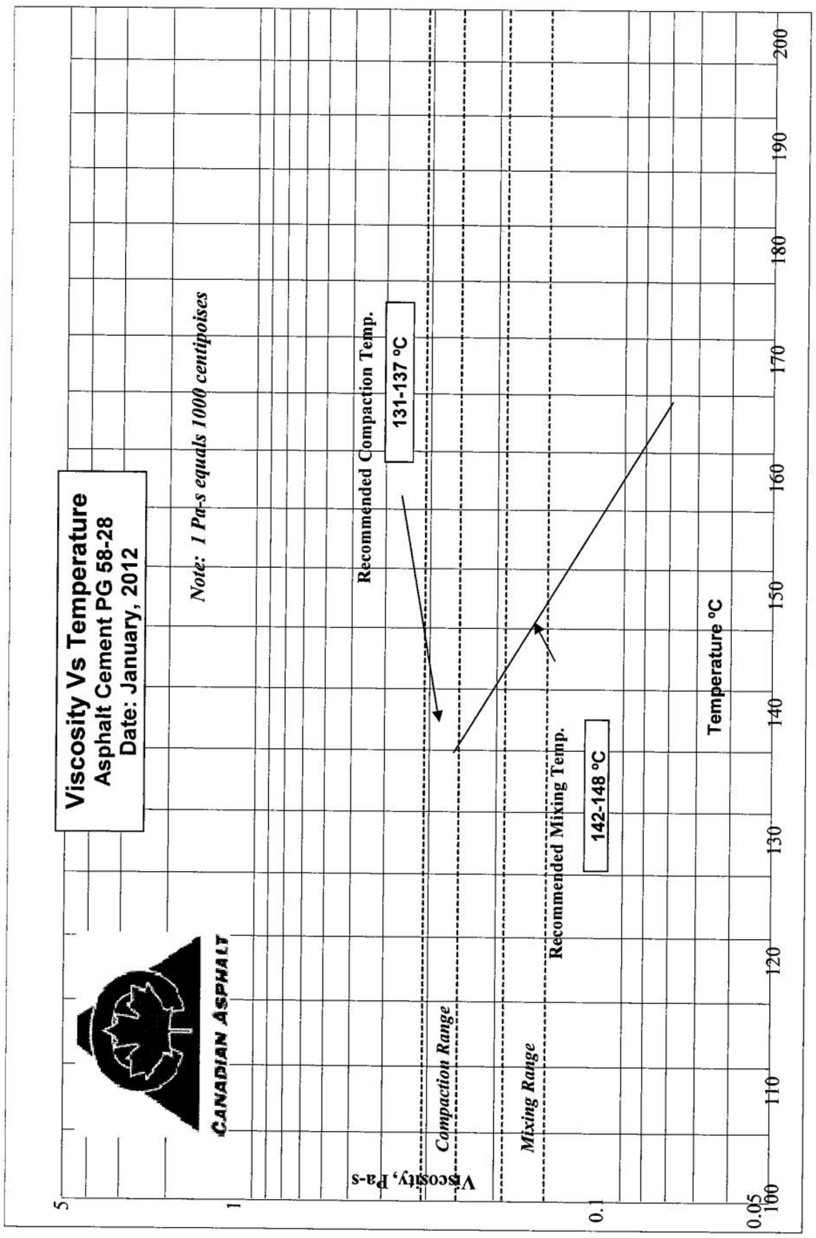
	Dry Subset				**Conditioned Subset**			
	1	**3**	**5**	**Average**	**2**	**4**	**6**	**Average**
Specimen Diameter (mm)	150	150	150		150	150	150	
Specimen Height (mm)	95.0	95.0	95.0		95.0	95.0	95.0	
Dry Mass in Air	3887.1	3883.0	3887.5		3881.0	3885.2	3886.4	
SSD Mass, g	3907.4	3906.3	3909.4		3904.3	3906.1	3907.1	
Mass in Water,g	2263.1	2254.2	2262.5		2253.3	2261.9	2263.8	
Volume, cc	1644.3	1652.1	1646.9		1651.0	1644.2	1643.3	
Bulk Specific Gravity	2.364	2.350	2.360		2.351	2.363	2.365	
Maximum Specific Gravity	2.541	2.541	2.541	**2.541**	2.541	2.541	2.541	**2.541**
Percent Air Voids	7.0	7.5	7.1	**7.2**	7.5	7.0	6.9	**7.1**
Volume of Air	114.548	123.961	116.991		123.649	115.196	113.823	
Thickness, mm					95.000	95.100	95.000	
SSD Mass, g					3970	3971	3970	
Vol of Absorbed Water					89.0	85.7	83.4	
Percent Saturation					72.0	74.4	73.3	**73.2**
Maximum Load (Newtons)	10500	9650	10800		9050	10200	10550	
Tensile Strength (kPa)	469	431	482	**461**	404	455	471	**443**
Tensile Strength Ratio (%)								**96.2**
Visual Moisture Damage Rating (No = 0 to Most Stripped = 5)								**1**
Cracked / Broken Aggregate (Nil / Slight / Medium / High)								**Slight**

Comments:

DBA Engineering Ltd.

ASP-216-00

Vince Aurilio, P. Eng.



Viscosity Vs Temperature
Asphalt Cement PG 58-28
Date: January, 2012
CANADIAN ASPHALT
Note: 1 Pa-s equals 1000 centipoises
Recommended Compaction Temp.
131-137 °C
Recommended Mixing Temp.
142-148 °C
Compaction Range
Mixing Range
Viscosity, Pa-s
Temperature °C
5
1
0.1
0.05
100
110
120
130
140
150
160
170
180
190
200

40% RAP PG 58-28

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SUPERPAVE MIX DESIGN REPORT

Mix Number: 2120 **Project No.: 11-2115-01**
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A

Test Data Certified By: Vince Aurilio, P.Eng.,

Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12

Mix Type: 12.5 mm
Traffic Category: C
Asphalt Cement Type: 58-28
Asph. Cement Supplier: Canadian Asphalt
Mixing Temperature: 145 °C
Compaction Temperature: 134 °C

JOB MIX FORMULA GRADATION PERCENT PASSING

%AC / Sieves	% AC	50	37.5	25	19	16	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.08
JMF	5.1	100.0	100.0	100.0	100.0	100.0	98.6	85.3	52.8	46.1	30.8	20.7	12.1	7.4	4.6
	Percent	Aggregate Gradation													
CA 1	35	100.0	100.0	100.0	100.0	100.0	96.2	67.0	4.7	1.6	1.1	1.0	0.9	0.8	0.6
CA 2															
CA 3															
FA 1	25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	96.4	55.1	30.8	15.3	7.9	3.5
FA 2															
FA 3															
FA 4															
RAP 1	40	100.0	100.0	100.0	100.0	100.0	99.8	92.2	65.3	53.6	41.5	31.5	19.8	13.0	8.7
RAP 2															

	Selected	Specification	
BRD (Gmb)	2.451		
MRD(Gmm)	2.553		
% Air Voids (Va)	4.0	4	
% VMA	14.3	14	
% VFA	72.1	65	75
D/P	1.1	0.6	1.2
% Gmm @ ini	88.1	89	
% Gmm @ des	96	96	
% Gmm @ max	97.1	98	

2.7773

TSR	92.1 Spec. Min 80
Additive Supplier	N / A
Additive Type	N / A
% Additive	N / A

% RAP	40.0
% AC From RAP	1.8
Virgin AC	3.3

Nini	7
Ndes	75
Nmax	115
Dust Returned	0.0
Briquette Wt.	4936
Recomp Temp.	134
Water Absorp.	0.3

	Aggregate Name	Aggregate Source	Aggregate Inventory #
CA 1	HL-3 Stone	Capital Paving - Waynco Pit	Not Provided
CA 2			
CA 3			
FA 1	High Stability Sand	Lafarge - Dundas Quarry	H03-033
FA 2			
FA 3			
FA 4			
RAP 1	Capital Paving - Fine RAP	Capital Paving - Fine RAP	
RAP 2			

Coarse Specific Gravity	2.707
Coarse Absorption	1.08
Fine Specific Gravity	2.722
Fine Absorption	0.94
Combined Specific Gravity	2.715

1 The pass 4.75mm portion of the blend gradation has been adjusted for fines returned to mix.
2 No SSD air voids correction is required.
3 Gradation is based on Process control and sample results.

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SUPERPAVE MIX SUMMARY REPORT

Mix Number: 2120 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Mix Type: 12.5 mm
Category: C
Mixing Temp: 145 °C
Compaction Temp: 134 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12

					N max		
Asphalt Cement	**4.6**	**5.1**	**5.6**	**6.1**	**5.2**	**Criteria**	
Bulk Specific Gravity (Gmb)	2.440	2.451	2.472	2.481	2.472		
Maximum Specific Gravity(Gmm)	2.571	2.553	2.529	2.511	2.547		
% Air Voids (Va)	5.1	4.0	2.3	1.2		4.0	4.0
% VMA	14.3	14.3	14.0	14.2		14.0	
% VFA	64.1	72.2	83.9	91.6		65.0	75.0
Dust / Asphalt Ratio	1.07	1.05	1.10	1.08		0.6	1.2
% Gmm @ ini	87.5	88.1	89.5	90.6	87.8		89.0
% Gmm @ des	94.9	96.0	97.7	98.8	95.8		96.0
% Gmm @ max					97.0		98.0

Specific Gravity of Aggregate (GSb) 2.715
Specific Gravity of Binder (Gb) 1.02

Input By: ____________________ **Verified By:** ____________________

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SUPERPAVE LABORATORY WORKSHEET

Mix Number: 2120 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Mix Type: 12.5 mm **Contractor:** University of Waterloo
Category: C

										Nmax	
% Asphalt Cement		4.6		5.1		5.6		6.1		5.2	
Briquette Number		1	2	3	4	5	6	7	8	9	10
N ini	7	123.7	124.6	125.4	124.9	123.4	124.2	121.5	124.4	125.2	126.3
N des	75	114.2	114.8	115	114.7	113	113.7	112	113.4	114.8	115.6
Nmax	115									113.4	114.1
Wt in Air		4879.8	4882.1	4879.8	4880	4876.9	4878.4	4873.7	4875.3	4879.4	4883.7
SSD		4888.6	4891.8	4885	4884.8	4878.4	4880.2	4874.4	4876.9	4882	4886.8
Wt in water		2886.6	2892.3	2891.8	2896.1	2905.5	2907.3	2908.8	2913.8	2912.2	2906.8
Volume		2002	1999.5	1993.2	1988.7	1972.9	1972.9	1965.6	1963.1	1969.8	1980
BRD (Gmb)		**2.437**	**2.442**	**2.448**	**2.454**	**2.472**	**2.473**	**2.479**	**2.483**	**2.477**	**2.467**
Water Absorption		0.44	0.49	0.26	0.24	0.08	0.09	0.04	0.08	0.13	0.16

Flask Number	11	12	11	12
Flask & Mix air	2597.8	2570.3	2633.2	2567.8
Flask in air	644.4	604.1	644.4	604.1
Mix in air	1953.4	1966.2	1988.8	1963.7
Flask & Mix Water	1752.2	1722.8	1766.1	1714.7
Flask in Water	563	527.9	563	527.9
Mix in Water	1189.2	1194.9	1203.1	1186.8
Volume	764.2	771.3	785.7	776.9
MRD (Gmm)	**2.556**	**2.549**	**2.531**	**2.528**

Input By: __________ **Verified By:** __________

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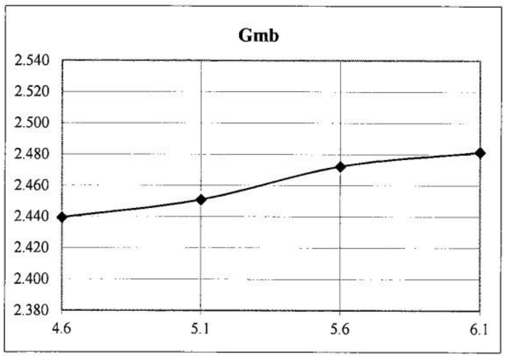
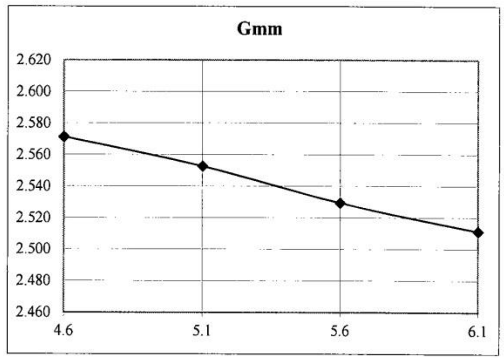
SUPERPAVE MIX SUMMARY REPORT

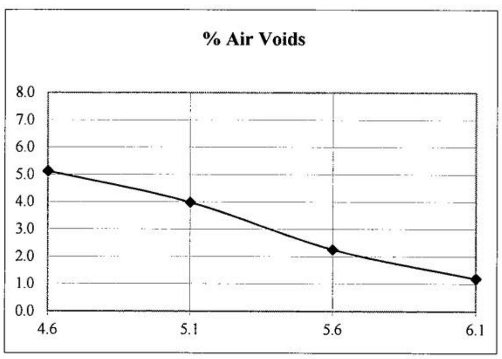
Mix Number: 2120 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

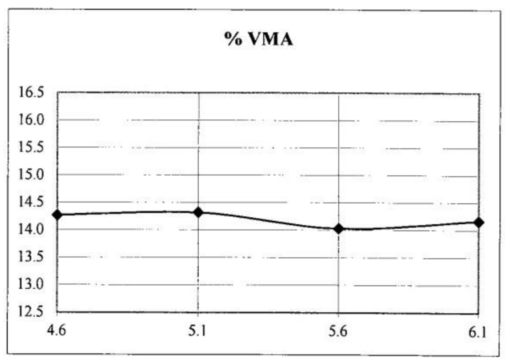
Mix Type: 12.5 mm
Category: C
Mixing Tempeture: 145 °C
Compaction Temp: 134 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12









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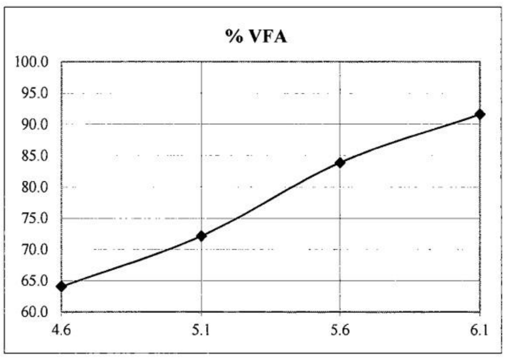
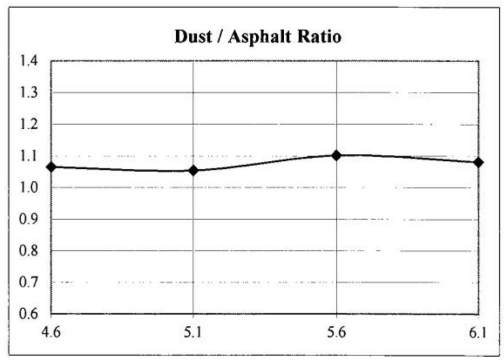
SUPERPAVE MIX SUMMARY REPORT

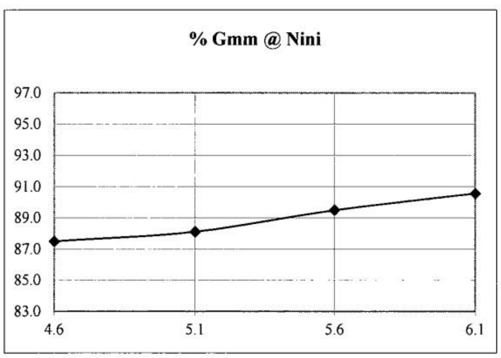
Mix Number: 2120 **Project No.:** 11-2115-01 **Date:** 12-Mar-12

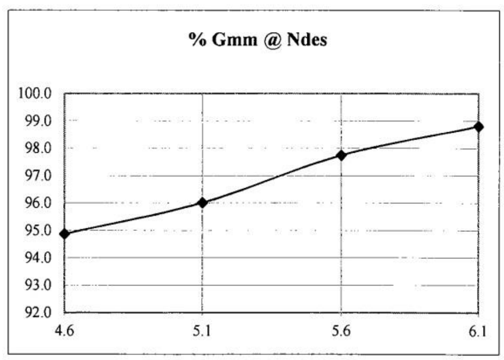
Contract:	MTO / OHMPA RAP Study
Location:	DBA Engineering Ltd. and University of Waterloo
Item Number:	N / A
Contractor:	University of Waterloo
Client:	University of Waterloo
Plant Location:	N / A
Date Sampled:	07-Dec-11
Date Completed:	12-Mar-12

Mix Type:	12.5 mm
Category:	C
Mixing Tempeture:	145 °C
Compaction Temp:	134 °C









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CONSENSUS PROPERTIES

Mix Number:	2120	**Project No.:** 11-2115-01	**Date:** 12-Mar-12
Contract:	MTO / OHMPA RAP Study		
Location:	DBA Engineering Ltd. and University of Waterloo	**Mix Type:**	12.5 mm
		Category:	C
Item Number:	N / A		
Contractor:	University of Waterloo		
Client:	University of Waterloo		
Plant Location:	N / A		
Date Sampled:	07-Dec-11		
Date Completed:	12-Mar-12		

COARSE AGGREGATE

	Min	Max	Blend
% Crushed 1 Face	**85**		97.2
% Crushed 2 Face	**80**		96.9
Flat and Elogated		**10**	0.7

FINE AGGREGATE

	Min	Max	Blend
Uncompacted Void	**45**		44.4
Sand Equivalent	**45**		88.0

Notes 1 As per SP No. 110F12M, uncompacted void content of 43 % is acceptable as long as the selected mix satisfies the mix volumetrics

Input By: ____________________ **Verified By:** ____________________

Ontario

Ministry of Transportation

AGGREGATE TEST DATA – HOT MIX ASPHALT
Superpave - Consensus Properties (SSP 110S12)

Contract No.: MTO/OHMPA RAP Study	Contractor: University of Waterloo	Contract Location: DBA Engineering Ltd. & University of Waterloo	
Testing Laboratory: DBA Engineering Ltd.		Telephone No.: 905-851-0090	Fax No.: 905-851-0091
Sampled by (Print Name): University of Waterloo		Date Sampled: (YY/MM/DD) 11/12/07	
Mix Type: 12.5mm	Lot No.:	Quantity (tonnes):	

2120

FINE AGGREGATE(S)

Source Name & Location: Mix # 2120	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:

Laboratory Test and Number		Requirement – Traffic Level Category A	B	C	D	E	Test Result – Sample	Meets Requirement (Y / N)
LS-629 Uncompacted Void Content, % Minimum	≤100 mm (Note 1)	–	40	45 (Note 3)	45 (Note 3)	45 (Note 3)	44.4	Y
	>100 mm (Note 1)	–	40	40	40	45 (Note 3)	-	-
AASHTO T176 Sand Equivalent Method 1, % minimum, (Note 2)		40	40	45	45	50	88	Y

COARSE AGGREGATE(S)

Source Name & Location: Mix # 2120	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:

Laboratory Test and Number		Requirement – Traffic Level Category A	B	C	D	E	Test Result – Sample	Meets Requirement (Y / N)
ASTM D 5821 Fractured Particles in Coarse Aggregate, % minimum, (Note 4)	≤100 mm (Note 1)	55/-	75/-	85/80	95/90	100/100	97.2/96.9	Y
	>100 mm (Note 1)	–	50/-	60/-	80/75	100/100	-	-
ASTM D 4791 Flat and Elongated Particles (5:1), % maximum		–	10				0.7	Y

Notes:

1. Denotes the depth of the top of lift below the final pavement surface. If less than 25% of a layer is within 100 mm of the surface, the layer may be considered to be below 100 mm.
2. Where the total combined fine aggregate includes aggregate derived from RAP or RST or both, this requirement shall be met prior to blending with RAP or RST or both.
3. A minimum uncompacted void content of 43% is acceptable provided that the selected mix satisfies the mix volumetrics specified elsewhere in the Contract Documents.
4. 85/80 denotes that 85% of the coarse aggregate has one fractured face and 80% has two or more fractured faces.

Issued by (Testing Laboratory Representative):

Kevin Jackson (PRINT NAME) — Kevin Jackson (SIGNATURE) — Feb. 24/12 (DATE)

Received by (Contract Administrator Representative):

PRINT NAME — SIGNATURE — DATE

Copies to: ☐ Contract Administrator; ☐ Contractor; ☐ Regional Quality Assurance; ☐ Regional Geotechnical; ☐ MERO (Soils and Aggregates)

PH-CC-449c June-11

DBA ENGINEERING LTD.

DHILLON BURLEIGH & ASSOCIATES
Consulting Engineers

401 Hanlan Road
Vaughan, Ontario L4L 3T1

ASPHALTIC CONCRETE MOISTURE SUSCEPTIBILITY TEST REPORT

AASHTO Designation: T283-07

Project No.:	11-2115-01	**Mix Type:**	12.5 mm
Contract No.:	MTO / OHMPA RAP Study	**Mix No.:**	2120
Highway:	DBA Engineering Ltd. and Unive	**Additive**	N / A
Client:	University of Waterloo	**Dose:**	0.0
Date:	March 12, 2012	**A.C. Type:**	58-28

	Dry Subset				Conditioned Subset			
	2	**3**	**4**	**Average**	**1**	**5**	**6**	**Average**
Specimen Diameter (mm)	150	150	150		150	150	150	
Specimen Height (mm)	94.7	94.8	94.9		94.6	94.7	94.7	
Dry Mass in Air	3885.0	3883.1	3887.2		3890.2	3886.2	3882.2	
SSD Mass, g	3910.3	3909.3	3913.1		3914.7	3911.6	3914.1	
Mass in Water,g	2271.1	2265.0	2271.6		2274.1	2269.4	2269.9	
Volume, cc	1639.2	1644.3	1641.5		1640.6	1642.2	1644.2	
Bulk Specific Gravity	2.370	2.362	2.368		2.371	2.366	2.361	
Maximum Specific Gravity	2.553	2.553	2.553	**2.553**	2.553	2.553	2.553	**2.553**
Percent Air Voids	7.2	7.5	7.2	**7.3**	7.1	7.3	7.5	**7.3**
Volume of Air	117.461	123.305	118.899		116.824	119.991	123.558	
Thickness, mm					94.800	94.800	94.800	
SSD Mass, g					3978	3976	3976	
Vol of Absorbed Water					87.8	90.1	93.4	
Percent Saturation					75.2	75.1	75.6	**75.3**
Maximum Load (Newtons)	17000	16050	16750		15650	15250	15000	
Tensile Strength (kPa)	762	718	749	**743**	700	682	671	**685**
Tensile Strength Ratio (%)								**92.1**
Visual Moisture Damage Rating (No = 0 to Most Stripped = 5)								**0**
Cracked / Broken Aggregate (Nil / Slight / Medium / High)								**Slight**

Comments:

DBA Engineering Ltd.

20% RAP PG 58-34

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Fax: (905) 851-0091

SUPERPAVE MIX DESIGN REPORT

Mix Number: 2121 **Project No.: 11-2115-01**
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A

Mix Type: 12.5 mm
Traffic Category: C
Asphalt Cement Type: 58-34
Asph. Cement Supplier: Coco AE
Mixing Temperature: 151 °C
Compaction Temperature: 139 °C

Test Data Certified By:
Vince Aurilio, P.Eng.,

JOB MIX FORMULA GRADATION PERCENT PASSING

%AC / Sieves	% AC	50	37.5	25	19	16	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.08
JMF	5.2	100.0	100.0	100.0	100.0	100.0	98.4	84.6	53.0	48.0	30.1	19.2	11.4	7.5	5.3
	Percent	Aggregate Gradation													
CA 1	42	100.0	100.0	100.0	100.0	100.0	96.2	67.0	4.7	1.6	1.1	1.0	0.9	0.8	0.6
CA 2															
CA 3															
FA 1	38	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	96.4	55.1	30.8	15.3	7.9	3.5
FA 2															
FA 3															
FA 4															
RAP 1	20	100.0	100.0	100.0	100.0	100.0	99.8	92.2	65.3	53.6	41.5	31.5	19.8	13.0	8.7
RAP 2															

	Selected	Specification		
BRD (Gmb)	2.446			
MRD(Gmm)	2.547			
% Air Voids (Va)	4.0	4		
% VMA	14.7	14		
% VFA	73.1	65	75	
D/P	1.2	0.6	1.2	2.7749
% Gmm @ ini	87.6	89		
% Gmm @ des	96	96		
% Gmm @ max	97.3	98		

% RAP	20.0
% AC From RAP	0.9
Virgin AC	4.3

Nini	7
Ndes	75
Nmax	115

TSR	98.7 Spec. Min 80
Additive Supplier	N / A
Additive Type	N / A
% Additive	N / A

Dust Returned	2.0
Briquette Wt.	4928
Recomp Temp	139
Water Absorp.	0.3

	Aggregate Name	Aggregate Source	Aggregate Inventory #
CA 1	HL-3 Stone	Nellson Aggreg. - Waynco Pit	Not Provided
CA 2			
CA 3			
FA 1	High Stability Sand	Lafarge - Dundas Quarry	H03-033
FA 2			
FA 3			
FA 4			
RAP 1	Capital Paving - Fine RAP	Capital Paving - Fine RAP	
RAP 2			

Coarse Specific Gravity	2.693
Coarse Absorption	1.31
Fine Specific Gravity	2.745
Fine Absorption	0.79
Combined Specific Gravity	2.720

1 The pass 4.75mm portion of the blend gradation has been adjusted for fines returned to mix.
2 No SSD air voids correction is required.
3 Gradation is based on Process control and sample results.

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SUPERPAVE MIX SUMMARY REPORT

Mix Number: 2121 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Mix Type: 12.5 mm
Category: C
Mixing Temp: 151 °C
Compaction Temp: 139 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12

					N max		
Asphalt Cement	**4.7**	**5.2**	**5.7**	**6.2**	**5.2**	**Criteria**	
Bulk Specific Gravity (Gmb)	2.434	2.446	2.465	2.485	2.481		
Maximum Specific Gravity(Gmm)	2.569	2.547	2.530	2.509	2.549		
% Air Voids (Va)	5.3	4.0	2.6	1.0		4.0	4.0
% VMA	14.7	14.7	14.5	14.3		14.0	
% VFA	64.3	73.2	82.3	93.2		65.0	75.0
Dust / Asphalt Ratio	1.2	1.2	1.2	1.2		0.6	1.2
% Gmm @ ini	86.6	87.6	88.9	90.8	87.2		89.0
% Gmm @ des	94.7	96.0	97.4	99.0	96.1		96.0
% Gmm @ max					97.3		98.0

Specific Gravity of Aggregate (GSb) 2.720
Specific Gravity of Binder (Gb) 1.02

Input By: ____________________ **Verified By:** ____________________

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SUPERPAVE LABORATORY WORKSHEET

Mix Number: 2121 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Mix Type: 12.5 mm **Contractor:** University of Waterloo
Category: C

										Nmax	
% Asphalt Cement		4.7		5.2		5.7		6.2		5.2	
Briquette Number		1	2	3	4	5	6	7	8	9	10
N ini	7	126.8	126.2	126.8	126.6	124.1	125	124.9	121.7	126.4	127.8
N des	75	115.8	115.5	115.8	115.4	113.1	114.1	113.7	112.3	115.2	115.5
Nmax	115									113.7	114.0
Wt in Air		4910.5	4904	4908.3	4905.2	4911.4	4906.7	4910.6	4901.2	4903.2	4909.5
SSD		4920.5	4914	4914.5	4911.6	4912.9	4908.7	4911.7	4902.2	4906	4912.4
Wt in water		2900.7	2901.4	2906	2908	2920	2919.1	2934.8	2930.1	2929.5	2933.5
Volume		2019.8	2012.6	2008.5	2003.6	1992.9	1989.6	1976.9	1972.1	1976.5	1978.9
BRD (Gmb)		**2.431**	**2.437**	**2.444**	**2.448**	**2.464**	**2.466**	**2.484**	**2.485**	**2.481**	**2.481**
Water Absorption		0.50	0.50	0.31	0.32	0.08	0.10	0.06	0.05	0.14	0.15
Flask Number				11	12	9	10				
Flask & Mix air				2631.5	2656.8	2672.9	2668.5				
Flask in air				644.4	604.1	646.5	636.8				
Mix in air				1987.1	2052.7	2026.4	2031.7				
Flask & Mix Water				1769.1	1775.3	1790.6	1785				
Flask in Water				563	527.9	564.8	556.4				
Mix in Water				1206.1	1247.4	1225.8	1228.6				
Volume				781	805.3	800.6	803.1				
MRD (Gmm)				**2.544**	**2.549**	**2.531**	**2.530**				

Input By: ______________________ **Verified By:** ______________________

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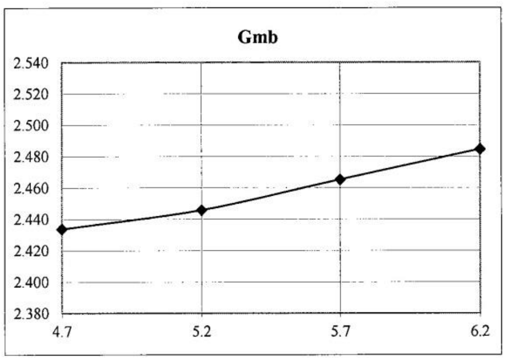
Fax: (905) 851-0091

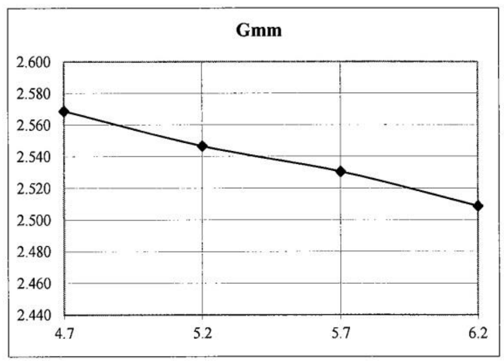
SUPERPAVE MIX SUMMARY REPORT

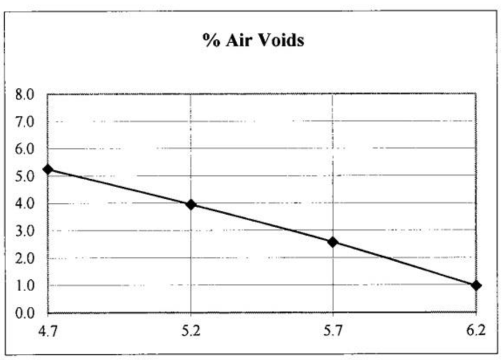
Mix Number: 2121 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

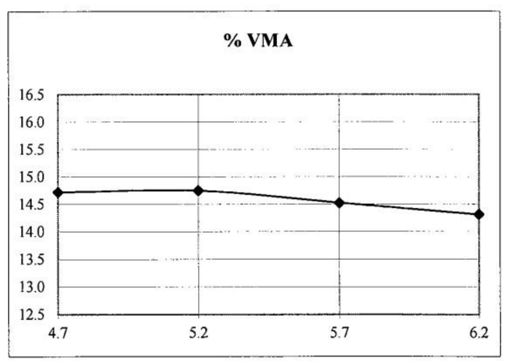
Mix Type: 12.5 mm
Category: C
Mixing Tempeture: 151 °C
Compaction Temp: 139 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12









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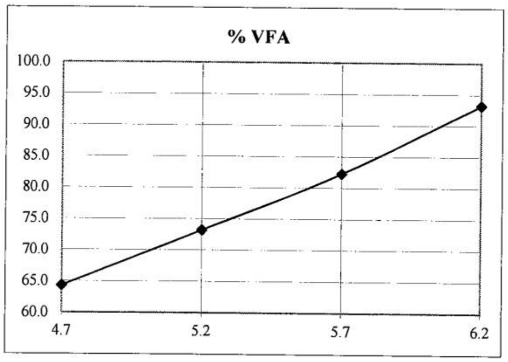
Toll Free: 1-800-819-8833
Fax: (905) 851-0091

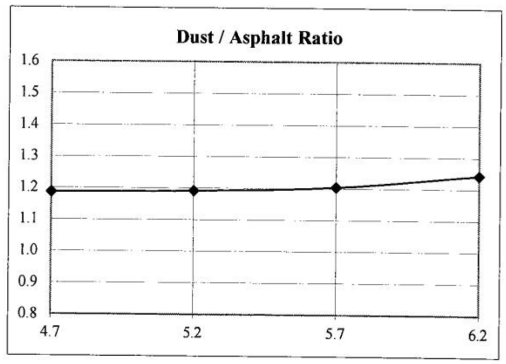
SUPERPAVE MIX SUMMARY REPORT

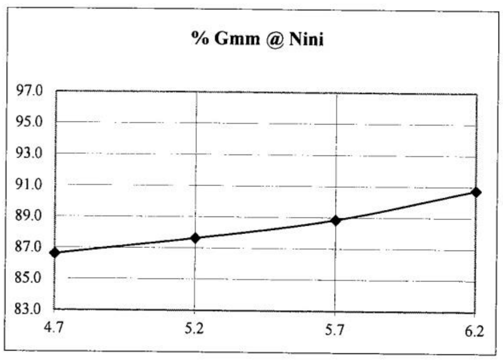
Mix Number: 2121 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

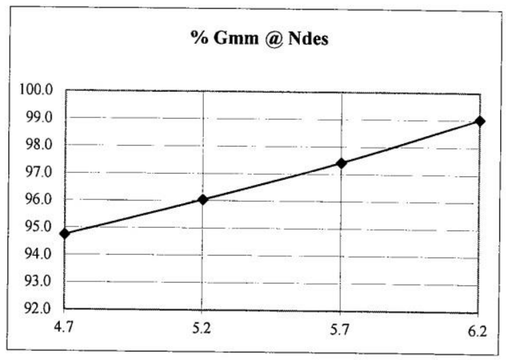
Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12

Mix Type: 12.5 mm
Category: C
Mixing Tempeture: 151 °C
Compaction Temp: 139 °C









Professional Engineers Ontario CCIL Certified Concrete Testing Laboratory ohmpa ISO 9001

ENGINEERING RESEARCH DEVELOPMENT

Offices in Greater Toronto, Kingston & Trenton

DBA ENGINEERING LTD.

DHILLON BURLEIGH & ASSOCIATES
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CONSENSUS PROPERTIES

Mix Number: 2121 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo **Mix Type:** 12.5 mm
Category: C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12

COARSE AGGREGATE

	Min	Max	Blend
% Crushed 1 Face	85		98.4
% Crushed 2 Face	80		98.2
Flat and Elogated		10	0.1

FINE AGGREGATE

	Min	Max	Blend
Uncompacted Void	45		45.9
Sand Equivalent	45		73.0

Notes 1 As per SP No. 110F12M, uncompacted void content of 43 % is acceptable as long as the selected mix satisfies the mix volumetrics

Input By: ____________ **Verified By:** ____________

Professional Engineers Ontario CCIL Certified Concrete Testing Laboratory ohmpa ONTARIO HOT MIX PRODUCERS ASSOCIATION ISO 9001

ENGINEERING RESEARCH DEVELOPMENT

Offices in Greater Toronto, Kingston & Trenton

Ontario

Ministry of Transportation

AGGREGATE TEST DATA – HOT MIX ASPHALT
Superpave - Consensus Properties (SSP 110S12)

Contract No.: MTO/OHMPA RAP Study	Contractor: University of Waterloo	Contract Location: DBA Engineering Ltd. & University of Waterloo
Testing Laboratory: DBA Engineering Ltd.	Telephone No.: 905-851-0090	Fax No.: 905-851-0091
Sampled by (Print Name): University of Waterloo	Date Sampled: (YY/MM/DD) 11/12/07	
Mix Type: 12.5mm / Lot No.:	Quantity (tonnes):	

2121

FINE AGGREGATE(S)

Source Name & Location: Mix # 2121	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:

Laboratory Test and Number		Requirement – Traffic Level Category A	B	C	D	E	Test Result – Sample	Meets Requirement (Y / N)
LS-629 Uncompacted Void Content, % Minimum	≤100 mm (Note 1)	–	40	45 (Note 3)	45 (Note 3)	45 (Note 3)	45.9	Y
	>100 mm (Note 1)	–	40	40	40	45 (Note 3)	-	-
AASHTO T176 Sand Equivalent Method 1, % minimum, (Note 2)		40	40	45	45	50	73	Y

COARSE AGGREGATE(S)

Source Name & Location: Mix # 2121	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:

Laboratory Test and Number		Requirement – Traffic Level Category A	B	C	D	E	Test Result – Sample	Meets Requirement (Y / N)
ASTM D 5821 Fractured Particles in Coarse Aggregate, % minimum, (Note 4)	≤100 mm (Note 1)	55/-	75/-	85/80	95/90	100/100	98.4/98.2	Y
	>100 mm (Note 1)	–	50/-	60/-	80/75	100/100	-	-
ASTM D 4791 Flat and Elongated Particles (5:1), % maximum		–	10				0.1	Y

Notes:

1. Denotes the depth of the top of lift below the final pavement surface. If less than 25% of a layer is within 100 mm of the surface, the layer may be considered to be below 100 mm.
2. Where the total combined fine aggregate includes aggregate derived from RAP or RST or both, this requirement shall be met prior to blending with RAP or RST or both.
3. A minimum uncompacted void content of 43% is acceptable provided that the selected mix satisfies the mix volumetrics specified elsewhere in the Contract Documents.
4. 85/80 denotes that 85% of the coarse aggregate has one fractured face and 80% has two or more fractured faces.

Issued by (Testing Laboratory Representative):

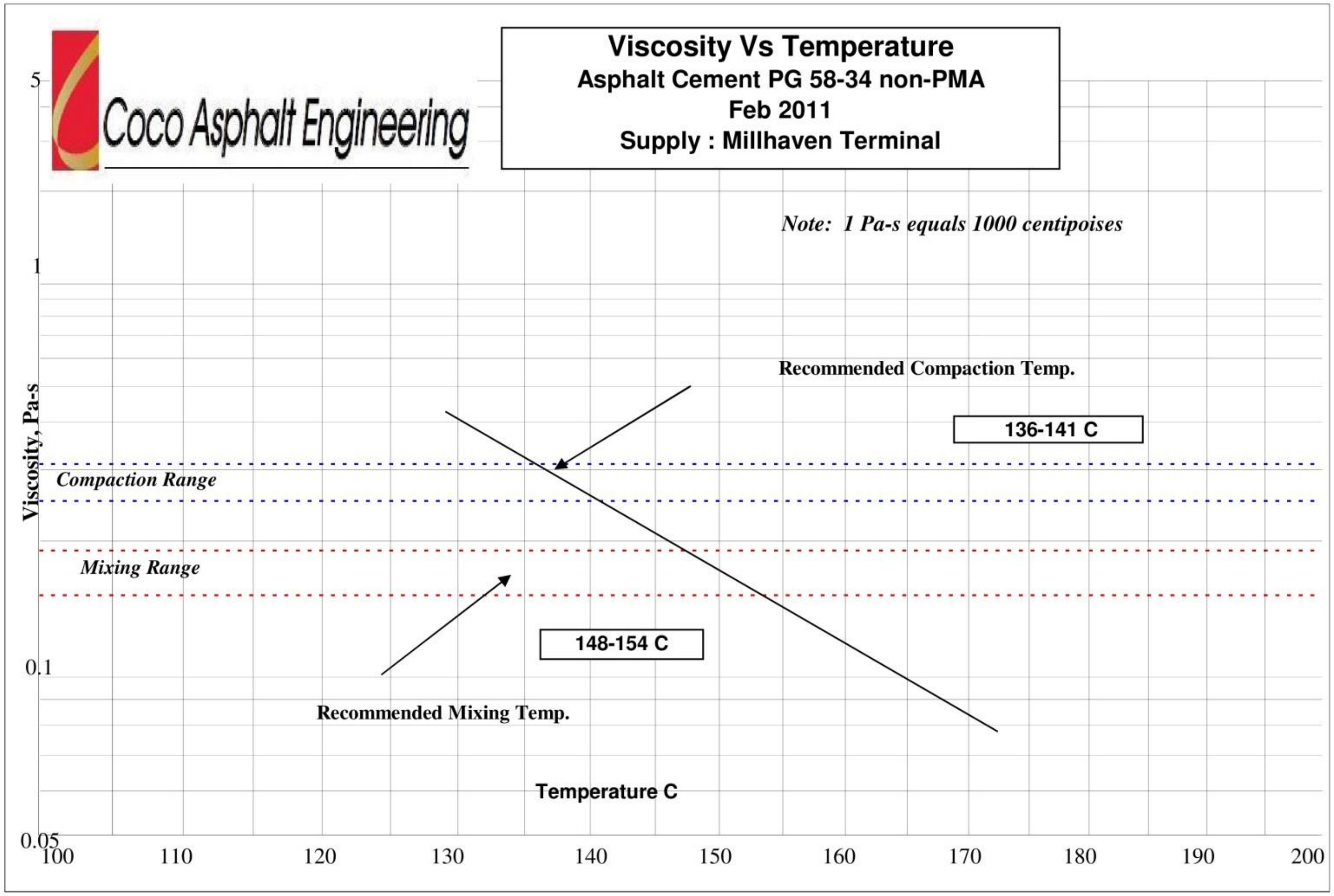
Kevin Jackson (PRINT NAME) — Kevin Jackson (SIGNATURE) — Feb. 16/12 (DATE)

Received by (Contract Administrator Representative):

PRINT NAME — SIGNATURE — DATE

Copies to: ☐ Contract Administrator; ☐ Contractor; ☐ Regional Quality Assurance; ☐ Regional Geotechnical; ☐ MERO (Soils and Aggregates)

PH-CC-449c June-11


Coco Asphalt Engineering
Viscosity Vs Temperature
Asphalt Cement PG 58-34 non-PMA
Feb 2011
Supply : Millhaven Terminal
Note: 1 Pa-s equals 1000 centipoises
Recommended Compaction Temp.
136-141 C
Compaction Range
Mixing Range
148-154 C
Recommended Mixing Temp.
Viscosity, Pa-s
5
1
0.1
0.05
Temperature C
100
110
120
130
140
150
160
170
180
190
200

0% RAP PG 52-34

DBA ENGINEERING LTD.

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Fax: (905) 851-0091

SUPERPAVE MIX DESIGN REPORT

Mix Number:	2122	**Project No.:**	**11-2115-01**
Contract:	MTO / OHMPA RAP Study		
Location:	DBA Engineering Ltd. and University of Waterloo		
Item Number:	N / A		
Contractor:	University of Waterloo		
Client:	University of Waterloo		
Plant Location:	N / A		

Date Sampled:	07-Dec-11
Date Completed:	12-Mar-12
Mix Type:	12.5 mm
Traffic Category:	C
Asphalt Cement Type:	52-34
Asph. Cement Supplier:	Bitumar Inc.
Mixing Temperature:	140 °C
Compaction Temperature:	129 °C

Test Data Certified By:
V. Aurilio, P.Eng

JOB MIX FORMULA GRADATION PERCENT PASSING

%AC / Sieves	% AC	50	37.5	25	19	16	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.08
JMF	5.2	100.0	100.0	100.0	100.0	100.0	98.3	84.8	52.9	43.5	30.6	19.8	9.5	4.3	3.2
	Percent	**Aggregate Gradation**													
CA 1	**46**	100.0	100.0	100.0	100.0	100.0	96.2	67.0	4.7	1.6	1.1	1.0	0.9	0.8	0.6
CA 2															
CA 3															
FA 1	**26**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	96.4	55.1	30.8	15.3	7.9	3.5
FA 2	**18**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.9	95.3	84.3	58.9	22.9	3.3	2.6
FA 3	**10**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	69.2	5.6	2.6	1.7	1.4	1.2	0.9
FA 4															
RAP 1															
RAP 2															

	Selected	Specification	
BRD (Gmb)	2.433		
MRD(Gmm)	2.534		
% Air Voids (Va)	4.0	4	
% VMA	15.0	14	
% VFA	73.4	65	75
D/P	0.7	0.6	1.2
% Gmm @ ini	88.5	89	
% Gmm @ des	96	96	
% Gmm @ max	96.8	98	

2.7586

TSR	96	Spec. Min 80
Additive Supplier	N / A	
Additive Type	N / A	
% Additive	N / A	

% RAP	0.0
% AC From RAP	0.0
Virgin AC	5.2

Nini	7
Ndes	75
Nmax	115
Dust Returned	1.5
Briquette Wt.	4900
Recomp Temp	129
Water Absorp.	0.2

	Aggregate Name	Aggregate Source	Aggregate Inventory #
CA 1	HL-3 Stone	Nellson Aggreg. - Waynco Pit	Not Provided
CA 2			
CA 3			
FA 1	High Stability Sand	Lafarge - Dundas Quarry	H03-033
FA 2	Blend Sand	WSMI Pit	S11-050
FA 3	1/4" Chip	Capital Paving - Wellington Pit	C44-352
FA 4			
RAP 1			
RAP 2			

Coarse Specific Gravity	2.686
Coarse Absorption	1.41
Fine Specific Gravity	2.737
Fine Absorption	0.66
Combined Specific Gravity	2.712

1 The pass 4.75mm portion of the blend gradation has been adjusted for fines returned to mix.
2 No SSD air voids correction is required.
3 Gradation is based on Process control and sample results.

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Fax: (905) 851-0091

SUPERPAVE MIX SUMMARY REPORT

Mix Number: 2122 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Mix Type: 12.5 mm
Category: C
Mixing Temp: 140 °C
Compaction Temp: 129 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12

					N max		
Asphalt Cement	**4.7**	**5.2**	**5.7**	**6.2**	**5.2**	**Criteria**	
Bulk Specific Gravity (Gmb)	2.401	2.433	2.447	2.465	2.453		
Maximum Specific Gravity(Gmm)	2.554	2.534	2.515	2.495	2.534		
% Air Voids (Va)	6.0	4.0	2.7	1.2		4.0	4.0
% VMA	15.6	15.0	14.9	14.7		14.0	
% VFA	61.6	73.4	81.9	91.9		65.0	75.0
Dust / Asphalt Ratio	0.7	0.7	0.7	0.7		0.6	1.2
% Gmm @ ini	86.7	88.5	89.7	91.0	88.1		89.0
% Gmm @ des	94.0	96.0	97.3	98.8	95.7		96.0
% Gmm @ max					96.8		98.0

Specific Gravity of Aggregate (GSb) 2.712
Specific Gravity of Binder (Gb) 1.02

Input By: ____________________ **Verified By:** ____________________

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SUPERPAVE LABORATORY WORKSHEET

Mix Number: 2122 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Mix Type: 12.5 mm **Contractor:** University of Waterloo
Category: C

										Nmax	
% Asphalt Cement		4.7		5.2		5.7		6.2		5.2	
Briquette Number		1	2	3	4	5	6	7	8	9	10
N ini	7	127.2	126.7	125.5	125.4	125.2	125.2	123.5	124.1	125.6	126.1
N des	75	117.3	116.9	115.7	115.5	115.7	115	113.9	114.1	115.8	116.1
Nmax	115									114.4	114.8
Wt in Air		4874.6	4871.2	4874.6	4874.4	4869.6	4865.2	4870.3	4870.1	4871.5	4873.2
SSD		4889.4	4888.2	4880.1	4878.7	4873.2	4868.2	4871.8	4872.3	4875.1	4878.2
Wt in water		2857.8	2860.5	2876.5	2874.5	2884.9	2878.9	2896.5	2896.8	2893.3	2887.2
Volume		2031.6	2027.7	2003.6	2004.2	1988.3	1989.3	1975.3	1975.5	1981.8	1991
BRD (Gmb)		**2.399**	**2.402**	**2.433**	**2.432**	**2.449**	**2.446**	**2.466**	**2.465**	**2.458**	**2.448**
Water Absorption		0.73	0.84	0.27	0.21	0.18	0.15	0.08	0.11	0.18	0.25
Flask Number				9	10	9	10				
Flask & Mix air				2739.5	2595.6	2595.3	2746.4				
Flask in air				646.5	636.8	646.5	636.8				
Mix in air				2093	1958.8	1948.8	2109.6				
Flask & Mix Water				1831.9	1741.9	1739.2	1826.8				
Flask in Water				564.8	556.4	564.8	556.4				
Mix in Water				1267.1	1185.5	1174.4	1270.4				
Volume				825.9	773.3	774.4	839.2				
MRD (Gmm)				**2.534**	**2.533**	**2.517**	**2.514**				

Input By: ____________________ **Verified By:** ____________________

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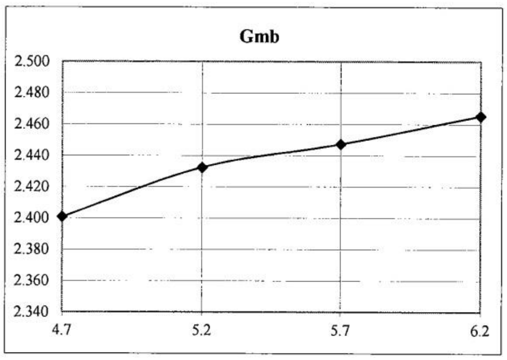
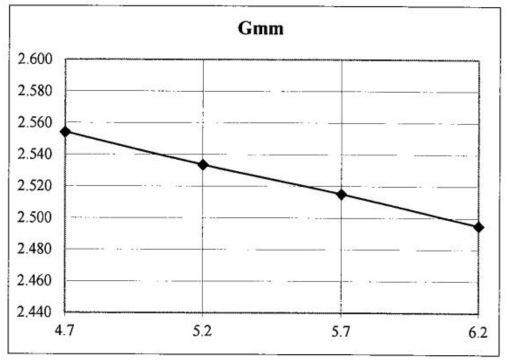
SUPERPAVE MIX SUMMARY REPORT

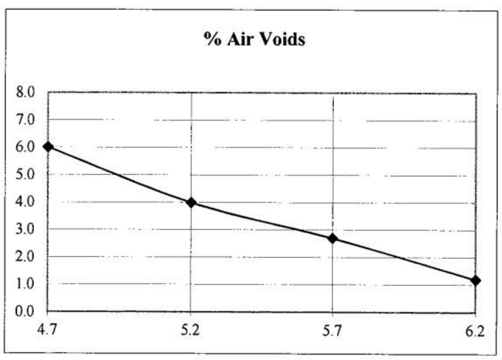
Mix Number: 2122 **Project No.:** 11-2115-01 **Date:** 12-Mar-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

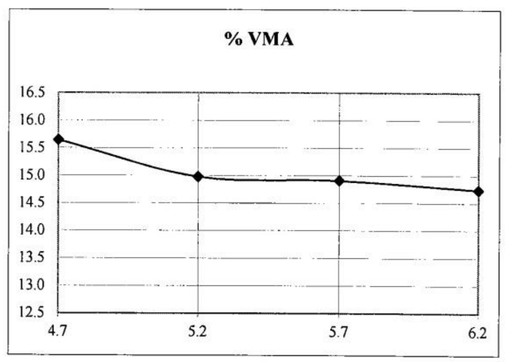
Mix Type: 12.5 mm
Category: C
Mixing Tempeture: 140 °C
Compaction Temp: 129 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 12-Mar-12









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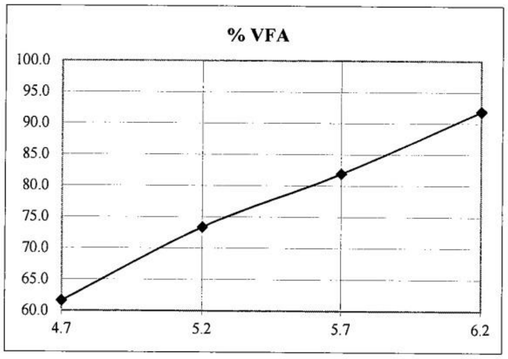
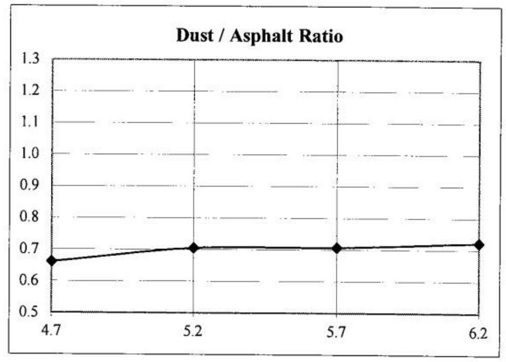
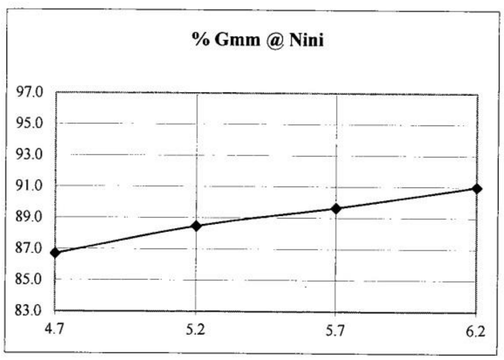
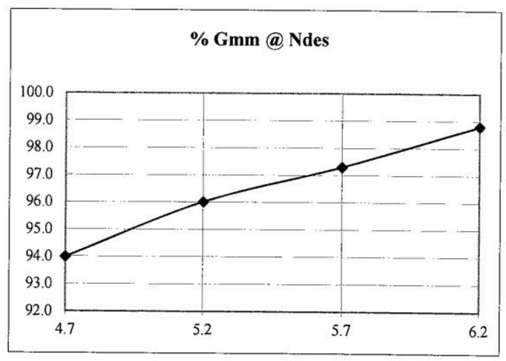
SUPERPAVE MIX SUMMARY REPORT

Mix Number:	2122	**Project No.:** 11-2115-01	**Date:** 12-Mar-12
Contract:	MTO / OHMPA RAP Study		
Location:	DBA Engineering Ltd. and University of Waterloo	**Mix Type:**	12.5 mm
		Category:	C
Item Number:	N / A	**Mixing Tempeture:**	140 °C
Contractor:	University of Waterloo	**Compaction Temp:**	129 °C
Client:	University of Waterloo		
Plant Location:	N / A		
Date Sampled:	07-Dec-11		
Date Completed:	12-Mar-12		









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CONSENSUS PROPERTIES

Mix Number:	2122	**Project No.:** 11-2115-01	**Date:** 12-Mar-12
Contract:	MTO / OHMPA RAP Study		
Location:	DBA Engineering Ltd. and University of Waterloo	**Mix Type:**	12.5 mm
		Category:	C
Item Number:	N / A		
Contractor:	University of Waterloo		
Client:	University of Waterloo		
Plant Location:	N / A		
Date Sampled:	07-Dec-11		
Date Completed:	12-Mar-12		

COARSE AGGREGATE

	Min	Max	Blend
% Crushed 1 Face	85		98.9
% Crushed 2 Face	80		98.5
Flat and Elogated		10	0.4

FINE AGGREGATE

	Min	Max	Blend
Uncompacted Void	45		44.4
Sand Equivalent	45		77.0

Notes 1 As per SP No. 110F12M, uncompacted void content of 43 % is acceptable as long as the selected mix satisfies the mix volumetrics

Input By: ____________________ **Verified By:** ____________________

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Ontario

Ministry of Transportation

AGGREGATE TEST DATA – HOT MIX ASPHALT
Superpave - Consensus Properties (SSP 110S12)

Contract No.: MTO/OHMPA RAP Study	Contractor: University of Waterloo	Contract Location: DBA Engineering Ltd. & University of Waterloo	
Testing Laboratory: DBA Engineering Ltd.		Telephone No.: 905-851-0090	Fax No.: 905-851-0091
Sampled by (Print Name): University of Waterloo		Date Sampled: (YY/MM/DD) 11/12/07	
Mix Type: 12.5mm	Lot No.:	Quantity (tonnes):	

2122

FINE AGGREGATE(S)

Source Name & Location: Mix # 2122	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:

Laboratory Test and Number		Requirement – Traffic Level Category A	B	C	D	E	Test Result – Sample	Meets Requirement (Y / N)
LS-629 Uncompacted Void Content, % Minimum	≤100 mm (Note 1)	–	40	45 (Note 3)	45 (Note 3)	45 (Note 3)	44.4	Y
	>100 mm (Note 1)	–	40	40	40	45 (Note 3)	-	-
AASHTO T176 Sand Equivalent Method 1, % minimum, (Note 2)		40	40	45	45	50	77	Y

COARSE AGGREGATE(S)

Source Name & Location: Mix # 2122	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:

Laboratory Test and Number		Requirement – Traffic Level Category A	B	C	D	E	Test Result – Sample	Meets Requirement (Y / N)
ASTM D 5821 Fractured Particles in Coarse Aggregate, % minimum, (Note 4)	≤100 mm (Note 1)	55/-	75/-	85/80	95/90	100/100	98.9/98.5	Y
	>100 mm (Note 1)	–	50/-	60/-	80/75	100/100	-	-
ASTM D 4791 Flat and Elongated Particles (5:1), % maximum		–	10				0.4	Y

Notes:

1. Denotes the depth of the top of lift below the final pavement surface. If less than 25% of a layer is within 100 mm of the surface, the layer may be considered to be below 100 mm.
2. Where the total combined fine aggregate includes aggregate derived from RAP or RST or both, this requirement shall be met prior to blending with RAP or RST or both.
3. A minimum uncompacted void content of 43% is acceptable provided that the selected mix satisfies the mix volumetrics specified elsewhere in the Contract Documents.
4. 85/80 denotes that 85% of the coarse aggregate has one fractured face and 80% has two or more fractured faces.

Issued by (Testing Laboratory Representative):

Kevin Jackson (PRINT NAME)   Kevin Jackson (SIGNATURE)   Feb. 10/12 (DATE)

Received by (Contract Administrator Representative):

PRINT NAME   SIGNATURE   DATE

Copies to: ☐ Contract Administrator; ☐ Contractor; ☐ Regional Quality Assurance; ☐ Regional Geotechnical; ☐ MERO (Soils and Aggregates)

PH-CC-449c June-11

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ASPHALTIC CONCRETE MOISTURE SUSCEPTIBILITY TEST REPORT

AASHTO Designation: T283-07

Project No.:	11-2115-01	**Mix Type:**	12.5 mm
Contract No.:	MTO / OHMPA RAP Study	**Mix No.:**	2121
Highway:	DBA Engineering Ltd. and Unive	**Additive**	N / A
Client:	University of Waterloo	**Dose:**	0.0
Date:	March 12, 2012	**A.C. Type:**	58-34

	Dry Subset				Conditioned Subset			
	1	2	3	Average	4	5	6	Average
Specimen Diameter (mm)	150	150	150		150	150	150	
Specimen Height (mm)	94.6	94.8	94.7		94.6	94.6	94.7	
Dry Mass in Air	3877.0	3879.9	3878.4		3878.7	3879.6	3878.2	
SSD Mass, g	3899.3	3904.1	3899.1		3903.0	3901.5	3900.6	
Mass in Water,g	2262.0	2264.8	2261.0		2268.2	2260.6	2261.3	
Volume, cc	1637.3	1639.3	1638.1		1634.8	1640.9	1639.3	
Bulk Specific Gravity	2.368	2.367	2.368		2.373	2.364	2.366	
Maximum Specific Gravity	2.547	2.547	2.547	**2.547**	2.547	2.547	2.547	**2.547**
Percent Air Voids	7.0	7.1	7.0	**7.0**	6.8	7.2	7.1	**7.0**
Volume of Air	115.117	115.978	115.367		111.950	117.696	116.646	
Thickness, mm					94.600	94.600	94.700	
SSD Mass, g					3963	3968	3967	
Vol of Absorbed Water					84.3	88.1	88.6	
Percent Saturation					75.3	74.9	76.0	**75.4**
Maximum Load (Newtons)	12250	13250	12250		12300	12750	12200	
Tensile Strength (kPa)	549	593	549	**564**	552	572	547	**557**
Tensile Strength Ratio (%)								**98.7**
Visual Moisture Damage Rating (No = 0 to Most Stripped = 5)								**2**
Cracked / Broken Aggregate (Nil / Slight / Medium / High)								**Slight**

Comments:

DBA Engineering Ltd.

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ASPHALTIC CONCRETE MOISTURE SUSCEPTIBILITY TEST REPORT

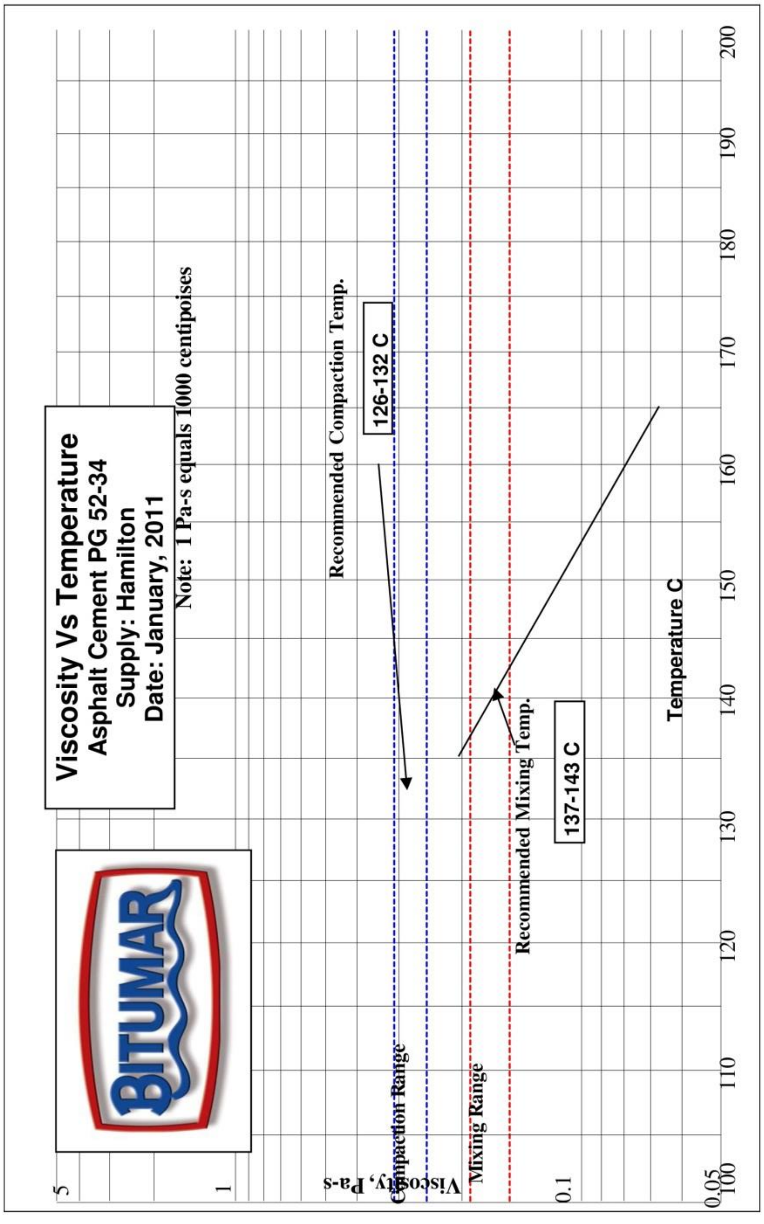
AASHTO Designation: T283-07

Project No.:	11-2115-01	**Mix Type:**	12.5 mm
Contract No.:	MTO / OHMPA RAP Study	**Mix No.:**	2122
Highway:	DBA Engineering Ltd. and Unive	**Additive**	N / A
Client:	University of Waterloo	**Dose:**	0.0
Date:	March 12, 2012	**A.C. Type:**	52-34

	Dry Subset				**Conditioned Subset**			
	1	**2**	**3**	**Average**	**4**	**5**	**6**	**Average**
Specimen Diameter (mm)	150	150	150		150	150	150	
Specimen Height (mm)	94.7	94.7	94.8		94.7	94.5	94.5	
Dry Mass in Air	3877.9	3873.9	3873.7		3875.1	3873.3	3878.5	
SSD Mass, g	3896.8	3892.8	3893.2		3890.5	3894.5	3898.4	
Mass in Water,g	2251.8	2247.1	2247.3		2248.8	2250.1	2248.5	
Volume, cc	1645.0	1645.7	1645.9		1641.7	1644.4	1649.9	
Bulk Specific Gravity	2.357	2.354	2.354		2.360	2.355	2.351	
Maximum Specific Gravity	2.534	2.534	2.534	**2.534**	2.534	2.534	2.534	**2.534**
Percent Air Voids	7.0	7.1	7.1	**7.1**	6.9	7.0	7.2	**7.0**
Volume of Air	114.653	116.931	117.210		112.458	115.868	119.316	
Thickness, mm					94.800	94.600	94.700	
SSD Mass, g					3959	3960	3968	
Vol of Absorbed Water					84.3	86.9	89.5	
Percent Saturation					75.0	75.0	75.0	**75.0**
Maximum Load (Newtons)	5500	6150	5300		5200	5600	5450	
Tensile Strength (kPa)	246	276	237	**253**	233	251	244	**243**
Tensile Strength Ratio (%)								**95.9**
Visual Moisture Damage Rating (No = 0 to Most Stripped = 5)								**1**
Cracked / Broken Aggregate (Nil / Slight / Medium / High)								**Slight**

Comments:

DBA Engineering Ltd.



Viscosity Vs Temperature
Asphalt Cement PG 52-34
Supply: Hamilton
Date: January, 2011
Note: 1 Pa-s equals 1000 centipoises
BITUMAR
Recommended Compaction Temp.
126-132 C
Recommended Mixing Temp.
137-143 C
Compaction Range
Mixing Range
Viscosity, Pa-s
Temperature C
5
1
0.1
0.05
100
110
120
130
140
150
160
170
180
190
200

20% RAP PG 52-40

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SUPERPAVE MIX DESIGN REPORT

Mix Number: 2123 **Project No.: 11-2115-01**
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A

Test Data Certified By: Vince Aurilio, P.Eng.,

Date Sampled: 07-Dec-11
Date Completed: 27-Apr-12

Mix Type: 12.5 mm
Traffic Category: C
Asphalt Cement Type: 52-40 P
Asph. Cement Supplier: McAsphalt
Mixing Temperature: 150 °C
Compaction Temperature: 140 °C

%AC / Sieves	% AC	50	37.5	25	19	16	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.150	0.075
JMF	5.2	100.0	100.0	100.0	100.0	100.0	98.4	84.6	53.0	48.0	30.1	19.2	11.4	7.5	5.3
	Percent	Aggregate Gradation													
CA 1	**42**	100.0	100.0	100.0	100.0	100.0	96.2	67.0	4.7	1.6	1.1	1.0	0.9	0.8	0.6
CA 2															
CA 3															
FA 1	**38**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	96.4	55.1	30.8	15.3	7.9	3.5
FA 2															
FA 3															
FA 4															
RAP 1	**20**	100.0	100.0	100.0	100.0	100.0	99.8	92.2	65.3	53.6	41.5	31.5	19.8	13.0	8.7
RAP 2															

	Selected	Specification	
BRD (Gmb)	2.449		
MRD(Gmm)	2.551		
% Air Voids (Va)	4.0	4.0	
% VMA	14.3	14.0	
% VFA	72.1	65	75
D/P	1.2	0.6	1.2
% Gmm @ ini	88.2	89.0	
% Gmm @ des	96.0	96.0	
% Gmm @ max	97.0	98.0	

% RAP	20.0
% AC From RAP	0.9
Virgin AC	4.3

Nini	7
Ndes	75
Nmax	115
Dust Returned	2.0
Briquette Wt.	4932
Recomp Temp	140
Water Absorp.	0.4

TSR	96.2 Spec. Min 80
Additive Supplier	N / A
Additive Type	N / A
% Additive	N / A

	Aggregate Name	Aggregate Source	Aggregate Inventory #
CA 1	HL-3 Stone	Capital Paving. - Waynco Pit	Not Provided
CA 2			
CA 3			
FA 1	High Stability Sand	Lafarge - Dundas Quarry	H03-033
FA 2			
FA 3			
FA 4			
RAP 1	Capital Paving - Fine RAP	Capital Paving - Fine RAP	
RAP 2			

Coarse Specific Gravity
2.692
Coarse Absorption
1.22
Fine Specific Gravity
2.726
Fine Absorption
1.07
Combined Specific Gravity
2.710

1. The pass 4.75mm portion of the blend gradation has been adjusted for fines returned to mix.
2. No SSD air voids correction is required.
3. Gradation is based on Process control and sample results.

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Consulting Engineers

401 Hanlan Road
Vaughan, Ontario L4L 3T1
Tel: (905) 851-0090
Toll Free: 1-800-819-8833
Fax: (905) 851-0091

SUPERPAVE MIX SUMMARY REPORT

Mix Number: 2123 **Project No.:** 11-2115-01 **Date:** 27-Apr-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Mix Type: 12.5 mm
Category: C
Mixing Temp: 150 °C
Compaction Temp: 140 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 27-Apr-12

					N max		
Asphalt Cement	**4.7**	**5.2**	**5.7**	**6.2**	**5.2**	**Criteria**	
Bulk Specific Gravity (Gmb)	2.437	2.449	2.470	2.476	2.473		
Maximum Specific Gravity(Gmm)	2.571	2.551	2.529	2.511	2.550		
% Air Voids (Va)	5.2	4.0	2.4	1.4		4.0	4.0
% VMA	14.3	14.3	14.1	14.3		14.0	
% VFA	63.5	71.9	83.2	90.4		65.0	75.0
Dust / Asphalt Ratio	1.2	1.23	1.27	1.2		0.6	1.2
% Gmm @ ini	87.1	88.2	89.6	90.5	87.1		89.0
% Gmm @ des	94.8	96.0	97.6	98.6	95.8		96.0
% Gmm @ max					97.0		98.0

Specific Gravity of Aggregate (GSb) 2.710
Specific Gravity of Binder (Gb) 1.02

Input By: ____________

Verified By: ____________

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SUPERPAVE LABORATORY WORKSHEET

Mix Number: 2123 **Project No.:** 11-2115-01 **Date:** 27-Apr-12
Mix Type: 12.5 mm **Contractor:** University of Waterloo
Category: C

									Nmax	
% Asphalt Cement	4.7		5.2		5.7		6.2		5.2	
Briquette Number	1	2	3	4	5	6	7	8	9	10
N ini 7	124.8	125.4	124.5	125.2	123.6	124	123.9	122.8	126.2	127.3
N des 75	114.7	115.2	114.4	115	113.5	113.8	113.3	113	114.9	115.7
Nmax 115									113.5	114.2
Wt in Air	4921.2	4919.4	4918.6	4917.7	4918.2	4916.7	4915.3	4911.9	4914.2	4912.4
SSD	4934.4	4930.3	4926.4	4927.7	4921.8	4920	4916.2	4913.6	4919.4	4917.1
Wt in water	2914.6	2911.5	2923.2	2913.6	2933.1	2926.3	2932.7	2928.7	2930.5	2933
Volume	2019.8	2018.8	2003.2	2014.1	1988.7	1993.7	1983.5	1984.9	1988.9	1984.1
BRD (Gmb)	**2.436**	**2.437**	**2.455**	**2.442**	**2.473**	**2.466**	**2.478**	**2.475**	**2.471**	**2.476**
Water Absorption	0.65	0.54	0.39	0.50	0.18	0.17	0.05	0.09	0.26	0.24
Flask Number			11	12	11	12				
Flask & Mix air			2662.3	2631.1	2649.3	2659.5				
Flask in air			644.4	604.1	644.4	604.1				
Mix in air			2017.9	2027	2004.9	2055.4				
Flask & Mix Water			1790.2	1760.2	1775	1771				
Flask in Water			563	527.9	563	527.9				
Mix in Water			1227.2	1232.3	1212	1243.1				
Volume			790.7	794.7	792.9	812.3				
MRD (Gmm)			**2.552**	**2.551**	**2.529**	**2.530**				

Input By: ______________ **Verified By:** ______________

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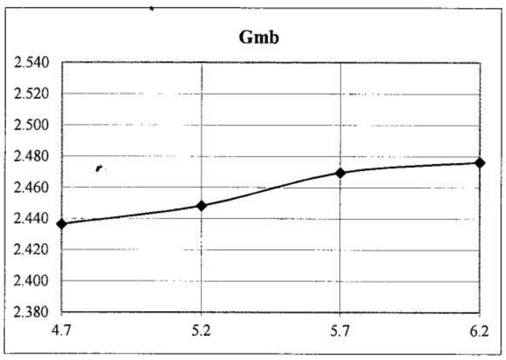
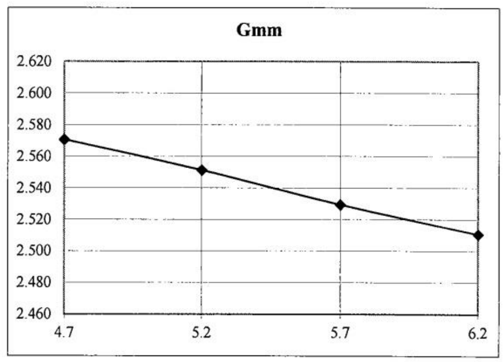
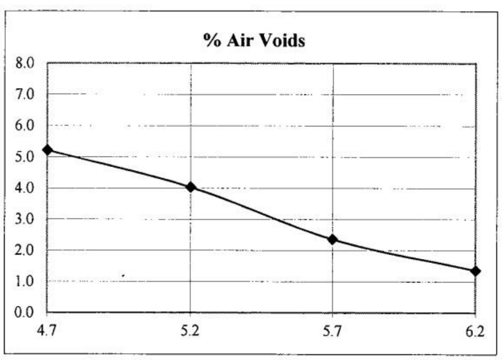
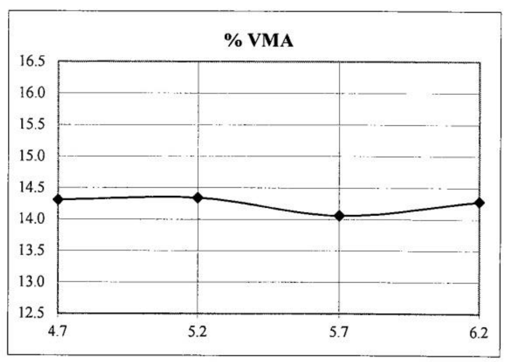
SUPERPAVE MIX SUMMARY REPORT

Mix Number:	2123 **Project No.:** 11-2115-01	**Date:**	27-Apr-12
Contract:	MTO / OHMPA RAP Study		
Location:	DBA Engineering Ltd. and University of Waterloo	**Mix Type:**	12.5 mm
		Category:	C
Item Number:	N / A	**Mixing Tempeture:**	150 °C
Contractor:	University of Waterloo	**Compaction Temp:**	140 °C
Client:	University of Waterloo		
Plant Location:	N / A		
Date Sampled:	07-Dec-11		
Date Completed:	27-Apr-12		









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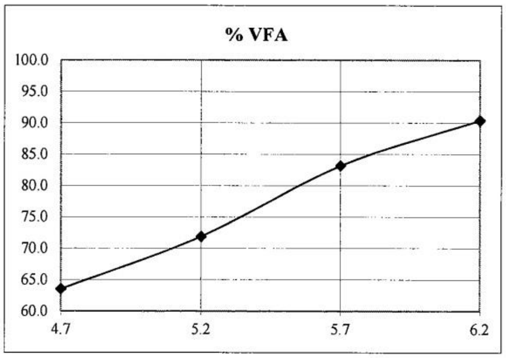
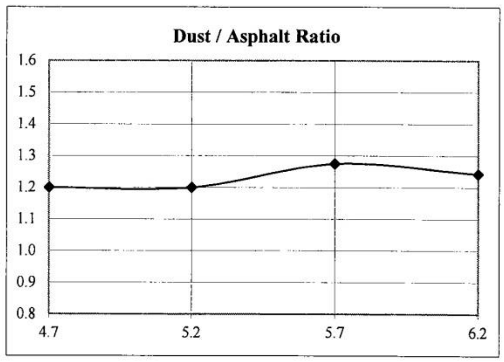
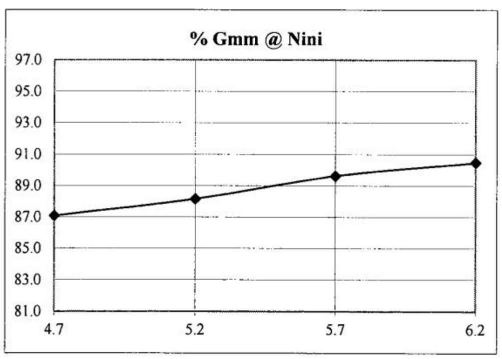
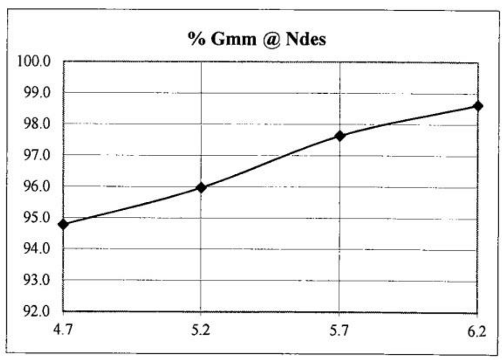
SUPERPAVE MIX SUMMARY REPORT

Mix Number:	2123	**Project No.:** 11-2115-01	**Date:** 27-Apr-12
Contract:	MTO / OHMPA RAP Study		
Location:	DBA Engineering Ltd. and University of Waterloo	**Mix Type:**	12.5 mm
		Category:	C
Item Number:	N / A	**Mixing Tempeture:**	150 °C
Contractor:	University of Waterloo	**Compaction Temp:**	140 °C
Client:	University of Waterloo		
Plant Location:	N / A		
Date Sampled:	07-Dec-11		
Date Completed:	27-Apr-12		









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CONSENSUS PROPERTIES

Mix Number:	2123	**Project No.:** 11-2115-01		**Date:** 27-Apr-12
Contract:	MTO / OHMPA RAP Study			
Location:	DBA Engineering Ltd. and University of Waterloo		**Mix Type:**	12.5 mm
			Category:	C
Item Number:	N / A			
Contractor:	University of Waterloo			
Client:	University of Waterloo			
Plant Location:	N / A			
Date Sampled:	07-Dec-11			
Date Completed:	27-Apr-12			

COARSE AGGREGATE

	Min	Max	Blend
% Crushed 1 Face	85		99.1
% Crushed 2 Face	80		98.8
Flat and Elogated		10	0.1

FINE AGGREGATE

	Min	Max	Blend
Uncompacted Void	45		45.7
Sand Equivalent	45		74.0

Notes 1 As per SP No. 110F12M, uncompacted void content of 43 % is acceptable as long as the selected mix satisfies the mix volumetrics

Input By: ____________

Verified By: ____________

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Ontario

Ministry of Transportation

AGGREGATE TEST DATA – HOT MIX ASPHALT
Superpave - Consensus Properties (SSP 110S12)

2123

Contract No.: MTO/OHMPA RAP Study	Contractor: University of Waterloo	Contract Location: DBA Engineering Ltd. & University of Waterloo	
Testing Laboratory: DBA Engineering Ltd.		Telephone No.: 905-851-0090	Fax No.: 905-851-0091
Sampled by (Print Name): University of Waterloo		Date Sampled: (YY/MM/DD) 11/12/07	
Mix Type: 12.5 mm	Lot No.:	Quantity (tonnes):	

FINE AGGREGATE(S)

Source Name & Location: Mix # 2123	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:

Laboratory Test and Number		Requirement – Traffic Level Category A	B	C	D	E	Test Result – Sample	Meets Requirement (Y / N)
LS-629 Uncompacted Void Content, % Minimum	≤100 mm (Note 1)	–	40	45 (Note 3)	45 (Note 3)	45 (Note 3)	45.7	Y
	>100 mm (Note 1)	–	40	40	40	45 (Note 3)	-	-
AASHTO T176 Sand Equivalent Method 1, % minimum, (Note 2)		40	40	45	45	50	74	Y

COARSE AGGREGATE(S)

Source Name & Location: Mix # 2123	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:
Source Name & Location:	Aggregate Inventory Number (AIN):	Pit (P) or Quarry (Q):	% of Mix:

Laboratory Test and Number		Requirement – Traffic Level Category A	B	C	D	E	Test Result – Sample	Meets Requirement (Y / N)
ASTM D 5821 Fractured Particles in Coarse Aggregate, % minimum, (Note 4)	≤100 mm (Note 1)	55/-	75/-	85/80	95/90	100/100	99.1/98.8	Y
	>100 mm (Note 1)	–	50/-	60/-	80/75	100/100	-	-
ASTM D 4791 Flat and Elongated Particles (5:1), % maximum		–	10				0.1	Y

Notes:

1. Denotes the depth of the top of lift below the final pavement surface. If less than 25% of a layer is within 100 mm of the surface, the layer may be considered to be below 100 mm.
2. Where the total combined fine aggregate includes aggregate derived from RAP or RST or both, this requirement shall be met prior to blending with RAP or RST or both.
3. A minimum uncompacted void content of 43% is acceptable provided that the selected mix satisfies the mix volumetrics specified elsewhere in the Contract Documents.
4. 85/80 denotes that 85% of the coarse aggregate has one fractured face and 80% has two or more fractured faces.

Issued by (Testing Laboratory Representative):

Kevin Jackson — PRINT NAME

[signature] — SIGNATURE

March 9/12 — DATE

Received by (Contract Administrator Representative):

PRINT NAME — SIGNATURE — DATE

Copies to: ☐ Contract Administrator; ☐ Contractor; ☐ Regional Quality Assurance; ☐ Regional Geotechnical; ☐ MERO (Soils and Aggregates)

PH-CC-449c June-11

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Vaughan, Ontario L4L 3T1

ASPHALTIC CONCRETE MOISTURE SUSCEPTIBILITY TEST REPORT

AASHTO Designation: T283-07

Project No.:	11-2115-01	**Mix Type:**	12.5 mm
Contract No.:	MTO / OHMPA RAP Study	**Mix No.:**	2123
Highway:	DBA and University of Waterloo	**Additive**	N / A
Client:	University of Waterloo	**Dose:**	0.0
Date:	April 27, 2012	**A.C. Type:**	52-40 P

	Dry Subset				**Conditioned Subset**			
	1	**2**	**4**	**Average**	**3**	**5**	**6**	**Average**
Specimen Diameter (mm)	150	150	150		150	150	150	
Specimen Height (mm)	94.8	94.9	94.8		94.7	94.7	95.1	
Dry Mass in Air	3914.1	3913.8	3914.4		3913.4	3915.6	3911.8	
SSD Mass, g	3933.5	3929.3	3931.2		3938.7	3930.5	3929.0	
Mass in Water,g	2288.5	2285.3	2285.0		2285.4	2288.0	2287.1	
Volume, cc	1645.0	1644.0	1646.2		1653.3	1642.5	1641.9	
Bulk Specific Gravity	2.379	2.381	2.378		2.367	2.384	2.382	
Maximum Specific Gravity	2.551	2.551	2.551	**2.551**	2.551	2.551	2.551	**2.551**
Percent Air Voids	6.7	6.7	6.8	**6.7**	7.2	6.5	6.6	**6.8**
Volume of Air	110.661	109.778	111.743		119.235	107.573	108.462	
Thickness, mm					94.800	94.800	95.200	
SSD Mass, g					3999	4002	3994	
Vol of Absorbed Water					85.1	85.9	82.0	
Percent Saturation					71.4	79.9	75.6	**75.6**
Maximum Load (Newtons)	10450	10250	11250		10000	10000	10750	
Tensile Strength (kPa)	468	458	503	**476**	448	448	479	**458**
Tensile Strength Ratio (%)								**96.1**
Visual Moisture Damage Rating (No = 0 to Most Stripped = 5)								**1**
Cracked / Broken Aggregate (Nil / Slight / Medium / High)								**Slight**

Comments:

DBA Engineering Ltd.

Vince Aurilio, P. Eng.

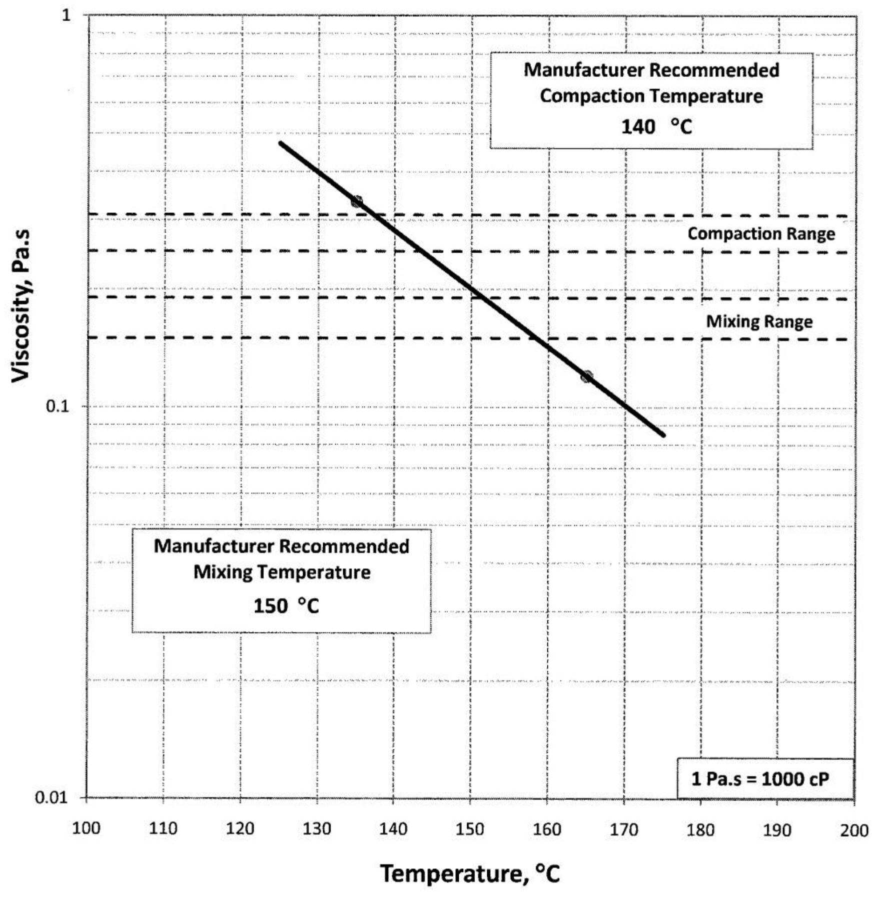
ASP-216-00

McAsphalt Engineering Services
Research Centre
8800 Sheppard Avenue East
Toronto, ON, M1B 5R4
Phone: (416) 281-8181
Fax: (416) 281-7509

January 2012

PG 52-40 P

HAMILTON, OSHAWA & VALLEYFIELD TERMINALS



40% RAP PG 52-40

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SUPERPAVE MIX DESIGN REPORT

Mix Number: 2124
Project No.: 11-2115-01
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Date Sampled: 07-Dec-11
Date Completed: 27-Apr-12

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A

Mix Type: 12.5 mm
Traffic Category: C
Asphalt Cement Type: 52-40 P
Asph. Cement Supplier: McAsphalt
Mixing Temperature: 150 °C
Compaction Temperature: 140 °C

Test Data Certified By:
Vince Aurilio, P.Eng.,

JOB MIX FORMULA GRADATION PERCENT PASSING

%AC / Sieves	% AC	50	37.5	25	19	16	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
JMF	4.9	100.0	100.0	100.0	100.0	100.0	98.6	85.3	52.8	46.1	30.8	20.7	12.1	7.4	4.6
	Percent	Aggregate Gradation													
CA 1	35	100.0	100.0	100.0	100.0	100.0	96.2	67.0	4.7	1.6	1.1	1.0	0.9	0.8	0.6
CA 2															
CA 3															
FA 1	25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	96.4	55.1	30.8	15.3	7.9	3.5
FA 2															
FA 3															
FA 4															
RAP 1	40	100.0	100.0	100.0	100.0	100.0	99.8	92.2	65.3	53.6	41.5	31.5	19.8	13.0	8.7
RAP 2															

	Selected	Specification	
BRD (Gmb)	2.451		
MRD(Gmm)	2.554		
% Air Voids (Va)	4.0	4.0	
% VMA	14.2	14.0	
% VFA	71.5	65	75
D/P	1.1	0.6	1.2
% Gmm @ ini	88.0	89.0	
% Gmm @ des	96.0	96.0	
% Gmm @ max	96.7	98.0	

% RAP	40.0
% AC From RAP	1.8
Virgin AC	3.1

Nini	7
Ndes	75
Nmax	115
Dust Returned	0.0
Briquette Wt.	4934
Recomp Temp.	140
Water Absorp.	0.4

TSR: 91.5 Spec. Min 80
Additive Supplier: N / A
Additive Type: N / A
% Additive: N / A

	Aggregate Name	Aggregate Source	Aggregate Inventory #
CA 1	HL-3 Stone	Capital Paving - Waynco Pit	Not Provided
CA 2			
CA 3			
FA 1	High Stability Sand	Lafarge - Dundas Quarry	H03-033
FA 2			
FA 3			
FA 4			
RAP 1	Capital Paving - Fine RAP	Capital Paving - Fine RAP	
RAP 2			

Coarse Specific Gravity	2.703
Coarse Absorption	1.36
Fine Specific Gravity	2.726
Fine Absorption	0.74
Combined Specific Gravity	2.715

1. The pass 4.75mm portion of the blend gradation has been adjusted for fines returned to mix.
2. No SSD air voids correction is required.
3. Gradation is based on Process control and sample results.

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SUPERPAVE MIX SUMMARY REPORT

Mix Number: 2124 **Project No.:** 11-2115-01 **Date:** 27-Apr-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

Mix Type: 12.5 mm
Category: C
Mixing Temp: 150 °C
Compaction Temp: 140 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 27-Apr-12

					N max		
Asphalt Cement	**4.4**	**4.9**	**5.4**	**5.9**	**4.9**	**Criteria**	
Bulk Specific Gravity (Gmb)	2.427	2.451	2.461	2.482	2.468		
Maximum Specific Gravity(Gmm)	2.573	2.554	2.531	2.513	2.552		
% Air Voids (Va)	5.7	4.0	2.8	1.2		4.0	4.0
% VMA	14.6	14.2	14.3	14.0		14.0	
% VFA	61.0	71.5	80.6	91.2		65.0	75.0
Dust / Asphalt Ratio	1.0	1.1	1.1	1.1		0.6	1.2
% Gmm @ ini	87.1	88.0	89.2	90.6	87.8		89.0
% Gmm @ des	94.3	96.0	97.2	98.8	95.5		96.0
% Gmm @ max					96.7		98.0

Specific Gravity of Aggregate (GSb) 2.715
Specific Gravity of Binder (Gb) 1.02

Input By: ____________

Verified By: ____________

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SUPERPAVE LABORATORY WORKSHEET

Mix Number: 2124
Mix Type: 12.5 mm
Category: C

Project No.: 11-2115-01
Contractor: University of Waterloo

Date: 27-Apr-12

										Nmax	
% Asphalt Cement		4.4		4.9		5.4		5.9		4.9	
Briquette Number		1	2	3	4	5	6	7	8	9	10
N ini	7	125.5	127.1	126.1	125.3	124.6	125.6	123.6	124.5	125.8	126.1
N des	75	116.3	117	115.3	115.3	114.5	115.1	113.5	114	115.8	115.8
Nmax	115									114.4	114.4
Wt in Air		4897.5	4896.3	4896.7	4895.3	4896.4	4892.4	4893.2	4893.3	4897	4896.8
SSD		4916.3	4926.3	4904.5	4905.3	4901.3	4898.3	4895.4	4896.3	4905	4905.7
Wt in water		2899.3	2907.5	2908.8	2905.4	2915	2906.7	2922.8	2925.6	2920	2922.3
Volume		2017	2018.8	1995.7	1999.9	1986.3	1991.6	1972.6	1970.7	1985	1983.4
BRD (Gmb)		**2.428**	**2.425**	**2.454**	**2.448**	**2.465**	**2.457**	**2.481**	**2.483**	**2.467**	**2.469**
Water Absorption		0.93	1.49	0.39	0.50	0.25	0.30	0.11	0.15	0.40	0.45

Flask Number	11	12	9	10
Flask & Mix air	2571.1	2599.5	2690.3	2539
Flask in air	644.4	604.1	646.5	636.8
Mix in air	1926.7	1995.4	2043.8	1902.2
Flask & Mix Water	1736.5	1740.7	1800.2	1707.7
Flask in Water	563	527.9	564.8	556.4
Mix in Water	1173.5	1212.8	1235.4	1151.3
Volume	753.2	782.6	808.4	750.9
MRD (Gmm)	**2.558**	**2.550**	**2.528**	**2.533**

Input By: ______________

Verified By: ______________

DBA ENGINEERING LTD.
DHILLON BURLEIGH & ASSOCIATES
Consulting Engineers

401 Hanlan Road
Vaughan, Ontario L4L 3T1
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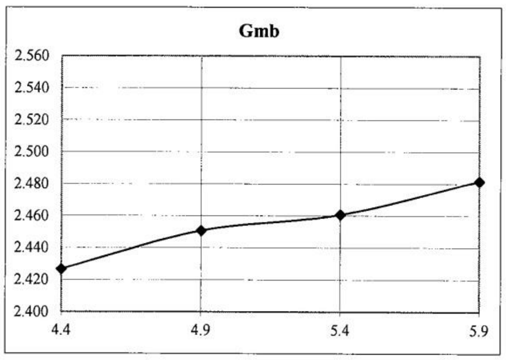
Toll Free: 1-800-819-8833
Fax: (905) 851-0091

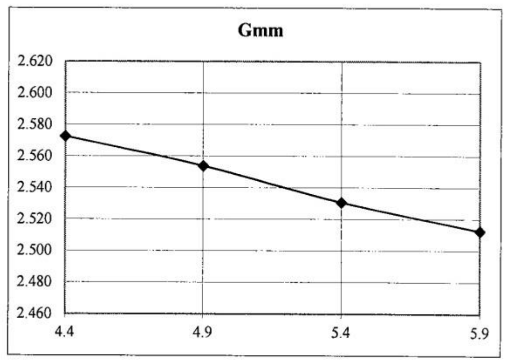
SUPERPAVE MIX SUMMARY REPORT

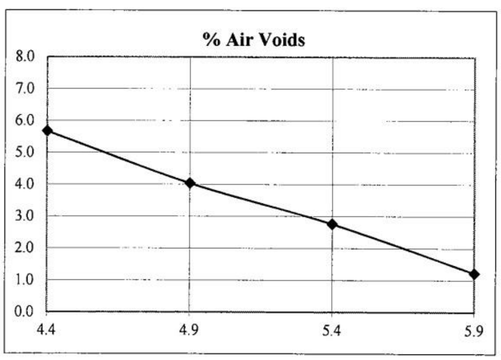
Mix Number: 2124 **Project No.:** 11-2115-01 **Date:** 27-Apr-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo

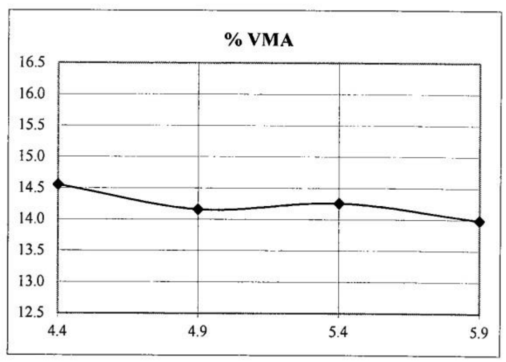
Mix Type: 12.5 mm
Category: C
Mixing Tempeture: 150 °C
Compaction Temp: 140 °C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 27-Apr-12









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ENGINEERING **RESEARCH** **DEVELOPMENT**

Offices in Greater Toronto, Kingston & Trenton

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SUPERPAVE MIX SUMMARY REPORT

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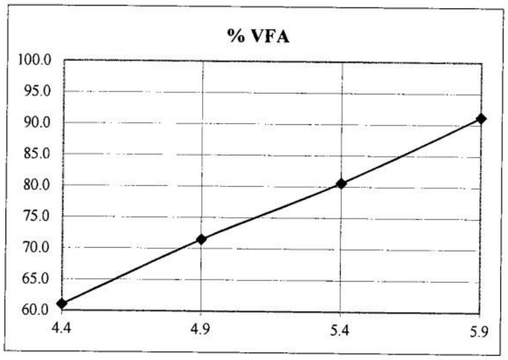

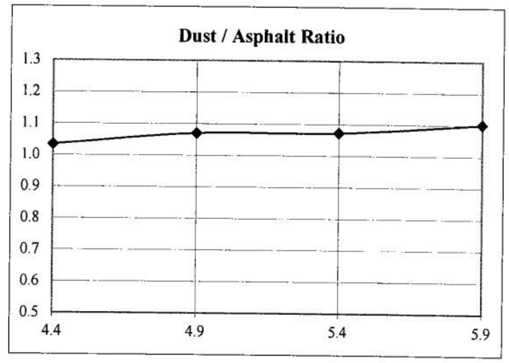

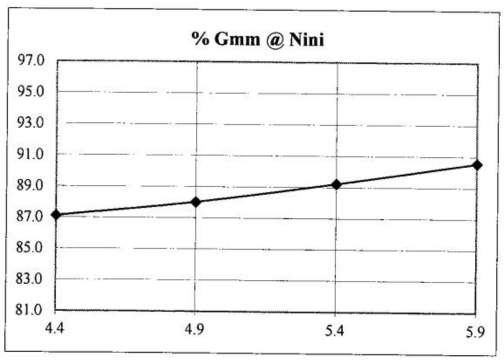

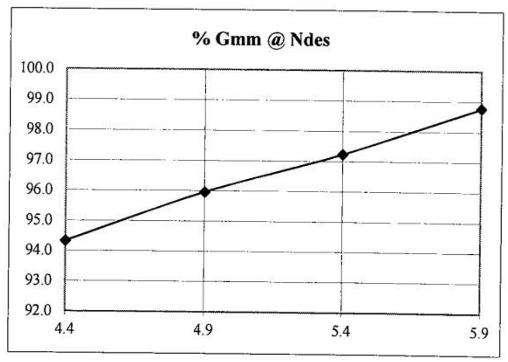

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CONSENSUS PROPERTIES

Mix Number: 2124 **Project No.:** 11-2115-01 **Date:** 27-Apr-12
Contract: MTO / OHMPA RAP Study
Location: DBA Engineering Ltd. and University of Waterloo **Mix Type:** 12.5 mm
Category: C

Item Number: N / A
Contractor: University of Waterloo
Client: University of Waterloo
Plant Location: N / A
Date Sampled: 07-Dec-11
Date Completed: 27-Apr-12

COARSE AGGREGATE

	Min	Max	Blend
% Crushed 1 Face	85		99.8
% Crushed 2 Face	80		98.6
Flat and Elogated		10	0.0

FINE AGGREGATE

	Min	Max	Blend
Uncompacted Void	45		44.9
Sand Equivalent	45		93.0

Notes 1 As per SP No. 110F12M, uncompacted void content of 43 % is acceptable as long as the selected mix satisfies the mix volumetrics

Input By: ______________

Verified By: ______________

Professional Engineers Ontario CCIL Certified Concrete Testing Laboratory ohmpa ONTARIO HOT MIX PRODUCERS ASSOCIATION ISO 9001

ENGINEERING **RESEARCH** **DEVELOPMENT**

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Ontario

Ministry of Transportation

AGGREGATE TEST DATA – HOT MIX ASPHALT
Superpave - Consensus Properties (SSP 110S12)

Contract No.: MTO/OHMPA RAP Study	Contractor: University of Waterloo	Contract Location: DBA Engineering Ltd. & University of Waterloo
Testing Laboratory: DBA Engineering Ltd.		Telephone No.: 905-851-0090 / Fax No.: 905-851-0091
Sampled by (Print Name): University of Waterloo		Date Sampled: (YY/MM/DD) 11/12/07
Mix Type: 12.5 mm	Lot No.:	Quantity (tonnes):

2124

FINE AGGREGATE(S)

Source Name & Location	Aggregate Inventory Number (AIN)	Pit (P) or Quarry (Q)	% of Mix
Mix # 2124			

Laboratory Test and Number		Requirement: Traffic Level Category A	B	C	D	E	Test Result: Sample	Meets Requirement (Y / N)
LS-629 Uncompacted Void Content, % Minimum	≤100 mm (Note 1)	–	40	45 (Note 3)	45 (Note 3)	45 (Note 3)	44.9	Y
	>100 mm (Note 1)	–	40	40	40	45 (Note 3)	-	-
AASHTO T176 Sand Equivalent Method 1, % minimum, (Note 2)		40	40	45	45	50	93	Y

COARSE AGGREGATE(S)

Source Name & Location	Aggregate Inventory Number (AIN)	Pit (P) or Quarry (Q)	% of Mix
Mix # 2124			

Laboratory Test and Number		Requirement: Traffic Level Category A	B	C	D	E	Test Result: Sample	Meets Requirement (Y / N)
ASTM D 5821 Fractured Particles in Coarse Aggregate, % minimum, (Note 4)	≤100 mm (Note 1)	55/-	75/-	85/80	95/90	100/100	99.8/98.6	Y
	>100 mm (Note 1)	–	50/-	60/-	80/75	100/100	-	-
ASTM D 4791 Flat and Elongated Particles (5:1), % maximum		–	10				0	Y

Notes:

1. Denotes the depth of the top of lift below the final pavement surface. If less than 25% of a layer is within 100 mm of the surface, the layer may be considered to be below 100 mm.
2. Where the total combined fine aggregate includes aggregate derived from RAP or RST or both, this requirement shall be met prior to blending with RAP or RST or both.
3. A minimum uncompacted void content of 43% is acceptable provided that the selected mix satisfies the mix volumetrics specified elsewhere in the Contract Documents.
4. 85/80 denotes that 85% of the coarse aggregate has one fractured face and 80% has two or more fractured faces.

Issued by (Testing Laboratory Representative):

Kevin Jackson (PRINT NAME) — [signature] (SIGNATURE) — Apr. 17/12 (DATE)

Received by (Contract Administrator Representative):

PRINT NAME — SIGNATURE — DATE

Copies to: ☐ Contract Administrator; ☐ Contractor; ☐ Regional Quality Assurance; ☐ Regional Geotechnical; ☐ MERO (Soils and Aggregates)

PH-CC-449c June-11

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ASPHALTIC CONCRETE MOISTURE SUSCEPTIBILITY TEST REPORT

AASHTO Designation: T283-07

Project No.:	11-2115-01	**Mix Type:**	12.5 mm
Contract No.:	MTO / OHMPA RAP Study	**Mix No.:**	2124
Highway:	DBA and University of Waterloo	**Additive**	N / A
Client:	University of Waterloo	**Dose:**	0.0
Date:	April 27, 2012	**A.C. Type:**	52-40 P

	Dry Subset				**Conditioned Subset**			
	1	**3**	**6**	**Average**	**2**	**4**	**5**	**Average**
Specimen Diameter (mm)	150	150	150		150	150	150	
Specimen Height (mm)	94.7	94.7	94.7		94.7	94.6	94.6	
Dry Mass in Air	3893.7	3892.7	3893.7		3890.5	3892.2	3891.9	
SSD Mass, g	3925.2	3926.1	3921.5		3924.1	3924.7	3925.4	
Mass in Water,g	2283.9	2283.3	2278.4		2279.3	2287.2	2288.0	
Volume, cc	1641.3	1642.8	1643.1		1644.8	1637.5	1637.4	
Bulk Specific Gravity	2.372	2.370	2.370		2.365	2.377	2.377	
Maximum Specific Gravity	2.554	2.554	2.554	**2.554**	2.554	2.554	2.554	**2.554**
Percent Air Voids	7.1	7.2	7.2	**7.2**	7.4	6.9	6.9	**7.1**
Volume of Air	116.750	118.642	118.550		121.503	113.538	113.555	
Thickness, mm					94.800	94.700	94.700	
SSD Mass, g					3982	3977	3979	
Vol of Absorbed Water					91.6	84.3	86.7	
Percent Saturation					75.4	74.2	76.4	**75.3**
Maximum Load (Newtons)	12000	12750	13000		11750	12000	10750	
Tensile Strength (kPa)	538	571	582	**564**	526	538	482	**515**
Tensile Strength Ratio (%)								**91.4**
Visual Moisture Damage Rating (No = 0 to Most Stripped = 5)								**1**
Cracked / Broken Aggregate (Nil / Slight / Medium / High)								**Slight**

Comments:

DBA Engineering Ltd.

Vince Aurilio, P. Eng.

ASP-216-00