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# RECYCYLED ASPHALT PAVEMENT (RAP) EFFECTS ON BINDER AND MIXTURE QUALITY

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# RECYCYLED ASPHALT PAVEMENT (RAP) EFFECTS ON BINDER AND MIXTURE QUALITY

**Final Report**

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# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# EXECUTIVE SUMMARY

Recycled Asphalt Pavement (RAP) has been used in Minnesota for over 25 years. The most commonly used method is to mill material from an existing pavement and incorporate it into a new asphalt mix. Previous experience and specifications allow various RAP percentages depending on the traffic level. Past research has also shown the effects of RAP on both the high- and low-temperature properties of asphalt cement and the asphalt mixtures. Therefore, it becomes an important priority to study and determine the effects various types and percentages of RAP have on the asphalt cement and mixture quality. This will result in a rational design for asphalt mixture that contain RAP and could change Mn/DOT's asphalt specification.

Ten mixtures, which were the combination of three RAP percentages (0, 20% and 40%), two different virgin asphalt cements (PG 58-28 and PG 58-34), and two different RAP sources (RAP and millings), were studied in this research. RAP material was blended with virgin aggregate such that all samples tested had approximately the same gradation. The Superpave mix design process was used to determine the optimum asphalt content for the mixtures. The volumetric properties were determined and deemed reasonable. Moisture susceptibility tests were conducted according to AASHTO T 283 to evaluate if the mixtures would be durable or susceptible to moisture related problems. Test results showed all ten mixtures pass the minimum tensile strength ratio of 75%. All ten mixtures were subject to dynamic complex modulus testing and indirect tensile (IDT) creep and strength testing. The asphalt cement was extracted from the tested dynamic modulus samples and the PG grades were determined according to current Superpave specifications (AASHTO M320).

Dynamic modulus samples were prepared according to the procedure recommended in NCHRP Report 9-19. Dynamic modulus tests were performed at five temperatures (-20, -10, 4, 20, and 40°C) and five frequencies (25, 10, 1, 0.1, 0.01 Hz) and the testing procedure was based on AASHTO TP 62. A modified version of the SINAAT 2.0 program which is based on the recommendations for the analysis of dynamic data as part of NCHRP 9-19 was used to analyze the testing results. Complex modulus master curves were constructed for each mixture using nonlinear regression techniques to fit the experimental data to a sigmoidal function. The limited data obtained in this project showed that the addition of RAP increased the complex modulus and that the asphalt binder and RAP source had a significant effect on the mixture modulus. It was also found that the mixtures containing RAP illustrated variability and that the variability increased with the addition of RAP. Complex modulus test results were observed to have more variability at low temperatures.

Indirect tensile creep and strength tests were performed on the ten mixtures at -18°C and -24° according to AASHTO TP 9. It was difficult to obtain consistent results with the creep tests because of problems with the extensometers. The creep test data showed that as the percentage of RAP or millings increases, the stiffness increases and that the mixtures with PG 58-34 binder were softer than the mixtures with PG 58-28 binder at -18°C.

Asphalt binders extracted from tested dynamic modulus samples were tested at high and low temperatures. The high PG temperature was determined by AASHTO T 315 and the low PG temperature was determined by AASHTO T 313 with the exception that the binders were only aged in the Rolling Thin Film Oven (RTFOT) to correspond the aged condition of the binders extracted from laboratory-mixed samples. Blending charts were constructed based on the test data. The limited test data showed that as the percentage of RAP or millings increased, the stiffness of the extracted binder increased. It was also found that the mixtures with PG 58-28 binders were stiffer than the mixtures containing PG 58-34 binder and the mixtures containing millings were stiffer than those containing RAP, although the effects were less pronounced at low temperatures.

Recommendations for further study include testing more mixtures and asphalt binders to encompass a wider range of materials used in Minnesota, comparing the laboratory test data to the field, and studying the effects of the recycled materials on the performance of the mixtures at low temperature.

# CHAPTER 1
# INTRODUCTION

## Background

Recycled asphalt pavement (RAP) has been used in Minnesota for over 25 years. The most commonly used method is to mill the asphalt material from an existing pavement and incorporate it into a new asphalt mix. Mn/DOT Specification 2350 allows up to 30% recycled material depending on the traffic level and Specification 2360 allows 20%. Recent NCHRP studies have shown that RAP influences both the high- and low-temperature properties of the asphalt cements and the asphalt mixtures. This research effort investigates the effect of RAP type and percentage on the final asphalt mixture properties using both traditional methods as well as the complex dynamic modulus as proposed by the new AASHTO design guide. The use of dynamic modulus to analyze the effect of RAP has not been previously reported in the literature.

## Objectives

The objective of this study was to investigate the effect of various types and percentages of RAP on asphalt binder and asphalt mixture properties for typical Minnesota asphalt mixtures. This is a first step in the more complex process of developing a rational design for asphalt mixtures that contain RAP which may change Mn/DOT current specifications.

## Scope

Ten mixtures were prepared and tested in this project. The aggregate for these mixtures passed the current Mn/DOT 2360 aggregate specification including the quality requirements. Current PG requirements were used as a basis for selecting the asphalt binders for the control mixtures (0% RAP). Two RAP sources, identified as RAP and Milling, and two asphalt binders, PG 58-28 and PG 58-34, were selected. In addition to the control mixtures asphalt mixtures were prepared with 20% and 40% of each of the RAP sources. Current volumetric design procedures were used to develop the mixture design. The dynamic modulus proposed by the recent AASHTO design guide was used to determine the effect of various percentages of RAP on mixture properties. Stiffness and moisture susceptibility results were also used to determine the effect of RAP on the asphalt mixture properties.

**Report Organization**

This report contains seven chapters: Introduction, Literature Review, Mixture Design and Experimental Plan, Dynamic Modulus Testing, IDT Creep and Strength Testing, Asphalt Cement Testing, and Conclusions and Recommendations. The Literature Review provides a background of RAP characteristics, the Superpave mix design method, and methods for testing mixtures composed of RAP and virgin materials. Mixture Design and Experimental Plan describes the details of the specification, the materials, the gradation and asphalt content, and the planned testing for the mixtures and asphalt binders. Dynamic Modulus Testing discusses the experimental work including the testing equipment, specimen preparation, dynamic modulus test method, and the data analysis. IDT Creep and Strength describes the IDT creep and strength testing procedures and presents the test results and data analysis. Asphalt Cement Testing provides the testing methods and data analysis for the asphalt binders extracted from the mixture specimens. The report closes with final conclusions and recommendations and an appendix that contains plots of the experimental data obtained in this project.

# CHAPTER 2
# LITERATURE REVIEW

## Introduction

Asphalt pavement is the leader in recycling of various materials in U.S.A. A Federal Highway Administration report shows that 80 percent of the asphalt pavement that is removed each year during widening and resurfacing projects is reused [1].

Both research efforts and experience field have shown that the recycling of asphalt pavement is very beneficial from the technical, environmental and economical perspectives. The advantages of utilizing recycled asphalt pavement (RAP) include the preservation of the natural resources, the reduction of the life-cycle costs and solving the environmental problems related to the disposal of the solid waste. Research by Little and Epps [2], Brown [3], Meyers et al [4] has shown that the structural performance of RAP is similar or even better than that of the conventional virginal asphalt mixtures.

## Asphalt Binder

In the design of mixtures that incorporate RAP, it is critical to know the asphalt content, the properties of the asphalt binders and the aggregate gradation of the RAP. So far, the only way to get all the above information is to separate the asphalt binder from the aggregate. There are many methods to separate the binder and aggregate in the RAP. These include: solvent extraction, nuclear asphalt content gauge, pycnometer method, automatic recordation and the ignition oven method. The solvent extraction and the ignition oven methods are the most widely used, because they allow for both the determination of binder content and of aggregate gradation [5].

Typically, the solvent extraction method requires the use of some solvents such as methylene chloride or trichloroethylene to dissolve and separate the asphalt from the mineral aggregates. From the difference in the mass before and after the extraction, asphalt content is calculated. In the ignition oven, the mix sample is heated to 538 °C for 30 to 40 minutes until all the asphalt is burned off. From the mass difference before and after the ignition, the asphalt content for the sample is calculated. The possible disadvantages for the solvent extraction include the effect of the solvents on the degradation of the aggregate and the high standard deviation of the test [6]. If the properties of the asphalt binder are desired, the solvent extraction and recovery procedures must be followed. Peterson et al [7] showed that the amount of extracted asphalt binder differs by approximately 0.3% to 0.5% when comparing different extraction methods using solvents. For the ignition method, the disadvantages include the aggregate degradation because of the combustion of the aggregate in the oven. Research by the National Center for Asphalt Technology (NCAT) showed that the ignition method was accurate and precise [8].

**Mineral Aggregate**

The mineral aggregate provides most of the loading support in an asphalt pavement. Therefore, determining the properties of the aggregate in the mixture is an important priority. The gradation of the aggregate is the most important of all these properties. The shape and other physical properties of the aggregate such as gradation, particle size and distribution of the particles are also very important. Due to the combined work of the compaction during the construction and service, the gradation and some physical properties such as shape of the RAP aggregates can change. The main change includes the size reduction of the large aggregate and the angularity decrease of the particles, which may lead to the decrease of the rutting resistance and friction resistance. Research by Paul et al [9] in Louisiana confirmed that little or no degradation of mixture had occurred after comparing the gradations from the extracted cores of 5 recycled projects.

**Asphalt Binder Aging**

There are two kinds of aging for the asphalt binder in the pavement. The first one is the short term aging due to the volatilization during the mixing and construction. The second one is the long term aging mainly due to the aging during the pavement service period. Aging brings a lot changes to the properties of the asphalt binder. It causes an increase in the viscosity and stiffness of the asphalt and a decrease in the penetration and ductility, resulting in a harder and more brittle asphalt material with a lower resistance to cracking in the field.

The properties of the mixtures containing RAP are influenced mainly by the aged RAP binder properties and the amount of RAP in the mixture. It was found that the addition of RAP binder generally increases the resistance against permanent deformation [10]. It was also observed that the compressive strength and the stiffness increased and the ductility decreased as the amount of RAP binder increased [10]. Kiggundu et al. [11] showed that the mixture containing the recycled asphalt binder ages at a slower rate than the virgin mixture. This may be due to the fact that the RAP material has already aged during the construction and further aging occurs at a much slower rate.

A number of methods have been developed to examine and simulate the field actual aging process of the asphalt mixture. Currently, the Rolling Thin Film Oven Test (RTFOT) is used to simulate short aging and the Pressure Aging Vessel (PAV) is used for the simulation of a five to ten years aging condition during the pavement service life [12].

**Superpave Method for the Binder Evaluation**

In addition to the methods used to simulate the aging process, Superpave uses the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) to evaluate binder performance. The DSR is used to measure the complex shear modulus $|G^*|$ and the phase angle $\delta$ for the asphalt binder at high and intermediate temperature. The BBR is used to measure the low-temperature creep stiffness (S) and the logarithmic creep rate (slope, m) of the asphalt binder. DSR data is used to evaluate the fatigue and permanent deformation resistance for the asphalt binder. The BBR test is performed to evaluate the resistance characteristics of asphalt binder against thermal cracking at low temperatures.

Kennedy et al [12] studied the effect of reclaimed asphalt pavement on binder properties using the Superpave specification. In this research, six asphalts that are part of the core asphalts used in the SHRP were chosen. Two of these six asphalts were aged for 85 minutes at 163 °C to simulate RAP binder with short-term aging and aged for 20 hours at 100 °C and a pressure of 2.1 MPa using the pressure aging vessel (PAV) to simulate the field aging in the first 5 to 10 years of pavement service. Both DSR and BBR test were performed on the virgin-RAP blends. Some of the conclusions of this research are:

- The stiffness ($|G^*|/\sin\delta$, $|G^*|\sin\delta$ or creep stiffness) of the binder is higher at higher percentage of RAP binder.

- The rate of change of stiffness ($|G^*|/\sin\delta$, $|G^*|\sin\delta$ or creep stiffness) is either constant or increases with lower temperature for different RAP binder percentages from 0-100% in the mixture.
- The rate of change of stiffness is either constant or increases at higher percentage of RAP binder in the blend for different percentages from 0-100% in the mixture.

Soleymani et al [13] investigated the time-temperature dependency of blended and rejuvenated asphalt binder using four asphalt binders and two recycling agents. The main objective of this research was to characterize blended and rejuvenated binders with PG testing parameters ($|G^*|$, $\delta$, S and m-value) and with their master curves. The relationships between master curve parameters, rheological index (R), and crossover frequency ($\omega_c$) of binders with proportion of soft asphalts or recycling agents were studied. Two soft asphalt binders and two recycling agents were selected as the test material. The original binder was aged twice in the RTFOT and PAV and rejuvenated binders were aged with the RTFOT and PAV to characterize the binders at intermediate and low temperature. The DSR and the BBR tests were performed on unaged and aged binders. The conclusions of this research were:

- A linear relationship was shown to be adequate for the prediction of PG testing parameters (log $G^*$, d, log S, and m-value) and performance criteria parameters (log $G^*$/sind, log $G^*$·sind, log S and m-value) versus the proportion (by weight) of soft binders.
- The blending charts based on PG parameters can be used to select recycling agent.
- A linear relationship can be used to predict the change in rheological index and crossover frequency.

Soupharath [10] studied the rutting resistance characteristics of asphalt binder containing recycled asphalt pavement. In his study, one base asphalt binder (AC-20 or PG 64-22) typically used in Rhode Island was blended with different amounts 0-100% of RAP binders obtained from one source The DSR was used to evaluate the blended asphalt binders at high temperatures. A good linear relationship between logarithm of rheological parameters and the amount of RAP binders was obtained. It was found that the addition of RAP binder generally increases the resistance to rutting.

Another study by Lee et al. [14] investigated the rheological and mechanical properties of blended asphalts containing recycled asphalt pavement binders. In this research, two typically used asphalt binders PG 58-28 and PG 64-22, were blended with different amounts of RAP binders in proportions of 0, 10, 20, 30, 40, 50, 75 and 100 percent by weight. DSR tests were performed at 52, 58, 64, 70 and 76°C, and at 19, 22, 25, 28 and 31 °C. A good linear relationship between log-log rheological parameters and the amount of RAP was observed from the study. The BBR tests were performed at –6, -12, -18 and –24 °C. It was observed that the creep stiffness increased and the m-value decreased for all temperatures as the amount of RAP content increased, which means that the addition of the RAP content reduces the binder's resistance to low temperature cracking.

Negulescu et at [15] researched the recycling of polymer modified asphalt pavements. The composition and rheological properties of polymer modified asphalt cement (PMAC) and of blends containing PMAC and different amounts of aged PMAC were evaluated using analytical methods and Superpave binder tests. An industrial PMAC that meets Louisiana DOT specifications for PG 76-22 was chosen in this research. The representative asphalt and PMAC were subjected to RTFOT or TFOT (thin film oven test) and PAV aging. The DSR and BBR were used to measure the viscosity and the low temperature creep properties for the blends of the PAV-aged PMAC with unaged PMAC. All the test results met the Superpave performance grading specification for the $G^*$/sind, stiffness S(t) and creep rate m, which indicated that aged PMAC could be blended successfully with fresh PMAC.

**Mixture Performance**

The mixture containing RAP material can show very different performance due to the properties of the binder in the RAP, the RAP content and the environmental conditions.

Kandhal et al [16] studied the performance of recycled hot mix asphalt mixtures. In this research, five projects that consist of a recycled section and a control section in each project were subjected to detailed evaluation. In-situ mix properties (such as percent air voids, resilient modulus and indirect tensile strength), recovered asphalt binder properties such as penetration, viscosity, $|G^*|/\sin\delta$ and $|G^*|*\sin\delta$ and laboratory recompacted mix properties such as Gyratory Stability Index and confined dynamic creep modulus were measured. A paired t-test statistical analysis indicated no significant difference between the properties of virgin and recycled mix pavements which have been in service from 1.5 to 2.25 years. Therefore, it was concluded that the recycled pavements are generally performing as well as the virgin pavements.

Kennedy and Perez [17] obtained higher tensile strength values for the mixtures containing RAP than the conventional mixtures using the indirect tensile test. Sondag [18] measured the resilient modulus for 18 different mix designs incorporating three different asphalt binders, two sources of RAP and varying amounts of RAP. He showed that at 25ºC adding 40% District 6 RAP to a PG 58-28 control mixture resulted in a 74% increase in stiffness and a 164% increase with a PG 46-40 control mixture, and the increase in stiffness was also observed with the addition of District 8 RAP. Therefore, the addition of RAP increased the resilient modulus, while the source of the RAP affected the resilient modulus results.

One of the main concerns is the effect of RAP on mixture durability. Moisture susceptibility is regarded as the main cause of poor mixture durability. Moisture susceptibility can be evaluated by performing stability, resilient modulus or tensile strength testing on unconditioned and moisture conditioned tests. Stroup-Gardiner et al [19] used the tensile strength ratio (ratio of unconditioned tensile strength and moisture conditioned tensile strength) to evaluate moisture sensitivity. She showed that the inclusion of coarse RAP decreased the moisture susceptibility. Brownie and Hironaka [20] used Marshall Stability and stability retained to evaluate the stripping potential of RAP mixtures. They showed that the addition of RAP doesn’t improve the moisture sensitivity of the mixtures. Sondag [18] used the tensile strength ratio to evaluate the moisture sensitivity for 18 different mix designs incorporating three different asphalt binders, two sources of RAP and varying amounts of RAP. He found that the addition of RAP to a mixture had no positive or negative influence on the mixture moisture susceptibility.

**RAP Content**

As expected, the content of the RAP in the mixture significantly affect the properties of the mixture. There is no any specification about the content of RAP in the mixture, different pavement agencies vary a lot in U.S. For example, most of the recycled pavements in Georgia have been constructed using AC-20 asphalt cement with 10 to 25% RAP material [20]. Minnesota DOT uses as high as 30% RAP in the base and binder courses and shoulders and 15% in wearing courses [18].

McDaniel et al. [21] investigated the performance of Superpave asphalt mixtures incorporating RAP from the North Central and Midwestern regions of U.S. Materials from the

Michigan, Missouri and Indiana were tested. PG binder tests were performed on each binder from each source. The RAP and plant mix binders were extracted, recovered, and then tested as original binder in the DSR at high temperatures. The recovered binders were then RTFOT aged and tested as RTFOT in the DSR at high temperatures. The recovered binders were further tested in the DSR at intermediate temperatures and in the BBR at low temperatures as if they had been RTFOT and PAV aged. Mixtures were analyzed using the Superpave shear tester. The specific tests conducted were the Frequency Sweep test at constant height (FS), the Simple Shear test (SS) and the Repeated Shear at Constant Height tests (RSCH). The main conclusions were:

- Superpave mixtures could be designed with up to 40 to 50% RAP.
- Linear blending charts proved appropriate for estimating the effects of the RAP binder on blended binder properties.
- Adding 20 to 25% RAP raised the high temperature grade of the plant mixed material by one grade.
- Frequency sweep testing and simple shear tests showed the higher the RAP content, the higher the mixture stiffness due to the effect of the hardened RAP binder.
- The addition of RAP can lead to improved rutting resistance by stiffening the binder.

**Mixture Design**

From 1987 through 1993, the Strategic Highway Research Program carried out several major research projects to develop the Superpave method for performance based HMA design. This method has now widely superseded the Marshall and Hveem design methods in the United States and Canada. A distinct shortcoming of the Superpave method is that it makes no specific provision for the use of the RAP in the mix design process [12]. As a result of a number of research efforts addressed the use of RAP in Superpave mixtures and proposed guidelines for the design of these mixtures.

Kandhal et al [22] conducted a research project on the design of recycled hot mix asphalt mixtures using Superpave technology. This research project was undertaken to develop a procedure for selecting the PG of virgin asphalt binders used in the mixture containing RAP. In this research, the virgin asphalt binders were PG 64-22, PG 58-22 and PG 52-28. The PG 64-22 binder was PAV aged at 100 ℃ and 2.07 MPa for 20 hours and PAV aged at 110 ℃ and 2.07 MPa for 30 hours respectively to simulate aged asphalt cement, and the third aged asphalt cement was recovered from RAP by using the centrifuge extraction method (ASTM D 2172 Method A). The fourth recycled binder was the mixture of the PG 58-22 and the first aged binder. Superpave temperature sweep blending charts were constructed and evaluated based on test parameters obtained from the DSR for these four recycled asphalt binders at different percentages. This research concluded that:

- The high temperature value of the recycled asphalt binder performance grade can be determined by using only one high temperature sweep blending chart "$G^*/\sin\delta$=1 KPa.
- A three-tier system of selecting the PG grade of the virgin asphalt binder has been recommended for recycled mixes. The 1.0 KPa stiffness line can be used to determine the maximum amount of virgin asphalt binder in the recycled asphalt binder, while the 2.0 KPa stiffness line is used to determine the minimum amount of virgin asphalt binder.
- The criteria based on the fatigue parameter $G^* * \sin\delta$=5 MPa maximum was determined to be too liberal to be recommended.

MacGregor et al. [23] evaluated the structural number, which is a function of layer thickness, layer coefficients, and drainage coefficients and can be computed from equation 1, for RAP base and subbase course mixes.

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \quad (2.1)$$

where

SN = structural number;

$D_1$, $D_2$ and $D_3$ = thickness of the asphaltic concrete, base and subbase, respectively;

$a_1$,$a_2$ and $a_3$ = layer coefficients of the asphaltic concrete, base and subbase respecitively;

$m_2$ and $m_3$ = drainage coefficients of the base and subbase, respectively.

In her research, a series of resilient modulus tests was carried out on mixtures of crushed stone base with 0, 10, 30 and 50% RAP and subbase with 0, 10, 30 and 50% RAP materials. The resilient modulus is correlated to the layer coefficients $\alpha_2$ and $\alpha_3$ of the base and subbase. The hydraulic conductivity tests on RAP mixtures of crushed stone and gravel were also performed to evaluate the drainage coefficients $m_2$ and $m_3$ of the base and subbase RAP mixtures. It found that the resilient modulus of the RAP base and subbase increased with the increase in RAP content, which means the layer coefficients and therefore the structural number increases, while the addition of up to 50% RAP to the crushed stone base had little effect on the hydraulic conductivity. RAP is therefore considered to be a beneficial additive to the base and subbase materials.

**Dynamic Complex Modulus**

The dynamic complex modulus of asphalt mixtures is related to the major distress modes such as permanent deformation, fatigue and low temperature cracking [24]. More and more pavement agencies are using the dynamic complex modulus to evaluate the properties of the asphalt mixtures. The new AASHTO Design Guide proposed the complex modulus of asphalt mixture as a parameter in the flexible pavement design.

The loading time and temperature are the most important factors that affect the absolute value of the dynamic complex modulus and the phase angle. Sondag [18] tested the complex modulus of 18 different mix designs incorporating three different asphalt binders, two sources of RAP and varying amounts of RAP. In his experimental work he used the IDT testing configuration; the current AASHTO procedure used sinusoidal compression on cylindrical specimens. The complex modulus was tested at –18, 1, 25 and 32 °C, and the loading frequencies were 0.3, 5 and 30 Hz. He found that the complex modulus was affected by asphalt binder grade and the addition of RAP increased the absolute value of the complex modulus; the addition of RAP to the PG 58-28 mixture caused a larger increase in complex modulus than the addition of RAP to the PG 46-40 mixture.

Fonseca and Witczak [25] developed a model to predict the dynamic modulus of field aged asphalt concrete. They used a database of dynamic modulus and viscosity values to construct the model. This database consists of 1,429 points on 149 separate asphalt mixes finished in the past 25 years. The complex modulus could be computed from the equation 2.2.

$$\log\left|E^*\right| = -1.249937 + 0.029232P_{200} - 0.001767(P_{200})^2 + 0.002841P_4 - 0.058097V_a$$
$$- 0.802208\frac{V_{beff}}{(V_{beff} + V_a)} + \frac{\left[3.871977 - 0.0021P_4 + 0.003958P_{38} - 0.000017(P_{38})^2 + 0.00547P_{34}\right]}{1 + e^{(-0.603313 - 0.313351\log f - 0.393532\log h)}} \tag{2.2}$$

where

$|E^*|$ = asphalt mix dynamic modulus, in $10^5$ psi;

$\eta$ = bitumen viscosity, in $10^6$ poise;

f = load frequency, in Hz;

$V_a$ = percent air voids in the mix, by volume;

$V_{beff}$ = percent effective bitumen content, by volume;

$P_{34}$ = percent retained on ¾-in. (19-mm) sieve, by total aggregate weight (cumulative);

$P_{38}$ = percent retained on 3/8-in. (9-mm) sieve, by total aggregate weight (cumulative);

$P_4$ = percent retained on #4 (4.75-mm) sieve, by total aggregate weight (cumulative); and

$P_{200}$ = percent passing #200 (0.075-mm) sieve, by total aggregate weight.

This modified model allows it to be used to predict dynamic modulus for mixtures exhibiting any degree of binder aging including short- or long –term effects.

As mentioned earlier, the properties of the mixtures containing RAP are influenced mainly by the aged RAP binder properties and the amount of RAP in the mixture. Daniel et al. [26] investigated the effect of aging on the asphalt mixtures using complex modulus. They simulated four aging processes: one short term aging, three different levels of long term aging.

**Conclusions**

Past research shows that the properties of the mixtures containing RAP are influenced mainly by the aged RAP binder properties and the amount of RAP in the mixture. The effects of aged asphalt can be assessed through the comparison of different RAP percentages and different virgin binder grades. The performance grade of the original asphalt binders and the resulting performance grade with various percentages of RAP can be determined and blending charts can be established to determine the maximum and minimum amount of virgin RAP asphalt binder. Dynamic modulus testing measures the viscoelastic characteristics of asphalt mixtures and the indirect tension type tests provide information about the strength and stripping potential of the RAP. Moisture susceptibility is regarded as the main cause of poor mixture durability. Moisture susceptibility can be evaluated by performing stability, resilient modulus or tensile strength testing on unconditioned and moisture conditioned tests.

# CHAPTER 3

# MIXTURE DESIGN AND EXPERIMENTAL PLAN

## Introduction

The experimental plan was developed based on information from the literature review and discussion with Mn/DOT staff. The next paragraphs provide a description of the mix designs and detail the testing proposed for both the asphalt binders and asphalt mixtures used in this study.

## Materials

Ten mixtures were prepared and evaluated in this project. Two asphalt binders were used to prepare the asphalt mixtures:

- PG 58-28 – standard binder used throughout Minnesota
- PG 58-34 – softer binder grade used for cold temperatures or with large amounts of RAP

Koch provided 5-gallon buckets of PG 58-28 and PG 58-34 binders.

Two different RAP sources, provided by Commercial Asphalt were used to prepare the asphalt mixtures. They are identified as follows:

- Millings – RAP from a single source, milled up from I-494 in Maple Grove
- RAP – RAP combined from a number of sources and crushed at the HMA plant

The asphalt binder content (by chemical extraction) was 4.3% and 5.4%, respectively. After the binder was extracted, gradations were performed on the aggregates. The results are shown in Table 3.1.

The aggregates used to prepare the ten asphalt mixtures were provided by Commercial Asphalt and consisted of four types of aggregates:

- Kraemer 9/16” chip – coarse limestone
- BA ½” – intermediate glacial gravel
- Kraemer sand – fine washed limestone sand
- Nelson sand – fine granite sand (100% crushed)

The gradations for these aggregates are shown in Table 3.2.

**Table 3.1 RAP and Milling Gradations**

| | | RAP | millings |
|---|---|---|---|
| | **Gsb** | 2.632 | 2.632 |
| | **Gsa** | 2.683 | 2.683 |
| **Sieve Size (in)** | **Sieve Size (mm)** | **% Passing** | |
| 3/4 inch | 19 | 100 | 100 |
| 1/2 inch | 12.5 | 96 | 93 |
| 3/8 inch | 9.5 | 90 | 89 |
| 1/4 inch | 6.3 | 82 | 82 |
| # 4 | 4.75 | 74 | 75 |
| # 8 | 2.36 | 62 | 61 |
| # 16 | 1.18 | 51 | 48 |
| # 30 | 0.6 | 40 | 37 |
| # 50 | 0.3 | 20 | 19 |
| # 100 | 0.15 | 9 | 11 |
| # 200 | 0.075 | 4.4 | 6.6 |

**Table 3.2 Aggregate Gradations**

| | | Kraemer 9/16 | Kraemer sand | Nelson sand | BA 1/2 inch |
|---|---|---|---|---|---|
| | **Gsb** | 2.645 | 2.710 | 2.646 | 2.634 |
| | **Gsa** | 2.820 | 2.782 | 2.761 | 2.705 |
| | **FAA** | NA | 47.9 | 46.9 | 40.8 |
| **Sieve Size (in)** | **Sieve Size (mm)** | **Percent Passing** | | | |
| 3/4 inch | 19 | 100 | 100 | 100 | 100 |
| 1/2 inch | 12.5 | 96 | 100 | 100 | 99 |
| 3/8 inch | 9.5 | 46 | 100 | 100 | 97 |
| 1/4 inch | 6.3 | 25 | 98 | 99 | 89 |
| # 4 | 4.75 | 2.8 | 96 | 97 | 81 |
| # 8 | 2.36 | 2.0 | 63 | 63 | 69 |
| # 16 | 1.18 | 1.8 | 43 | 40 | 58 |
| # 30 | 0.6 | 1.7 | 33 | 26 | 42 |
| # 50 | 0.3 | 1.5 | 23 | 15 | 17 |
| # 100 | 0.15 | 1.2 | 9.9 | 7.8 | 7.5 |
| #200 | 0.075 | 0.8 | 2.7 | 5.1 | 5.0 |

A total of ten mixtures were prepared, combining two different asphalt binders, two RAP sources, and three RAP percentages (0%, 20%, and 40%). A summary of the mixtures used in his study is shown in Table 3.3. The mix designations given in the last column of the table will be used throughout the report to identify the ten different mixtures.

**Table 3.3 Mixture Details**

| Mixture | Binder | RAP source | RAP % | Designation |
|---|---|---|---|---|
| 1 | PG 58-28 | RAP | 0 | R028 |
| 2 | PG 58-28 | RAP | 20 | R2028 |
| 3 | PG 58-28 | RAP | 40 | R4028 |
| 4 | PG 58-28 | millings | 20 | M2028 |
| 5 | PG 58-28 | millings | 40 | M4028 |
| 6 | PG 58-34 | RAP | 0 | R034 |
| 7 | PG 58-34 | RAP | 20 | R2034 |
| 8 | PG 58-34 | RAP | 40 | R4034 |
| 9 | PG 58-34 | millings | 20 | M2034 |
| 10 | PG 58-34 | millings | 40 | M4034 |

**Mix Design**

The mixture designs followed the Minnesota Department of Transportation (Mn/DOT) Specification 2360. Specifically, the mixes would be designated SPWEB240B and SPWEB240C. The particulars of this specification are shown in Table 3.4.

**Table 3.4 2360 Specification Parameters**

| | |
|---|---|
| Traffic Level | 2 (< 1 million ESALs) |
| Coarse Aggregate Angularity | 30/- |
| Fine Aggregate Angularity | 40 |
| Air Voids | 4.0 % |
| Voids in Mineral Aggregate (VMA) | 14.0 % |
| Voids Filled with Asphalt (VFA) | 65 – 78 % |
| Tensile Strength Ratio | 75 % |
| % Gmm @ $N_{ini}$ | (not required) |
| % Gmm @ $N_{max}$ | $\leq$ 98.0 % |

A control mixture was designed first, to serve as a baseline for the other mixtures. The first mixture had no RAP and used PG 58-28 binder. The Superpave mix design process was used to determine the optimum asphalt content for this mixture. The volumetric properties of the mixture were determined and deemed reasonable. The next step consisted of designing the mixtures containing RAP and millings. The goal was to make the gradation for each subsequent mixture as close as possible to the 0% RAP mixture. This was done by varying the percentages of the aggregates in the mixtures.

Given that the asphalt binder grade should not significantly affect the binder content in the mix, the mix designs were only performed with the PG 58-28 binder. Mixtures with PG 58-34 binder were designed with the same proportions as those with the PG 58-28 binder. Table 3.5 shows the proportions of aggregates and binder in each mixture as well as the volumetric properties. The combined aggregate gradations for the mixtures are shown in Figure 3.1.

**Table 3.5 Mixture Proportions**

| Mixture | R028 | R2028 | R4028 | M2028 | M4028 |
|---|---|---|---|---|---|
| **Kraemer 9/16 %** | 42.0 | 33.0 | 27.0 | 33.0 | 27.0 |
| **Kraemer Sand %** | 25.0 | 18.0 | 13.0 | 18.0 | 13.0 |
| **Nelson Sand %** | 16.0 | 14.7 | 9.7 | 14.9 | 10.2 |
| **BA ½ inch %** | 17.0 | 14.0 | 9.6 | 14.2 | 10.0 |
| **RAP aggregates %** | 0.0 | 20.3 | 40.7 | 0.0 | 0.0 |
| **Millings aggregates %** | 0.0 | 0.0 | 0.0 | 19.9 | 39.8 |
| **RAP content %** | 0 | 20 | 40 | 20 | 40 |
| **Asphalt Content %** | 5.85 | 5.38 | 5.29 | 5.32 | 5.05 |
| **Air Voids %** | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| **VMA %** | 15.3 | 14.4 | 13.9 | 13.9 | 13.8 |
| **VFA %** | 73.6 | 72.3 | 71.3 | 71.6 | 68.5 |

**Mixing**

For the mixtures with PG 58-28 binder, mixing was performed at 145°C. For the mixtures containing PG 58-34 binder, mixing was performed at 139°C. The batched aggregates were heated to this temperature and poured into the mixing pail. If applicable, heated RAP or millings was broken up and poured into the mixing pail. Finally, the heated asphalt binder was poured into the mixer at the proper proportion. After adequate mixing in the bucket mixer, the batch was transferred into a large pan and mixed by hand to ensure that all of the materials were well blended. The mixture was aged in the oven according to AASHTO R 30: Mixture Conditioning of Hot-Mix Asphalt (HMA).

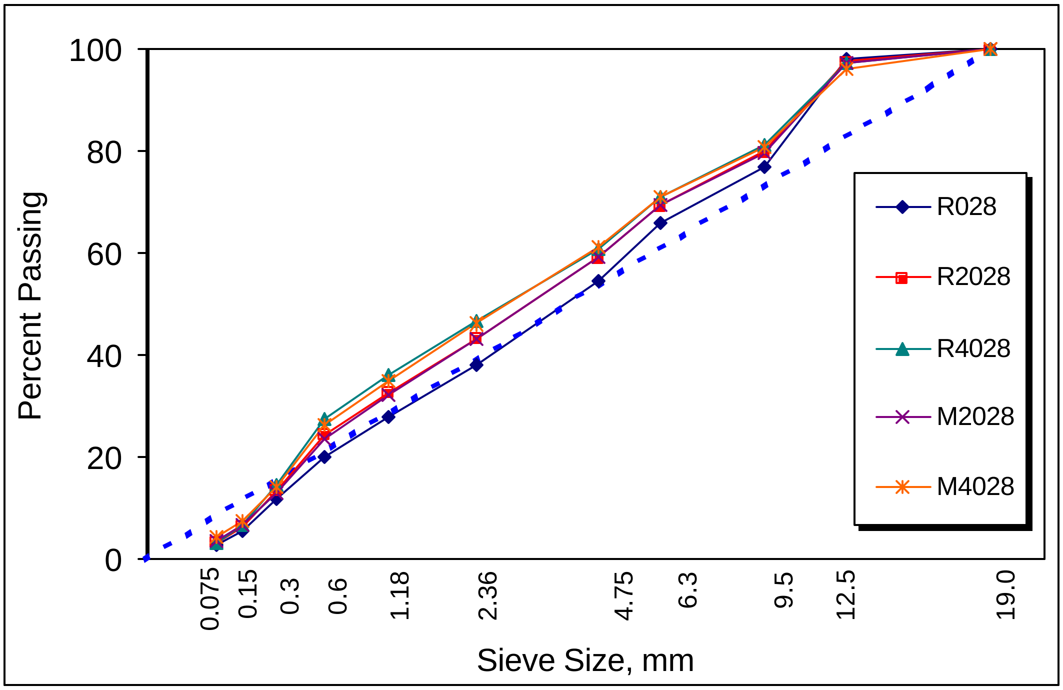


**Figure 3.1 Mixture Gradations**

## Compaction

The mixtures were compacted in the Brovold gyratory compactor at 133°C and 118°C for PG 58-28 and PG 58-34 binders, respectively. Based on the traffic level assumed for the mixture designation, the number of gyrations was as follows: $N_{ini} = 6$, $N_{des} = 40$, and $N_{max} = 60$.

## Moisture Susceptibility Testing

After the mixture design was finished, moisture susceptibility testing was performed on the ten mixtures according to AASHTO T 283: Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage. The University of Minnesota prepared all of the samples, and the Minnesota Department of Transportation conducted the tests. For each mixture, four specimens were prepared in the gyratory compactor at 7.0% air voids. Two of the specimens were tested in the dry condition, and the other two specimens were subject to a warm-water soaking cycle before being tested for indirect tensile strength. No freeze-thaw conditioning cycles were performed on the conditioned specimens.

The raw wet (conditioned) and dry (unconditioned) strength values for the ten mixtures are shown in Figure 3.2.

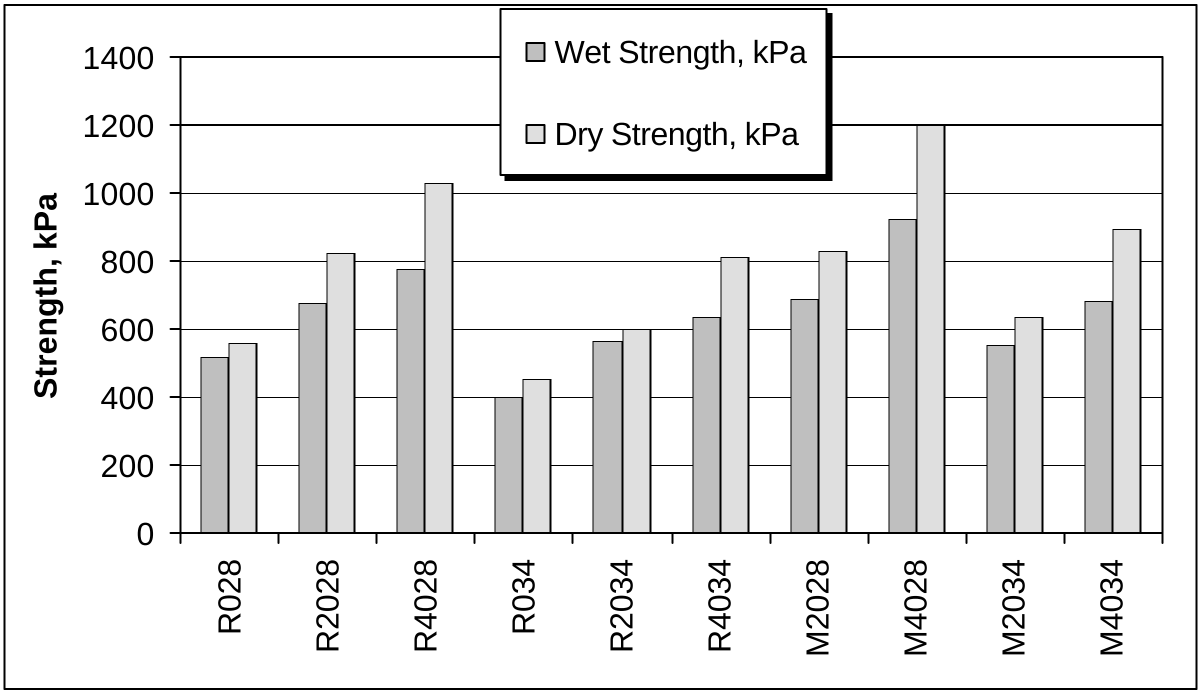


**Figure 3.2 Moisture Susceptibility Test Data – Raw Strength Values**

The results indicate that as the percentage of RAP or millings increased the strength also increased. The mixtures containing millings generally had higher strengths than the mixtures containing RAP. The tensile strength values varied greatly for different mixtures. For many of the mixtures, the strength results were 500-700 kPa, but some mixtures were a bit higher while others were significantly lower. Stroup-Gardiner et al recognized in a previous research project [27] that there should be limits established for both the minimum unconditioned tensile strength and the minimum percent retained tensile strength after conditioning.

Figure 3.3 shows the tensile strength ratio (wet strength ÷ dry strength x 100%) for each of the ten mixtures. All ten mixtures pass the minimum ratio of 75%. The results indicate that as the percentage of RAP or millings increases, the tensile strength ratio decreases. This is true except for the R2034 mixture, which may be an outlier.

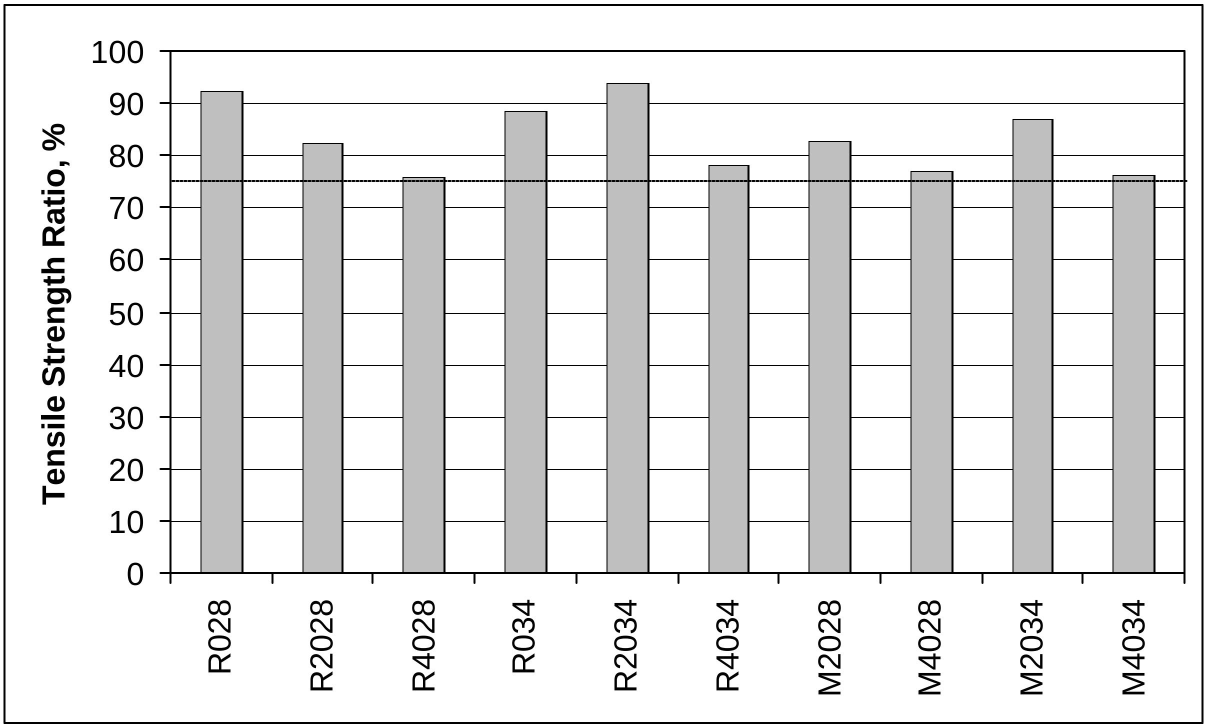


**Figure 3.3 Moisture Susceptibility Test Data – Tensile Strength Ratio**

**Mixture Testing Plan**

The mixture testing consists of three components: dynamic modulus, IDT creep and strength, and moisture susceptibility. Four cylindrical specimens were prepared for each mixture according to the 2002 Design Guide. Dynamic modulus tests were performed at five temperatures (-20, -10, 4, 20, and 40°C) and five frequencies (25, 10, 1, 0.1, 0.01 Hz). Creep and strength tests were performed at -24 and -18°C.

**Asphalt Cement Testing**

Two original asphalts were used for this project and two RAP sources. The PG grading of the original asphalts were determined according to current Superpave specifications (AASHTO M320). Binders were extracted from the RAP and millings, and the recovered binders were graded. After the dynamic modulus tests were completed, the asphalt binders were extracted from each of the ten mixtures and graded. Based on these test results blending charts were established. All binder extractions were performed at Mn/DOT chemical laboratory.

# CHAPTER 4

# DYNAMIC MODULUS TESTING

## Testing Equipment

All tests were performed on an MTS servo-hydraulic testing system. The TestStar IIs control system was used to set up and perform the tests and to collect the data. The software package MultiPurpose TestWare was used to custom-design the tests and collect the raw test data.

Flat, circular load platens were used to apply the cyclic compressive load to the specimen. Teflon paper was used to reduce friction at the end plates. The vertical deformation measurements were obtained using two MTS extensometers with a 114-mm gage length. They were attached to the specimen by springs, along with a drop of glue at the knife-edges. One average strain measurement was obtained from the two extensometers. The test setup is shown in Figure 4.1.

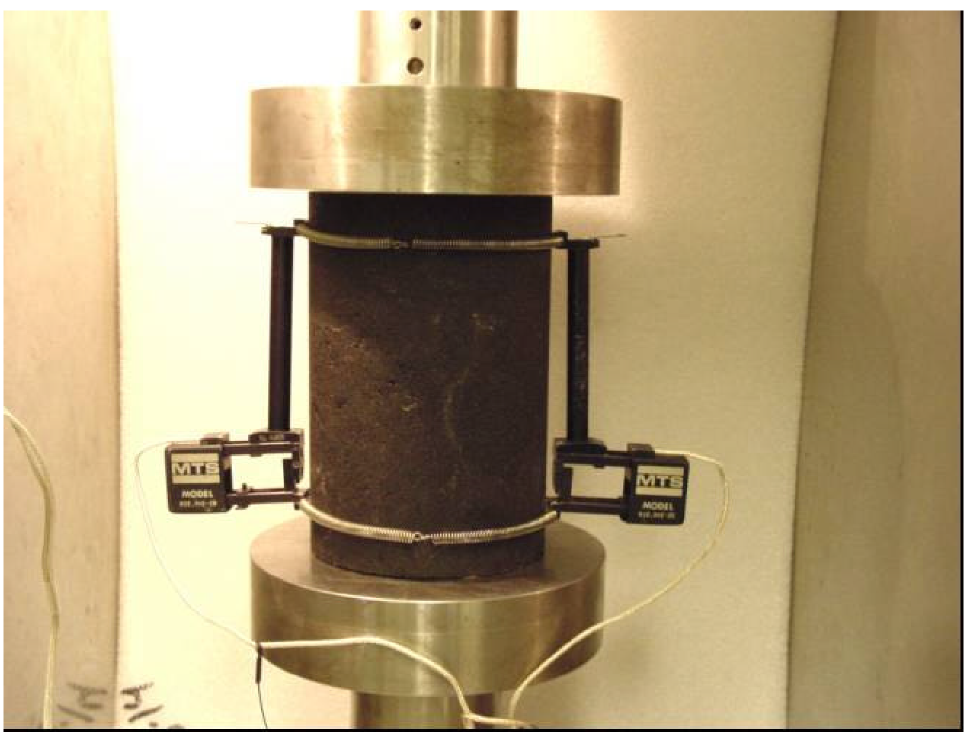


**Figure 4.1 Dynamic Modulus Test Setup**

All tests were performed inside an environmental chamber. Liquid nitrogen tanks were used to cool the chamber below room temperature, and mechanical heating was used for the higher test temperatures. The temperature was controlled by MTS temperature controller and verified using an independent platinum RTD thermometer.

**Sample Preparation**

Cylindrical specimens 100-mm by 150-mm were prepared according to the procedure recommended in NCHRP Report 9-19 [28]. Cylindrical specimens with dimensions 150-mm by 170-mm were compacted in the laboratory using the Brovold gyratory compactor. They were then cored to a 100-mm diameter and saw cut to a final height of 150 mm. The air voids were measured on the finished test specimens. Adjustments were made to the number of gyrations during compaction to achieve about 5.0% air voids. This sample preparation procedure was followed to prepare four samples for each of the ten mixtures. Table 4.1 shows the parameters obtained during sample preparation, including air voids, compaction temperature, number of gyrations, height, and diameter of the specimens.

**Testing Procedures**

The testing procedure was based on AASHTO TP 62: *Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*. The procedure describes performing tests at several different temperatures and loading frequencies. Tests were performed at temperatures of -20, -10, 4.4, 21.1 and 37.8$^{\circ}$C and frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz. Each specimen was tested for 30 combinations of temperature and frequency. Testing began with the lowest temperature and proceeded to the highest. At a given temperature, the testing began with the highest frequency of loading and proceeded to the lowest.

On the night previous to testing, the extensometers were placed on the test specimen using springs and glue as mentioned above. On the morning of testing, the specimen was placed in the environmental chamber at -20$^{\circ}$C and allowed to equilibrate for 2 hours. Teflon paper was placed between the specimen and steel plates at the top and bottom.

To begin testing, the extensometers were zeroed and a minimal contact load was applied to the specimen. A sinusoidal axial compressive load was applied to the specimen without impact in a cyclic manner.

### Table 4.1 Sample Preparation Data

| Sample No. | Asphalt Content % | Compact Temp °C | Gyration Number | Air Voids % | Height mm | Diameter mm |
|---|---|---|---|---|---|---|
| R028-9 | 5.85 | 139 | 19 | 5.65 | 148.7 | 100.66 |
| R028-10 | 5.85 | 139 | 19 | 5.73 | 149.25 | 100.5 |
| R028-11 | 5.85 | 139 | 19 | 5.41 | 152.23 | 100.7 |
| R028-13 | 5.85 | 139 | 10 | 5.41 | 149.02 | 100.7 |
| R2028-5 | 5.377 | 139 | 19 | 5.76 | 149.83 | 100.64 |
| R2028-6 | 5.377 | 139 | 19 | 5.46 | 148.5 | 100.65 |
| R2028-7 | 5.377 | 139 | 19 | 5.44 | 149.35 | 100.74 |
| R2028-9 | 5.377 | 139 | 13 | 4.77 | 150.48 | 100.68 |
| R4028-5 | 5.288 | 139 | 19 | 4.75 | 148.21 | 100.7 |
| R4028-6 | 5.288 | 139 | 19 | 4.35 | 149.7 | 100.6 |
| R4028-7 | 5.288 | 139 | 19 | 4.48 | 150.89 | 100.79 |
| R4028-9 | 5.288 | 139 | 19 | 5.11 | 151.2 | 100.78 |
| M2028-1 | 5.318 | 139 | 19 | 5.09 | 150.58 | 101.1 |
| M2028-2 | 5.318 | 139 | 19 | 5.13 | 150.3 | 101.02 |
| M2028-3 | 5.318 | 139 | 19 | 5.08 | 148.15 | 101.06 |
| M2028-5 | 5.318 | 139 | 19 | 4.94 | 148.99 | 100.75 |
| M4028-1 | 5.05 | 139 | 19 | 5.02 | 149.01 | 101.11 |
| M4028-2 | 5.05 | 139 | 19 | 4.91 | 148.45 | 101.09 |
| M4028-3 | 5.05 | 139 | 19 | 5.14 | 150.21 | 101.11 |
| M4028-5 | 5.05 | 139 | 19 | 4.89 | 151.96 | 100.76 |
| R034-1 | 5.85 | 118 | 18 | 4.90 | 150.77 | 100.72 |
| R034-2 | 5.85 | 118 | 18 | 4.98 | 150.54 | 100.65 |
| R034-3 | 5.85 | 118 | 18 | 5.20 | 150.62 | 100.54 |
| R034-5 | 5.85 | 118 | 10 | 4.76 | 148.91 | 100.42 |
| R2034-1 | 5.377 | 118 | 19 | 5.20 | 149.52 | 100.61 |
| R2034-2 | 5.377 | 118 | 19 | 4.80 | 149.2 | 100.7 |
| R2034-3 | 5.377 | 118 | 19 | 4.97 | 150.48 | 100.69 |
| R2034-5 | 5.377 | 118 | 13 | 4.62 | 149.63 | 100.73 |
| R4034-1 | 5.288 | 118 | 19 | 5.74 | 149.34 | 101.1 |
| R4034-2 | 5.288 | 118 | 19 | 5.73 | 149.53 | 101.23 |
| R4034-3 | 5.288 | 118 | 19 | 4.98 | 149.23 | 101.35 |
| R4034-5 | 5.288 | 118 | 13 | 5.66 | 151.02 | 100.71 |
| M2034-1 | 5.318 | 118 | 19 | 5.23 | 148.46 | 101.06 |
| M2034-2 | 5.318 | 118 | 19 | 4.96 | 148.79 | 101.16 |
| M2034-3 | 5.318 | 118 | 19 | 5.33 | 150.09 | 101.08 |
| M2034-5 | 5.318 | 118 | 19 | 4.76 | 151.57 | 100.71 |
| M4034-1 | 5.05 | 118 | 19 | 5.25 | 150.94 | 100.73 |
| M4034-2 | 5.05 | 118 | 19 | 4.90 | 151.16 | 100.78 |
| M4034-3 | 5.05 | 118 | 19 | 5.05 | 148.09 | 100.71 |
| M4034-5 | 5.05 | 118 | 19 | 4.53 | 149.04 | 100.75 |

The load was adjusted in each case to attempt to keep the axial strains between 50 and 150 $\mu\varepsilon$. The first step was to apply a preconditioning load to the specimen with 200 cycles at 25 Hz. Testing continued with different numbers of cycles for each frequency as shown in Table 4.2. The data acquisition system was set up to record the last 5 cycles for analysis at each frequency with about 200 points per cycle.

**Table 4.2 Cycles for Test Sequence**

| Frequency, Hz | Number of Cycles |
|---|---|
| Preconditioning (25) | 200 |
| 25 | 200 |
| 10 | 200 |
| 5 | 100 |
| 1 | 20 |
| 0.5 | 15 |
| 0.1 | 15 |

After the entire cycle of testing was complete at -20°C, the environmental chamber was set to the next temperature. After 2 hours conditioning, the above steps were repeated until the entire sequence of temperatures and frequencies was completed.

**Results**

To analyze the complex modulus data, a modified version of the SINAAT 2.0 program developed by Don Christensen [29] was used. This program is based on the recommendations for the analysis of dynamic data as part of NCHRP 9-19 [28]. At high temperatures, the displacement curves were not sinusoidal but increased with time. This drift rate was subtracted out in the program to obtain sinusoidal displacement curves.

Three replicate specimens were tested for each asphalt mixture for all 5 test temperatures. An additional replicate (number 4) was tested only at -20ºC, -10ºC and 4ºC. After all the complex dynamic modulus and phase angle values were obtained for each specimen under the same test conditions, the average values for both of these parameters were calculated. The dynamic modulus and phase angle values determined can be found in Appendix A.

**Dynamic Modulus Master Curves**

The dynamic modulus and phase angle of asphalt mixtures can be shifted along the frequency axis to form master curves at a desired reference temperature. This procedure assumes that asphalt mixtures are thermorheologically simple materials and the time-temperature superposition principle is applicable.

Typically the shift factors $\alpha_T$ are obtained from the WLF equation [30]:

$$\log a_T = \frac{C_1(T - T_S)}{C_2 + T - T_S} \tag{4.1}$$

where $C_1$ and $C_2$ are constants, $T_s$ is the reference temperature, and T is the temperature of each individual test.

A new method of developing the master curve for asphalt mixtures was developed in the research conducted by Pellinen [31]. In this study, master curves were constructed fitting a sigmoidal function to the measured compressive dynamic modulus test data using non-linear least squares regression techniques. The shift can be done by solving the shift factors simultaneously with the coefficients of the sigmoidal function. The sigmoidal function is defined by equation 4.2.

$$\log\left|E^*\right| = d + \frac{a}{1 + e^{b - g\left(\log(f_r) + s_T\right)}} \tag{4.2}$$

where

$\log|E^*|$ = log of dynamic modulus,

d = minimum modulus value,

$f_r$ = reduced frequency,

a = span of modulus values,

$s_T$ = shift factor according to temperature, and

ß, $\gamma$ = shape parameters.

The master curve can be constructed using any non-linear curve-fitting technique. In this research the reference temperature for all mixtures was 4°C. The commercial computer program SigmaStat was used to fit the master curve for each set of data. This program uses the Marquardt-Levenberg algorithm to find the parameters that give the "best fit" between the equation and the data. The nonlinear regression algorithm seeks the values of the parameters that minimize the sum of the squared differences between the observed and the predicted values of the dynamic modulus. Figure 4.2 to 4.11 show the data calculated from the model (equation 4.2) for each test specimen.

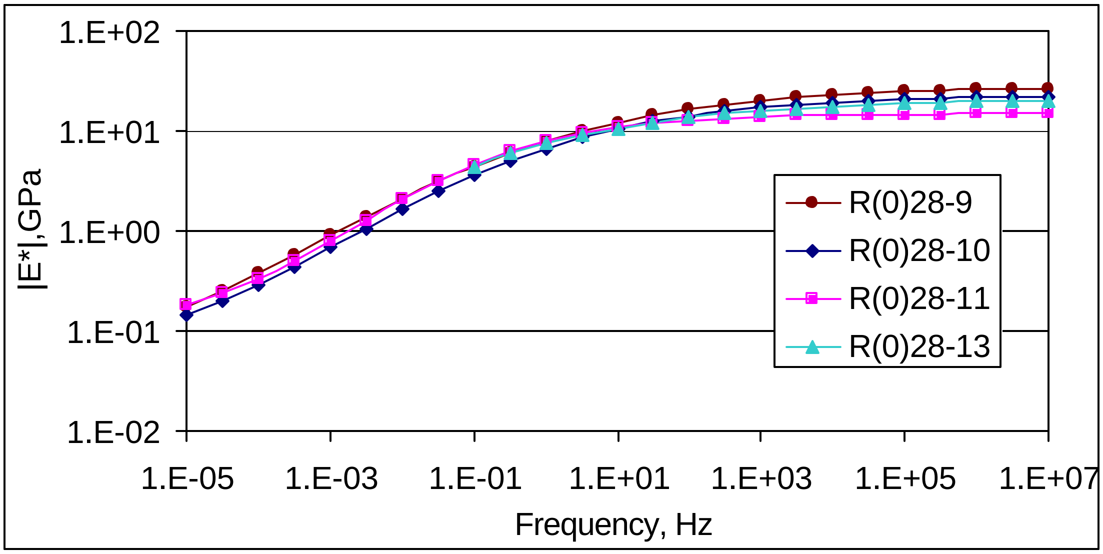


**Figure 4.2 Complex Modulus Master Curve for R028**

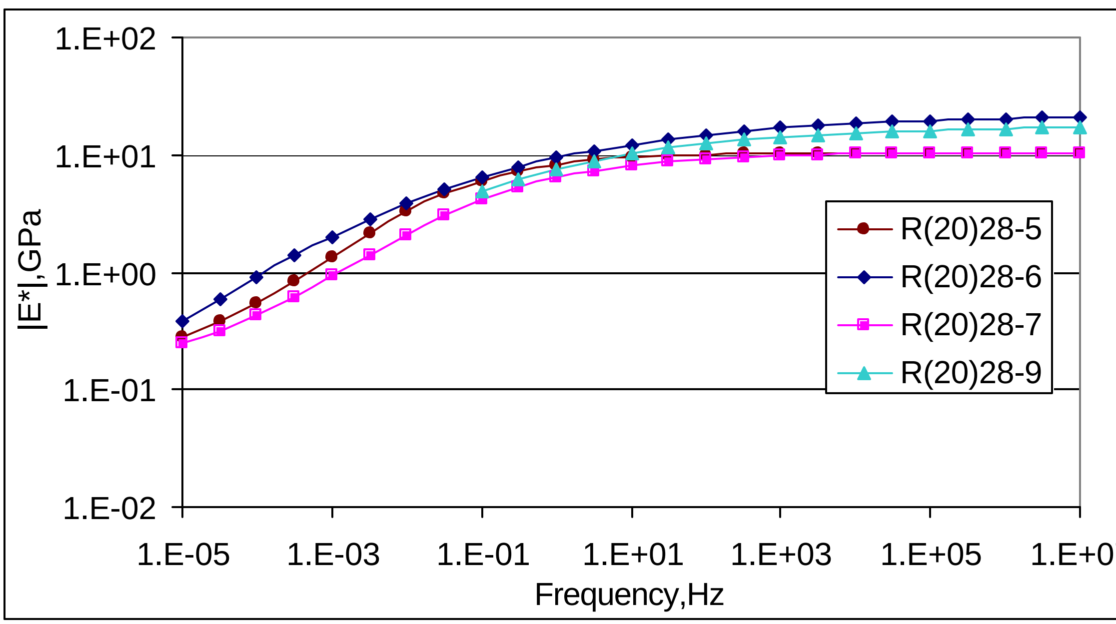


**Figure 4.3 Complex Modulus Master Curve for R2028**

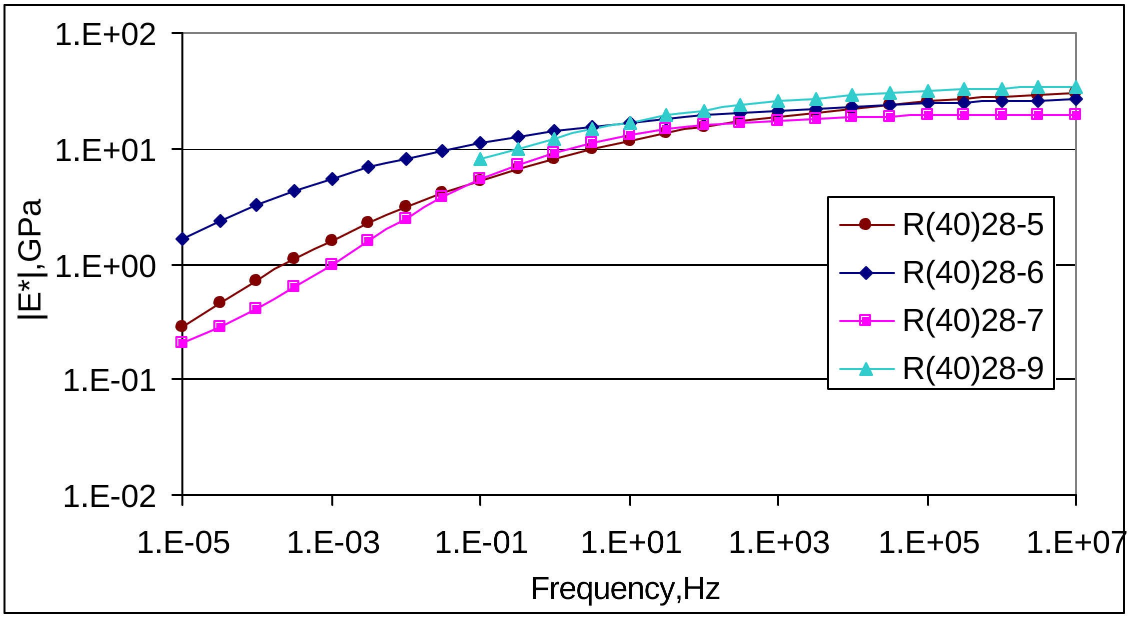


**Figure 4.4 Complex Modulus Master Curve for R4028**

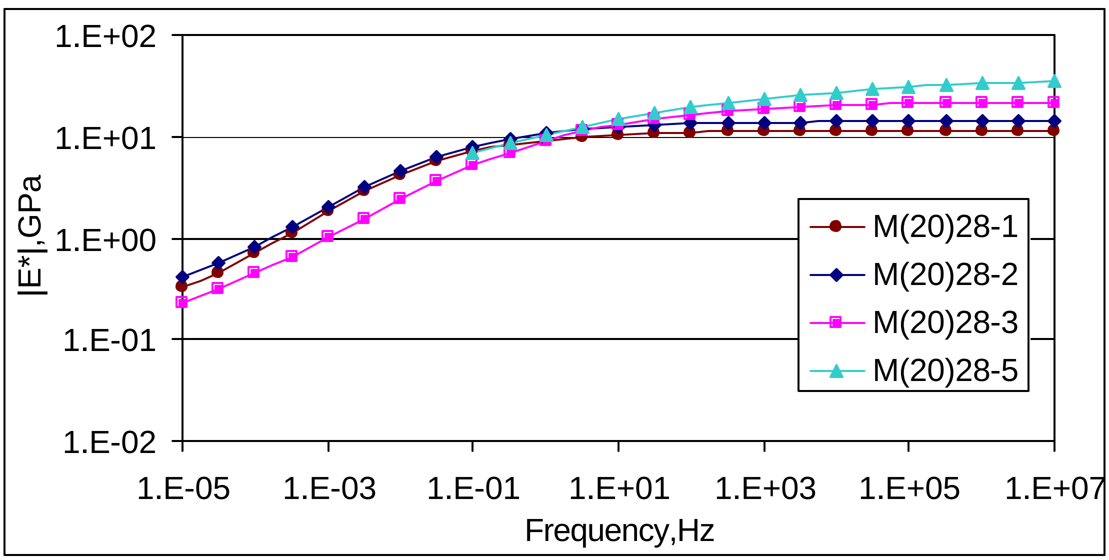


**Figure 4.5 Complex Modulus Master Curve for M2028**

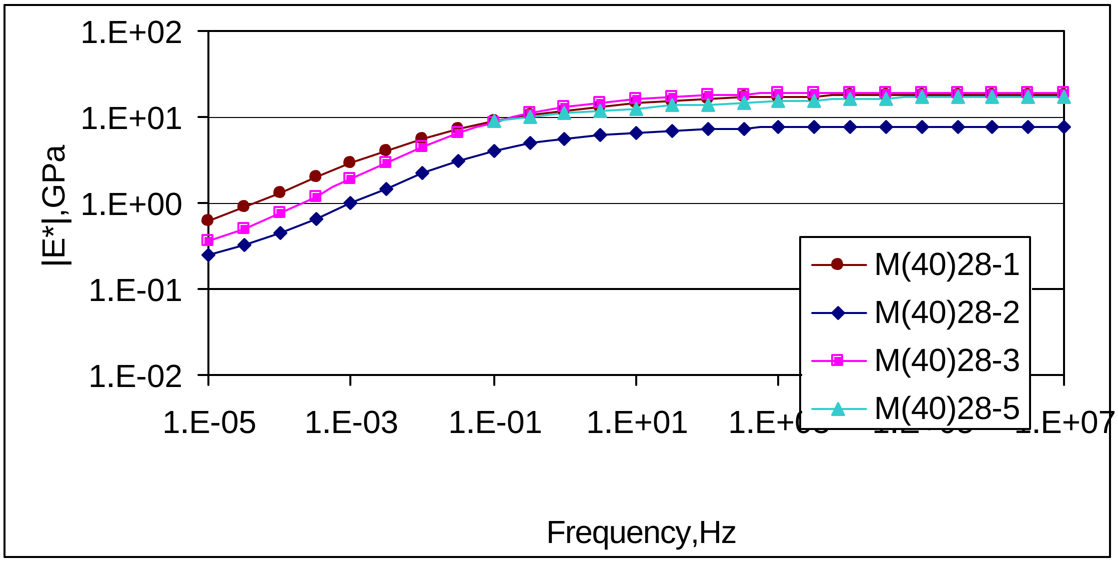


**Figure 4.6 Complex Modulus Master Curve for M4028**

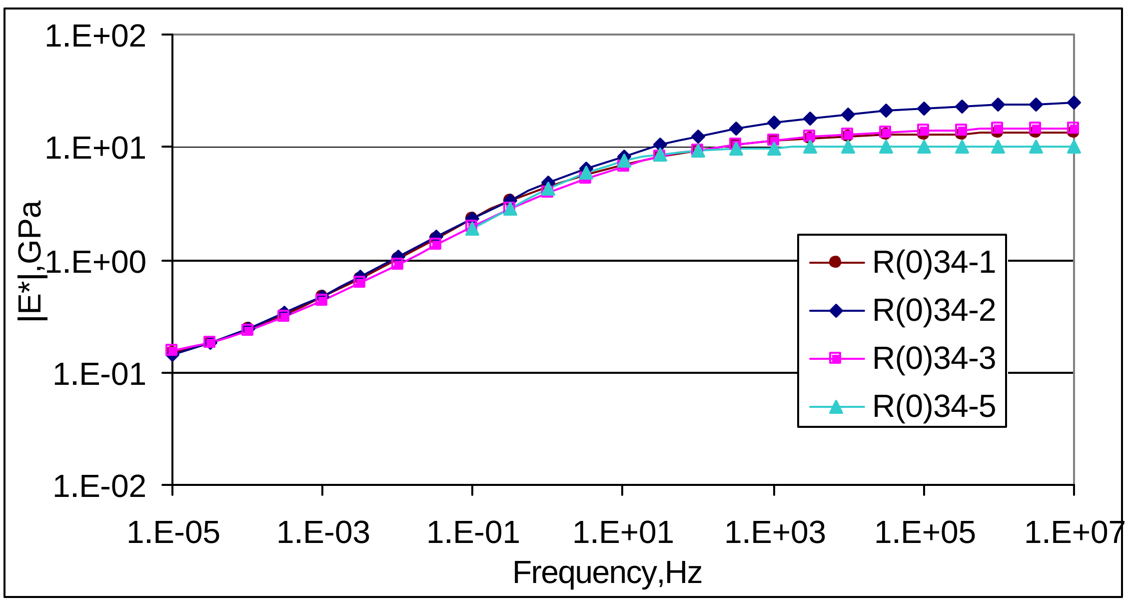


**Figure 4.7 Complex Modulus Master Curve for R034**

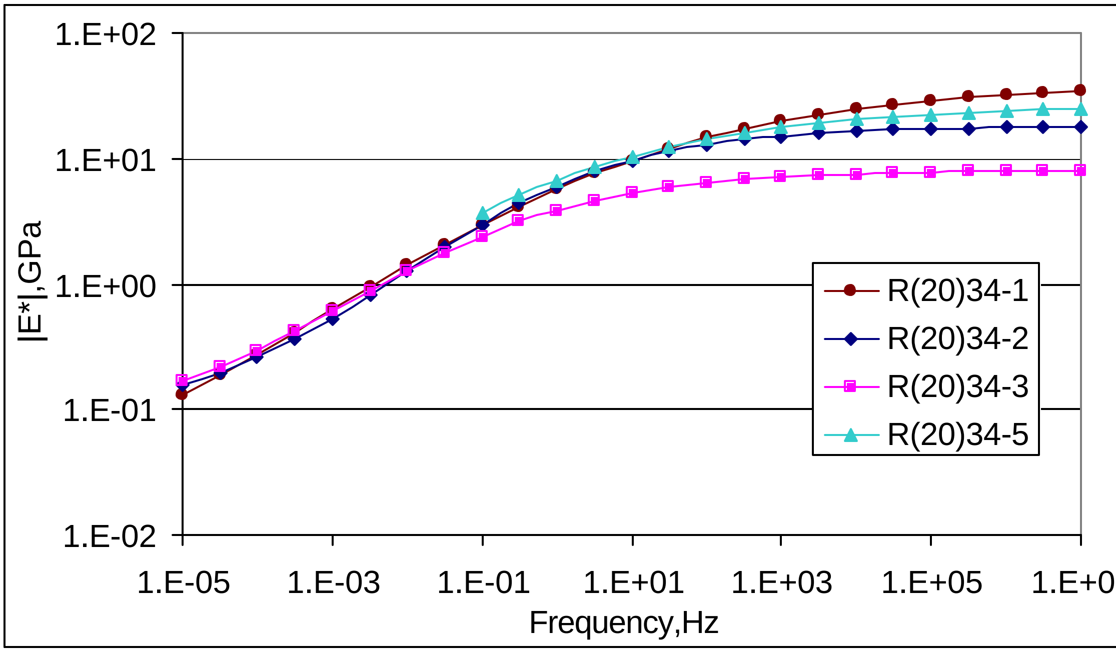


**Figure 4.8 Complex Modulus Master Curve for R2034**

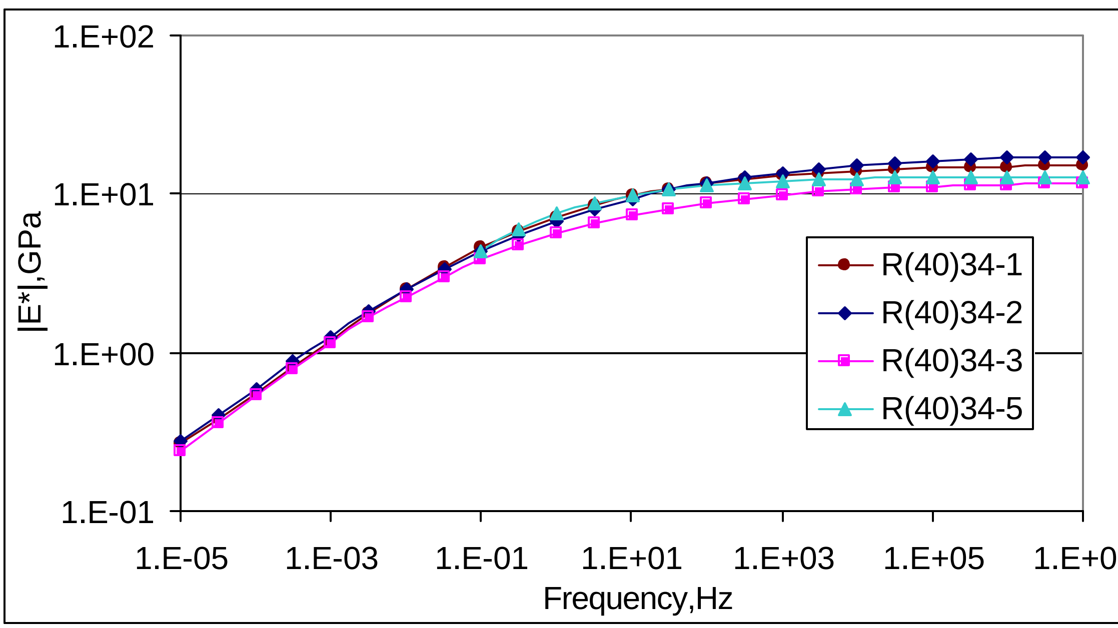


**Figure 4.9 Complex Modulus Master Curve for R4034**

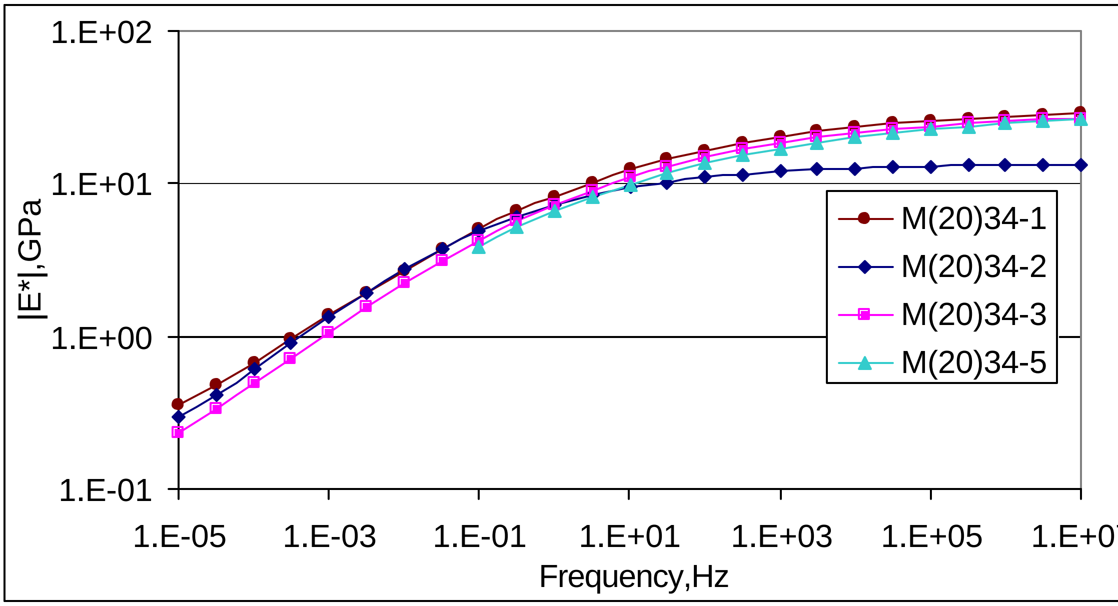


**Figure 4.10 Complex Modulus Master Curve for M2034**

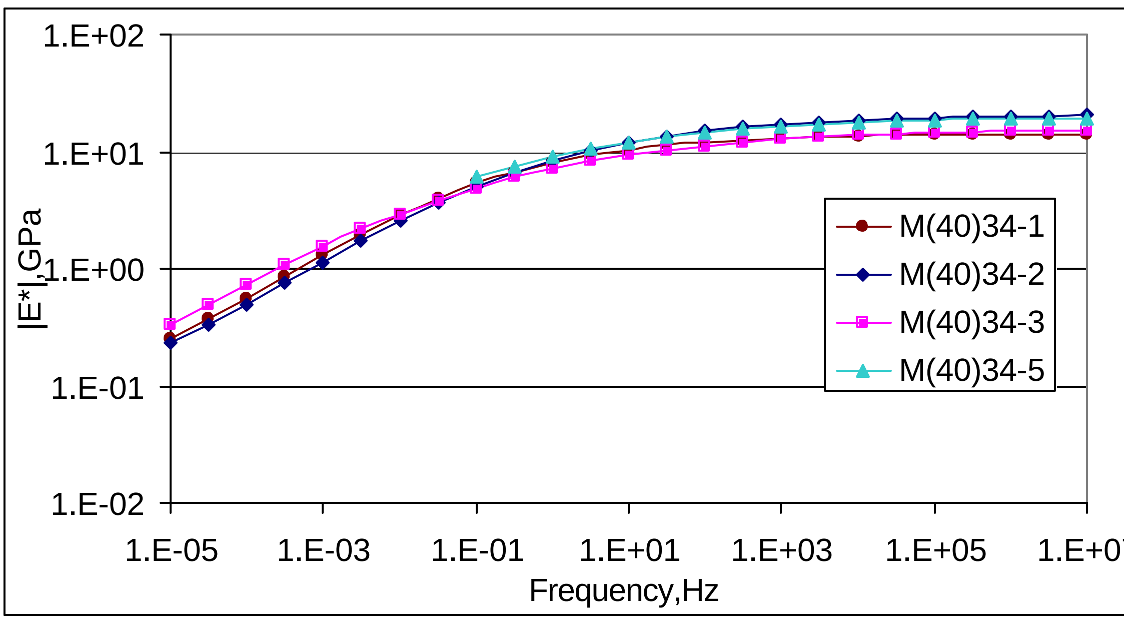


**Figure 4.11 Complex Modulus Master Curve for M4034**

The average complex modulus and coefficient of variation were calculated for each mixture after deleting the obvious outlier points. The average data is shown in Figures 4.12 to 4.15.

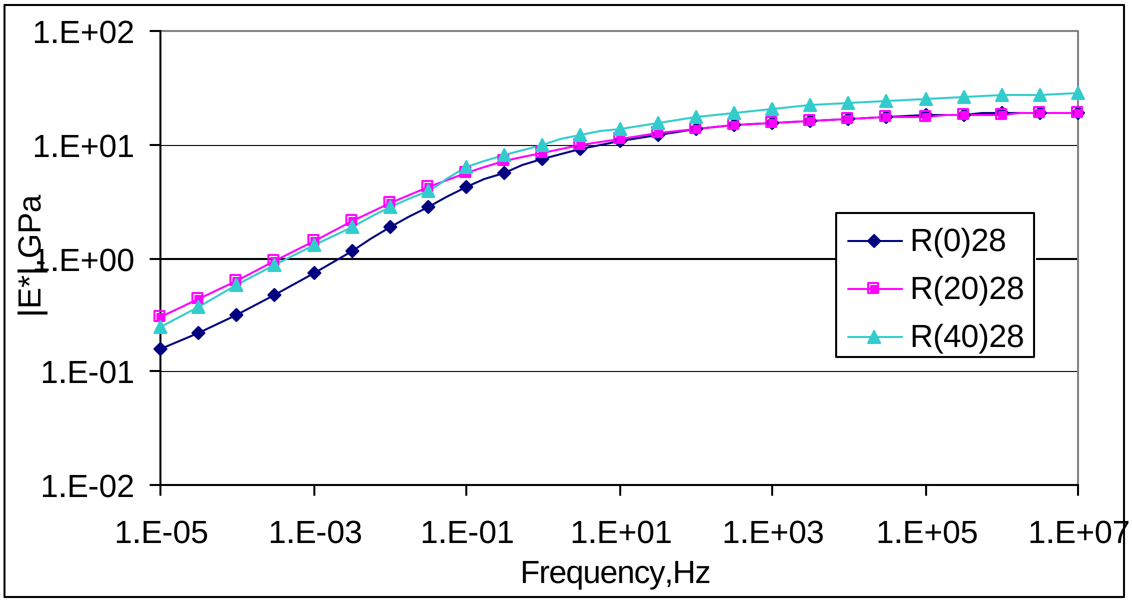


**Figure 4.12 Average Complex Modulus for R028, R2028 and R4028**

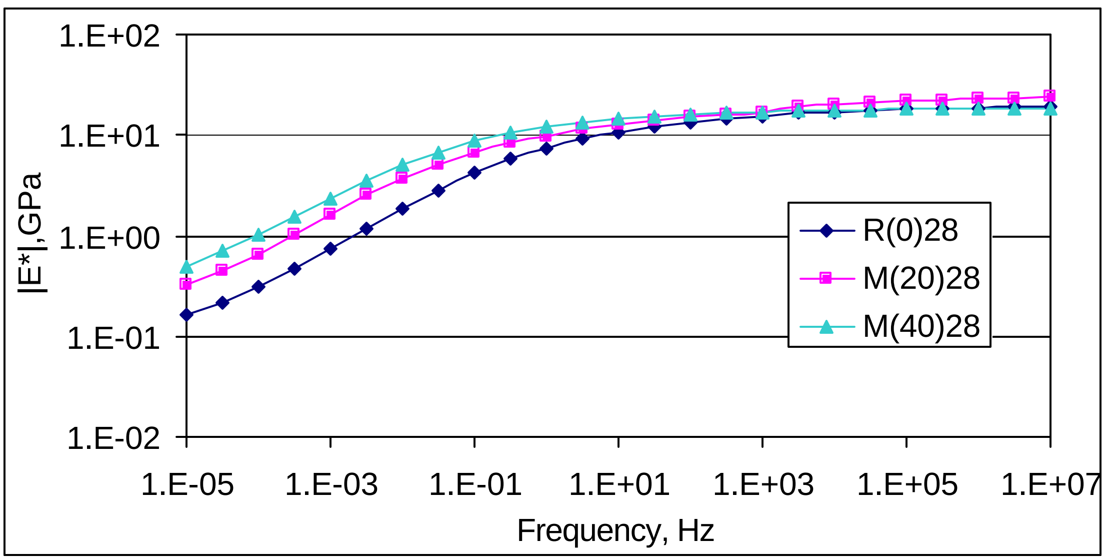


**Figure 4.13 Average Complex Modulus for R028, M2028 and M4028**

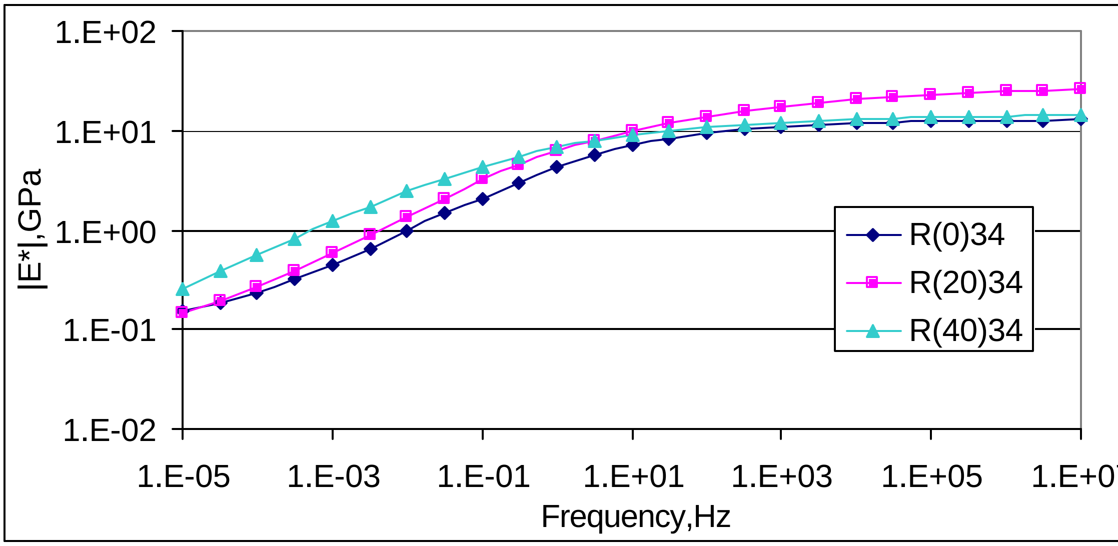


**Figure 4.14 Average Complex Modulus for R034, R2034 and R4034**

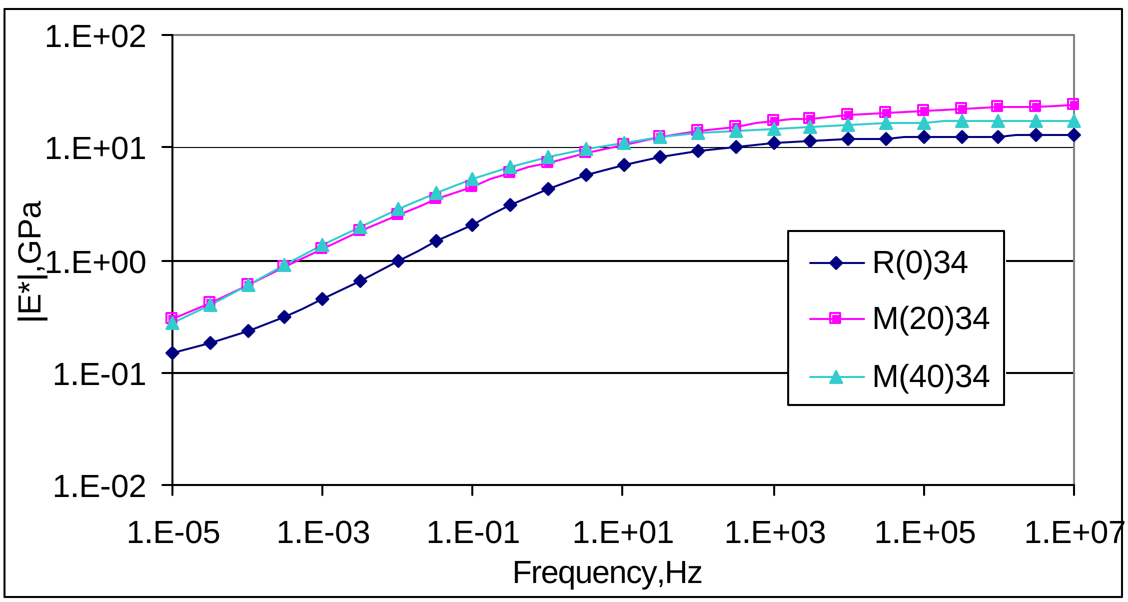


**Figure 4.15 Average Complex Modulus for R034, M2034 and M4034**

**Analysis and Discussion**

The complex modulus of an asphalt mixture defines the relationship between the viscoelastic stress and strain during sinusoidal loading. Testing was performed in order to evaluate:

(1) The change in complex modulus with the addition of RAP;

(2) Asphalt binder grade effect on asphalt mixture complex modulus;
(3) RAP source effect on asphalt mixture complex modulus (RAP and millings);
(4) The effect of test temperature and loading frequency on the complex modulus;
(5) The variability of complex modulus with the percent RAP incorporated in the new mixture.

*General Observations and Comments*

Several conclusions can be drawn from the test data and the above plots. Generally, the complex modulus for the mixtures with recycled asphalt pavement is higher than the control (0% RAP) asphalt mixtures modulus. However, at low temperatures the complex modulus does not always increase with the addition of RAP or milling. For example, Figure 4.14 shows the complex modulus for R2034 is higher than that for R4034 at a low temperature or high frequency. As described previously, the complex modulus is a property of a viscoelastic material, and it is related to many characteristics of the material such as the asphalt content, air voids, viscosity of the asphalt binder, gradation and characteristics of the aggregate and so on. The ten mixtures used in this research were designed to obtain similar gradations and air voids using different asphalt contents depending on the RAP content. The result is that the higher the RAP content, the lower the total asphalt content and the finer aggregate especially in the 0.3 mm to 4.75 mm particle size range was used, as was shown in Table 3.2 and 3.5. The finer gradations typically have lower stiffness from previous research [32]. As a result, the effect of the stiffer asphalt binder and lower asphalt content on the complex modulus can be offset by a finer gradation. One other possible reason for this result is the use of recycled asphalt pavement itself. Stiffer and brittle asphalt material can crack more easily at low temperatures. The use of more RAP may cause some micro-cracks in the testing sample at low temperatures, which will lead to the decrease in the stiffness of the mixture. This may also affect the property of the mixture at higher temperature, because the dynamic modulus test was performed from low temperature to high temperature.

The test results from the four samples for each mixture show more variability at -20ºC and -10ºC test temperatures than at the other temperatures. The variability can also be seen in plots of the load and deformation responses, which show more scatter at the lower test temperatures. The strains are significantly lower at the low test temperatures and the electronic noise in the sensors can significantly affect the measured response. Higher variability at the colder test temperatures may also be a result of non-uniform contact of the loading platens. The sample surface may not be compliant enough at the low temperatures to ensure good contact, and therefore the stress distribution may vary. These results are in agreement with those reported by Sondag [33] and Advanced Asphalt Technologies [34].

*Effect of RAP Content on Complex Modulus*

The addition of RAP to the mixture had a pronounced effect on the complex modulus. As found by other researchers the addition of RAP results in a stiffer mixture [19]. Just as described previously, the complex modulus is not controlled only by the stiffness of the binder but also many other factors including the gradation and angularity of the aggregate. For the mixture with more RAP material, more fine aggregates were used. Long time service in the pavement may cause the aggregate less angularity, which may also be a contributor to lower dynamic modulus. Therefore, the increased stiffness brought about by the addition of RAP may be offset by the use of finer and round aggregate. These results are also in agreement with a previous research [32]. Figures 4.12 to 4.15 illustrate that the complex modulus increases with the addition of RAP at temperatures above -10ºC, but for -10ºC and -20ºC, mixtures with 20% RAP or milling have the highest complex modulus, and mixtures with 40% RAP or milling have the second highest complex modulus, and the mixtures without any RAP have the lowest complex modulus. One typical plot of this relationship between the complex modulus and RAP content for all temperatures at one frequency is shown in Figure 4.16.

Figure 4.17 illustrates the effect of RAP on complex modulus for all ten mixtures at 21ºC and 1.0 Hz. The complex modulus for all ten mixtures increases with the addition of RAP or millings at this testing temperature and frequency. For the mixture with PG 58-28 asphalt binder, the complex modulus increased by 23% with 20% addition of RAP, and adding 40% RAP resulted in a 62% increase. For the mixture with PG 58-34 asphalt binder, the complex modulus increased by 97% with 20% addition of millings, and adding 40% millings resulted in a 133% increase in complex modulus. The increase of the stiffness at high temperature with the addition of RAP is beneficial for the mixture in terms of its resistance to permanent deformation.

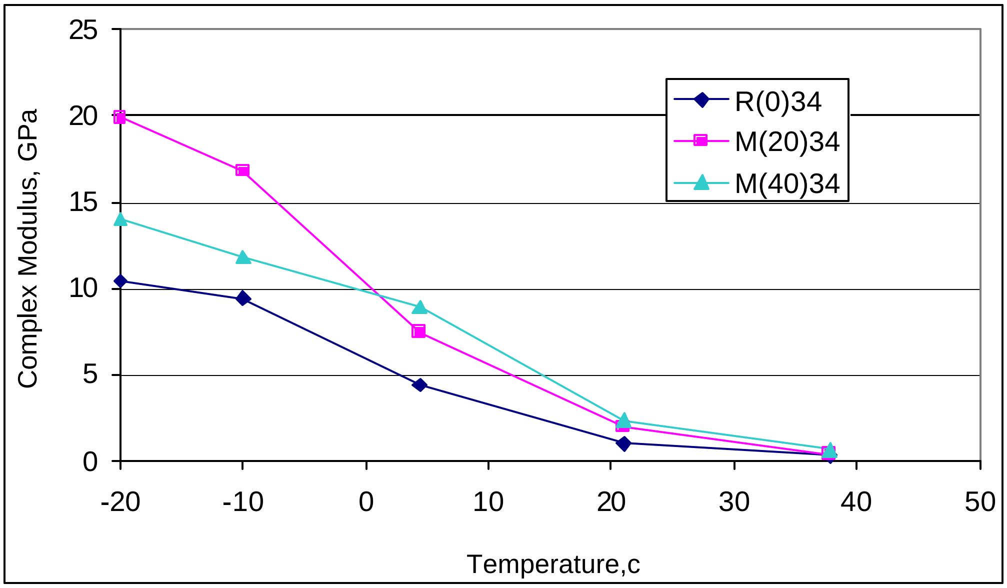


**Figure 4.16 Effect of RAP on Complex Modulus for Mixtures with Millings and PG 58-34 Binder, 1.0 Hz**

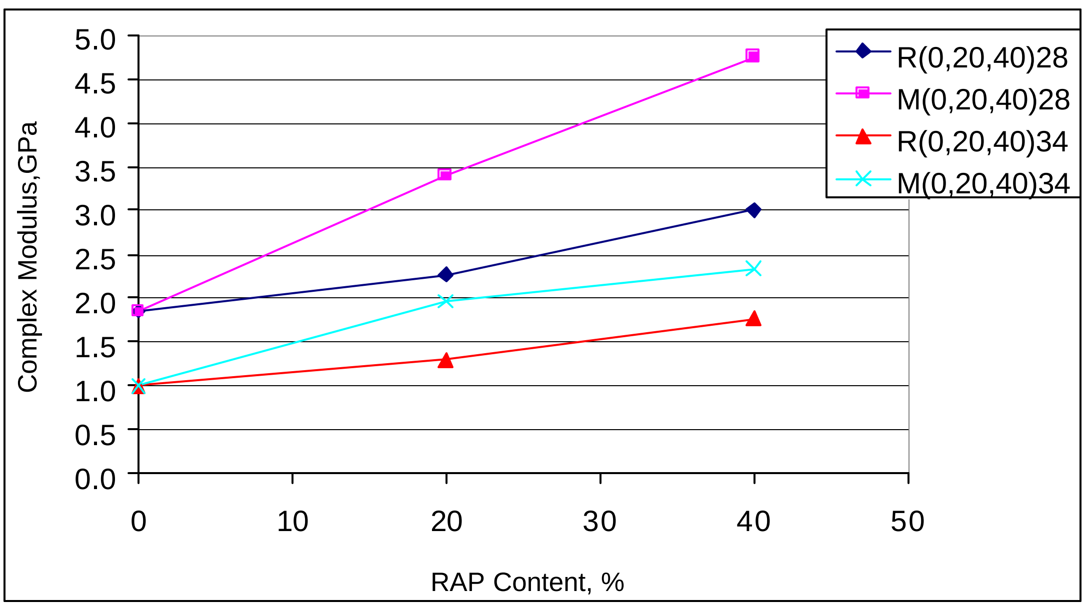


**Figure 4.17 Effect of RAP on Complex Modulus for all Ten Mixtures @ 21°C, 1.0 Hz**

Figure 4.17 can also be used to determine how much RAP may be added to a mixture while maintaining a complex modulus similar to a mixture composed of entirely virgin material.

At 21ºC, about 18% of millings may be used with a PG 58-34 asphalt binder to achieve a complex modulus equal to that of a virgin mixture made with PG 58-28 asphalt binder.

*Effect of Asphalt Binder on Complex Modulus*

The complex modulus of the mixture increases with increasing the stiffness of the asphalt binder. This was observed for all mixtures tested, which means the complex modulus for the mixtures made with PG 58-28 asphalt binder is always higher than that from the mixtures made with a softer PG 58-34 asphalt binder, considering the other variables constant (testing temperature and frequency). Figure 4.18 illustrates the typical behavior of complex modulus for the two asphalt binders used in this research. The complex modulus master curve clearly shows that mixture R028 has higher complex modulus than R034 for all frequency ranges (or temperature ranges), which means the asphalt binder grade has a significant effect on the complex modulus for the entire temperature and frequency range. Figure 4.18 shows that the complex modulus was 50% higher for the mixture incorporating the stiffer PG 58-28 asphalt binder as compared to PG 58-34 at 4ºC and 10 Hz.

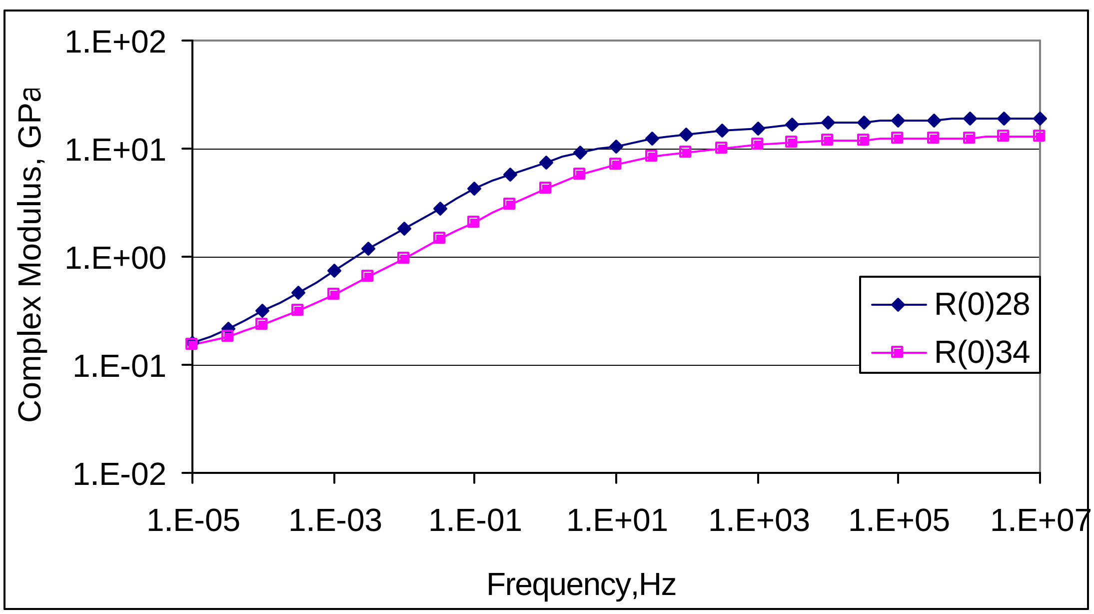


**Figure 4.18 Master Curve for Complex Modulus for R028 and R034, $T_{ref}$ = 4ºC**

The two mixtures used in Figure 4.18 were made without RAP. However, a similar trend between the complex modulus and the asphalt binder grade is observed for the mixtures incorporating RAP.

*Effect of RAP Source on Complex Modulus*

Two different RAP sources, RAP and millings, were used to prepare the mix specimens for complex modulus testing. Figure 4.19 shows the mixture with 20% RAP and PG 58-34 asphalt binder has a slightly higher complex modulus than the mixture with 20% millings, at high testing frequency or low temperature. However, at low frequency or high temperature, the mixture with 20% millings shows much higher complex modulus than the mixture with 20% RAP.

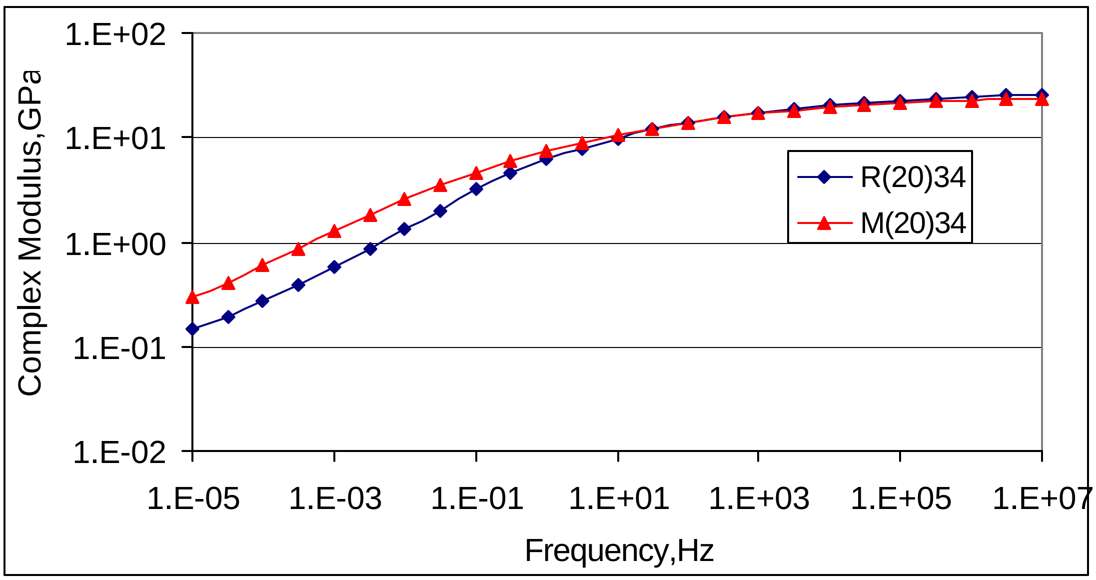


**Figure 4.19 Master Curve for the Complex Modulus for R2034 and M2034, $T_{ref}$ = 4ºC**

Figure 4.20 shows that at all testing frequencies or temperatures the mixture with 40% millings has higher complex modulus than that with 40% RAP, although the difference is not very significant. A similar relationship is observed for the mixtures with PG 58-28 asphalt binder. This suggests that the addition of the millings led to a larger increase in stiffness than the similar addition of RAP.

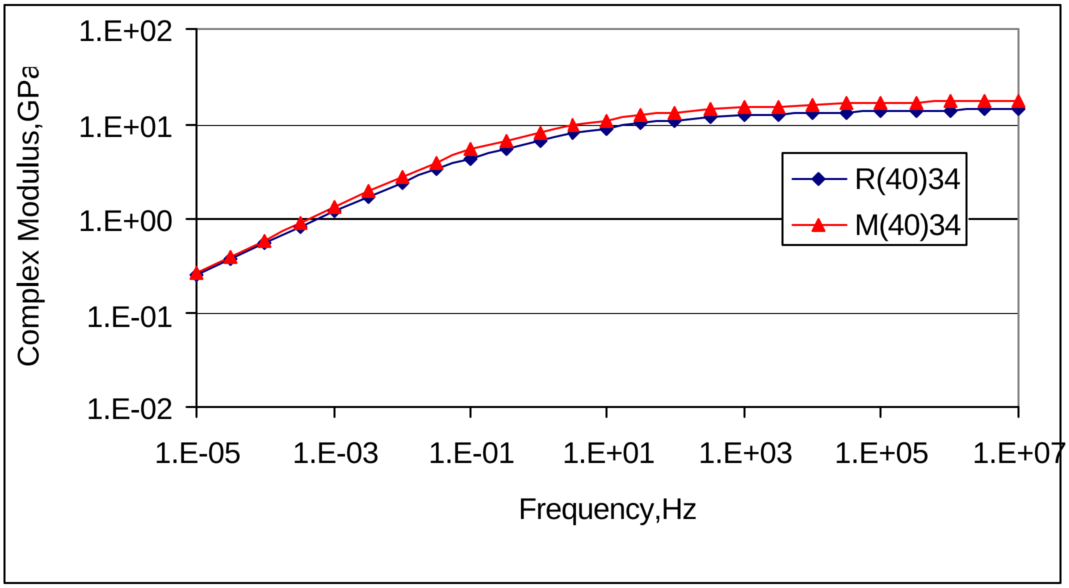


**Figure 4.20 Master Curve for the Complex Modulus for R4034 and M4034, $T_{ref}$ = 4ºC**

*Effect of Temperature and Loading Frequency on Complex Modulus*

Previous research indicated that the complex modulus increased as the test temperature decreased or test frequency increased. This was observed for all mixtures. Figure 4.21 shows the typical behavior of complex modulus with temperature at a frequency of 1.0 Hz.

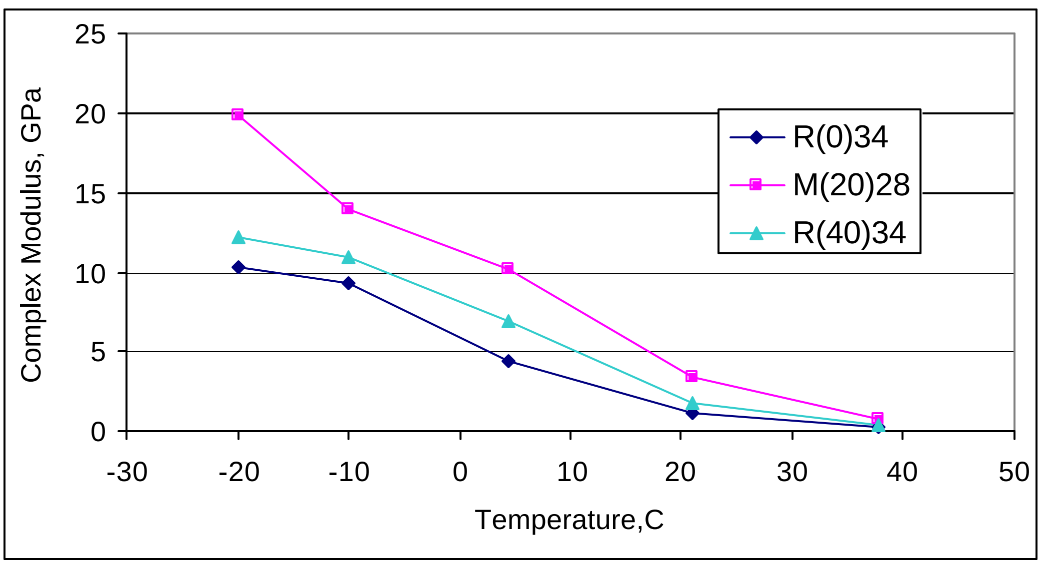


**Figure 4.21 Complex Modulus Changes with Temperature at 1.0 Hz**

The typical relationship between the complex modulus and the loading frequency at 21ºC is shown in Figure 4.22. As expected the complex modulus increases significantly with increase in test frequency.

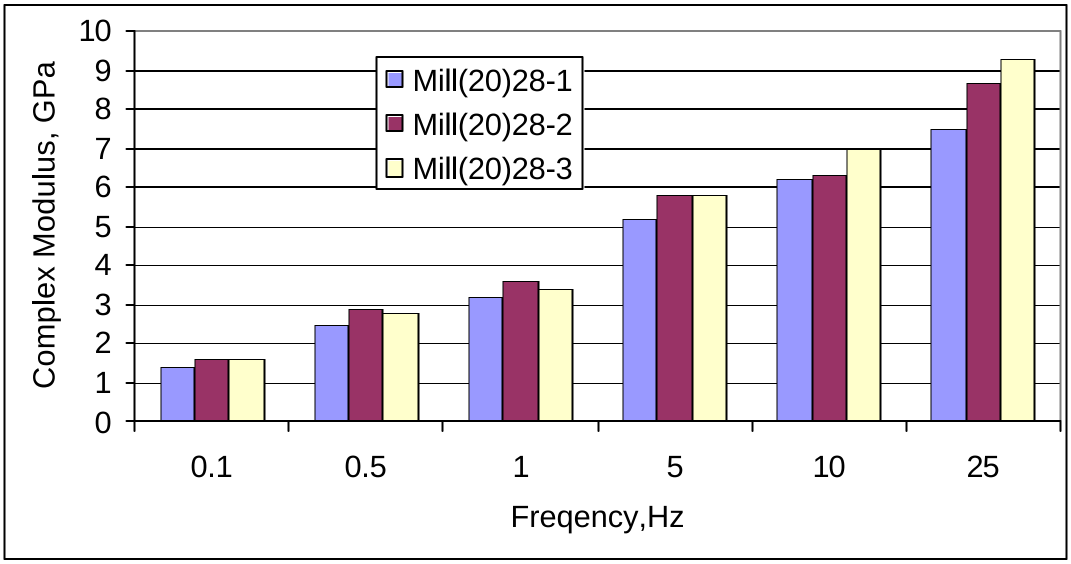


**Figure 4.22 Complex Modulus Changes with Frequency at 21ºC**

*Effect of RAP on Variability*

Past research indicated that the addition of RAP increases the variability of the test results, especially at low temperatures [33, 34]. This was also observed in this research. From the coefficient of variation of the test data the following results can be observed:

(1) More variability occurs at low temperature for the complex modulus test;

(2) Addition of RAP increases the variability of complex modulus.

As described previously, more variability at low temperatures is possibly caused by the high stiffness of the mixture and the small deformation at low temperatures, resulting in the non-uniform contact of the loading platens and a significant effect of the electronic noise. The increase in variability with the addition of RAP is most likely due to the variability of the RAP itself. Long term aging may cause variable aging over the thickness of the pavement; in addition, collecting RAP from different locations leads inevitably to more variability. It is worth mentioning that it was very difficult to obtain consistent air voids using the RAP, even when the asphalt content was held constant during the compaction of the test samples.

**Conclusions**

Based on the above analysis and discussion, the following conclusions can be drawn:

1. The addition of RAP to a mixture increased the complex modulus. At 21ºC and 1 Hz, adding 20% RAP to the mixture with binder PG 58-28 resulted in a 23% increase of complex modulus, and adding 40% RAP resulted in a 62 % increase of the complex modulus.
2. The complex modulus test indicated that the asphalt binder had a significant effect on the mixture stiffness. The complex modulus was increased by 50% for the mixture incorporating stiffer asphalt binder, PG 58-28, compared to the mixture with PG 58-34, at 4ºC and 10 Hz.
3. The RAP source also had an effect on the complex modulus values. Mixtures incorporating millings exhibited a higher complex modulus than those with RAP in the range of testing temperatures and frequencies, with the other variables the same.
4. The complex modulus increased as the test temperature decreased or as the loading frequency increased for the whole testing temperature and frequency range.
5. At 21ºC and 1.0 Hz, about 18% of millings may be used with a PG 58-34 asphalt binder to obtain a complex modulus equal to a mixture made with PG 58-28 asphalt binder.
6. Mixtures containing RAP showed increased variability with the increase in RAP content.
7. Complex modulus test results had more variability at low temperatures.

# CHAPTER 5

# IDT CREEP AND STRENGTH TESTING

## Indirect Tensile Tests (IDT)

Indirect tensile tests (IDT) were performed on the ten mixtures according to AASHTO TP 9: Standard Test Method for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the indirect Tensile Test Device.

In the indirect tensile creep (ITC) test, a specimen with dimensions of 150 mm diameter by 38 to 50 mm height was loaded in static compression across its diametral plane. The load was applied rapidly until the horizontal deformation on one face reached 0.002 mm (~ 50 $\mu\varepsilon$) and was then held constant for 1000 seconds. Two horizontal and two vertical extensometers (model # MTS OSDME) were used to record the deformation from both sides of the sample (see Figure 5.1). The creep compliance and stiffness were calculated using the load and resulting displacements as a function of time. For each mixture the specimens were compacted with the gyratory compactor and saw cut into four slices. Slices 1 and 3 were used to perform the creep test at -18°C, while slices 2 and 4 were tested at -24°C.

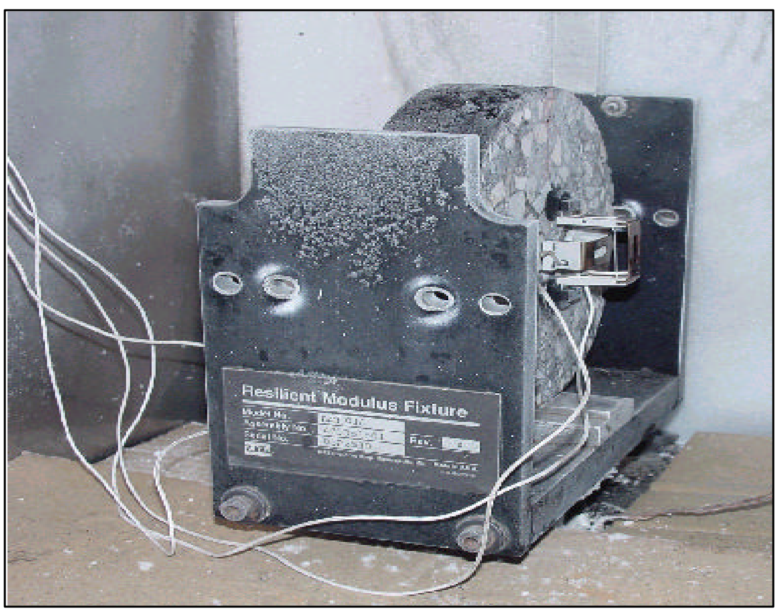


**Figure 5.1 Indirect Tensile Test Setup**

At the end of the creep test on each sample, the indirect tensile strength (ITS) test was performed at the same temperature. The tensile strength was obtained by loading the specimen at a constant rate of 12.5 mm/min stroke until failure. The specimen dimensions and peak load were used to calculate the failure strength.

Several experimental problems were encountered during testing and by the end of the creep testing three out of the four extensometers malfunctioned. The experimental data was thoroughly analyzed to eliminate any erroneous information and in some instances was corrected based on limiting values placed on the calculated Poisson's ratios. It is recommended that, if additional funding becomes available, the creep tests should be repeated to increase the level of confidence in the experimental results reported in this research

During initial trial runs of the IDT strength tests, the samples failed catastrophically. In order to protect the integrity of the extensometers it was decided to perform the strength tests without the extensometers attached to the specimens. The extensometers indicate the point of first failure in the specimen and therefore, the yield strength. The maximum load is used to calculate the ultimate strength. The difference between yield strength and ultimate strength is most likely minimal at these low temperatures, and therefore they can be considered approximately equal.

## IDT Creep Test Results

The data from IDT creep tests is shown in Table 5.1 and Figure 5.2. For convenience the stiffness value at 60 seconds was chosen as a point of comparison between the mixtures. The coefficient of variation is included in Table 5.1. This statistic is quite large for a number of the mixtures. Because of all the problems with the extensometers that were mentioned earlier, it was difficult to get consistent results with the creep tests. At -24°C for five out of ten mixtures, the stiffness was lower than the stiffness at -18°C, which is the opposite of what was expected. At -18°C the trends are as expected: the stiffness increases as the percentage of RAP or millings increases. The mixtures with PG 58-34 binder were softer than the mixtures with PG 58-28 binder. With the PG 58-28 binder, the mixtures containing millings were stiffer than those containing RAP. However, with the PG 58-34 binder the trend is reversed: the mixtures containing millings were softer than those containing RAP.

**Table 5.1 Indirect Tensile Creep Test Results**

| | -18°C | | -24°C | |
|---|---|---|---|---|
| **Mixture** | **S(60), GPa** | **COV** | **S(60), GPa** | **COV** |
| R028 | 7.89 | 6.5% | 15.12 | 14.6% |
| R2028 | 13.34 | 14.0% | 9.05 | 56.4% |
| R4028 | 17.68 | 3.0% | 11.47 | 77.3% |
| R034 | 6.32 | 16.5% | 4.84 | 14.2% |
| R2034 | 9.00 | 12.6% | 4.70 | 29.2% |
| R4034 | 14.42 | 15.5% | 17.26 | |
| M2028 | 17.93 | 12.9% | 24.44 | |
| M4028 | 19.25 | 37.0% | | |
| M2034 | 7.44 | 38.9% | 16.18 | 47.5% |
| M4034 | 11.83 | 36.1% | 11.19 | 2.4% |

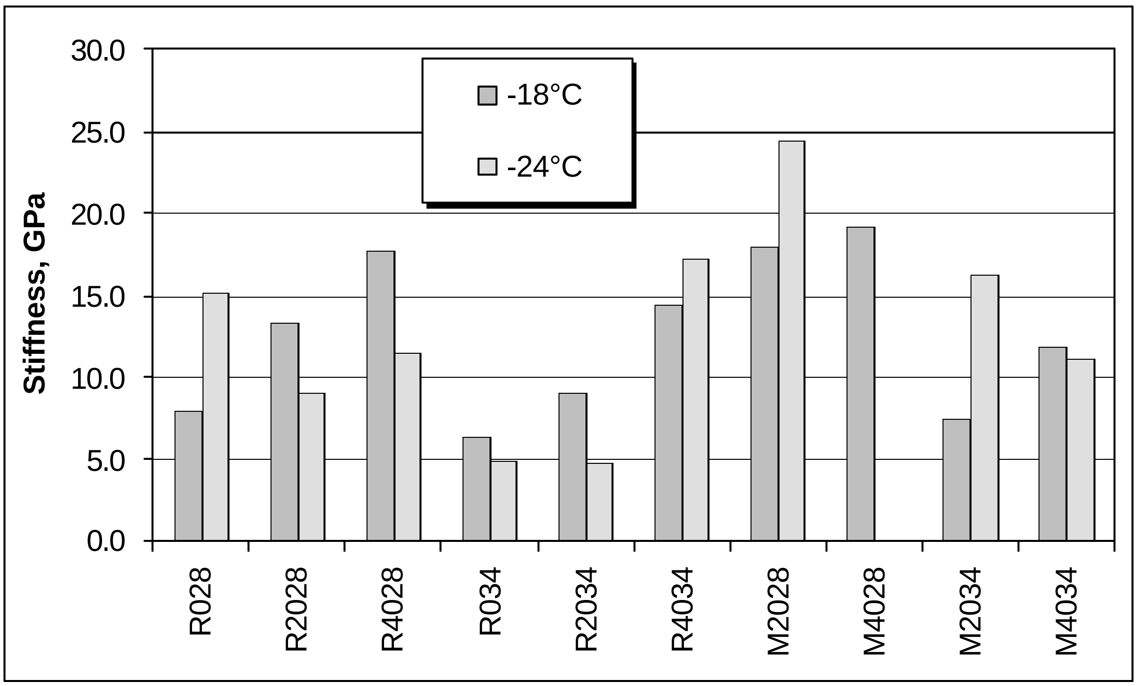


**Figure 5.2 Indirect Tensile Creep Test Results**

### IDT Strength Test Results

The data from IDT strength testing is shown in Table 5.2 and Figure 5.3. The strength data at each temperature is shown in the table as well as the coefficient of variation. The data was fairly consistent, as the coefficient of variation was 20% or lower for each mixture. The strength values range from 3 to 6 MPa for the different mixtures. For the mixtures with PG 58-28 binder, as the percentage of RAP or millings increased, the strength increased. The mixtures with PG 58-34 binder did not show the same trend. In seven of the ten mixtures, the stiffness at -24°C was greater than the stiffness at -18°C.

It is not clear why the strength values did not show the trends that were expected. Similar to the complex modulus results, it is possible that some of the mixtures were significantly microcracked before the strength procedure.

**Table 5.2 Indirect Tensile Strength Test Results**

| | -18°C | | -24°C | |
|---|---|---|---|---|
| Mixture | $S_{ave}$, MPa | COV | $S_{ave}$, MPa | COV |
| R028 | 3.65 | 4.8% | 3.75 | 17.3% |
| R2028 | 4.04 | 10.2% | 3.85 | 13.9% |
| R4028 | 4.55 | 5.5% | 4.46 | 5.8% |
| R034 | 5.38 | 9.3% | 6.10 | 0.8% |
| R2034 | 4.46 | 9.8% | 4.83 | 1.6% |
| R4034 | 4.35 | 0.6% | 4.38 | 6.7% |
| M2028 | 4.44 | 13.4% | 4.42 | |
| M4028 | 4.71 | 20.5% | 5.18 | 16.3% |
| M2034 | 4.04 | 6.8% | 5.18 | 6.1% |
| M4034 | 4.71 | 6.6% | 4.77 | 13.9% |

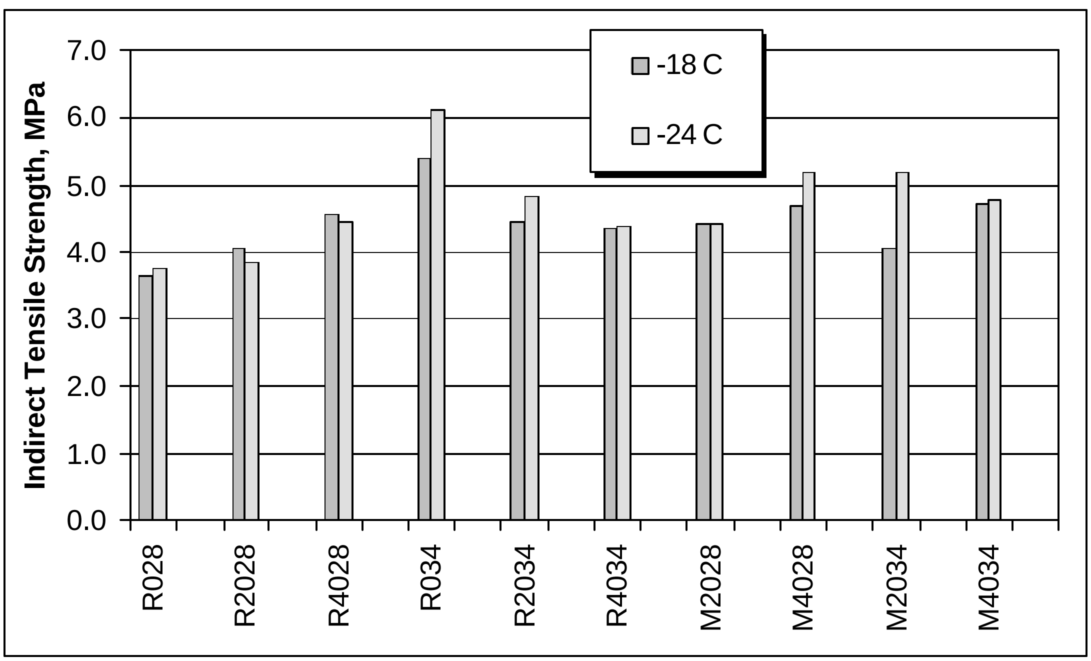


**Figure 5.3 Indirect Tensile Strength Test Results**

# CHAPTER 6
# ASPHALT CEMENT TESTING

**Asphalt Cement Testing**

The performance grading (PG) of the asphalt binders used in this project were determined. The original binders (PG 58-28 and PG 58-34), the extracted binders from the RAP and millings, and the extracted binders from each of the ten mixtures were tested at high and low temperatures. AASHTO specification T 315 and T 313 were followed to determine the PG limiting temperatures. The binders extracted from the laboratory-prepared mixtures were only aged in the Rolling Thin Film Oven (RTFOT) to simulate in service aging.

The results from the DSR tests are plotted in Figures 6.1 to 6.4. The temperature of 64°C was chosen as a point of comparison, which is 6° above the PG temperature of the original binders. On the left of each plot is the value for the original binder. On the right is the value of the extracted binder from either 10% RAP or millings. The three bars in the middle represent the values for the extracted binders from 0, 20, or 40% RAP or millings. A number of observations can be made from these plots. The stiffness of the 0% RAP mixtures does not match the stiffness of the original binders; the binders that went through the mixing and extraction process were significantly stiffer than the original binders. Secondly, with the exception of the M4034 mixture, the 40% RAP was higher than the pure RAP or millings.

The results from BBR tests are plotted in Figures 6.5 to 6.12. Figures 6.5 to 6.8 show the stiffness value at 60 seconds, and Figures 6.9 to 6.12 show the m-value at 60 seconds. The temperature of -24°C was chosen as a point of comparison. Similar to the DSR data, the stiffness of the binders increased with increasing RAP content. In this case the 0% RAP extracted binder matched the original binder. The mixtures containing millings followed a logical trend. However, the extracted binders from the RAP mixtures were actually stiffer than the extracted binders from the 100 % RAP. The extracted binders from the RAP and millings had the lowest m-value. The general trends were followed, except for the M4034 mixture, which seems to be an outlier.

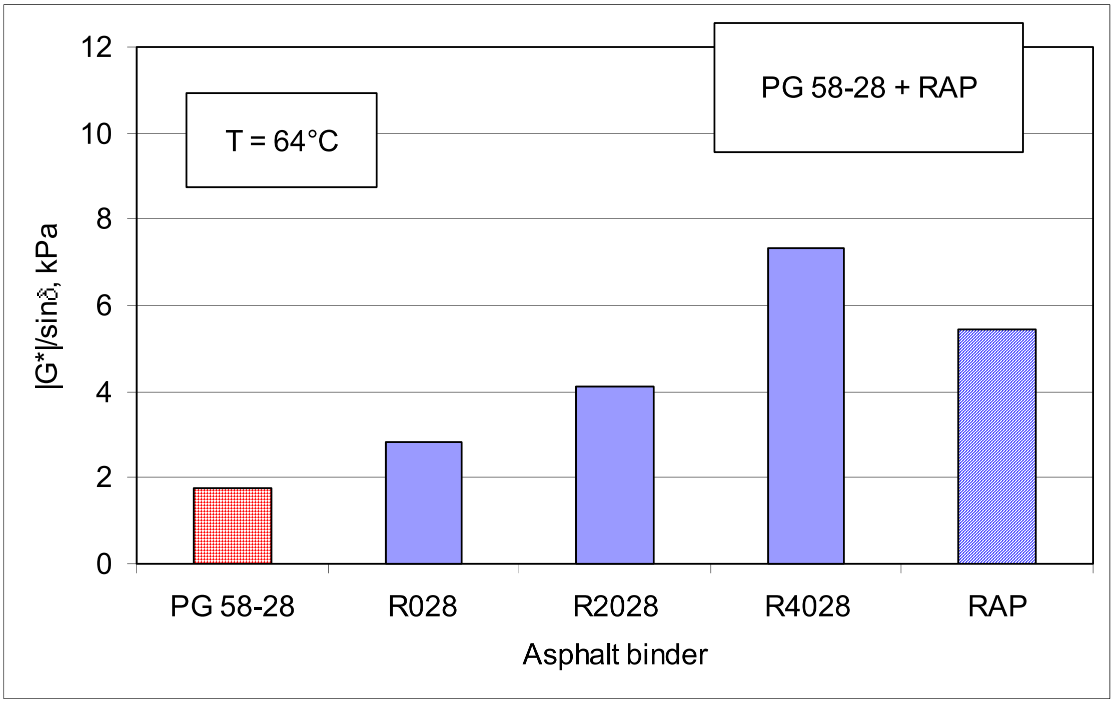


**Figure 6.1 DSR Test Results @ 64°C, PG 58-28 + RAP**

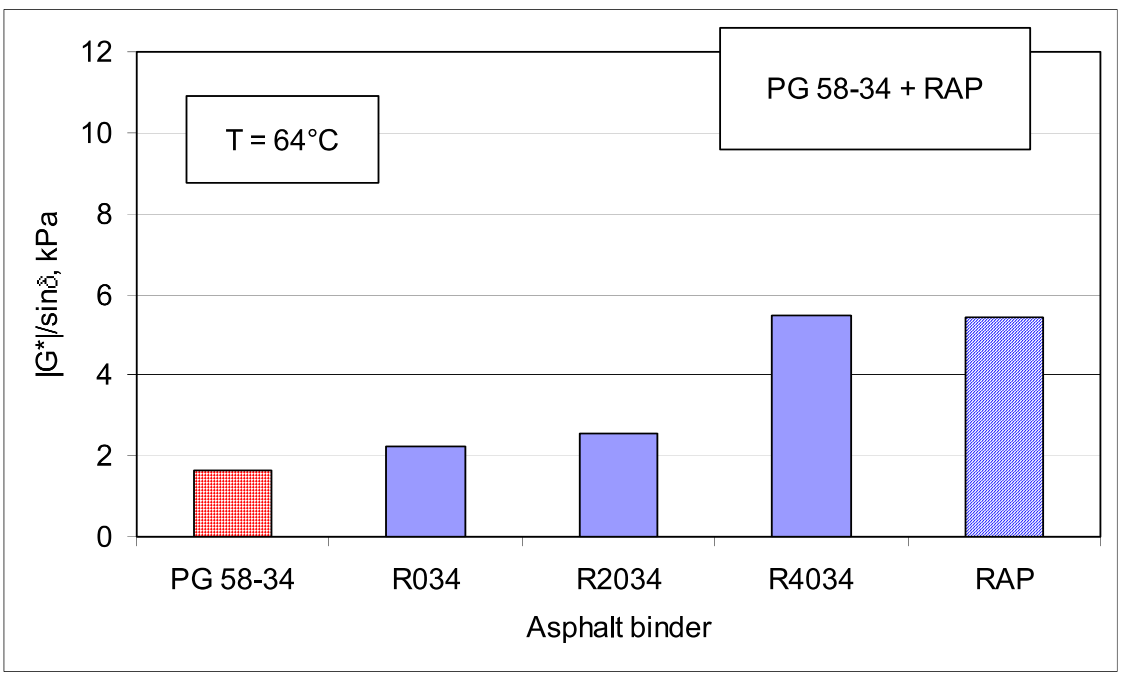


**Figure 6.2 DSR Test Results @ 64°C, PG 58-34 + RAP**

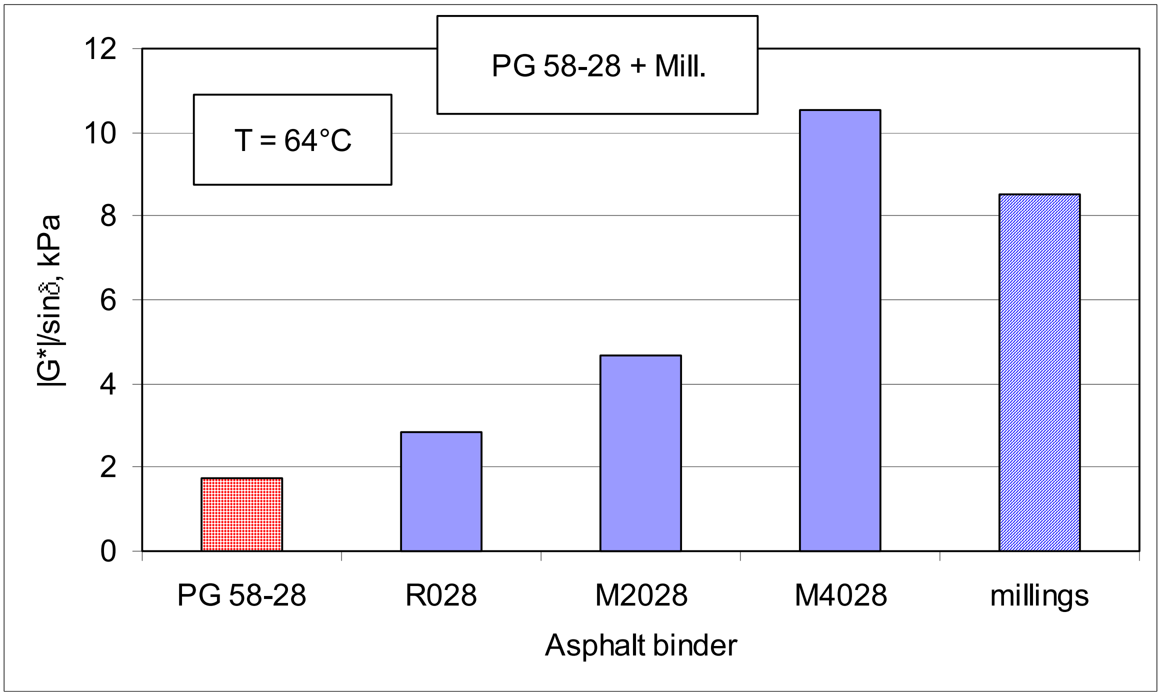


**Figure 6.3 DSR Test Results @ 64°C, PG 58-28 + Millings**

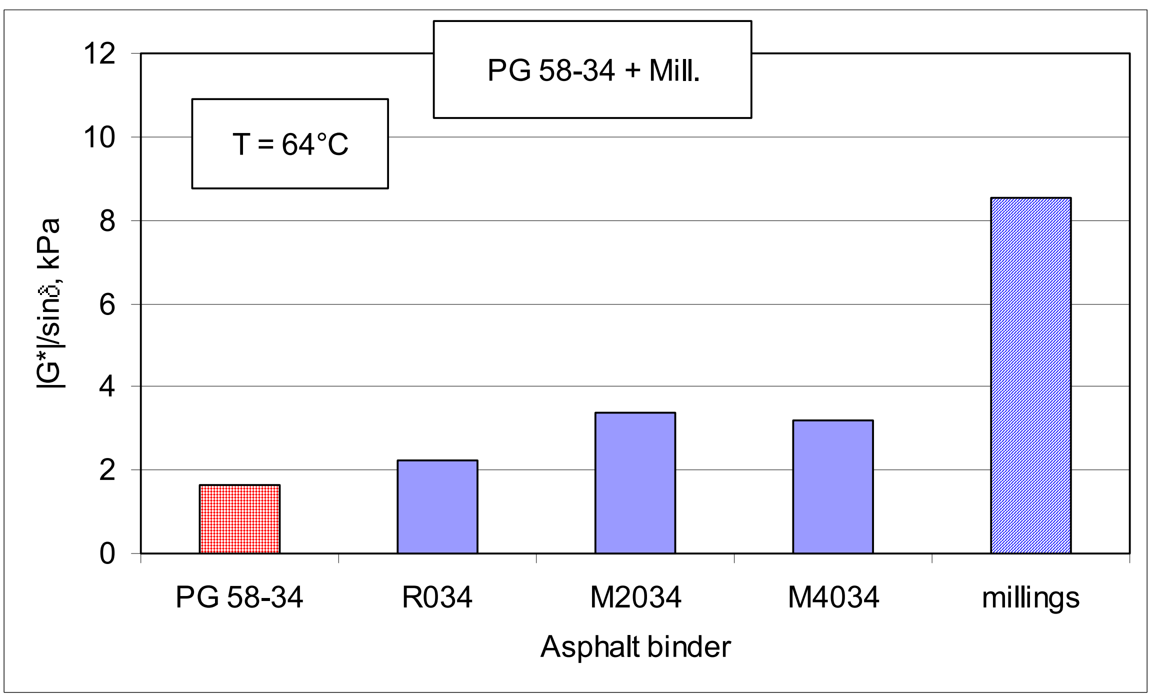


**Figure 6.4 DSR Test Results @ 64°C, PG 58-34 + Millings**

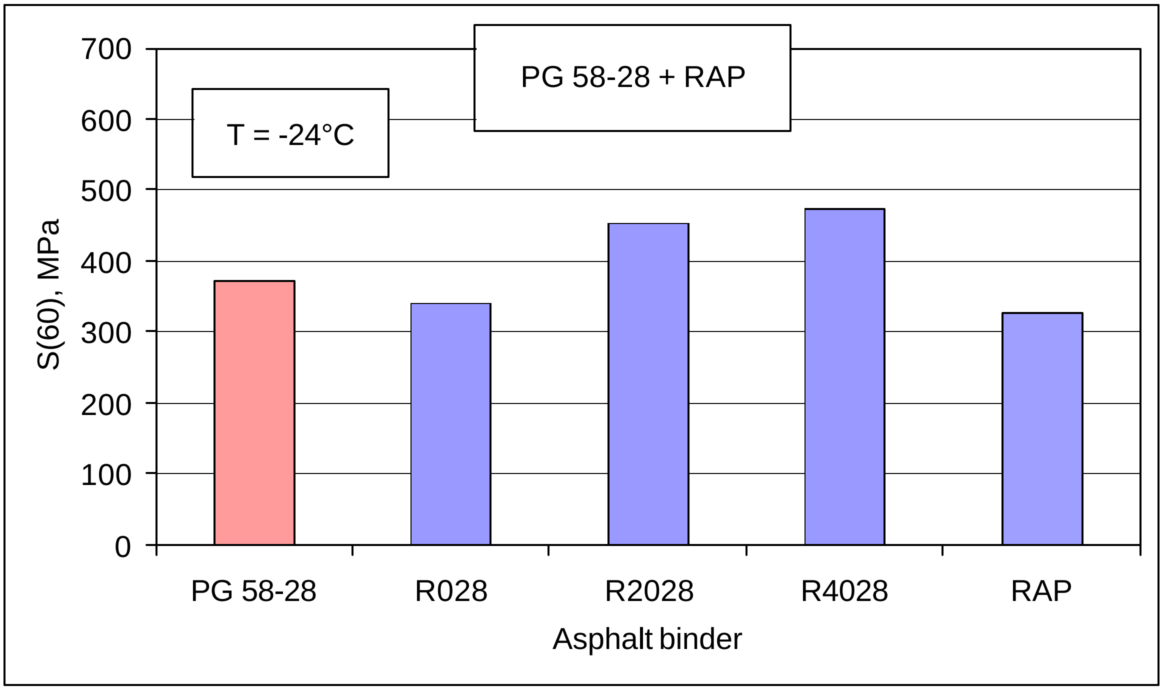


**Figure 6.5 BBR Stiffness Results @ -24°C, PG 58-28 + RAP**

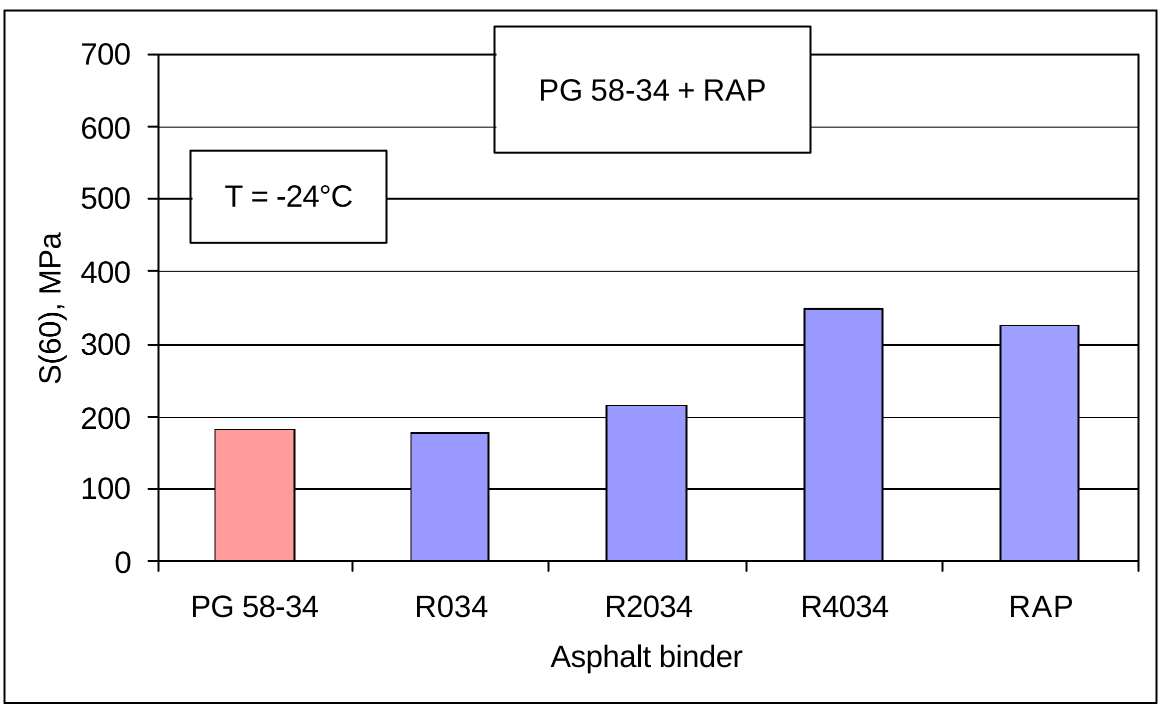


**Figure 6.6 BBR Stiffness Results @ -24°C, PG 58-34 + RAP**

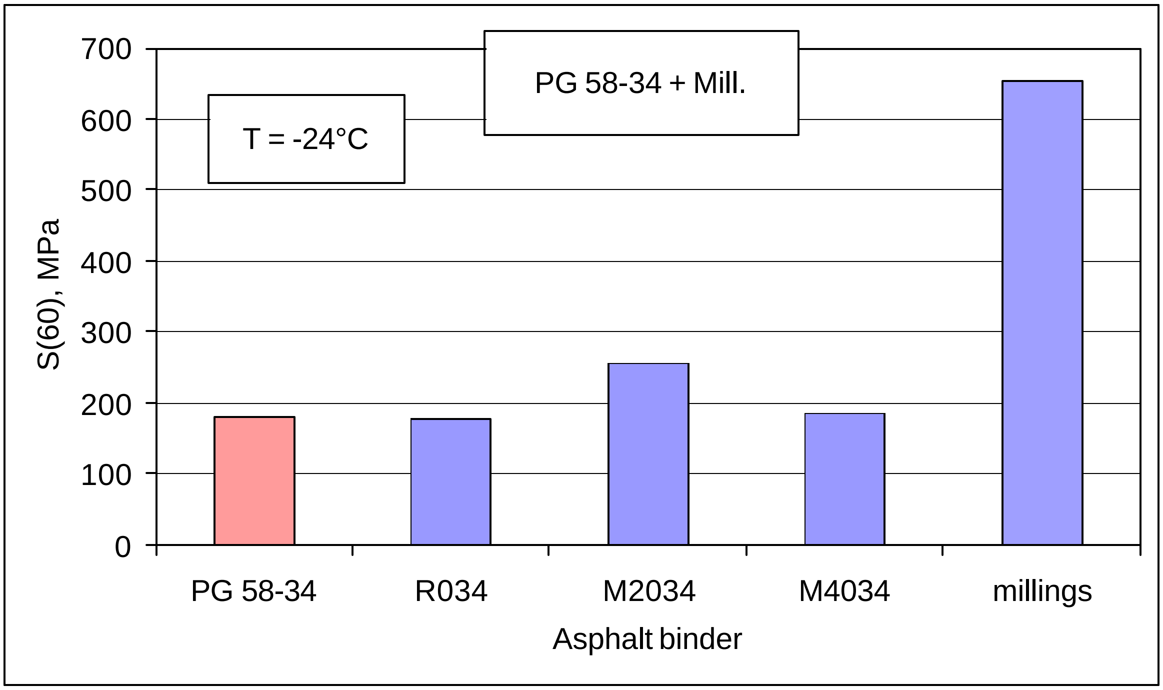


**Figure 6.7 BBR Stiffness Results @ -24°C, PG 58-28 + Millings**

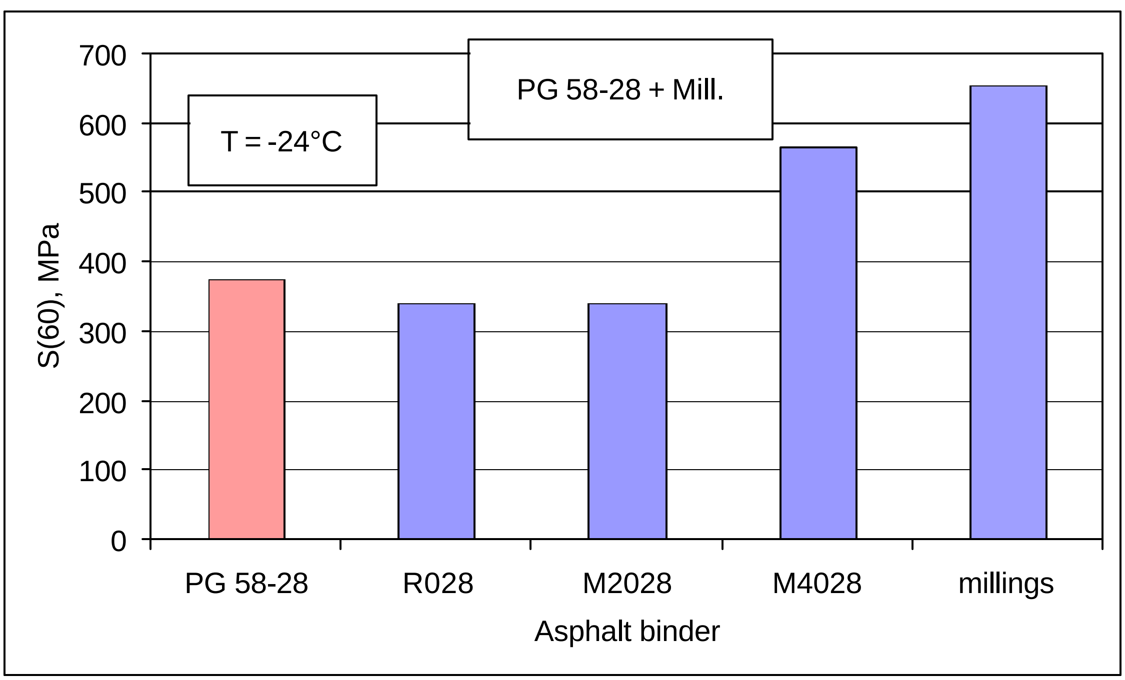


**Figure 6.8 BBR Stiffness Results @ -24°C, PG 58-34 + Millings**

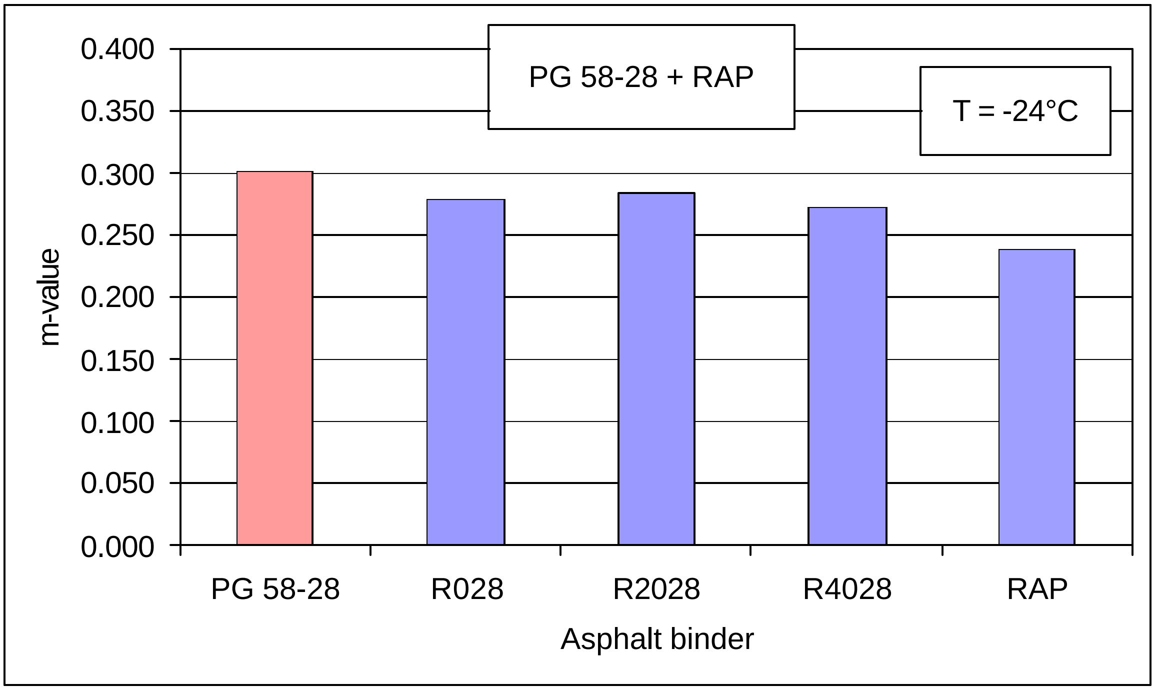


**Figure 6.9 BBR m-value Results @ -24°C, PG 58-28 + RAP**

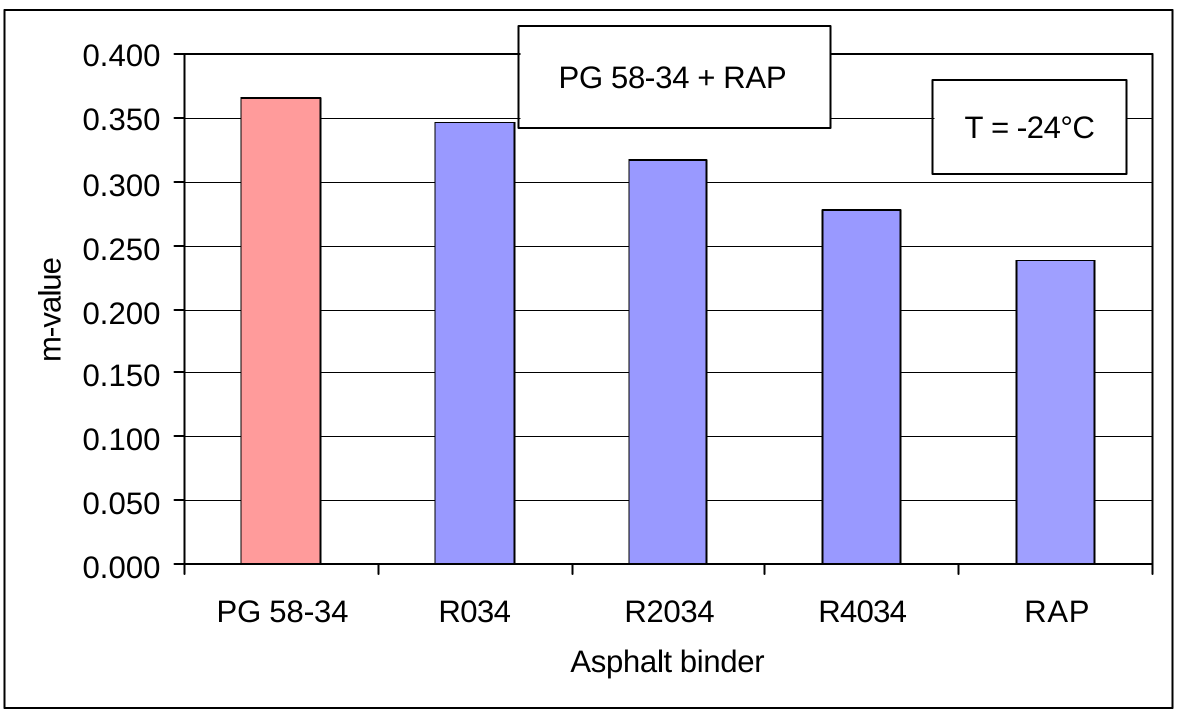


**Figure 6.10 BBR m-value Results @ -24°C, PG 58-34 + RAP**

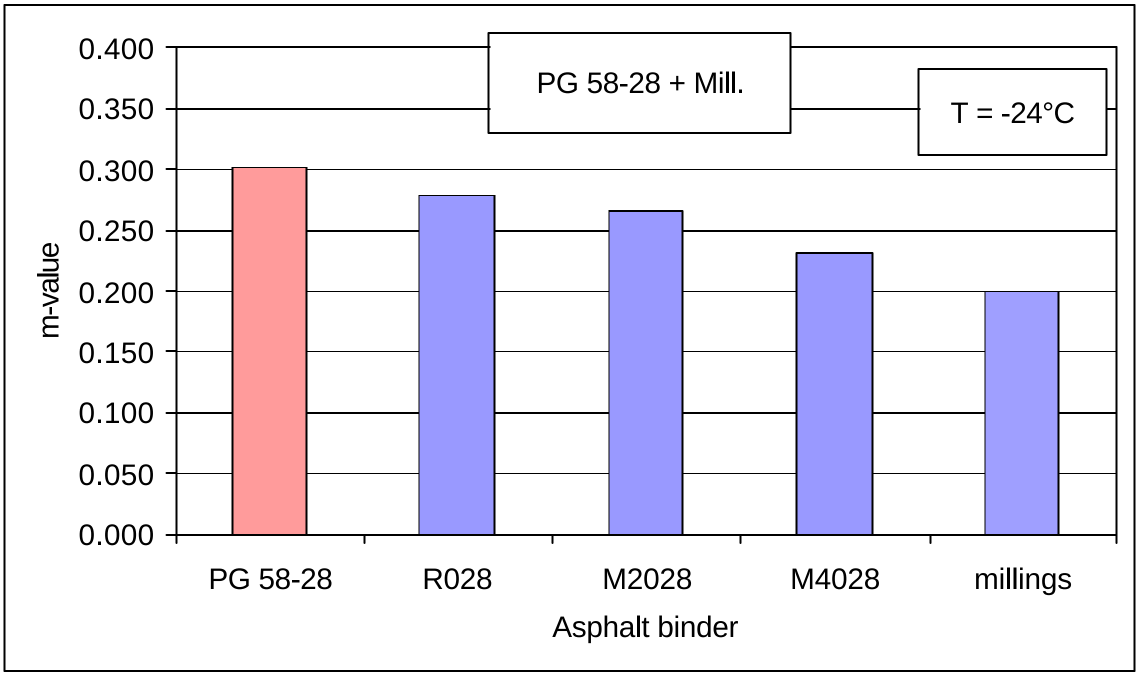


**Figure 6.11 BBR m-value Results @ -24°C, PG 58-28 + Millings**

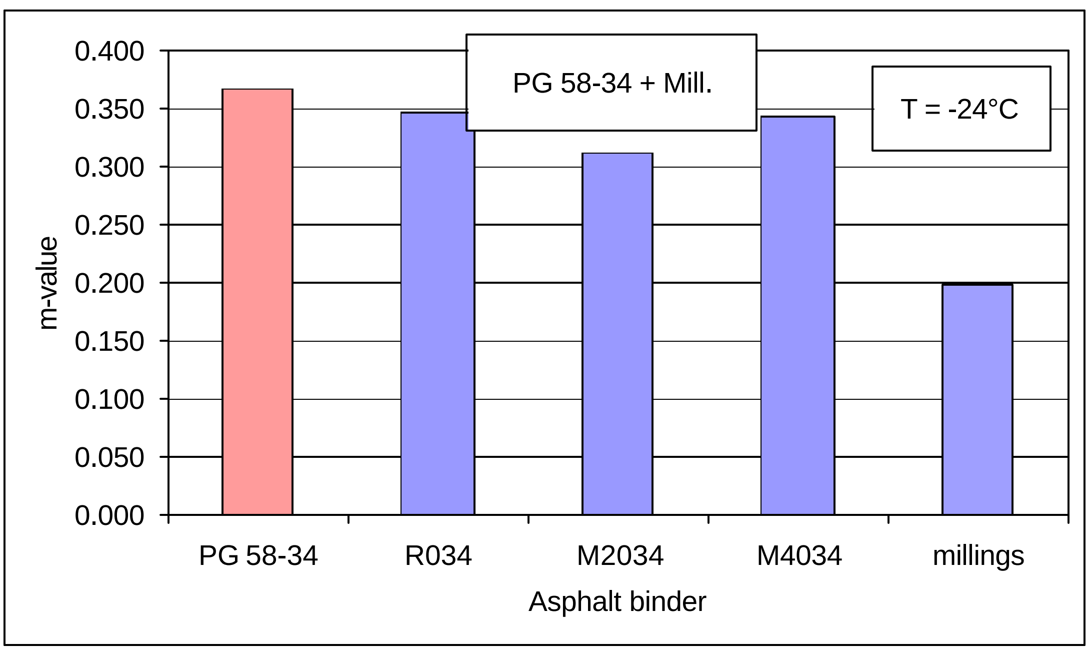


**Figure 6.12 BBR m-value Results @ -24°C, PG 58-34 + Millings**

## Limiting Temperatures

At high temperatures a linear interpolation was done to predict the temperature at which $|G^*|/\sin\delta = 2.2$ kPa. Likewise, at low temperatures linear interpolations were done to predict the temperatures at which S(60s) = 300 MPa and m(60s) = 0.300 (the failure temperature is the higher of the two temperatures). Table 6.1 shows the high and low limiting temperatures of each original binder, extracted binder from RAP and millings, and extracted binder from the ten mixtures. The last column shows the PG grade as currently determined by 6° increments. The data is shown graphically in Figures 6.13 and 6.14.

**Table 6.1 PG Failure Temperatures**

| Mixture | high temp | low temp | PG grade |
|---|---|---|---|
| PG 58-28 | 62.2 | -32.7 | 58-28 |
| PG 58-34 | 61.3 | -37.6 | 58-34 |
| RAP | 72.0 | -27.9 | 70-22 |
| millings | 77.5 | -22.8 | 76-22 |
| R028 | 65.8 | -32.4 | 64-28 |
| R2028 | 68.6 | -30.4 | 64-28 |
| R4028 | 72.9 | -29.7 | 70-28 |
| R034 | 64.3 | -37.7 | 64-34 |
| R2034 | 65.2 | -35.3 | 64-34 |
| R4034 | 71.7 | -32.0 | 70-28 |
| M2028 | 69.6 | -30.8 | 64-28 |
| M4028 | 75.5 | -28.3 | 70-28 |
| M2034 | 67.7 | -34.9 | 64-34 |
| M4034 | 67.3 | -37.2 | 64-34 |

## Blending Charts

Standard tests were performed on the original asphalt binders to determine the high and low failure temperatures as described above. This represents 0% RAP added to the mixture. Then the extracted binders from both the RAP and millings were run through the same standard tests to determine the high and low failure temperatures. This condition represents 100% RAP. A straight line was drawn between the two points to empirically determine the failure temperature of the mixture if the percentage of RAP in the mixture is known. Plots were generated in this manner for both high and low temperatures in Figures 6.15 and 6.16 respectively.

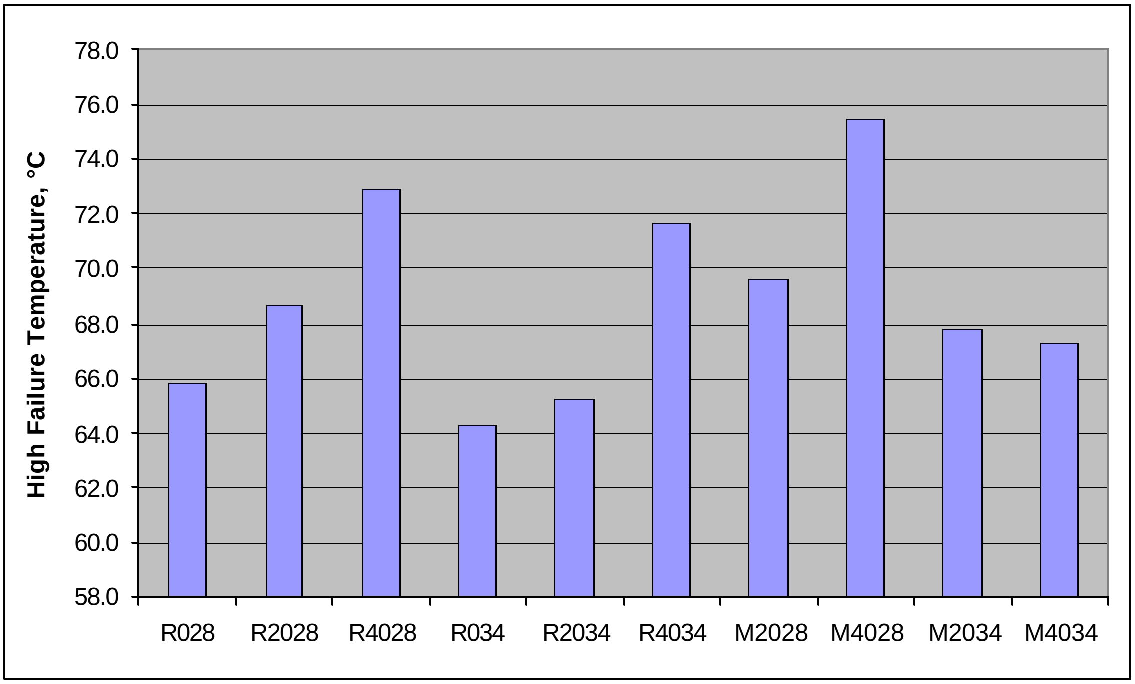


**Figure 6.13 Extracted Binder High Failure Temperatures**

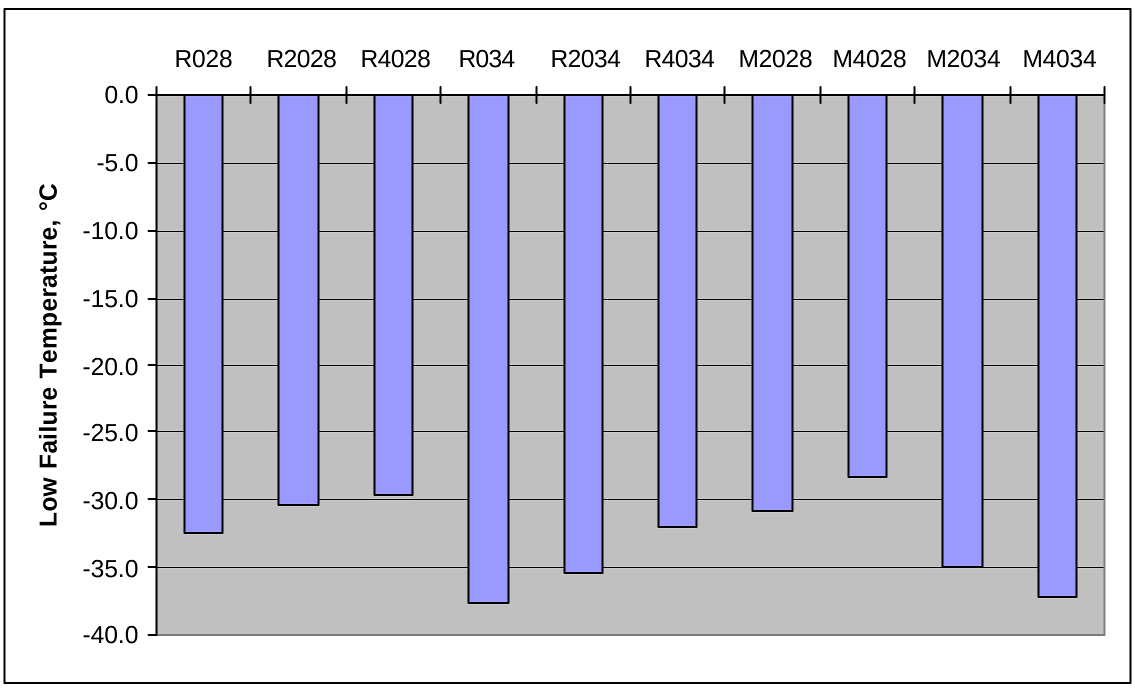


**Figure 6.14 Extracted Binder Low Failure Temperatures**

After the asphalt mixture complex modulus tests were performed one specimen from each mixture was used for extracting the asphalt binder. Both the outer ring and inner core (that come from preparing mixture complex modulus test specimens) were used. The asphalt binder was extracted from each mixture by chemical extraction. The failure temperatures determined by this method were compared to those determined by blending charts. The points are plotted on the blending charts in Figures 6.15 and 6.16.

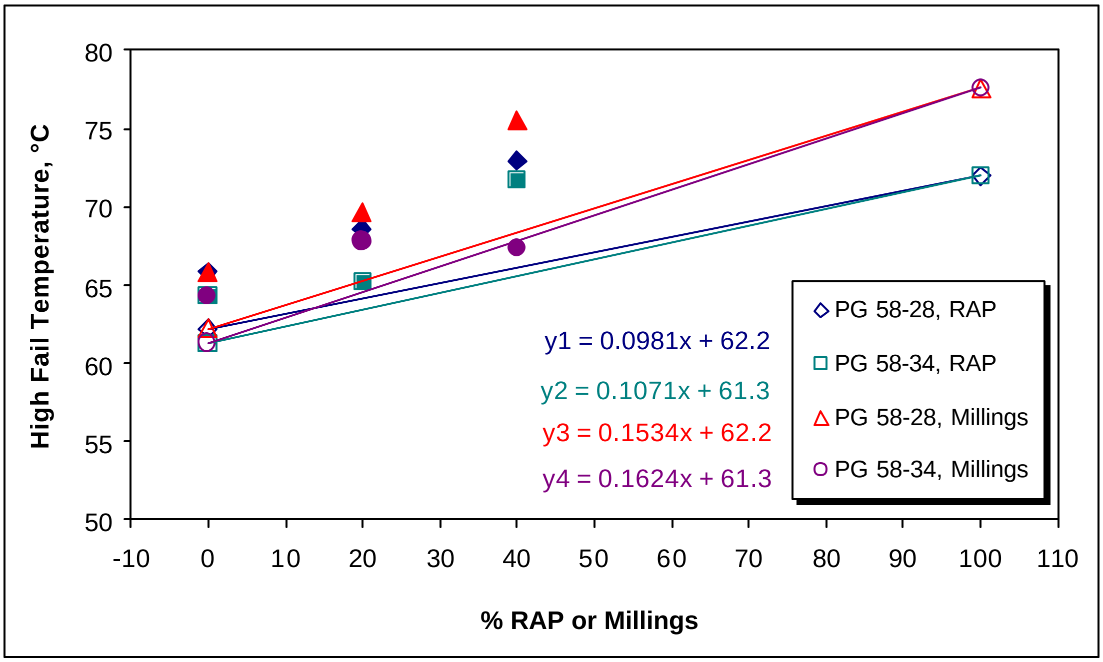


**Figure 6.15 Blending Chart – High Temperature**

Figures 6.1 to 6.16 indicate that the extracted binders tested at high and low temperatures exhibit unexpected behavior; the binders extracted from 100% RAP and millings are not as stiff as the mixtures containing only 20 or 40% RAP or millings. To try to get the results to fall more in line of expected trends, an additional set of extractions was performed on the RAP and millings, and the high and low temperature behaviors were again tested in the DSR and BBR. Material originally sampled from the same stockpiles and stored in the laboratory were again sampled and given to Mn/DOT for extraction and PG grading.

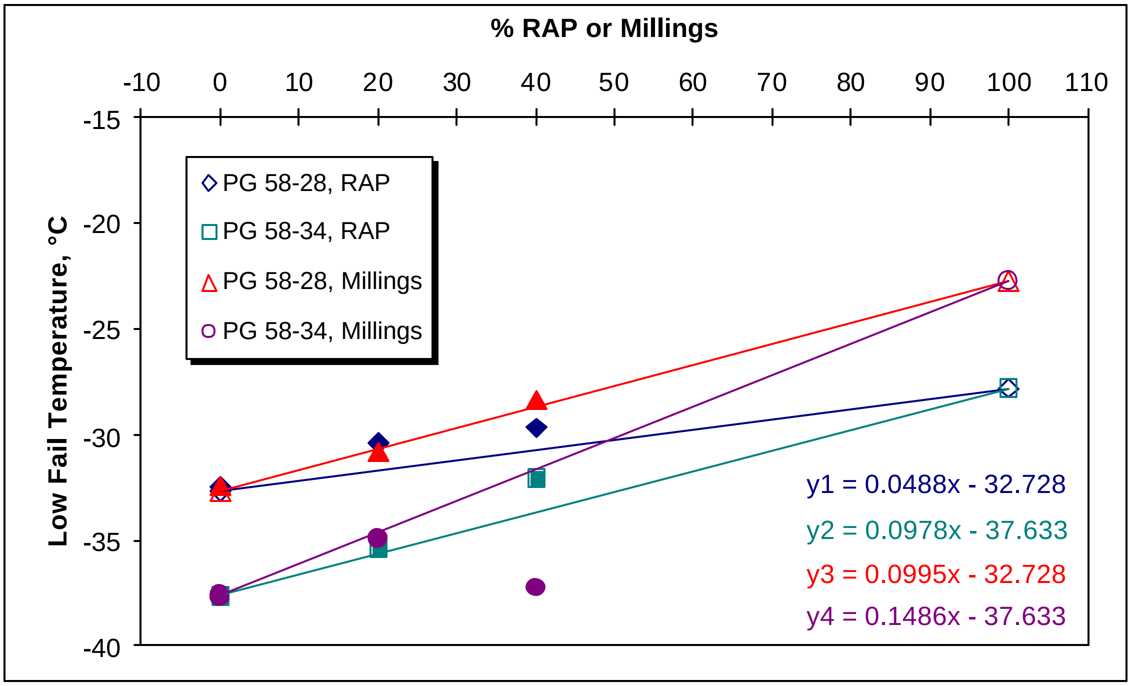


**Figure 6.16 Blending Chart – Low Temperature**

Table 6.2 shows the raw test results from each set of DSR testing, and Table 6.3 shows the average stiffness values as well as the high failure temperature.

**Table 6.2 Raw DSR Test Results**

| Date | Sample | Temp, °C | freq, rad/s | % strain | G*, Pa | d, degrees | G*/sind, kPa |
|---|---|---|---|---|---|---|---|
| 5/28/2003 | RAP | 64.1 | 9.987 | 9.9977 | 3755 | 81.95 | 3.792 |
| | | 70.0 | 9.987 | 10.136 | 1857 | 84.67 | 1.865 |
| 6/16/04 (recheck) | RAP | 64.0 | 9.987 | 9.9759 | 7729 | 81.15 | 7.823 |
| | | 70.0 | 9.987 | 10.023 | 3357 | 83.52 | 3.378 |
| | | 76.0 | 9.987 | 10.129 | 1524 | 85.09 | 1.529 |
| 6/18/04 (recheck) | RAP | 64.0 | 9.987 | 9.9413 | 4661 | 81.78 | 4.709 |
| | | 70.1 | 9.987 | 9.9464 | 2067 | 83.97 | 2.079 |
| 5/27/2003 | millings | 63.9 | 9.987 | 10.049 | 8417 | 81.45 | 8.511 |
| | | 70.0 | 9.987 | 9.9644 | 3670 | 83.83 | 3.692 |
| | | 75.9 | 9.987 | 10.117 | 1660 | 85.50 | 1.666 |
| 6/17/04 (recheck) | millings | 70.0 | 9.987 | 9.8458 | 7484 | 81.68 | 7.563 |
| | | 76.0 | 9.987 | 10.028 | 3284 | 84.02 | 3.302 |

**Table 6.3 Average DSR Test Results and High Failure Temperatures**

| Sample | Temp, °C | freq, rad/s | % strain | G*, Pa | d, degrees | G*/sind, kPa | T, °C where G*/sind=2.2 kPa |
|---|---|---|---|---|---|---|---|
| RAP | 64.0 | 9.987 | 9.9716 | 5382 | 81.63 | 5.441 | 72.0 |
| | 70.0 | 9.987 | 10.035 | 2427 | 84.05 | 2.441 | |
| | 76.0 | 9.987 | 10.129 | 1524 | 85.09 | 1.529 | |
| millings | 63.9 | 9.987 | 10.049 | 8417 | 81.45 | 8.511 | 77.5 |
| | 70.0 | 9.987 | 9.9051 | 5577 | 82.76 | 5.628 | |
| | 76.0 | 9.987 | 10.073 | 2472 | 84.76 | 2.484 | |

Table 6.4 shows the raw test results from each set of BBR testing, and Table 6.5 shows the average stiffness and m values as well as the low failure temperature.

**Table 6.4 Raw BBR Test Results**

| | | | Sample #1 | | Sample #2 | |
|---|---|---|---|---|---|---|
| | Sample | Temp, °C | S(60), MPa | m(60) | S(60), MPa | m(60) |
| | RAP | -12 | 166 | 0.339 | 146 | 0.338 |
| | | -18 | 171 | 0.280 | | |
| | millings | -12 | 214 | 0.315 | 179 | 0.320 |
| | | -18 | 357 | 0.255 | 381 | 0.255 |
| re-check | RAP | -18 | 276 | 0.324 | 241 | 0.310 |
| | | -24 | 463 | 0.259 | 469 | 0.251 |
| | millings | -18 | 401 | 0.249 | 424 | 0.252 |
| | | -24 | 658 | 0.207 | 570 | 0.202 |

**Table 6.5 Average BBR Test Results and Low Failure Temperatures**

| sample | T, $^{o}$C | S(60), MPa | m(60) | T, °C where S=300 MPa | T, °C where m=0.300 |
|---|---|---|---|---|---|
| RAP | -12 | 150 | 0.359 | -22.8 | -17.9 |
| | -18 | 215 | 0.299 | | |
| | -24 | 327 | 0.238 | | |
| millings | -12 | 237 | 0.307 | -14.8 | -12.8 |
| | -18 | 391 | 0.253 | | |
| | -24 | 653 | 0.199 | | |

The BBR tests were much more repeatable than the DSR tests. The coefficient of variation for BBR tests was between 5 and 20%, while the COV for DSR tests was between 35 and 50%. Even though the RAP or millings source was the same for each extraction and care was taken in the sampling process, the stiffness values were vastly different. This is likely due to variability within the RAP source. There was not necessarily less variability in the millings than in the RAP even though the millings came from a single source. It should be noted that the average test results shown in Tables 6.3 and 6.5 were the values used in all of the previous analyses.

**Discussion**

Figure 6.16 indicates that at low temperatures blending charts are a relatively accurate way to obtain binder properties of mixtures containing RAP. However, Figure 6.15 indicates that this is not the case at high temperatures. The extracted binders were significantly stiffer than predicted. There is additional aging that occurs during the laboratory mixing, compaction, and extraction processes that does not occur during standard RTFOT aging. One could speculate that the binder may have undergone a chemical reaction with the toluene used for extractions. During the extraction process the original binder is thoroughly mixed with the binder from the RAP. There may be some interaction between the two binders that causes the stiffness to increase.

Figures 6.13 and 6.14 show the relative effects of RAP type, RAP percentage, and original binder type on mixture stiffness. Mixture M4034 (40% millings, PG 58-34 binder) appears to be an outlier – the stiffness does not follow the expected trend. The behavior of the mixtures used in this study is similar at both high and low temperatures. As the percentage of RAP or millings increases, the stiffness of the extracted binder increases. The mixtures with PG 58-28 binders were stiffer than the mixtures containing PG 58-34 binder. The mixtures containing millings were stiffer than those containing RAP, although the effects were less pronounced at low temperatures.

The last column in Table 6.1 lists the performance grade of each extracted binder based on current performance specifications. In all ten mixtures, the high temperature performance grade was increased by one or two grades with the addition of RAP or millings. Each of the binders went from a PG 58-xx to either a PG 64-xx or PG 70-xx. This is as expected, since it is known that the addition of RAP will increase a mixture's performance in terms of rutting. In only one of the cases was the low temperature performance grade increased by a grade. This was the R4034 mixture, which went from a PG xx-34 to a PG xx-28.

Based on the results presented it may be concluded that the addition of RAP improved the binder grade in terms of high temperature performance, while the low temperature performance did not change significantly except for the case when 40% RAP was added. The tests on the binders indicate that using 20% RAP in asphalt mixtures does not significantly affect the performance. Amounts of RAP of 40% have a significant effect on the performance of the mixtures. This research suggests that the current allowable levels of RAP in Mn/DOT specifications are adequate.

# CHAPTER 7

# CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis performed on the experimental data obtained in this study the following conclusions can be drawn:

- The complex modulus and the stiffness of asphalt mixtures increase with the addition of RAP. For example at 21ºC and 1 Hz, the addition of 20% RAP to the mixture with binder PG 58-28 resulted in a 23% increase in complex modulus, and adding 40% RAP resulted in a 62 % increase in complex modulus.
- The experimental data indicated that the asphalt binder grade had a significant effect on the stiffness of the resulting asphalt mixture and asphalt binder. For example the complex modulus of the mixture incorporating the stiffer asphalt binder, PG 58-28, was 50% higher than the mixture containing the PG 58-34 at 4ºC and 10 Hz.
- The RAP source significantly affects the asphalt mixture and the corresponding asphalt binder properties. Mixtures incorporating millings exhibited a higher complex modulus than those with RAP under similar testing conditions.
- The complex modulus increased as the test temperature decreased or as the loading frequency increased for the whole testing temperature and frequency range.
- At 21ºC and 1.0 Hz, about 18% of millings may be used with a PG 58-34 asphalt binder to obtain a complex modulus equal to a mixture made entirely with PG 58-28 asphalt binder.
- Mixtures containing RAP showed significant variability and the variability increased with the increase in RAP content. The mixture complex modulus test results had more variability at low temperatures than the rest of the temperature range.
- The experimental data obtained for the binders and mixtures investigated in this study indicate that using 20% RAP in asphalt mixtures does not significantly affect the performance of the resulting mixtures. Amounts of RAP totaling 40% have a much larger effect on the performance of the mixtures, which indicates that the current allowable levels of RAP in Mn/DOT specifications are adequate.

Based on the analysis performed on the experimental data obtained in this study the following recommendations are made:

- Extend the asphalt mixture testing to investigate the performance of RAP mixtures under repeated loading cycles, such as repeated creep and fatigue tests
- Perform moisture susceptibility tests at lower temperatures, such as 10ºC
- Extend the asphalt binder testing to include low temperature direct tension (and calculate MP1a critical temperature), repeated creep and strain sweeps at high and low temperatures.

It is also recommended to increase the number of RAP sources for future research and to collect existing information about the materials being recycled if possible.

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