FINAL REPORT

Detection of Recycled Asphalt Pavement (RAP) in Bituminous Mixtures

Project IA-H1, FY 02

Report No. ITRC FR 02-2

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16. Abstract

The overall goal of this study was to assist the Illinois Department of Transportation (IDOT) in identifying and developing methods for quality assurance of hot-mix asphalt (HMA) containing recycled asphalt pavement (RAP). Although the use of RAP can lead to economical and environmental benefits, the assurance of proper RAP handling and usage in HMA is needed to ensure adequate pavement performance. The two main areas of investigation in this study were: 1) to evaluate current practices for RAP handling and monitoring in Illinois, and ; 2) to identify and/or develop laboratory tests to detect and quantify the amount of RAP in a given mixture.

A detailed survey of Illinois contractors was used to characterize current practices of RAP stockpiling and handling, and to assess the capabilities of the current infrastructure of HMA plants in Illinois, particularly with respect to the ability to control and monitor the rate of RAP proportions in a given mixture. Since most plants have the capability of recording mix composition, it is recommended the IDOT require these records to be kept as part of routine HMA quality control. The results of the plant surveys also suggest that it may be feasible at this time for IDOT to phase in the requirement for all HMA plants to be capable of recording mixture proportions during production including RAP, since the cost of upgrading the relatively small number of plants without this capability is not cost prohibitive to the contractor.

Laboratory investigations led to the successful development of prototype test methods for both rapid and rigorous determination of the presence and quantity of RAP in a mixture sample. The most promising rapid detection method developed involves a visual inspection of residue obtained after subjecting the sample to careful washing with solvents. For more rigorous determination of RAP amount , the binder from the mixture in question is recovered and tested in the dynamic shear rheometer, along with samples of the virgin binder and recovered binder to determine the in-situ RAP percentage. Two sets of blind samples were used to validate the most promising rapid and rigorous test methods. Although promising results were obtained, more testing is recommended in order to validate the forensic RAP detection and quantification methods developed in this study for a broader range of materials, including polymer-modified asphalts

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EXECUTIVE SUMMARY

The overall goal of this study was to assist the Illinois Department of Transportation (IDOT) in identifying and developing methods for quality assurance of hot-mix asphalt (HMA) containing reclaimed asphalt pavement (RAP). The use of RAP can reduce the amount of new materials (aggregates and binders) required for a project, thereby reducing the contractors overall material costs, often leading to lower bid estimates. However, the assurance of proper RAP handling and usage in HMA is of critical importance, since the type and amount of RAP used in a mixture can significantly affect its long term performance in the field. Increased amounts of RAP can lead to decreased control over asphalt binder properties, aggregate gradation, and moisture levels in the mixture produced.

The two main areas of investigation in this study were: 1) to evaluate current practices for RAP handling and monitoring in Illinois, and; 2) to identify and/or develop laboratory tests to detect and quantify the amount of RAP in a given mixture. A detailed survey of Illinois contractors was used to characterize current practices of RAP stockpiling and handling, and to assess the capabilities of the current infrastructure of HMA plants in Illinois, particularly with respect to the ability to control and monitor the rate of RAP proportion in a given mixture. Laboratory test methods were developed and assessed using field samples from a number of HMA projects containing RAP across Illinois. To validate the most promising of these methods, two sets of blind samples were evaluated.

From the survey responses, it was found that the vast majority of HMA plants in Illinois (89%) are capable of continuously monitoring and recording the amount of RAP incorporated during mixture production. The cost of upgrading older plants to be able to monitor and record information about mixture proportions including RAP amount varied widely; from negligible cost to as much as $45,000 depending upon the nature of existing equipment, the desired upgrades, installation costs, etc. Furthermore, it was learned that most contractors in Illinois are aware of the need for RAP stockpile management, and

nearly all of the contractors surveyed reported that they maintained at least one homogeneous RAP stockpile at their plant. Since most plants have the capability of recording mix composition, it is recommended that IDOT require these records to be kept as part of routine HMA quality control. The results of the plant surveys also suggests that it may be feasible at this time for IDOT to phase in the requirement for all HMA plants to be capable of recording mixture proportions during production including RAP, since the cost of upgrading the relatively small number of plants without this capability is not cost prohibitive to the contractor. Furthermore, it is recommended that RAP stockpile split samples be collected, labeled, and stored as part of contractor quality control.

Laboratory investigations led to the successful development of prototype test methods for both rapid and rigorous determination of the presence and quantity of RAP in a mixture sample. The most promising rapid detection method developed involves a visual inspection of residue obtained after subjecting the sample to carefully controlled washing with solvents. A variation of this technique was also developed as a means to obtain a rough estimate of the amount of RAP in a given mixture, by developing comparison samples of known RAP amount. For more rigorous determination of RAP amount, the binder from the mixture in question is recovered and tested in the dynamic shear rheometer to determine complex modulus, along with samples of the virgin binder and recovered RAP binder. Analytical procedures were developed which can predict the complex modulus of a mixture based upon the properties of the virgin and RAP binder and the percentage of RAP in the blended binder. It was demonstrated that this prediction tool could be used to estimate the amount of RAP in an asphalt mixture. After formalized procedures for the laboratory methods were developed, the procedures were validated using two sets of blind field samples, where the design RAP amount was not originally disclosed to the researchers. From this exercise, very satisfactory results were obtained. Predictions of RAP proportions from the rapid and rigorous methods varied between zero and seven percent from the reported RAP proportions.

Although promising results were obtained, more testing is recommended in order to further validate the forensic RAP detection and quantification methods developed in this study. Further validation efforts should include a broader range of materials, especially polymer-modified asphalts. These and other recommendations are provided in this report to facilitate implementation of the proposed quality assurance tools. The positive results obtained in the blind testing program suggest that it would be feasible to immediately use the proposed test procedures and RAP detection methods from this report in field demonstration projects.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

1.1 Introduction:

The economical use of pavement milling in recent years has resulted in the availability of significant amounts of recycled asphalt pavement (RAP). The use of RAP in new bituminous mixtures can result in cost savings to the producer by reducing the amount of virgin materials required per ton of mixture. A properly designed and produced RAP mixture should have similar performance to a mixture composed entirely of virgin materials. However, cost savings may not be realized by the owner and there may be a loss in serviceability of the pavement when unauthorized use occurs. Therefore, methods for monitoring plant inputs are needed to discourage unauthorized RAP usage. Furthermore, there is a need to develop laboratory test procedures to determine the presence and amount of RAP in post-production mixtures for use as a practical quality assurance tool to ensure proper RAP usage.

1.2 Problem Statement:

The use of RAP in asphalt mixtures provides a means to recycle the existing roadway and to use that material, in a limited amount, in the construction of new pavements. This is an environmentally-friendly means to recycle the existing pavement and to provide a new pavement surface. Asphalt overlays are the primary means of pavement rehabilitation used throughout the State of Illinois. The surfacing layer is generally 10 to 15 years old before rehabilitation is pursued. Before a new overlay is placed, the existing surface is usually milled, creating RAP. Milling removes the environmentally-aged and traffic-worn surface, corrects pavement profile, and creates a rough surface onto which the new overlay can readily bond.

The use of RAP presents an opportunity for the contractor to utilize a very economical ingredient in hot-mix asphalt production. However, excessive amounts of RAP in the mix can have detrimental effects on the pavement performance for several reasons, including: 1) the binder in the RAP material has

age-hardened in the field; 2) RAP stockpiles have inherent variability and possibly contamination, depending upon the degree of conglomeration of various RAP sources and stockpiling techniques, and; 3) mixes with high RAP amounts require heating of virgin components to higher levels to drive out moisture and to facilitate blending of binder attached to the RAP and the virgin binder. All of these factors may contribute to lower mixture quality, especially when targeting higher RAP levels. A careful RAP mixture design will achieve proper binder stiffness by considering the aged binder stiffness, virgin binder stiffness, and the proportions of these two binder components to be present in the final blend. For mixtures with RAP contents greater than 15% of total mixture weight, a softer virgin binder grade is generally required to arrive at the target binder grade for the mixture containing RAP. Increased percentages of RAP may lead to premature pavement deterioration from distresses such as thermal or block cracking, raveling, and weathering (Solaimanian and Kennedy, 1995).

Once a mixture design involving RAP is established, it is also necessary to ensure that the target RAP amount is closely controlled in production. Excessive RAP can lead to a brittle pavement which may have poor crack resistance. Conversely, the production of mixtures with deficient RAP relative to the design may lead to an excessively soft mixture, especially when a softer virgin binder grade is used to compensate for the stiffer RAP binder. Deviations from target RAP amounts may alter other important mixture characteristics, such as gradation, air voids, and asphalt content. These deviations may also lead to decreased pavement performance. Because RAP material in a given stockpile often has variation in gradation and asphalt physical properties that in turn create variations in overall mix properties, it is important to carefully control the percentage of RAP used to prevent even greater variation in mix properties.

The methods that are used to control the quantity and quality of RAP in an asphalt mix are varied, and depend upon:

- Plant Type (batch, drum, etc.)
- Plant Control Systems

- Agency Requirements/ Contractor Practices

Currently, the Illinois Department of Transportation (IDOT) does not have a formal quality assurance program to monitor and enforce the proper use of RAP in hot-mix asphalt (HMA). Methods for monitoring plant readouts, such as RAP belt yield (tons per hour and/or percent of mix), need to be developed. Also, for rigorous quality assurance, forensic test methods are needed that can be used to determine the presence and amount of RAP in post-production mixtures. Tests for RAP detection and quantification can be placed in two categories: 1) Rapid tests that could be performed in the field to test the presence of RAP and/or to determine approximate amount, and; 2) rigorous tests, that could predict RAP presence and amount with greater accuracy.

1.3 Objectives:

The objectives of this study were to:

1. Identify current practices pertaining to mix security at plants utilizing RAP in bituminous mixtures.
2. Identify the types of plant read-outs and automatic data reporting currently used to monitor pre-production inputs and plant output.
3. Identify possible standard or easily modifiable standard tests that could be used to determine the presence and amount of RAP in bituminous mixtures.
4. Conduct a laboratory study to determine the sensitivity and validity of candidate RAP detection methods.
5. Investigate the effect of RAP variability within typical Illinois RAP stockpiles on RAP detection and quantification test procedures.
6. Develop recommendations for improving IDOT's RAP quality assurance program.
7. Based upon these recommendations, develop proposed quality assurance procedures and test methods for the security, detection and quantification of RAP in asphalt paving mixtures.

1.4 Study Tasks:

To accomplish these objectives the following tasks were conducted:

TASK A) A comprehensive review of the literature was conducted, focusing on mix security when recycled asphalt pavement (RAP) is used in bituminous mixtures. This review also included the analysis of results from a survey of other state highway agencies, previously conducted by IDOT. Specific information regarding plant read-outs and automatic data reporting to monitor pre-production inputs and plant output were examined. An extensive literature review to identify promising methods for RAP detection was also carried out.

TASK B) The literature review was supplemented with visits and informal phone surveys to representative hot-mix asphalt plants in Illinois. Based upon these preliminary findings, more comprehensive written surveys were developed and distributed. In addition, IDOT HMA plant certification records were collected and analyzed. Based upon these results and the results of Task A, a summary report was developed to summarize the current practices and plant recordation capabilities, and to identify any problems that might be encountered in implementing RAP amount monitoring practices in Illinois asphalt plants.

TASK C) Based on the findings of Task A, possible standard tests or easily modified standard tests that could be used to identify the presence and amount of RAP in bituminous mixtures were identified.

TASK D) Based on the findings of Task C, laboratory studies were designed and conducted to determine the sensitivity and validity of candidate RAP detection and quantification methods. A RAP variability

study was also conducted to investigate the variability of physical properties of binder among various RAP stockpiles across Illinois.

TASK E) This task involved the compilation of this final report. The contents of this report are summarized in the following section.

1.5 Organization of Report:

This report summarizes research efforts, findings and recommendations resulting from the main tasks of the project described in the previous section. The remainder of this report is organized as follows:

- Chapter 2: *Literature Review*.
- Chapter 3: *Contractor use of RAP*. Describes current contractor practices related to RAP usage and provides various recommendations to ensure RAP security.
- Chapter 4: *Preliminary Testing and Identification of Potential RAP Detection and Quantification Methods*. This chapter describes preliminary testing that was performed for evaluating the potential of various laboratory methods identified through literature review. In the same chapter a *Calibration Study* is also described that was performed for determining suitable lab testing parameters.
- Chapter 5: Rapid RAP Detection Methods. Describes development of different rapid methods for detection and quantification of RAP. Rapid methods for RAP detection are those that are suitable for performing in field for quick evaluation of mix. Rapid methods discussed in this chapter include partial extraction and partial ignition methods.
- Chapter 6: *Rigorous RAP Detection Methods*. This chapter describes development of different rigorous RAP detection methods that are suitable for determining the amount of RAP in mix. As characterized by their name, these methods require more involve more time-consuming testing and analysis. Methods discussed included a RAP detection and

quantification method based on physical testing of recovered binders and a method based on visual comparison of partial extraction residue with comparison samples.

- Chapter 7: *RAP Variability and Effect of Field Aging*. This chapter provides discussion on testing and analyses that was performed to characterize the effect of RAP variability and aging level on the RAP detection and quantification methods developed.
- Chapter 8: *RAP Detection and Quantification Methods and Testing of Blind Samples*. This chapter describes procedures and recommendations for different RAP detection and quantification methods that were developed during the course of this study. Preliminary verification of RAP detection methods using blind samples provided by Technical Review Panel is also presented.
- Chapter 9: *Summary and Conclusions.* Contains the summary, conclusions, and recommendations of this study.
- Appendices: Provides raw test results, detailed analysis of data, a copy of the plant survey given to Illinois HMA contractors, and includes a description of software programs developed in this study.

2. Literature Review

2.1 Introduction:

An initial literature search on recycled or recycled asphalt pavement (RAP) revealed close to 1,500 articles. Preliminary screening of articles identified the following broad categories:

- Characteristics of the blended binder in RAP mixes
- Mix design methods involving RAP
- Laboratory and field performance studies of RAP mixes
- Production variability of RAP mixes

Interestingly, no published literature was found dealing specifically with mixture security. However, the results of recent surveys of state highway agencies (SHA's) related to RAP security (both written and by telephone) is presented.

2.2 An Overview of RAP Usage and Key Issues:

Experience has indicated that the recycling of asphalt pavements is a very beneficial approach from technical, economical, and environmental perspectives. Some of the advantages of utilizing RAP include the preservation of the existing profile, conservation of asphalt and aggregate resources, conservation of energy, and possible reduction in life-cycle costs. However, the improper use of RAP can lead to a decrease in pavement performance, and hence, the proper design, control, and assurance of RAP mixtures is essential.

While up to 80% RAP has been reportedly used in hot-mix asphalt pavements (FHWA, 1993), 10-50% RAP is more typically used (Flynn, 1992; Solaimanian and Tahmoressi, 1996). The Florida Department of Transportation reported a savings of 15–30% for RAP mixtures as compared to the cost of

mixtures containing all virgin materials (Page, 1988). The effective rehabilitation of asphalt pavements sometimes requires the removal of old asphalt layers. Severely cracked or rutted layers can be removed so that their damage is not reflected through a new surface layer (Page and Murphy, 1987). Furthermore, a milled asphalt concrete surface is very rough, and provides an excellent surface for bonding of an asphalt overlay. The use of RAP also reduces landfill space.

Despite the potential benefits of RAP, a legitimate concern is that since RAP contains aged asphalt binder, it may not perform as well as mixes with virgin binder. However, several studies have indicated that the structural performance of properly designed RAP mixes can be equal to and in some instances better than that of conventional HMA mixes (Little and Epps, 1980; Little et al., 1981; Brown, 1984; Meyers et al., 1983; and Kandhal et al., 1989).

Material variability is also a significant factor affecting the overall quality and consistency of RAP mixes. Because RAP is removed from an old roadway, it may include material from various asphalt concrete pavement layers along with road marking materials, patching materials, surface treatment materials, crack sealants, and other maintenance treatments such as geotextiles or other interlayer materials. Reclaimed material from several projects is sometimes mixed in a single stockpile, although this mixing may result in restrictions on the usage of the resulting RAP. These mixed or *conglomerate* stockpiles may possibly also include materials from private work that may be of inferior quality.

Solaimanian and Kennedy (1995) showed that the variability in RAP material greatly affects the variability of the asphalt content and gradation of the production mixture, especially at higher percentages of RAP. However, Nady (1997) reported that the variability of RAP can be controlled by careful stockpiling techniques and may not be as great as previously reported. Given that the use of RAP in HMA can create both positive and negative impacts, the issues surrounding proper RAP mixture design, quality control, and quality assurance must be fully understood and addressed.

2.3 Mix Security:

A survey of RAP usage and mix security among various state highway agencies (SHA's) in the United States was conducted by IDOT prior to the initiation of this study. Findings from this survey and the results of a follow-up telephone survey conducted by the research team are presented in this section.

2.3.1 State Survey:

The results of the SHA survey conducted by IDOT prior to this study are summarized in Table 2.1. The survey was conducted via e-mail and the response to five questions was collected. A follow-up phone survey was conducted to gather information that would be useful developing test methods to detect and quantify RAP along with additional information regarding the different practices used to enforce mix security among the SHA's. The results are summarized in Table 2.2. Additional comments received in the course of phone surveys include the following:

- Variations in RAP may be reflected in mixture volumetrics, such as gradation, asphalt content and air voids.
- Virgin liquid binder setting (volume of binder per unit time) may be a good measure of whether an increase in RAP percentage was pursued by the contractor, in an effort to save on binder cost.
- There seems to be some agreement among the states that plant readouts are sufficient to ensure a secure mix.
- Most states check the plant readout randomly then either shut down the plant or increase frequency of inspection in cases where they suspect unauthorized use of RAP.

Table 2.1 Summary of Survey of State DOTs Performed by IDOT

State	Does Your State Allow RAP?	Do You Limit the Amount of RAP?	Method of Checking the Amount of RAP?	Do you have an Electronic Method to be Assured of RAP Usage?	Do you Insure Mix Production is Secure?
CT	Yes	Yes	No	No	No
FL	Yes	Yes	No	No	Yes
GA	Yes	Yes	Yes	Yes	Yes
IA	Yes	Yes	No	No	No
IL	Yes	Yes	No	No	No
IN	Yes	Yes	No	No	No
KY	Yes	No	No	Yes	No
LA	Yes	Yes	Yes	Yes	Yes
ME	Yes	Yes	No	Yes	No
MO	Yes	No	No	No	Yes
MS	Yes	Yes	No	No	No
MT	Yes	Yes	Yes	Yes	Yes
NE	Yes	No	Yes	No	No
NH	Yes	Yes	No	Yes	Yes
NM	Yes	Yes	Yes	No	No
NV	No	NA	NA	NA	NA
NY	Yes	Yes	Yes	Yes	No
OH	Yes	Yes	Yes	No	No
OK	Yes	Yes	No	No	No
SC	Yes	Yes	Yes	No	No
UT	Yes	Yes	No	No	No
WY	Yes	Yes	No	No	No

Table 2.2 Summary of Telephone Survey of State DOTs

State	Method for checking the amount of RAP	How is RAP percentage checked?	How would you check for RAP?
CT	No	--	Plant Readout
FL	No		
GA	Yes	Abson Extraction and DSR Viscosity between 6,000 and 16,000 Poises	--
IA	No	--	Gradation and Asphalt Content
IN	No		
KY	No	--	Plant Readout
LA	Yes	Plant Readout	--
ME	No	--	Plant Readout
MO	No	--	Gradation and Asphalt Content
MS	No	--	Plant Readout
MT	Yes	Plant Readout	--
NE	Yes	Gradation, Air Voids and Volumetrics	--
NH	No	--	Plant Readout
NH	No	--	Plant Readout
NM	Yes	Gradation, Air Voids and Volumetrics	--
NV	NA	NA	--
NY	Yes	Gradation, Air Voids and Volumetrics	--
OH	Yes	Virgin Binder Setting	--
OK	No	--	Gradation and Asphalt content
SC	Yes	Abson Extraction AASHTO T170	--
UT	No		
WY	No	--	Virgin Binder Setting

- Since RAP calibration factors directly affect the RAP percentage obtained from plant readouts, it is recommended that plant readout checking be performed randomly. The recorded plant readout should be periodically checked with more rigorous RAP percentage measurements for added quality assurance.

2.3.2 Plant Recordation for Monitoring Proportion of RAP in HMA:

A review of the literature did not reveal any formal publications related to security issues and related specifications for the production of RAP mixtures. Information on HMA plant controls and monitoring was found to be readily available on the World Wide Web and from manufacturers' literature. Based on information provided by Illinois highway contractors, the most common systems that were examined in this study are those manufactured by Libra Systems Corporation, Astec Inc., Gencor Industries Inc., and CMI Terex Corporation (including Cedar Rapids, and Standard Havens). Three of these manufactures were contacted by phone to gather data. Specific information about these systems is provided in section 3.10.

2.4 Related RAP Studies:

A great deal of literature was found in the area of RAP mixture design and laboratory characterization of RAP components and mixtures. Even though the current study is focused on mix security and RAP detection, the literature related to RAP mixture design is briefly summarized below as it provides useful background information on some of the concepts explored in the current study.

2.4.1 RAP Mixture Design Recommendations:

Guidelines for designing mixtures containing RAP as per the Superpave specifications have been developed by the Federal Highway Administration

(FHWA, 1997). These guidelines identified three tiers for the design of mixtures containing RAP, as follows:

(i) For mixtures with less than or equal to 15% RAP by weight of total mixture no asphalt binder grade adjustment is made to compensate for the stiffness of the asphalt binder in the RAP.

(ii) For mixtures between 15% and 25% RAP by weight of total mixture the selected binder grade for the asphalt binder is one grade lower than the grade required for a virgin asphalt binder (both high and low temperature grades in the Superpave Performance Graded (PG) binder specification).

(iii) For mixtures with more than 25% RAP by weight the binder grade for the new asphalt binder is selected using an appropriate blending chart for high and low temperatures.

Blending charts have been developed to eliminate the need to construct a "temperature sweep" chart using multiple data points collected with the Dynamic Shear Rheometer (DSR), which is very time consuming. These charts were developed for high and intermediate service temperatures (Kandhal and Foo, 1997). For low temperatures, blending charts were developed by Bahia et al. (1996). Both of these studies indicate that in the development of a test to detect the presence of RAP, careful consideration of the test temperature is needed to separate the difference in behavior of the blended binder at high and low temperatures.

2.4.2 RAP Binder Studies:

A wealth of information was gathered from NCHRP Project 9-12 (McDaniel and Anderson, 1997) and NCHRP project RRD-253 (McDaniel and Anderson, 1997). The above projects dealt with testing of recovered asphalt binder from RAP before and after blending with virgin binder. In reviewing these

reports, it was concluded that the complex modulus (in the form of $G^*/\sin\delta$) obtained from the dynamic shear rheometer (DSR) might be a promising parameter for determining the amount of recycled asphalt pavement (RAP) in the mix. In their study, the Strategic Highway Research Program (SHRP) extraction and recovery procedure (currently AASHTO T319-03) was used to recover the binder sample from the mix with minimal residual solvent after recovery and minimal additional aging caused by the procedure itself. This is accomplished through the use of a rotovap unit under vacuum and the use of nitrogen gas during the solvent removal process.

Lee et al. (1999) also reported variations in complex modulus (in form of $G^*/\sin\delta$) with change in recycled asphalt pavement (RAP) binder amount in the blend. Binder recovered from the AASHTO T319-03 procedure was mechanically blended with various amounts of virgin binder recovered from three different RAP materials. Rolling Thin Film Oven aged binder data from Lee et al. shows that with increasing recycled asphalt pavement (RAP) binder amounts, complex modulus (in form of $G^*/\sin\delta$) drastically increases. Over a change from 0% recycled asphalt pavement (RAP) binder to 100% recycled asphalt pavement (RAP) binder the increase in complex modulus (in form of $G^*/\sin\delta$) can be greater than a factor of ten. The data also shows that with different variability in RAP samples that might be obtained, a variation of about one-third of a log decade may be expected (factor of 2), as presented in graphical form in Figure 2.1.

The study also showed that binder processed in the pressure-aging vessel (PAV) showed lower variability. However, the benefit may outweighed by the fact that the range of variation in the complex modulus (in form of $G^* \sin\delta$) reduces to around one-third of decade on log cycle, as illustrated in Figure 2.2.

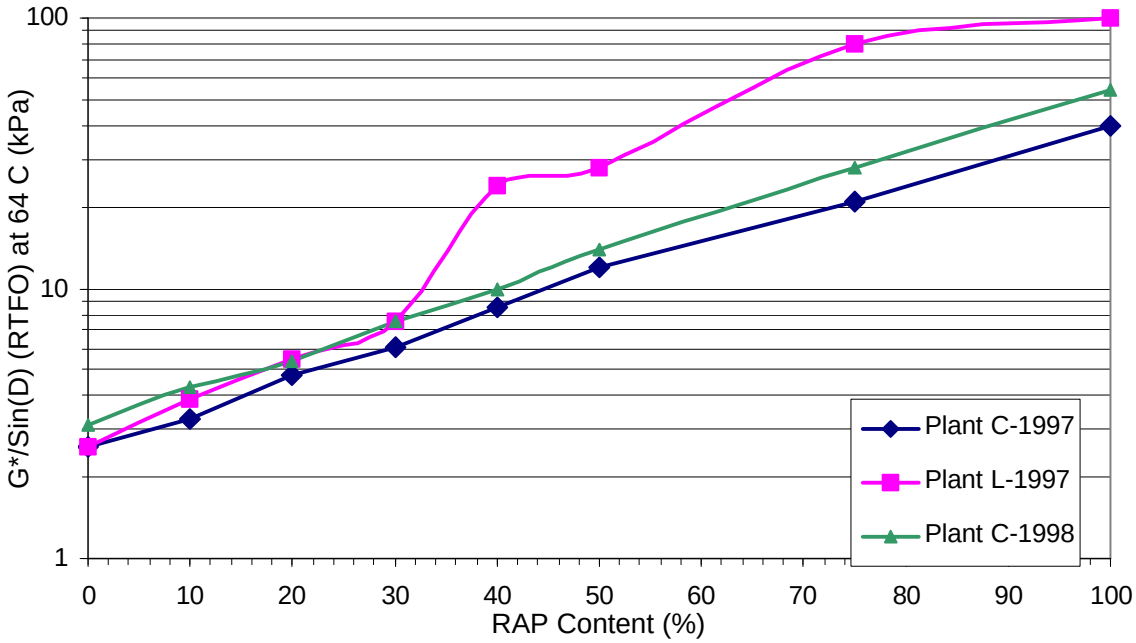

Figure 2.1 Relation between $G^*/\sin\delta$ and Recycled Asphalt Pavement Binder Content for RTFO Aged Binder (reproduced from Lee et al., 1999)

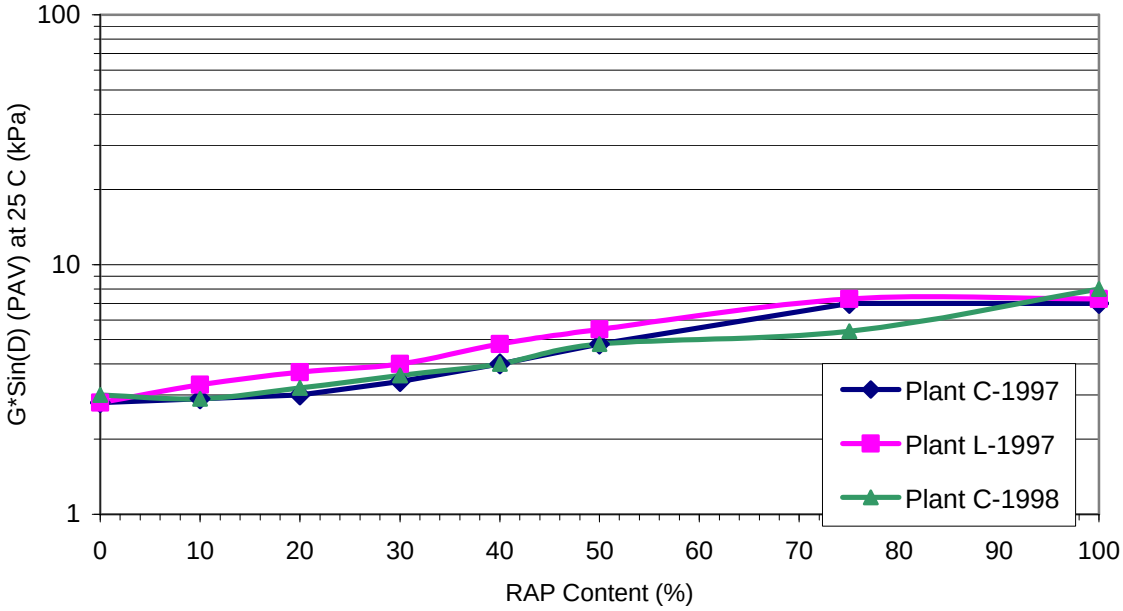

Figure 2.2 Relation between $G^* \sin\delta$ and Recycled Asphalt Pavement Binder Content for PAV aged binder (reproduced from Lee et al., 1999)

The second most significant finding from this portion of the literature review was related to the National Center for Asphalt Technology (NCAT) method for determining asphalt binder content in the mix using the ignition oven (Brown and Murphy, 1995). This study showed that the presence of RAP in the mixture can cause a fluctuation in asphalt content of 0.3 percent by weight of the mix. Malik et al. (1999) reported a fluctuation of 0.2 percent in asphalt content due to RAP binder content variation. Malik et al. also stated that during the ignition oven testing there is initially a high rate of weight loss inside the ignition furnace. The author gives an explanation behind this phenomenon by comparing the process inside the ignition oven with the "cracking" phenomenon in asphalt refining. This suggests that initially the asphalt binder in the mix undergoes molecular cracking and that lighter fractions (mainly light hydro-carbons) are volatilized leaving carbon chains known as carbenes and carboids, which are less volatile. These remaining chains volatilize at a much slower rate, yielding a lower weight loss rate in the later stage of the ignition oven procedure.

During ignition oven testing, the furnace unit supplies maximum heating until the temperature in the chamber reaches the set point, which is about 482^{o}C. The test continues until the asphalt mixture sample reaches a constant mass. The bituminous mix undergoes an exothermic reaction at approximately 250^{o}C (flash point of asphalt), at which point the subsequent temperature rise inside the chamber is due to the ignition of the mix itself (Roberts et. al., 1996). Thus the rate of heating of the sample cannot be closely controlled; it is highly non-uniform and mixture dependent. This suggests that possible limitations may exist for using the ignition oven to detect RAP in bituminous mixtures. For instance, it could be hypothesized that if incomplete mixing of binder occurs during RAP mixture production, then it might be possible to run the ignition just long enough to burn off the lighter, more volatile virgin binder, while leaving visible traces of RAP binder on RAP aggregates. However, this technique might be difficult to control, given the lack of control of the heating process discussed above.

The NCHRP 9-12 (McDaniel and Anderson, 1997) report discusses that aged RAP material is lean in volatile fractions and rich in heavier hydrocarbons.

Thus, when a sample containing recycled asphalt pavement (RAP) is tested in the ignition oven it could exhibit a different trend in weight loss versus time relative to a mixture with 100 percent virgin binder and/or maximum chamber temperature reached.

2.4.3 RAP Mixture Studies:

McDaniel and Anderson (1997) demonstrated that the incorporation of RAP in a mixture can influence mixture mechanical properties and the properties of the recovered binder. However, it was found that mixture properties such as indirect tensile strength, shear strength, etc., show non-uniform results with different RAP types. In the case of mix properties, the variability in results was found to be problematic. That notwithstanding, a more recent study (Stroup-Gardiner and Wagner, 1999) reported a noticeable increase in mixture stiffness with as little as 15% RAP. At low temperatures, creep compliance measurements generally decreased when RAP was added. A relatively minor decrease was noted at $-20^{o}C$, while a 30 to 50 percent difference was noted at $-10^{O}C$ and $0^{o}C$, respectively. It has also been shown that the resilient modulus of stabilized RAP base course mixtures increased with increased percentages of RAP (MacGregor et. al., 1999).

In a study performed on the variability of Texas HMA mixes containing a high percentage of RAP, it was concluded that the deviations in gradation from the job-mix formula (JMF) on the number 10 and number 200 sieves for RAP mixes were considerably lower than those for mixes without RAP. Deviations in asphalt content were also higher for mixes containing high percentages of RAP. However, air voids and densities were not affected by high RAP percentages. (Solaimanian and Tahmoressi, 1996).

2.4.4 Other RAP Studies:

The possibility of splitting the RAP stockpile into coarse RAP and fine RAP was investigated by Stroup-Gardiner and Wagner (1999). The study was driven by the concern that RAP stockpiles may have widely variable gradations as well as high percentages of minus 0.075mm material, such that its use in Superpave mix designs may be seriously limited. Some of the key findings of the study are summarized in Table 2.3.

Table 2.3 Advantages and Disadvantages of Stockpile Splitting (after Stroup-Gardiner and Wagner, 1999)

Screened RAP Fraction	Advantages	Disadvantages
1.2 mm and Above	• Increases uniformity in coarser aggregate fractions • Significantly reduces the amount of 0.075 mm material in the RAP material • Reduces the neat/tank asphalt requirement by 18 to 33 % • Can be easily used at high percentages and still meet tight gradation and minus 0.075 mm Superpave requirement	• Appears to have a significant influence on mixture properties • The need to change grade of neat asphalt may have to be assessed • Could require reducing the grade for neat/tank asphalt
< 1.2 mm	• Reduces the neat/tank asphalt requirement by 25% for a minimum RAP content (15%) • Can be used at limited percentages to produce Superpave gradations • Decrease rutting potential • Decreases temperature susceptibility	• High minus 0.075 mm material limits the quantity of RAP • Requires a leaner, more uniformly graded virgin aggregate • Could require reducing the grade of neat asphalt to compensate for the contribution of RAP binder at low percentages of RAP • May increase potential for low temperature cracking

In a study by Salomon and Newcomb (2000), the gradation of RAP materials was found to vary considerably from one source to another. It was concluded that a universal gradation for RAP in mix design cannot be assumed. Although related to cold-in-place recycling, this study also showed that the number of gyrations required to reach maximum constant density during gyratory compaction may show variations as a result of RAP inclusion.

Nondestructive test methods have also been used to evaluate RAP. Noureldin et al. (1989) tested compacted HMA samples containing different RAP types at different binder contents using pulse velocity. Pulse velocity tests measure the rate of propagation of sound waves in a test specimen. The sound wave velocity is a function of the elastic modulus, Poisson's ratio and density. This technique has been widely used for evaluating conventional bituminous mixtures. Samples were prepared to have the same aggregate gradation but different RAP types and overall binder content. Statistical analyses of the results showed that there was a slight difference in pulse velocity values between the RAP types (Noureldin et al., 1989). It was also found in that the resilient modulus and Marshall stability values were higher for the virgin mixtures than the RAP mixtures.

2.5 Summary:

It was found that majority of published literature was in the area of design and characterization of RAP mixtures. No literature was found pertaining to a study similar to this project where the main objective is to determine the presence and amount of RAP for quality assurance purposes. Very limited research has been performed in the area of mix security and plant monitoring of RAP amount. However, a significant body of literature was uncovered that was useful in shaping the test methods selected in this study for the determination of RAP in bituminous mixtures.

3. Contractor Use of Recycled Asphalt Pavement

3.1 Introduction:

This chapter explores current practices for contractor use of RAP in Illinois, including: stockpiling techniques, plant types and recordation of RAP, RAP security and handling, and RAP sampling. Since the quality of RAP mixtures can be enhanced both by proper quality control and quality assurance specifications, it was important to assess the current practices and current infrastructure in Illinois to determine the suitability of current methods and to assess the feasibility of implementing new specifications.

3.2 Survey of Illinois Contractors:

A questionnaire was developed and distributed to answer questions about the use of RAP, the controls used, and the security measures implemented by HMA contractors in the State of Illinois. Information sought involved determining the type of plant used since it is recognized that newer plants are typically drum plants instead of the older style batch plants. Older plants are less likely to have the sophisticated computer controls and recording devices that make it easier to control and monitor the mix ingredients. The availability of control devices and possible cost of retrofitting such plants was also of interest.

Contractor handling of RAP was of particular interest. The study attempted to characterize the various methods used for RAP stockpiling, RAP handling, quality control, and record keeping. Such information could be useful in case of disputes.

Appendix A contains a copy of the questionnaire used in this study.

3.3 Response Information:

The quality control officer at all construction firms on IDOT's list of certified HMA plants was sent a copy of the questionnaire at least once. A follow-up fax

was also sent. A total of 85 firms across the State of Illinois were contacted. From these, a total of 41 firms replied for a very good response rate of 48%. Many firms have more than one plant and as a result, information on 86 plants was accumulated. Of these 86 plants, it was reported that 20 did not use RAP and thus no further information was provided. Responses received were distributed among the IDOT districts and plant locations are shown in Table 3.1.

Table 3.1 Questionnaire Responses by IDOT District

District	No. of Plants	No RAP	Use RAP
1	30	0	30
2	14	9	5
3	11	3	8
4	5	2	3
5	15	4	11
6	6	2	4
7	1	0	1
8	3	0	3
9	1	0	1

3.4 Types of Plants:

Hot-mix asphalt plants must be capable of heating and mixing the aggregates and asphalt cement under highly controlled conditions. While the basic elements of storage silos, dust collection, and scales remain the same, technology has greatly improved over time. Drum and batch plants are the most common types with drum plants becoming the primary source of new sales since they are more economical and tend to meet EPA standards easier.

Older style batch plants are still in use in Illinois and the survey found that 22 of 83 sites had batch plants only. However, a large percentage of locations had either a drum plant alone (66%) or had a drum plant included with other plants on the same site (73%), as shown in Figure 3.1.

It should be noted that drum mix plants, despite their many advantages, do pose special difficulties. Since all heating and mixing is performed within the

drum and is discharged continually, the materials must be weighed prior to feeding into the drum without the capability of adjusting the final blend afterwards. Thus, the moisture content must be monitored and the amount of aggregate adjusted to account for the required dry weights.

Both types of plants need additional equipment to handle RAP as one of the aggregates. Since the asphalt within the RAP cannot be exposed to direct flame, the RAP must be introduced to the mix at a point where the virgin aggregate has already been heated and can transfer heat to the RAP.

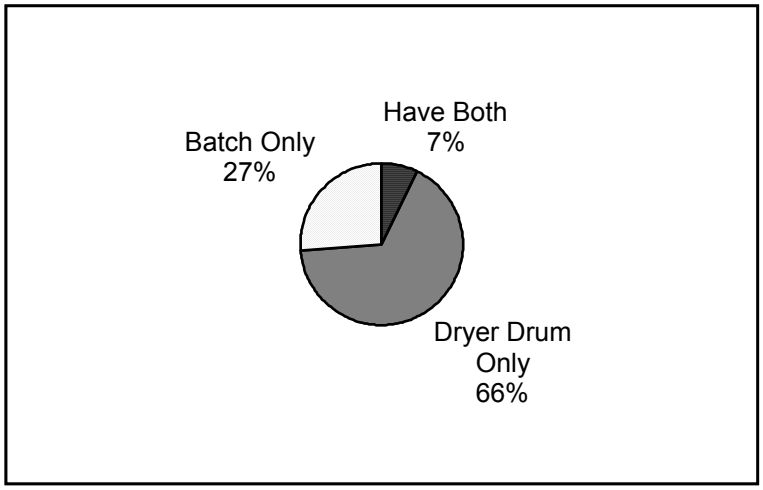

Figure 3.1 Types of Plants in Illinois

3.5 Plant Recording:

Records of how much RAP has been introduced to a mix are valuable in cases where problems or conflicts arise. A total of 66 responses were received for the survey question directed at identifying the nature of RAP recordation as it relates to as-produced mixture composition. These 66 responses included both batch and drum plants. Although most of these plants were reported to have an automated method of recording the mix composition, 7 of these 66 plants only had manual recordation capabilities. Thus, 59 of the 66 plants have automatic recording of RAP proportion either by weight basis (weight/time or weight/batch)

or based upon a percentage of the total weight of the mix. Thus the plants that record mix composition is a combined 89% of all plants as shown in the breakdown of Figure 3.2.

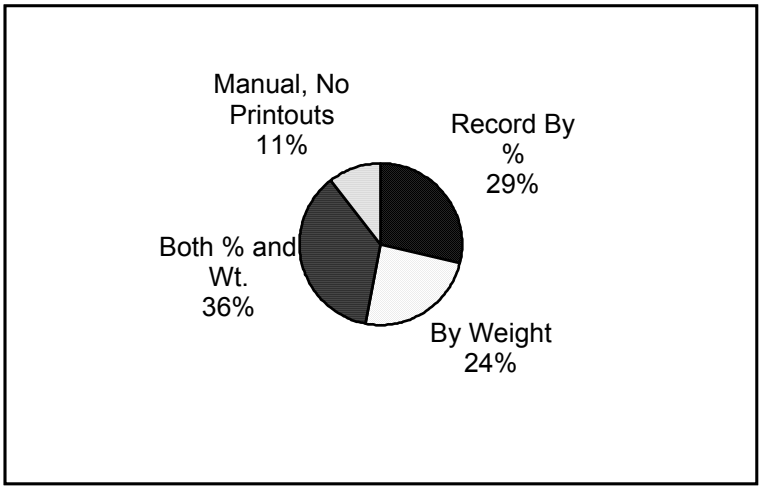

Figure 3.2 Recording of RAP in the Mix

3.6 Stockpile Security:

Since mixing RAP from different sites in the same stockpile could cause fluctuations in mixture properties, it is important to determine how materials are stored. Most plants indicated that they do exercise some care in stockpiling the RAP materials. Of the 65 contractors responding, 62 indicated that they implement some kind of control over their RAP piles as shown in Figure 3.3 with only 3 plants having a conglomerate pile only.

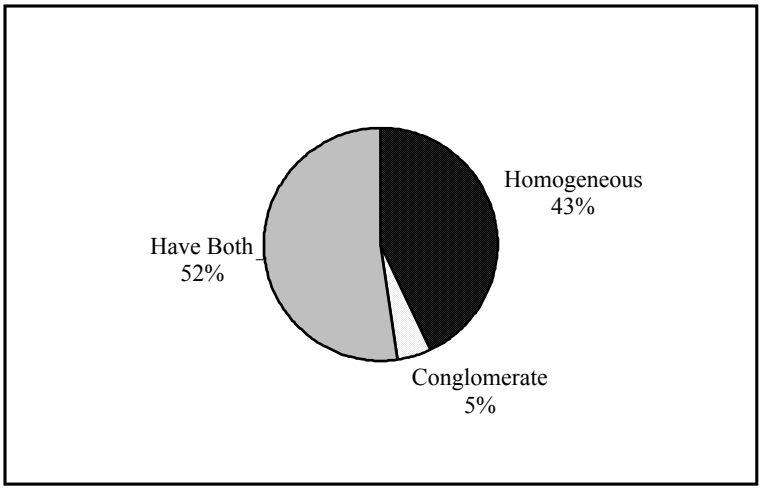

Figure 3.3 RAP Stockpiling Practices

The extra comments provide further information about the piles. Some responded that the pile was kept as specific as the “same source with the same gradation and surface originating from jobs built under state specs.” Others indicated that “surface is kept & separated from full depth. The conglomerate pile is processed, sampled, and kept separate from surface RAP piles. All piles are marked & mix designs are proportioned to match each RAP pile/source.” This suggests that contractors are aware of the need to keep homogeneous RAP piles.

3.7 Handling of RAP:

Figures 3.4 and 3.5 illustrate how the RAP materials are handled at the plant. RAP might be crushed (25 plants) or screened (11 plants) prior to use, with many (26 plants) doing both. For example one respondent indicated their “roll crusher & screens were located on RAP cold feed/belt system.”

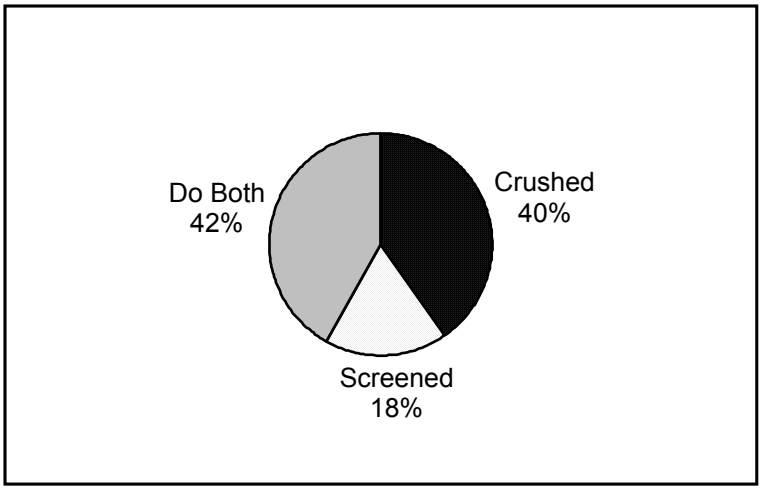

Figure 3.4 Processing of RAP Prior to Use

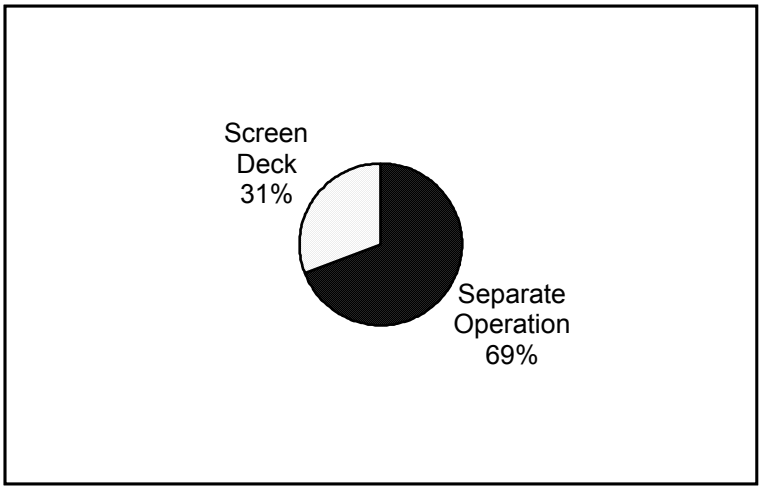

Figure 3.5 Method of Crushing/Screening RAP

Comments indicate that answers to these questions could depend on the material condition. For example, one response indicated it would depend on “If RAP is in good condition it is screened just prior to entering plant”. Likewise, when the question was asked “if RAP is crushed or screened, is it accomplished in a separate operation or just prior to entering the plant through a “gator” or screen deck”—there were many variable answers. For example, one answer was “it depends on application & gradation.” To meet specifications in Illinois, materials in conglomerate stockpiles must be reduced finer than 5/8”.

One respondent answered that the RAP was “prescreened to 1 1/4" size; additional screen on plant assures that oversized material does not enter drum,” presumably referring to the use of a scalping screen. Another respondent reported that “RAP [was] sent into a crusher, screened and stockpiled for use as needed.”

Those that answered that they used a separate operation may have meant that it was stockpiled for a later use, but at least one respondent indicated that it was separately crushed on an as-needed basis.

3.8 Retention of Samples:

It could be of value to have samples retained after production so that materials could be examined without coring completed projects. The majority indicated that samples are kept, but even when they are not kept—records of the mix may be retained. Although samples are kept, the retention time may vary. The following example responses indicate the variability of time: “yes for a short time until new RAP is produced”, “split samples of hot mix are kept for approximately 30 days, no samples of RAP are kept”, “mix design material is kept as long as stockpiles remain”, and “mix samples saved as per IDOT QC/QA.”

Figure 3.6 shows the percentage breakdown of the 61 responses to this question.

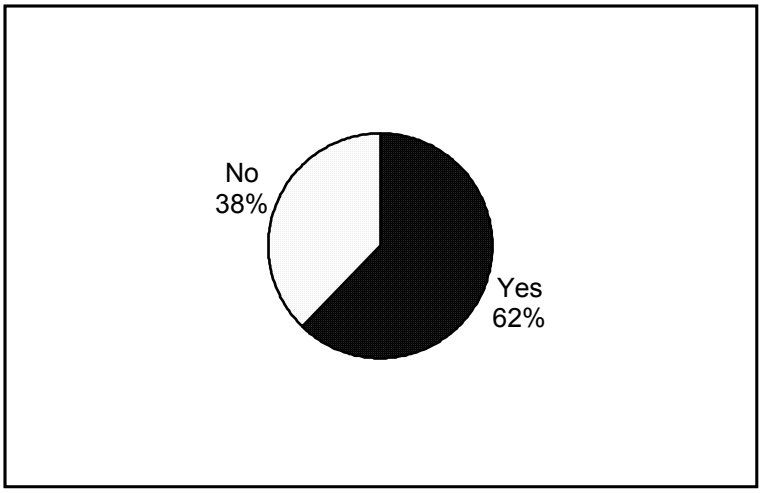

Figure 3.6 Samples Kept after RAP has been Used

3.9 Quality Control:

The plants reported a variety of comments about quality control techniques. As previously mentioned, many comments about stockpiling techniques were reported. Daily testing was the most common response pertaining to the frequency of testing. Methods of testing that were listed included: ignition oven or extraction tests; “testing in accordance with IDOT specs;” testing similar to AGCS program during the crushing operation, and visual inspections techniques.

3.10 Control Systems:

Control systems can and have been retrofit on existing HMA plants in Illinois, which allow the monitoring and control of various plant systems including the RAP and virgin aggregate belts. The systems on the market now are computer controlled, display the entire process graphically, and provide a log of mixture components by weight and percent. Integration of the software can accommodate multiple aggregates and RAP sources. Silo loadout is also available as an option. Though some contractors with drum plants did not reply to the survey with information on control systems, most new plants are drum plants

instead of batch plants and are already typically supplied with computerized controls.

The costs that manufacturers reported for retrofitting existing plants with the newer computer controls vary depending on the type of plant, the manufacturer, the number of bins, and are specific to an individual situation. The costs reported herein were gathered in the 2003/2004 time period. In addition, information regarding plant upgrade costs was also collected from the industry by members of the Technical Review Panel of this project. Based upon these sources, it was found that the cost of a basic system that does blending only ranges from zero to $24,000 for retrofitting a batch plant. However, installation involves an additional charge between $3,000 and $10,000 depending on how many days are required. Installation costs include operator training and initial calibration. Further options such as silo loadouts involve additional cost.

3.11 Discussion and Recommendations for RAP Monitoring and Security:

Variations in the quality of the mixes that use RAP can come from several sources. Uniformity of the RAP stockpile is obviously very important. Stockpiles that are intentionally kept as “homogeneous” are certainly preferred, but even then the degree of uniformity can vary. Questions can arise whether a RAP stockpile pile is exclusively composed of millings from state road projects, and whether the pile includes surface only or other layers, such as the binder course and/or shoulder mixes.

If records are to be kept, it is certainly easier and more accurate to keep a log on the computer control system. However, not all plants have such systems and the cost of requiring such a retrofit for all plants must be considered, since it was found that approximately 11% of plants in Illinois do not have automated plant controls and recording equipment. In addition, if specifications require the retention of samples and/or plant records, it would be necessary for the agency to periodically examine them. If they were never examined or checked, attitudes about such requirements become lax and could lead to a feeling that such

requirements are not necessary and carelessness about maintaining accurate records could result. In the rare event of an unscrupulous operation, this would be a hindrance.

4. Preliminary Testing and Identification of Potential Methods for RAP Detection and Quantification

4.1 Introduction:

This chapter presents discussion on the preliminary testing that was performed on the basis of information collected through the literature review. Various potential test methods identified in the literature review were investigated and their feasibility for further development as RAP detection and quantification methods was evaluated. The later phase involved determining suitable system parameters that were required for the development of more formal RAP detection methods. This phase of the testing will hereafter be referred to as the *calibration study*.

Based upon the literature review and with guidance from the project Technical Review Panel, the following experimental methods were explored:

- Ignition Oven Study
- Partial Extraction
- Extraction, Recovery, and Measurement of Physical Properties of the Asphalt Binder
- Gradation Analysis and Void Analysis of Gyratory-Compacted Specimens

4.2 Ignition Oven Study:

4.2.1 Introduction:

The literature review included a synopsis of the NCAT ignition oven method used for determination of the presence and amount of RAP. The NCAT ignition oven method for determination of asphalt content is simple to perform and the equipment is available at most contractor and agency labs. However, it was not clear from the literature if the same device could be used to determine the presence and amount of RAP. The basic objective of this study was therefore to evaluate the potential of the method for determination of presence

and amount of RAP, and the repeatability of this measurement for different types of RAP encountered in Illinois.

4.2.2 Material Details:

A virgin binder of PG64-22 (AC-20) grade was used for the study. A local HMA contractor, University Asphalt of Champaign, Illinois provided two distinctly different RAP samples. The first RAP sample was manufactured by milling the surface and binder course of I-57 near Champaign. No records about the original design and materials of RAP were available, although a PG64-22 binder grade with high quality crushed dolomitic/limestone aggregate would be expected. The aggregate gradation of RAP (after the Ignition Oven Test) showed it to have a typical gradation for 9.5-mm nominal sized mix used for surface courses in Illinois. The ignition oven was calibrated based upon the results of a solvent extraction, carried out using AASHTO T-240 procedures. The ignition oven tests showed an approximate binder content of 5% in the RAP, which is reasonable for an interstate facility. The second RAP sample was manufactured by milling the surface course and binder course from a low-volume rural roadway in Paxton, IL, creating a conglomerate stockpile. The ignition oven results indicated an approximate asphalt content of 5.5% for this RAP source, which is a reasonable value for a low volume road in Illinois.

A 19-mm nominal sized virgin mix with a target asphalt content of approximately 6% by weight of mix was used for this preliminary study. Mixing was done at 165^{o}C using standard bucket mixing procedure in the lab. Details regarding the aggregate gradation and mix are presented in *Appendix B*. Virgin asphalt binder was added to the mix based upon the weight of virgin aggregates. The final asphalt content in the RAP mixtures was slightly lower than 6%, varying slightly depending on the percent and type of RAP used. Twelve samples were used, consisting of two RAP sources and six RAP amounts, ranging from: 0%, 15%, 30%, 45%, 60% and 100% by weight of total mix.

4.2.3 Testing:

Two replicates of each sample were tested to determine the variability for different RAP types and the repeatability of the test. The standard ASTM D4125 procedure for determination of asphalt content using an NCAT ignition oven was used for testing purposes. The oven was an NCAT Asphalt Content Tester, manufactured by Barnstead-Thermolyne, model F-85930 shown in Figure 4.1. An RC232 serial communication link with a laptop computer was used to capture records for chamber temperature, percent weight loss, time elapsed, filter temperature, etc., once per second.

Figure 4.1 Ignition Oven

4.2.4 Results:

Selected results of chamber temperature and percent weight loss against time are presented in this section, while extensive measurements are provided in Appendix C. Figures 4.2 and 4.3 present chamber temperature versus time for two series of replicate tests performed on mixes with varying amounts of virgin materials and the I-57 RAP. Figures 4.4 and 4.5 present percent weight loss against time (due to asphalt ignition) for two repetitions of the second RAP, which was from Paxton Road. A detailed analysis of the results was also performed in order to identify any peculiar behavior in the chamber temperature, percent asphalt content and other outputs obtained that might exhibit a relationship with amount of RAP. The results from these analyses are presented in *Appendix D* in graphical form for various parameters, such as: time to first peak in chamber temperature; time to second peak; chamber temperature at first and second peak; chamber temperature at first trough after peak; initial and final slope of weight loss versus time; etc.

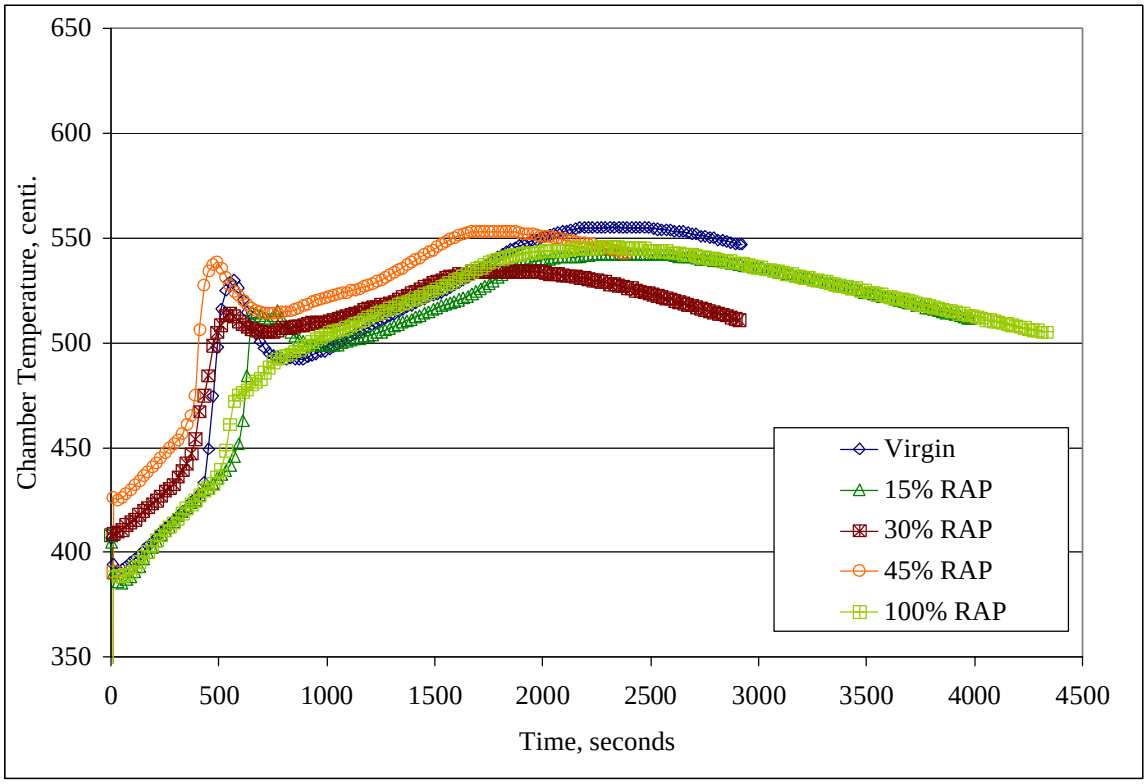

Figure 4.2 Chamber Temperature Profile for I-57 RAP (First Repetition)

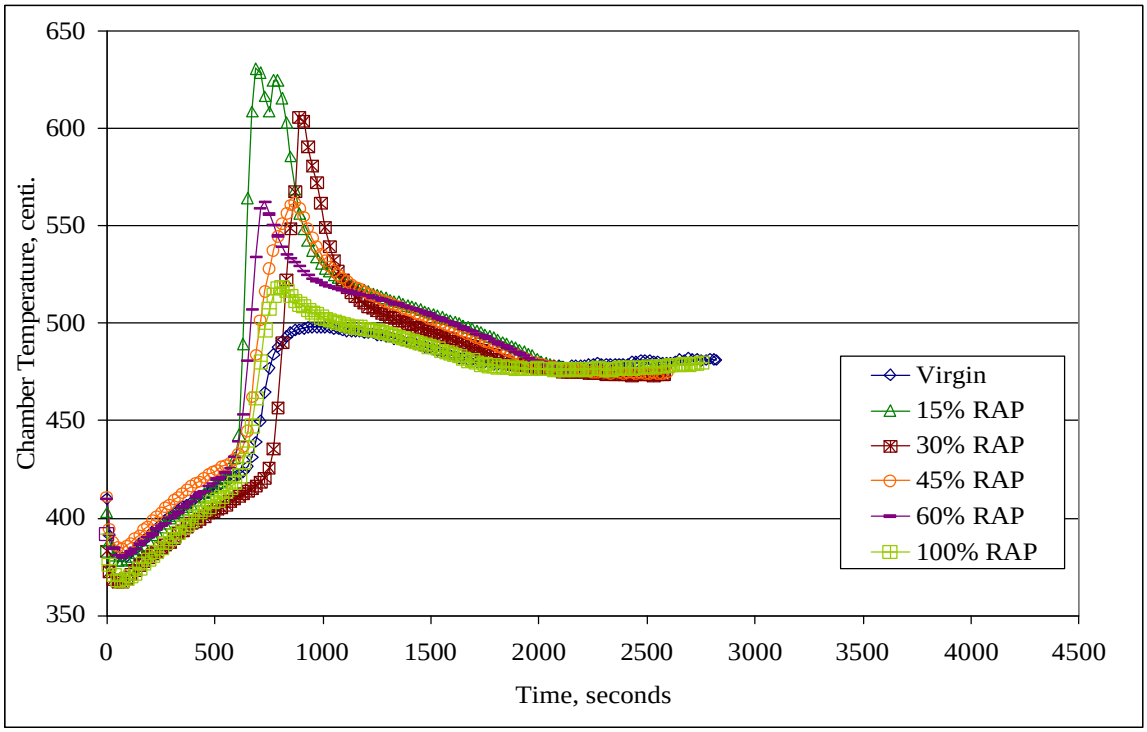

Figure 4.3 Chamber Temperature Profile for I-57 RAP (Second Repetition)

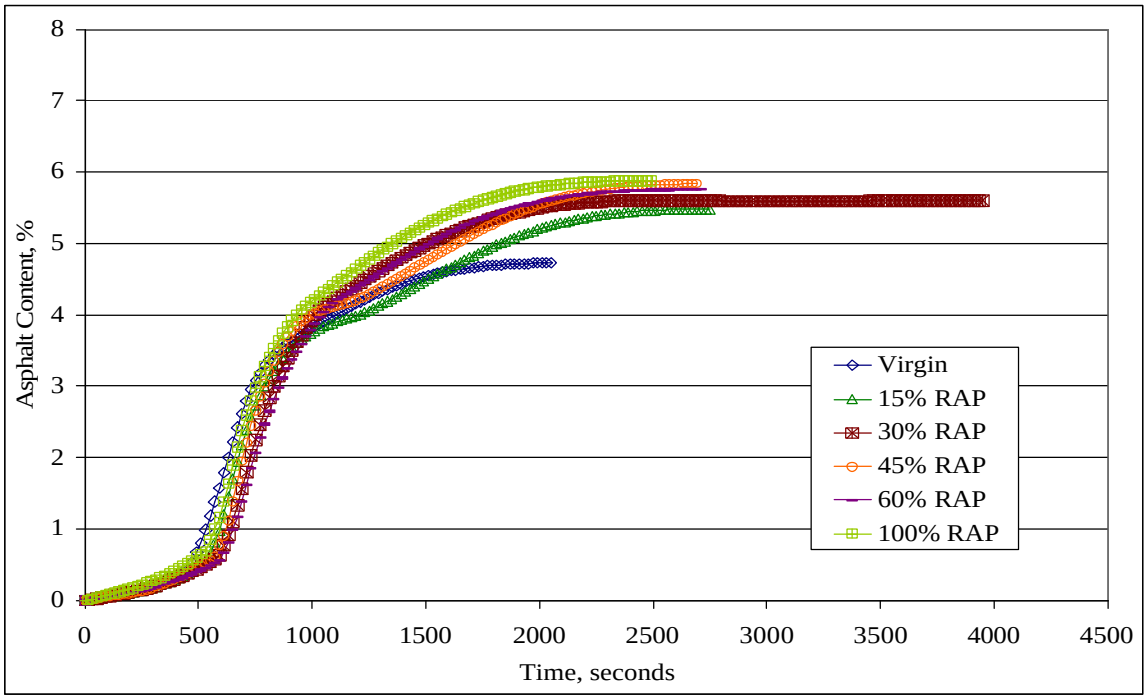

Figure 4.4 Percent Asphalt Content against Time for Paxton Road RAP (First Repetition)

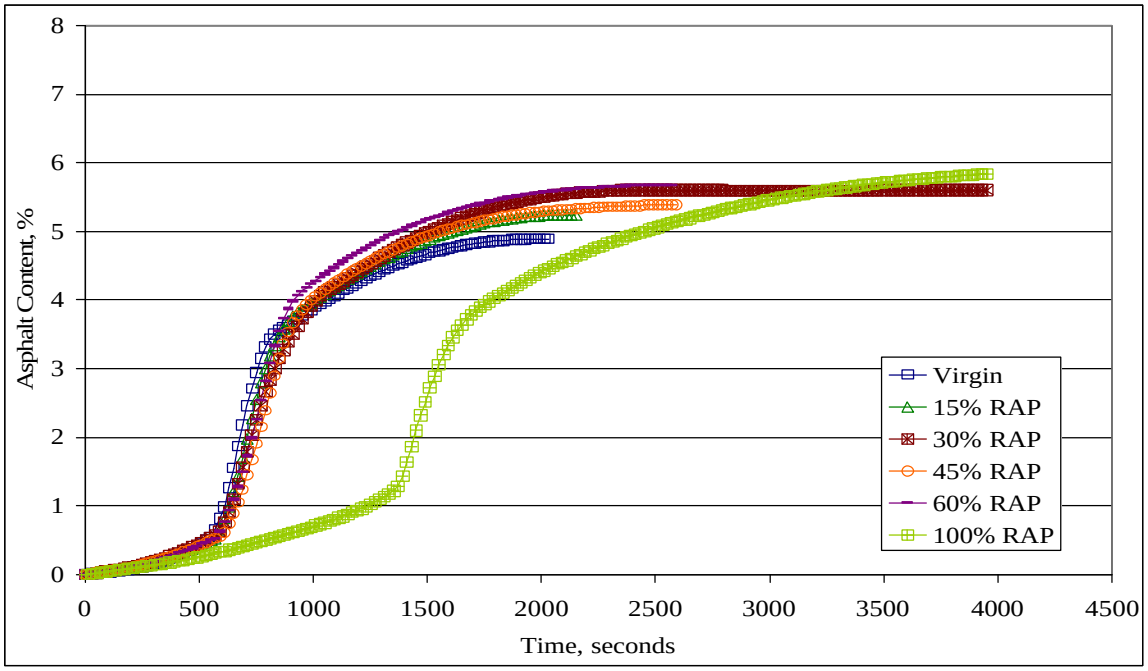

Figure 4.5 Percent Asphalt Content against Time for Paxton Road RAP (Second Repetition)

4.2.5 Discussion of Results:

The results from this study generally agreed with findings of the literature review. The chamber temperature profile shows an initial peak due to heat produced by the lighter fraction of mix. Similarly, the weight loss profile also shows a sudden loss in mass followed by a more stable period, which represents the slow oxidation of heavier hydrocarbons. But the current limitation with this test is the absence of control over the heat generation by the oven. Due to absence of this control, the results do not show any repeatable pattern with respect to the presence and amount of RAP. Furthermore, the results from two repetitions of split samples show significant differences. Thus, with the current test method and equipment, the ignition oven method does not appear to show much promise for the accurate determination of RAP amount. Detailed analysis of other ignition oven parameters (as reported in Appendix D) led to the same conclusion. However, future studies might be aimed at looking into simple modifications in the test procedure or test equipment that would be more sensitive to mixture differences, e.g., better control over chamber temperature, the use of additional temperature probes placed near the specimen, etc.

4.3 Partial Extraction and Visual Observation Study:

4.3.1 Introduction:

The next method investigated for RAP amount determination involved subjecting RAP mixtures to partial extraction (solvent washing) and visually observing the partially cleaned aggregate residue. The asphalt extraction equipment described in AASHTO T 164-01, "Quantitative Extraction of Bitumen from Bituminous Paving Mixtures" was used to partially dissolve the asphalt from the RAP mixture samples. After letting the residual solvent evaporate under a fume hood, visual observation was undertaken in an effort to identify "RAP aggregates." The above approach was initially based on the assumption that an adequate portion of RAP aggregates have a partial or complete inner-coating of harder (field-aged) RAP binder and an over-coating of softer, easier-to-dissolve virgin binder. This assumption is consistent with the concept of "black rock" RAP mixtures, that is, the idea that RAP aggregates, which are coated with aged binder experience incomplete blending with virgin binder during production. It was hypothesized that the extraction process could be customized through choice of solvent and by determining a wash duration that would remove most of the virgin binder while leaving a sufficient amount of RAP binder for visual identification of RAP aggregates. As such, the process had the potential for determining both the presence and amount of RAP in a mixture. A short study was conducted at University of Illinois to evaluate the potential of this test method for the aforementioned uses.

4.3.2 Materials:

For preliminary investigation of the partial extraction method, the I-57 RAP sample was used exclusively. A 30% RAP mix was manufactured for testing, which was identical to that used in the ignition oven study. A 30% RAP mix is defined here as a mix containing 30% RAP material by weight of aggregates.

4.3.3 Testing:

The test procedure used in this study was a version of AASHTO T164-01 (Method B); modified to facilitate RAP detection and quantification as described in the previous section. For the purpose of partial washing with solvent, three main factors can be controlled: 1) the duration of solvent washing; 2) the rate at which solvent flows through the mix, and; 3) the "aggressiveness" of the solvent used, as affected by, for instance, solvent polarity, or percent dilution with a less aggressive solvent, such as ethyl alcohol. Examples of commonly used aggressive solvents are trichloroethylene and methylene chloride.

In this test setup the asphalt mix sample is placed in a conical filter paper, which in turn is placed in a wire mesh basket. A glass jar with approximately 800ml of solvent is used. The jar is initially heated and a condenser closes the top of the jar. As the solvent is heated it vaporizes and condenses through the condenser. Once the constant rate of vaporization and condensation is achieved, the wire mesh baskets are placed into the jar. The solvent drips into the basket dissolving the asphalt and passing it through the filter paper. The recirculation of solvent continues due to its low boiling point, and the dissolved asphalt continues to be deposited at the base of the jar.

The AASHTO T164-01 procedure recommends continuation of the test until complete extraction of asphalt binder is achieved. The filter paper specified in AASHTO T164-01 leads to a solvent buildup in the basket such that the sample is completely submerged for most of the extraction. As a result, the rate of extraction was very rapid and difficult to control. To solve this problem, a fast filtering filter paper (WHATMAN #1) was used. In addition, various solvents were investigated, including trichloroethylene (TCE), EnSolv (n-propyl bromide), DeSolv (orange based solvent) and methylene chloride. In the end, methylene chloride was selected due to its lower toxicity and for economical reasons. However, since this study did not consider polymer-modified virgin binders, more work will be needed to determine if the solvents and test procedures developed can adequately handle polymers. Potential issues to consider with polymers include clogging of filters and differences in extraction rate.

4.3.4 Summary of Results:

The preliminary tests conducted indicated that the concept of partial extraction indeed showed promise for the purpose of RAP identification and quantification. For example, Figure 4.6 shows the residue from a mix which contained 30% RAP after 35-minutes of extraction. The presence of RAP aggregates was apparent (binder film was not completely removed); whereas the virgin aggregates appeared to be washed completely clean of binder.

Despite the encouraging initial results, several issues needed to be resolved after the preliminary testing. The non-uniform extraction in the basket from the top to down caused the portion of mix in the lower part of basket to have more contact with solvent, as some solvent condenses upon contact with the mix while evaporating and rising. Another problem is the “truncated conical” shape of condenser, which leads to more solvent dripping into the peripheral portion of mix. A consequence of these two issues was the inability to accurately determine the amount of RAP present in the mix, although the presence of RAP was apparent. Details on further evaluation and development of visual identification methods employing partial extraction are discussed in later chapters.

Figure 4.6 Partially Extracted Sample of Bituminous Mixture with 30% RAP

4.4 Use of Physical/Rheological Properties of Asphalt Binder:

4.4.1 Introduction:

The literature review (Chapter 2) clearly indicated that the presence of RAP binder causes changes in the physical properties of a binder blend (virgin and RAP binder), as one would expect. The literature also seemed to suggest that asphalt binder testing using the Dynamic Shear Rheometer (DSR) would provide the suitable parameters for detection and quantification of RAP in the asphalt mix. Given the availability, practicality, and versatility of the DSR device, it was selected for use in evaluating the potential for determining RAP amount through physical testing of age-processed virgin and recovered RAP binder.

4.4.2 Materials:

This method requires testing of binders to determine their physical properties and then the graphical analysis of those properties to predict the presence and amount of RAP. The asphalt binders used in this study were PG 64-22 virgin binder and recovered binder from the I-57 RAP. The extraction and recovery procedure used to obtain RAP binder is described in the following section. Blends of binder were made for 0%, 15%, 30%, 45% and 100% RAP binder amounts by weight. Approximately 40-gm samples were produced for each blend percentage and blending was performed at 135^{o}C. Blending of asphalt binders was performed by means of mechanical mixing using a paddle mixer.

4.4.3 Extraction and Recovery of Asphalt Binder from Asphalt Mixes and RAP:

The extraction and recovery of binders for DSR testing was carried out using the AASHTO T319-03 specification for “Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures.” This method involves the use of an extraction vessel for asphalt extraction and a *Roto-Vap* unit for the binder recovery. Testing was conducted at the Advanced Transportation Research and

Engineering Laboratory (ATREL). The apparatus used is shown in Figures 4.7 and 4.8. The solvent required by AASHTO T319-03 is a blend of Toluene and Ethyl Alcohol.

Figure 4.7 Extraction Vessel for AASHTO T319-03

Figure 4.8 Recovery Equipment (*Roto-Vap Unit*)

The AASHTO T319-03 specifies centrifuging the asphalt-solvent mixture before final distillation of the solvent. However, that step was performed prior to initial reduction of the volume of asphalt-solvent mixture for the purpose of reducing testing time. Even though the centrifuge extraction was not performed exactly as per AASHTO T319-03, complete removal of fines was ensured. This modified AASHTO method leads to reduction in total recovery time by amount of 2-4 hours. During each run about 1200-gm of RAP sample was used, yielding approximately 30-gm of binder. All the recovery procedures carried out in this project were performed with this modification to the AASHTO method. To

minimize aging during centrifuge processing, the asphalt-solvent mixture was blanketed with nitrogen in the centrifuge bottles. Figure 4.9 shows the centrifuge equipment used for this study.

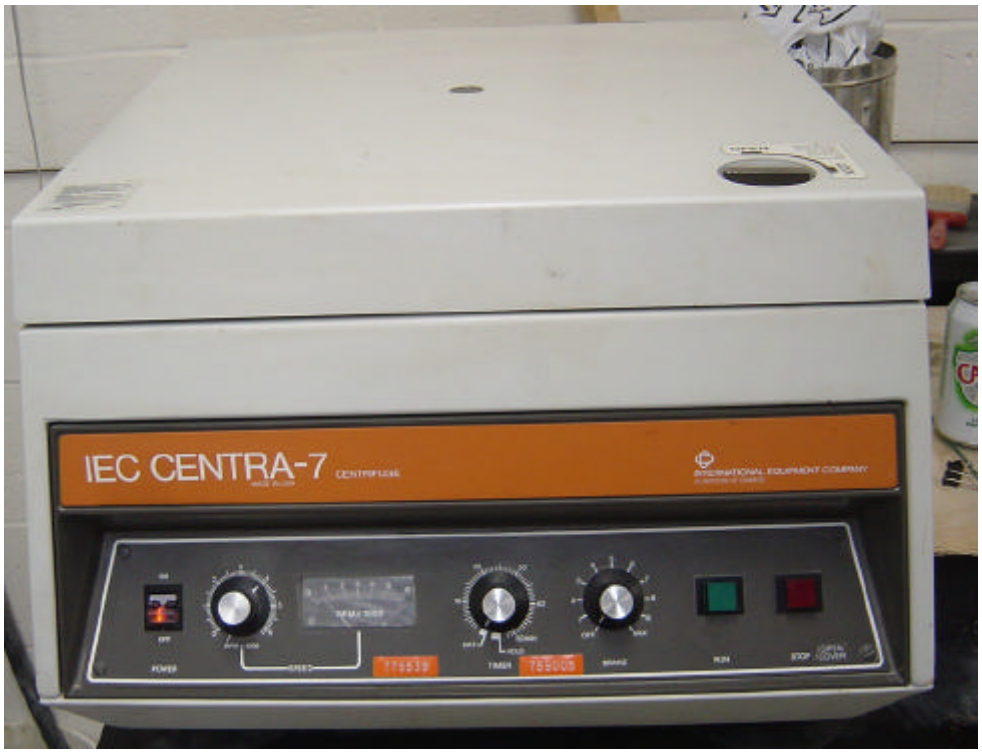

Figure 4.9 Centrifuge Unit used for Extraction/Recovery

The NCHRP 9-12 report (McDaniel and Anderson, 1997) states that for the NCHRP study N Propyl Bromide was used as the extraction solvent due to its less harmful nature towards operator. The report also states that it is more difficult to remove 100% of N Propyl Bromide from an asphalt-solvent mixture, whereas a Toluene-Alcohol Mixture is easier to remove in its entirety, thus for this study Toluene-Alcohol Mixture was used. Adequate safety features were observed during the study and thereafter to ensure against environmental or health issues. The safety features included the following:

- Fume Hood with sufficient face velocity (Approved/Certified by UIUC Environmental Health Department on Annual Basis)
- Use of an Active Charcoal Gas Mask by the operator to ensure against fumes or vapors that might come in direct contact with the operator.
- Built-in laboratory Fire Safety system.
- Use of Nitryl-Rubber gloves to prevent direct skin contact.
- Use of the "BUCHI Plastic+Glas" brand Roto-Vap and Flasks, to ensure against solvent spillage or injuries from the shattering of glass.

4.4.4 Testing:

The AASHTO T315 test procedure was used for determining complex shear modulus (G*) of the binder blends using Dynamic Shear Rheometer (DSR). The test method for testing of virgin binder was followed unless otherwise stated, which requires the use of a 25-mm plates, 1-mm gap and test temperature of 64^{o}C (high temperature grade of virgin binder). A Bohlin Dynamic Shear Rheometer shown in Figure 4.10 was used for testing the binder samples at a frequency of 10 radians/second.

4.4.5 Results:

The results from this study are summarized in Table 4.1 (details in Appendix C). The results are illustrated in graphical form in Figure 4.11 (arithmetic scales) and 4.12 (semi-log scales). It should be noted that testing in this portion of the study was carried out using a blend of tank or virgin asphalt binder and RAP binder with no additional aging such as rolling thin film oven (RTFO).

Figure 4.10 Dynamic Shear Rheometer

Table 4.1 Results from Preliminary Study on Binder Properties for RAP Detection

RAP Binder Amount (Percent by Weight)	Average Complex Modulus, G* (kPa)
0	1.14
15	2.92
30	4.54
45	7.76
100	25.36

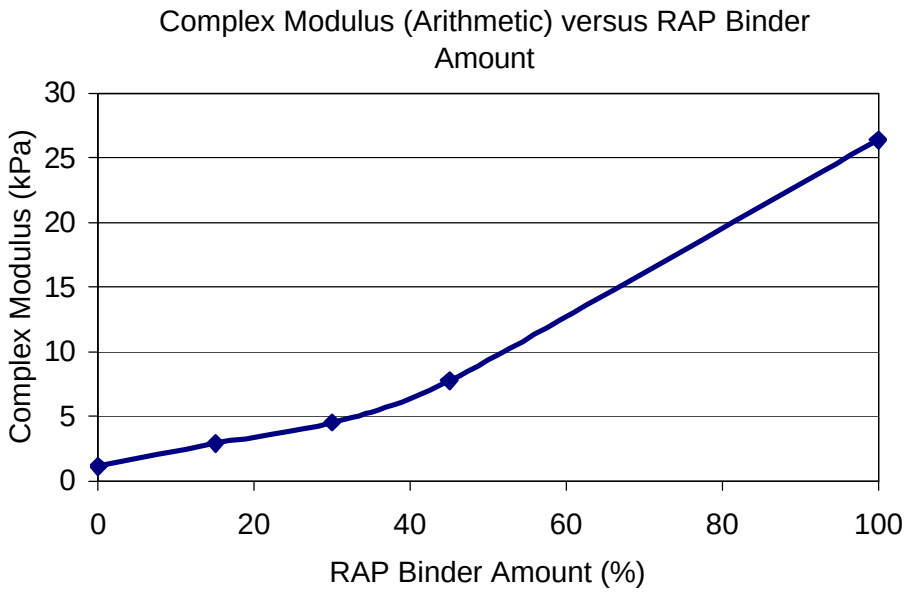

Figure 4.11 Results for Complex Modulus of Asphalt Binder Blends (Tank and RAP Binders)

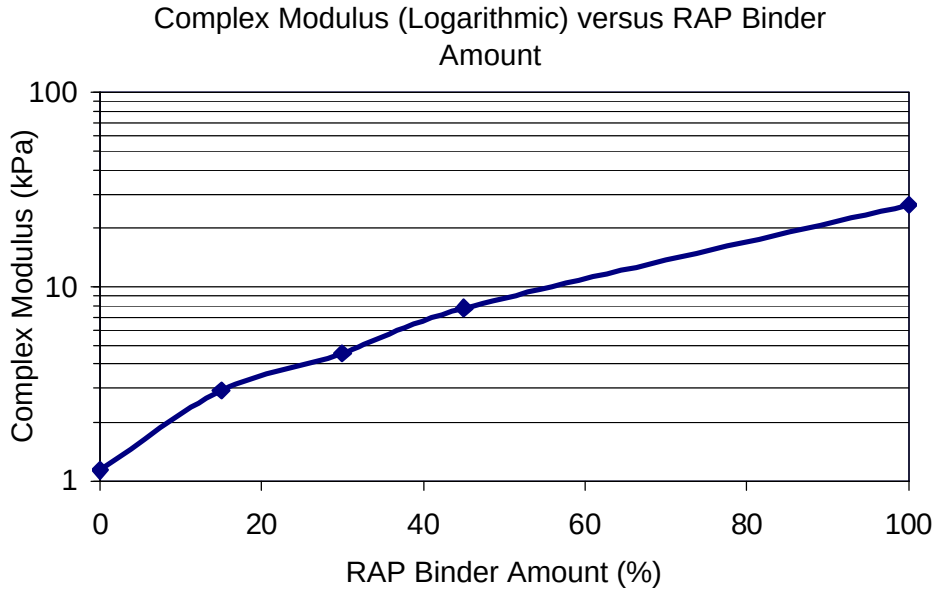

Figure 4.12 Results for Complex Modulus (Log) of Asphalt Binder Blends (Tank and RAP Binders)

4.4.6 Summary:

The results from the preliminary study indicate that complex modulus of asphalt binder is quite sensitive to the amount of RAP binder in the blend. Thus, if complex moduli for the tank binder, recovered binder from the asphalt mix and the RAP binder can be determined, then the RAP amount can be back-calculated. However, this back-calculation procedure requires the development of a model that can predict complex modulus of the asphalt binder blends at different RAP binder amounts. The development of such a model will be discussed in detail in later chapters.

The following example illustrates the nature of the back-calculation method for determining RAP amount:

Example:

Given:

- Complex Modulus of Tank Binder (RTFO aged), G^*_{Tank} = 2.8-kPa
- Complex Modulus of Binder Recovered from Asphalt Mix, G^*_{Mix} = 10-kPa
- Complex Modulus of RAP Binder, G^*_{RAP} = 75-kPa

Solution:

Assuming a model is available that can predict the complex modulus for various RAP amounts for given values of G^*_{Tank} and G^*_{RAP} (plotted as the end points of the curve in Figure 4.13, at 0% and 100% RAP, respectively), then one could construct a curve as shown in Figure 4.13, labeled as “Prediction.” The intersection of the horizontal line at 10 kPa (representing the G* of the sample in question, i.e., the RAP mixture) and the “Prediction” curve as shown in Figure 4.13 leads to an estimated RAP amount of 27%.

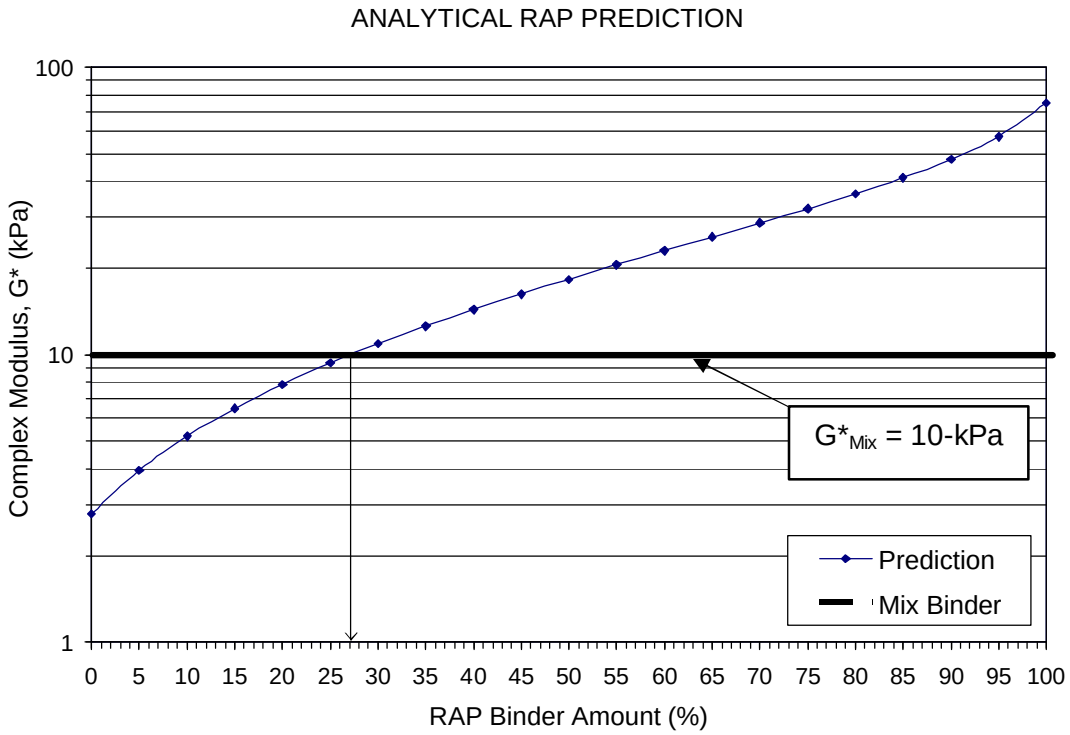

Figure 4.13 Example Illustrating Potential Method for RAP Detection and Quantification using Binder Physical Properties

4.5 Calibration Study to Determine Proper Blending and Aging Protocols:

4.5.1 Introduction:

The main objective of the "calibration study" was to determine the most appropriate aging procedure for binder blends. Aging of binder is required for lab samples since the field samples are undergo "short-term" aging during plant mixing and laydown. It was important to develop a suitable aging procedure for binder blends since preliminary results showed that the physical properties of binders manufactured by blending *prior to short term aging* (Rolling Thin Film Oven aging) versus those blended *after short term aging* differed dramatically. The binder blends described in this section are mainly blends of virgin (tank) and RAP binders, subjected to various combinations of blending and aging procedures. However, as a part of the calibration study, the effect of aging was

also studied to a limited extent by carrying out oven aging of various RAP mixtures.

4.5.2 Testing and Material Details:

The Superpave binder specifications require that short-term aging be carried out using the Rolling Thin Film Oven (RTFO), as specified by AASHTO T240. Figure 4.14 shows the equipment used in this study. As described earlier, the main objective of this portion of the study was to determine most suitable aging and blending procedures. The various methods investigated were:

1. RTFO AGING of BLENDS ("blend-then-age"): In this procedure the blends of virgin and recovered RAP Binders were produced and then the blended binders were subjected to Rolling Thin Film Oven Aging as per AASHTO T-240.

2. RTFO AGING SEPERATELY ("age-then-blend"): This procedure involved RTFO aging of virgin and recovered RAP binders separately, followed by blending. Standard RTFO aging as per AASHTO T-240 was carried out on the components.

3. OVEN AGING of BITUMINOUS MIX CONTAINING RAP: In this procedure, bituminous mixtures were produced in the lab and then oven-aged at mixing temperatures for various durations. Once aged, extraction and recovery was carried out to obtain the aged binder samples.

Figure 4.14 Rolling Thin Film Oven

All tests for the calibration study were performed using a controlled tank binder sample of PG64-22 grade and RAP binder recovered from the RAP-C. RAP-C is the RAP material that was sampled along with Peoria Surface Mix (Mix-C). Additional details regarding sampled materials are presented in *Appendix A*. Binder blends were prepared with 0%, 15%, 30% and 45% RAP binder amounts using the first two aging procedures described above (age-then-blend and blend-then-age). Binder samples were tested for determining their physical properties using Dynamic Shear Rheometer (DSR) as per AASHTO T315 test procedure. Complex Shear Modulus (G*) of the binder was used for the purpose of comparison. The test temperature was selected as the Superpave high temperature grade of the tank binder, or 64^{o}C, with 25-mm plates and a 1-mm gap setting on the DSR.

Mixture specimens portraying Mix-C were prepared two different RAP percentages, 15% and 30%. It should be noted that the 15% and 30% RAP mixes were designed in such a way that RAP binder amounts were 15% and 30% of the total binder in the mix. Thus, recovered binder from those mixes contained 15% and 30% RAP binder.

The mixture samples were aged for 2 hours in a forced-draft oven at a temperature of 165 ^{o}C as recommended by Superpave lab mixing specifications (Superpave, SP-2). Then, the mix was split into four equal portions, each subjected to a different extent of additional aging at the mixing temperature. Additional aging periods of 0-hours, 2-hours, 6-hours and 10-hours were used. Next, binder samples from each aged mix sample were obtained via extraction and recovery as per AASHTO T319 specifications. Recovered binders from the mixture specimens were tested in the same manner as the binder blends described earlier. A minimum of three test replicates were used for DSR testing.

4.5.3 Results:

Figure 4.15 presents a summary of results obtained from the calibration study. Detailed results from the calibration study have been tabulated in *Appendix C*. It should be noted that the results for binder recovered from the 30% RAP mix subjected to 6-hours of aging was not included, since the samples were inadvertently damaged and insufficient materials remained for retesting.

From the results shown, it is clear that blending binders prior to the RTFO aging produces results that match better to the results obtained from the binders recovered from actual mix sample. It should be noted that the 0-hour oven aged mix sample from the field should most closely represent a lab sample that was oven aged for 2-hours as per the Superpave lab mixing recommendations (Superpave, SP-2). Also the testing indicated that continued oven aging will produced a significantly aged binder, indicating the need to adhere to precise oven aging times. The reason for the slight hump in the “blend-then-age” curve was unknown, although such a trend was observed in several other mixtures, as described later in this report.

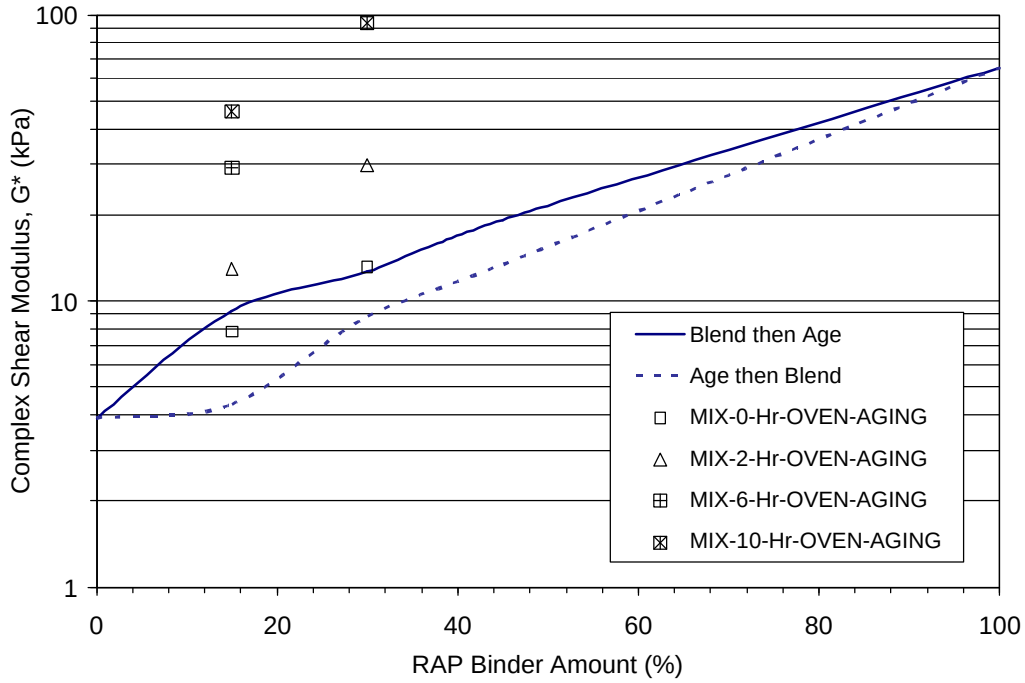

Figure 4.15 Results from Calibration Study

4.5.4 Findings and Recommendations:

Based upon the results obtained from the testing performed in the calibration study, the most suitable aging procedure for binder blends consisting of tank and RAP binders is to RTFO-age the blended RAP and virgin binders instead of aging them separately. Also from this calibration study it was learned that binder properties are significantly affected by the aging caused during plant mixing and construction. Finally, the need for an analytical method to predict G* of RAP mixtures as a function of RAP content was described, which will be addressed later in this report.

4.6 Gradation Analysis and Void Analysis of Gyratory-Compacted Specimens:

In addition to the contractor survey and mix security study (Chapter 3), the Bradley University research team also participated in a limited laboratory study to

evaluate potential RAP detection methods. Two rapid methods were developed for RAP detection; one looks into the variation of aggregate gradation and the other looks into the variation of voids in gyratory-compacted asphalt concrete specimens. These methods were found to have limitations for use in quality assurance, but they have been documented in Appendix G for possible use by contractors as a rapid quality control for RAP mixture production. The main principles and limitations of these methods can be summarized as follows:

- **Use of gradation for RAP detection and quantification:** This technique is based upon the principle that the gradation of the aggregates in the RAP material will likely differ from that of the blended virgin aggregate. Thus, the analysis of the aggregate from the plant produced mixture in question (obtained as aggregate residue from the ignition oven or solvent extraction) might provide a means for estimating the relative proportions of RAP and virgin materials. A spreadsheet was developed to solve the linear programming problem of back-estimating the RAP proportion in a mixture, given the gradation data from the virgin, RAP, and combined mixture in question. The main problem with using this method as a quality assurance tool, is that the predictive accuracy of the method becomes unreliable as the gradation of the RAP and virgin materials approach one-another.
- **Use of gyratory voids for RAP detection and quantification:** This technique is based upon the principle that the void level in gyratory compacted asphalt concrete specimens will be affected by the amount of RAP present in a mixture. These differences would arise from differences in gradation, aggregate shape and texture, and binder viscosity. The main problem with using this method as a quality assurance tool is that the void level in gyratory-compacted specimens has inherent variability during normal mixture production and therefore cannot reliably be used to develop a distinct relationship between RAP amount and void level.

5. Rapid RAP Detection Methods

5.1 Introduction:

This chapter describes the development and evaluation of various rapid RAP detection and quantification techniques that could be employed in the field for quality assurance purposes. The techniques evaluated in this phase of study include modified solvent extraction and modified ignition oven techniques. The major task for this phase of the study included the development of a suitable partial extraction conditioning method and the determination of the optimum test duration and set point temperature for a modified ignition oven conditioning procedure.

5.2 Development Approach:

The approach used to develop partial ignition and partial extraction sample conditioning techniques was based upon the assumption that RAP could be detected in HMA mixtures by carefully removing most of the softer virgin binder coating from the mixtures, thereby exposing the harder, residual RAP binder on the original RAP aggregates. Thus, there was an assumption that the mixing of RAP and virgin binders during HMA production is incomplete (sometimes referred to as a “black rock” condition). Based upon this assumption, the goal was then to come up with a reliable method to melt away (i.e., partial solvent extraction) or burn off (i.e., partial ignition oven conditioning) the virgin binder so that the presence of RAP could be identified in the mix. Furthermore, it was hoped that one or more of the methods developed could also be used to obtain an estimate (perhaps a rough estimate) of the amount of RAP in the mixture. The approach taken was to develop promising techniques on one of the plant manufactured mixes in the study and then to verify and/or calibrate the technique based on testing of other plant and lab manufactured samples. For the purpose of initial development of the partial ignition and partial extraction techniques a broad range of testing was carried out on Mix-C (plant

manufactured surface mix from Peoria, IL). The most suitable method was then verified and further refined by testing additional plant mixes and lab manufactured mixes.

5.3 Material Details:

Various plant-produced asphalt mixtures, RAP, aggregate and binder samples were acquired during the course of this project. The first round of asphalt mix, RAP, aggregate and binder samples were collected during the fall of 2002 by the research team at Bradley University. The samples were collected for surface and shoulder mixes from Collinsville, Illinois (Mix-A and Mix-B) and Peoria, Illinois (Mix-C and Mix-D). The second round of sampling, for the RAP variability study, was coordinated by IDOT. Samples from eleven different RAP sources (RAP-1 through RAP-11) across Illinois were collected and delivered to the University of Illinois in the Spring of 2003. Another set of asphalt mix, RAP, aggregate, binder and field core samples were also collected and delivered by IDOT from District 6 (Mix-E) and District 2 (Mix-F) during fall of 2003. Along with Mix-E and Mix-F IDOT also provided blind samples BS-1 and BS-2 whereby field cores, RAP and aggregates were delivered without any information about the amount of RAP present in the mix. Some of the test results from the preliminary study were also used in the development and calibration of test procedures. Those tests were performed on two of the RAP samples (I-57 RAP and Paxton Road RAP) collected by University of Illinois research team. Details regarding various mix and RAP samples are presented in *Appendix A*.

5.4 Development of Partial Extraction Technique:

Preliminary tests indicated that the existing asphalt binder extraction techniques (as AASHTO T164) would need to be modified in order to successfully carry out partial extraction (removal of virgin binder traces). Some of the drawbacks of conventional techniques included lack of control over the extent of extraction and non-uniform solvent flow through the mix.

To overcome these limitations and to have complete control over the extent of extraction a set of lab tests were conducted where asphalt concrete samples were soaked in solvent for a given time and then partially extracted aggregates were sieved out. The amount of time for which the mix stayed in the contact with solvent played an important role in extent of binder dissolution and therefore the extent of extraction. An important factor affecting the dissolution rate was the type and concentration of solvent; i.e., very aggressive solvents tended to rapidly dissolve all of the binder (virgin and RAP) making it impossible to distinguish between RAP and non-RAP mixes. Conversely, very mild solvents were not able to dissolve the virgin binder in a reasonable time period.

An ideal partial extraction is one where the mix containing only virgin aggregate and binder (no RAP), after partial extraction, yielded aggregates with zero or trace amounts of binder and where mix containing RAP, subjected to the same conditioning, yield a residue with binder traces present on the partially extracted aggregates (presumably the RAP aggregates). Furthermore, it was hypothesized that the method could also be potentially used to estimate approximate RAP amounts if comparison samples with known RAP amounts were available for cross-referencing.

Various solvents were used for development of partial extraction procedure include Tri-Chloro Ethylene, Toluene, Methylene Chloride, Mineral Spirits, citrus-based solvent products, etc. Some of the organic solvents are very aggressive in dissolving the asphalt binder, and thus, to retard the rate of dissolution their concentration or strength was reduced by diluting them with ethyl alcohol. For example a 50% strength methylene chloride was produced by mixing 50% methylene chloride and 50% ethyl alcohol by volume.

Initial tests were carried out with single stage extractions, whereby the mix was soaked in various trial solvent for a given time, after which the aggregates were sieved out. Different solvents, solvent concentrations and soaking times were attempted. At full concentration, most of the partially extracted aggregates from Mix-C, which contains about 15% RAP, showed very little trace of binder

after relatively short soaking times. Figure 5.1 shows a case where 2-hour soaking in 70% strength toluene led to nearly complete binder removal.

Figure 5.1 Partial Extraction Residue for Mix-C (2-hour soaking with 70% Toluene)

From the tests performed using single-step extractions, it was observed that the mild solvents acting over longer time periods were more effective in overall loosening of the mastic and mix, while aggressive solvents were effective at dissolving the binder from aggregate surfaces. Thus, two-step partial extractions procedures were attempted. For two-step partial extractions, mix samples were initially soaked in relatively mild solvents such as mineral spirits or 50% strength methylene chloride for longer time periods, ranging from 30 minutes to 2 hours. The mix samples were then washed with alcohol over the ASTM #8 sieve. Next, the second stage of extraction was carried out with stronger solvents, such as 100% toluene or 85% strength toluene using shorter durations in the range of 30 seconds to 2 minutes. The second extraction stage

also involved vigorous agitation of the soaked samples using a metal spatula. The aggregates were again washed with alcohol over the #8 sieve and then placed in a vented oven at 50^{o}C for drying. Plant Mixes B and C were primarily used in comparing different combinations of two-step partial extraction methods. Figures 5.2 and 5.3 show results from various two-step partial extractions.

Figure 5.2 Partial Extraction Residue for Mix-C (Initial Soaking Time = 90-min, Initial Solvent = 50% Toluene, Final Soaking Time = 30-sec, Final Solvent = 85% Toluene)

Figure 5.3 Partial Extraction Residue for Mix-C (Initial Soaking Time = 120-min, Initial Solvent = 50% Methylene Chloride, Final Soaking Time = 1-min, Final Solvent = 85% Methylene Chloride)

5.5 Verification of Partial Extraction Technique:

From the tests conducted on Mix-B and Mix-C, a technique involving 2-hours of soaking in 50% methylene chloride and 1-minute of vigorous mixing in 85% methylene chloride appeared to be the most promising. For verification of this method, partial extraction tests were carried out on the three virgin mix samples and the other four plant manufactured RAP mixes (Mix-A, Mix-D, Mix-E and Mix-F). The virgin mix samples were manufactured without RAP. Virgin Mix-1 was manufactured to have a similar gradation, binder content, and binder type as Mix-C. Virgin Mix-2 was manufactured with similar gradation, binder content, and binder type as Mix-A, while Virgin Mix-3 was manufactured with a similar gradation and binder type as Mix C, but with a different binder content.

Figure 5.4 shows typical aggregates without any trace of binder, whereas the aggregates shown in Figure 5.5 have clearly identifiable traces of binder.

Figure 5.4 Typical Aggregates with No Binder Traces

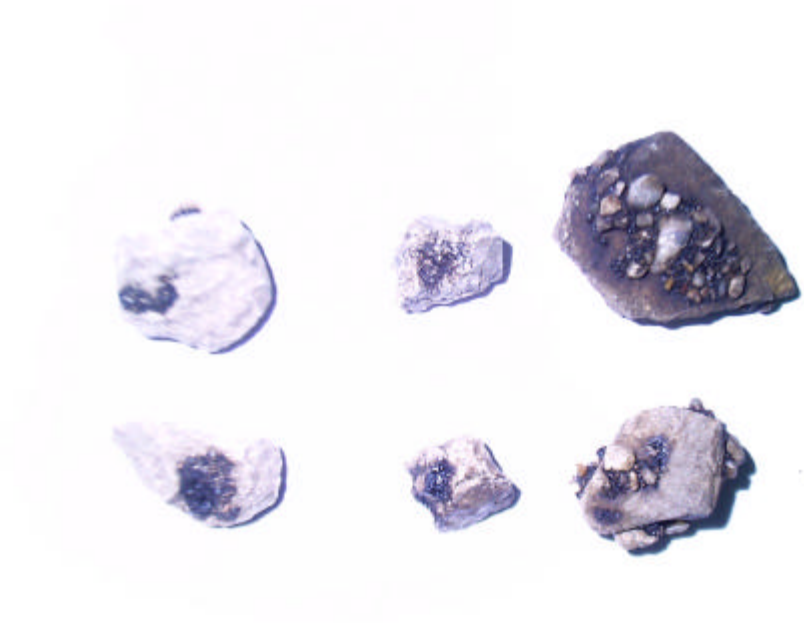

Figure 5.5 Typical Aggregates with Binder Traces (present in mixes with RAP)

Figures 5.6, 5.7 and 5.8 show partial extraction residue from three of the virgin mixes. The residue from virgin mixes were essentially binder-free. Thus,

irrespective of aggregate gradation, binder type and binder amount (which all varied in these samples), the proposed method seemed to work well in correctly identifying virgin mixes. Next, it was necessary to assess the ability to detect RAP, particularly lower RAP amounts, as it was entirely possible that the proposed technique was overly aggressive in removing solvent for such mixtures.

The partial extraction residue from all plant manufactured mixes with RAP (Mixes A, B, C, D, E & F) had a visible number of aggregates with binder traces on them after conditioning with the proposed procedure. Figures 5.9, 5.10, 5.11, 5.12 and 5.13 illustrate partial extraction residues from plant manufactured mixes containing RAP. It should also be noted that the RAP amount, RAP type, binder amount, binder type, aggregate type and gradation varied among these mixes. In beginning to develop a method to estimate RAP amounts by visual inspection, it was obvious that the amount needed to be adjusted for loss of finer aggregates as a result of washing over the #8 sieve.

Figure 5.6 Partial Extraction Residue of Virgin Mix-1 (No RAP)

Figure 5.7 Partial Extraction Residue of Virgin Mix-2 (No RAP)

Figure 5.8 Partial Extraction Residue of Virgin Mix-3 (No RAP)

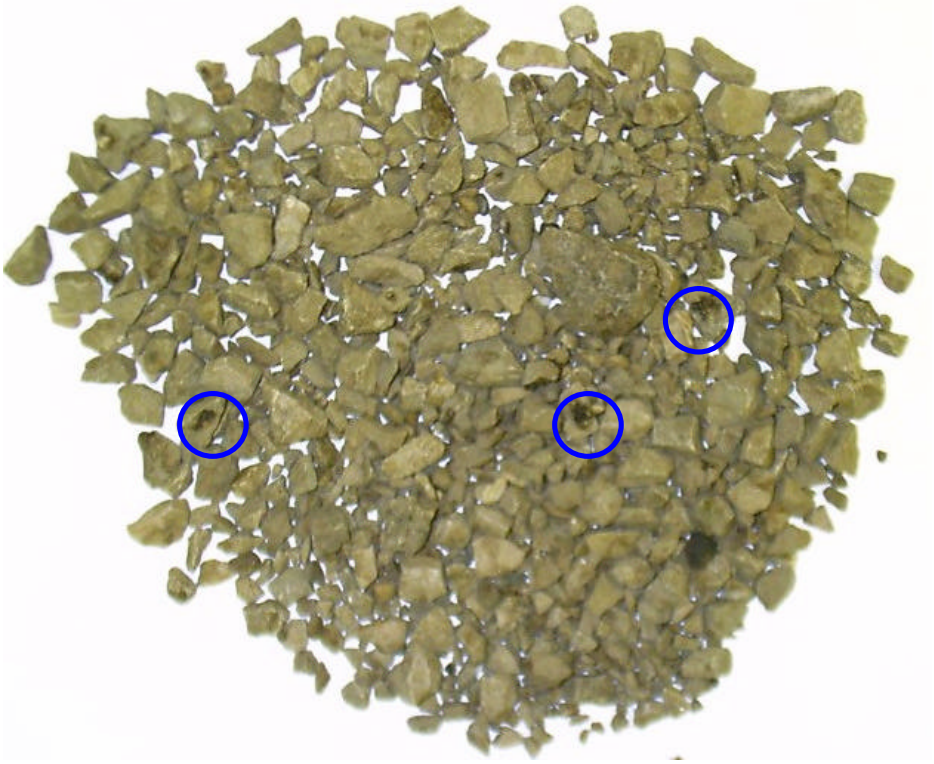

Figure 5.9 Partial Extraction Residue of Mix-A (12.4% RAP)

Figure 5.10 Partial Extraction Residue of Mix-B (29.5% RAP)

Figure 5.11 Partial Extraction Residue of Mix-D (29.3% RAP)

Figure 5.12 Partial Extraction Residue of Mix-E

Figure 5.13 Partial Extraction Residue of Mix-F

5.6 Proposed Partial Extraction Method:

The proposed method involves a two-step partial extraction of the candidate mixture. As a first step, about 400-gm of loose mix sample is soaked in 50% strength methylene chloride solvent for two hours in a glass or steel bowl. Enough solvent should be used to fully immerse the sample, which depends on shape of the bowl, but typically ranges from 400-600ml. Upon completion of the first stage, the mix should then be strained over the #8 sieve and washed using mineral spirits, taking care to limit exposure to mineral spirits to no more than 30-seconds. The mix is then soaked and washed using ethyl alcohol to make sure that all of the mineral spirit solvent is washed away. The final step is carried out by soaking and vigorously mixing the aggregates in 85% strength methylene chloride for one minute. Aggregates should then be strained over a #8 sieve and then washed with ethyl-alcohol. Prior to visual observation, aggregates should be placed in oven at 50^{o}C for drying. It is strongly recommended that this partial extraction procedure should be carried out in a certified fume hood and all related

safety measures be followed (use of solvent-resistant gloves, eye protection, avoidance of open flames, etc.).

5.7 Rigorous Partial Extraction Method:

The partial extraction method showed promising results for characterizing mixes containing RAP, therefore a more detailed study was carried out to determine if an approximate amount of RAP could also be determined. Inspection of most of the conditioned samples suggested that partially extracted aggregates exhibit a visual correlation with RAP amount. Accordingly, it was hypothesized that the comparison of these samples to samples having known RAP amounts might enable the approximate RAP amount to be determined. Because the procedure is much more involved and time-consuming, a detailed discussion of this procedure is deferred until the next chapter, along with descriptions of other rigorous test methods. The issue of RAP variability was also addressed for partial extraction technique, which will be described in the chapter on RAP variability (Chapter 7).

5.8 Development of the Partial Ignition Technique:

As discussed earlier, the partial ignition method was envisioned to create a controlled process where most of the virgin binder is removed by exposure to very high temperatures in the ignition oven (furnace), while traces of the RAP binder would leave a visible remnant on the RAP aggregates. Thus, in an ideal partial-ignition conditioning process, the mix containing only virgin materials should show no traces of binder on the aggregates, whereas the aggregates from the mix containing RAP should show traces of binder, preferably in proportion to the RAP amount.

For the purpose of achieving partial ignition, ignition oven equipment used for asphalt content determination was used. The ignition oven determines asphalt content of the mix by calculating the difference in the weight before and after ignition. The ignition oven supplies heat to the sample when ever the temperature in the chamber drops below set point temperature (typically 482^{o}C).

Ignition ovens are programmed to continue the process until the weight of the sample stabilizes. For determining optimum time of ignition to achieve targeted partial ignition, various trials were carried out using a plant manufactured mix, specifically Mix-C (the Peoria surface mix).

A Thermolyne ignition furnace available at the University of Illinois' ATREL facility was used and the ASTM D4125 test procedure for determining asphalt content of bituminous mixtures was followed. The only variation to the test procedure used was in limiting the time duration for which the mix sample was placed in the ignition oven. Since a factor affecting the rate of ignition is the weight of sample placed in the oven, a fixed sample weight of 1000-grams was used.

Asphalt mixes used in this procedure were broken down to particles of 25-mm or smaller prior to testing. Since the ignition oven is highly insulated and thus maintains high chamber temperatures for long periods after it is turned off, the samples were removed from the oven and allowed to cool in an operational fume hood. Once the partially ignited aggregates were cool enough to handle, they were placed in a Plugge aggregate washer and washed over an ASTM #8 sieve (2.36-mm opening) with tap water.

Figures 5.14 and 5.15 show the partially ignited virgin and RAP aggregates from Mix-C samples. At the initial stage of study it was assumed that the aggregates showing any trace of binder were RAP aggregates and aggregates with no binder trace were virgin aggregates; however, this was later determined to be an incorrect conclusion at times. Thus, further development of the partial ignition method was focused on determining presence or absence of RAP rather than as a tool for RAP quantification.

Figure 5.14 Portion of Mix-C Partial Ignition Residue without Binder Traces

Figure 5.15 Portion of Mix-C Partial Ignition Residue with Binder Traces

From numerous trials of partial ignition tests performed on Mix-C it was found that at 482^{o}C test temperature and 40-minute ignition time the mix gave reasonable results. The ratio of weight of aggregates with traces of binder on them to the total weight was found to agree reasonably well with the known RAP amount present in Mix-C.

5.9 Verification of Partial Ignition Procedure:

This section presents the evaluation of the aforementioned partial ignition procedure (developed using a single mix) with the other plant and lab manufactured mixes. The plant manufactured mixes Mix-A, Mix-B and lab manufactured mixes Virgin Mix-1 were initially tested using 482^{o}C chamber temperature and 40-minute ignition time setup. Some of the partially ignited aggregates from Mix-A and Mix-B showed traces of binder, where as Virgin Mix-1 aggregates showed no binder traces. In a repeatability trial, Mix-A showed no binder traces on aggregates and thus failed to show any presence of RAP. *Further Mix-D samples showed similar problems with the initially proposed procedure.* As a result, a modified procedure was developed where lower chamber temperatures were used in an attempt to establish better control over the rate of binder ignition. The results from the lower temperature partial ignition experimental trails are described in following section.

5.10 Low Temperature Partial Ignition:

The low temperature partial ignition trials were performed at chamber set point temperatures of 350^{o}C and 400^{o}C using primarily Mix-C samples. In the case of lower temperature conditioning, the oven was operated in the standard mode, e.g., the oven was run until the sample reached constant weight and terminated the conditioning process. At the 350^{o}C test temperature, the test continued for nearly 270-minutes without true ignition. The resulting residue resembles a highly aged asphalt mix rather than the standard aggregate residue normally obtained. At a 400^{o}C chamber temperature set point, the Mix-C aggregates showed traces of partially ignited binder and the test exhibited good

repeatability in terms of test time and appearance of the aggregates. Figure 5.16 shows the partially ignited aggregates of Mix-C conditioned at 400^{o}C. The lab manufactured virgin mixes, Mix-2 and Mix-3, were tested at 400^{o}C chamber temperature set point to further validate the results obtained on Mix-C. Unfortunately, the virgin mixes showed binder traces on partially ignited aggregates, and thus the low temperature partial ignition method did not appear to be promising (Figure 5.17).

Figure 5.16 Low Temperature Partial Ignition of Mix-C (400^{o}C)

Figure 5.17 Low Temperature Partial Ignition of Virgin Mix-2 (400^{o}C)

5.11 Findings and Recommendations:

Based upon various tests performed for development and verification of rapid RAP detection techniques, the experimental findings can be summarized as:

- The partial extraction method described in this chapter shows promising results for its use as a quick test for determining the presence of RAP in the mix.
- The two-step partial extraction method with 120-minutes of soaking in 50% methylene chloride and 1-minute soaking/mixing in 85% methylene chloride is the most promising method among all experimental trials.
- The partial extraction method also appears to be a promising quality assurance tool for RAP amount determination. Further testing was carried out to explore this possibility, as described in the next chapter.

- The concept of partial ignition oven testing does not appear to be a promising method for RAP detection or quantification. The technique would require calibration for each mix, since the ideal chamber temperature and ignition duration appears to be highly mix-dependent. Additionally, partial ignition tests did not exhibit good repeatability. It is suspected that the relative lack of temperature control in the oven, which was developed to simply burn off all of the asphalt, led to the variability observed.
- It may be possible to modify the controls on the ignition oven so that a more controlled ignition process could be obtained. Such modifications might enable RAP detection and quantification procedures to be developed in the future.

6. Rigorous Methods for Estimating Amount of RAP

6.1 Introduction:

This chapter provides a detailed presentation of the development of rigorous methods for estimating the amount of RAP in plant samples and field cores of asphalt concrete. As described earlier, rigorous methods involve more time-consuming tests and procedures, with the goal of producing more accurate and precise estimates of RAP amount. The use of binder physical properties such as complex shear modulus (G*) or viscosity on recovered binders from RAP mixes as a means to detect RAP presence and amount was found to be a promising technique based upon preliminary tests conducted early in this study.

During the course of the study, various tests were performed to develop and calibrate a method that could be used to determine RAP amount on the basis of binder complex modulus (G*). Viscosity measurements, while convenient, did not appear to be as reliable as DSR measurements of G* at high in-service pavement temperatures (typically at the Superpave Performance Graded (PG) binder high temperature grade, such as 64 ^{o}C). Low temperature testing with the Bending Beam Rheometer was originally considered as another option, since the device relates to low-temperature cracking, which could be a significant distress observed in mixtures with excessive RAP. However, due to the additional asphalt processing (long-term aging) and testing requirements (larger samples), it was felt that the DSR test was the most practical option. The calibration study for determining an appropriate aging methodology was discussed in Chapter 4. Discussions on the use of the partial extraction procedure for estimating RAP amount will be addressed later in this chapter.

6.2 Background of Complex Modulus Method:

During the life of a pavement, the asphalt binder within an asphalt mixture tends to stiffen with time due to oxidation. The NCHRP 9-12 (McDaniel and Anderson, 1997) project and other studies such as one by Lee et al (1999)

illustrated increasing stiffening of binders and mixtures with increasing RAP amounts. For the purpose of this study complex shear modulus or simply complex modulus (G*) was used as a parameter for RAP detection. Some preliminary tests showed that the viscosity of binder at 135^{o}C, while simpler to measure, did not satisfactorily correlate with RAP amount.

As discussed in previous chapters, this method requires performing extraction and recovery of binder from the asphalt mixture in question and the RAP material used in the mixture. All extraction and recoveries were performed as per AASHTO T319 test procedures. The setup was available at University of Illinois' ATREL testing facility. For verification of the extraction-recovery procedure several blind samples were run through the equipment. The results indicated that original and recovered binders showed very little difference, as tabulated in *Appendix C*. Binder testing for the determination of complex modulus was performed using the Dynamic Shear Rheometer (DSR). A newly purchased specification grade device by Bohlin Instruments (DSR-II) was available at University of Illinois' Asphalt testing lab. This model is capable of testing wide range of binder stiffness and at various temperature ranges. For this study it was decided that all complex modulus tests should be performed at the Superpave high temperature grade of the design asphalt binder. Superpave binder specifications suggest testing of binder at high temperature grade to be performed with 25-mm diameter plates and 1-mm gap setting. While most virgin binders and binder blends tests were performed with the Superpave settings, in the case of stiff RAP binders, gap settings up to 2.5-mm were used to achieve the target strain rate according to binder stiffness. It was assumed that the Bohlin rheometer would be capable of producing reasonably accurate results without recalibration at this gap setting. However, this assumption should be validated before adopting this method as a standard practice.

6.3 RAP Detection Method Based on Complex Modulus Testing:

For the goal of RAP detection this method requires binder complex modulus values for the virgin binder (subjected first to short-term oven aging

(RTFO)), binder recovered from the mix in question, and binder recovered from a RAP stockpile sample. It should be noted that the virgin binder is subjected to the rolling thin film oven test to simulate short-term aging during asphalt production and laydown. Since the RAP binder has generally undergone long term field aging, the recovered RAP binder shows very high complex modulus relative to the short-term aged virgin binder. If RAP is present in the mix, the recovered binder from the mix will be a blend of RAP and tank binders. Thus, the presence of RAP will significantly increase the complex modulus of the recovered binder from the plant-produced RAP mixture as compared to tank binder. Conversely, if the complex modulus values for tank binder (RTFO aged) and recovered mix binder are identical or very close, this would indicate that little or no RAP was incorporated into the mix.

If the trend followed by variation of complex modulus with increasing RAP binder could be predicted, then the complex modulus of the recovered as-produced mix binder could be used to backcalculate the RAP amount in the mixture. The example first presented in Chapter 4 (Section 4.4.6) will now be revisited and expanded upon. For convenience, the example is presented again as Figure 6.1.

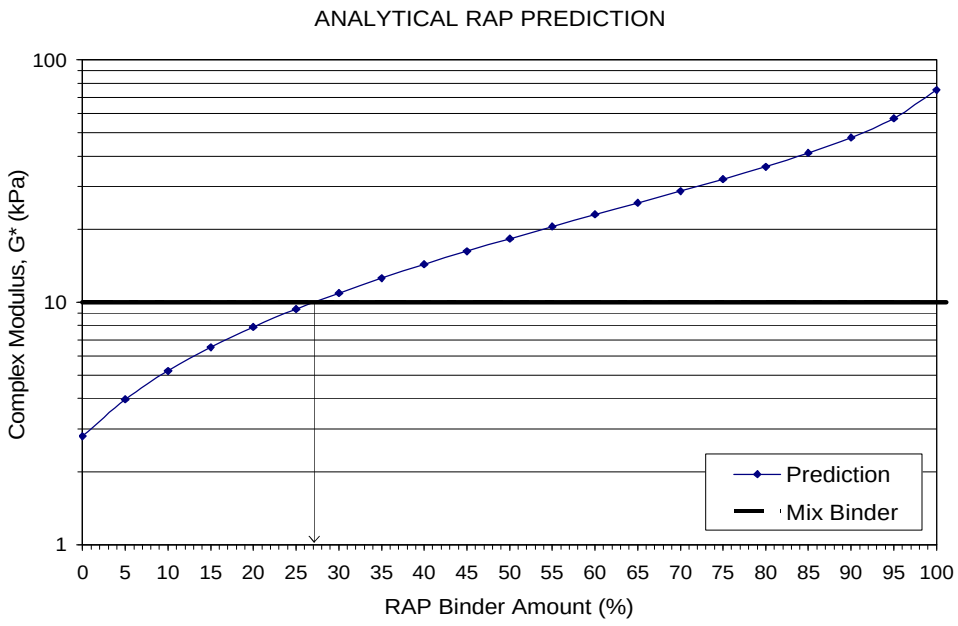

Figure 6.1 RAP Amount Prediction Example

It should be noted that the RAP amount predicted in the above example is the amount of RAP binder in terms of the total binder. To determine the actual RAP amount in a mix, a correction must be applied. The correction factor should first be calculated using the following relationship:

$$c = \frac{AC_{mix}}{AC_{RAP}}$$

Where,

c = Correction Factor

AC_{mix} = Asphalt Content of Mix

AC_{RAP} = Asphalt Content of RAP

The actual RAP amount in the mix can then be computed by multiplying the predicted RAP binder amount by c. Thus, in the case of the example of Figure 6.1, if the asphalt content of RAP was 5% and the asphalt content of the mix was 4%, then:

c = 4/5 = 0.8

*RAP Amount in Mix = 0.8*27% = 21.6%.*

The asphalt content of the mix and RAP can be found using one of several asphalt content determination techniques. Typically IDOT performs asphalt content tests on mix samples as a QC/QA practice using the ignition oven and therefore this quantity is typically readily available.

The trend followed by the variation of complex modulus with changing RAP amounts is very important to understand. In other words, a model is required to be developed for predicting complex modulus values at various RAP binder amounts when tank and RAP binder complex modulus is available as input. *Micromechanics* models have been extensively used to predict physical properties of composite materials using the physical properties of the individual materials. These models are similar to the simple proportionality approach given by “Law of Mixtures,” but are more rigorously derived from microstructural

models and are more accurate and/or more precise. The binder at intermediate RAP amounts is a blend of tank and RAP binders and thus with known complex modulus of tank and RAP binders complex moduli of blends can be experimentally determined. The next section provides more information on the selection of a micromechanics model that is capable of predicting a G* versus RAP amount trend that agrees with the lab results.

6.4 Selection of Appropriate Micromechanics Model:

Various micromechanics models that were evaluated include:

- Paul's Rule of Mixtures (Paul, 1960)
- Hashin's Arbitrary Phase Geometry Model (Hashin and Shtrikman, 1963)
- Hashin's Composite Sphere Model (Hashin, 1962)
- Christensen and Lo Generalized Self Consistent Scheme Model (Christensen and Lo, 1986)
- Mori-Tanaka Model (Mori and Tanaka, 1973)
- Hirsch Model (Hirsch, 1962)

Some of these models predict properties as a range in terms of lower and upper bound values, whereas other models are geared toward directly predicting the modulus. Due to their complicated nature, the prediction equations for these models are presented in *Appendix E.* Figure 6.2 provides sample predictions made by various models at intermediate RAP binder amounts. The tank binder G* was assumed as 2.5-kPa and RAP G* was assumed as 60-kPa.

The findings of the calibration study (Chapter 4) were important inputs for the selection of an appropriate micromechanics model. In Chapter 4 it was shown that complex modulus values for the binder blends produced by mixing prior to short term aging were quite close to the G* values measured on the actual binder samples recovered from the asphalt mixtures. Initially data sets from two different RAP materials were used. In both cases binder blends were prepared at 0%, 15%, 30%, 45% and 100% RAP binder concentrations. One data set consisted of measurements taken on binder blends of an unaged PG

64-22 virgin binder and a recovered I-57 RAP binder. The other data set was based upon measurements taken on RTFO-aged binder blends of PG 64-22 asphalt binder with the recovered RAP-C binder. The results for various I-57 and RAP-C binder blends are presented in Figure 6.3 and are tabulated in *Appendix C*. Figure 6.4 shows the results for I-57 RAP binder blends as predicted by various micromechanics models. The detailed data is tabulated in *Appendix D*.

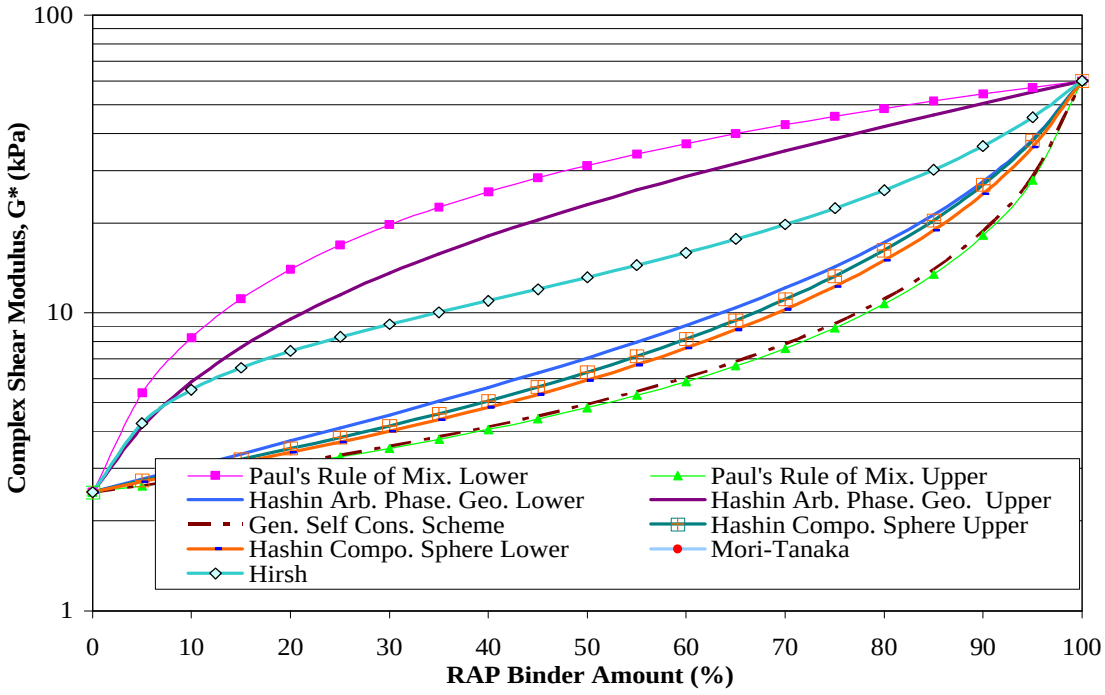

Figure 6.2 Graphical Representations of Predictions by Various Micromechanics Models

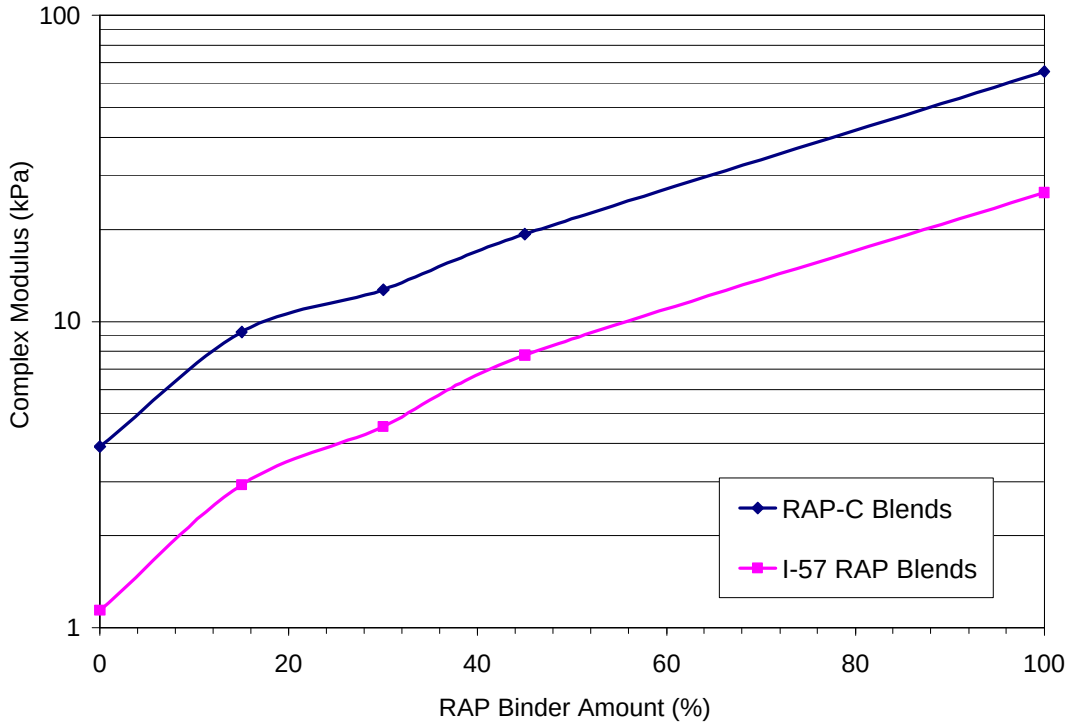

Figure 6.3 Results from RAP-C and I-57 RAP Binder Blends

The results for I-57 RAP blends show that lab results are within the upper and lower bounds on the possible moduli predicted by Paul's *Law of Mixtures*. The lab results also agree with bounds calculated by Hashin's arbitrary phase geometry model, which is known to be a theoretically sound improvement over the law of mixtures bounds (e.g., the bounds are closer and are exact). The composite spheres model, the generalized self consistent scheme model and the Mori-Tanaka model, which provide estimates of the blended binder shear modulus (as opposed to bounds), were all found to underpredict the test results significantly. The Hirsch model results shown above are for a parallel coefficient value of 0.75, hence the model considered 75% materials in parallel arrangement and 25% in series arrangement. With this configuration the model predicted values closest to lab results, but diverged from the results for RAP amounts greater than 50%.

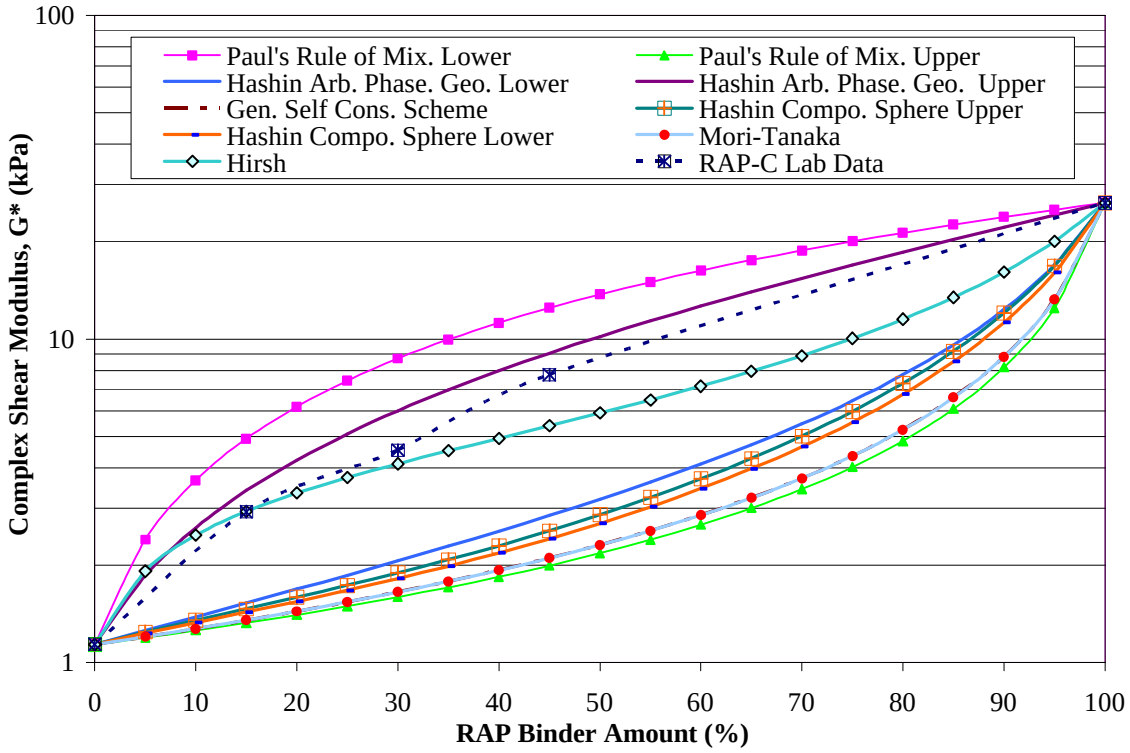

Figure 6.4 Predicted and Actual (from lab data) Complex Shear Modulus for Binder Blends of I-57 RAP

The results for other binder blends containing RAP-C binder are as shown in Figure 6.5, and detailed results have been tabulated in *Appendix D.* The results for the RAP-C binder blends also show similar trends as I-57 RAP results. The lab data is once again in agreement with bounds provided by Paul's *Law of Mixtures* and Hashin's arbitrary phase geometry model. In this case Hirsch model provides good correlation with lab data for RAP binder amounts of 30% or less, the parallel coefficient *x* was taken as 0.75 in this case also. It was observed that if the parallel coefficient was increased in order to make the model predict values closer to lab results at higher RAP amounts, then the values at lower RAP binder amounts were significantly over-predicted. The other models under-predicted the complex modulus (G^*) values once again. The preliminary conclusion was that none of the models, in their original, uncalibrated form, could sufficiently predict measured G* as a function of RAP amount. Since the Hirsch model did not show

promise when calibrated, it was decided to pursue calibration of the other models.

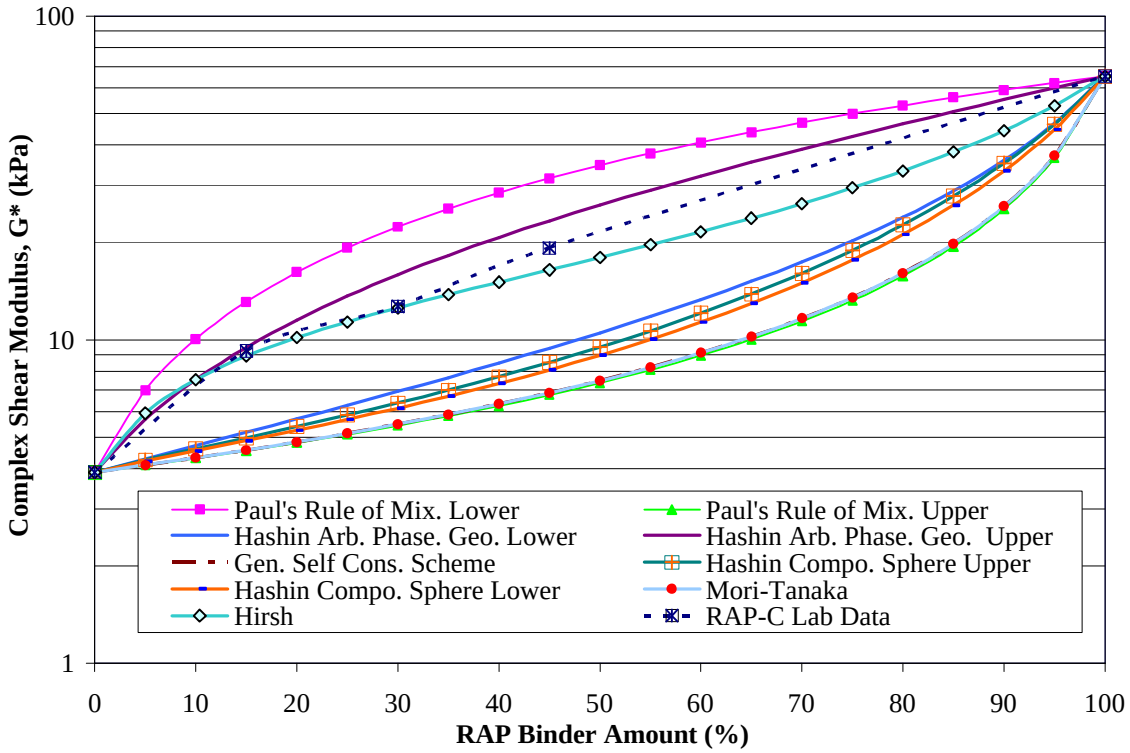

Figure 6.5 Predicted and Actual (from lab data) Complex Shear Modulus Values for Binder Blends of RAP-C

Based on the results presented above it can be seen that Hashin's Arbitrary Phase Geometry Model predictions are closest to lab results. Thus Hashin's Arbitrary Phase Geometry Model is a suitable candidate to be used for further investigation since it would require minimum amount of calibration. One of the other advantages of selecting Hashin's model is that it provides a bound for complex modulus and hence lends itself well to model calibration through interpolation between the theoretical bounds.

6.5 Calibration of Micromechanics Model:

Usually calibration is required when applying micromechanics models to all but the simplest materials, since these models are developed either for

specific microstructure or for accommodating a broad range of microstructural features. The calibration procedures also take care of the other factors causing variability such as aging due to handling of materials and chemical interaction between the binders. From the upper and lower bound values of Hashin's Arbitrary Phase Geometry (APG) model a unique value was proposed to be found using following relation:

$$G^* = G_l^* + \left(G_u^* - G_l^*\right)s$$

Where,

G^* = Predicted Complex Shear Modulus

G^*_l = Lower Bound Complex Shear Modulus as per Hashin's APG Model

G^*_u = Upper Bound Complex Shear Modulus as per Hashin's APG Model

s = Calibration Factor

The model shown above yields the lower bound on complex modulus when s = 0 and the upper bound complex modulus when s = 1 and essentially interpolates between the bounds for values of s between 0 and 1. The objective of the calibration process is to determine the best possible value of the calibration factor, s. It should be noted that the model presented above is the final form for predicting intermediate complex modulus values, the development of model was a continuous process throughout the study and thus some of the results shown and presented in RAP variability chapter show slightly different trends. Preliminary models were based entirely on the results obtained from RAP-C and I-57 RAP binder blend data sets.

The calibration procedure was carried out by use of different data sets from laboratory testing of various binder blends and binders recovered from asphalt mixtures. Two of the binder blend data sets from Lee, et al. (1999) were also utilized for calibration. Table 6.1 shows information on the various data sets used:

Table 6.1 Information on Calibration Datasets

Data Set	Type	Project/Material
1	Binder Blend	AC-20 Plant C (Lee et al)
2	Binder Blend	AC-20 Plant L (Lee et al)
3	Binder Blend	RAP-C
4	Binder Blend	I-57 RAP
5	Asphalt Mix	Mix-A
6	Asphalt Mix	Mix-B
7	Asphalt Mix	Mix-C
8	Asphalt Mix	Mix-D
9	Binder Blends	RAP-E
10	Binder Blends	RAP-F
11	Asphalt Mix	Mix-E
12	Asphalt Mix	Mix-F
13	Field Core	Mix-E Core
14	Field Core	Mix-F Core

Detailed data for all of the above data sets are presented in *Appendix C.* Determination of a suitable calibration factor for each of the above data sets was carried out by trying to best fit the prediction with laboratory data. Best fitting was carried out manually by trial and error. While carrying out the fitting procedure data in range of 0 to 40% RAP amounts was given more importance as compared to other ranges of RAP amounts. A Microsoft Excel spreadsheet program with visual basic application program was used for performing calibrations. Figure 6.6 shows the predictions for RAP-F Binder blends with calibration factor, s = 0.39. The calibrated model appears to fit extremely well in this case, although the data point (measured value) at the very high RAP concentration of 65% appears to be an outlier. The calibration factors for various data sets are presented in Table 6.2, while detailed prediction results for each dataset is presented in *Appendix D:*

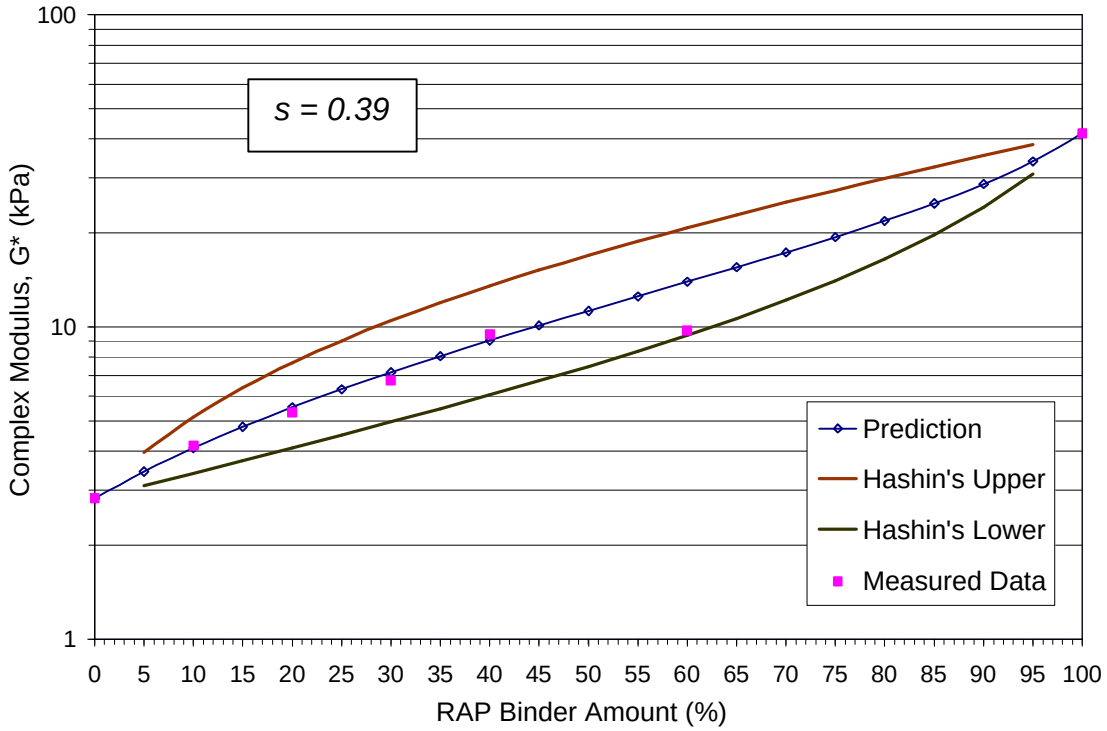

Figure 6.6 Predicted and Lab Results for RAP-F Binder Blends

Table 6.2 Calibration Factors for Various Datasets

Data Set	Calibration Factor, *s*	RAP G* (kPa)
1	0.20	40
2	0.07	100
3	0.70	26.36
4	0.78	65.4
5	0.78	15.92
6	-1.10	15.92
7	1.13	68.79
8	0.50	45.84
9	0.31	95.05
10	0.39	41.76
11	0.11	95.05
12	0.90	41.76
13	0.45	95.05
14	1.30	41.76

For the available datasets, the average calibration factor was found to be 0.47, with standard deviation of 0.58. The maximum and minimum values ranged from 1.1 to -1.3. The wide scatter in the value of the calibration factor seems to suggest an extreme variation in chemical interactions between RAP and virgin binders upon blending and aging. The average value of 0.47 shows that method is promising since it essentially means that on an average binder blends lie in middle of upper and lower bound predictions.

Figure 6.7 shows various calibration factors plotted against RAP binder complex modulus values. This figure also shows an exponential function fitted through data-points lying within the Hashin's upper and lower bounds as an example. It should be noted that the example shown in Figure 6.7 is just for purpose of illustrating one of many ways to come up with a function for the calibration factor. If with sufficient data a typical trend is seen for calibration factor and a known quantity (such as RAP binder G* in this example), this type of approach could be developed for predicting a variable calibration factors, which would enhance the predictive accuracy of the approach.

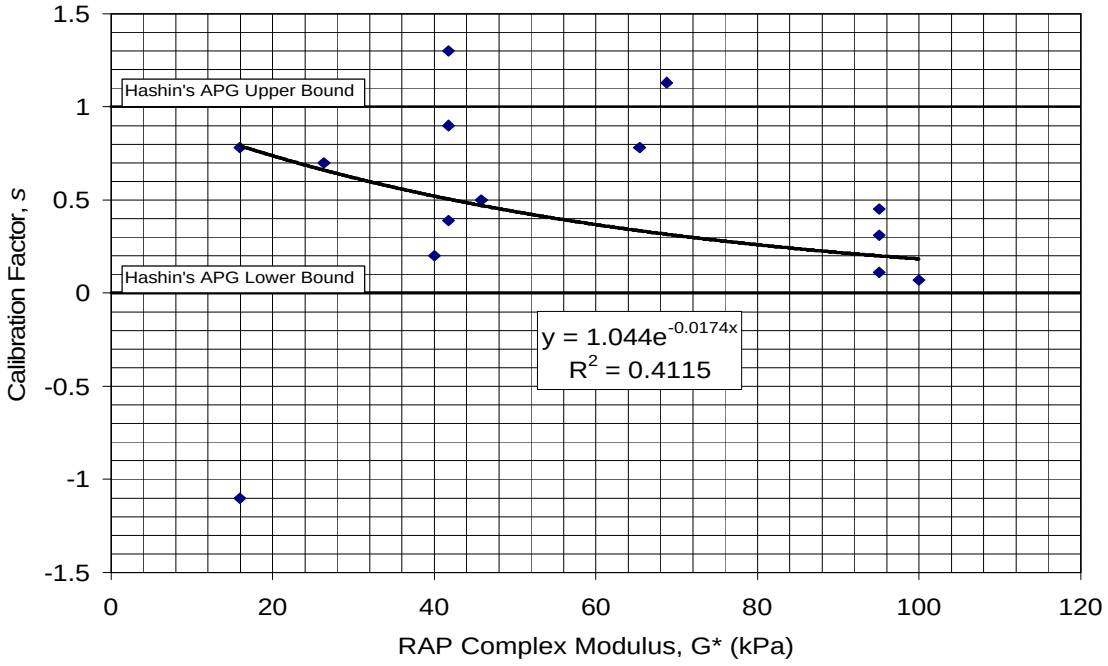

Figure 6.7 Example Illustrating Method for Predicting Calibration Function

Based upon the results of this portion of the study, the following conclusions can be drawn:

1. The prediction method developed can be used in a procedure to estimate the amount of RAP in a given mixture sample.
2. Because a universally calibrated model has not yet been identified, the model will need to be calibrated to each individual mixture to obtain the most accurate results. Thus, samples of the RAP mixture, virgin binder, and virgin aggregates would be needed to produce the most accurate RAP amount prediction.
3. Predictions made using this model without measurements of RAP binder G* and/or virgin binder G* would be more approximate. More work is needed to assess the additional variability introduced in predicting RAP amounts in this manner.

6.6 RAP Detection Method Based on Partial Extraction:

The partial extraction method for identifying the presence of RAP discussed in Chapter 5 (section 5.4) appeared to be a promising method for determining the approximate amount of RAP in a mix. The method described here requires producing comparison or training samples of mix containing different known amounts of RAP. One of the advantages of this method is that it does not require very sophisticated tests and analyses. It is, however, more cumbersome then the RAP identification procedure presented in Chapter 5.

The development of a procedure for predicting RAP amount was based upon the procedure for detecting the presence of RAP. The hypothesis developed was that increasing RAP amount leads to higher number of aggregates showing binder traces and amount of binder sticking to aggregates after partial extraction. To develop this procedure, two sets of lab manufactured asphalt mixes were used. Both the mix sets, Mix-LA and Mix-LB were produced with different binder grades, aggregate gradations, binder amounts and RAP types. For each of the sets, four different training samples were produced with

0%, 15%, 30% and 100% RAP amounts. The tank binder amounts were adjusted and reduced according to the RAP amounts. Best results were obtained when the 100% RAP mixes were also conditioned, that is, they were heated to mixing temperature and bucket mixed in a similar manner as the RAP/virgin mixtures. One mix sample for each of the sets was produced to simulate a mix with unknown RAP amount, in order to evaluate the visually-based procedure using a panel of evaluators. The unknown RAP mix for Mix-LA was produced using 22.5% RAP and the one for Mix-LB was produced with 12.5% RAP.

All the comparison and unknown RAP mixes were partially extracted as per the procedure described in Chapter 5. Figures 6.8 through 6.11 show pictures of training samples for Mix-LA and Figure 6.12 shows a picture of the partially extracted Mix-LA “candidate” sample, for which the RAP amount is to be determined. Similarly, Figures 6.13 through 6.16 show pictures of training samples for Mix-LB and Figure 6.17 shows a picture of the partially extracted Mix-LB candidate sample.

Figure 6.8 Partial Extraction Residue of Mix-LA (0% RAP) Comparison Sample

Figure 6.9 Partial Extraction Residue of Mix-LA (15% RAP) Comparison Sample

Figure 6.10 Partial Extraction Residue of Mix-LA (30% RAP) Comparison Sample

Figure 6.11 Partial Extraction Residue of Mix-LA (100% RAP) Comparison Sample

Figure 6.12 Partial Extraction Residue of Mix-LA Candidate RAP Sample (22.5% RAP)

Figure 6.13 Partial Extraction Residue of Mix-LB (0% RAP) Comparison Sample

Figure 6.14 Partial Extraction Residue of Mix-LB (15% RAP) Comparison Sample

Figure 6.15 Partial Extraction Residue of Mix-LB (30% RAP) Comparison Sample

Figure 6.16 Partial Extraction Residue of Mix-LB (100% RAP) Comparison Sample

Figure 6.17 Partial Extraction Residue of Mix-LB Candidate RAP Sample (12.5% RAP)

Two faculty members at University of Illinois volunteered to participate in determining RAP amounts for the candidate mixes. They were provided with training samples and unknown RAP samples. Based upon the promising results (first two entries in Table 6.3), a similar exercise was also carried out at one of the quarterly meetings with project's technical review panel. These results were also very promising, as shown in the remainder of Table 6.3.

Table 6.3 RAP Amount Predictions by Partial Extraction Technique

ID	Mix-LA	Error, Mix-LA	Mix-LB	Error, Mix-LB
WGB-1	25.0%	2.5%	12.0%	-0.5%
MRT-1	25.0%	2.5%	10.0%	-2.5%
42	20.0%	-2.5%	10.0%	-2.5%
66	20.0%	-2.5%	10.0%	-2.5%
8	25.0%	2.5%	20.0%	7.5%
0	20.0%	-2.5%	10.0%	-2.5%
73	20.0%	-2.5%	10.0%	-2.5%
xxx	25.0%	2.5%	13.0%	0.5%
18	23.0%	0.5%	11.0%	-1.5%
Actual	**22.5%**	**--**	**12.5%**	**--**
Average	**22.6%**	**0.1%**	**11.9%**	**-0.7%**
Standard Deviation	**2.4%**	**2.5%**	**3.1%**	**3.3%**

Presumably, the accuracy of this method could be further improved by using a greater number of comparison samples. In the case where an approximate amount of RAP is known, the comparison samples could be prepared with the different RAP amounts concentrated in that range. For example, if the field test presented in the previous chapter shows that the mix contains RAP and it seems to be in range of 15% to 45%, comparison samples with 0%, 15%, 25%, 35%, 45% and 100% RAP amounts could be prepared.

Partial extractions for Mix-E and Mix-F samples were also carried out. In the case of those samples the field cores as well as plant mix samples were available. Prior to carrying out partial extraction, the field core samples were heated to 135^{o}C and were broken by hand into loose mix. In the case of Mix-E and Mix-F, comparison samples were prepared only for 0% and 100% RAP amounts. The 0% RAP mixes did not show any traces of binder on the aggregates, which further validated that the partial extraction method does in fact reliably remove virgin binder traces. The 0% comparison samples were produced

using the same aggregates, binder content and binder type as the plant mixes. In these trials, a different method for preparing 100% RAP samples was sought. The desire to develop a different method was due to the fact that many times the RAP sample has most of its binder in the form of a mastic powder (stripped film of binder and fines) and, hence the coarse aggregates are very clean with no little or no binder attached. This could be caused due to mechanical forces and grinding which occur during initial removal of the RAP using a rotomill, the processing of the RAP in a crusher, and/or just a characteristic of a particular RAP material. The problem with the previous method of preparing the sample is that during the process of mixing, most of the mastic forms lumps instead of forming a homogeneous film over the aggregates. The RAP material used in Mix-E and Mix-F both had the characteristic of clean RAP aggregates (no binder coating on them). Various trials with different mixing procedures and temperatures were performed to address this problem, including some trials performed by compacting the heated RAP material in the Superpave gyratory compactor. The samples prepared by compacting RAP material in the gyratory compactor and then breaking down the compacted specimens by hand showed promising results. The compacted specimens were allowed to completely cool down and then were reheated to the compaction temperature for separation into loose mix. It is interesting to note that when the compacted specimen was not allowed to cool down, the results were not as favorable.

Figures 6.18 and 6.19 show pictures of 0% and 100% RAP comparison samples for Mix-E, while Figures 6.20 and 6.21 show partial extraction residues for the plant manufactured Mix-E and the Mix-E field cores. Figures 6.22 and 6.23 show training samples for Mix-F and Figures 6.24 and 6.25 show partial extraction residues for the plant manufactured Mix-F and the Mix-F field cores. The partial extraction residue for Mix-E and Mix-F agree well with the RAP amounts of 20% for Mix-E and 10% for Mix-F. It was reassuring to observe that the partially extracted specimens for field cores and plant mixes looked very similar and thus it appears that the partial extraction method is both a reliable and versatile RAP quantification method.

Figure 6.18 Partial Extraction Residue of Mix-E (0% RAP) Comparison Sample

Figure 6.19 Partial Extraction Residue of Mix-E (100% RAP) Comparison Sample

Figure 6.20 Partial Extraction Residue of Mix-E (Plant Mix) Sample (20% RAP)

Figure 6.21 Partial Extraction Residue of Mix-E (Field Core) Sample (20% RAP)

Figure 6.22 Partial Extraction Residue of Mix-F (0% RAP) Comparison Sample

Figure 6.23 Partial Extraction Residue of Mix-F (100% RAP) Comparison Sample

Figure 6.24 Partial Extraction Residue of Mix-F (Plant Mix) Sample (10% RAP)

Figure 6.25 Partial Extraction Residue of Mix-F (Field Core) Sample (10% RAP)

6.7 Findings and Recommendations:

Based upon the tests and analyses performed for the development, calibration and verification of different rigorous RAP detection methods, the following findings were made:

- Significant stiffening of asphalt binder with increasing RAP amounts was seen for all the mixes containing RAP, as expected.
- The most suitable micromechanics model for predicting complex modulus values at intermediate RAP levels based upon tank and RAP binder complex moduli and RAP amount was found to be an adaptation of Hashin's arbitrary phase geometry model, which involves a calibration factor to interpolate between lower and upper bound estimates.
- Calibration of this model with the available data sets showed relatively high variability in the calibration coefficient. This appears to suggest that different chemical interactions are occurring during blending and aging of the diverse array of materials investigated in this study. This also suggests that predictions using this method would be most accurate if samples of virgin binder and RAP were available, so that a specific calibration coefficient could be obtained for the given materials prior to making RAP predictions.
- The partial extraction method using comparison samples showed very promising results for predicting RAP amounts.
- The partial extraction method yielded similar accuracy in RAP amount predictions for plant mixes and field cores.
- A single procedure for producing comparison samples with 100% RAP was not firmly established. Two procedures were developed: one for samples of RAP with binder adhering to the aggregates, and a second procedure for samples of RAP with relatively clean aggregates. More work is needed to work towards a single procedure suitable for all RAP types.

7. RAP Variability and Effect of Field Aging

7.1 Introduction:

This chapter presents the testing performed to evaluate the variability of physical properties of binder recovered from RAP from different sources across Illinois. Complex moduli of recovered RAP stockpile and RAP mix binders are required for predicting RAP amount when using the method based on physical properties of the recovered binder. It is important to estimate the potential variability of RAP binder properties within a stockpile and the effect of this variability on RAP prediction accuracy, since many times conglomerate stockpiling of the RAP is performed. As a result, mix produced at a typical hot-mix plant might utilize significantly different RAP material during the course of a single project. The effect of RAP variability on the partial extraction method was also evaluated, and is presented in this chapter. Also included is an analysis to quantify the effect of field aging on RAP prediction accuracy.

7.2 Approach of Evaluating the Variability of RAP within a Stockpile:

The overall goal in assessing RAP variability was to develop an estimate of RAP variability within given stockpiles, so that these variabilities could be used to estimate effects of stockpile variability on RAP amount prediction accuracy. However, the ability to take multiple samples and measurements from different points within a stockpile and to repeat this process for multiple stockpiles was beyond the scope of this study. Instead, the approach taken was to sample a number of different RAP stockpiles from across the State of Illinois and to assume as a worst-case scenario that a highly conglomerated stockpile could potentially consist of a range of RAP materials similar to those found when sampling multiple stockpiles across Illinois. Obviously, if the prediction method was found to produce acceptable results for this worst-case scenario, then it would be expected to produce even more accurate results for more homogeneous stockpiles.

Table 7.1 shows information regarding the RAP samples that were used in the RAP variability study. Figure 7.1 shows the approximate location of RAP sources. Locations 1 through 11 represent the RAP samples that were specifically collected for the RAP variability study, whereas the other locations (12 through 16) represent the RAP samples that were available from earlier sampling efforts conducted in this study.

Table 7.1 Details of RAP Variability Samples

Sample Name	RAP ID	Description (Contractor-Location-Source)
RAP 1	1	(SHC - Litchfield - I-55)
RAP 2	2	(Howell - Greenup - I-70)
RAP 3	3	(SIA - Mt. Vernon - I-57)
RAP 4	4	(Cullinan - Hopedale - I-155)
RAP 5	5	(Tickle - Rock Island - I-280)
RAP 6	6	(D Const - Morris - IL 47)
RAP 7	7	(Propheter - Annawan - I-80)
RAP 8	8	(Rowe - Griggsville - I-72)
RAP 9	9	(Simonds - Anna - IL-146)
RAP 10	10	(Gallagher-Thornton-Rt-53)
RAP 11	11	(Maclair - State Park - Conglomerate)
I-57 RAP	12	(University Const-Urbana-I-57)
Paxton Rd	13	(University Const-Urbana-Pax. Rd)
RAP A/B	14	(ASAP-Lebanon-Unknown)
RAP C	15	(Cullinan-Peoria-Unknown)
RAP D	16	(Cullinan-Peoria-Unknown)

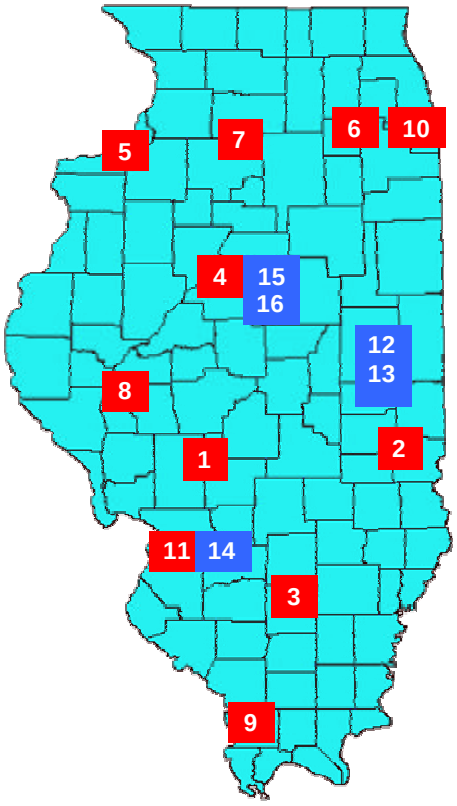

Figure 7.1 RAP Stockpile Sampling Locations across the State of Illinois

7.3 Testing and Results from RAP Variability Study:

The extraction and recovery procedures were performed on all 11 RAP samples obtained from various locations in Illinois. Extraction and recoveries were performed as per the AASHTO 319 test procedure. The recovered binders were tested to determine their complex shear modulus using the DSR test. The DSR testing was carried out at 64^{o}C and 10% strain amplitude and 25-mm sized plates were used with a 2-mm gap setting. The gap setting of 2-mm was selected since past experience showed that for stiffer RAP binders, the equipment was not able to attain the recommended strain amplitude with 1-mm gap settings. It should be noted that the DSR used in this study is run through a computer by means of software provided by Bohlin. The software has capability of considering the actual gap as input and further taking it into consideration when performing calculations. Three test replicates were tested for each binder sample.

The average complex shear modulus values for each of the eleven RAP variability samples and the other five RAP samples are plotted in Figure 7.2. Detailed test results are tabulated in *Appendix C. In general, the range of RAP G* values obtained were remarkably high, with minimum and maximum values of around 6 and 94 kPa, respectively*. This is probably due to a number of contributing factors, including: age of pavement at time of milling, duration of RAP in stockpile, binder grade(s) in RAP, thickness of milling (RAP near surface is extremely aged, whereas RAP taken at several inches below surface may not be), in-place density of pavement, location within Illinois (which spans approximately 400 miles from north to south), etc.

The average complex shear modulus, G* for all RAP sources was 33.5 kPa with a standard deviation of 26.4-kPa. Hence, the complex shear modulus range for one standard deviation interval (Average ± Standard Deviation) comes out to be 7.1-kPa to 59.8-kPa. One standard deviation interval usually corresponds to about 67% confidence interval, that is about 67% of the random samples should lie within that range.

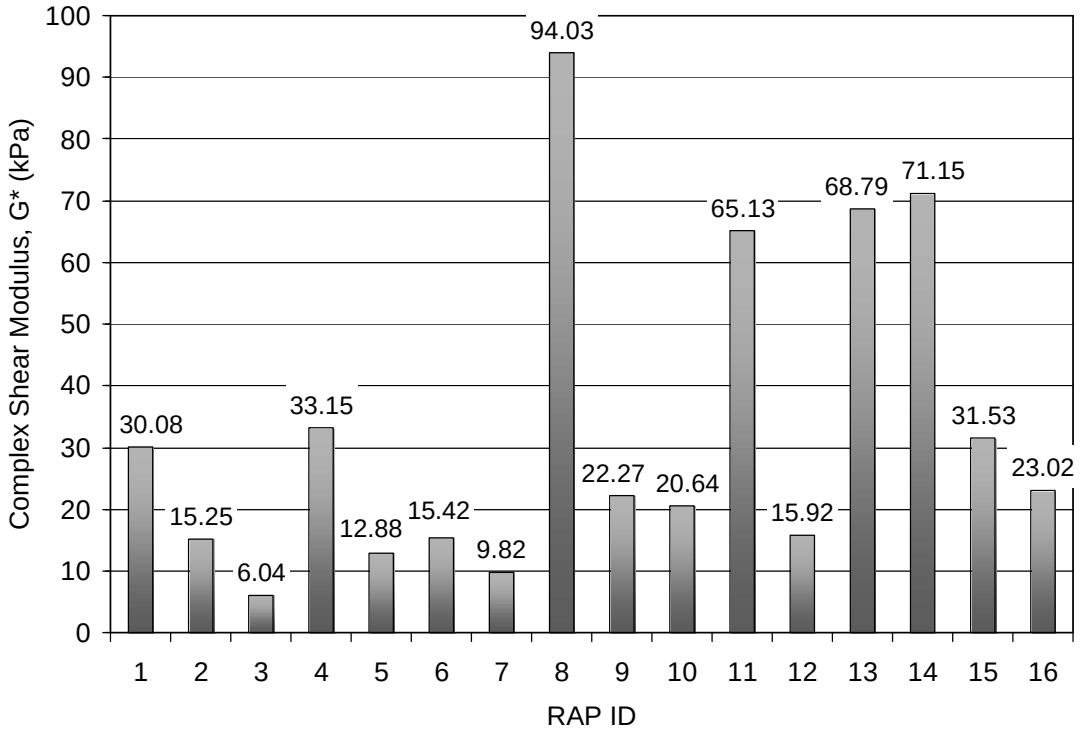

Figure 7.2 Range in RAP G* Values within Illinois

7.4 Analysis of Results from RAP Variability Study:

The complex shear modulus values of the *variability study* samples combined with the samples previously collected and tested in this study were used to assess how variability in RAP G* values would impact the ability to back-calculate RAP amount. For instance, by reviewing the graphical back-calculation method (Figure 6.1), it is clear that uncertainty in the RAP G* value (the right end point of the curve plotted on the right vertical axis) will cause uncertainty in the RAP G* prediction. Using the measured values from the RAP variability study, the magnitude of these prediction uncertainties will now be quantified through a series of numerical examples. For the purpose of these examples, a very typical RTFO-aged virgin binder complex shear modulus value of 2.5-kPa was selected (Superpave PG binder specifications requires a minimum value of 2.0 kPa). Two analysis scenarios are now presented:

- Full range of RAP variability – As a worst-case scenario, minimum and maximum values for RAP G* found in the study were used to establish an upper bound on the prediction variability possible for a conglomerate stockpile with unknown RAP G* values.
- Grouped ranges of RAP variability – Because RAP G* values appeared to have some relationship with IDOT District, a second analysis was run using grouped G* values.

7.4.1 Prediction Variability using Full Range of RAP Variability

Using the first analysis scenario, curves of complex shear modulus versus RAP amount were generated using the micromechanics approach presented in Chapter 6 for all RAP samples tested in the study, as presented in Figure 7.3. Detailed data is tabulated in Appendix D.

Figure 7.3 indicates that for a stockpile consisting of RAP from the low and high extremes of the 16 sources tested in this study, this could lead to a maximum variability of +/-35% in RAP amount prediction.

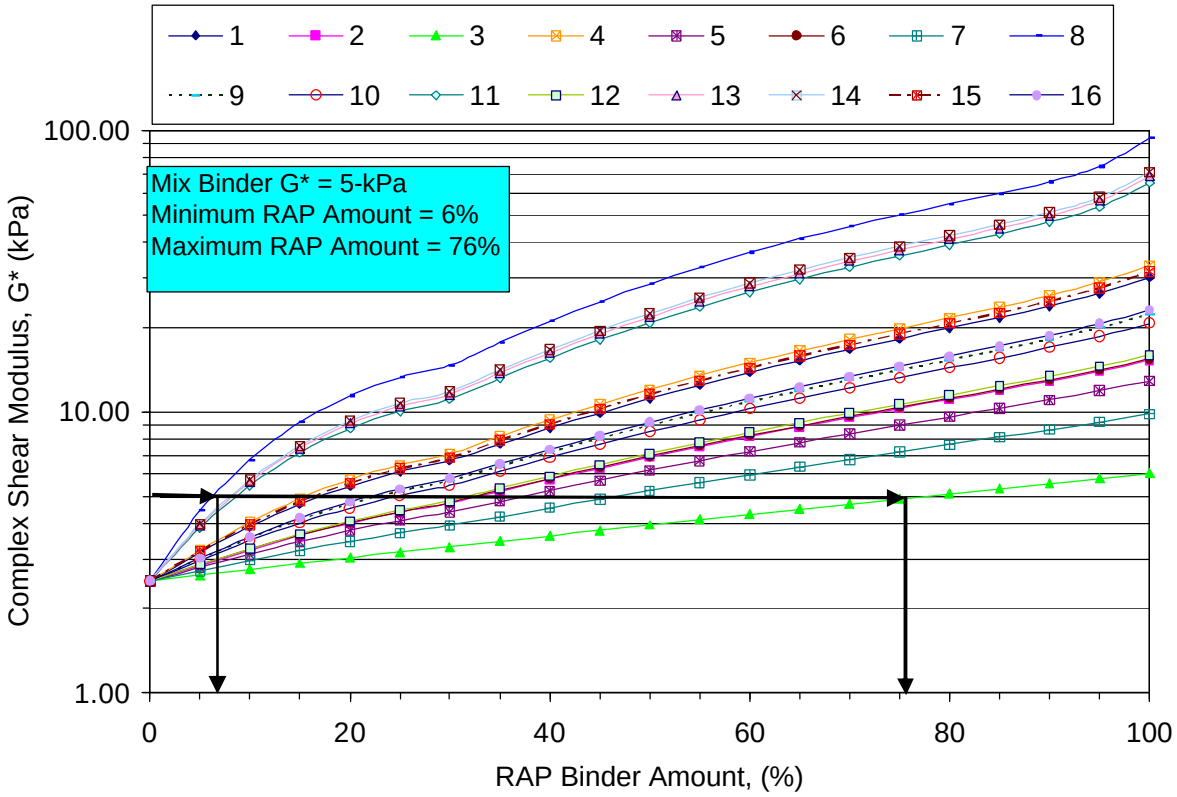

Figure 7.3 Prediction Range for RAP Amount for RAP from All Sources

7.4.2 Prediction Variability using Grouped Ranges of RAP Variability

In most practical cases, the RAP materials with such extreme properties would not be expected to be stockpiled together due to some of the regionality associated with RAP composition. This is based on climatic difference between various geographic locations and respective traffic trends. For example typical binder grades used in Northern Illinois are softer then those in Southern Illinois. Furthermore, it is highly likely that the varied source materials within a conglomerate stockpile would experience some mixing during stockpile formation, manipulation during storage, manipulation during mix production (front loaded, cold bins, plant mixing, truck loading and unloading, remixing on site, etc.). This mixing would statistically move values away from the extremes and more towards the average.

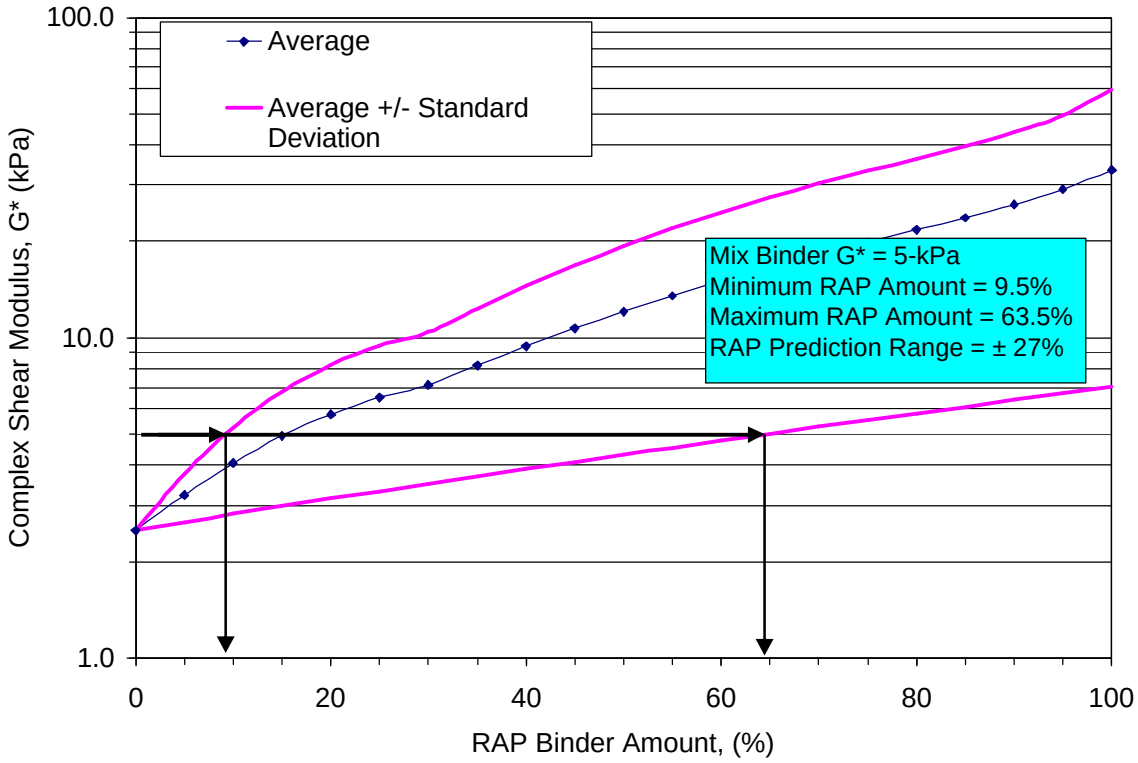

Figure 7.4 Predictions of G^* for One Standard Deviation Interval (67% Confidence Interval)

By examining the complex modulus values from the eleven RAP sources a trend was observed. The RAP obtained from northern Illinois and/or from lower volume routes tended to have lower complex modulus values. Conversely, the two RAP sources from southern Illinois that were reclaimed from high volume roads had the two greatest moduli values. Another method used to estimate the effect of RAP variability was to divide the RAP binders into two different groupings based upon their complex shear modulus values. If we divide the data into two groups one with a RAP $G^* < 35$-kPa and the other with a $G^* > 35$-kPa, then the 67% confidence intervals obtained are as shown in Table 7.2 and are plotted in Figure 7.4. Detailed data for this analysis has been tabulated in Appendix D.

Table 7.2 Average and Standard Deviation Intervals for Grouped RAP Data

For G^* < 35-kPa		For G^* > 35-kPa	
Average =	19.7-kPa	Average =	74.8-kPa
Standard Deviation =	8.7-kPa	Standard Deviation =	13.1-kPa
Ave. + Std. Dev. =	28.4-kPa	Ave. + Std. Dev. =	87.9-kPa
Ave. – Std. Dev. =	11.0-kPa	Ave. – Std. Dev. =	61.7-kPa

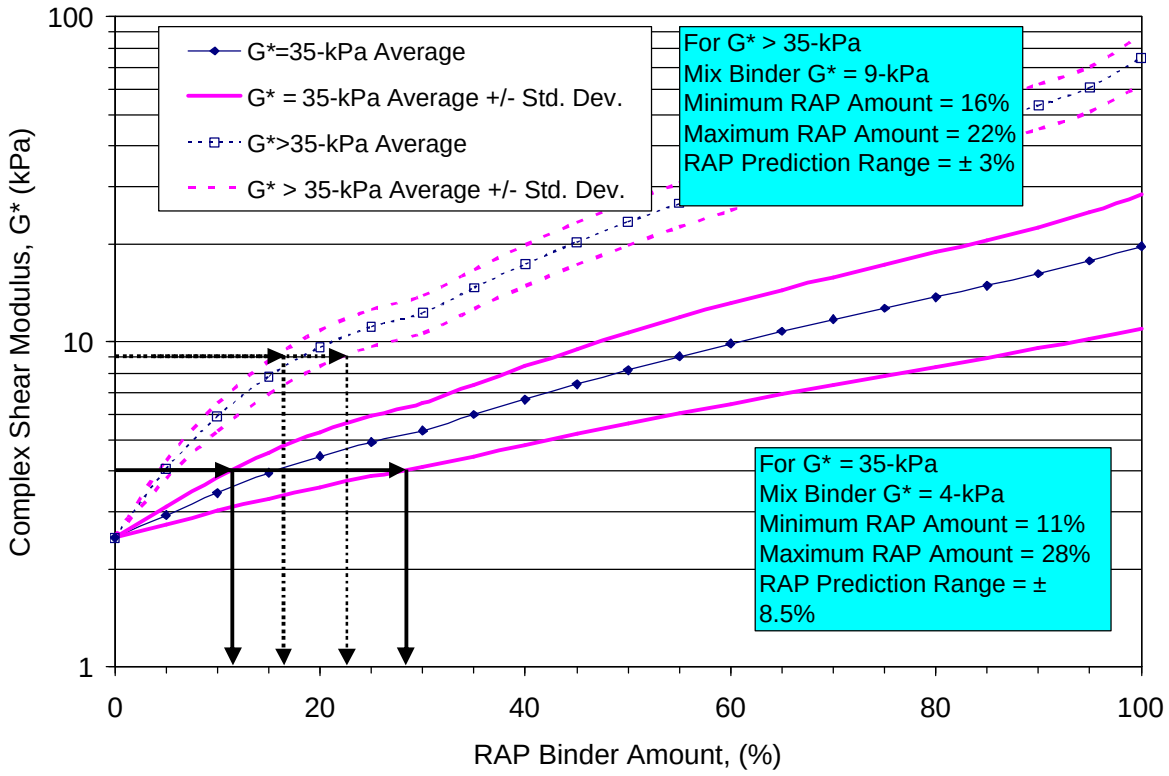

Figure 7.5 Predictions of G^* for Grouped RAP Data (G^* < 35-kPa & G^* > 35-kPa)

Figure 7.5 shows the variabilities associated with the predicted RAP amounts for grouped RAP data sets: RAP prediction intervals of ±3% and ±8.5% were obtained for the high and low G* groupings, respectively, using 67% confidence intervals.

7.4.3 Discussion of RAP Variability

Obviously, much more reasonable RAP predictions can be obtained when the nature of the RAP material is better defined, or if the RAP stockpile is truly homogeneous. The practical outcomes of these results are:

- The variation in binder G* values from RAP sources across Illinois are very high.
- One must be very careful to obtain representative samples of RAP from conglomerate stockpiles for the purposes of mix design, RAP QC and QA, and for sampling to support forensic RAP amount determinations.
- Caution must be exercised in conducting forensic determinations of RAP amount due to the effect of RAP variability on prediction accuracy.
- It is recommended that multiple stockpile sampling locations be used for the purpose of RAP physical property determination.
- The use of a single sample or the prediction of RAP amount using assumed values (no samples taken) could lead to significant prediction errors.

7.5 Effect of RAP Variability on Partial Extraction Method:

In Chapter 5, the partial extraction method was shown to be a promising method for predicting the amount of RAP in an asphalt mixture. However, it was important to verify the ability of the partial extraction method to handle a wide variety of RAP materials. From the results of binder tests performed on the RAP variability samples it was apparent that within the State of Illinois a wide variability in RAP characteristics can be expected. It was assumed that stiffer binders would take a longer time to dissolve as compared to the softer binders and thus the broad variation in binder stiffness for RAP materials might cause problems with the partial extraction procedure developed. To evaluate this, a set of tests were conducted whereby two mixes were manufactured using the RAP

materials with the stiffest and softest binders; namely RAP-3 (softest, G* = 6-kPa) and RAP-8 (Stiffest, G* = 94-kPa).

In manufacturing these mixes, a similar gradation, binder type and binder amounts were used, as per the Mix-C composition (Peoria Surface Mix). Details are provided in Appendix B. These mixes were manufactured with 20% RAP amounts. The partial extraction method proposed in Chapter 5 was used for partial extraction of these materials. Figures 7.6 and 7.7 show partially extracted aggregates from these mixes.

Figure 7.6 Partially Extracted Mix with 20% RAP-3 (Softest)

Figure 7.7 Partially Extracted Mix with 20% RAP-8 (Stiffest)

Figures 7.6 and 7.7 indicated that binder stiffness did not directly affect the results obtained from partial extraction. The mix containing RAP-3 (with softer binder) actually had a greater amount of aggregates with binder traces. More validation of this finding is still needed. The testing of blind samples carried out at the end of this study, as presented in Chapter 8, provides additional validation of the partial extraction method for RAP amount determination.

7.6 Effect of Field Aging on RAP Prediction:

For the purpose of determining RAP presence and amount by use of binder physical properties, one must account for the aging that occurs in the field between the time of laydown and the time of forensic evaluation. Mirza and Witczak (1995) developed a global aging model that can predict asphalt binder viscosity at any given time interval past its construction. This model also takes into account various parameters such as environmental conditions, depth of layer

from the surface, amount of the air voids in asphalt mixture, etc. (Mirza and Witczak, 1995). For determining the presence and amount of RAP by use of physical properties of asphalt binder this model could be used to reverse-age (or back estimate) the measured properties back to the values that would have been present at laydown.

An analysis study was carried out to illustrate the possibility of using the aging model for predicting RAP amounts when a sample was procured from the field at various times after construction. Required input variables for the global aging model were assumed based upon a typical flexible pavement structure. The asphalt concrete layer was assumed to be 100-mm thick, the gradation and asphalt content was taken to coincide with Mix-C of this study, binder type was taken as PG64-22, design air voids were set as 4% and in-place air voids were taken as 7%. The initial complex modulus of binder in the mix was assumed as 5-kPa. The analyses were carried out for two different average pavement temperatures of 35^{o}C and 55^{o}C and at two different pavement depths of 0.5-inch and 2-inch. Usually the pavement stiffness varies exponentially with depth, where maximum aging and hence stiffening takes place close to surface but decays rapidly with depth back towards the properties present at laydown. For each of the depth and temperature combinations, binder properties were evaluated for time periods ranging from the time of construction to two years after construction. The results are summarized in Figure 7.8; detailed results have been tabulated in Appendix D.

The results presented in Figure 7.8, from the global aging model show that the delayed collection of specimens for determining the presence and amount of RAP will result in higher G* values and could reduce the accuracy of the prediction unless accounted for properly.

If it is not possible to collect specimens immediately after construction, the field core results should be analytically reverse-aged. This can be accomplished by applying an aging correction factor, A_f as shown below.

$$G^*_{0-months} = G^*_{x-months} \times A_f$$

Where,

$G^*_{0\text{-months}}$ = Reverse-aged Complex Modulus for Field Aged Sample

$G^*_{x\text{-months}}$ = Measured Complex Modulus for Field Aged Sample (Collected after x-months of construction)

A_f = Aging Correction Factor

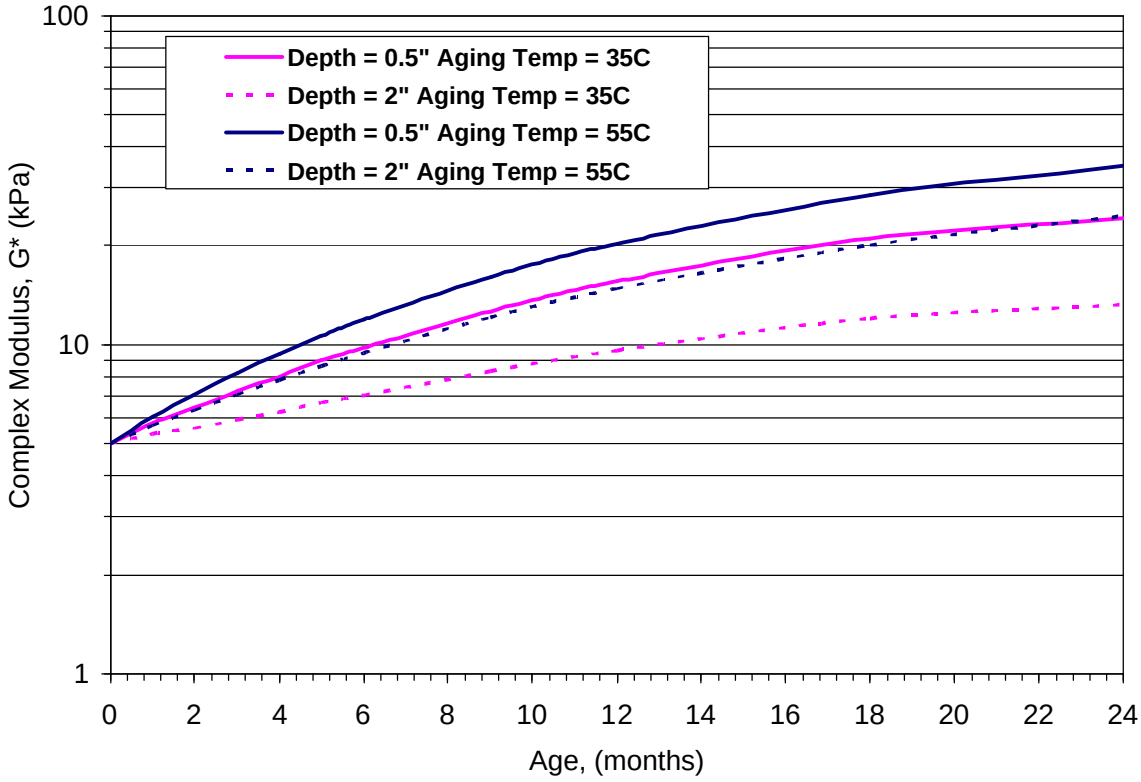

Figure 7.8 Binder Aging Predictions by Global Aging Model

A table of typical aging correction factors was obtained using the global aging model. For each pavement thickness, binder type, air void content and climatic condition, values of the aging correction factor are different. Table 7.3 shows an example where aging correction factors were determined for a pavement section (8-inch thick, 4% design air voids, 7% in-place air voids, PG64-22 binder and gradation similar to Mix-C) with different pavement ages, climatic conditions (using annual average temperatures for various IDOT Districts) and depth from surface. The worst case shown in this table is for a 2-year old, near-surface core taken in southern Illinois, since closer proximity to

surface and hotter climates lead to more rapid aging. In this case, G* values from recovered binder taken from cores from a 24-month old pavement would have to be multiplied by a factor of 0.41 (a modulus reduction of 59%). Although the age-corrected G* estimate would be superior to the uncorrected value, it should be acknowledged that the global aging model requires many sophisticated inputs. Some these inputs, i.e., emissivity, in place air voids, pavement temperature profiles would not be readily available to the analyst and would need to be estimated from typical values. Furthermore, the model has its own inherent prediction error, which increases with increasing pavement age. The prediction accuracy could be improved with calibration using local materials. However, it is clear that the longer the delay in coring for forensic evaluation of RAP amount, the greater the potential for prediction error. Finally, it should be noted that

Table 7.3 Example Showing Aging Correction Factors

	IDOT Districts								
	1, 2			**3, 4, 5, 6**			**7, 8, 9**		
Depth (mm) -->	**25**	**75**	**200**	**25**	**75**	**200**	**25**	**75**	**200**
Age (months)	Age Correction Factors								
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.5	0.98	0.99	1.00	0.97	0.99	1.00	0.97	0.99	1.00
1	0.95	0.98	0.99	0.95	0.98	0.99	0.95	0.98	0.99
1.5	0.93	0.97	0.99	0.93	0.97	0.99	0.92	0.97	0.99
2	0.91	0.97	0.99	0.90	0.96	0.98	0.90	0.96	0.98
2.5	0.89	0.96	0.98	0.88	0.95	0.98	0.87	0.95	0.98
3	0.87	0.95	0.98	0.86	0.94	0.98	0.85	0.94	0.97
4	0.84	0.93	0.97	0.82	0.92	0.97	0.81	0.92	0.96
6	0.77	0.90	0.96	0.75	0.89	0.95	0.73	0.88	0.95
9	0.69	0.86	0.94	0.66	0.84	0.93	0.64	0.82	0.92
12	0.63	0.82	0.92	0.59	0.79	0.91	0.57	0.78	0.90
18	0.54	0.76	0.89	0.50	0.73	0.87	0.47	0.70	0.85
24	0.48	0.71	0.86	0.44	0.67	0.84	0.41	0.65	0.82

Table 7.3 provides an example of how aging correction factors can be developed. This table should be expanded in the future to include more depths, and should also be validated with field cores taken at various time intervals after construction.

7.7 Findings and Recommendations:

Based on the tests and analysis performed for evaluating effects of RAP variability, the following findings and recommendations can be made:

- For evaluating variability within a stockpile RAP, materials from various sources from all across the State of Illinois were tested. This assumption considers an extreme case since in most cases conglomerate RAP stockpiles will not see these extremes and will experience some material blending.
- The RAP predictions based on physical properties of recovered binder show very high variability when considering the worst-case scenario for variability in conglomerate stockpiles.
- By grouping RAP data on the basis of complex modulus values, the error of prediction estimate was reduced significantly. Still, it is highly recommended that measured RAP G* values are used rather than assumed typical values for the purpose of RAP amount determination.
- The variability study conducted herein helped the research team quantify the range in G* values that might be present in Illinois conglomerate stockpiles. Follow-up research is recommended to measure the actual variabilities present in Illinois conglomerate and homogeneous stockpiles. In any case, this analysis further indicates the potential benefits of homogeneous stockpiling.
- For detecting RAP in field collected samples that are procured at a time later than the time of construction, an aging correction factor is needed. An example aging correction factor, A_f was developed and used to predict G* of asphalt mix at time of construction from field

cores. Further validation of this approach, including local calibration and validation is recommended.

- Whenever possible, it is recommended that samples for detecting RAP should be procured either prior to construction (sampling loose asphalt mix) or immediately after construction (taking cores), to minimize prediction errors.
- The variability measured within stockpiles in Illinois may not only make it difficult to determine RAP amounts, it could also lead to serious effects on mix properties. An alternative approach for quality assurance of RAP mixes could involve the use of an end result type specification. End result specifications could be employed by controlling viscosity or G* of recovered binder from the mix, along with other mix parameters, such as gradation. An ERS approach could have benefits in both the design and control of mixtures to have desirable as-built stiffness characteristics, gradation, etc., rather than just enforcing RAP amount, which should be more closely linked to pavement performance.

8. Detailed Procedures for Proposed Test Methods and Validation with Blind Sample Testing

8.1 Introduction:

In this chapter, detailed procedures for the most promising RAP detection and quantification methods identified in earlier chapters are provided along with illustrative examples. The three most promising methods, listed from least to most rigorous, are:

1. Rapid Partial Extraction Method (Section 8.2.1)
2. Rigorous Partial Extraction Method (Section 8.2.2)
3. Extraction, Recovery, and G* Test Method (Section 8.2.3)

Also included in this chapter is a summary of a limited validation program conducted using blind field samples provided to the researchers by the Technical Review Panel (TRP). Four-inch diameter pavement cores taken from newly constructed projects were used as a first-order validation of the RAP detection methods developed in this study. Details regarding mix design and target RAP amounts were not provided to the research team until the test results and findings were reported to the TRP. The main objective of the blind testing was to evaluate the more rigorous methods for RAP quantification; i.e., methods 2 and 3 in the list above. It should be noted that none of the procedures reported in this study have been validated with the use of polymer-modified virgin binders, so they are currently recommended for use on projects without polymer modified virgin binders.

8.2 RAP Detection and Quantification Methods – Detailed Procedures:

8.2.1 Rapid Partial Extraction Method:

Rapid partial extraction is a RAP detection method that would be the most readily performed method in the field of the three methods under consideration in this chapter. A single test on the asphalt mix is used to detect the presence of

RAP. The method is based on visual observation of partial extraction residue. The following steps describe the proposed procedure for carrying out rapid RAP detection through partial extraction.

Sampling and Sample Preparation:

(1) If the asphalt mix sample is to be sampled prior to construction, a representative sample should be obtained from the hot-mix plant, haul truck or paver. If the sample is to be collected after construction, cores will be needed (4" diameter is sufficient).

(2) A minimum of 1000-gm of mix should be used to prepare the sample for partial extraction. Sample preparation is slightly different for loose mix as compared to cored samples. Loose mix samples should be heated to compaction temperature (compaction temperature for the virgin binder) and should be allowed to cool down in the pan with continuous manual mixing with a spatula. The cored samples should be heated to the mixing temperature (mixing temperature for the virgin binder), broken apart and mixed using a standard laboratory mixing technique (such as bucket mixing). Once uniformly mixed, the sample should be allowed to cool in the pan with continuous manual mixing with a spatula. Care should be taken that in either case (loose mix or core), the sample is not placed in oven for more than 1-hour (in single event of more then one hour or multiple events with total time of more then 1 hour).

(3) From this step onwards the asphalt mix samples and cored samples are treated in the same way. The following steps should be performed in a certified fume hood and proper eye protection, gloves and protective clothing should be used.

Partial Extraction of Samples:

(4) A glass or steel bowl should be used for the partial extraction portion of the procedure, which is described in this section. Recommended sizes of bowls range from 750-ml to 1000-ml. Round-bottomed bowls may be inconvenient for this procedure.

(5) Reagent-grade Methylene Chloride and Ethyl Alcohol are required for performing the partial extractions. A total of about 600-ml methylene chloride and 750-ml ethyl alcohol is required per sample (including initial soaking, aggregate washing and final extraction).

(6) A sample weighing about 400-gm, prepared as per step (2), should be placed in bowl. Next, 50% strength methylene chloride solvent (50% Methylene Chloride + 50% Ethyl Alcohol by volume) should be poured into the bowl with the sample, taking care to use enough solvent to completely submerge the sample.

(7) After 2-hours of soaking in 50% methylene chloride, the residue (aggregates) should be washed over ASTM #8 sieve using mineral spirits. The washing period using mineral spirits should be at least 20-seconds but not more then 40-seconds. A continuous flow washing tank is recommended for this purpose, like the one typically used for cleaning pans and utensils in an asphalt laboratory.

(8) Once washed with mineral spirits the residue should be again washed with ethyl alcohol to ensure complete removal of the mineral spirits.

(9) The residue should be placed back into a clean bowl. An 85% methylene chloride (85% Methylene Chloride + 15% Ethyl Alcohol by volume) solvent should be prepared and residue should be soaked in it for period of 1-minute with vigorous mixing using a steel spatula or glass stirrer.

(10) On completion of the 1-minute of soaking period, the residue should again be washed on ASTM #8 sieve using ethyl alcohol to ensure complete removal of methylene chloride.

(11) The residue should be allowed to dry in a fume-hood or in a forced draft oven set at 50^{o}C. When using forced draft oven, ensure that the exhaust from the oven is directed into a fume-hood.

(12) In case of natural drying (in fume hood), the residue should be ready for observation in about 2 to 3 hours depending upon the ambient temperature. In the case of oven drying, residue should be available for observation after about 30-minutes.

Observation and Analysis:

(13) The residue of the partial extraction (aggregates, possibly with binder or mastic residue) should be observed to identify any aggregates with binder traces or binder material sticking to its surface. Figures 8.1 and 8.2 illustrate aggregates with and without binder residue, respectively.

(14) The mixture is judged as containing RAP if any aggregates with binder or mastic residue remain after the solvent extraction and drying steps are completed. It should be noted that even if very few aggregates have binder residue, the positive presence of RAP should be concluded until more replicate measurements or results from more rigorous tests are performed.

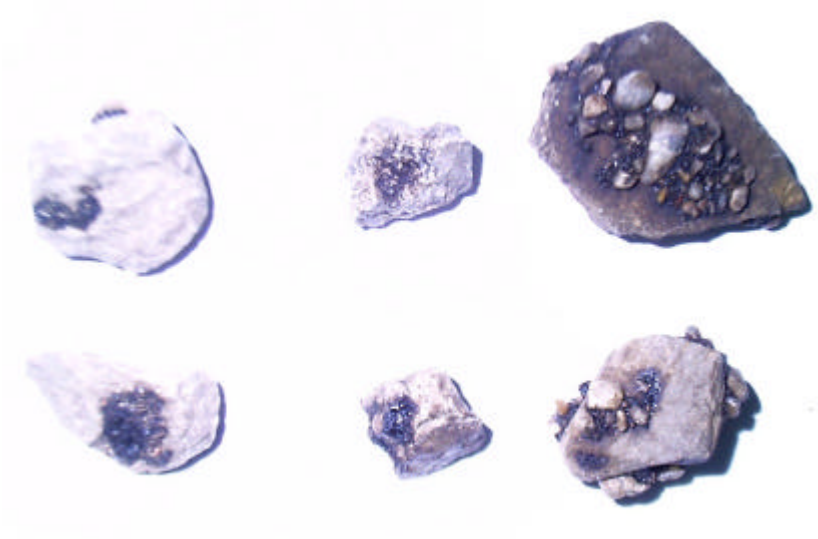

Figure 8.1 Aggregates with Binder Residue

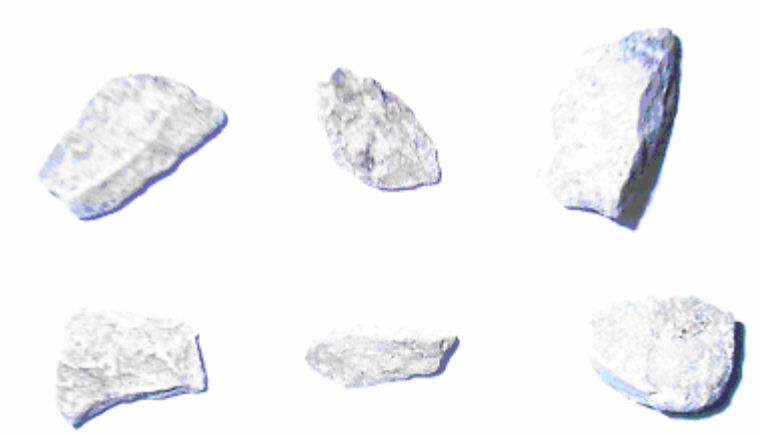

Figure 8.2 Aggregates with No-Binder Residue

Example 1:

Figures 8.3 and 8.4 show pictures of partial extraction residue for Virgin Mix-2 and Mix-E. Virgin Mix-2 does not contain RAP where as Mix-E contains 10% RAP.

Figure 8.3 Partial Extraction Residue for Virgin Mix-2 Indicating the Absence of RAP

Figure 8.4 Partial Extraction Residue of Mix-E Indicating the Presence of RAP (10% RAP was Present in the Actual Mix)

8.2.2 Rigorous Partial Extraction Method:

This method is suitable for detecting the presence and the approximate amount of the RAP in asphalt mixes. For this method, partial extraction residue of the asphalt mix is compared against comparison samples of partial extraction residues created across a range of RAP contents. This method is most accurate if the RAP material available for testing is truly representative of the RAP material that was used for manufacturing the asphalt mix. The procedure for conducting rigorous partial extraction is as following:

Sampling and Sample Preparation:

(1) The asphalt mix should be sampled as loose mix or in the form of core samples as per steps 1-3 of the rapid partial extraction method. When this method is performed after the rapid partial extraction method has been completed (Section 8.2.1), partial extraction residue for the asphalt mix will already be available. If the partial extraction residue from the asphalt mix is not available, then steps 4-12 of the rapid partial extraction method (see

Section 8.2.1) must be completed before continuing to step 2 of this section.

(2) The number of comparison samples to be used must first be determined. A minimum of two comparison samples should be produced, although more comparison samples will produce better results. While there is no upper limit, for practical purposes no more than five comparison samples should be needed. The two absolutely necessary comparison samples are the 0% and 100% RAP samples. It is also highly recommended to produce at least one more comparison sample, preferable at or near the expected RAP content. Judicious selection of other RAP amounts for additional comparison samples may be used. For example, if the expected RAP amount is 25%, then comparison samples of 0%, 15%, 25%, 35% and 100% RAP amounts could be used. For an expected RAP amount of 10%, samples at 0%, 10%, 20%, and 100% could be used.

(3) If the approximate RAP amount is unknown, comparison samples manufactured at 0%, 15%, 25%, 35% and 100% RAP amounts are recommended to be used.

(4) The comparison samples should be prepared using the same or similar aggregate types, binder type, aggregate gradation and RAP material present in the plant mixture. RAP and aggregate samples should be collected as per the IDOT aggregate sampling specifications.

(5) In the plant manufactured mixes containing RAP, the virgin binder amount used is typically adjusted based upon binder present in RAP to arrive at the target asphalt content for the mixture. The comparison samples should also be prepared in a similar fashion. Asphalt content of the RAP stockpile sample and the asphalt mix under investigation should be determined using any suitable asphalt content determination method, such as the ignition oven procedure (ASTM D4125). The following relationship shows how to compute the adjusted virgin binder content for the comparison samples:

$$AC_{Virgin} = AC_{Target} - \left(\frac{\%RAP}{100} \times AC_{RAP} \right)$$

Where,

AC_{Virgin} = Adjusted Virgin Binder Content (%)
(to be added to comparison sample)

AC_{Target} = Binder Content of Plant Manufactured Mix (%)

AC_{RAP} = Binder Content of RAP (%)

% RAP = Percent RAP in Comparison Sample

(6) All comparison samples except the 100% RAP sample should be prepared in the laboratory as per the laboratory mixing recommendations of the Superpave Mix Design (SP2) manual. Approximately 2000-gm or more mix should be prepared for each sample.

(7) The 100% RAP sample should be prepared by heating 4000-gm of RAP material to compaction temperature (compaction temperature of virgin binder) and then compacting it using Superpave gyratory compactor with 100-gyrations. The laboratory compaction guidelines as per AASHTO T312 specifications should be followed. This portion of the procedure was found to be necessary to "seat" loose mastic particles typically observed RAP sources where significant separation of aggregates and mastic have taken place as a result of milling and/or crushing RAP materials.

(8) Comparison samples should be allowed to cool before proceeding. Once room temperature is achieved, all samples should be placed in a draft oven at the compaction temperature of the virgin binder for a period of 2-hours to simulate short term aging.

(9) After the short term aging period is complete, the specimens should be allowed to cool in the pan with continuous spatula mixing. The 100% RAP sample, which is in the form of a gyratory specimen, should be broken apart to form loose mix after completion of the aging process. From this step onward, all comparison samples are treated using identical procedures.

(10) All comparison samples should be partially extracted as per the method described in steps 1-12 of the simple partial extraction method (see Section 8.2.1).

Observation and Analysis:

(11) Comparison samples should be arranged in the order of increasing RAP amount, as shown in Figure 8.5.

(12) The partial extraction residue from the plant manufactured mix or field core should be compared with the residues from the comparison samples. The method is based on visual observation. The approximate amount of coarser aggregates (greater then 4.75mm) with binder residues should be visually compared to predict the RAP content of the plant mix.

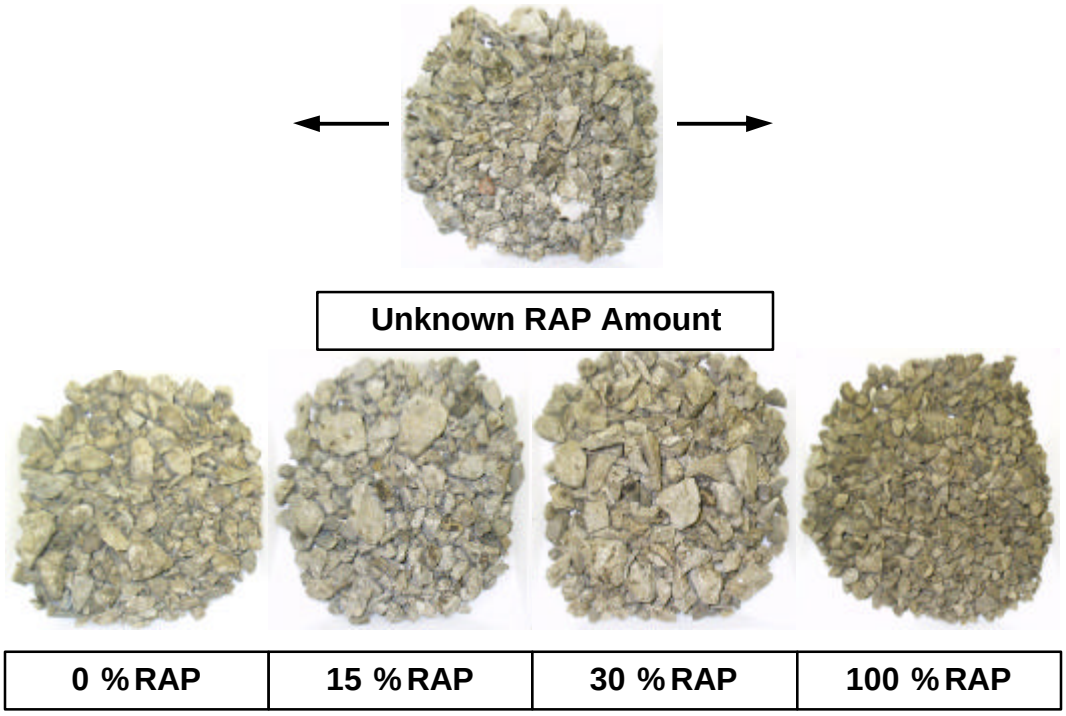

Figure 8.5 Setup for Determining RAP Amount using Partial Extraction Method (Illustration of Visually-Based Procedure)

Example 2:

Figures 8.6 through 8.9 show the pictures of partial extraction residue for comparison samples of Mix-LA. The comparison samples were prepared at 0%, 15%, 30% and 100% RAP amounts. Figure 8.10 shows a picture of a partial extraction residue for Mix-LA with unknown RAP amount. Based on the comparison samples it is estimated that the mix in question contains about 20-25% RAP. The actual RAP amount was 22.5% for Mix-LA.

Figure 8.6 Partial Extraction Residue of Mix-LA (0% RAP) Comparison Sample

Figure 8.7 Partial Extraction Residue of Mix-LA (15% RAP) Comparison Sample

Figure 8.8 Partial Extraction Residue of Mix-LA (30% RAP) Comparison Sample

Figure 8.9 Partial Extraction Residue of Mix-LA (100% RAP) Comparison Sample

Figure 8.10 Partial Extraction Residue of Mix-LA Unknown RAP Sample (22.5% RAP)

8.2.3 Rigorous RAP Detection Method Using Physical Properties of Binder:

The section describes how physical properties of recovered binders can be used to predict the approximate amount of RAP in mixture. This method is hereafter referred to as the Extraction, Recovery, and G* Test. If the desired outcome is simply to determine the presence of RAP, a less rigorous testing and analysis procedure could be selected. Section 8.2.3.1 presents a procedure to detect the presence of RAP in an HMA mixture. Section 8.2.3.2 presents a more involved procedure for estimating the amount of RAP in an HMA mixture.

8.2.3.1 Detecting the Presence of RAP Using the Extraction, Recovery and G* Test:

Sampling and Sample Preparation:

(1) For determining the presence of RAP, the complex moduli of tank binder and recovered binder from the plant mix or field cores is required. The tank binder sample is not required if the Dynamic Shear Rheometer (DSR) test results, as per the Superpave binder specifications (AASHTO M320) are available for the virgin binder used.
(2) The method is based on a simple comparison of binder G* for the virgin binder and binder recovered from the plant mix or field core.

Testing:

(3) If Superpave binder specification results are not available, the complex modulus of the short term aged (RTFO Aged) tank binder must be determined. Short term aging should be performed as per the AASHTO T240 specifications. Following the short term aging DSR testing of the binder should be performed. DSR testing should be performed as per the Superpave specified procedure (AASHTO T315) for the RTFO aged binder (25-mm diameter plates, 1-mm gap and 10 radians/sec strain amplitude and temperature setting at high binder temperature grade). Three repetitions for each binder sample should be performed and the

average value should be determined for the purpose of analysis. Record the complex modulus of the short term aged tank binder as G^*_{Tank} (kPa).

(4) Asphalt binder must be recovered from the plant mix or field core. Prior to the recovery, field core samples should be broken apart by heating to the design compaction temperature. Care should be taken such that the mix is not left in the oven for more than 1-hour. It is recommended that the time interval between sampling and recovery of binder be minimized.

(5) The AASHTO T319 test procedure for quantitative extraction and recovery of asphalt binder should be used to recover asphalt binder from the asphalt mix.

(6) Recovered binder from the asphalt mix should be tested to determine the complex modulus using the DSR. DSR tests should be performed as per recommendations of the Superpave specified procedure (AASHTO T315) for testing of short term aged (RTFO aged) asphalt binder.

Analysis:

(7) Three replicates for each binder sample should be tested and the average value be used for further analysis. If a field core sample is used then the measured complex modulus of the recovered binder needs to be back-aged using the following relationship:

$$G^*_{0-months} = G^*_{x-months} \times A_f$$

Where,

$G^*_{0\text{-months}}$ = Back-aged Complex Modulus for Field Core Binder

$G^*_{x\text{-months}}$ = Measured Complex Modulus for Field Core Binder (Collected after x-months of construction)

A_f = Aging Correction Factor (refer to Chapter 7, Section 7.6 for details)

(8) If plant mix is sampled, the measured value of the complex modulus for the recovered binder is $G^*_{Plant\ Mix}$ (kPa). If a field core is sampled, the back-aged complex modulus for recovered binder, which is computed as $G_{0\text{-months}}$ is taken as $G^*_{Plant\ Mix}$ (kPa).

(9) The comparison of $G^*_{Tank\ Binder}$ and $G^*_{Plant\ Mix}$ should be used to determine the presence of RAP. If the difference between them ($G^*_{Plant\ Mix} - G^*_{Tank\ Binder}$) is greater than or equal to 2-kPa, a positive identification of RAP is concluded. A difference of less then 2-kPa leads to the conclusion of zero or minimal RAP. Differences in the 0 to 2 kPa range could be due to variability in aging during handling and sample preparation, and differences due to non-representative sampling, etc., and therefore cannot be concluded as a positive identification of the presence of RAP.

8.2.3.2 Procedure for Predicting RAP Amount Using the Extraction, Recovery and G* Test:

Sampling, Sample Preparation and Testing:

(1) For predicting RAP amount, the complex moduli of the tank binder after RTFO aging and the recovered binders from the plant mix and RAP must be determined.
(2) The steps 3 through 8 from Section 8.2.3.1 for RAP detection should be followed for determining the complex moduli of tank binder (G^*_{Tank}) and recovered binder from plant mix ($G^*_{Plant\ Mix}$).
(3) Representative RAP material should be sampled from the stockpile. If possible, RAP stockpile information such as RAP source, stockpiling procedure, etc. should also be collected. It should be noted that if the RAP stockpile has material from various sources (conglomerate pile) the variability associated with the RAP amount prediction might be higher as compared to predictions for mixture with RAP material from uniform stockpiles.
(4) Recovered asphalt binder from the RAP sample is required. Binder recovery should be performed as per the recommendations of the AASHTO T319-03 Test Procedure for Quantitative Extraction and Recovery of the Asphalt Binder.

(5) DSR testing of the recovered RAP binder should then be performed as per Superpave specifications for the short term aged binder (AASHTO T315-03). It should be noted that AASHTO T315-03 test procedures recommends using 1-mm gap for the DSR testing. However, if RAP the material is >15 kPa, then larger gap settings (1.5-mm, 2-mm, 2.5-mm) might be required to attain the target strain amplitude.

(6) Three replicates should be tested for each recovered RAP binder sample. The average should be used for G^*_{RAP} (kPa).

(7) Using the tank binder complex modulus G^*_{Tank} and G^*_{RAP}, the complex modulus predictions for complex modulus at various RAP binder amounts can be made using the Hashin's Arbitrary Phase Geometry Model (APG) (refer to Chapter 6, Section 6.4) and the following relationship:

$$G^* = G_l^* + \left(G_u^* - G_l^*\right)s$$

Where,

G* = Predicted Complex Shear Modulus

G^*_l = Lower Bound Complex Shear Modulus as per Hashin's APG Model

G^*_u = Upper Bound Complex Shear Modulus as per Hashin's APG Model

s = Calibration Factor

A spreadsheet program (UI_RAP.xls) was developed by the research team that performs calculations for predicting the G* versus percent RAP binder amount using Hashin's APG model. The spreadsheet program is attached in Appendix G (on CD-Rom). Based on the test results available a typical calibration factor was found to be 0.47. Rather than assuming this value, the operator can conduct additional tests to determine a specific calibration factor for increased prediction reliability. This optional step is outlined in step 7b.

(7b) Optional – Very Rigorous Method. This optional step can be followed to determine the calibration factor, s, on a project-by-project basis. This involves the preparation of one or more binder blends with known RAP binder amounts and then RTFO aging and testing the samples to

determine the complex moduli. The calibration factor can then be determined by trial and error by minimizing the difference between predicted G* values (following the procedures outlined in step 7, above) and measured G* values for the binder blends at known RAP amounts.

(8) By using a graphical procedure, the RAP binder amount in the recovered binder (from the asphalt mix) can be predicted. The RAP binder amount is the percentage of RAP binder in the total binder mass. Figure 8.11 illustrates this graphical procedure where G^*_{Tank} = 2.8-kPa, G^*_{RAP} = 75-kPa and $G^*_{Plant\ Mix}$ = 10-kPa. The predicted RAP binder amount in this example is 27%. The RAP binder amount can be used to determine RAP amount in the mix using following relationship:

$$\text{RAP Amount in Mix} = \text{RAP Binder Amount}^*(AC_{Mix}/AC_{RAP})$$

Where,

AC_{Mix} = Asphalt Content of Plant Mix

AC_{RAP} = Asphalt Content of RAP

Asphalt contents of RAP and plant mix can be determined with any suitable asphalt content determination method, such as the ignition oven (using ASTM D4125).

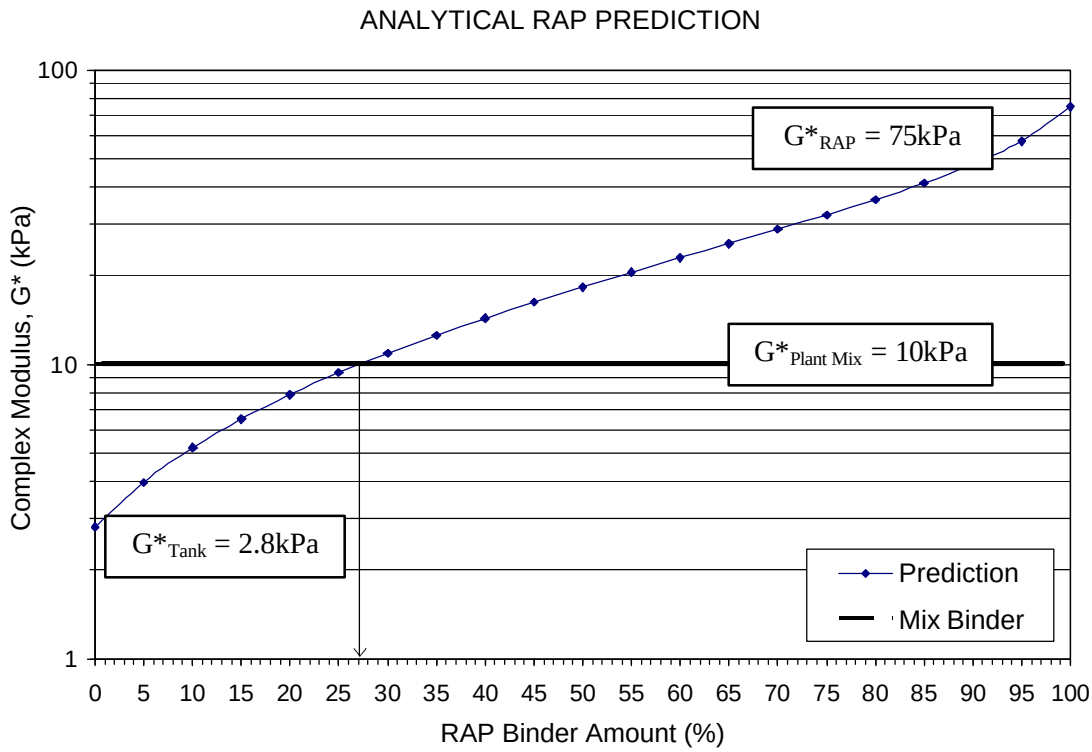

Figure 8.11 Illustration Showing Prediction of RAP Binder Amount

Example 3:

This example is divided in two parts. The first part demonstrates the procedure for detection of RAP, and the second part demonstrates the prediction of RAP amount. It should be noted that the age correction factors (A_f) used in this example were calculated using the Integrated Climatic Model for the specific mixture attributes, pavement age, and depth to surface given in this example (e.g., the values were not obtained using Table 7.3).

(1) RAP Presence Detection (two examples provided):

a) RAP Detection for Plant Mix Sample:

Let G^*_{Tank} = 2.4-kPa and $G^*_{Plant\ Mix}$ = 6.2-kPa

$G^*_{Plant\ Mix} - G^*_{Tank}$ = 3.8-kPa > 2-kPa

Since the difference of complex moduli is greater then 2-kPa, RAP may be present in the plant mix.

b) RAP Detection for Field Core Sample:

Let G^*_{Tank} = 2.4-kPa and $G^*_{12\text{-months}}$ = 4.8-kPa (core sampled 12-months after construction)

$G^*_{Plant\ Mix} = A_f\ (G^*_{12\text{-months}})$

Where,

Aging Correction Factor, A_f = 0.64 (corresponding to climate, mix properties, binder properties and depth at which sample is collected)

$G^*_{Plant\ Mix}$ = 0.64*4.8 = 3.1-kPa

$G^*_{Plant\ Mix} - G^*_{Tank}$ = 0.7-kPa < 2-kPa

Since the difference of complex moduli is less then 2-kPa, RAP may not be present.

(2) RAP Amount Determination:

The RAP amount determination example involves a case where a field core sample was collected. The procedure for a plant mix sample would be identical except that no aging correction factor would be applied.

Let G^*_{Tank} = 3.2-kPa, G^*_{RAP} = 105-kPa and $G^*_{10\text{-month}}$ = 15-kPa

Asphalt Content of Plant Mix, $AC_{Plant\ Mix}$ = 4.2% and Asphalt Content of RAP, AC_{RAP} = 4.8%

$G^*_{Plant\ Mix} = A_f\ (G^*_{10\text{-month}})$ = 0.78*(15.0) = 11.7

Aging Correction Factor, A_f = 0.78 (corresponding to climate, mix properties, binder properties and depth at which sample was collected)

$G^*_{Plant\ Mix}$ = 11.7-kPa

The predictions for complex modulus at various RAP binder amounts are shown in Figure 8.12. The predictions are made using Hashin's arbitrary phase geometry model with calibration factor, s = 0.47. The $G^*_{Plant\ Mix}$ is used to predict RAP binder amount, which is 25% as determined by the graphical method shown in Figure 8.12. Thus, the *Predicted RAP Amount in Mix* is:

%RAP = (AC_{Mix}/AC_{RAP}) RAP Binder Amount = (4.2/4.8)*25% = 21.9%

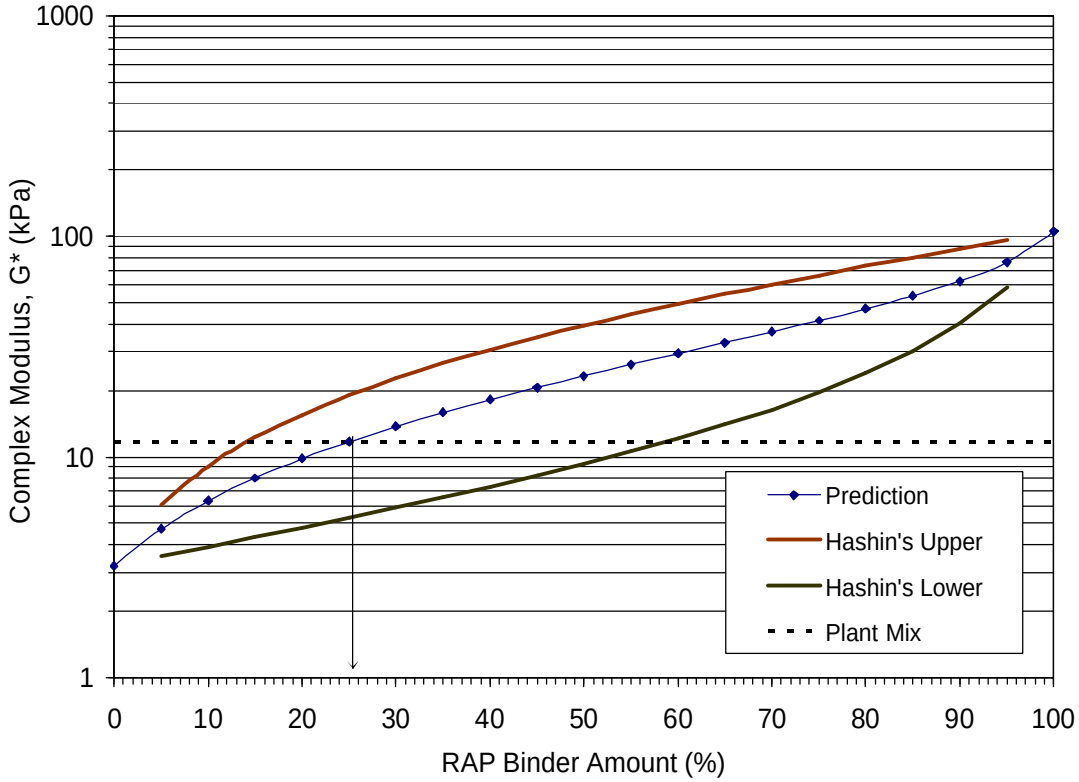

Figure 8.12 RAP Binder Amount Prediction for Example 3

8.3 Initial Validation of Proposed Test Methods through Testing of Blind Samples:

This section describes the testing and analysis of blind field samples provided by the TRP to provide initial validation of the two proposed RAP quantification methods (the two rigorous methods), as described in Sections 8.2.2 and 8.2.3. The blind samples were supplied in the form of 100-mm diameter field cores. The aggregates and RAP corresponding to blind samples were also provided. Tank binder samples were not made available and in their absence a binder sample of the same grade was obtained from a local asphalt blending terminal (Emulsicoat, Inc., Urbana, IL). On contacting Emulsicoat, Inc., in Urbana, IL it was realized that they do not manufacture one of the virgin binder grades (PG58-28) at their local facility. Instead, a sample was obtained from their Indianapolis facility. Testing was initiated by recovering binder from blind

samples and RAP materials. Partial extractions were performed on both blind samples.

The binder samples were recovered from dismantled cores of the blind samples (Mix-BS1 and Mix-BS-2) and from their respective RAP materials (RAP-BS1 and RAP-BS2). All binder recoveries were performed in accordance with the AASHTO T319 Test Specifications for Extraction and Recovery of the Asphalt Binders. Dynamic shear rheometer (DSR) tests were performed on the recovered binders to determine the complex moduli. The tank binder grades used for Mix-BS1 and Mix-BS2, as reported by the TRP, were PG58-28 and PG58-22 respectively. Thus, all DSR tests were performed at 58^{o}C. The RAP binder exhibits very high stiffness at this test temperature and thus the DSR testing was performed with 2.5-mm gap settings. Table 8.1 shows the results from complex modulus testing of binder samples, while detailed test results are tabulated in Appendix C. As expected, the G* values from the RAP samples were much higher than the mixture G* values. Also, it can be seen that mixture BS1 has higher mixture stiffness than sample BS2, giving an initial indication of a higher RAP amount, even before conducting the analysis.

Table 8.1 Complex Modulus Results for Blind Samples

Binder Type	**Complex Modulus, G* (kPa)**
Mix-BS1	54.0
Mix-BS2	8.9
RAP-BS1	441.8
RAP-BS2	255.9

Ignition oven tests were performed to determine the asphalt content of both the field mixes and RAP stockpile samples. Results from ignition oven testing are presented in Appendix B.

8.3.1 Predictions Using Rigorous Partial Extraction Method:

The partial extraction procedures described in Section 8.2.2 were then performed on the field cores. Comparison samples with 0%, 30%, 60% and 100% RAP were prepared. The gradation details were not provided for the blind samples; therefore an approximate gradation was selected based on the aggregate structure of the mixes. Comparison samples for both mixes were prepared and partially extracted. Figures 8.13 and 8.14 show partial extraction residues for Mix-BS1 and Mix-BS2. Figures 8.15 through 8.18 show comparison samples for Mix-BS1 and figures 8.19 through 8.22 show comparison samples for Mix-BS2.

Based upon the visual examination performed, it was estimated that Mix-BS1 contained 30% RAP and that Mix BS-2 contained 20% RAP. Comparisons of predictions to actual RAP contents are presented in Section 8.4.

Figure 8.13 Partial Extraction Residue for Mix-BS1

Figure 8.14 Partial Extraction Residue for Mix-BS2

Figure 8.15 Comparison Sample for Mix-BS1 (0% RAP)

Figure 8.16 Comparison Sample for Mix-BS1 (30% RAP)

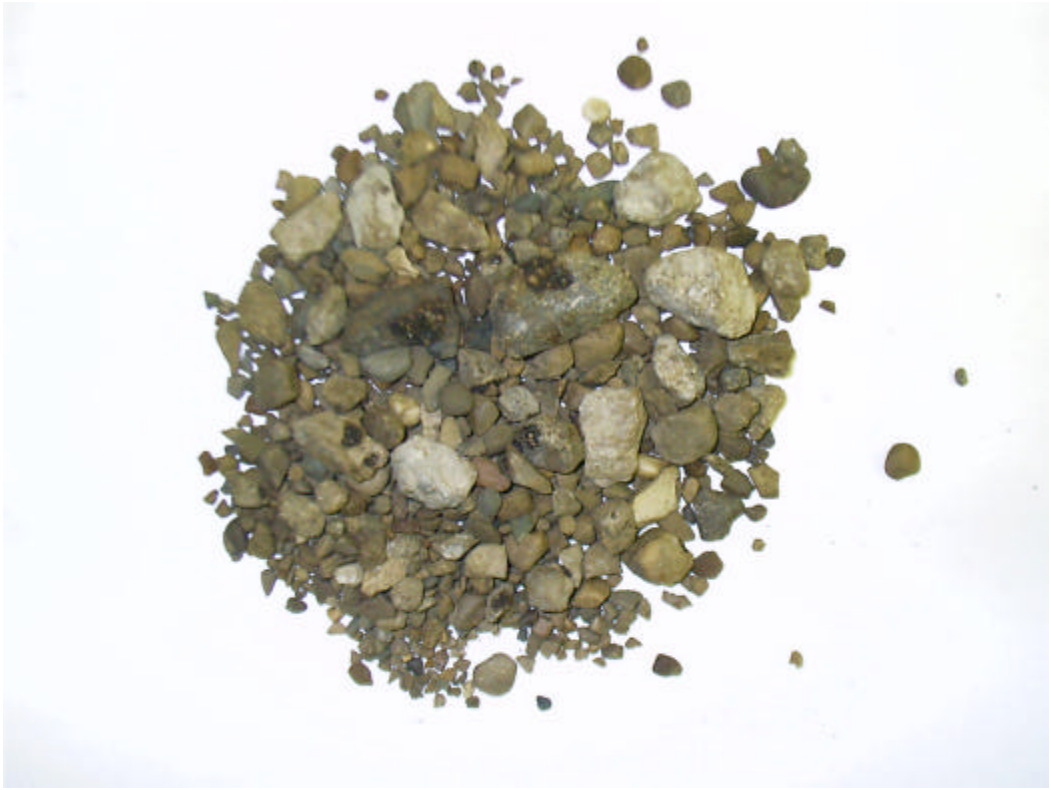

Figure 8.17 Comparison Sample for Mix-BS1 (60% RAP)

Figure 8.18 Comparison Sample for Mix-BS1 (100% RAP)

Figure 8.19 Comparison Sample for Mix-BS2 (0% RAP)

Figure 8.20 Comparison Sample for Mix-BS2 (30% RAP)

Figure 8.21 Comparison Sample for Mix-BS2 (60% RAP)

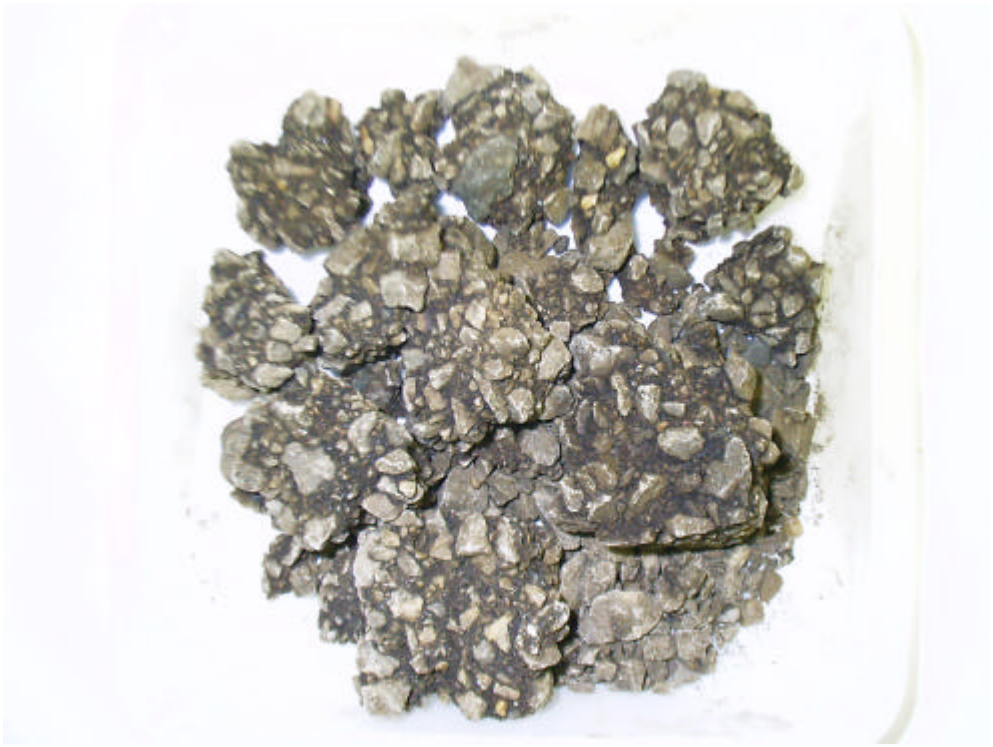

Figure 8.22 Comparison Sample for Mix-BS2 (100% RAP)

8.3.2 Predictions of Blind Samples Using the Extraction, Recovery, and G* Test Procedure:

For the representative tank binders obtained from Emulsicoat, Inc., complex modulus values (G^*_{Tank}) at 58^{o}C were found to be 3.49 kPa and 3.05 kPa for the PG 58-28 and PG 58-22 binders used in Mix-BS1 and Mix-BS2, respectively. As mentioned earlier, this RAP quantification approach requires selection of an appropriate calibration factor for the micromechanics model. The micromechanics model predicts complex modulus values at intermediate RAP amounts when tank and RAP binder complex moduli are provided as an input (ref. Chapter 6, Section 6.4). As discussed earlier, because sufficient data was not yet available to develop a universal calibration factor or a reliable method for estimating the calibration factor, predictions were made using an average calibration factor. The very rigorous procedure was not pursued herein.

Tables 8.2 and 8.3 provide predictions of RAP amounts for Mix-BS1 and Mix-BS2 using the calibration factors described above. Figures 8.23 and 8.24

show the graphical determination of RAP amount based upon the measured RAP G* value and the predicted trend of G* versus RAP amount that was obtained from the micromechanics model. The predicted RAP amounts were 33.8% and 7.7% for mixes BS-1 and BS-2, respectively, which differ somewhat from the predictions obtained with the partial extraction methods, but follow the same trend.

Table 8.2 Predictions for Mix BS-1

Calibration Factor, s	Predicted RAP Binder Amount (%)	Predicted RAP Amount (%)
Average, 0.47	35.5	33.8

Table 8.3 Predictions for Mix BS-2

Calibration Factor, s	Predicted RAP Binder Amount (%)	Predicted RAP Amount (%)
Average, 0.47	8.0	7.7

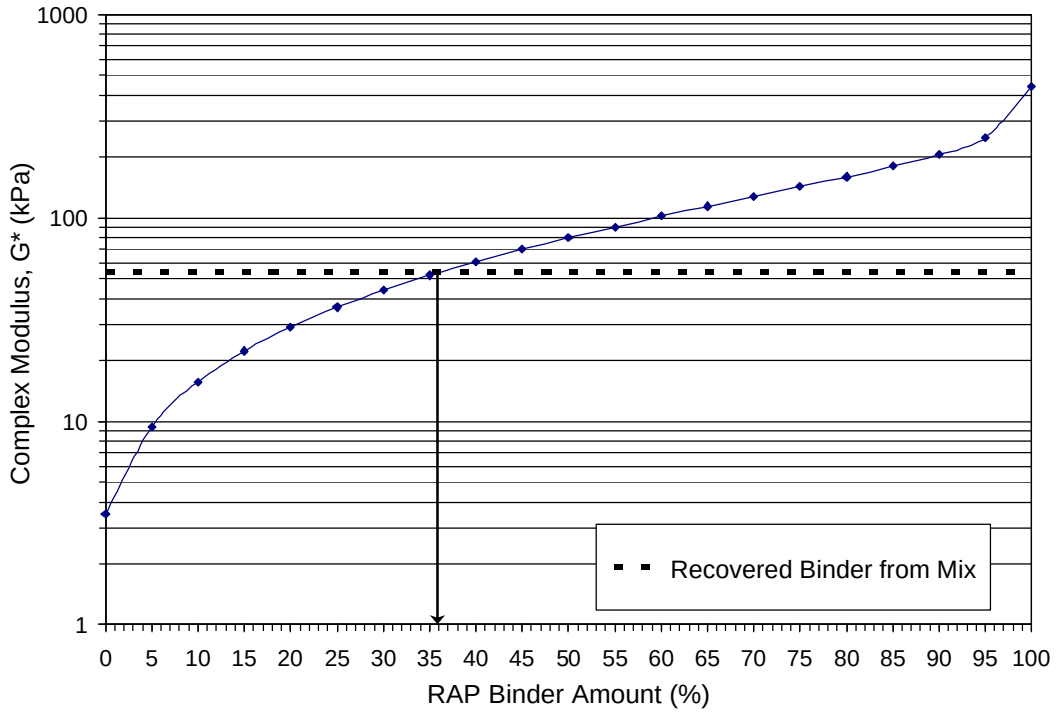

Figure 8.23 Prediction for Mix BS-1

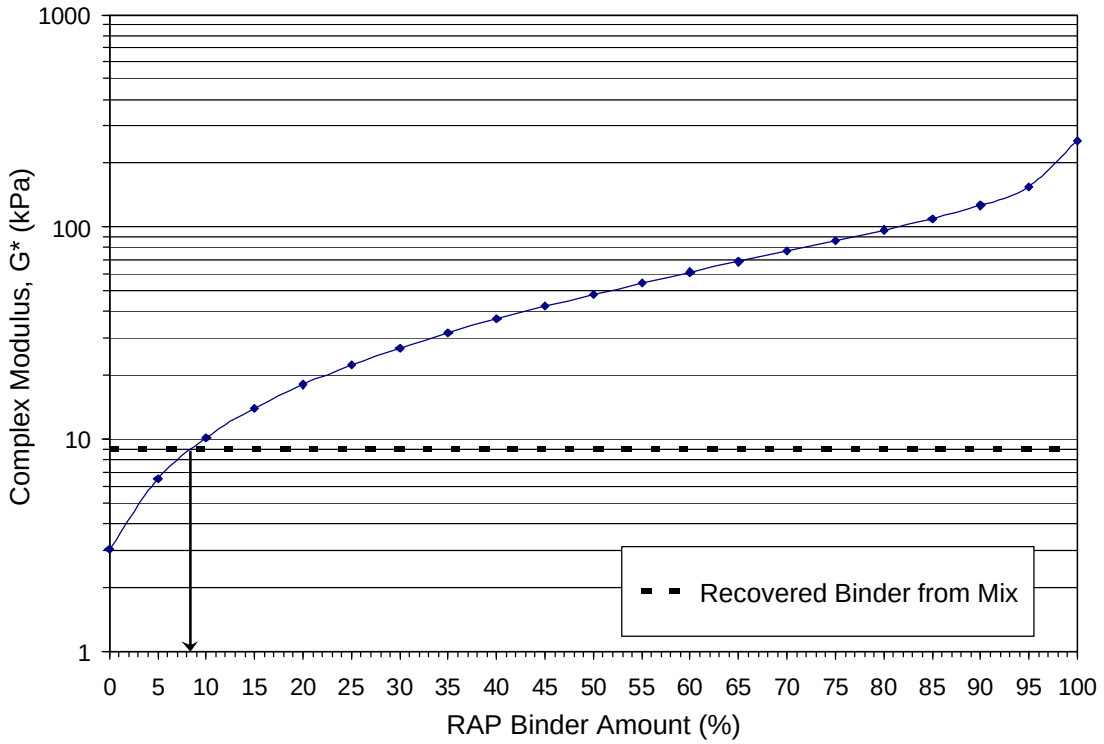

Figure 8.24 Prediction for Mix BS-2

8.4 Discussion of Results:

After predictions were made and reported to the TRP, the research team was informed that blind samples BS-1 and BS-2 consisted of 30% and 15% RAP, respectively. Table 8.4 summarizes the predictions made using the two methods and Table 8.5 presents comparison between predicted and actual RAP amounts.

The first conclusion that could be drawn was that both methods were successfully able to predict the presence of RAP in each of the two mixes. The second conclusion that could be drawn is that the two methods provided differing, yet reasonable estimates of RAP amount. For the rigorous partial extraction method, the predicted and actual RAP amounts were identical for mix BS-1, and differed only by 5% for mix BS-2 (predicted RAP amount minus reported RAP amount). For the extraction, recovery, and G* test method, the predicted and measured RAP amounts differed by 4% and 7% for mixes BS-1 and BS-2, respectively. Although the more rigorous extraction, recovery, and G* test method showed slightly less predictive accuracy for the two blind samples,

additional testing would need to be carried out to thoroughly evaluate the relative predictive accuracy of the two methods. Additionally, two factors were present that put the extraction, recovery, and G* test method at a slight disadvantage, namely:

1. Actual virgin binder samples were not collected on the project. Instead samples of the same PG binder grade were obtained. However, due to the physical and chemical property differences among binders of the same PG grade, the results obtained in the blind sample testing could have been strongly influenced by the difference between the actual tank binder used in the mixture and that used in the forensic evaluation.
2. For sample BS-2, since the design binder grade was not known beforehand, testing was by default conducted at the virgin binder PG high temperature grade (58^{o}C). Normally, the design binder grade would be known. However, since the predicted RAP amount was in excess of 30%, it is suspected that the target binder grade (mix design grade) might be PG 64-22, and that a softer virgin binder was used to compensate for the higher amount of stiff RAP binder. Ideally, testing should be conducted at the design PG high temperature grade, or 64^{o}C if design grade is PG 64-22 this case. However, this prediction method is, in theory, applicable to other test temperatures, so the predictions made at 58^{o}C were judged as reliable but not optimally obtained.

In the future, it is expected that both prediction methods could be further improved through refinement of test methods and through additional experience, especially in the case of the visual inspection method. Also, proper sampling techniques and having detailed construction and quality control records would help increase prediction accuracy. The calibration factor plays a very important role in determining RAP amount using the extraction, recovery, and G* approach. If a measured calibration factor for a given RAP mix could be obtained during mixture design, then additional prediction accuracy could be achieved during forensic investigations.

Overall, the proposed RAP prediction methods appear to be accurate enough to satisfy IDOT's desire to have forensic tool that can be used for RAP quality assurance. However, the methods have not yet been verified for polymer-modified virgin binders and follow-up validations studies are recommended to address these materials. Although not verified, it is possible that one or more of the RAP sources used in this study contained polymer-modified binder. The main concern over polymer-modified binders is their compatibility with extraction and recovery procedures (the clogging of filters), partial extraction procedures (they may alter the manner in which the binder adheres to the aggregate), and RAP back-calculation methods (they may affect the manner in which virgin and RAP binders combine, thereby creating a new class of calibration factors for the analytical back-calculation method).

Table 8.4 Summary of Results for Blind Samples

Detection Type	Method	Blind Sample-1 (30% RAP)		Blind Sample-2 (15% RAP)	
		Results	Comments	Results	Comments
RAP Presence Detection	Partial Extraction	RAP Present	--	RAP Present	--
	Binder Physical Property (G*)	RAP Present	--	RAP Present	--
RAP Amount Determination	Partial Extraction with Comparison Samples	Approximately 30% RAP	Comparison Samples with 0%, 30%, 60% and 100% RAP	Approximately 20%	Comparison Samples with 0%, 30%, 60% and 100% RAP
	Binder Physical Property (G*)	Approximately 34% RAP	Calibration Factor, s = 0.47	Approximately 8%	Calibration Factor, s = 0.47

Table 8.5 Comparison of Actual and Predicted RAP Amounts

	Actual RAP Amount (as Reported by Contractor)	Partial Extraction Method		Binder Physical Testing	
		Prediction	Difference (%)	Prediction	Difference (%)
Mix-BS 1	30%	30%	0%	34%	+4%
Mix-BS 2	15%	20%	+5%	8%	-7%

9. Summary and Conclusions

This chapter summarizes the various findings, conclusions and recommendations derived from the ITRC project IA-H1 FY02 “Detection of Recycled Asphalt Pavement in Bituminous Mixtures.” The overall goal of the study was to help IDOT address a shortcoming in available quality assurance options for the use of reclaimed asphalt pavement (RAP) in the production of hot-mix asphalt (HMA). Detailed recommendations are provided to assist IDOT in moving towards implementation of the methods and test procedures developed in this study.

9.1 Summary:

Based upon a comprehensive survey of HMA contractors in Illinois, the following key findings were obtained:

- Most contractors are aware of the benefits of keeping RAP stockpiles homogeneous and have a strategy for management of their RAP stockpiles. About 52% of contractors reported having both conglomerate and homogeneous stockpiles, while 43% reported having only homogeneous stockpiles. About 5% of contractors surveyed reported having only conglomerate stockpiles.
- The majority of RAP in Illinois is screened and/or crushed before use in HMA production.
- About 60% of the contractors responding reported that RAP samples were kept for some period of time after construction.
- The vast majority (89%) of HMA plants in Illinois are capable of automated recordation of RAP proportion. Note that this figure is based upon the survey responses received, or about half of the contractors in Illinois. This percentage is expected to increase with time, since new HMA plants almost always have this capability.

- It should be noted that controls are not perfect as there are also manually entered quantities and it is always possible to manipulate the system.
- The cost of retrofitting HMA plants with automated recordation equipment varies with the circumstances, but is thought to have an upper range of $50,000 to $80,000, including installation, training, and the typical options that contractors purchase. On the lower end, it may be possible to upgrade certain HMA plants for under $20,000.

A major portion of this study was devoted to the development testing techniques for quality assurance of asphalt mixtures to detect the presence of RAP. One goal of the study was to develop one or more forensic testing procedures that could be used to *identify* and, more preferably, *quantify* the amount of RAP in a bituminous mixture sample or field core taken during or after construction. The development of both rapid and rigorous testing options was of interest. The literature review and preliminary testing led investigators to evaluate the ignition oven and solvent extraction apparatus as potential methods for rapid evaluation of RAP mixes. However, due to lack of control over the exothermic reaction of mixture ignition in conventional ignition ovens, the development of QA procedures involving the ignition oven was not pursued further. By modifying an existing binder extraction procedure, test methods were successfully developed for both the identification and quantification of RAP in bituminous mixtures. A solvent washing procedure was developed that was found to remove virgin binder but which leaves ample traces of RAP binder and mastic deposits on aggregates for RAP quantification. An extraction, recovery, and binder physical testing scheme involving the dynamic shear rheometer (DSR) and the measurement of complex modulus (G*) was developed and evaluated for use as a more accurate and more rigorous approach for RAP quantification. Thus, promising techniques for both rapid and rigorous quality assurance testing procedures were successfully developed.

Experimentation with blends of RAP and virgin binders at various RAP concentration levels was conducted, which led to several key findings. A clear and consistent difference was noted between the practice of blending the binder components (RAP and virgin binder) before versus after aging in the rolling thin film oven (RTFO). In general, blends that were combined first and aged together were stiffer than blends made from RAP and virgin binders that were RTFO aged individually before combining. The former practice ("blend, then age"), consistently matched field results better and was therefore adopted as a standard practice.

A strategy for selecting among the most promising techniques for RAP detection and/or quantification can be summarized as follows (refer also to Table 9.1):

- If the primary goal is to quickly determine whether or not RAP is present in a given HMA mixture sample, the rapid partial extraction method developed in this study (without comparison samples) should be performed.
- If it is known that RAP is present in the mix and the main objective is to determine the approximate amount of RAP, the partial extraction procedure can be performed with comparison samples. Partial extraction with comparison samples is suitable when a subjective decision based on visual observation is acceptable.
- When the most accurate RAP amount determination is preferred, a more rigorous employment of the extraction, recovery, and G* test methods can be performed. Three variations of the procedure can be employed, all of which rely on a graphical technique to "back-calculate" the amount of RAP in the mixture from measured G* values from a series of binder samples, as described below. The simplest option is strictly used for the detection of the presence of RAP in a sample, and requires sampling and testing the virgin binder and the mixture in question. The second option, which is used to estimate the amount of RAP in a mixture, involves sampling and testing of the virgin binder, the mixture under investigation, and the RAP

Table 9.1 Comparison of RAP Detection and Quantification Methods

Method	Objective	Test Type	Analysis Type	Required Materials	Known Limitations
Partial Extraction (no comparison samples)	Detect Presence of RAP	Rapid	Subjective; Visual Assessment	Plant Mix or Field Core	
Partial Extraction with Comparison Samples	Detect Presence and Approximate Amount of RAP	Rigorous	Subjective; Visual Assessment	Plant Mix or Field Core, Aggregates, RAP and Asphalt Binder	Method may not predict RAP amount accurately if variability within a RAP stockpile is high
Binder Physical Property Method	Detect Presence of RAP	Rigorous	Limited Accuracy	Plant Mix or Field Core and Asphalt Binder	Method may not be very accurate if RAP material consists of very soft binder
	Detect Presence and Approximate Amount of RAP	More Rigorous	Rigorous	Plant Mix or Field Core, Asphalt Binder and RAP	More investigation is needed for determining calibration factors for analysis and the method is sensitive to variability of RAP within a stockpile
	Detect Presence and Amount of RAP	Most Rigorous	Rigorous	Plant Mix or Field Core, Asphalt Binder, RAP and Binder Blends with known RAP binder amounts	Highly variable RAP stockpiles with Limited Mixing

stockpile material. The third and method (the “very rigorous method”) is employed when the most accurate RAP estimate is desired. Because of the significant amount of testing required, its use might be limited to when disputes arise. In addition to DSR testing of the virgin binder, the recovered RAP binder, and the binder recovered from mixture under investigation, one or more additional reference samples are produced over a range of RAP contents and tested in the DSR. These reference points result in a more accurate employment of the graphical back-calculation procedure for RAP quantification.

After formalized procedures for the laboratory methods were developed, the procedures were validated using two sets of blind field samples, where the design RAP amount was not originally disclosed to the researchers. From this exercise, very satisfactory results were obtained. Predictions of RAP proportions from the rapid and rigorous methods varied between zero and seven percent from the reported RAP proportions.

Although promising, more testing is recommended in order to validate the forensic RAP detection and quantification methods developed in this study. For instance, the methods have not yet been verified for polymer-modified virgin binders. Although not verified, it is possible that one or more of the RAP sources used in this study contained polymer-modified binder. The main concern over polymer-modified binders is their compatibility with extraction and recovery procedures (the clogging of filters), partial extraction procedures (they may alter the manner in which the binder adheres to the aggregate), and RAP back-calculation methods (they may affect the manner in which virgin and RAP binders combine, thereby creating a new class of calibration factors for the analytical back-calculation method).

9.2 Conclusions:

On the basis of the literature review, contractor surveys, and laboratory testing conducted in this study, the following conclusions could be drawn:

- Contractors are aware of the need to keep homogeneous RAP piles, but confirmation is needed to insure consistency, enhance mixture quality, and enhance the accuracy of RAP quantification methods.
- Because the vast majority of HMA plants in Illinois have the capability to automatically record the amount of RAP being placed in a mixture, it may now be a good time to consider a policy change requiring this feature as a condition for plant approval and to develop requirements for monitoring and reporting this information as part of the quality control process.
- The partial extraction method can be used as a rapid tool for detecting the presence of RAP in an asphalt mixture.
- The partial extraction method can also be conducted with comparison samples to estimate the amount of RAP in an asphalt mixture by means of visual observation. This technique was successfully employed with over ten mixtures in this study, and worked very well in blind sample testing.
- RAP presence can be detected by comparing complex moduli of tank binder after short-term aging to recovered binder from the asphalt mixture in question.
- A calibrated version of Hashin's Arbitrary Phase Geometry model can be used to predict the complex shear modulus of blends of virgin and RAP binders based upon the moduli of the individual components (virgin and RAP binder).
- RAP amount can be determined using the complex moduli of recovered asphalt mix binder, recovered RAP binder and tank binder, given that a suitable calibration factor for the micromechanics model is known.
- Variability within a stockpile reduces the accuracy with which RAP amount can be predicted.
- The experimental techniques developed in this study appear to be suitable for implementation in demonstration projects. Additional

validation and simplification of methods is needed before they can be implemented as part of a routine, practical QA program.

9.3 Recommendations:

On the basis of the findings and conclusions from the contractor surveys, the following recommendations are made:

- HMA supplied for IDOT projects should require the use of plant control systems that automatically record the mix composition.
- IDOT should require that these records be kept as part of routine HMA quality control. Records should be regularly monitored to legitimize the process.
- IDOT should require that RAP stockpile split samples be collected, labeled, and stored by the contractor. RAP samples should be collected by IDOT periodically along with the plant records. However, the pros and cons of implementing this change should be carefully considered; as this recommendation would create additional duties for IDOT and contractor field personnel and would create additional sample storage and management issues.

On the basis of the findings and conclusions from the laboratory component of this study, the following recommendations are made:

- A follow-up laboratory study should be conducted to develop a database of calibration factors for the RAP prediction model proposed herein. More specific recommendations are given in the final section of this chapter.
- More testing is needed to validate and improve the forensic RAP detection and quantification methods proposed. Additional testing is also needed to develop standardized methods for DSR testing of very stiff binder samples, such as RAP. The source of the high testing variability noted in some of the DSR tests conducted in this study on

very stiff samples should be further studied. In addition, polymer-modified virgin binders should be included in the study.

- If possible, mix samples should be collected at the time of construction or immediately after construction to avoid the need for analytically adjusting test results to account for field aging, which introduces additional variability in predictions. The longer the delay in sampling, the higher the potential variability.

9.4 Detailed Follow-up Testing Recommendations:

This section details some of the recommendations for follow-up testing to facilitate implementation of the proposed methods for quality assurance of RAP mixtures. Although suitable methods for RAP detection and quantification were developed in this study, verification of these methods was carried out with a relatively small number of samples and did not include polymer-modified virgin binders. In addition, some of the identified methods will require follow-up testing to enhance model calibration. Additional testing will also allow IDOT to assess their confidence level with each of the procedures, and to better select between choices based upon costs versus benefits. The following testing is recommended:

- RAP binders should be recovered from RAP material milled from different pavement types, classified on the basis of:
    - Climatic conditions
    - Average annual daily traffic and or roadway classification
    - Location of layer in pavement cross-section (surface course, binder course etc.)
    - Different rehabilitation techniques applied (joint sealing, fog seal, geotextile interlayers, etc.), since these products might be present in the RAP
- Recovered RAP binders should be blended with different virgin asphalt binders, due to the importance of chemical interaction observed in this study. For example if RAP material is milled in the vicinity of Chicago,

tank binder grades that are typically supplied in northern Illinois should be used in testing. Polymer-modified binder should also be included, since the applicability of the test methods developed in this study for polymer-modified binders has not yet been investigated.

- It is recommended that binder blends should be prepared for at least two RAP binder amounts. Tank binders and binder blends should be short term aged using RTFO equipment. All binder samples should be tested using the DSR at the high PG grade of the tank binder.
- Using the spreadsheet program developed in this study, calibration factors should be determined for each set of tank binders, RAP binders and their blends.
- Statistical evaluation of calibration factors should be conducted to identify relationships with any of the known parameters, such as complex modulus G*, climatic conditions, traffic, etc. and/or on the basis of virgin binder properties such as Superpave performance grade, G*, etc.

The following recommendations relate to follow-up testing that can be used to extensively verify the RAP detection techniques developed in this study:

- The proposed RAP detection methods should be used for both plant manufactured HMA and field cores.
- The HMA mix and core samples should have known RAP amounts for the purpose of verification.
- It is recommended that samples from each of the nine IDOT district be collected and tested.
- A few projects should be monitored and tested, where plant manufactured HMA and field cores are sampled and tested at regular intervals after construction. This will provide an opportunity to evaluate the veracity of the analytical reverse aging adjustment factors proposed herein, and if necessary, will provide a basis for adjusting these factors. Field core samples should be collected periodically from the projects that were evaluated in this study to supplement this database.

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Appendix A

Contractor Questionnaire

Sample Questionnaire

A study has been commissioned by the Illinois Transportation Research Center (ITRC) for IDOT, to conduct a project investigating the use of Recycled Asphalt Pavement (RAP). Your help in examining the production of mixes will be of great value to the research team.

Company Name:_____
Contact Person:_____
Phone, Address:_____
PLANT INFORMATION (Please make photocopy duplicates of questions 1-6 for each plant)

1. List each type of plant in your operation:
   Location _____
   _____ Dryer Drum
   _____ Batch
   _____ Combination (Dratch)

2. Is the amount of RAP in the mix recorded for this plant?
   a. ____ by percent
   b. ____ by weight
   c. ____ manual, no printouts are available

3. What type of recordation is used for this plant?
   a. Manufacturer, software, etc. _____
   b. Can you identify other systems that are available (please list) _____

4. How do you stockpile your RAP aggregate at this plant?
   a. ____ Homogenous (from one removal site)
   b. ____ Conglomerate (several sites in the same pile)
   c. ____ Other/comments _____

5. Prior to using RAP at this plant, is it:
   a. ____ Crushed
   b. ____ Screened
   c. ____ Other method of processing (explain) _____

6. If RAP is crushed or screened, is it accomplished in a separate operation or just prior to entering the plant through a “gator” or screen deck? (explain) _____

(Please answer the questions on the back for your company)

GENERAL RAP QUESTIONS

7. What is the typical RAP percentage used:
   a. ____ Surface
   b. ____ Binder
   c. ____ BAM
8. Are samples kept after the RAP has been used? _____
9. How is the quality of the RAP controlled? _____

Appendix B

Material Details

B.1 Details of Plant manufactured Mixes:

(1) Mix A – Collinsville, IL Surface Mix

Aggregate Gradation Information:

	CM-11		FA-20		FA-01		Mineral Filler, MF-01		RAP	
	Amount(%) =	55.4	Amount(%) =	17.8	Amount(%) =	9.1	Amount(%) =	3.32	Amount(%) =	14.4
Sieve #	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend
1"	100.0	55.40	100.0	17.80	100.0	9.10	100.0	3.30	100.0	14.40
3/4"	100.0	55.40	100.0	17.80	100.0	9.10	100.0	3.30	100.0	14.40
1/2"	100.0	55.40	100.0	17.80	100.0	9.10	100.0	3.30	99.8	14.37
3/8"	98.0	54.29	100.0	17.80	100.0	9.10	100.0	3.30	95.4	13.74
#4	38.0	21.05	100.0	17.80	99.1	9.02	100.0	3.30	66.6	9.56
#8	4.8	2.66	83.0	14.77	92.0	8.37	100.0	3.30	44.6	6.42
#16	3.0	1.66	50.4	8.97	71.3	6.49	100.0	3.30	37.6	5.41
#30	2.6	1.44	27.0	4.81	42.0	3.82	100.0	3.30	31.6	4.55
#50	2.3	1.27	15.0	2.67	16.7	1.52	100.0	3.30	22.8	3.28
#100	2.1	1.16	6.9	1.23	4.9	0.45	98.0	3.20	10.0	1.44
#200	2.0	1.11	4.8	0.85	3.0	0.27	76.0	2.50	6.1	0.88

Optimum AC = 5.6%

Virgin Binder Grade = PG 64-22

(2) Mix B – Collinsville, IL Shoulder Mix

Aggregate Gradation Information:

	CM-11		CM-16		FA-01		Mineral Filler, MF-01		RAP	
	Amount(%) =	38.5	Amount(%) =	8.4	Amount(%) =	11.5	Amount(%) =	3.6	Amount(%) =	38
Sieve #	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend
1"	100.0	38.50	100.0	8.40	100.0	11.50	100.0	3.60	100.0	38.00
3/4"	93.8	36.11	100.0	8.40	100.0	11.50	100.0	3.60	99.4	37.77
1/2"	44.0	16.94	100.0	8.40	100.0	11.50	100.0	3.60	93.8	35.64
3/8"	16.7	6.43	96.3	8.09	100.0	11.50	100.0	3.60	88.6	33.67
#4	3.6	1.39	38.0	3.19	99.7	11.47	100.0	3.60	56.2	21.36
#8	2.2	0.85	4.8	0.40	89.3	10.27	100.0	3.60	35.6	13.53
#16	1.9	0.73	3.1	0.26	67.8	7.80	100.0	3.60	26.2	9.96
#30	1.7	0.65	2.7	0.23	46.3	5.32	100.0	3.60	20.0	7.60
#50	1.5	0.58	2.5	0.21	16.2	1.86	100.0	3.60	13.2	5.02
#100	1.4	0.54	2.2	0.18	3.1	0.36	98.0	3.53	9.8	3.72
#200	1.3	0.50	2.1	0.18	1.4	0.16	75.0	2.70	7.9	3.00

Optimum AC = 4.7%

Virgin Binder = PG 58-22

(3) Mix C – Peoria, IL Surface Mix

Aggregate Gradation Information:

	CM-11		CM-16		FA-01		RAP	
	Amount(%) =	34.7	Amount(%) =	32.1	Amount(%) =	13.2	Amount(%) =	20
Sieve #	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend
1"	100.0	34.70	100.0	32.10	100.0	13.20	100.0	20.00
3/4"	88.6	30.74	100.0	32.10	100.0	13.20	100.0	20.00
1/2"	47.0	16.31	100.0	32.10	100.0	13.20	99.5	19.90
3/8"	21.6	7.50	96.0	30.82	100.0	13.20	95.8	19.16
#4	6.6	2.29	34.0	10.91	96.0	12.67	62.5	12.50
#8	4.9	1.70	8.0	2.57	89.0	11.75	44.5	8.90
#16	3.8	1.32	5.0	1.61	75.0	9.90	39.5	7.90
#30	3.5	1.21	4.0	1.28	56.0	7.39	28.5	5.70
#50	3.1	1.08	4.0	1.28	22.0	2.90	19.2	3.84
#100	2.8	0.97	3.0	0.96	4.0	0.53	14.0	2.80
#200	2.8	0.97	3.0	0.96	2.2	0.29	9.9	1.98

Optimum AC = 4.6%
Actual AC = 4.2%
RAP AC = 5.1%
Virgin Binder = PG58-22

(4) Mix D – Peoria Shoulder, IL Mix

Aggregate Gradation Information:

	CA-10		FA-01		Mineral Filler, MF-01		RAP	
	Amount(%) =	57	Amount(%) =	12	Amount(%) =	1	Amount(%) =	30
Sieve #	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend
1"	100.0	57.00	100.0	12.00	100.0	1.00	100.0	30.00
3/4"	94.0	53.58	100.0	12.00	100.0	1.00	100.0	30.00
1/2"	81.1	46.23	100.0	12.00	100.0	1.00	99.5	29.85
3/8"	71.8	40.93	100.0	12.00	100.0	1.00	95.8	28.74
#4	50.9	29.01	96.0	11.52	100.0	1.00	62.5	18.75
#8	33.2	18.92	82.1	9.85	100.0	1.00	44.5	13.35
#16	17.1	9.75	67.2	8.06	100.0	1.00	39.5	11.85
#30	8.1	4.62	49.2	5.90	100.0	1.00	28.5	8.55
#50	5.9	3.36	19.0	2.28	99.3	0.99	19.2	5.76
#100	4.6	2.62	4.5	0.54	97.9	0.98	14.0	4.20
#200	3.1	1.77	3.3	0.40	91.3	0.91	9.9	2.97

Optimum AC = 5.6%
Actual AC = 4.1%
RAP AC = 5.0%
Virgin Binder = PG64-22

(5) Mix E – North Bottom Road

- Mix Number: 86 BIT 3329
- Mix Code: 17512R
- Job Number: C9622798
- Contract Number: 93352
- Location Adams County, north bound lane of North Bottom Road
- RAP Source: I-72 Surface
- AC: PG 64-22 from Marathon @ Meredosia
- Aggregate used:
    - 042CM11 from Central Stone 52302-04
    - 042CM16 from Central Stone 52302-04
    - 037FM01 from Central Stone 52300-39
    - 017 CM13 (RAP) from Diamond 514-03

- Samples Taken:
    1 bag of CM11
    1 bag of CM16
    1 bag of FM01
    1 gallon of AC
    4 bags of RAP
    4 bags of Mix
    10-4” Cores

Asphalt Content of RAP: 4.6 %
Total Asphalt Content: 4.6 %
Adjusted Virgin Asphalt Content: 3.7 %

Aggregate Gradation Information:

	CM-11		CM-16		FA-01		Mineral Filler, MF-01		RAP	
	Amount(%) =	57	Amount(%) =	13	Amount(%) =	10	Amount(%) =	1.1	Amount(%) =	20
Sieve #	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend
1"	100.0	57.00	100.0	13.00	100.0	10.00	100.0	1.10	100.0	20.00
3/4"	92.0	52.44	100.0	13.00	100.0	10.00	100.0	1.10	100.0	20.00
1/2"	45.0	25.65	100.0	13.00	100.0	10.00	100.0	1.10	100.0	20.00
3/8"	24.0	13.68	93.0	12.09	100.0	10.00	100.0	1.10	89.0	17.80
#4	8.0	4.56	34.0	4.42	95.0	9.50	100.0	1.10	57.0	11.40
#8	3.0	1.71	10.0	1.30	82.0	8.20	100.0	1.10	40.0	8.00
#16	3.0	1.71	3.0	0.39	70.0	7.00	100.0	1.10	31.0	6.20
#30	3.0	1.71	3.0	0.39	41.0	4.10	100.0	1.10	25.0	5.00
#50	3.0	1.71	3.0	0.39	12.0	1.20	100.0	1.10	18.0	3.60
#100	2.0	1.14	2.0	0.26	3.0	0.30	95.0	1.05	11.0	2.20
#200	2.0	1.14	2.0	0.26	0.5	0.05	90.0	0.99	7.5	1.50

(6) Mix F – Route 76 (IL-76) (District 2)

- Mix Number: 82 BIT 4052
- Mix Code: 19524R
- Job Number: C9622798
- Contract Number: 64637
- Location: Surface and Level Course, North Bound Lane of IL-76, IDOT District 2
- RAP Source: Unknown
- AC: PG 64-22 from Seneca @ Lemont
- Aggregate used:
    - 032CM16 from Vulcan Materials 50372-01
    - 038FM20 from Vulcan Materials 50372-01

- 037FM01 from Prairie Materials 51110-39
- 004MF01 from Franklin Aggregates 52402-99
- 017CM16 (RAP) from Peter Baker 164-07

- Samples Taken:
  11 bags of Aggregates
  4 bags of Mix
  1 gallon of AC
  6-6" Cores

Asphalt Content of RAP: 4.9 %
Total Asphalt Content: 5.7 %
Virgin Asphalt Content: 5.2 %

Aggregate Gradation Information:

	CM-16		FM-20		FM-02		Mineral Filler, MF-01		RAP	
	Amount(%) =	60	Amount(%) =	21.7	Amount(%) =	7	Amount(%) =	1.3	Amount(%) =	10
Sieve #	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend	% Passing	% of Blend
1"	100.0	60.00	100.0	21.70	100.0	7.00	100.0	1.30	100.0	10.00
3/4"	100.0	60.00	100.0	21.70	100.0	7.00	100.0	1.30	100.0	10.00
1/2"	100.0	60.00	100.0	21.70	100.0	7.00	100.0	1.30	100.0	10.00
3/8"	93.5	56.10	100.0	21.70	100.0	7.00	100.0	1.30	99.0	9.90
#4	26.9	16.14	98.0	21.27	99.8	6.99	100.0	1.30	75.0	7.50
#8	8.4	5.04	76.1	16.52	88.7	6.21	100.0	1.30	54.0	5.40
#16	4.5	2.70	51.0	11.07	71.5	5.01	100.0	1.30	40.0	4.00
#30	3.5	2.10	34.4	7.46	54.6	3.82	100.0	1.30	29.2	2.92
#50	3.1	1.86	19.0	4.12	21.7	1.52	100.0	1.30	18.0	1.80
#100	2.8	1.68	6.6	1.43	1.9	0.13	95.0	1.24	11.0	1.10
#200	2.0	1.20	3.5	0.76	0.7	0.05	90.0	1.17	8.3	0.83

B.2 Details on Various Lab Prepared Mixes:

Material Information about the mixes produced for Ignition Oven Study:

Percentage of Aggregates and RAP by Weight in mix

Mix Type	RAP Amount (%)	Aggregate Type and Amount (%)				
		CM-11	CM-16	FA-21	FA-01	Filler
Virgin	0	8.0	50.0	25.0	15.0	2.0
15% RAP	15	6.4	40.3	20.1	12.1	1.6
30% RAP	30	5.3	33.2	16.6	10.0	1.3
45% RAP	45	4.2	26.1	13.0	7.8	1.0
60% RAP	60	3.0	19.0	9.5	5.7	0.8
100% RAP	100	0.0	0.0	0.0	0.0	0.0

Actual Amount of Aggregates and RAP in the mix

Mix Type	RAP Amount (gm)	Aggregate Type and Amount (gm)				
		CM-11	CM-16	FA-21	FA-01	Filler
Virgin	0.0	160.0	1000.0	500.0	300.0	40.0
15% RAP	300.0	128.8	805.3	402.6	241.6	32.2
30% RAP	600.0	106.1	663.2	331.6	198.9	26.5
45% RAP	900.0	83.4	521.0	260.5	156.3	20.8
60% RAP	1200.0	60.6	378.9	189.5	113.7	15.2
100% RAP	2000.0	0.0	0.0	0.0	0.0	0.0

MIX Designs for Virgin Mix-1, MIX C~20% RAP3 and MIX C~20% RAP 8

Virgin Mix-1: (Similar to Mix-C but no RAP)		
Aggregate	(ori. + adjusted for RAP)	
CM-11=	35% + 8%	43%
CM-16=	32% + 8%	40%
FA-02=	13% + 4%	17%

20% RAP Mixes	
Aggregates	Amount
CM-11	35%
CM-16	32%
FA-02	13%
RAP	20%

Virgin Binder Type and Amounts:

Virgin Mix-1	PG 58-22	5% by weight of aggregate weight
Mix with RAP 3	PG 58-22	4.2% by weight of aggregates
Mix with RAP 8	PG 58-22	4.2% by weight of aggregates

Mix Designs for Virgin Mix 2 and Virgin Mix 3

Aggregate Information for Virgin Mix-2 and 3

Type	Percentage	Weight
CM-11	7.6	400
CM-16	47.3	2500
FA-21	23.7	1250
FA-01	19.5	1030
Filler	1.9	100
Total=	100	5280

Virgin Binder Types and Amounts:

	Type	Origin	Weight (gm)	% (mix weight)
Virgin Mix-2	PG 58-22	Peoria Surface	128.1	4.6
Virgin Mix-3	PG 64-22	Collin. Surface	138.8	5.0

Mix Designs for Mix-LA and Mix-LB

(RAP Binder Content Assumed as 4%)

Design Binder Contents
Mix LA = 4.6% (by wt of mix)
Mix LB = 5.0% (by wt of mix)

Sample Name	Aggregate Amount	RAP Amount	RAP Binder	Virgin Binder
(Percentages)				
Mix-LA-0	100	0	0.0	4.6
Mix-LA-15	85	15	0.6	4.0
Mix-LA-30	70	30	1.4	3.2
Mix-LA-100	0	100	4.0	0.6
Mix-LB-0	100	0	0.0	5.0
Mix-LB-15	85	15	0.6	4.4
Mix-LB-30	70	30	1.2	3.8
Mix-LB-100	0	100	4.0	1.0

Weights (gm)

Mix-LA-0	2000	0	0	96.4
Mix-LA-15	1700	300	12.1	83.3
Mix-LA-30	1400	600	28.0	66.5
Mix-LA-100	0	2000	83.3	12.1
Mix-LB-0	2000	0	0.0	105.3
Mix-LB-15	1700	300	12.1	92.1
Mix-LB-30	1400	600	24.3	79.0
Mix-LB-100	0	2000	83.3	20.2

Aggregate Gradations:

(percent)	CM-11	CM-16	FA-01	FA-21	Filler	Total
Mix-LA-0	7.6	47.3	23.7	19.5	1.9	100
Mix-LA-15	6.46	40.21	20.15	16.58	1.62	85
Mix-LA-30	5.32	33.11	16.59	13.65	1.33	70
Mix-LA-100	0	0	0	0	0	0
Mix-LB-0	7.6	47.3	23.7	19.5	1.9	100
Mix-LB-15	6.46	40.21	20.15	16.58	1.62	85
Mix-LB-30	5.32	33.11	16.59	13.65	1.33	70
Mix-LB-100	0	0	0	0	0	0

Weight (gm)	CM-11	CM-16	FA-01	FA-21	Filler	Total
Mix-LA-0	152.0	946.0	474.0	390.0	38.0	2000
Mix-LA-15	129.2	804.1	402.9	331.5	32.3	1700
Mix-LA-30	106.4	662.2	331.8	273.0	26.6	1400
Mix-LA-100	0.0	0.0	0.0	0.0	0.0	0.0

Mix-LB-0	152.0	946.0	474.0	390.0	38.0	2000
Mix-LB-15	129.2	804.1	402.9	331.5	32.3	1700
Mix-LB-30	106.4	662.2	331.8	273	26.6	1400
Mix-LB-100	0.0	0.0	0.0	0.0	0.0	0

Appendix C
Lab Testing Results

C.1 Lab Results from Preliminary Study:

RAP Binder Amount (%)	Complex Modulus, G* (kPa)			
	Repetition1	Repetition2	Repetition3	Average
0	1.139	1.15	1.125	1.138
15	2.711	3.7187	2.345	2.9249
30	3.4415	6.3777	3.788	4.535733
45	4.277	9.85513	9.1544	7.762177
100	25.765	26.542	26.784	26.36367

DSR Results for Various Test Repetitions

C.2 Lab Results for Aging Calibration Study:

(1) Results for Blending Before Aging:

%RAP	G* (kPa)	Delta (Deg.)	G*/Sin(Delta) (kPa)
0	3.61	84.50	3.63
0	3.69	84.80	3.71
0	4.39	84.40	4.41
15	10.94	82.00	11.05
15	9.67	81.90	9.77
15	10.29	81.70	10.40
15	6.55	81.40	6.62
15	8.48	82.10	8.56
15	9.54	81.70	9.64
30	13.86	79.70	14.09
30	11.30	79.40	11.50
30	12.90	79.20	13.13
30	11.38	79.70	11.56
30	14.00	79.80	14.22
45	16.62	78.40	16.97
45	16.96	76.20	17.46
45	17.20	78.00	17.58
45	27.06	76.10	27.88
45	18.60	78.00	19.02
45	19.07	75.50	19.70
100	55.24	65.50	60.70
100	76.75	64.00	85.40
100	54.64	66.30	59.67
100	74.86	64.90	82.67

DSR Results for Different Test Repetitions

(2) Results for Blending After Aging:

%RAP	G* (kPa)	Delta (Deg.)	G*/Sin(Delta) (kPa)
0.00	3.61	84.50	3.63
0.00	3.69	84.80	3.71
0.00	4.39	84.40	4.41
15.00	4.31	84.30	4.33
15.00	4.52	84.00	4.54
15.00	4.24	83.90	4.27
30.00	8.58	80.50	8.70
30.00	9.08	80.00	9.22
30.00	8.80	80.30	8.93
45.00	12.02	78.40	12.27
45.00	12.04	78.60	12.28
45.00	16.17	76.90	16.60
100.00	55.24	65.50	60.70
100.00	76.75	64.00	85.40
100.00	54.64	66.30	59.67
100.00	74.86	64.90	82.67

DSR Results for Different Test Repetitions

(3) Results for Oven Aging:

Mix TYPE	Aging Time	Repetition	G*	Delta	RAP%	G*/Sin(Delta)
	(hr)					
15% RAP	0	1	7.84	81.20	15	7.93
	0	2	8.45	80.90	15	8.56
	0	3	7.15	81.40	15	7.23
	2	1	13.84	76.10	15	14.26
	2	2	9.31	78.10	15	9.51
	2	3	15.67	76.60	15	16.10
	6	1	37.42	71.10	15	39.56
	6	2	26.28	72.40	15	27.57
	6	3	23.92	72.60	15	25.07
	10	1	45.22	68.00	15	48.77
	10	2	49.84	67.80	15	53.83
	10	3	43.13	68.00	15	46.52
30% RAP	0	1	13.25	79.60	30	13.48
	0	2	13.46	79.30	30	13.70
	0	3	12.81	80.20	30	13.00
	2	1	26.39	71.60	30	27.81
	2	2	29.34	71.40	30	30.95
	2	3	33.47	70.50	30	35.50
	10	1	100.31	62.50	30	113.09
	10	2	86.73	62.80	30	97.52
	10	3	94.68	62.70	30	106.55

C.3 Results from Verification of Extraction Recovery Equipment:

Original Binder:

Repetition	Complex Modulus, G* (kPa)
1	2.67
2	2.73
3	2.63
Average	2.68

Binder Dissolved in Solvent and Recovered:

Repetition	Complex Modulus, G* (kPa)
1	2.71
2	2.77
3	2.72
Average	2.73

C.4 Binder Blend Results:

I-57 RAP Binder Blends:

RAP Binder Amount (%)	Complex Modulus, G* (kPa)			
	Rep1	Rep2	Rep3	Average
0	1.14	1.15	1.13	1.14
15	2.71	3.72	2.35	2.92
30	3.44	6.38	3.79	4.54
45	4.28	9.86	9.15	7.76
100	25.77	26.54	26.78	26.36

Results for Mix-E and Mix-F Binder Blends:

Mix-E-0%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	3.33	83.50	3.35
2.00	4.23	83.50	4.26
3.00	3.53	84.00	3.55
Average	3.70	83.67	3.72

Mix-E -10%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	5.77	81.70	5.83
2.00	5.69	81.60	5.75
3.00	5.71	82.00	5.77
Average	5.72	81.77	5.78

Mix-E -20%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	10.37	78.80	10.58
2.00	8.09	79.60	8.23
3.00	8.16	80.00	8.29
Average	8.88	79.47	9.03

Mix-E -30%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	10.88	77.90	11.13
2.00	11.41	78.20	11.66
3.00	11.59	77.60	11.87
Average	11.30	77.90	11.55

Mix-E -40%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	28.92	73.50	30.16
2.00	24.86	73.80	25.89
3.00	14.89	76.20	15.33
Average	22.89	74.50	23.79

Mix-E -60%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	28.49	72.10	29.93
2.00	26.29	72.40	27.57
3.00	25.58	72.50	27.22
Average	26.79	72.33	28.24

Mix-E -100%-RAP-Binder-Blend (RAP RTFO)

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	99.12	64.00	110.25
2.00	95.88	64.00	106.67
3.00	90.15	64.30	100.01
Average	95.05	64.10	105.64

Mix-F-0%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	2.71	85.30	2.72
2.00	3.09	85.10	3.10
3.00	2.66	85.90	2.88
Average	2.82	85.43	2.90

Mix-F -10%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	3.79	83.30	3.82
2.00	4.16	83.50	4.18
3.00	4.54	83.10	4.57
Average	4.16	83.30	4.19

Mix-F -20%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	6.07	82.00	6.13
2.00	4.96	82.80	5.00
3.00	4.94	82.70	4.98
Average	5.33	82.50	5.37

Mix-F -30%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	7.05	80.80	7.14
2.00	6.51	80.90	6.59
3.00	6.68	80.90	6.76
Average	6.74	80.87	6.83

Mix-F -40%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	8.65	79.30	8.80
2.00	11.19	78.40	11.42
3.00	8.50	79.70	8.64
Average	9.45	79.13	9.62

Mix-F -60%-RAP-Binder-Blend

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	9.50	79.40	9.67
2.00	7.17	80.70	7.27
3.00	12.54	78.80	12.78
Average	9.74	79.63	9.91

Mix-F -100%-RAP-Binder-Blend (RAP RTFO)

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	32.54	69.60	34.71
2.00	60.43	67.00	65.63
3.00	32.31	70.30	34.32
Average	41.76	68.97	44.89

C.5 Lab Results from Other Binder Tests:

Mix A	Complex Shear Modulus, G* (kPa)		
Test Repetition	RTFO Virgin Binder	Rec. Mix Binder	RAP Binder
% RAP Binder →	0.00	11.87	100.00
1	3.08	3.78	12.63
2	2.90	3.93	17.79
3	2.87	3.93	17.34
Average	2.95	3.88	15.92
Mix B	Complex Shear Modulus, G* (kPa)		
Test Repetition	RTFO Virgin Binder	Rec. Mix Binder	RAP Binder
% RAP Binder →	0.00	37.66	100.00
1	2.66	5.25	12.63
2	5.41	5.15	17.79
3	3.18	4.57	17.34
Average	3.75	4.99	15.92

Mix C	Complex Shear Modulus, G* (kPa)		
Test Repetition	RTFO Virgin Binder	Rec. Mix Binder	RAP Binder
% RAP Binder →	0.00	18.26	100.00
1	1.81	7.58	76.85
2	1.49	8.99	54.64
3	1.38	7.45	74.86
Average	1.56	8.01	68.79
Mix D	Complex Shear Modulus, G* (kPa)		
Test Repetition	RTFO Virgin Binder	Rec. Mix Binder	RAP Binder
% RAP Binder →	0.00	22.50	100.00
1	3.35	7.60	46.69
2	2.84	6.86	44.52
3	2.94	6.27	46.32
Average	3.04	6.91	45.84

Mix-E DATA:

Mix-E-Virgin-Binder (RTFO)

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	3.33	83.50	3.35
2.00	4.23	83.50	4.26
3.00	3.53	84.00	3.55
Average	3.70	83.67	3.72

Mix-E -Plant-Mix-Binder

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	6.50	81.40	6.58
2.00	7.18	80.80	7.27
3.00	7.12	80.50	7.22
Average	6.93	80.90	7.02

Mix-E -RAP-Binder

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	59.60	68.20	64.18
2.00	63.36	67.90	68.38
3.00	70.00	67.80	75.63
Average	64.32	67.97	69.39

Mix-E -RAP (RTFO Aged)-Binder

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	99.12	64.00	110.25
2.00	95.88	64.00	106.67
3.00	90.15	64.30	100.01
Average	95.05	64.10	105.64

Mix-F DATA:

Mix-F-Virgin-Binder (RTFO)

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	2.71	85.30	2.72
2.00	3.09	85.10	3.10
3.00	2.66	85.90	2.88
Average	2.82	85.43	2.90

Mix-F-Plant-Mix-Binder

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	4.85	80.80	4.95
2.00	4.95	81.30	5.01
3.00	4.94	80.60	5.00
Average	4.91	80.90	4.99

Mix-F-RAP-Binder

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	35.83	69.80	38.18
2.00	25.44	71.60	26.81
3.00	41.67	68.90	44.67
Average	34.31	70.10	36.55

Mix-F-RAP-Binder (RTFO Aged)

Repetition	G* (kPa)	Delta	G*/Sin(Delta)
1.00	32.54	69.60	34.71
2.00	60.43	67.00	65.63
3.00	32.31	70.30	34.32
Average	41.76	68.97	44.89

C.6 Lab Results for RAP Variability Study:

Name	Description	G* (3 reps.)			Ave G*
RAP 1	(SHC - Litchfield - I-55)	25.13	33.00	32.12	30.08
RAP 2	(Howell - Greenup - I-70)	11.01	16.58	18.15	15.25
RAP 3	(SIA - Mt. Vernon - I-57)	5.85	5.20	7.08	6.04
RAP 4	(Cullinan - Hopedale - I-155)	33.52	32.88	33.07	33.15
RAP 5	(Tickle - Rock Island - I-280)	13.12	12.59	12.95	12.88
RAP 6	(D Const - Morris - IL 47)	12.54	14.55	19.18	15.42
RAP 7	(Propheter - Annawan - I-80)	10.59	10.08	8.80	9.82
RAP 8	(Rowe - Griggsville - I-72)	72.78	73.47	135.85	94.03
RAP 9	(Simonds - Anna - IL-146)	22.17	22.71	21.93	22.27
RAP 10	(Gallagher-Thornton-Rt-53)	15.71	31.34	14.87	20.64
RAP 11	(Maclair - State Park - Conglo)	97.53	41.21	56.66	65.13
I-57 RAP	(University Const-Urbana-I-57)	12.63	17.79	17.34	15.92
Paxton Rd	(University Const-Urbana-Pax. Rd)	76.85	54.64	74.86	68.79
RAP A/B	(ASAP-Lebanon-Unknown)	46.69	85.05	81.70	71.15
RAP C	(Cullinan-Peoria-Unknown)	33.56	29.99	31.05	31.53
RAP D	(Cullinan-Peoria-Unknown)	24.10	20.37	24.58	23.02

C.7 Lab Results for Blind Sample Binders:

Blind Sample 1 RAP Binder tested at 58C

Repetition	G* (kPa)	Delta	G*/Sin(D)
1	482.64	59.00	563.00
2	410.50	59.10	478.44
3	432.12	58.70	505.49
Average	**441.75**	58.93	515.64

Blind Sample 2 RAP Binder tested at 58C

Repetition	G* (kPa)	Delta	G*/Sin(D)
1	336.47	60.20	387.83
2	301.21	60.60	345.83
3	130.11	65.30	143.21
Average	**255.93**	62.03	292.29

Blind Sample 1 Core Binder tested at 58C

Repetition	G* (kPa)	Delta	G*/Sin(D)
1	42.65	72.40	44.74
2	47.04	72.00	49.45
3	72.31	71.90	44.50
Average	**54.00**	72.10	46.23

Blind Sample 2 Core Binder tested at 58C

Repetition	G* (kPa)	Delta	G*/Sin(D)
1	6.29	83.70	6.33
2	8.97	82.40	9.05
3	11.57	82.40	11.67
Average	**8.94**	82.83	9.02

C.8 Ignition Oven Results for Blind Samples:

Blind Sample 1 Ignition Oven Results for Asphalt Content:

BS-1 Core	4.91%
BS-1 RAP	5.15%

Blind Sample 2 Ignition Oven Results for Asphalt Content:

BS-2 Core	5.08%
BS-2 RAP	5.30%

Appendix D

Detailed Results of Various Analyses

D.1 Detailed Analysis of Ignition Oven Data:

D.1.1 Key Points Identified for Analysis:

- Points Identified from Chamber Temperature Profile Curves:
  - First Trough
  - First Peak
  - Second Peak
  - Point of First Slope Change
  - Second Trough
  - Initial Slope Value
  - Second Slope Value
  - Final Slope Flattening Point

- Points Identified from Weight Loss Profile:
  - Initial Slope
  - Final Slope

D.1.2 Results from Analysis:

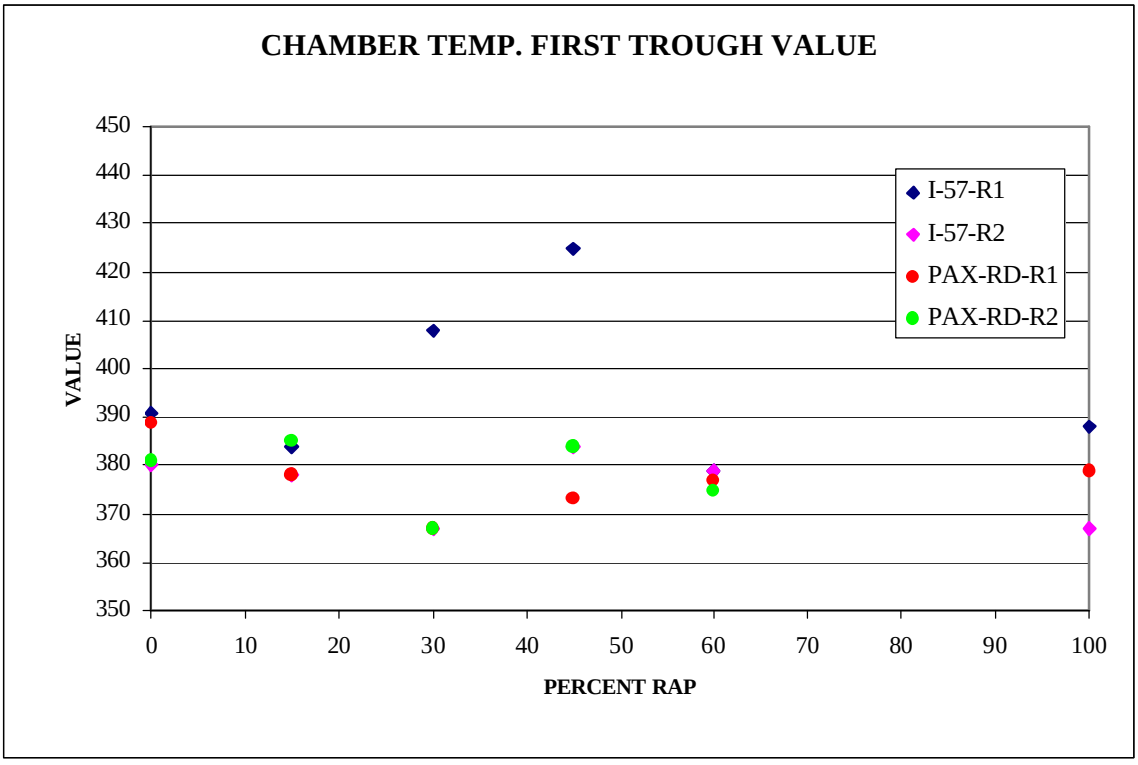

Figure D-1

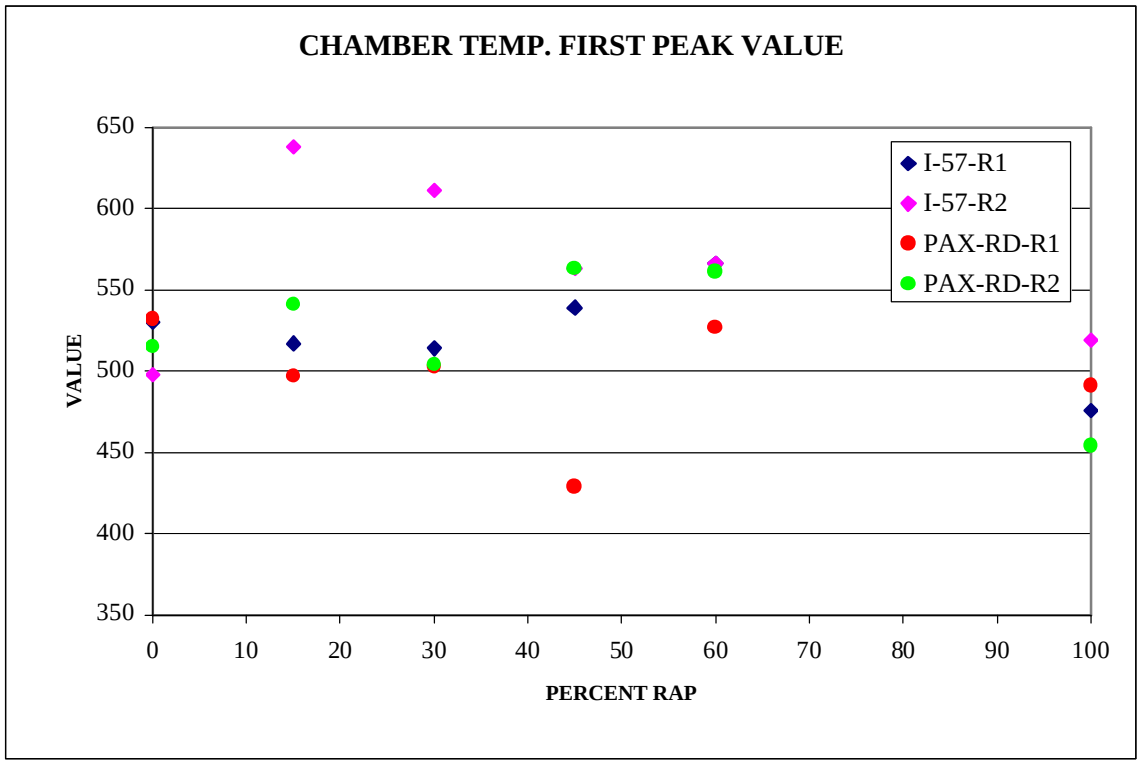

Figure D-2

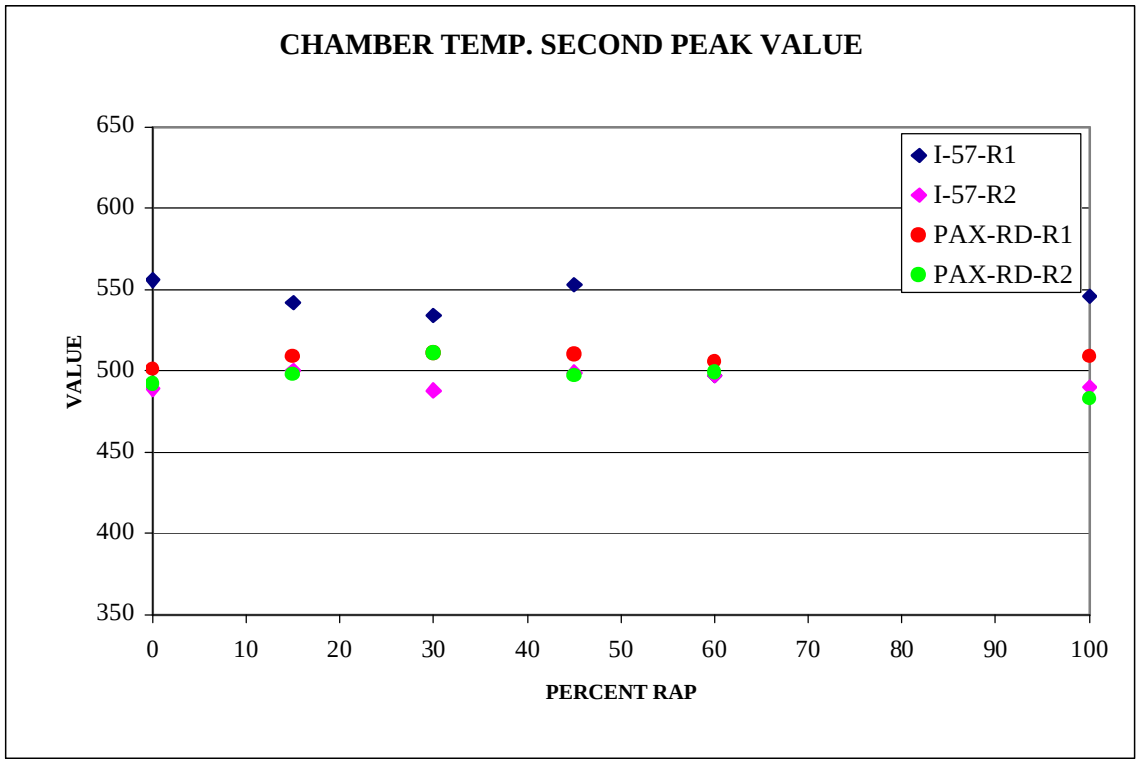

Figure D-3

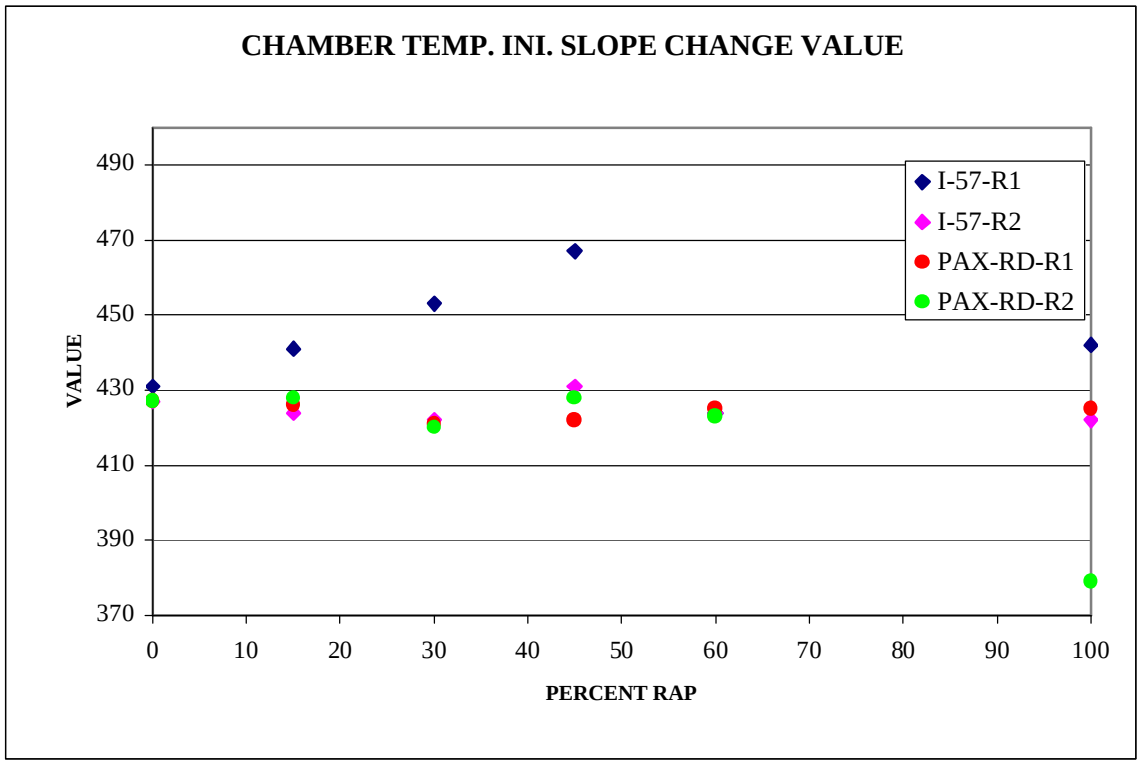

Figure D-4

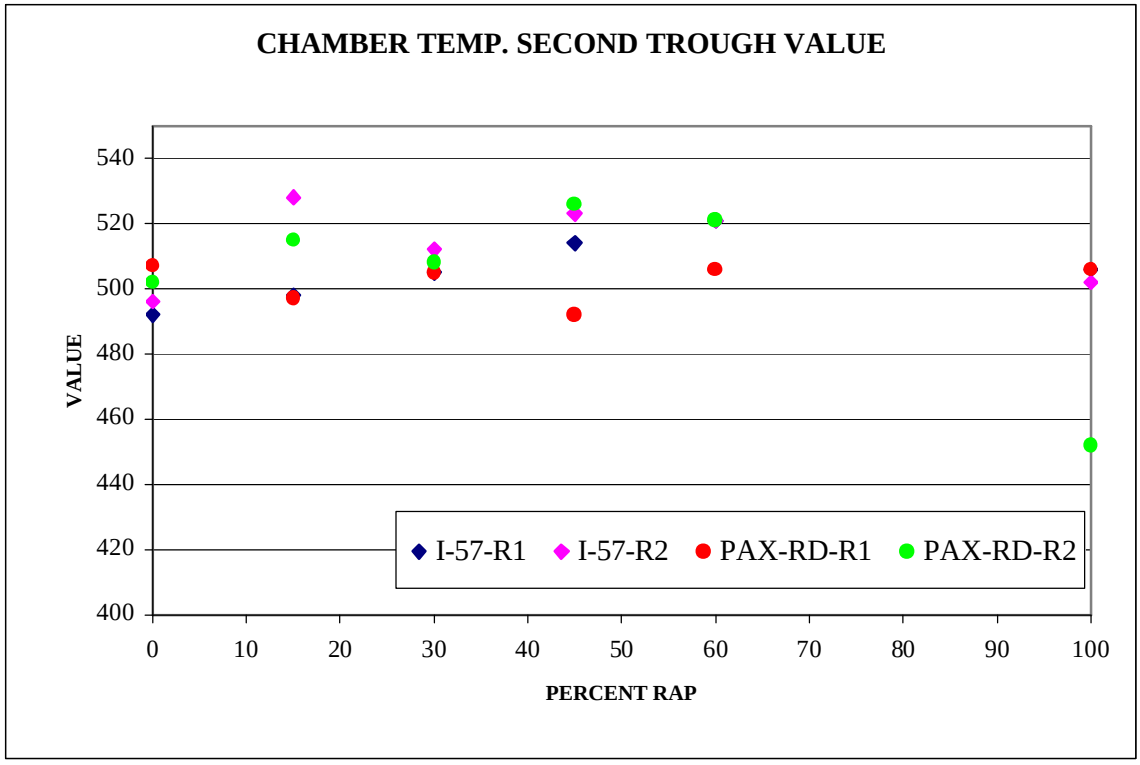

Figure D-5

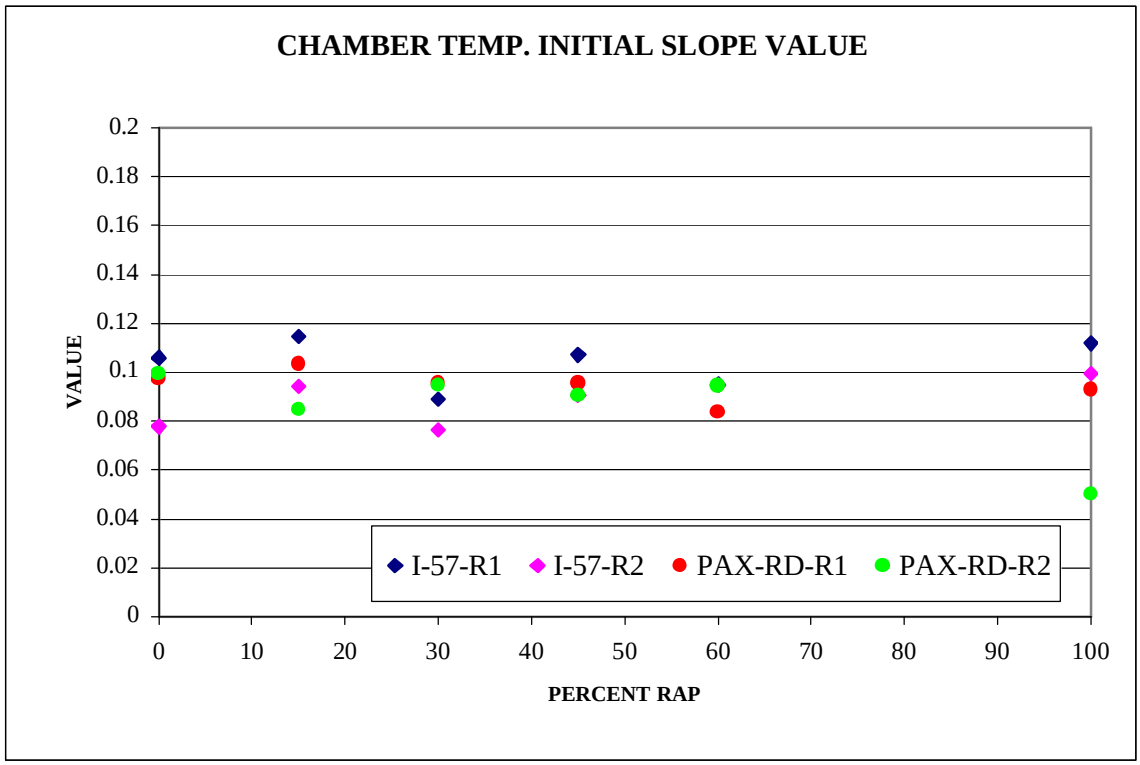

Figure D-6

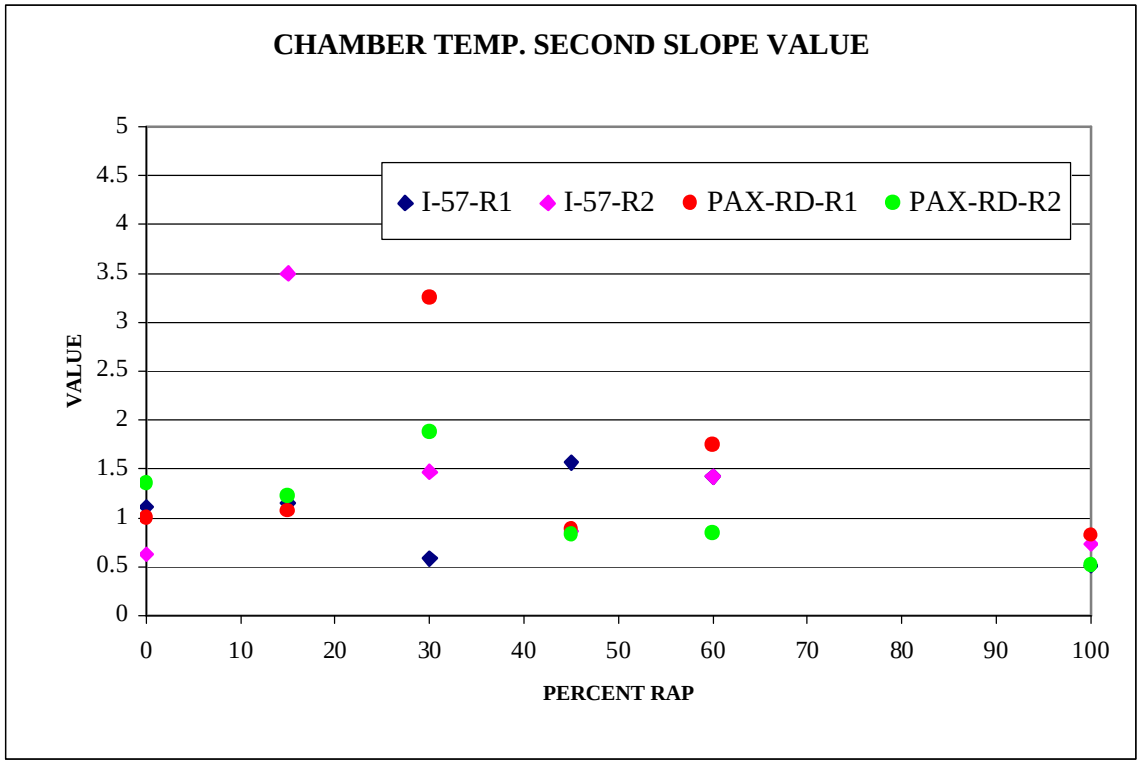

Figure D-7

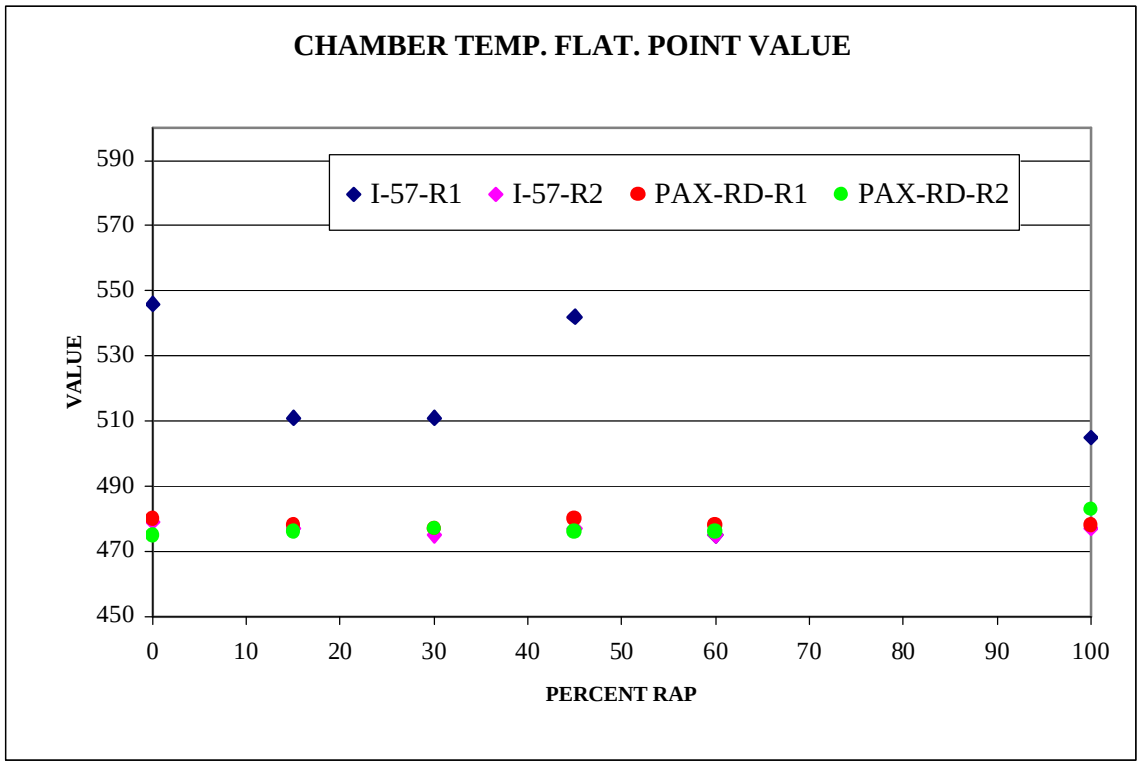

Figure D-8

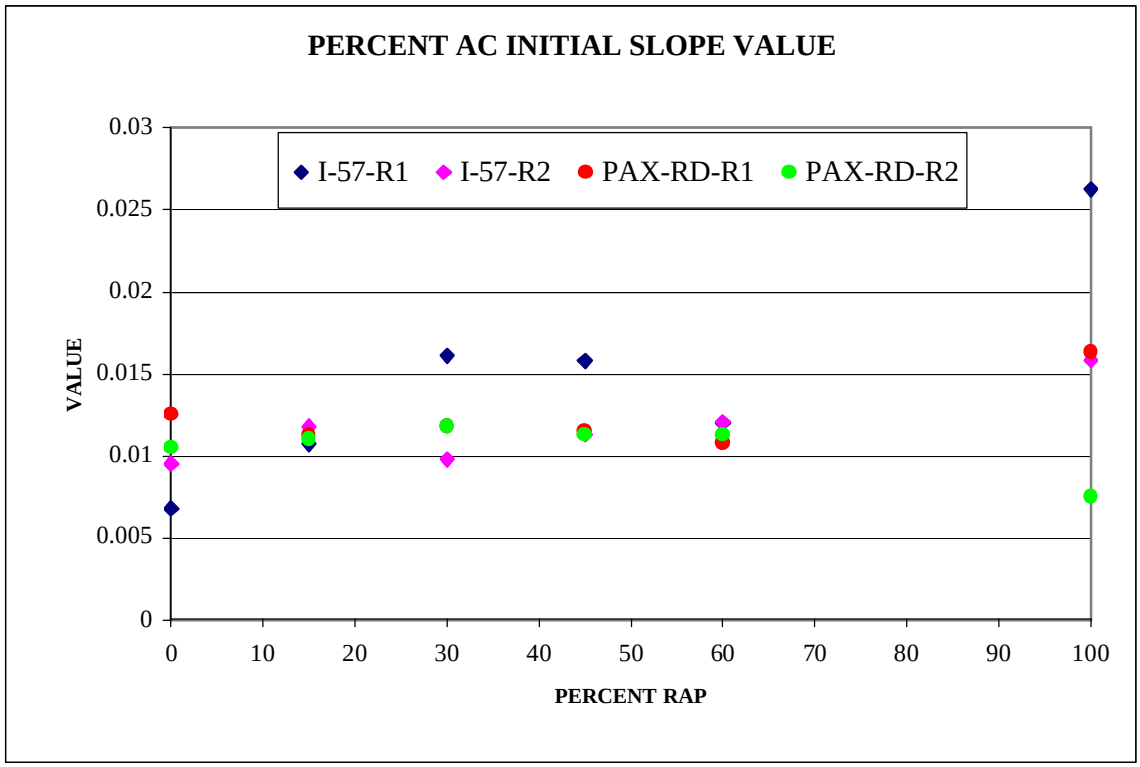

Figure D-9

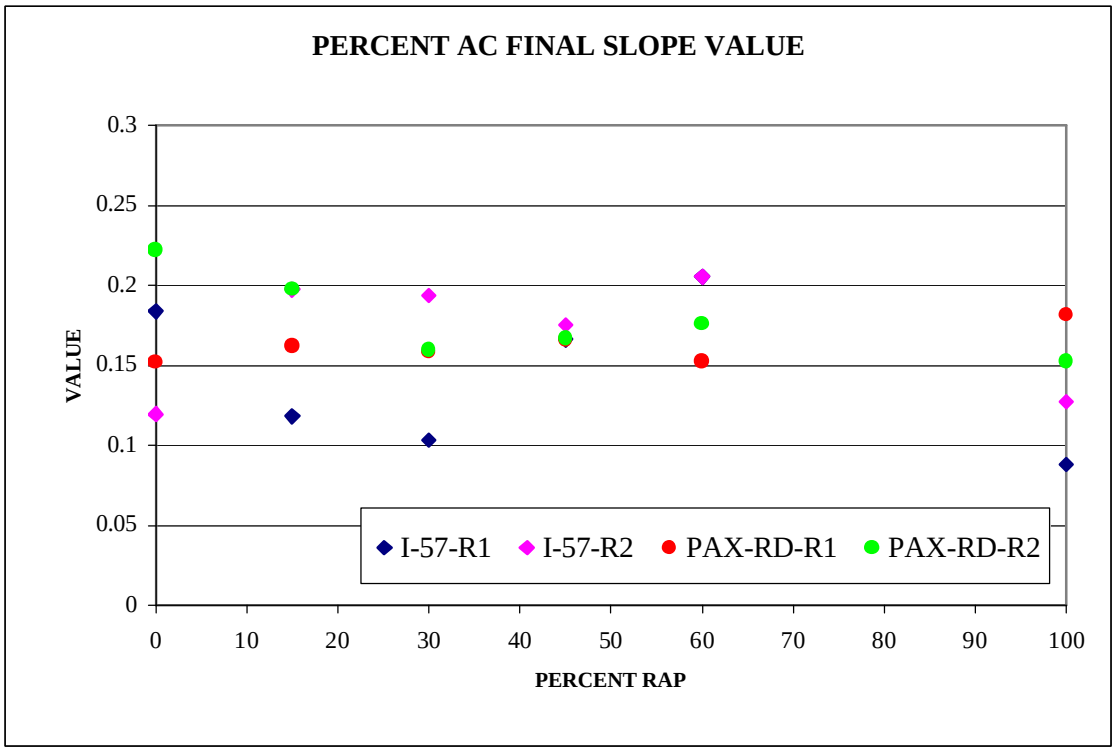
PERCENT AC FINAL SLOPE VALUE
VALUE
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
70
80
90
100
PERCENT RAP
I-57-R1
I-57-R2
PAX-RD-R1
PAX-RD-R2

Figure D-10

D.2 Predictions for I-57 Material by Various Micromechanics Models:

RAP Binder Amount %		0	5	10	15	20	25	30	35	40
Paul's Rule of Mixtures	G-upper =	1.14	2.40	3.66	4.92	6.18	7.44	8.71	9.97	11.23
	G-lower =	1.14	1.20	1.26	1.33	1.41	1.50	1.60	1.71	1.84
Hashin APG	G-lower=	1.14	1.26	1.39	1.53	1.69	1.87	2.07	2.29	2.55
	G-upper =	1.14	1.86	2.61	3.40	4.23	5.10	6.01	6.97	7.98
Hashin CS	G-lower=	1.14	1.23	1.33	1.43	1.55	1.67	1.82	1.99	2.19
	G-upper =	1.14	1.25	1.35	1.47	1.59	1.73	1.90	2.08	2.30
Christ. & Lo GSCS	G-Eff =	1.14	1.20	1.27	1.35	1.44	1.54	1.65	1.78	1.93
Mori-Tanaka	G-Eff =	1.14	1.20	1.27	1.35	1.44	1.54	1.65	1.78	1.93
Hirsch (x = 0.75)	G-Eff =	1.14	1.92	2.48	2.94	3.35	3.73	4.12	4.52	4.94

45	50	55	60	65	70	75	80	85	90	95	100
12.49	13.75	15.01	16.27	17.53	18.80	20.06	21.32	22.58	23.84	25.10	26.36
2.00	2.18	2.40	2.67	3.01	3.45	4.03	4.85	6.10	8.20	12.50	26.36
2.85	3.20	3.61	4.11	4.72	5.48	6.46	7.76	9.60	12.36	16.99	26.36
9.05	10.18	11.37	12.64	13.98	15.41	16.93	18.56	20.31	22.18	24.19	26.36
2.42	2.70	3.04	3.45	3.98	4.65	5.54	6.76	8.53	11.27	16.06	26.36
2.56	2.87	3.24	3.70	4.28	5.02	5.99	7.31	9.19	12.05	16.84	26.36
2.11	2.31	2.56	2.86	3.23	3.72	4.36	5.26	6.60	8.83	13.27	26.36
2.11	2.31	2.56	2.86	3.23	3.72	4.36	5.26	6.60	8.83	13.27	26.36
5.40	5.91	6.49	7.16	7.95	8.89	10.06	11.53	13.47	16.14	20.05	26.36

D.3 Predictions for RAP-C Material by Various Micromechanics Models:

RAP Binder Amount %		0	5	10	15	20	25	30	35	40
Paul's Rule of Mixtures	G-upper =	3.90	6.97	10.04	13.12	16.19	19.27	22.34	25.41	28.49
	G-lower =	3.90	4.09	4.30	4.54	4.80	5.10	5.43	5.81	6.25
Hashin APG	G-lower=	3.90	4.29	4.71	5.18	5.70	6.28	6.92	7.65	8.48
	G-upper =	3.90	5.68	7.53	9.48	11.52	13.65	15.90	18.26	20.74
Hashin CS	G-lower=	3.90	4.21	4.53	4.87	5.25	5.67	6.14	6.69	7.33
	G-upper =	3.90	4.25	4.61	4.98	5.40	5.86	6.38	6.99	7.69
Christ. & Lo GSCS	G-Eff =	3.90	4.10	4.32	4.56	4.83	5.14	5.48	5.88	6.33
Mori-Tanaka	G-Eff =	3.90	4.10	4.32	4.56	4.83	5.14	5.48	5.88	6.33
Hirsch (x = 0.75)	G-Eff =	3.90	5.93	7.53	8.91	10.16	11.36	12.56	13.78	15.07

45	50	55	60	65	70	75	80	85	90	95	100
31.56	34.64	37.71	40.78	43.86	46.93	50.00	53.08	56.15	59.23	62.30	65.37
6.76	7.36	8.07	8.94	10.02	11.40	13.22	15.73	19.42	25.36	36.55	65.37
9.43	10.52	11.80	13.33	15.16	17.41	20.25	23.92	28.87	35.92	46.71	65.37
23.35	26.12	29.03	32.12	35.40	38.88	42.59	46.54	50.76	55.29	60.14	65.37
8.08	8.97	10.04	11.34	12.96	15.00	17.65	21.18	26.08	33.27	44.70	65.37
8.51	9.49	10.66	12.09	13.86	16.07	18.92	22.67	27.81	35.15	46.38	65.37
6.86	7.48	8.22	9.12	10.23	11.65	13.52	16.09	19.85	25.88	37.11	65.37
6.86	7.48	8.22	9.12	10.23	11.65	13.52	16.09	19.85	25.88	37.11	65.37
16.46	17.97	19.66	21.58	23.79	26.38	29.50	33.31	38.13	44.41	52.97	65.37

D.4 Predictions for Various Data Sets used in Model Calibration:

%age RAP-->	0	5	10	15	20	25	30	35	40	45	50	55
Data Set 1	2.80	3.23	3.70	4.20	4.74	5.32	5.95	6.64	7.39	8.23	9.16	10.21
Data Set 2	2.80	3.27	3.78	4.33	4.93	5.59	6.32	7.13	8.04	9.06	10.23	11.60
Data Set 3	1.14	1.68	2.24	2.84	3.47	4.13	4.83	5.57	6.35	7.19	8.08	9.04
Data Set 4	3.90	5.37	6.92	8.54	10.24	12.04	13.93	15.93	18.05	20.30	22.70	25.26
Data Set 5	2.95	3.32	3.71	4.11	4.53	4.97	5.44	5.92	6.44	6.97	7.54	8.15
Data Set 6	3.75	3.84	3.94	4.07	4.21	4.39	4.59	4.82	5.10	5.42	5.80	6.24
Data Set 7	1.56	3.67	5.88	8.20	10.62	13.17	15.85	18.67	21.64	24.78	28.08	31.58
Data Set 8	3.04	3.81	4.63	5.49	6.40	7.36	8.39	9.50	10.68	11.95	13.32	14.82
Data Set 9	3.70	4.77	5.91	7.12	8.40	9.78	11.26	12.85	14.58	16.46	18.53	20.82
Data Set 10	2.82	3.43	4.08	4.76	5.49	6.27	7.10	8.00	8.97	10.02	11.17	12.43
Data Set 11	3.70	4.33	5.01	5.74	6.53	7.40	8.35	9.40	10.57	11.88	13.36	15.06
Data Set 12	2.82	3.87	4.96	6.11	7.32	8.58	9.91	11.31	12.79	14.35	16.00	17.76
Data Set 13	3.70	5.08	6.54	8.08	9.71	11.45	13.29	15.27	17.39	19.67	22.15	24.85
Data Set 14	2.82	4.21	5.66	7.17	8.75	10.39	12.11	13.91	15.78	17.75	19.80	21.94

60	65	70	75	80	85	90	95	100	*s*
11.40	12.78	14.39	16.31	18.67	21.66	25.63	31.25	40.00	0.20
13.20	15.13	17.53	20.58	24.68	30.53	39.73	56.69	100.00	0.07
10.08	11.20	12.43	13.79	15.32	17.09	19.23	22.03	26.36	0.70
28.00	30.96	34.17	37.69	41.58	45.97	51.05	57.21	65.40	0.78
8.78	9.46	10.19	10.96	11.79	12.69	13.67	14.74	15.92	0.78
6.75	7.34	8.04	8.86	9.83	10.97	12.33	13.96	15.92	-1.10
35.28	39.20	43.34	47.73	52.35	57.18	62.10	66.72	68.79	1.13
16.47	18.29	20.33	22.65	25.36	28.59	32.62	37.98	45.84	0.50
23.39	26.30	29.68	33.69	38.62	44.98	53.82	67.72	95.05	0.31
13.83	15.41	17.20	19.27	21.73	24.74	28.58	33.83	41.76	0.39
17.05	19.40	22.26	25.83	30.47	36.84	46.28	62.08	95.05	0.11
19.63	21.62	23.76	26.05	28.55	31.27	34.29	37.71	41.76	0.90
27.83	31.14	34.88	39.20	44.32	50.67	59.10	71.66	95.05	0.45
24.17	26.49	28.90	31.38	33.89	36.39	38.76	40.74	41.76	1.30

D.5 Predictions for RAP Variability Data Sets:

%age RAP->	0	5	10	15	20	25	30	35	40	45
G*										
RAP 1	2.50	3.15	3.90	4.69	5.45	6.12	6.69	7.68	8.75	9.91
RAP 2	2.50	2.84	3.23	3.62	4.02	4.39	4.73	5.22	5.75	6.31
RAP 3	2.50	2.62	2.76	2.89	3.03	3.17	3.30	3.46	3.62	3.79
RAP 4	2.50	3.22	4.04	4.91	5.74	6.47	7.08	8.17	9.36	10.64
RAP 5	2.50	2.79	3.11	3.45	3.78	4.10	4.40	4.81	5.24	5.70
RAP 6	2.50	2.85	3.23	3.64	4.04	4.41	4.76	5.25	5.79	6.36
RAP 7	2.50	2.72	2.96	3.21	3.46	3.70	3.94	4.24	4.55	4.89
RAP 8	2.50	4.44	6.74	9.16	11.42	13.25	14.61	17.65	21.01	24.67
RAP 9	2.50	2.99	3.55	4.14	4.70	5.22	5.68	6.41	7.20	8.05
RAP 10	2.50	2.96	3.48	4.02	4.55	5.03	5.46	6.14	6.87	7.65
RAP 11	2.50	3.86	5.46	7.15	8.73	10.05	11.06	13.18	15.51	18.05
I-57 RAP	2.50	2.86	3.26	3.67	4.08	4.47	4.83	5.34	5.89	6.48
Paxton Rd	2.50	3.94	5.63	7.41	9.07	10.45	11.51	13.75	16.21	18.89
RAP A/B	2.50	3.98	5.73	7.57	9.29	10.72	11.80	14.11	16.66	19.43
RAP C	2.50	3.18	3.97	4.80	5.59	6.28	6.87	7.91	9.04	10.26
RAP D	2.50	3.01	3.58	4.19	4.78	5.31	5.78	6.53	7.35	8.23

50	55	60	65	70	75	80	85	90	95	100
11.15	12.44	13.80	15.20	16.66	18.18	19.81	21.61	23.72	26.38	30.08
6.90	7.52	8.17	8.84	9.54	10.28	11.06	11.92	12.86	13.95	15.25
3.96	4.13	4.32	4.51	4.70	4.90	5.11	5.32	5.55	5.79	6.04
12.00	13.44	14.93	16.48	18.09	19.76	21.55	23.54	25.88	28.87	33.15
6.19	6.70	7.23	7.78	8.35	8.96	9.60	10.29	11.04	11.90	12.88
6.96	7.58	8.24	8.92	9.63	10.38	11.17	12.04	13.00	14.11	15.42
5.23	5.60	5.97	6.36	6.77	7.19	7.64	8.12	8.63	9.20	9.82
28.57	32.67	36.91	41.25	45.64	50.09	54.69	59.69	65.69	74.52	94.03
8.94	9.89	10.87	11.90	12.97	14.08	15.28	16.60	18.11	19.93	22.27
8.48	9.35	10.26	11.20	12.18	13.22	14.32	15.53	16.92	18.56	20.64
20.75	23.59	26.54	29.57	32.67	35.84	39.17	42.85	47.28	53.54	65.13
7.10	7.75	8.43	9.14	9.88	10.65	11.48	12.37	13.38	14.53	15.92
21.74	24.74	27.86	31.05	34.31	37.65	41.15	44.99	49.64	56.25	68.79
22.38	25.49	28.71	32.01	35.37	38.82	42.42	46.38	51.16	57.99	71.15
11.55	12.91	14.33	15.81	17.33	18.93	20.64	22.53	24.75	27.56	31.53
9.16	10.14	11.16	12.22	13.32	14.48	15.72	17.09	18.66	20.56	23.02

D.6 Predictions for RAP Variability Data (Untrimmed Data):

%age RAP-->	0	5	10	15	20	25	30	35	40	45
Average	2.50	3.22	4.06	4.93	5.77	6.50	7.12	8.21	9.41	10.71
Ave+SD	2.50	3.76	5.23	6.78	8.24	9.46	10.41	12.36	14.50	16.83
Ave-SD	2.50	2.65	2.81	2.98	3.15	3.32	3.48	3.68	3.88	4.09

50	55	60	65	70	75	80	85	90	95	100
12.08	13.53	15.04	16.61	18.22	19.92	21.72	23.73	26.09	29.11	33.45
19.31	21.92	24.64	27.42	30.28	33.21	36.30	39.72	43.83	49.58	59.84
4.31	4.54	4.77	5.02	5.27	5.53	5.80	6.08	6.39	6.71	7.05

D.7 Predictions for RAP Variability Data (Trimmed Data):

%age RAP-->	0	5	10	15	20	25	30	35	40	45
Average	2.50	3.17	3.95	4.76	5.54	6.23	6.82	7.84	8.95	10.15
Ave+SD	2.50	3.61	4.90	6.27	7.55	8.64	9.49	11.21	13.09	15.13
Ave-SD	2.50	2.72	2.95	3.20	3.44	3.68	3.92	4.21	4.52	4.85

50	55	60	65	70	75	80	85	90	95	100
11.43	12.77	14.17	15.62	17.12	18.70	20.38	22.24	24.43	27.20	31.08
17.31	19.60	21.97	24.42	26.94	29.54	32.28	35.33	38.99	44.00	52.47
5.19	5.54	5.91	6.30	6.69	7.11	7.55	8.01	8.52	9.07	9.68

D.8 Predictions for RAP Variability Data (Grouped Data):

G* <35kPa:

%age RAP-->	0	5	10	15	20	25	30	35	40
Average	2.50	2.94	3.43	3.95	4.45	4.92	5.33	5.98	6.67
Ave + SD	2.50	3.12	3.83	4.57	5.29	5.92	6.47	7.40	8.41
Ave – SD	2.50	2.75	3.02	3.30	3.58	3.85	4.12	4.46	4.82

45	50	55	60	65	70	75	80	85	90	95	100
7.41	8.20	9.02	9.89	10.78	11.71	12.69	13.74	14.89	16.19	17.74	19.67
9.50	10.67	11.89	13.16	14.48	15.85	17.29	18.82	20.52	22.50	24.98	28.36
5.20	5.60	6.02	6.45	6.91	7.38	7.87	8.39	8.95	9.55	10.22	10.98

G* >35kPa:

%age RAP-->	0	5	10	15	20	25	30	35	40
Average	2.50	4.06	5.89	7.82	9.63	11.12	12.25	14.67	17.35
Ave + SD	2.50	4.32	6.47	8.73	10.84	12.57	13.85	16.70	19.84
Ave - SD	2.50	3.79	5.31	6.91	8.41	9.67	10.64	12.65	14.86

45	50	55	60	65	70	75	80	85	90	95	100
20.26	23.36	26.63	30.01	33.47	37.00	40.61	44.37	48.50	53.48	60.64	74.77
23.25	26.90	30.73	34.70	38.75	42.87	47.05	51.39	56.11	61.80	70.11	87.85
17.26	19.82	22.51	25.31	28.18	31.12	34.14	37.31	40.82	45.05	50.98	61.70

D.9 Predictions by Global Aging Model:

Aging Time	Aging Temp	Depth	Test Temperature	Air Voids	Initial G*	Initial Viscosity	Aged G*
(months)	(C)	(inch)	(C)	(%)	(kPa)	(cP)	(kPa)
0	35	0.5	64	7%	5	50936	5.00
1	35	0.5	64	7%	5	50936	5.78
2	35	0.5	64	7%	5	50936	6.43
3	35	0.5	64	7%	5	50936	7.21
4	35	0.5	64	7%	5	50936	8.01
5	35	0.5	64	7%	5	50936	8.96
6	35	0.5	64	7%	5	50936	9.79
9	35	0.5	64	7%	5	50936	12.66
12	35	0.5	64	7%	5	50936	15.57
18	35	0.5	64	7%	5	50936	21.05
24	35	0.5	64	7%	5	50936	24.19

Aging Time	Aging Temp	Depth	Test Temperature	Air Voids	Initial G*	Initial Viscosity	Aged G*
(months)	(C)	(inch)	(C)	(%)	(kPa)	(cP)	(kPa)
0	35	2	64	7%	5	50936	5.00
1	35	2	64	7%	5	50936	5.36
2	35	2	64	7%	5	50936	5.58
3	35	2	64	7%	5	50936	5.91
4	35	2	64	7%	5	50936	6.24
5	35	2	64	7%	5	50936	6.68
6	35	2	64	7%	5	50936	7.02
9	35	2	64	7%	5	50936	8.30
12	35	2	64	7%	5	50936	9.60
18	35	2	64	7%	5	50936	12.02
24	35	2	64	7%	5	50936	13.24

Aging Time	Aging Temp	Depth	Test Temperature	Air Voids	Initial G*	Initial Viscosity	Aged G*
(months)	(C)	(inch)	(C)	(%)	(kPa)	(cP)	(kPa)
0	45	0.5	64	7%	5	50936	5.00
1	45	0.5	64	7%	5	50936	6.03
2	45	0.5	64	7%	5	50936	7.05
3	45	0.5	64	7%	5	50936	8.19
4	45	0.5	64	7%	5	50936	9.39
5	45	0.5	64	7%	5	50936	10.64
6	45	0.5	64	7%	5	50936	11.92
9	45	0.5	64	7%	5	50936	16.10
12	45	0.5	64	7%	5	50936	20.31
18	45	0.5	64	7%	5	50936	28.52
24	45	0.5	64	7%	5	50936	34.89

Aging Time	Aging Temp	Depth	Test Temperature	Air Voids	Initial G*	Initial Viscosity	Aged G*
(months)	(C)	(inch)	(C)	(%)	(kPa)	(cP)	(kPa)
0	35	2	64	7%	5	50936	5.00
1	35	2	64	7%	5	50936	5.68
2	35	2	64	7%	5	50936	6.32
3	35	2	64	7%	5	50936	7.05
4	35	2	64	7%	5	50936	7.82
5	35	2	64	7%	5	50936	8.61
6	35	2	64	7%	5	50936	9.43
9	35	2	64	7%	5	50936	12.12
12	35	2	64	7%	5	50936	14.82
18	35	2	64	7%	5	50936	20.10
24	35	2	64	7%	5	50936	24.62

Appendix E

Micromechanics Formulations

E.1 Paul's Rule of Mixtures:

$$K_l^* = [\sum \frac{V_n}{K_n}]^{-1}$$

$$K_u^* = \sum K_n V_n$$

$$G_l^* = [\sum \frac{V_n}{G_n}]^{-1}$$

$$G_u^* = \sum G_n V_n$$

Where, K^*_l and K^*_u are the lower and upper bound effective bulk moduli values for the composite. Similarly G^*_l and G^*_u are upper and lower effective shear moduli values for the composite. The label *n* in subscript represents phase *n* present in the composite material. Subsequently G_n and K_n are the shear and bulk moduli for the n^{th} phase and V_n is the volume of the n^{th} phase. Same notations will be used throughout the appendix.

E.2 Hashin and Shtrikman Arbitrary Phase Geometry Model:

$$K_l^* = K_1 + \frac{V_2}{1/(K_2 - K_1) + 3V_1/(3K_1 + 4G_1)}$$

$$K_u^* = K_2 + \frac{V_1}{1/(K_1 - K_2) + 3V_2/(3K_2 + 4G_2)}$$

When, $K_1 < K_2$

$$G_l^* = G_1 + \frac{V_2}{1/(G_2 - G_1) + 6V_1(K_1 + 2G_1)/5G_1(3K_1 + 4G_1)}$$

$$G_u^* = G_2 + \frac{V_1}{1/(G_1 - G_2) + 6V_2(K_2 + 2G_2)/5G_2(3K_2 + 4G_2)}$$

When, $G_1 < G_2$

$$n_l = n_1 + \frac{V_2}{1/n_2 - n_1 + 6(K_1 + 2n_1)V_1/5n_1(3K_1 + 4n_1)}$$

$$n_u = n_2 + \frac{V_1}{1/n_1 - n_2 + 6(K_2 + 2n_2)V_2/5n_2(3K_2 + 4n_2)}$$

Where, n_l and n_u represent the upper and lower bound Poisson's ratio for the composite material, and n_n represents the Poisson's ratio for the n^{th} material. All other notations are same as described earlier.

E.3 Hashin's Composite Sphere Model:

$$K^* = K_m + (K_p - K_m)\frac{(4G_m + 3K_m)c}{4G_m + 3K_p + 3(K_m - K_p)c}$$

Where, c is volume concentration of particulate (spherical inclusion) in matrix and is given by

$$c = \frac{V_p}{V_m} = \frac{\overline{V}_n}{V_n}$$

Where, $\overline{V}_n$ and V_n represents the volume of single inclusion and volume of surrounding matrix.

The bounds for the shear modulus for composite material with one kind of an inclusion are presented here.

$$G_l^* = \frac{G_m}{1 + (1-h)y_1^{(s)}c}$$

$$G_u^* = G_m[1+(h-1)y_1^{(e)}c]$$

Where,

$$h = \frac{G_p}{G_m}$$

$y_1^{(s)}$ and $y_1^{(e)}$ are complicated functions of elastic constants. The solutions for $y_1^{(s)}$ and $y_1^{(e)}$ are presented below

$$y_1^{(e)} = \frac{1}{F - \frac{DG}{E}}$$

$$y_1^{(s)} = \frac{1}{J - \frac{DG}{H}}$$

Where:

$$D = \frac{2(1-h)}{5(1-n_m)}(r^7 - r^5)$$

$$E = [(7-10n_p)-(7-n_m)J]4r^7 + 4(7-10n_m)J$$

$$F = h + \frac{7-5n_m}{15(1-n_m)}(1-h) + \frac{2(4-5n_m)}{15(1-n_m)}(1-h)r^3$$

$$G = 21J(\frac{1}{r^2}-1)$$

$$H = [(7-10n_p)-(7-10n_m)J]4r^7 - (7-5n_m)J$$

$$I = h + \frac{7-5n_m}{15(1-n_m)}(1-h)(1-r^3)$$

$$r = c^{\frac{1}{3}}$$

$$J = \frac{4(7-10n_p)+h(7+5n_p)}{35(1-n_m)}$$

E.4 Christensen and Lo Generalized Self-Consistent Scheme Model:

The solution for the shear modulus is given in terms of a quadratic equation,

$$A\left(\frac{G^*}{G_m}\right)^2 + B\left(\frac{G^*}{G_m}\right) + C = 0$$

Expressions for coefficients of above quadratic equation are as following for spherical

inclusion,

$$A = 8[\frac{G_p}{G_m}-1](4-5n_m)h_1c^{\frac{10}{3}} - 2[63(\frac{G_p}{G_m}-1)h_2 + 2h_1h_3]c^{\frac{7}{3}} + 252[\frac{G_p}{G_m}-1]h_2c^{\frac{5}{3}}$$

$$-50[\frac{G_p}{G_m}-1](7-12n_m+8n_m^2)h_2c + 4(7-10n_m)h_2h_3$$

$$B = -4[\frac{G_p}{G_m}-1](1-5n_m)h_1c^{\frac{10}{3}} + 4[63(\frac{G_p}{G_m}-1)h_2 + 2h_1h_3]c^{\frac{7}{3}} - 504[\frac{G_p}{G_m}-1]h_2c^{\frac{5}{3}}$$

$$+150[\frac{G_p}{G_m}-1](3-n_m)n_mh_2c + 3(15n_3-7)h_2h_3$$

$$C = 4[\frac{G_p}{G_m}-1](5n_m-7)h_1c^{\frac{10}{3}} + 2[63(\frac{G_p}{G_m}-1)h_2 + 2h_1h_3]c^{\frac{7}{3}} + 252[\frac{G_p}{G_m}-1]h_2c^{\frac{5}{3}}$$

$$25[\frac{G_p}{G_m}-1](n_m^2-7)h_2c - (7+5n_m)h_2h_3$$

Where $?_1$, $?_2$ and $?_3$ are as shown in following equations,

$$h_1 = [\frac{G_p}{G_m}-1](49-50n_pn_m) + 35(\frac{G_p}{G_m})(n_p-2n_m) + 35(2n_p+n_m)$$

$$h_2 = 5\eta_p[\frac{G_p}{G_m} - 8] - 7[\frac{G_p}{G_m} + 4]$$

$$h_3 = (\frac{G_p}{G_m})(8 - 10\eta_m) + (7 - 5\eta_m)$$

All notations in above equations are same as used earlier

E.5 Mori-Tanaka Model:

$$K^* = K_m + \frac{c(K_p - K_m)K_m}{(1-c)(K_p - K_m)a_1 + K_m}$$

Where:

$$a_1 = \frac{3K_m}{3K_m + 4\eta_m}$$

And:

$$G^* = G_m + \frac{c(G_p - G_m)G_m}{(1-c)(G_p - G_m)b_1 + G_m}$$

Where:

$$b_1 = \frac{6(K_m + 2G_m)}{5(3K_m + 4G_m)}$$

E.6 Hirsch Model:

$$\frac{1}{E_c} = (1-x)\left(\frac{V_1}{E_1} + \frac{V_2}{E_2}\right) + x\left(\frac{1}{V_1E_1 + V_2E_2}\right)$$

$$G = \frac{E}{3(1+n)}$$

Where, E_c = *Effective Young's modulus of composite*

E_1 *and* E_2 = *Young's modulus of phase one and two respectively*

x = Ratio of phases in parallel arrangement to the total volume

Appendix F
RAP Detection and Calibration Tool (on CD-Rom)

F.1 RAP Detection and Calibration Tool: (IL_RAP.xls)

It is a spreadsheet program that could be used for predicting RAP binder amount in the recovered HMA binder. The same program could also be used for determining the calibration factors when the test results from binder blends (of tank and RAP binder) are available.

The program is user friendly and is attached on the CD-ROM provided with this report.

The program is created by implementing the methods described in Chapter 6 on rigorous RAP detection and quantification method using physical properties of asphalt binders. It is easier to use this program since the micromechanics model is very cumbersome to evaluate by hand.

Appendix G

Description of Lab Testing, Analysis and Findings from Bradley University (Complete Write-up with Appendix and Proposed Program “Bradley.xls” are Provided on the Companion CD-Rom to this Report)

G.1 Introduction:

The following report was prepared by the research team at Bradley University. The main objective was to explore RAP detection and quantification method. The method developed requires use of an MS-Excel spreadsheet program. The program (Bradley.xls) is provided on the CD-Rom in Appendix G folder.

Quick Detection methods

G.1.1 Introduction

Two rapid methods were developed for RAP detection; one looks into the variation of aggregate gradation and the other looks into the variation of voids in gyratory-compacted asphalt concrete specimens. These methods were found to have limitations for use in quality assurance, but they have been documented for possible use by contractors as a rapid quality control for RAP mixture production.

G.1.2. RAP and Mix Gradation

G.1.2.1 Sampling

Hot Mix Asphalt plants in Illinois were selected based on their productivity of mixes containing Reclaimed Asphalt Pavement (RAP). Plants that produced mixes with different percent of RAP were selected. Three plants were selected, one in Collinsville, IL, and two in Peoria, IL,. The Collinsville plant produces two mixes containing RAP, the first Mix, which is a surface mix, has 15 percent RAP, and the second mix, which is a shoulder mix, has 40 percent RAP. One of the Peoria plants produced a mix containing 20 percent RAP and the other produced a mix containing 30 percent RAP.
Illinois Department of Transportation (IDOT) sampling procedures were followed in all sampling activities for this project. In addition, several points were considered that are specific for this study. These include:

1. Samples of the RAP material were obtained from homogeneous stockpiles only, Homogeneous RAP stockpiles shall consist of RAP from Class I/SuperPave^{TM}, This was done to reduce variability associated with other stockpiles.
2. The production mix was sampled in the same day. This was also done to reduce variability of the stockpiled aggregate material by sampling before and after mixing.
3. Samples were taken under IDOT supervision in all three plants, and using IDOT aggregate sampling procedures.

Sample sizes were chosen based on proportioning the Job Mix Formula (JMF) to the required number of laboratory specimen to be prepared at Bradley University.

Table G.1: Size and Quantity of Samples

Material	Number of sample bags	
RAP	6	
Aggregates	6	
Binder	3 cans	
Mixes	3	

G.2.1 Testing Plan

Adding higher or lower percentages of RAP in a mix affects both the aggregate gradation and the binder properties. Attempting to deduce any information about the RAP percentages by studying mixture properties will become cumbersome. Accordingly, the first step will be to isolate the effect of the aggregate from those of the binder. This is achieved by changing the aggregate percentages to include more RAP aggregate but without changing the final aggregate blend gradation, or the JMF. Using simple optimization techniques in Microsoft Excel spreadsheet does this. A spreadsheet was developed to search for the aggregate percentages required to maintain the same JMF while changing RAP aggregate percentages. Examples of these percentages is given in table G.2 through table G.9.

Table G.2 JMF Information for Mix A, Collinsville Surface Mix

Mix Type	Plant	Gradation											
(A)	Collinsvill ,IL		1-(032CMM16)		2-(038FAM20)		3-(037FAM01)		4-(004MFM01)		Rap		
	Surface Mix		Perct 1=	55.4	Perct 2=	17.8	Perct 3=	9.1	Perct 3=	3.3	Perct 4=	14.4	100
		Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend		Formula
		1	100.0	55.40	100.0	17.80	100.0	9.10	100.0	3.3	100.0	14.40	100.00	100.0
		3/4	100.0	55.40	100.0	17.80	100.0	9.10	100.0	3.3	100.0	14.40	100.00	100.0
		1/2	100.0	55.40	100.0	17.80	100.0	9.10	100.0	3.3	99.8	14.37	99.97	100.0
		3/8	98.0	54.29	100.0	17.80	100.0	9.10	100.0	3.3	95.4	13.74	98.23	98.0
		#4	38.0	21.05	100.0	17.80	99.1	9.02	100.0	3.3	66.6	9.59	60.76	61.0
		#8	4.8	2.66	83.0	14.77	92.0	8.37	100.0	3.3	44.6	6.42	35.53	36.0
		#16	3.0	1.66	50.4	8.97	71.3	6.49	100.0	3.3	37.6	5.41	25.84	26.0
		#30	2.6	1.44	27.0	4.81	42.0	3.82	100.0	3.3	31.6	4.55	17.92	18.0
		#50	2.3	1.27	15.0	2.67	16.7	1.52	100.0	3.3	22.8	3.28	12.05	12.0
		#100	2.1	1.16	6.9	1.23	4.9	0.45	98.0	3.2	10.0	1.44	7.51	8.0
		#200	2.0	1.11	4.8	0.85	3.0	0.27	76.0	2.5	6.1	0.88	5.62	5.6

Table G.3 JMF for Mix A, Collinsville Surface Mix, 18% RAP

Mix Type	Plant	Gradation											
(A-1)	Collinsvill ,IL		1-(032CMM16)		2-(038FAM20)		3-(037FAM01)		4-(004MFM01)		Rap		
	Surface Mix		Perct 1=	52.6	Perct 2=	20.1	Perct 3=	6.3	Perct 3=	3.0	Perct 4=	18	100	Formula
		Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend		
		1	100.0	52.6	100.0	20.08	100.0	6.26	100.0	3.0	100.0	18.00	100.00	100.0
		3/4	100.0	52.6	100.0	20.1	100.0	6.3	100.0	3.0	100.0	18.0	100.0	100.0
		1/2	100.0	52.6	100.0	20.1	100.0	6.3	100.0	3.0	99.8	18.0	100.0	100.0
		3/8	98.0	51.6	100.0	20.1	100.0	6.3	100.0	3.0	95.4	17.2	98.1	98.0
		#4	38.0	20.0	100.0	20.1	99.1	6.2	100.0	3.0	66.6	12.0	61.3	61.0
		#8	4.8	2.5	83.0	16.7	92.0	5.8	100.0	3.0	44.6	8.0	36.0	36.0
		#16	3.0	1.6	50.4	10.1	71.3	4.5	100.0	3.0	37.6	6.8	26.0	26.0
		#30	2.6	1.4	27.0	5.4	42.0	2.6	100.0	3.0	31.6	5.7	18.1	18.0
		#50	2.3	1.2	15.0	3.0	16.7	1.0	100.0	3.0	22.8	4.1	12.4	12.0
		#100	2.1	1.1	6.9	1.4	4.9	0.3	98.0	3.0	10.0	1.8	7.6	8.0
		#200	2.0	1.1	4.8	1.0	3.0	0.2	76.0	2.3	6.1	1.1	5.6	5.6

Table G.4 JMF for Mix A, Collinsville Surface Mix, with 12% RAP

Mix Type	Plant	Gradation											
(A-2)	Collinsvill ,IL		1-(032CMM16)		2-(038FAM20)		3-(037FAM01)		4-(004MFM01)		Rap		
	Surface Mix		Perct 1=	57.4	Perct 2=	13.8	Perct 3=	13.1	Perct 3=	3.8	Perct 4=	12	100	Formula
		Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend		
		1	100.0	57.4	100.0	13.8	100.0	13.1	100.0	3.8	100.0	12.0	100.0	100.0
		3/4	100.0	57.4	100.0	13.8	100.0	13.1	100.0	3.8	100.0	12.0	100.0	100.0
		1/2	100.0	57.4	100.0	13.8	100.0	13.1	100.0	3.8	99.8	12.0	100.0	100.0
		3/8	98.0	56.2	100.0	13.8	100.0	13.1	100.0	3.8	95.4	11.4	98.3	98.0
		#4	38.0	21.8	100.0	13.8	99.1	13.0	100.0	3.8	66.6	8.0	60.3	61.0
		#8	4.8	2.8	83.0	11.4	92.0	12.1	100.0	3.8	44.6	5.4	35.4	36.0
		#16	3.0	1.7	50.4	6.9	71.3	9.3	100.0	3.8	37.6	4.5	26.3	26.0
		#30	2.6	1.5	27.0	3.7	42.0	5.5	100.0	3.8	31.6	3.8	18.3	18.0
		#50	2.3	1.3	15.0	2.1	16.7	2.2	100.0	3.8	22.8	2.7	12.1	12.0
		#100	2.1	1.2	6.9	0.9	4.9	0.6	98.0	3.7	10.0	1.2	7.7	8.0
		#200	2.0	1.1	4.8	0.7	3.0	0.4	76.0	2.9	6.1	0.7	5.8	5.6

Table G.5 JMF for Mix A, Collinsville Surface Mix, with 9%RAP.

Mix Type	Plant	Gradation											
(A-3)	Collinsvill ,IL		1-(032CMM16)		2-(038FAM20)		3-(037FAM01)		4-(004MFM01)		Rap		
	Surface Mix		Perct 1= 57.3		Perct 2= 18.7		Perct 3= 11.4		Perct 3= 3.6		Perct 4= 9		100
		Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend		Formula
		1	100.0	57.3	100.0	18.7	100.0	11.4	100.0	3.6	100.0	9.0	100.0	100.0
		3/4	100.0	57.3	100.0	18.7	100.0	11.4	100.0	3.6	100.0	9.0	100.0	100.0
		1/2	100.0	57.3	100.0	18.7	100.0	11.4	100.0	3.6	99.8	9.0	100.0	100.0
		3/8	98.0	56.2	100.0	18.7	100.0	11.4	100.0	3.6	95.4	8.6	98.4	98.0
		#4	38.0	21.8	100.0	18.7	99.1	11.3	100.0	3.6	66.6	6.0	61.4	61.0
		#8	4.8	2.8	83.0	15.5	92.0	10.5	100.0	3.6	44.6	4.0	36.4	36.0
		#16	3.0	1.7	50.4	9.4	71.3	8.1	100.0	3.6	37.6	3.4	26.3	26.0
		#30	2.6	1.5	27.0	5.0	42.0	4.8	100.0	3.6	31.6	2.8	17.8	18.0
		#50	2.3	1.3	15.0	2.8	16.7	1.9	100.0	3.6	22.8	2.1	11.7	12.0
		#100	2.1	1.2	6.9	1.3	4.9	0.6	98.0	3.5	10.0	0.9	7.5	8.0
		#200	2.0	1.1	4.8	0.9	3.0	0.3	76.0	2.7	6.1	0.5	5.7	5.6

Table G.6 JMF Information for Mix B, Collinsville Shoulder Mix.

Mix Type	Plant	Gradation											
(B)	Collinsvill ,IL		1-(042CMM11)		2-(032CMM16)		3-(037FAM01)		4-(004MFM01)		Rap		
	Soulder Mix		Perct 1= 38.5		Perct 2= 8.4		Perct 3= 11.5		Perct 3= 3.6		Perct 4= 38		100
		Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend		Formula
		1	100.0	38.50	100.0	8.40	100.0	11.50	100.0	3.6	100.0	38.00	100.0	100.0
		3/4	93.8	36.11	100.0	8.40	100.0	11.50	100.0	3.6	99.4	37.77	97.4	97.0
		1/2	44.0	16.94	100.0	8.40	100.0	11.50	100.0	3.6	93.8	35.64	76.1	76.0
		3/8	16.7	6.43	96.3	8.09	100.0	11.50	100.0	3.6	88.6	33.67	63.3	63.0
		#4	3.6	1.39	38.0	3.19	99.7	11.47	100.0	3.6	56.2	21.36	41.0	41.0
		#8	2.2	0.85	4.8	0.40	89.3	10.27	100.0	3.6	35.6	13.53	28.6	29.0
		#16	1.9	0.73	3.1	0.26	67.8	7.80	100.0	3.6	26.2	9.96	22.3	22.0
		#30	1.7	0.65	2.7	0.23	46.3	5.32	100.0	3.6	20.0	7.60	17.4	17.0
		#50	1.5	0.58	2.5	0.21	16.2	1.86	100.0	3.6	13.2	5.02	11.3	11.0
		#100	1.4	0.54	2.2	0.18	3.1	0.36	98.0	3.5	9.8	3.72	8.3	8.0
		#200	1.3	0.50	2.1	0.18	1.4	0.16	75.0	2.7	7.9	3.00	6.5	6.5

Table G.7 JMF for Mix B, Collinsville Shoulder Mix, with 40%RAP.

Mix Type	Plant	Gradation											
(B-2)	Collinsvill ,IL Soulder Mix	1-(042CMM11) Perct 1= 38.5		2-(032CMM16) Perct 2= 8.4		3-(037FAM01) Perct 3= 11.5		4-(004MFM01) Perct 3= 3.6		Rap Perct 4= 38		100	Formula
		Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend		
		1	100.0	38.50	100.0	8.40	100.0	11.50	100.0	3.6	100.0	38.00	100.0	100.0
		3/4	93.8	36.11	100.0	8.40	100.0	11.50	100.0	3.6	99.4	37.77	97.4	97.0
		1/2	44.0	16.94	100.0	8.40	100.0	11.50	100.0	3.6	93.8	35.64	76.1	76.0
		3/8	16.7	6.43	96.3	8.09	100.0	11.50	100.0	3.6	88.6	33.67	63.3	63.0
		#4	3.6	1.39	38.0	3.19	99.7	11.47	100.0	3.6	56.2	21.36	41.0	41.0
		#8	2.2	0.85	4.8	0.40	89.3	10.27	100.0	3.6	35.6	13.53	28.6	29.0
		#16	1.9	0.73	3.1	0.26	67.8	7.80	100.0	3.6	26.2	9.96	22.3	22.0
		#30	1.7	0.65	2.7	0.23	46.3	5.32	100.0	3.6	20.0	7.60	17.4	17.0
		#50	1.5	0.58	2.5	0.21	16.2	1.86	100.0	3.6	13.2	5.02	11.3	11.0
		#100	1.4	0.54	2.2	0.18	3.1	0.36	98.0	3.5	9.8	3.72	8.3	8.0
		#200	1.3	0.50	2.1	0.18	1.4	0.16	75.0	2.7	7.9	3.00	6.5	6.5

Table G.8 JMF for Mix B, Collinsville Shoulder Mix, with 36%RAP.

Mix Type	Plant	Gradation											
(B-3)	Collinsvill ,IL Soulder Mix	1-(042CMM11) Perct 1= 38.9		2-(032CMM16) Perct 2= 9.4		3-(037FAM01) Perct 3= 11.9		4-(004MFM01) Perct 3= 3.7		Rap Perct 4= 36.0		100	Formula
		Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend		
		1	100.0	38.93	100.0	9.41	100.0	11.95	100.0	3.7	100.0	36.00	100.0	100.0
		3/4	93.8	36.52	100.0	9.41	100.0	11.95	100.0	3.7	99.4	35.78	97.4	97.0
		1/2	44.0	17.13	100.0	9.41	100.0	11.95	100.0	3.7	93.8	33.77	76.0	76.0
		3/8	16.7	6.50	96.3	9.06	100.0	11.95	100.0	3.7	88.6	31.90	63.1	63.0
		#4	3.6	1.40	38.0	3.58	99.7	11.91	100.0	3.7	56.2	20.23	40.8	41.0
		#8	2.2	0.86	4.8	0.45	89.3	10.67	100.0	3.7	35.6	12.82	28.5	29.0
		#16	1.9	0.74	3.1	0.29	67.8	8.10	100.0	3.7	26.2	9.43	22.3	22.0
		#30	1.7	0.66	2.7	0.25	46.3	5.53	100.0	3.7	20.0	7.20	17.4	17.0
		#50	1.5	0.58	2.5	0.24	16.2	1.94	100.0	3.7	13.2	4.75	11.2	11.0
		#100	1.4	0.55	2.2	0.21	3.1	0.37	98.0	3.6	9.8	3.53	8.3	8.0
		#200	1.3	0.51	2.1	0.20	1.4	0.17	75.0	2.8	7.9	2.84	6.5	6.5

Table G.9 JMF for Mix B, Collinsville Shoulder Mix, with 34%RAP.

Mix Type	Plant	Gradation												
(B-3)	Collinsvill ,IL Soulder Mix		1-(042CMM11) Perct 1= 39.1		2-(032CMM16) Perct 2= 10.5		3-(037FAM01) Perct 3= 12.5		4-(004MFM01) Perct 3= 3.9		Rap Perct 4= 34.0		100	Formula
		Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend		
		1	100.0	39.14	100.0	10.53	100.0	12.45	100.0	3.9	100.0	34.00	100.0	100.0
		3/4	93.8	36.71	100.0	10.53	100.0	12.45	100.0	3.9	99.4	33.80	97.4	97.0
		1/2	44.0	17.22	100.0	10.53	100.0	12.45	100.0	3.9	93.8	31.89	76.0	76.0
		3/8	16.7	6.54	96.3	10.14	100.0	12.45	100.0	3.9	88.6	30.12	63.1	63.0
		#4	3.6	1.41	38.0	4.00	99.7	12.41	100.0	3.9	56.2	19.11	40.8	41.0
		#8	2.2	0.86	4.8	0.51	89.3	11.12	100.0	3.9	35.6	12.10	28.5	29.0
		#16	1.9	0.74	3.1	0.33	67.8	8.44	100.0	3.9	26.2	8.91	22.3	22.0
		#30	1.7	0.67	2.7	0.28	46.3	5.76	100.0	3.9	20.0	6.80	17.4	17.0
		#50	1.5	0.59	2.5	0.26	16.2	2.02	100.0	3.9	13.2	4.49	11.2	11.0
		#100	1.4	0.55	2.2	0.23	3.1	0.39	98.0	3.8	9.8	3.33	8.3	8.0
		#200	1.3	0.51	2.1	0.22	1.4	0.17	75.0	2.9	7.9	2.69	6.5	6.5

For these mix it can easily be seen that the RAP percentages may be changed from 9 to18 for mix A and 34 to 40 for mix B without altering the JMF.

G.2.2 Optimization Excel Software

Optimization is an effective tool in implementing and planning efficient operations and increasing competitive advantage. Organizations need to make intelligent decisions to obtain optimal use of their available resources. The discipline of optimization, through the use of advanced mathematics and computer science techniques, can be used to assist organizations with solving their complex business problems.
Optimization in Microsoft Excel has become popular over the years because of the built-in solver functions. Spreadsheet optimization allows users to create models that are easy to use, enabling the user to quickly update the data and solve the model.
Spreadsheets in efficient at handling and managing two-dimensional dense data (rows and columns).
Excel also has the Visual Basic programming (VBA) language built in, which allows some programming capabilities in order to design a user- friendly interface.

For any aggregate blend :

$$p_i = A \times a_i + B \times b_i + C \times c_i + D \times d_i + \ldots\ldots \qquad (G.1)$$

where:

p_i =% of material passing a given sieve for the blended aggregates A,B,C,…

A, B, C… =% material passing a given for each aggregates A, B, C…

a, b, c… = Proportions (decimal fractions) of aggregates A,B,C,…to be used in blend.

This is one equation in n unknowns, where n is the number of aggregates .Considering the case of a blend containing 4 aggregates , i.e. n = 4, any four sieves may be chosen, then,

$$p_1 = A \times a_1 + B \times b_1 + C \times c_1 + D \times d_1$$

(3.2)

$$p_2 = A \times a_2 + B \times b_2 + C \times c_2 + D \times d_2 \quad \text{(G.3)}$$

$$p_3 = A \times a_3 + B \times b_3 + C \times c_3 + D \times d_3 \quad \text{(G.4)}$$

$$p_4 = A \times a_4 + B \times b_4 + C \times c_4 + D \times d_4 \quad \text{(G.5)}$$

Solving this system of linear equations is simple. However when the sieve numbers are more than the number of aggregates, the problems becomes an error minimization problem.
The error may be calculated using Equation G.6.

$$Error = \sum_{sieve} (\%Blend - \%T\arg et)^2 \times W_{sieve} \quad \text{(G.6)}$$

where:

%Blend = % of the blended gradation.

% Target = % of the JMF or %from or the gradation obtained from ignition oven samples

The developed spreadsheet can also assign weights to the more important sieves. A higher weight given to one sieve means that the solution will start by seeking the optimum aggregate percentages to satisfy the JMF for that sieve. These sieves may be chosen as the SuperPave™ designed sieves for the mix at hand.
Table G.10 shows the formulas used in the developed spread sheet. Columns D, F, and J calculate the percentage passing each sieve based on the aggregate proportions given in Row 3.
Column K shows the blended gradation. Column L shows the target values that could be either the JMF or the gradation obtained from ignition oven samples.
When using the ignition oven to determine the aggregates gradation of the mix, it is well known that some fines are lost with the burned asphalt binder. Accordingly more weight should be set to larger sieves. This can be done by entering values in column N in descending order (opposite to what is shown). Column M calculates the difference between the target and the blend .The sum of the difference multiplied by the weight across all sieve sized should be minimized. This is given in cell O16.

Table G.10 Formulas when different weights assign to the sieves.

	B	C	D	E	F	I	J	K	L	M	N	O
2		Agg(1)		Agg(2)		Rap		=J3+H3+F3+D3	Target	Diff^2	Weight	D *W
3		Perct 1=	25	Perct 2=	13	Perct 4=	22					
4	Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend					
5	1	100	=C5*$D$3/100	100	=E5*$F$3/100	100	=I5*$J$3/100	=D5+F5+H5+J5	100	=(K5-L5)^2	0	=M5*N5
6	0.75	100	=C6*$D$3/100	100	=E6*$F$3/100	100	=I6*$J$3/100	=D6+F6+H6+J6	100	=(K6-L6)^2	10	=M6*N6
7	1/2	100	=C7*$D$3/100	100	=E7*$F$3/100	100	=I7*$J$3/100	=D7+F7+H7+J7	100	=(K7-L7)^2	20	=M7*N7
8	3/8	96	=C8*$D$3/100	100	=E8*$F$3/100	100	=I8*$J$3/100	=D8+F8+H8+J8	97	=(K8-L8)^2	30	=M8*N8
9	#4	25	=C9*$D$3/100	97.2	=E9*$F$3/100	100	=I9*$J$3/100	=D9+F9+H9+J9	57	=(K9-L9)^2	40	=M9*N9
10	#8	4	=C10*$D$3/100	79.1	=E10*$F$3/100	100	=I10*$J$3/100	=D10+F10+H10+J10	38	=(K10-L10)^2	50	=M10*N10
11	#16	3	=C11*$D$3/100	58.5	=E11*$F$3/100	100	=I11*$J$3/100	=D11+F11+H11+J11	28	=(K11-L11)^2	60	=M11*N11
12	#30	3	=C12*$D$3/100	34.5	=E12*$F$3/100	100	=I12*$J$3/100	=D12+F12+H12+J12	20	=(K12-L12)^2	70	=M12*N12
13	#50	2	=C13*$D$3/100	8.6	=E13*$F$3/100	99.3	=I13*$J$3/100	=D13+F13+H13+J13	11.1	=(K13-L13)^2	80	=M13*N13
14	#100	2	=C14*$D$3/100	2	=E14*$F$3/100	97.9	=I14*$J$3/100	=D14+F14+H14+J14	7.38	=(K14-L14)^2	90	=M14*N14
15	#200	1.9	=C15*$D$3/100	1.2	=E15*$F$3/100	91.3	=I15*$J$3/100	=D15+F15+H15+J15	6.43	=(K15-L15)^2	100	=M15*N15
										=SUM(M5:M15)		=SUM(O5:O15)

Table G.11 Different weights assign to the sieves.

	B	C	D	E	F	G	H	I	J	K	L	M	N	O
2		Agg(1)-(042CMM11)		Agg(2)-(032CMM16)		Agg(3)-(037FAM01)		Rap		100	Target	Diff^2	Weight	D *W
3		Perct 1=	25.0	Perct 2=	13.0	Perct 3=	40.0	Perct 4=	22.0					
4	Seive	%pass	%Blend	%pass	%Blend	%pass	%Blend	%pass	%Blend					
5	1	100.0	25.00	100.0	13.00	100.0	40.00	100.0	22.00	100.0	100.00	0	0	0
6	0.75	100.0	25.00	100.0	13.00	100.0	40.00	100.0	22.00	100.0	100.00	0	10	0
7	1/2	100.0	25.00	100.0	13.00	99.7	39.88	100.0	22.00	99.9	100.00	0	20	0
8	3/8	96.0	24.00	100.0	13.00	98.3	39.32	100.0	22.00	98.3	97.00	2	30	52
9	#4	25.0	6.25	97.2	12.64	69.5	27.80	100.0	22.00	68.7	57.00	137	40	5463
10	#8	4.0	1.00	79.1	10.28	42.8	17.12	100.0	22.00	50.4	38.00	154	50	7692
11	#16	3.0	0.75	58.5	7.61	31.7	12.68	100.0	22.00	43.0	28.00	226	60	13563
12	#30	3.0	0.75	34.5	4.49	24.0	9.60	100.0	22.00	36.8	20.00	283	70	19839
13	#50	2.0	0.50	8.6	1.12	13.8	5.52	99.3	21.85	29.0	11.10	320	80	25587
14	#100	2.0	0.50	2.0	0.26	9.5	3.80	97.9	21.54	26.1	7.38	350	90	31533
15	#200	1.9	0.48	1.2	0.16	7.8	3.12	91.3	20.09	23.8	6.43	303	100	30300
												1774.8		134029

Since the excel software developed in the previous section acts like a black box with no control on the optimization routine, VBA was used to write code for a more efficient optimization. Details for the code are found in Appendix A. The first data set to be entered is shown in figure G.1. Step is the increment on the aggregate gradations to be used in finding a blend that meets the target. The Tolerance is the error value given by equations G.6 .In figure G.2 the gradation for the aggregates and the targets are entered. The data is then processed through a set of linear programming equations to solve for the optimal solution with respect to the constraints set by the user. The optimal solution could be further analyzed through simple calculations within Excel. The data input required from the user and the output given by the model would be further discussed in section G.3.1.

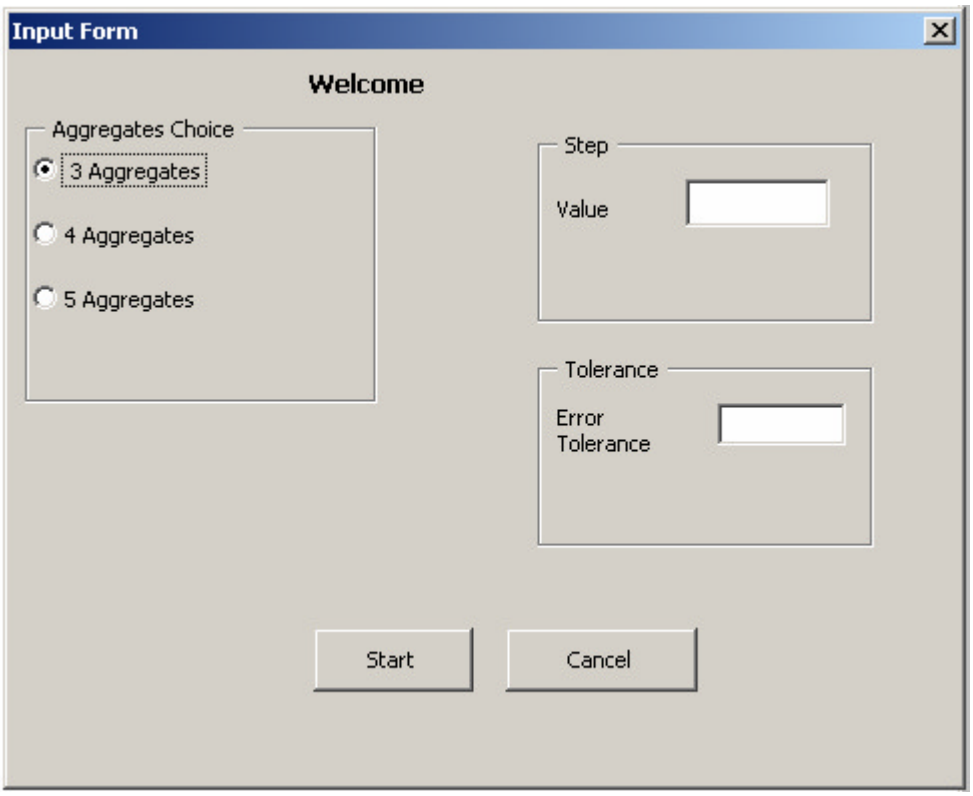

Figure G.1: Input Form

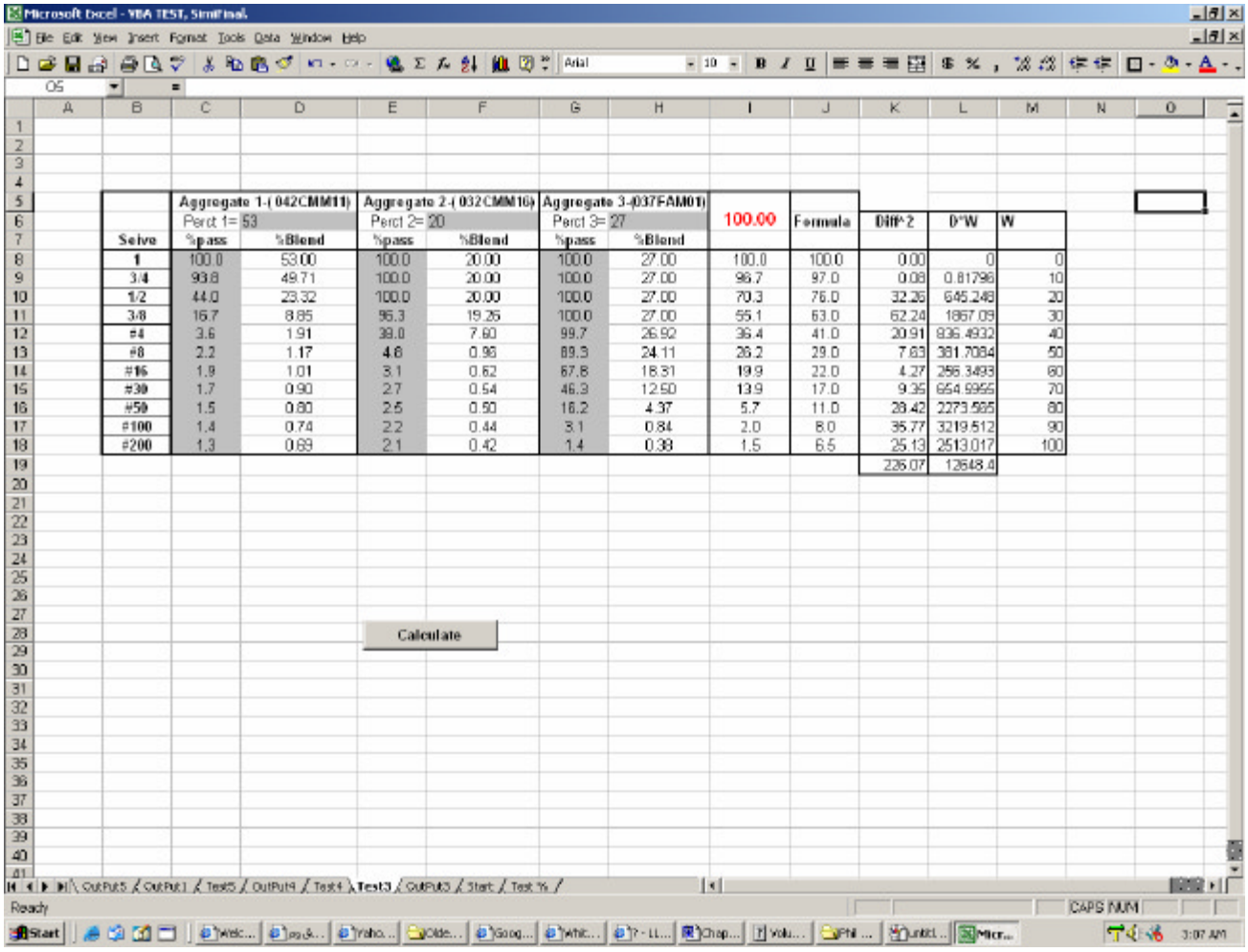

Figure G.2: Calculation Form

G.2.4 Gyratory lab testing

It is expected that the software may not yield accurate results in the in the following cases:

- If the blend consists of two aggregates with similar gradations.
- If the blend consists of a well graded aggregate.

Although these cases may not be realistically common, another test is needs to be performed if one of these cases exists .The following gyratory testing is recommended and is summarized in figure G.3.

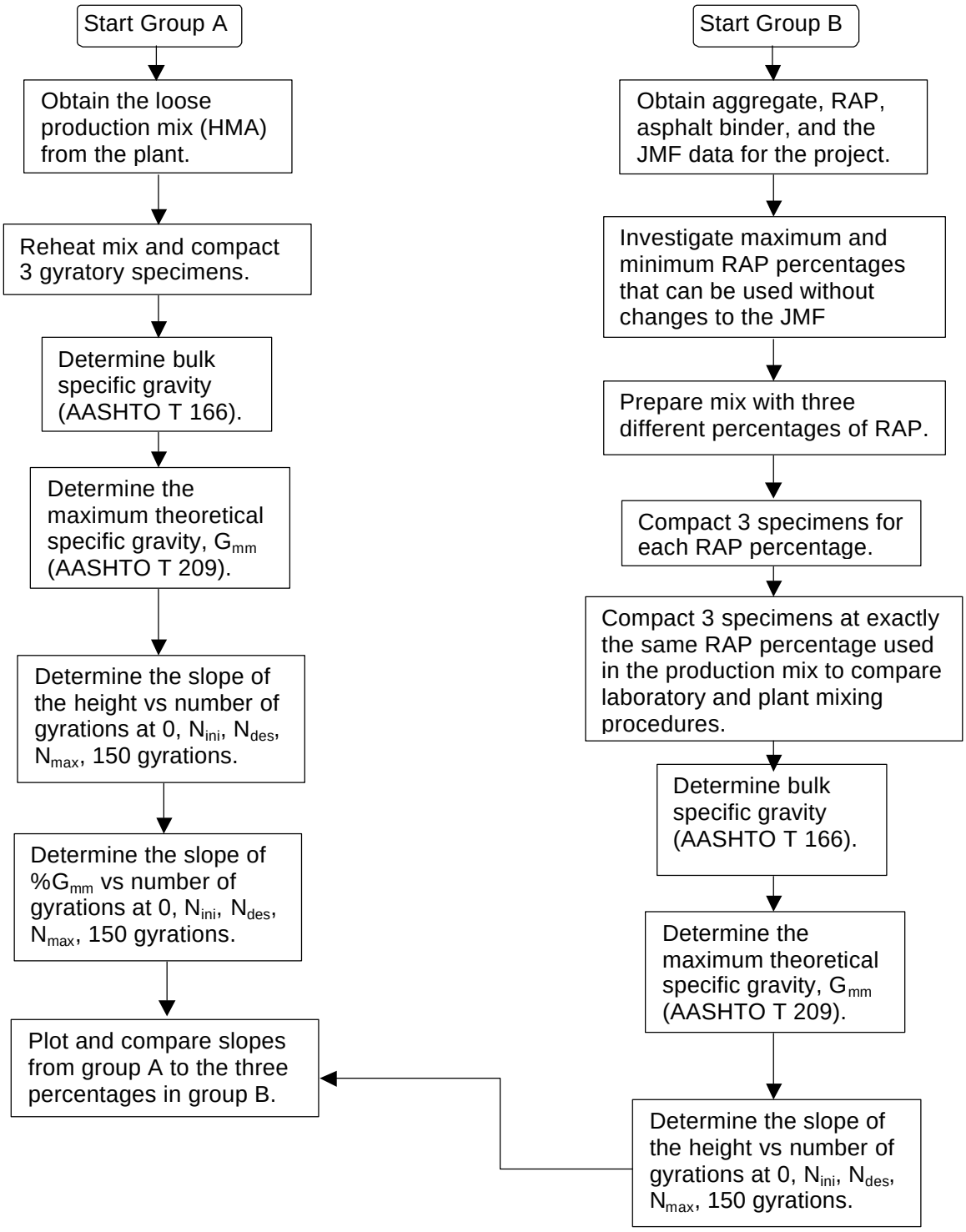

Figure G.3: Flow charts for gyratory lab testing

G.2.5 Results

In the previous section, the VBA optimization software we described. The software was used to calculate the percentages of different aggregate sizes allowed in the asphalt mix to reach the targeted values.

The Input screen in Figure G.1 shows the different choices the user has to state before running the software which are:-

- The number of aggregates used in the mix. Although the software has been developed for aggregates blends of 3 to 5 aggregates, the method is valid for more than 5 aggregate combinations.
- The Step value is usually taken as 1 to seek the most accurate optimization results. Increasing the step value reduces runtime and accuracy.
- The error tolerance is the sum of the sieves tolerance values previously stated by the SuperPave^{TM} design mix. This refers to the error calculated by Eq.G.6 .The final blend does not depend on this value. However the bigger this value the more accurate the results.

The output is in the form of a table showing all aggregate combinations that have a minimum error value less than the error tolerance value (see Figure G.4, Figure G.5). The average for each of each column showing individual aggregate percentage is calculated. The average value of all the different combinations is the desired value. This is because the optimization problem is linear, i.e. increasing or decreasing one or more percentages shifts the blend away form the target linearly. This can be explained graphically in Figure G.6. In this example the aggregate were combined using random percentages as a trial estimate. It can be seen that the blend is not overlapping with the target. It can also be seen that this is mainly in the upper part of the gradation curve. The trial estimate for aggregate number 3 is the main factor contribution to the difference between blend and target. Accordingly, it is easily deduced that the estimate for aggregate three is not accurate. Note that increasing or decreasing the percentage of aggregate 3 will move the upper portion of the blend gradation towards the left or the right, respectively, in a linear fashion. Hence, if all the different percentages have been considered the average of these values will overlap with the target. This same logic can be applied to the other aggregate used in the mix, knowing that they contribute to different parts of the blend gradation curve.

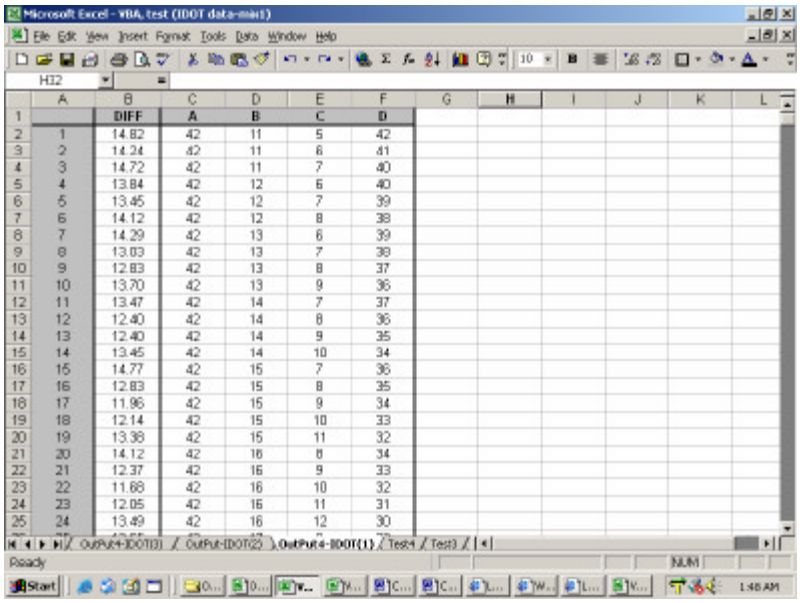

Fig G.4 Output Excel sheet

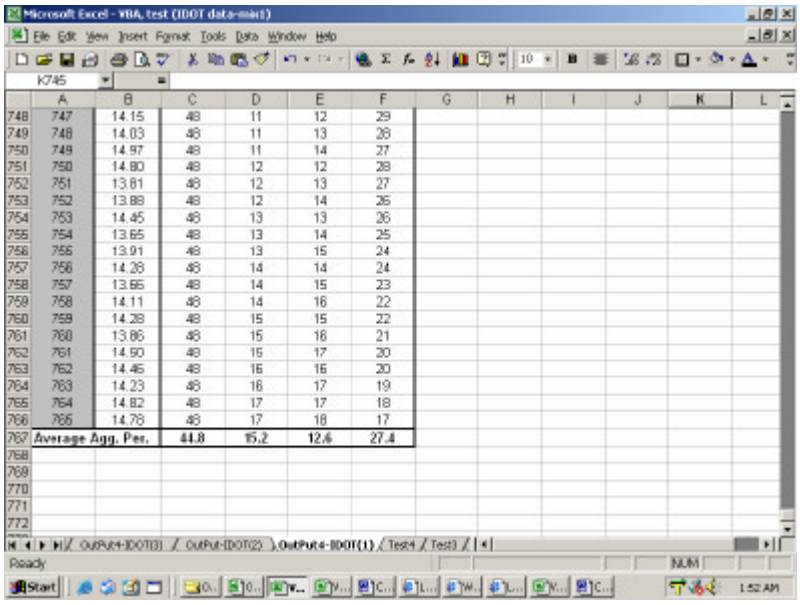

Fig G.5 Output Excel sheet (continued)

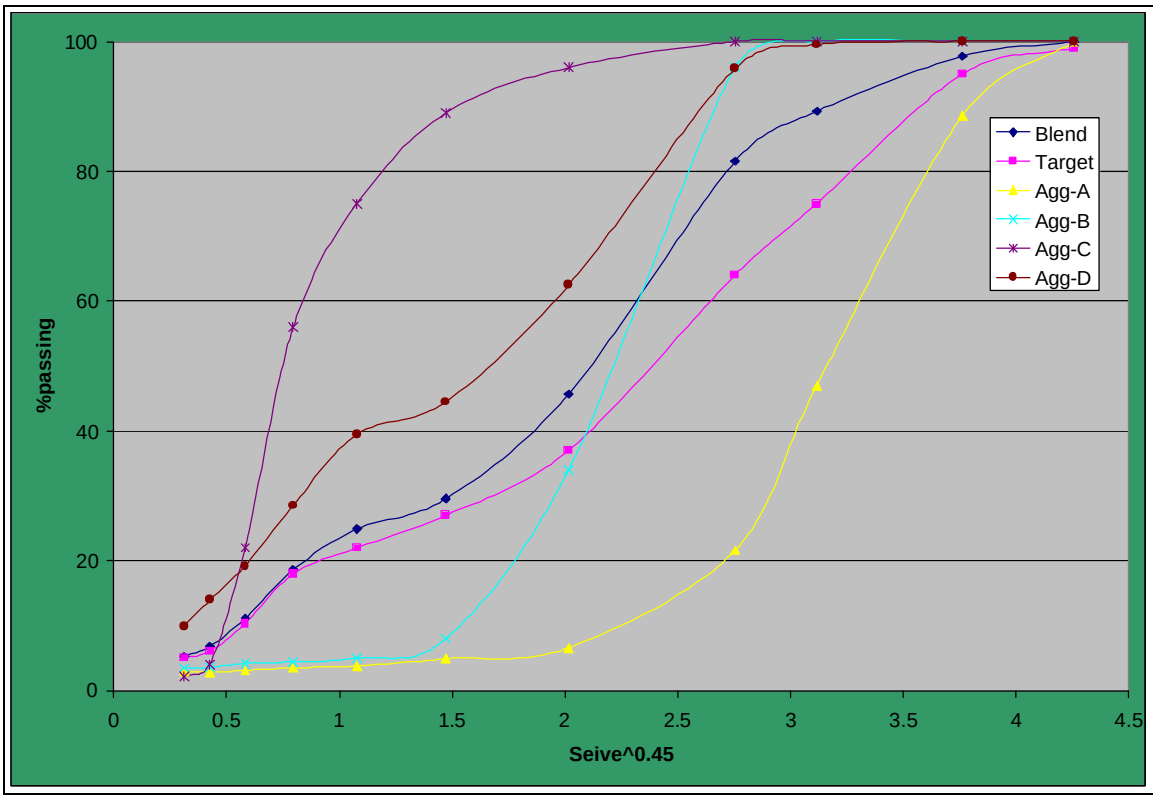

Figure G.6 Graphical Representation of Blending.

G.2.5.1 Verification of Excel

Quality control and quality assurance, QC/QA, data was collected from IDOT for four mixes already in-service in district four. Individual aggregate gradation where obtained from the contractor. Final blended aggregate gradation was obtained from ignition oven tests run by IDOT. For each of the four mixes, at least six samples were collected and tested in the ignition oven has part of the routine inspection activities for the IDOT QC/QA.

The software was run for each mix and the different combinations of the aggregates was obtained and documented in Appendix B. The averages for the aggregate percentages were obtained for each ignition oven test and the results are shown in table G.12 through G.15.

The last row in these tables' shows the percentages used in the design.

Table G.12 Aggregates % Output for Mix (1)

Test #	Aggregate1	Aggregate2	Aggregate3	Aggregate4
Test 1	44.8%	15.2%	12.6%	27.4%
Test 2	45.2%	14.1%	14.8%	25.9%
Test 3	39.3%	23.1%	12.6%	25.1%
Test 4	37.3%	25.7%	14.8%	22.2%
Test 5	44.5%	11.7%	14.8%	29.0%
Test 6	35.7%	24.3%	10.4%	29.7%
Test 7	35.1%	15.1%	6.8%	43.0%
Actual % of the mix	42.7%	24.0%	13.3%	20.0%

Table G.13 Aggregates % Output for Mix (2)

Test #	Aggregate1	Aggregate2	Aggregate3	Aggregate4	Aggregate5
Test 1	36.0%	34.0%	9.6%	15.3%	5.0%
Test 2	32.3%	35.5%	16.0%	12.9%	3.3%
Test 3	31.0%	46.8%	3.6%	14.7%	3.8%
Test 4	29.4%	40.6%	9.9%	16.9%	3.2%
Test 5	25.2%	37.5%	6.6%	26.9%	3.8%
Test 6	21.5%	50.2%	6.1%	18.6%	3.5%
Test 7	17.9%	50.2%	8.5%	20.2%	3.2%
Actual % of the mix	30.5%	40.5%	13.5%	12.0%	3.5%

From Table G.12 the actual percentage of aggregate1 is 42.7%, which represents the design value. The results from the seven tests varied from 35.1% to 45.2 %. Indicating that in this case the contractor was very close to the design value, with around 7% deviation from the design. Similar conclusions can be drawn for the mixes presented in table G.13 and G.15.

Table G.14 Aggregates % Output for Mix (3)

Test #	Aggregate1	Aggregate2	Aggregate3	Aggregate4
Test 1	49.1%	29.8%	16.6%	4.5%
Test 2	35.6%	27.1%	34.6%	2.8%
Test 3	31.8%	28.3%	37.4%	2.4%
Test 4	39.7%	30.1%	26.8%	3.3%
Test 5	21.0%	23.2%	54.9%	1.0%
Test 6	33.9%	29.1%	35.4%	1.6%
Actual % of the mix	45.2%	36.8%	14.3%	3.7%

From table G.14 the design percentage for aggregate 3 was 14.3% and the results from most of the tests show a much higher percentage. Therefore it may be concluded that the contractor didn't put the actual percentage in the mix.

G.2.5.2 Application in Mix Security

The developed Excel software can be used in two ways to ensure a secure mix. First, it can be incorporated into the plant readout system and the calculated RAP percentage, based on aggregate and mix gradations reported in the form of control charts. Second, the calculated RAP percentage may be calculated for every QC/QA test and included as a pay item in the end-result specifications.

(a) Control charts: The results may be implemented in the form of a control chart, where the backcalculated aggregate percentages are plotted versus the number of tests. Any deviation from the design value can then be quickly noticed and proper correction measures taken to correct the problem. For example, Figure G.7 shows the aggregates percentages versus the number of tests for mix 4. It shows clearly that aggregate 2 in sample 4 is far out of the actual limit- 15%. The limits on the control charts could be assigned on this chart and the errors can be spotted quickly after the ignition oven test is performed.

Table G.15 Aggregates % Output for Mix (4)

Test #	Aggregate1	Aggregate2	Aggregate3	Aggregate4
Test 1	61.5%	16.1%	18.7%	3.6%
Test 2	57.5%	16.8%	23.1%	2.6%
Test 3	59.6%	13.3%	23.8%	3.3%
Test 4	66.1%	3.0%	27.4%	3.5%
Test 5	69.7%	9.0%	17.9%	3.4%
Test 6	59.1%	13.7%	24.4%	2.8%
Actual % of the mix	63.0%	15.0%	20.0%	2.0%

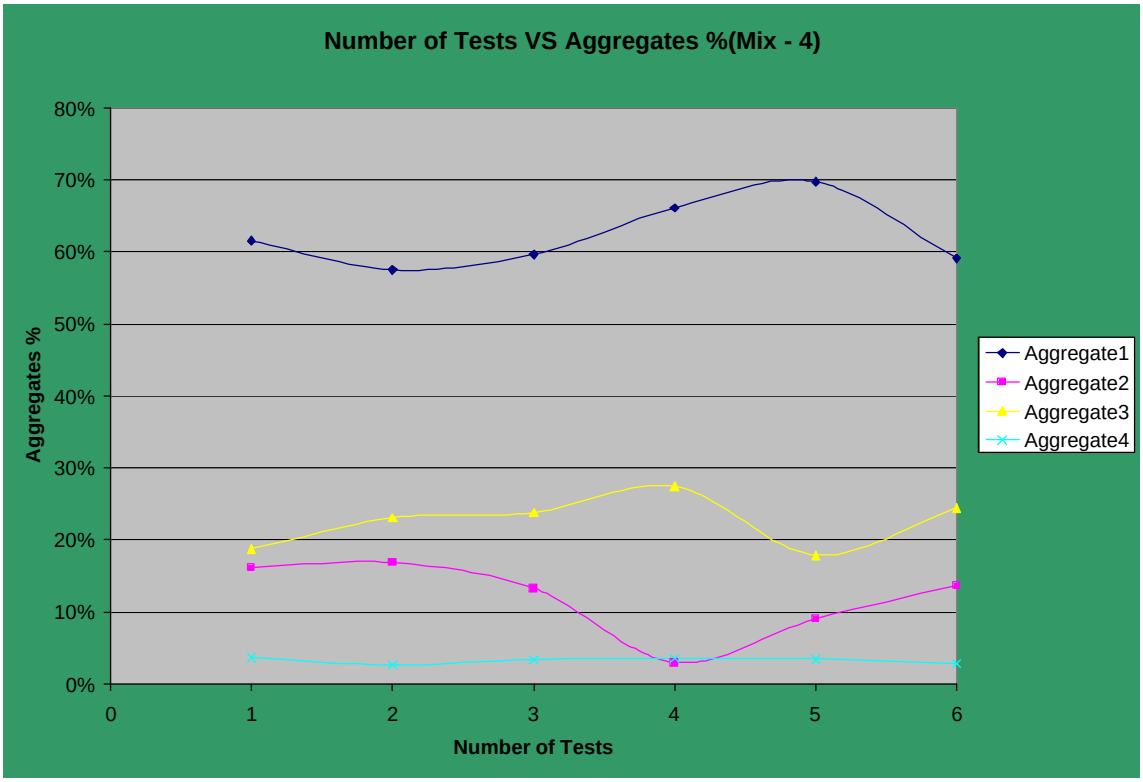

Figure G.7 Number of Tests VS Aggregates % for (Mix - 4)

(b) End Result Specification: Quality control and quality assurance data collected by both the contractor and the department can be directly entered in the Excel software and the RAP percentage calculated. If enough data is collected the upper and lower quality indices can be calculated and used to determine a pay factor for RAP percentage. This pay factor along with the asphalt content pay factor can be a strong indication of mix security.

G.2.5.3 Gyratory Compactor Output

Extensive laboratory simulation for the Excel software was performed to include all possible cases. It was found that:

- If two aggregates with similar gradations are used the software is not capable of determining which percentage belongs to which aggregate.
- Aggregates that are well graded or have a similar gradation to the JMF may make the backcalculation procedure ill-conditioned.

Although these limitations are conceptually valid, practically it is very difficult to find aggregates that have similar gradations. Furthermore, aggregates are typically either crushed down to required sizes or naturally occurring. Crushed aggregate are not well graded due to the crushed operations. On the other hand if well-graded aggregates exist there would be no need for blending in the first place. In the case that such aggregates do exist further testing is required such as that describe later in this section. A

methodology to distinguish between aggregate percentages was developed and applied to two mixes.

Table G.16 shows the RAP percentages used for sample preparation for the two mixes considered. Three samples for each RAP percentage were mixed and compacted using the gyratory compactor. In addition, three samples were prepared from the loose mixes for (A) and (B). The bulk specific gravity and the maximum theoretical gravity were determined using AASHTO T 166 and AASHTO T 209 respectively. Figure G.8 shows the Gyratory output from one of the samples.

sample(16)-surface mix
Mass (g) = 2987.5
Diameter (mm) = 150

# of gyration	Height	Volume	Density	Corrected I	%Gmm
1	85.7	1514444.01	1.97	2.01	84.64
2	84	1484402.53	2.01	2.05	86.35
3	82.9	1464963.92	2.04	2.08	87.50
4	82	1449059.61	2.06	2.10	88.46
5	81.1	1433155.30	2.08	2.12	89.44
6	80.5	1422552.42	2.10	2.14	90.10
7	80	1413716.69	2.11	2.15	90.67
8	79.5	1404880.96	2.13	2.17	91.24
9	79.1	1397812.38	2.14	2.18	91.70
10	78.7	1390743.80	2.15	2.19	92.16
11	78.4	13854	2.16	2.20	92.52
142	70.6	1247604.98	.39	2.44	102.74
143	70.6	1247604.98	2.39	2.44	102.74
144	70.6	1247604.98	2.39	2.44	102.74
145	70.5	1245837.84	2.40	2.44	102.88
146	70.5	1245837.84	2.40	2.44	102.88
147	70.5	1245837.84	2.40	2.44	102.88
148	70.5	1245837.84	2.40	2.44	102.88
149	70.5	1245837.84	2.40	2.44	102.88
150	70.5	1245837.84	2.40	2.44	102.88

Sample 1- ASTM D 2726

dry wt	wt in water	SSD wt	Bulk Specific Gravity
2987.5	1769.7	2992.7	2.442764
dry wt	wt of bowl+water	wt of bowl+water+sample	Gmm
1600	7419.49	8345.6	2.374

Figure G.8 Gyratory out put with G_{mb} &G_{mm} calculation.

Curves for the number of gyration versus the compaction height (gyratory compaction output) for Mix A and Mix B are shown in Figures G.9 and G.11, respectively.

The slopes of these curves were compared for each percentage of RAP. On the other hand, curves for the number of gyration versus corrected density for MixA and Mix B are shown in Figures G.9 and G.11, respectively. Each curve from the compacted HMA and the lab prepared specimens was obtained from the average results of three replicates.

The curves for the compacted HMA and the compacted prepared lab sample with the same amount of RAP run almost parallel to each other, which indicate similar trends of densification with gyrations. This means that the laboratory mixing procedures simulates plant mixing.

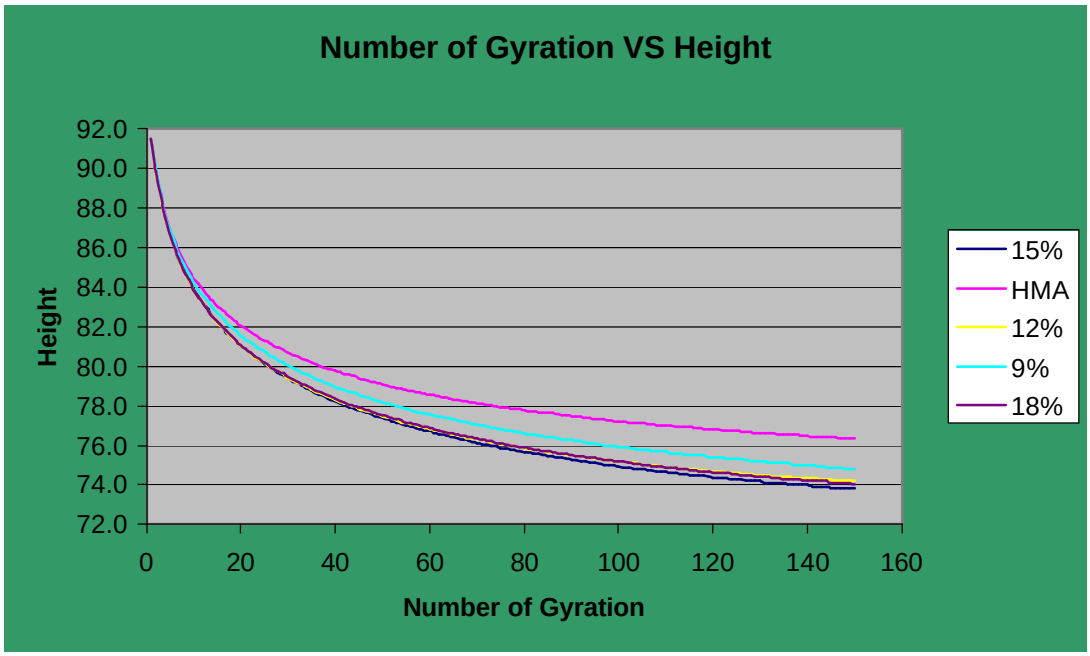

Fig G.9 Number of Gyration VS Height for Mix (A)

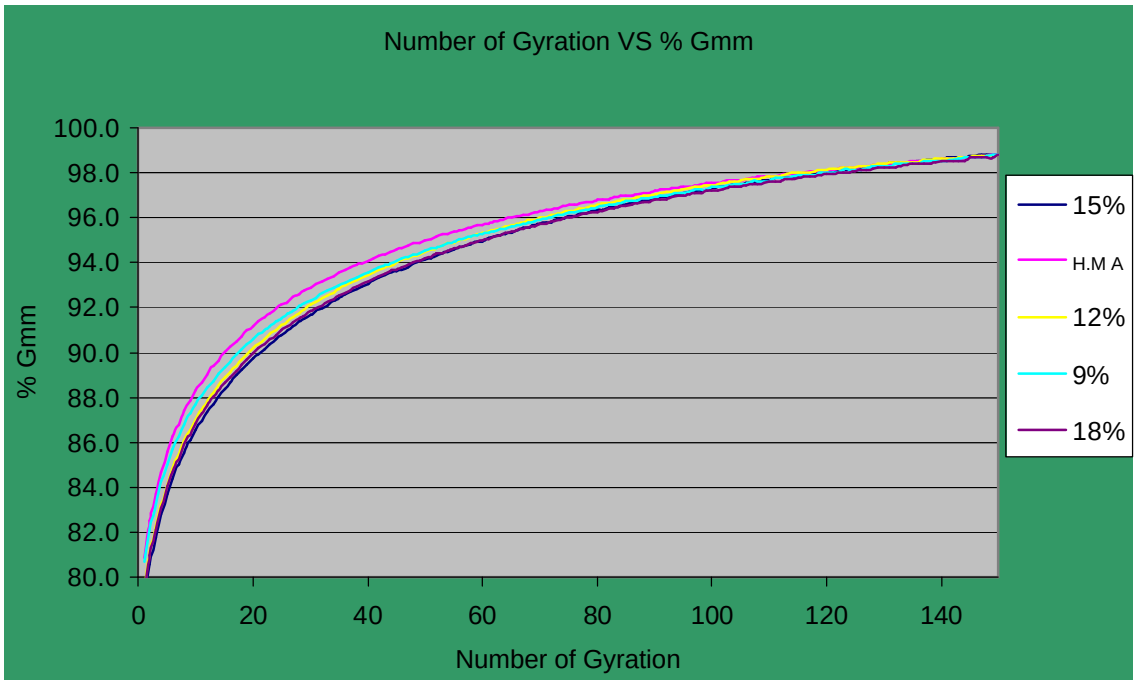

Fig G.10 Number of Gyration VS % Gmm for Mix (A)

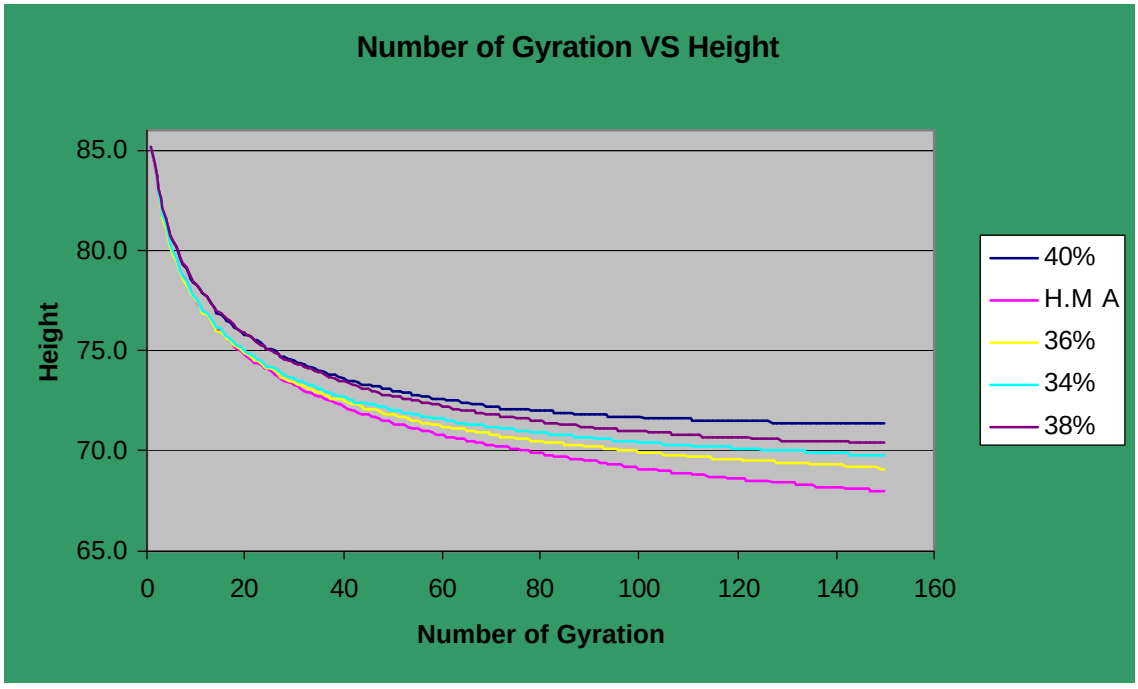

Fig G.11 Number of Gyration VS Height for Mix (B)

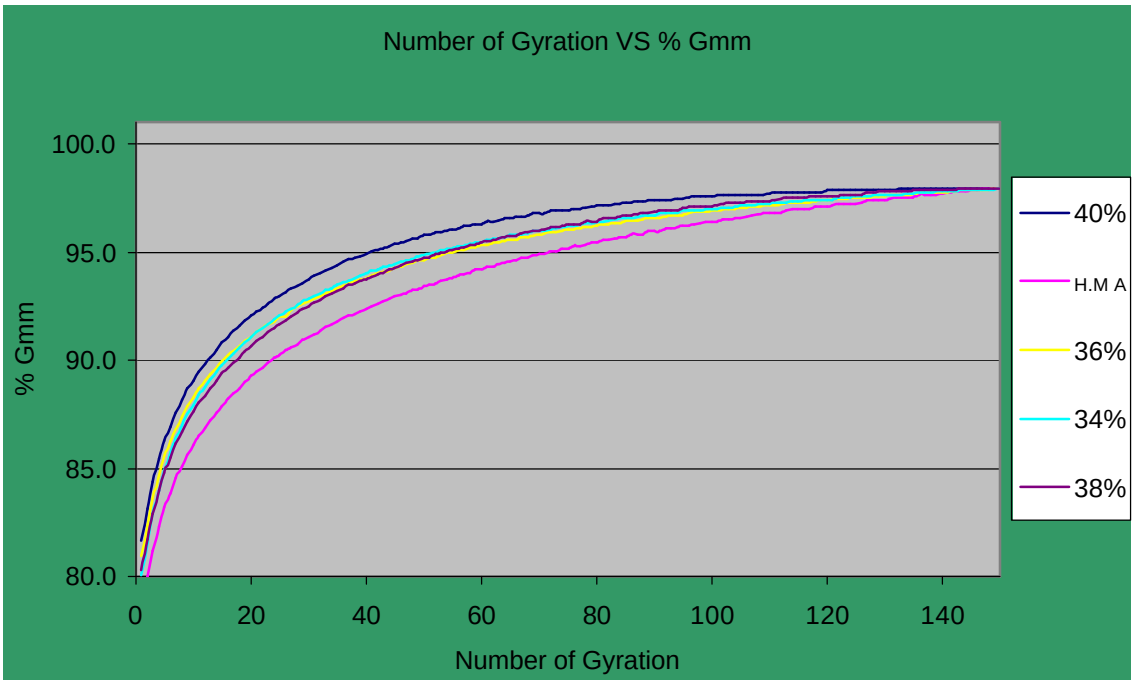

Fig G.12 Number of Gyration VS %Gmm for Mix (B)

Although the mixes were prepared with a small difference in the RAP percentage Figures G.10 and G.12 indicate that with a small difference in RAP amount there is a trend in the samples prepared in the lab, the higher the RAP percentage the lower the initial slope. Tables G.5 and G.7 show the height curve slopes for mix A and B, respectively. Other parameters were also considered and are shown in tables G.16 through table G.19.

Table G.16 Height curve slopes for Mix (A)

RAP %	0	N initial	N design	N max	150
9%	-1.6333	-0.7261	-0.0767	-0.0461	-0.0164
12%	-1.7333	-0.7172	-0.0722	-0.0467	-0.0182
15%	-1.5667	-0.6928	-0.0723	-0.0461	-0.0206
18%	-1.6667	-0.6533	-0.0603	-0.0378	-0.0130
HMA	-1.7667	-0.7189	-0.0731	-0.0433	-0.0139

Table G.17 %Gmm curve slopes for Mix (A)

RAP %	0	N initial	N design	N max	150
9%	1.407	0.679	0.087	0.058	0.027
12%	1.620	0.724	0.092	0.057	0.019
15%	1.492	0.727	0.096	0.060	0.022
18%	1.578	0.716	0.090	0.060	0.025
HMA	1.652	0.709	0.080	0.052	0.019

Table G.18 Height curve slopes for Mix (B)

RAP%	0	N initial	N design	N max	150
34%	-1.600	-0.886	-0.116	-0.076	-0.011
36%	-1.533	-0.869	-0.111	-0.070	-0.011
38%	-1.433	-0.779	-0.118	-0.077	-0.007
40%	-1.433	-0.787	-0.109	-0.066	0.000
HMA	-1.667	-0.865	-0.126	-0.087	-0.017

Table G.19 %Gmm curve slopes for Mix (B).

RAP %	0	N initial	N design	N max	150
34%	1.4270	0.8491	0.1315	0.0898	0.0150
36%	1.5600	0.8711	0.1545	0.1095	0.0242
38%	1.4394	0.8400	0.1527	0.1025	0.0104
40%	1.4938	0.9127	0.1414	0.0916	0.0151
HMA	1.4421	0.8489	0.1404	0.0879	0.0000