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Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method

Prepared for:

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ABSTRACT

This report summarizes the research conducted for NCHRP 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*. Chapter One reviews the background behind the project and discusses the research approach. Chapter Two outlines the research findings from all parts of the project. Chapter Three discusses the implications of these findings. Chapter Four summarizes the applicable conclusions from this research, makes recommendations for future practice based upon these conclusions and suggests additional research that may be necessary to address some unresolved issues.

The main research was conducted in three separate, but related, studies. The "black rock study" investigated the question of whether RAP acts like a black rock or whether there is, in fact, some blending that occurs between the old and new binders. The "binder effects study" examined issues related to RAP binder testing including extraction and recovery procedures, applicability of the AASHTO MP1 tests to RAP binders and the effects of RAP content and stiffness on blended binder properties. The "mixture effects study" was directed at assessing the effects of the added RAP on total mixture properties as measured by shear, indirect tensile and beam fatigue testing.

Two small-scale investigations, termed "mini-experiments," investigated the comparison of laboratory specimens to plant-produced mixtures and the effects of heating time and temperature on RAP properties.

Significant findings include the conclusion that RAP is not a black rock and significant blending does occur. This means that the use of blending charts is appropriate. Recommendations are included for the best laboratory procedures to use for development of these blending charts, including a modification of the SHRP extraction/recovery procedure. Other findings strongly support the conclusion that there is a threshold level of RAP below which its effects are negligible. This level is between 10 and 20%, depending on RAP binder stiffness.

These findings validate the three tiered approaches for RAP usage as recommended by the Mixture Expert Task Group.

The appendices contain some of the supplemental documents developed during this research. Appendix A is an annotated bibliography of some of the relevant research on reclaimed asphalt pavement over about the last thirty years. Appendix B consists of tables showing the statistical analysis of the data from the black rock study. Appendix C shows flow charts that demonstrate the sequence of steps involved in evaluating binder blending for mix design. Appendix D contains suggestions for consideration by owner agencies in the *Summary: Guidelines for the Use of Reclaimed Asphalt Pavement in the Superpave System.* The manual for field and laboratory technicians is in Appendix E. Appendix F is an implementation plan for moving these results into practice. And lastly, Appendix G is a possible procedure to use to verify the PG grade of a binder in a sample of hot mix asphalt. Appendix G is not a direct product of this research effort, but is a possible extension of the research findings and other research requested by the project panel.

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PREFACE

The North Central Superpave Center and Asphalt Institute research teams prepared the final report for NCHRP Project 9-12, "Incorporation of Reclaimed Asphalt Pavement in the Superpave System." The final report includes a detailed description of the experimental program, a discussion of the research results, and seven supporting appendices:

- Appendix A, Annotated Bibliography;
- Appendix B, Statistical Analysis of Black Rock Data;
- Appendix C, Flow Charts Showing Development of Blending Charts;
- Appendix D, Summary: Guidelines for Incorporating Reclaimed Asphalt Pavement in the Superpave System;
- Appendix E, Use of RAP in Superpave: Technicians' Manual;
- Appendix F, Use of RAP in Superpave: Implementation Plan; and
- Appendix G, Proposed Procedure for Determining the Asphalt Binder Grade Recovered from HMA.

The main report and appendices A, B, C, F, and G are published herein as *NCHRP Web Document 30*. Appendices D and E are not published herein. Appendix D is published as *NCHRP Research Results Digest 253*. Appendix E is published as *NCHRP Report 452,* "Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual."

The entire final report (including all appendixes) for NCHRP Project 9-12 will be distributed as a CD-ROM (CRP-CD-8) along with the complete final reports for NCHRP Projects 9-11 and 9-13.

SUMMARY

Why Use RAP?

The materials present in old asphalt pavements may have value even when the pavements themselves have reached the ends of their service lives. Recognizing the value of those existing aggregate and asphalt resources, states and contractors have made extensive use of Reclaimed Asphalt Pavements (RAP) in the past when producing new asphalt pavements. Use of RAP has proven to be economical and environmentally sound. In addition, mixtures containing RAP have, for the most part, been found to perform as well as virgin mixtures.

The original Superpave specifications contained no provisions to accommodate the use of RAP. Continued use of RAP in Superpave pavements is desired because:

- RAP has performed well in the past and is expected to perform well in Superpave mixtures also, if properly accounted for in the mix design,
- use of RAP is economical and can help to offset the increased initial costs sometimes associated with Superpave binders and mixtures,
- use of RAP conserves natural resources, and avoids disposal problems and associated costs.

For these reasons, a subgroup of the FHWA Superpave Mixtures Expert Task Group developed interim guidance for the use of RAP based on past experience. These guidelines established a tiered approach for RAP usage. Up to 15% RAP could be used with no change in binder grade. Between 15 and 25% RAP, the virgin binder grade should be decreased one grade

(6° increment) on both the high and low temperature grades. Above 25% RAP, blending charts should be used to determine how much RAP could be used.

When the aged binder from RAP is combined with new binder, it will have some effect on the resultant binder grade. At low RAP percentages, the change in binder grade is negligible. At higher percentages, however, the effect of the RAP becomes significant.

The aggregate in the RAP may also affect mixture volumetrics and performance. The design aggregate structure, crushed coarse aggregate content, dust proportion and fine aggregate angularity should take into account the aggregate from the RAP. Again, at low RAP percentages, the effects may be minimal.

One recurring question regarding RAP is whether it acts like a “black rock.” If RAP acts like a black rock, the aged binder will not combine, to any appreciable extent, with the virgin binder and will not change the binder properties. If this is the case, then the premise behind blending charts, which combine the properties of the old and new binders, is void.

These questions were addressed through NCHRP Project 9-12*, Incorporation of Reclaimed Asphalt Pavement in the Superpave System*. The objectives of that research effort were to investigate the effects of RAP on binder grade and mixture properties and develop guidelines for incorporating RAP in the Superpave system on a scientific basis. The products of the research include proposed revisions to applicable AASHTO standards, a manual for technicians and guidelines for specifying agencies.

NCHRP Project 9-12 Research Findings

Black Rock Study

The research effort was directed first at resolving the issue of whether RAP acts like a black rock or whether there is, in fact, some blending that occurs between the old, hardened RAP binder and the added virgin binder. This question was addressed by fabricating mixture specimens simulating actual practice, black rock and total blending. The so-called “black rock” and “total blending” cases represent the possible extremes. If RAP is a black rock, the mixture properties would depend on the virgin binder with no effect of the RAP binder. The black rock case therefore, was simulated by extracting the binder from a RAP mixture then blending the recovered RAP aggregate in the proper proportions with virgin aggregate and only the virgin binder. The actual practice samples were prepared as usual by adding the RAP with its coating intact to virgin aggregate and virgin binder. The total blending samples were fabricated by extracting and recovering the RAP binder and blending it into the virgin binder, then combining the blended binder with the virgin and RAP aggregates. All the samples were prepared on the basis of an equal volume of total binder.

Three different RAPs, two different virgin binders and two RAP contents (10 and 40%) were investigated in this phase of the project. The different cases of blending were evaluated through the use of various Superpave shear tests at high temperatures and indirect tensile creep and strength tests at low temperatures.

The results of this phase of the research indicated no significant differences between the three different blending cases at low RAP contents. Not enough RAP binder was present to significantly alter the mixture properties. At higher RAP contents, however, the differences became significant. In general, the black rock case demonstrated lower stiffnesses and higher deformations than the other two cases. The actual practice and total blending cases were not significantly different from each other.

These results provide compelling evidence that RAP does not act like a black rock. It seems unreasonable to suggest that total blending of the RAP binder and virgin binder ever occurs, but partial blending apparently occurs to a significant extent.

This means that at high RAP contents the hardened RAP binder must be accounted for in the virgin binder selection. The use of blending charts for determining the virgin binder grade or the maximum amount of RAP that can be used is a valid approach since blending does occur. Procedures for extracting and recovering the RAP binder with minimal changes in its properties and then developing blending charts are detailed in the final report and manual for technicians. The recommended extraction/recovery procedure uses either toluene and ethanol, as specified in AASHTO TP2, or an n-propyl bromide solvent, which was proven suitable for use in this research.

The findings also support the concept of a tiered approach to RAP usage since the effects of the RAP binder are negligible at low RAP contents. This is very significant since it means that lower amounts of RAP can be used without going to the effort of testing the RAP binder and developing a blending chart. The procedures for developing blending charts were perfected during the second portion of the project, the binder effects study.

Binder Effects Study

This phase of the research investigated the effects of the hardened RAP binder on the blended binder properties and lead to recommended procedures for testing the RAP binder for the development of blending charts.

The same three RAPs and two virgin binders were evaluated in this phase of the project at RAP binder contents of 0, 10, 20, 40 and 100%. The blended binders were tested according to the AASHTO MP1 binder tests.

The results show that the MP1 tests are applicable to RAP binders and linear blending equations are appropriate. The recovered RAP binder should be tested in the DSR to determine its critical high temperature as if it were unaged binder. The rest of the recovered binder should then be RTFO aged; linear blending equations are not appropriate without this additional aging. The high temperature stiffness of the RTFO-aged binder should then be determined. The remaining MP1 tests at intermediate and low temperatures should then be performed as if the RAP binder were RTFO and PAV aged. The RAP binder does not need to be PAV aged before testing for fatigue or low temperature cracking, as would be done for original binder. Since PAV aging is not necessary, the testing process is shortened by approximately one day. Conventional Superpave methods and equipment, then, can be used with the recovered RAP binder. (Above 40% RAP, or so, some non-linearity begins to appear.)

The binder effects study also supports the tiered usage concept. At low RAP contents, the effects of the RAP binder are negligible. At intermediate levels, the effects of the RAP binder can be compensated for by using a virgin binder one grade softer on both the high and low temperature grades. The RAP binder then stiffens the blended binder. At higher RAP contents, a blending chart should be used to either determine the appropriate virgin binder grade or to determine the maximum amount of RAP that can be used with a given virgin binder. The limits of the three tiers vary depending on the recovered binder stiffness. Higher RAP contents can be used if the recovered RAP binder stiffness is not too high.

These findings mean that, for the most part, conventional equipment and testing protocols can be used with RAP binders. The tiered approach allows for the use of up to 15 to 30% RAP without extensive testing. Higher RAP contents can also be used when additional testing is conducted.

Mixture Effects Study

The same three RAPs and two virgin binders were used in this portion of the research to investigate the effects of RAP on the resulting mixture properties. Shear tests and indirect tensile tests were conducted to assess the effects of RAP on mixture stiffness at high, intermediate and low temperatures. Beam fatigue testing was also conducted at intermediate temperatures. RAP contents of 0, 10, 20 and 40% were evaluated.

All of the tests indicated a stiffening effect from the RAP binder at higher RAP contents. At low RAP contents the mixture properties were not significantly different from those of mixtures with no RAP. The shear tests indicated an increase in stiffness and decrease in shear deformation as the RAP content increased. This would indicate that higher RAP content mixtures would exhibit more resistance to rutting. The indirect tensile testing also showed increased stiffness for the higher RAP content mixtures, which could lead to increased low temperature cracking, if no adjustment is made in the virgin binder grade. Beam fatigue testing also supports this conclusion since beam fatigue life decreased for higher RAP contents, when no change was made in the virgin binder grade.

The significance of these results is that the concept of using a softer virgin binder with higher RAP contents is again supported. The softer binder is needed to compensate for the increased mixture stiffness and help improve the fatigue and low temperature cracking resistance of the mixture. The results also support the tiered concept since low RAP contents, below 20%, yield mixture properties that are statistically the same as the virgin mixture properties.

Overall Conclusions

The findings of this research effort largely confirm current practice. The concept behind the use of blending charts is supported. The use of a tiered approach to the use of RAP is found to be appropriate. The advantage of this approach is that relatively low levels of RAP can be used without extensive testing of the RAP binder. If the use of higher RAP contents is desirable, conventional Superpave binder tests can be used to determine how much RAP can be added or which virgin binder to use.

The properties of the aggregate in the RAP may limit the amount of RAP that can be used. The RAP aggregate properties, with the exception of sand equivalent value, should be considered as if the RAP is another aggregate stockpile, which it in fact is. In the mix design, the RAP aggregates should be blended with virgin aggregates so that the final blend meets the consensus properties. Also in the mix design, the binder in the RAP should be taken into account and the amount of virgin binder added should be reduced accordingly.

Many specifying agencies will find that these recommendations largely agree with past practice. Dynamic shear rheometer and bending beam rheometer tests may replace the viscosity tests that were previously used, for example, but the concepts are still the same. These results should not be surprising, perhaps, since the asphalt binders and mixtures are largely the same as were previously used. This research effort, however, should give the agencies confidence in extending the use of RAP to Superpave mixtures.

The products of this research include suggested revisions to several AASHTO specifications; procedures for extracting and recovering the RAP binder, testing the RAP binder, developing blending charts, and designing RAP mixtures under the Superpave system; a manual for laboratory and field technicians; guidelines for the use of specifying agencies; and an implementation plan for moving these results into practice.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

The materials present in old asphalt pavements may have value even when the pavements themselves have reached the ends of their service lives. Recognizing the value of those existing aggregate and asphalt resources, agencies and contractors have made extensive use of Reclaimed Asphalt Pavements (RAP) in producing new asphalt pavements for decades. Use of RAP has proven to be economical and environmentally sound. In addition, mixtures containing RAP have, for the most part, been found to perform as well as virgin mixtures.

Old asphalt pavements can be milled up and recycled into new mixtures for the same project or stockpiled for later use. Some states, such as Indiana, allow the use of a higher percentage of RAP when it is reused on the same project on the presumption that it may be more consistent than materials from mixed stockpiles. The value attributed to the RAP should take into account the costs of transportation, handling, stockpiling, processing and testing.

Under the Superpave system, however, there are no provisions to accommodate the use of RAP, although many agencies have allowed its use. Continued use of RAP in Superpave pavements is desired because:

- RAP has performed well in the past and there is no reason to believe it will not perform well in Superpave mixtures as well, if properly accounted for in the mix design,
- use of RAP is economical and can help to offset the increased initial costs sometimes observed with Superpave binders and mixtures,
- use of RAP conserves natural resources, and
- not reusing RAP could cause disposal problems and increased costs.

Previous design practice assumed that RAP fully interacted with the virgin materials. Many, if not most, states allowing the use of RAP established limits on the amount of RAP that could be added. Frequently, relatively low levels of RAP, below 15 or 20%, could be used with minimal changes in the mix components. At higher levels of RAP, blending charts might be required to determine the grade of new binder to use or how much RAP could be added. The RAP binder content was considered part of the total binder content. Upper limits were frequently placed on the total amount of RAP that could be used in specific applications due to concerns about ability to obtain specified mix properties or about performance, especially in terms of durability, rutting, cracking and surface friction.

When the aged binder in RAP is combined with new binder, it will likely have some effect on the resultant binder grade. At low RAP percentages, the change in binder grade may be negligible. At higher percentages, however, the effect of the RAP may become significant. The aging behavior of the blended binder (RAP plus new binder) may be different from virgin binder as well. The binder from the RAP will already be aged and may not experience further significant aging.

The aggregate in the RAP may also affect mixture volumetrics and performance. The design aggregate structure, crushed coarse aggregate content, dust proportion and fine aggregate angularity should take into account the aggregate from the RAP. Again, at low RAP percentages, the effects may be minimal.

One recurring question is whether RAP acts like a black rock. If it does act like a black rock, the aged binder will not combine, to any appreciable extent, with the virgin binder and will not change the binder properties. If this is the case, then the premise behind blending charts, which combine the properties of the old and new binders, is void. The question cannot readily be resolved using binder tests, because the binder must be extracted from the aggregate for testing and the extraction process will remove at least some of the RAP binder, whether it has actually combined with the new binder or not. Mixture tests sensitive to the binder properties may be used to resolve this issue.

The Federal Highway Administration and its Superpave Expert Task Groups have developed a draft *Guide Specification for Construction of Superpave Hot Mix Asphalt Pavements* (1), which includes guidelines on the use of RAP. Under those draft guidelines, RAP can be used up to about 15% (depending on the mean and standard deviation of the asphalt content in the RAP) without changing the virgin binder grade from that selected for the project location and conditions. Between 16 and 25% RAP, the high and low temperature grades of the virgin binder are both reduced by one grade (i.e. a PG 58-28 would be added instead of a PG 64-22). If over 25% RAP is to be used in the mix, blending charts are developed to determine the percentage of RAP that can be used with a given virgin binder. For more than 25% RAP, the effects of the RAP on the binder grade are estimated as follows:

1. The desired binder grade for the roadway is selected according to AASHTO MP 2.
2. The asphalt is recovered from the existing roadway and the high temperature stiffness ($G^*/\sin\delta$) is determined for the recovered asphalt and the recovered asphalt after RTFO aging.
3. High temperature stiffness is determined for the desired virgin asphalt before and after RTFO aging.
4. The percentage of RAP that can be used is estimated from the blending charts, which allow estimation of how much of the hardened old binder can be added to the virgin binder and still achieve the performance grade selected for the project.

The suggested evaluation, then, focuses on the effects of RAP on the high temperature binder grade. No analysis of the effects on the low temperature grade is required. (Procedures exist for evaluating low temperature properties of the blended binder as well, but are not specifically called for in this interim guidance. (2))

Furthermore, the draft guidelines require that the aggregate portion of the RAP meet certain requirements as a part of the total aggregate blend. The gradation of the RAP must be included in the assessment of the design aggregate blend. The blended aggregates, including the RAP aggregates, must meet the Superpave requirements. There may, however, be no appreciable effect of the RAP aggregates on the combined blend when RAP is added at low percentages.

The guidelines recommend the use of the effective specific gravity in lieu of the bulk specific gravity of the RAP aggregate unless otherwise specified. Familiarity with local materials, however, may allow you to more accurately estimate the RAP aggregate bulk specific gravity by estimating the asphalt absorption and determining the effective specific gravity then using those values to calculate the aggregate bulk specific gravity.

These guidelines are based on limited research data and the primary emphasis of the guidelines is on RAP effects on the binder grade. More research was recommended to determine if the specified limits (15 and 25%) and evaluation techniques (high temperature stiffness) are appropriate, if refinements are advisable, or if entirely new procedures and limits are needed. In addition, there are a number of unresolved questions about RAP use including:

- use of effective specific gravity instead of bulk specific gravity of the RAP aggregate;
- impacts of RAP aggregate on blended aggregate properties including fine aggregate angularity, flat and elongated particles, etc.;
- effects of rejuvenating agents and modified binders;
- effects of RAP on high, intermediate and low temperature binder properties;
- appropriateness of further aging of the recovered RAP binder in the rolling thin film oven and/or pressure aging vessel; and
- effects of asphalt recovery techniques on the RAP asphalt properties.

PROBLEM STATEMENT

This research addresses issues related to how RAP can be accommodated in the Superpave system. The effects of RAP on the binder grade (low, intermediate and high) and mixture properties are evaluated.

RESEARCH OBJECTIVES

The objectives of this research project are to develop guidelines for incorporating RAP in the Superpave system and prepare a manual for RAP usage that can be used by laboratory and field technicians. This research effort considers the effects of RAP on binder grade, aggregate parameters, and resulting mixture properties and performance. Recommendations are made regarding the incorporation of RAP in the Superpave system and procedures for mixture design and material selection. A plan for the implementation of the recommended procedures is also offered.

SCOPE OF STUDY

The major products of this research effort include:

- clear and detailed guidelines for incorporating RAP in the Superpave system based on statistically valid laboratory data;
- a manual detailing the laboratory and field test procedures for the use of technicians;
- an implementation plan for moving the results of this research into practice; and
- this final report summarizing the work accomplished, the decisions made and the rationale behind those decisions.

Tasks

Two phases and twelve individual tasks were identified in order to accomplish the objectives of this research project. Tasks 1 through 7 comprised Phase I, during which the current state of knowledge was assessed, shortcomings were identified and plans were laid to overcome those shortcomings through a focused research plan. During Phase II, Tasks 8 through 12 were completed to meet the objectives of this research effort. The tasks include the following:

Phase I

Task 1. Review and evaluate literature dealing with specifications, test procedures, and design methods for use of RAP.

Task 2. Review and evaluate research related to the use of RAP within the Superpave system currently underway by FHWA, state departments of transportation, industry groups and other organizations.

Task 3. Review and evaluate results of NCHRP Project 9-7, *Field Procedures and Equipment to Implement SHRP Asphalt Specifications*, to determine adaptability of the recommended field quality control and quality assurance procedures for RAP mixtures.

Task 4. Review and evaluate binder extraction and recovery procedures and recommend an appropriate method for use in the Superpave system.

Task 5. Review and evaluate Superpave binder test methods relative to the characterization of recovered asphalt.

Task 6. Based on the results of Tasks 1 through 5, develop a plan, to be executed in Task 8, to develop, evaluate, and validate guidelines for incorporating RAP in the Superpave system.

Task 7. Prepare an interim report that (a) documents the research performed in Tasks 1 through 6 and (b) provides an updated work plan for Phase II based on the work performed in Task 6.

Phase II

Task 8. Execute the plan approved in Task 7.

Task 9. Based on the results of Task 8, recommend guidelines for incorporating RAP in the Superpave system. The guidelines shall include processes for mixture design and field quality control and be suitable for use by paving and materials engineers.

Task 10. Prepare a manual that provides a step-by-step procedure for incorporating RAP in the Superpave system. The manual shall be suitable for use by laboratory and field technicians.

Task 11. Develop an implementation plan for moving the results of this research into practice. The implementation plan must discuss the applicability of the research results to highway practice, the expected benefits to the using agency, and the actions that need to be taken to ensure use of the research results.

Task 12. Submit a final report that documents the entire research effort. The guidelines and manual shall be prepared as stand-alone documents.

RESEARCH APPROACH

Research Plan

Much of Phase I of this project was devoted to reviewing the state of the practice regarding RAP usage, such as through a literature review, and evaluating whether the Superpave protocols and recommendations would accommodate RAP usage, such as evaluating the MP1 binder tests and the quality control/quality assurance recommendations of NCHRP 9-7. This work was necessary to design the Phase II research plan. The results of this work are detailed in the interim report (3) and summarized here. One major task under Phase I that did involve laboratory testing and analysis was an evaluation of various extraction and recovery techniques and solvents. Due to the interest in extraction/recovery and solvents, the results of this task will be presented in some detail in the "Binder Effects Study" section of Chapter 2.

The research conducted under Task 8 was intended to address three primary topics. A major effort was expended to determine whether RAP acts like a black rock; that is, whether any significant blending occurs between the old, hardened RAP binder and the new binder added to the mixture. This portion of the research is called the "Black Rock Study." The research project also addressed the effects of RAP on binder properties through the "Binder Effects Study." Binder properties were evaluated primarily through the use of the standard Superpave binder testing protocols described in AASHTO (4) MP1, *Standard Specification for Performance Graded Asphalt Binder*, with some exceptions or modifications as noted below. The effects of RAP on the properties of the mix were evaluated in the "Mixture Effects Study."

All three major portions of the overall project were coordinated and interrelated. Three common RAP materials, one common virgin aggregate and two common virgin binders were used in all major portions of the project. This allows some overall conclusions to be drawn regarding the effects of RAP.

During the course of the research, some particular issues were identified that needed additional testing. These limited studies were called "mini-experiments." These two mini-experiments were not exhaustive studies, but were limited studies performed to address particular issues. (A third mini-experiment on changes in aggregate properties before and after solvent extraction or ignition burn-off was conducted to provide guidance for assessing RAP aggregate properties. Other, more complete research has been done on this issue, however, that is more useful.)

The research, then, consists of three main experiments plus two mini-experiments, as follows:

- Black Rock Study
- Binder Effects Study
  - Including an investigation of extraction/recovery methods and solvents
- Mixture Effects Study
- Mini-experiments
  - Plant vs. Lab Comparison
  - Effect of RAP Heating Time and Temperature

Descriptions of the individual materials used and the experimental design for each portion of the study follow.

Materials and Mixtures

The major portions of this study used three sources of RAP, two virgin binders and one virgin aggregate throughout. For the evaluation of binder extraction and recovery procedures (Task 4), two additional RAP materials were used. There were some exceptions to this for the mini-experiments as described below. For example, plant mixed material from one source was used in the plant vs. lab comparison.

Virgin Binder Properties

Two levels of virgin binder were selected corresponding to the expected range of asphalt binders that would normally be used with RAP mixtures within the United States. The PG 52-34 asphalt binder, supplied by Koch Materials Company, was selected to represent a soft base asphalt that could be blended with RAP mixtures in cool climates (such as the northern United States). The PG 64-22 asphalt binder, supplied by Marathon Ashland Petroleum LLC, was selected to represent a medium grade asphalt binder that could be blended with RAP mixtures in warm climates (such as the southern and southwestern United States). The Superpave binder properties of these two binders are shown in Table 1. (The material graded by the manufacturer as a PG 52-34 tested out here as a PG 52-28; this is discussed further in Chapter 2.)

Critical temperatures for the virgin binders are shown in Table 2. Critical temperatures are the temperatures at which a binder just meets the specified Superpave criteria, for example, 1.00 kPa for unaged binder high temperature stiffness ($G^*/\sin\delta$).

RAP Properties

The three RAPs used in the major studies were selected to provide different stiffnesses, as determined by recovered binder viscosity. A RAP from Florida (FL) was chosen as the low stiffness RAP, one from Connecticut (CT) was chosen as the medium stiffness RAP and one from Arizona (AZ) served as the high stiffness RAP. The recovered RAP viscosities are shown in Table 2.

All of the RAPs were extracted using the modified SHRP Rotavapor procedure with n-propyl bromide as the solvent. (This modified procedure is discussed in Chapter 2.) The RAP binder properties are shown alongside the virgin binder properties in Table 1. The RAP binder properties shown here were all tested on unaged, extracted RAP binder that was tested as if it had also been RTFO and PAV aged.

The Connecticut material graded as a PG 82-22. It was classified as a medium stiffness RAP (Viscosity at 60°C = 65, 192P). The RAP had a recovered asphalt content of 4.93%. The Florida RAP also graded as a PG 82-22 but was used as the low stiffness RAP on the basis of its viscosity (23, 760P). The FL RAP had an asphalt content of 5.01%. The Arizona RAP graded as a PG 88-10 and had an asphalt content of 5.31%. It was used as the high stiffness RAP (124, 975P).

The critical temperatures were determined for each recovered RAP binder without additional aging. The critical temperatures for each RAP binder are shown in Table 3.

The extracted RAP aggregates were sieved to determine the gradation. The average gradation for each RAP is shown in Table 4 and Figure 1.

Virgin Aggregate

A Kentucky limestone and natural sand were chosen as the common virgin aggregates for use in this study. These materials are the lab standards typically used at the Asphalt Institute. The gradations of these materials were artificially manipulated, as described below, to keep the gradation of the blends of virgin and RAP materials as consistent as possible.

Mixtures

The design aggregate blend chosen was a 12.5mm nominal mix using Kentucky limestone and natural sand. Figure 2 shows the design aggregate gradation used and the gradation is listed in the last column of Table 5. This gradation has been used frequently by the Asphalt Institute.

Blends were created using 10, 20 and 40% of the RAP materials, for different portions of the project. The virgin aggregate gradation was artificially adjusted so that the combined virgin and RAP aggregate gradations reasonably matched the design gradation. Table 5 shows the 10 and 40% RAP blend gradations compared to the target mix design gradation. None of the adjusted gradations differed from the design gradation by more than 3.5%.

Black Rock Study

Concept

RAP consists of two components that must be considered when designing an asphalt mix, aggregate and binder. An important question that needs to be answered in regards to adding RAP to new paving materials is to what extent, if any, does the recycled binder blend with the virgin binder? Does the recycled binder blend totally, partially, or not at all with the virgin binder?

Previous mix design systems treated RAP as if total blending occurs. For mixtures containing greater than 20% RAP, users must account for the stiffening effect that the RAP binder has on the virgin binder (5) This may or may not be true. If the user assumes that the material blends totally when it actually behaves as a black rock, then the mixture will not be as stiff as intended, since the RAP binder will have no effect. On the other hand, if the user assumes that the RAP behaves as a black rock, when it actually does blend with the virgin binder, then the mixture will be stiffer than intended.

The black rock study was designed to investigate the behavior of RAP materials when mixed with virgin aggregates and binders. Testing was performed to evaluate the high, intermediate and low temperature properties of the mixtures under different blending conditions.

The purpose of the black rock study was to determine whether RAP binder blends with virgin binder in a mix. If the RAP binder does not blend at all with the virgin binder, then the RAP can be considered part of the aggregate and it will not be necessary to account for the effect of the RAP binder on the binder properties of the mix. If, however, the RAP does blend with the virgin binder, either totally or to a limited extent, it will be important to account for the effects of adding the stiffer RAP binder to the virgin binder.

The null hypothesis, $H\phi$, of the experiment is stated as follows: RAP binder does not blend with virgin binder to any significant degree, as measured by mixture mechanical properties. The alternate hypothesis is that the RAP binder does blend with the virgin binder. Three cases simulating possible interactions between the old and new binders were studied to investigate the behavior of RAP blends.

- Black Rock (BR): Samples were made using virgin and recovered RAP aggregate with virgin binder, no recovered RAP binder.
- Actual Practice (AP): Samples were made using virgin binder and aggregate, mixed with RAP with its binder film intact.
- Total Blending (TB): Samples were made using virgin and recovered RAP aggregate. RAP binder was recovered, then blended with virgin binder in the specified percentages before mixing.

In all cases, the overall gradation and total asphalt content are constant.

Table 6 shows the test matrix for the study.

Three levels of RAP stiffness were selected (high, medium and low) as previously described. Two RAP contents were used, 10 and 40%. These levels correspond to typical minimum and maximum usage of RAP expected within wearing course mixtures. Two levels of virgin binder were selected corresponding to the expected range of asphalt binders that would normally be used with RAP mixtures within the United States.

Superpave performance test parameters, including the results of Frequency Sweep (FS), Simple Shear (SS), and Repeated Shear at Constant Height (RSCH) tests, were the response variables used to characterize the three mixture cases at high and intermediate temperatures as shown in Table 7. The Indirect Tensile Creep (ITC) and Strength (ITS) tests were used to characterize mixtures at low temperatures. (These tests are all described in Chapter 2.) The test temperatures used are generally standard values. The RSCH test temperatures were selected based on the virgin binder grades. For each test, three replicates were planned. This number was selected as a reasonable replicate testing number given the time consuming process of sample preparation in this study. This target was achieved for most cases.

Sample Preparation

Aggregates and binders were heated to reach their mixing temperature. Aggregates were heated overnight at 150°C. The binders were heated to the mixing temperature based on the binder grade; 155-160°C for the PG 64-22 and 134-140°C for the PG 52-34. When intact RAP was used in the "actual practice" mixtures, Case AP, it was heated for 2 hours at 110°C. The materials were then mixed for two minutes in a bucket mixer (total batch weight 5600g). All mixtures were aged in an oven for four hours after mixing (short term aging), then they were compacted in a Superpave gyratory compactor to reach a specific air void level. Specimens with PG 64-22 were compacted at 143-148°C and with PG 58-34 at 122-130°C. The compacted samples were cut to obtain two test samples 150mm in diameter and 50 ± 2mm in height. The target air void content for the repeated shear at constant height test was 3 ± 1% and for the other performance tests was 7 ± 1%.

To prepare the long-term oven aged samples, compacted specimens were aged for five days at 85°C before cutting. Three replicate samples were tested for each procedure.

The purpose of the different aging techniques used for the CT RAP (medium stiffness) was to determine what effect, if any, the RAP material has on the aging properties of the mixes. Long-term oven aging allows time for more blending of the RAP binder with the virgin binder and may, therefore, move the results of testing samples representing actual practice (Case AP) closer to total blending (Case TB) and further from the black rock case (Case BR). Long-term oven aging was used for all the IDT tests since cracking is a distress that typically occurs later in the life of the pavement after the mixture has aged.

Binder Effects Study

This experiment was designed to determine the effects of RAP amount and stiffness on blended asphalt binders. The study was also intended to provide recommended procedures for determining the appropriate amount of RAP or appropriate virgin asphalt binder to be used in a RAP asphalt mixture design.

As a part of the investigation into binder issues associated with the use of RAP, an experiment was conducted in Phase I of this research project to examine the effects of extraction and recovery procedures on RAP properties. This study also looked at alternate solvents. The results of this work will be summarized in Chapter 2.

Based upon this research this report will; recommend modifications to the extraction and recovery procedures for RAP, discuss testing of recovered asphalt binder, discuss selection of virgin asphalt binder to achieve a target “blended” asphalt binder grade (percentage and type of

RAP fixed), discuss selection of RAP amount to achieve a target "blended" asphalt binder grade (virgin asphalt binder fixed), and discuss the incorporation of testing reliability into the blending charts.

The experimental design for the binder effects study consisted of three variables as indicated in Table 8: virgin asphalt binder, RAP stiffness and RAP percentage.

The two virgin asphalt binders and three RAP sources described earlier were evaluated in the binder effects study. Three RAP percentages were selected in addition to the 0% (all virgin binder) and 100% (all recovered RAP binder) conditions. Blend percentages of 10%, 20% and 40% RAP binder were selected to represent the likely range of RAP usage in hot mix asphalt mixtures. The selected percentages also bracket the tiers recommended by the Mixtures Expert Task Group (1). The ETG recommendation is summarized in Table 9. As indicated in Table 9, the 10% level falls into the first category (no change in binder grade), the 20% level into the second category (one grade softer), and the 40% level falls into the third category (blending charts needed).

The null hypothesis for this study is that there is no effect of the main effect or two-way interactions on the response variable versus the alternative that the factor has a significant effect on the response variable.

The response variables for the experiment were the individual test results and critical temperatures determined at high and intermediate temperatures from the Dynamic Shear Rheometer (DSR) tests and at low temperatures from the BBR tests. The specific parameters studied were complex shear modulus (G*) and phase angle (δ) from the DSR and stiffness and m-value from the BBR.

Estimated critical temperatures were determined by equation for the blended binders by using the test results for the virgin and recovered RAP asphalt binders. Earlier research by the National Center for Asphalt Technology (6) and the Asphalt Institute (2) indicated that a linear equation appeared to be sufficient for high temperature shear stiffness measurements ($G^*/\sin\delta$) and low temperature stiffness measurements (S and m-value). Both studies indicated more non-linear response for the intermediate temperature shear stiffness ($G^*\sin\delta$).

Extraction and Recovery Study (Phase I)

An experiment was developed and executed in Phase I to evaluate the effect of extraction and recovery procedures on asphalt binder properties. This experiment was intended to allow the NCHRP 9-12 research team to select an appropriate extraction and recovery procedure for use in the detailed experiments in Task 8. Subsequently, the procedure could be recommended for inclusion in AASHTO TP2 if it proved to be significantly better than the existing method and is sufficiently practical. Many factors were considered when selecting the extraction and recovery procedures including selection of solvent, sample size, testing time and testing precision. Table 10 indicates the testing matrix for evaluating extraction and recovery procedures.

Two extraction methods were evaluated. Previous research indicated that the Reflux extraction procedure (ASTM D2172, Method B) appears to cause an increase in the solvent aging of the recovered asphalt binder, so it was not evaluated here. Of the current solvent extraction procedures, the Centrifuge extraction (ASTM D2172, Method A) appeared to be the most likely candidate for continued experimentation. The modified SHRP extraction procedure (AASHTO TP2) was also evaluated in the experiment.

Two recovery methods were evaluated, the Abson method and Rotavapor method. The Abson method (ASTM D1856) has been the standard recovery method used for many years. The Rotavapor method has recently gained in popularity and is the choice for use in combination with the SHRP extraction method. Note that the Rotavapor method (ASTM D5404) may be modified for use with the modified SHRP extraction method.

Three solvents were evaluated in the experiment: trichloroethylene, toluene/ethanol, and an alternative solvent (an N-Propyl Bromide (NPB) based solvent). Trichloroethylene (TCE) has been the solvent of choice for many years, and was identified by SHRP researchers as one of the best solvents. Unfortunately, health and environmental concerns have drastically reduced the availability of TCE in the past few years. The combination of toluene and ethanol was proposed as the solvent for use with the SHRP extraction and recovery procedures. The SHRP researchers believed that this solvent was comparable with TCE as a solvent, yet not as toxic. Still, there are potential health concerns with this solvent. Many agencies are interested in using alternative non-chlorinated solvents, such as NPBs. Therefore, one NPB was included to assess changes in the extraction and recovery process with an alternative solvent. (The NPB used in this research was Ensolv, manufactured by EnviroTech International in Melrose Park, IL.)

Two sources of RAP were used in the experiment. The Florida RAP used elsewhere in the project was included, as well as a typical central Kentucky RAP. The Kentucky RAP consisted of mostly hard limestone and natural sand. The binder viscosity was approximately 50,000 poises at 60°C. The FL RAP was described previously.

The response variables are those generated from the dynamic shear rheometer (DSR) test at high temperatures. Test temperatures include 64, 70, 76 and 82°C. A strain sweep was also performed at 82°C to check for assumptions of linearity. Also, aggregate gradation, asphalt content and testing time were evaluated. Three replicates were performed for each combination of extraction procedure, recovery procedure, solvent and RAP.

Dynamic shear rheometer (DSR) testing was performed at 4% shear strain for the 64, 70 and 76°C temperatures. The target shear strain of 4% corresponds to the shear strain level appropriate for a binder with a complex shear modulus (G*) of approximately 50 kPa at the test temperature. This equation is listed in AASHTO TP5 as follows:

$$\gamma\text{, percent} = 12.0 / (G^*)^{0.29}$$

Although the RAP stiffness was unknown at the time of testing, it was anticipated that G* would not be higher than 50 kPa at 64°C.

Linearity was tested in accordance with Annex A1 of AASHTO TP5. In this testing, an asphalt binder is tested at 2% increments from 2% to 30% shear strain at a specified temperature. The asphalt binder is considered linear if the G* at 12% shear strain is 90% or more of the G* at 2% shear strain.

Mixture Effects Study

The mixture effects study was designed to investigate the effects of the added RAP on mixture properties. The experimental design is shown in Table 11. The variables included:

- RAP Stiffness -- three levels, low, medium and high, as previously described.
- RAP Content – four levels, 0, 10, 20 and 40% RAP, by weight of total mix.
- Virgin Binder – two levels using the PG 52-34 and PG 64-22 described earlier.

This study was closely coordinated with the black rock study. The Case AP samples (actual practice) from the black rock study are identical to the mixture effects study results for the 10 and 40% RAP samples. Additional samples were prepared at 0 and 20% RAP to fill out the experimental cells for the mix effects study.

The response variables evaluated included the same tests used for the black rock study plus some additional testing. Specifically, the response variables include parameters from RSCH, FS, SS, ITC, ITS and beam fatigue testing.

Mini-Experiments

Two small-scale studies were conducted to address particular issues related to the use of RAP. Each is described below. A third experiment was conducted on changes in RAP aggregate properties but was dropped because it was too small in scale to provide meaningful data. Other, more complete studies of changes in aggregate properties have been conducted and those results have been reviewed.

Plant vs. Lab Comparison

This mini-experiment was conducted to get an indication of how representative the lab practices followed in this project were of actual field production. The question was whether the sample preparation techniques used, especially in the black rock experiment, produced specimens that were similar to plant-produced mixtures. If not, the conclusions drawn from this laboratory study could not reasonably be applied to field conditions.

For this mini-experiment, only the Connecticut RAP and plant-produced mixture using the same RAP were evaluated. The Connecticut RAP was used for this mini-experiment because plant-produced mix and raw materials were available.

The gradation and asphalt content of the plant mix were determined from the job mix formula and verified by extraction and sieve analysis. Samples similar to the Case AP (actual practice) samples from the black rock experiment were then prepared and compacted using the same RAP, virgin aggregate and virgin binder as were used in the plant mix. The same laboratory sample preparation techniques were used, but the proportions of materials were matched to the plant mix. That is, the virgin aggregate was heated to 150°C and the binder was heated to 135°C. The RAP was heated for two hours at 110°C and then all the components were mixed. The lab-prepared mixture was aged for four hours at 135°C to simulate short-term plant aging. Samples of the plant mix were heated to the appropriate compaction temperature, which typically took less than one hour. All samples were then compacted with a Troxler Gyratory Compactor to reach the specific air void contents required for the Superpave shear tests. Two samples were cut from each gyratory specimen for performance testing.

Table 12 presents the final aggregate gradation of the laboratory and plant asphalt mixtures. The optimum asphalt content was 4.8% of total weight of the mixture. A PG 52-28 asphalt binder containing 0.375% fiber was used as the new binder in the mixtures, to match the plant produced mix.

The two mixes were then compared using the frequency sweep (FS) and simple shear (SS) tests at 7 ± 1% air voids and the repeated shear at constant height (RSCH) test at 3 ± 1% air. The FS and SS tests were conducted at 20 and 40°C according to AASHTO TP7 and the RSCH tests were done at 58°C. At least five replicates were tested for each test and temperature.

Effects of RAP Handling

During the laboratory mix design process, it is necessary to heat the RAP in order to incorporate it in the new mixture. The goal of heating is to separate the particles enough to allow them to disperse through the mixture without artificially aging the RAP more.

This mini-experiment was designed to investigate the effects of heating time and temperature on RAP properties. Two RAPs (the low and high stiffness RAPs) were heated for different times and at different temperatures, then the changes in the properties of extracted RAP binder were measured. Because excessive heating is presumed to artificially age the RAP binder, binder properties were tested. The researchers also felt that the binder properties might be subject to less variability than volumetric properties, which could be influenced by compaction temperature, aggregate gradation and other variables. Ultimately, however, the real concern is whether the handling of the RAP affects the volumetric and mechanical properties of the mix. If the heating does not change the binder properties, it is reasonable to assume the mix properties would not change as a result. The experimental design used is shown in Table 13.

Following heating, then, the RAP binder was recovered for testing the binder properties. The main effects evaluated include:

- RAP, two levels. The high and low stiffness RAPs used in the main experiments were tested here to investigate whether initial stiffness of the RAP has any effect on handling precautions.
- Heating Time, three levels. Heating times from two hours to overnight were investigated, specifically 2 hours, 4 hours and 16 hours. In general, the shorter the aging time, the better from a production standpoint. However, there may also be advantages to being able to put the RAP in the oven the night before a mix design so that the material is ready to use the next morning, if the RAP properties do not change as a result of prolonged heating.
- Heating Temperature, two levels. Heating temperatures of 110 and 150°C were investigated.

After heating approximately 1 to 2 kg of RAP according to the different treatment combinations above, the binder was extracted and recovered using the techniques described in Chapter 2. The DSR was then used to measure the binder stiffness (G*) at two different temperatures (22 and 31°C).

The null hypothesis is that the main effects have no significant effect on the response variables. The alternate hypothesis is that the main effects do have a significant effect on the response variables. Again, analysis of variance techniques were used to analyze the impacts of the main effects and two-way interactions.

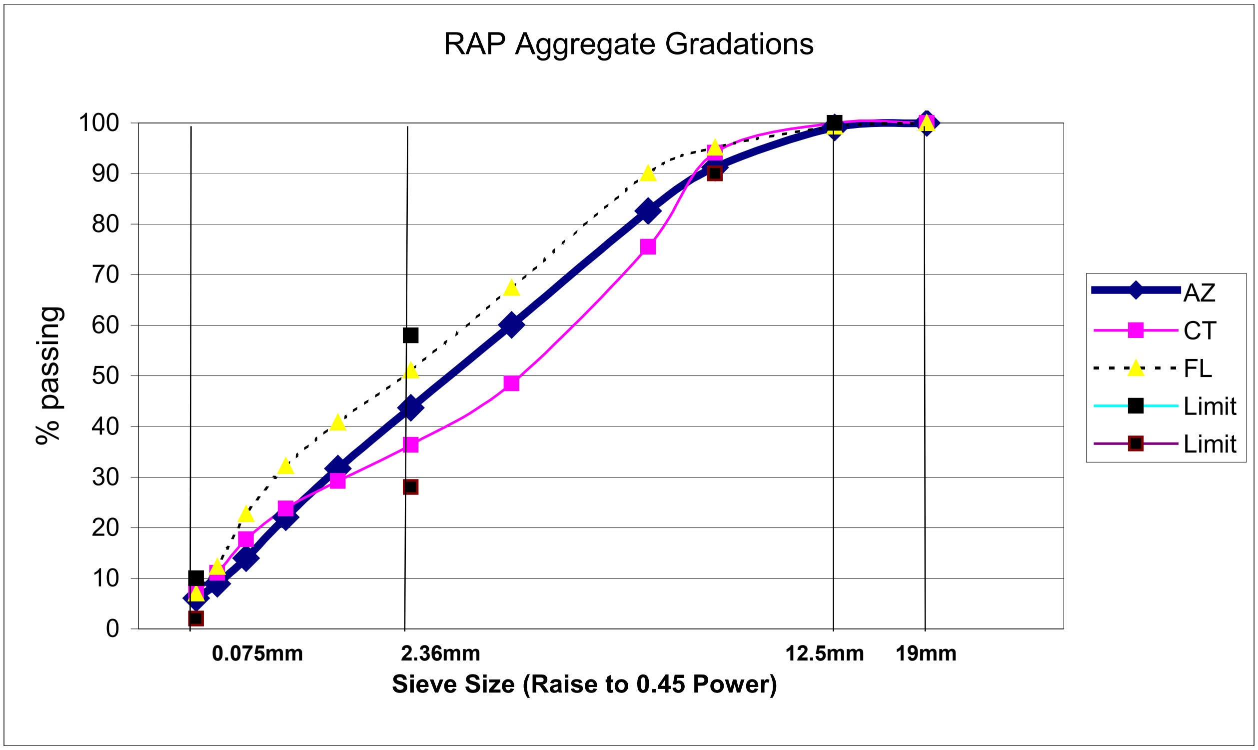

Figure 1. RAP Aggregate Gradations

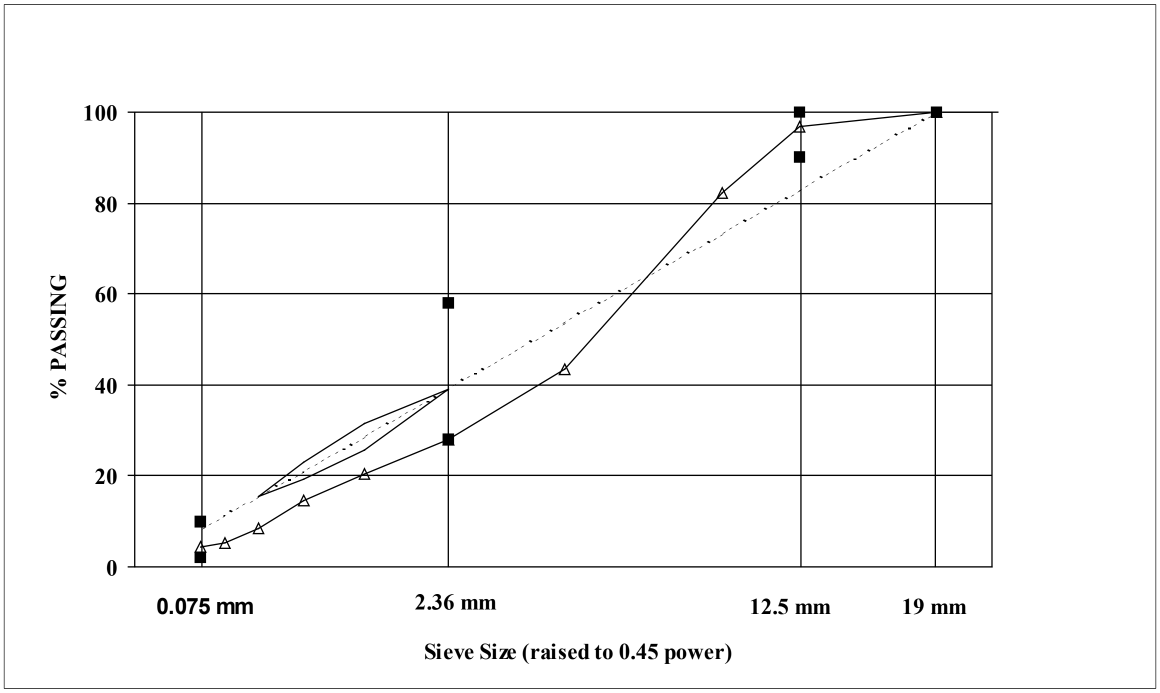

Figure 2. Design Gradation

Table 1. Virgin and Recovered RAP Binders

Aging	Property	Temp, C	Virgin Binders		RAP Binders - Unaged*		
			PG 52-34	PG 64-22	FL	CT	AZ
Original	G*/sinδ kPa	52	1.27				
		58	0.59				
		64		1.63			
		70		0.76			
		76			2.06	2.28	
		82			1.02	1.05	2.65
		88				0.52	1.16
RTFO	G*/sinδ kPa	52	3.13				
		58	1.40				
		64		3.09			
		70		1.42		4.70	
		76			2.06	2.13	
		82			1.02		3.44
		88					1.53
PAV	G*sinδ kPa	10	6,226				
		13	4,045				
		16					
		19		6,984		10,250	
		22		4,846	5,168	7,336	
		25			3,529	5,151	
		28				3,533	
		31					7,436
		34					4,891
	BBR Stiffness MPa	0					154
		-6					314
		-12		120	180	207	
		-18	127	296	393	427	
		-24	312				
	BBR m-value	0					0.376
		-6					0.312
		-12		0.344	0.349	0.325	
		-18	0.388	0.281	0.282	0.263	
		-24	0.321				

* Recovered RAP binders without additional aging were tested as if RTFO and PAV aged.

Table 2. Recovered RAP Viscosity

RAP Source	Viscosity @ 60°C, Poise
FL	23,760.18
CT	65,191.60
AZ	124,975.00

Table 3. Critical Temperatures and Performance Grades of Virgin and Recovered RAP Binders

		Virgin Binders		Recovered RAP Binders (Unaged)		
Aging	Property	PG 52-34	PG 64-22	FL	CT	AZ
Original	High Temp. Stiffness	53.9	67.8	82.2	82.4	89.0
RTFO	High Temp. Stiffness	54.6	66.6	75.4	75.8	85.3
PAV	Intermediate Temp. Stiffness	11.5	21.7	19.3	25.1	33.8
	BBR S	-23.7	-18.1	-15.9	-15.1	-5.6
	BBR m-value	-25.9	-16.2	-16.4	-14.4	-7.1
PG	Actual (Critical Temperature)	PG 53-33	PG 66-26	PG 82-25	PG 82-24	PG 89-15
	MP1 (Performance Grade)	PG 52-28	PG 64-22	PG 82-22	PG 82-22	PG 88-10

Table 4. RAP Gradation and Asphalt Content

	RAP		
Sieve	AZ	CT	FL
25 mm	100.0	100.0	100.0
19 mm	99.1	100.0	99.3
12.5 mm	91.2	94.1	95.1
9.5 mm	82.6	75.5	90.1
4.75 mm	60.1	48.5	67.4
2.36 mm	43.7	36.4	51.1
1.18 mm	31.7	29.2	40.8
600 µm	22.1	23.8	32.2
300 µm	14.0	17.7	22.7
150 µm	8.9	11.1	12.3
75 µm	6.1	7.3	7.0
AC Content, %	5.3	4.9	5.9

Table 5. Combined RAP and Virgin Aggregate Gradations

Sieve	Mix with AZ RAP		Mix with CT RAP		Mix with FL RAP		Target Mix Design
	10%	40%	10%	40%	10%	40%	
25 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19 mm	99.9	99.6	100.0	100.0	99.9	99.7	100.0
12.5 mm	94.3	95.8	94.6	97.0	94.7	97.3	96.8
9.5 mm	79.8	82.4	79.1	79.5	80.6	83.2	82.3
4.75 mm	43.0	45.3	41.8	40.6	43.7	40.2	43.5
2.36 mm	27.5	30.0	26.8	27.1	28.2	26.2	28.0
1.18 mm	19.7	21.9	19.4	20.9	20.6	20.7	20.4
600 µm	14.1	15.7	14.2	16.3	15.1	16.4	14.7
300 µm	8.7	9.6	9.0	11.1	9.5	11.5	8.4
150 µm	5.8	6.2	6.0	7.0	6.1	6.8	5.2
75 µm	4.8	4.7	5.0	5.2	4.9	4.5	4.5

Table 6. Black Rock Study Experimental Design

Virgin AC	RAP Stiffness	RAP %	Mixture Cases BR Black Rock	 AP Actual Practice	 TB Total Blending
52-34	Low	10	xxx	xxx	xxx
		40	xxx	xxx	xxx
	Medium	10	xxx	xxx	xxx
		40	xxx	xxx	xxx
	High	10	xxx	xxx	xxx
		40	xxx	xxx	xxx
64-22	Low	10	xxx	xxx	xxx
		40	xxx	xxx	xxx
	Medium	10	xxx	xxx	xxx
		40	xxx	xxx	xxx
	High	10	xxx	xxx	xxx
		40	xxx	xxx	xxx

Table 7. Response Variables for the Black Rock Study

Aging Condition	Tests	Testing Temperatures
Long-Term Oven Aged	Frequency Sweep at Constant Height*	4 and 20^{o}C
	Simple Shear at Constant Height*	4 and 20^{o}C
	Indirect Tensile Creep	0, -10, and –20°C
	Indirect Tensile Strength	-10°C
Short-Term Oven Aged	Frequency Sweep at Constant Height	20 and 40^{o}C
	Simple Shear at Constant Height	20 and 40^{o}C
	Repeated Shear at Constant Height	52 and 58^{o}C

* Completed for CT RAP only. Dropped for other RAPs.

Table 8. Binder Effects Experiment

		Virgin Asphalt Binder	
RAP Stiffness	% of RAP Binder	PG 52-34	PG 64-22
None	0%	×	×
Low (Florida)	10%	×	×
	20%	×	×
	40%	×	×
	100%	×	×
Medium (Connecticut)	10%	×	×
	20%	×	×
	40%	×	×
	100%	×	×
High (Arizona)	10%	×	×
	20%	×	×
	40%	×	×
	100%	×	×

Table 9. Mixtures ETG Guidelines for RAP

RAP Percentage	Recommended Virgin Asphalt Binder
Less than 15%	No change in binder selection.
15 – 25%	Select virgin binder one grade softer than normal (i.e., choose a PG 58-28 if a PG 64-22 would normally be used.).
Greater than 25%	Follow blending chart recommendations.

Table 10. Experimental Design for Extraction/Recovery Evaluation

Extraction Method	Recovery Method	Solvent	RAP Source	
			Florida	Kentucky
Centrifuge	Abson	TCE	xxx	xxx
	Rotavapor	TCE	xxx	xxx
		Toluene/Ethanol	xxx	xxx
Modified SHRP (TP2)	Rotavapor	TCE	xxx	xxx
		Toluene/Ethanol	xxx	xxx
		NPB	xxx	xxx

Table 11. Experimental Design, Mixture Effects Study

		RAP Content			
Virgin AC	RAP Stiffness	0%	10%	20%	40%
PG 52-34	Low (FL)	xxx	xxx	xxx	xxx
	Medium (CT)		xxx	xxx	xxx
	High (AZ)		xxx	xxx	xxx
PG 64-22	Low (FL)	xxx	xxx	xxx	xxx
	Medium (CT)		xxx	xxx	xxx
	High (AZ)		xxx	xxx	xxx

Table 12: RAP Aggregate Gradation for Lab and Plant Mixtures

Sieve	% Passing
25 mm	100
19 mm	100
12.5 mm	95.7
9.5 mm	72.7
#4	40.4
#8	27.4
#16	20
#30	15.6
#50	11.1
#100	5.9
#200	2.6

Table 13. Experimental Design for RAP Handling

Stiffness	Temp, °C	Heating Time, hours		
		2	4	16
Low (FL)	110	xx	xx	xx
	150	xx	xx	xx
High (AZ)	110	xx	xx	xx
	150	xx	xx	xx

CHAPTER TWO

FINDINGS

Review of Phase I Findings

The findings of Phase I are detailed in the interim report (3). A brief summary of the findings is presented here. The results of the literature review (Task 1) are presented in more detail in Appendix A.

Significant Findings from Literature Review (Task 1)

The literature review shows that there has not been a great deal of published research about RAP using the Superpave binder or mixture test protocols. There simply has not been enough time since the Superpave products debuted for much research to have been initiated or completed. We can, however, learn from past projects that used some of the Superpave procedures or that studied related topics using other specifications and test methods.

The research by Harvey et al. (7) is one of the few projects to use Superpave mixture tests. That research showed that the repetitive shear test at constant height and beam fatigue tests are sensitive to changes in mixture and binder properties. Mixtures evaluated in repetitive shear were compacted using rolling wheel compaction since the Superpave Gyratory Compactor had not yet been developed, but that would not be anticipated to significantly alter the results. Rolling wheel compaction is necessary for fabricating beam fatigue specimens in the lab.

Other studies (8, 9, and 10) exhibit the variety of results obtained in past research. For example, Tam et al. (8) found that mixes with RAP are less resistant to thermal cracking than non-recycled mixtures, while Kandhal et al. (9) found no significant difference in cracking performance, and Sargious and Mushule (10) found that the recycled mixture performed better than the virgin mixture in terms of cracking. The mixture behavior is responsive to binder properties at low, intermediate and high temperatures. A binder selected to perform well at high temperatures may not necessarily perform well at low temperatures. These studies were conducted with penetration or viscosity graded asphalts. The Superpave binder system gives us a tool to investigate the binder effects over a range of temperatures and aging conditions and should, therefore, allow us to better select the appropriate binder blend (RAP + virgin) for a given situation. The study by Sargious and Mushule did use a softer asphalt for the recycled mix than for the control mix, which may have rejuvenated the RAP, resulting in the improved performance noted.

Resilient modulus has been used in many studies to evaluate RAP mixtures (10, 11, 12, 13 and 14). This test method could be evaluated further, but it is not a preferred method of evaluation. Variability of test results, especially between labs, has posed problems in interpreting the data.

Many studies (14, 15, 16 and 17) document the fact that recycled mixtures can perform at least as well as conventional mixtures. Improved extraction, recovery and binder testing procedures should allow even better selection of the right binder for a recycled mixture leading to improved performance.

Several studies of solvents and extraction/recovery techniques have been completed (18, 19, 20, 21, 22 and 23). This research supports the use of the Rotavapor or SHRP methods over the Abson. Further work done as a part of the binder effects study confirms these findings and proposes additional modification to improve the SHRP method even more.

A variety of methods can be used to simulate mixture aging in the laboratory. Bell et al. (24) developed the short and long-term oven aging procedures recommended in Superpave. Ruth et al. (25) used the long-term oven aging procedure to fabricate RAP in the laboratory. This type of long-term aging was used in portions of this study, but testing of actual plant-produced and/or field aged materials was preferred for most portions of the study. The serious disadvantage to using long-term oven aging when designing a mixture with RAP is that the mix design process can then be delayed by days or weeks.

Several studies have been directed at examining changes in aggregate properties before and after solvent extraction or burn-off in an ignition oven. These studies have application to RAP mixtures as well, where the original aggregate properties may be unknown. A study by NCAT (26) showed that there is a significant difference between the virgin and recovered bulk specific gravity (G_{sb}) for three tested aggregates (lime rock fine, trap rock and granite) before and after burn-off. The G_{sb} decreased 0.021, 0.035 and 0.015 for the above aggregates respectively. The Virginia Transportation Research Center (27) compared the virgin G_{sb} calibration factor using a known asphalt content, and G_{se} calculated using an asphalt content determined with the ignition furnace for six aggregates types. VMA values calculated with G_{se} were always larger. The difference ranged from 0.01 to 0.43 percent.

Review of On-Going Research (Task 2)

Under this task, the research team attempted to identify on-going research related to the use of RAP, especially in relation to its use in Superpave. Research projects on related topics, such as evaluation of extraction and recovery procedures, were also sought. A variety of techniques was used to identify on-going research efforts.

This search revealed relatively little current research related to the usage of RAP. Only a few projects, as discussed below, were identified. This may, perhaps, be due to the fact that, regardless of the mix design process used, procedures had been developed to use RAP that were working in most cases. The performance of mixtures with RAP has been proven to be acceptable. Little new research related to the use of RAP in Superpave has been initiated, perhaps because states and industry are still growing accustomed to the use of Superpave with virgin materials.

With the implementation of Superpave, RAP again became an issue as states recognized the need for procedures to incorporate RAP in the Superpave system. A few field studies using RAP in Superpave mixtures have been initiated, but little field performance data is available. Many other states are allowing the use of RAP in Superpave mixtures, at relatively low levels, but have not included control sections without RAP for comparison purposes.

Field projects in Connecticut and Indiana do include control sections and will be thoroughly documented, sampled and monitored since both are SPS-9A projects. These studies are each limited in terms of the materials evaluated, but can help to provide a complete picture of the effects of RAP. In addition, the fact that these projects will be monitored long term would allow them to be used to tie the lab results from this project to field performance by researchers in the future. The Connecticut project was the source of the medium stiffness RAP used in this project and the Indiana project is being evaluated in a regional pooled fund research project at the North Central Superpave Center.

Work at the University of Connecticut, nearing completion at the time this report was published, was directed at determining how much blending is occurring in a hot mix with RAP and developing a method to estimate the effective PG grade of binder in a RAP mix. The work, by student Cory Dippold with Dr. Jack Stephens and James Mahoney, used unconfined compression at high temperatures and indirect tensile testing at low temperatures, to evaluate mixes with 15% RAP (and some 25% RAP). The increase in strength or stiffness of a RAP mix as preheating time prior to mixing increases is used to estimate the amount of blending that occurs. Unconfined compression and indirect tension are also used to estimate the effective PG grade of binder in a RAP mix. Two mixtures with the same aggregate structure but different virgin aggregates are used to establish a straight line relationship of binder grade versus strength. The strength of a RAP mix with the same gradation, but unknown blended binder grade, is then tested. The effective binder grade of the mix is estimated by comparison to the strengths of the mixes with known binder grades. Additional research is needed to verify these results for a wider range of materials.

Internal work at the Washington State DOT is also interesting, but is limited by the fact that it is based entirely on laboratory fabricated binder samples using one RAP source. They blended recovered RAP binder with two virgin binders at different levels and measured the change in properties in the DSR and BBR. The fact that they found a level at which no appreciable change in binder properties occurs (10% in their tests) supports the concept of a tiered system, the lowest tier of which would require no change in the binder grade.

Evaluation of NCHRP 9-7 (Task 3)

The NCHRP 9-7 final report (28) was reviewed to evaluate how the recommendations from that study might impact projects utilizing RAP. There was no mention of RAP in the report although two of the field projects used RAP. Conversations with Mr. Brian Killingsworth of BRE indicated that he believed there was nothing in the final report that would specifically change testing procedures for mixtures containing RAP.

Field quality control procedures for mixtures consist of two steps. The first step is the field verification of the laboratory trial mix formula (LTMF) developed during the mix design process. In this verification, the contractor is required to produce a minimum of 300 tons and a maximum of one day's production. The produced mixture is required to be within the ranges (based on pooled variances from the test projects) shown in Table 14.

Asphalt content can be determined by three methods: solvent extraction, nuclear asphalt content gauge or ignition oven. Gradation is determined from solvent extraction or cold feed samples. Volumetric properties are determined using the Superpave gyratory compactor. The target values are established if the produced mixture is within the LTMF tolerances. The average and standard deviation are calculated for each of the properties above.

The second step during production is to assure that the produced mixture meets the revised target from the LTMF. Upper and lower control limits are set at two standard deviations (warning limit, 2σ) and three standard deviations (action limit, 3σ). The control limits must be within the allowable LTMF tolerances, or adjustments are necessary to bring the mix production process more in control (reduce variability).

There are several potential problems with the recommended tolerances and procedures when mixtures are produced incorporating RAP. One potential problem is that gradation is specified as being performed on either extracted aggregate (from solvent extraction) or from cold feed samples. Cold feed samples will not include RAP as it is typically added downstream in the mixing process from the cold feeds. The same problem exists when employing the French Video Grader, an in-line optical scanning approach to determining aggregate gradation from the cold feed belt.

Another problem is that many agencies are no longer using solvent extraction for determination of asphalt content. If RAP is used in the mixture, the nuclear asphalt content gauge may be used for asphalt content determination, but aggregate gradation will have to be determined based on extracted aggregate. The ignition oven may be used to determine the asphalt content of mixtures containing RAP. The gradation of the aggregate recovered from the ignition oven is being used by many states without adjustments. However, some gradation adjustments may be necessary depending on aggregate type.

The NCHRP 9-7 report also did not indicate that any final determination of asphalt properties was necessary. Using the proposed system, a harder RAP (75,000P @ 60°C) could be substituted for a softer RAP (15,000P @ 60°C) with no apparent change in the quality of the mixture. Testing of the recovered asphalt binder, or mechanical property testing of the mixture, would be necessary to identify this situation.

The other concern is that the mixture component tolerances (asphalt content and gradation) appear to be slightly tighter than many agencies use currently. These tolerances were established based on the pooled variances of the test projects used in the research. Two of these projects used RAP in the mixtures (13% and 25%). Using the current tolerances, the properties of the RAP will have to be unusually consistent. At 25% RAP, a variation in RAP asphalt content from 4.7% to 5.3% (5.0% target with 0.3% variance, typical of previous acceptable mixtures) will result in an asphalt content change in the total mix of 0.15%. This variance in RAP, although it would generally be considered acceptable, will make quality control more difficult as the acceptable tolerance for asphalt content by solvent extraction is 0.25%. In other words, unless the RAP is extremely consistent, Superpave mixtures containing RAP are likely to experience a higher percentage of values outside the 2σ warning limit and 3σ action limit than mixtures that do not use RAP.

Summary. In summary of Task 3, it appears that NCHRP 9-7 did not consider RAP in the recommended field procedures. The relatively tight tolerances on the material components are likely to adversely affect Superpave mixtures using RAP. To maintain acceptable mixture properties, the contractor is likely to either need a very consistent source of RAP, or to use a lower percentage of RAP. As noted above, a mixture containing 25% RAP with reasonable variation will be difficult to produce using the current tolerances. There also does not appear to be any provision to ensure that the stiffness of the RAP remains consistent. Using the same assumption (mixture containing 25% RAP), a change in RAP binder viscosity at 60°C from 25,000 P to 50,000 P will result in a significant change in the total binder stiffness.

Evaluation of Binder Extraction and Binder Testing Procedures (Tasks 4 and 5)

Background. Before the Strategic Highway Research Program, extraction procedures for removing asphalt from aggregate in an asphalt mixture typically followed one of the methods listed in ASTM D2172, *Quantitative Extraction of Bitumen from Bituminous Paving Mixtures*. There are five test methods listed as Methods A-E. Method A (Centrifuge Extraction) is likely the most common extraction procedure used by asphalt testing laboratories. Many laboratories also use Method B (Reflux Extraction). Methods C and D are variations of the reflux extraction. Method E (Vacuum Extraction) is an option as a third extraction technique.

Before SHRP, recovery of asphalt binder from solution followed ASTM D1856, *Recovery of Asphalt from Solution by Abson Method*. This test method was introduced in 1933 and has been the principal recovery technique used by testing labs. Since the 1970's a second recovery procedure has been used by some testing laboratories. This method is ASTM D5404, *Recovery of Asphalt from Solution Using the Rotavapor Apparatus*, named for its use of a rotary evaporator as the recovery equipment.

Solvents used in the extraction and recovery procedures include:

- reagent grade trichloroethylene (Abson, Rotavapor, Centrifuge Extraction, Reflux Extraction)
- methylene chloride (Rotavapor, Centrifuge Extraction, Reflux Extraction, Vacuum Extraction)
- refined, reagent grade, or nitration grade benzene (Abson)
- 1,1,1-trichloroethane (Centrifuge Extraction, Reflux Extraction)

Of the four solvents listed, benzene would be considered the most toxic (1 ppm time-weighted average concentration for 8-hr exposure for 5-day week), followed by trichloroethylene (100 ppm), methylene chloride (200 ppm), and 1,1,1-trichloroethane (350 ppm).

The concerns over the toxicity of the solvents led to three main developments in the late-1980's and early-1990's in the determination of asphalt content (the primary purpose of the asphalt extraction methods):

- development of organic or biodegradable solvents,
- development of a nuclear asphalt content gauge, and
- development of an asphalt ignition oven.

Although each of these new developments was well suited to determining asphalt binder content without the use of solvents that were toxic to some degree, none of the new procedures could be used when recovering the asphalt binder from the mixture. Consequently, if it was desired to know the properties of an asphalt binder used in a mixture sample, a recovery was still required using trichloroethylene, benzene or methylene chloride.

During SHRP, researchers at Texas A&M University explored asphalt extraction and recovery procedures as part of the research program. Their research led to the development of a new extraction process with a modified recovery procedure. Several papers were reviewed that detailed the findings of their research (18, 19, 20, 21 and 22). These five papers provided much information regarding current (1990's) extraction and recovery techniques, as well as discussing the development of the SHRP extraction and recovery method.

The SHRP researchers indicated that the test results of the physical properties of asphalt binders recovered using the Abson or Rotavapor recovery procedures varied greatly. Typical coefficients of variation ranged from 25% to 42% for absolute viscosity of recovered asphalt binder. The researchers believed these errors could be attributed in large part to three factors:

1. The reaction of asphalt binder and solvent while in solution can alter the physical properties of the recovered asphalt binder.
2. Residual solvent often remains in the recovered asphalt binder at the completion of the recovery process, which alters the physical properties of the asphalt binder.
3. Asphalt binder is not completely extracted from the aggregate, leaving strongly adsorbed material that may have significantly different bulk physical properties than the remainder of the recovered asphalt binder.

The SHRP extraction and modified recovery procedures were developed to address each of these concerns. The SHRP extraction procedure (AASHTO TP2) uses an extraction cylinder that is rotated on its side, much like a rock polishing machine, with baffles in the cylinder to facilitate mixture-solvent contact. After the first application of solvent wash (toluene) the cylinder is set vertically, and the extract is removed from the sample by attaching a vacuum at the bottom of the extraction cylinder. The extract passes through a filtering system including an 8 mm polypropylene monofilament filter before being collected in a recovery flask. This extract is then further filtered through a fine filter (1 to 2 mm) to remove additional fine aggregate particles. Before final distillation, the extract is centrifuged to remove any remaining fines. Approximately seven solvent washes (3,000 ml of solvent contacting the sample) are sufficient to remove the asphalt binder from the aggregate. Recovery is performed using a modification of the Rotavapor method.

The SHRP research addressed the first factor listed above by evaluating the solvents and extraction methods used as part of current practice. A study by Abson and Burton (29) in 1960 examined several chlorinated solvents in the recovery procedure and discovered that some induced severe aging. Carbon tetrachloride appeared to harden the recovered asphalt binder the most. Another chlorinated solvent that caused severe aging was 1,1,1-trichloroethane. The

SHRP researchers, in evaluating the effects of solvent hardening, examined several solvents. Their conclusions were that solvent hardening appears to occur to roughly the same degree in most solvents, although they would expect somewhat lower hardening in toluene because it is a poorer solvent that leads to more aggregation or association in solution (21). The researchers indicated that while trichloroethylene with 15% ethanol is the most powerful solvent for extracting asphalts, toluene with 15% ethanol works well and has safety advantages (19).

The choice of extraction method also has an effect on solvent hardening. The Reflux method (ASTM D2172, B) has poor solvent contacting and exposes the asphalt to solvent at elevated temperatures for long periods of time. The recovery procedure was also modified in response to concerns with factor #1 above by utilizing two flasks for retaining solution before recovery. After the third solvent wash, the solution contains approximately 90% of the asphalt binder from the mix sample. This flask is set aside, and remaining washes are filtered into a second flask. The researchers believed this minimized solvent aging.

Early studies were also conducted that indicated that following the standard Abson recovery procedure can leave enough residual solvent to produce significant softening, particularly for large quantities of recovered asphalt binder and hardened asphalts (18). The research indicated that even 0.5% residual solvent could result in a 50% decrease in viscosity. The Rotavapor recovery procedure was modified to remove residual solvent from the sample.

The development of the SHRP extraction procedure was also intended to address factor #3 above. The research indicated that the SHRP extraction procedure removed all but approximately 1% of the asphalt from the aggregate while ASTM D2172 (Method A) left more asphalt that was not removed (typically 2% to 4%).

There are several potential disadvantages with the procedure (AASHTO TP2), as listed below:

1. Recovered asphalt binder is limited by the procedure to approximately 50 g (5% of

1,000 g mix sample). This is sufficient for high temperature testing (DSR) but may not be sufficient for further aging (PAV) and low temperature tests (BBR, DTT).

2. With the current extraction procedure and filtering system, the recovered aggregate is not suitable for gradation or other physical property testing. This is particularly a problem for pavement or RAP samples where the aggregate gradation is necessary information.
3. Testing time is not improved with the SHRP extraction and recovery procedure over traditional extraction and recovery procedures. Typical extraction and recovery time is approximately six hours in the Asphalt Institute laboratory. The Abson recovery procedure with D2172, Method A, extraction can require approximately four hours.
4. RAP samples that have been tested in the Asphalt Institute have required longer testing times due to the amount of fines typical in a RAP sample. The 0.008-mm "coarse" filter in the extraction cylinder becomes clogged rapidly requiring more time to remove the extract from the cylinder.
5. The solvents available for use are all toxic to some degree and may not be used, or available, in some agency labs. Alternative solvents should be explored.

To address these potential disadvantages, some modifications were made to the test method. The 0.008-mm filter was removed from the extraction vessel. In its place, a series of screens are used with metal spacers separating the individual screens rather than glass wool (borosilicate). A 2.00-mm screen is used followed by a spacer, a 0.3-mm screen, a second spacer and a 0.075-mm sieve. Figure 3 illustrates the screen configuration.

Also, a 0.020-mm cartridge filter was added outside the extraction vessel as an in-line filter in place of the 0.001-mm in-line filter. The use of a cartridge filter allows much more surface screening area (approximately four times) than a 0.020-mm filter added in the extraction vessel. The cartridge filter can be removed and dried to a constant mass to determine any increase in mass due to fines in the 0.075 to 0.020-mm size range.

Asphalt Content Determination. The evaluation of binder extraction and recovery techniques described in Chapter 1 was conducted to evaluate asphalt content, extracted binder properties, aggregate gradation and testing time. Table 15 indicates the results of the asphalt content determination.

Table 15 indicates that the asphalt content determined by the Centrifuge-Abson-TCE treatment is approximately 0.2% to 0.5% higher than the asphalt content determined by the Centrifuge-Rotavapor-Toluene/Ethanol, SHRP-Rotavapor-Toluene/Ethanol or SHRP-Rotavapor-Alt treatments. It is not clear what is causing the lower asphalt contents. One hypothesis is that the other solvents are not as aggressive as the TCE. The TCE may be removing more of the residual asphalt than the toluene/ethanol combination or the alternative solvent. However, these results do not match expectations as the extracted aggregates visually appear cleaner when using the SHRP extraction procedure than the centrifuge extraction.

Another hypothesis may be that the SHRP extraction procedure is removing more fines from the effluent than the centrifuge extraction procedure. Initial testing has indicated that the centrifuge extraction (2000 g sample) is typically indicating 10-15 g of fines removed from the effluent and filter. The SHRP extraction (1000 g sample) is indicating approximately 60 g of fines removed from the effluent and filter. Proportionally, it appears that the SHRP extraction process is removing 12 times the amount of fine material from the effluent than the centrifuge extraction. By removing more fines, the total aggregate mass increases relative to the sample mass. Consequently, the asphalt content will be calculated as lower than if these fines were not removed.

Combined, these two hypotheses would suggest that as a less aggressive solvent (toluene/ethanol or alternative) or a more aggressive extraction procedure (SHRP), relative to the recovery of fines, is used, the asphalt content will decrease.

Gradation Determination. Table 16 shows the average gradation determinations following the different extraction/recovery combinations. One major difference in the SHRP extraction and centrifuge extraction is that the SHRP extraction sample size is limited to approximately 1000 g. The centrifuge extraction typically uses a sample size of 2000 g. For an aggregate with a nominal size of 19 mm, 2000 g is the minimum sample size.

These results indicate that the gradations are similar regardless of treatment. The smaller sample size required for the SHRP extraction procedure did not apparently have an effect on the gradation. This is likely due to the small nominal size of the extracted RAP aggregate (9.5 mm nominal for both RAP sources). The SHRP extraction procedure did indicate finer gradations in the smaller size sieves than the centrifuge extraction. As noted previously, this is likely due to an increase in the fines recovered from the effluent. It is also possible that the tumbling action in the SHRP extraction vessel would generate fines by breaking some of the large aggregates down. However, if this were the case, the gradations would likely be finer in the intermediate to fine sieve sizes.

No other apparent problems or differences were noted among the samples tested. Gradation appears relatively unaffected by selection of extraction procedure except for the fine sieves. The SHRP extraction procedure appears to recover more fines from the effluent, thereby increasing the percents passing the finer sieves.

High Temperature Properties of Recovered Asphalt Binder. Once the asphalt binder was recovered, it was tested using the DSR at 64, 70, and 76°C to determine values for the high temperature stiffness ($G^*/\sin\delta$). Table 17 contains the average values for the treatments. In the table, T_c represents the critical temperature where the RAP binder will have a $G^*/\sin\delta$ value of 1.00 kPa.

The data in Table 17 indicates that the Centrifuge-Abson-TCE treatment has the lowest $G^*/\sin\delta$ values and the poorest repeatability of all the treatments tested. This validates the results of the previous SHRP research that indicated that the Abson recovery had poor precision. Research during SHRP also suggested that the Abson recovery method would be susceptible to incomplete solvent removal, thereby lowering the measured stiffness of the recovered asphalt binder. The SHRP researchers also indicated that this phenomenon was more apparent as harder RAP material was used. This last finding may be validated by this research since the harder RAP source, the Kentucky RAP, shows a much greater difference between the Abson recovery procedure and the Rotavapor recovery procedures than the softer RAP source (Florida).

The Rotavapor recovery treatments tested indicate similar precision with coefficients of variation (COV) much lower than the Abson recovery treatment (5-20% compared to 38-69%). The Centrifuge-Rotavapor-Toluene/Ethanol treatment indicated the highest $G^*/\sin\delta$ values for both RAP sources. There are two possibilities for the higher values with this treatment. The first is that, as discussed previously, more fines are apparently removed from the effluent with the SHRP extraction procedure than the centrifuge extraction procedure. The excess fines remaining in the recovered asphalt binder may have resulted in an increase in binder stiffness. The second possibility is that additional hardening is occurring with the standard Rotavapor recovery procedure compared to the modified SHRP Rotavapor recovery procedure. The modified procedure uses a lower temperature and higher vacuum than the standard Rotavapor recovery procedure. The lower temperature may help minimize hardening during the recovery process.

Analysis of the data in Table 17 indicates that the AASHTO TP2 procedures with the toluene-ethanol and the n-propyl bromide solvents and the centrifuge-Rotavapor extraction/recovery procedure were statistically the same ($\alpha = 0.05$). The n-propyl bromide solvent was selected for Phase II since it was statistically equivalent to the toluene/ethanol solvent in the modified AASHTO TP2 procedure.

Linearity of Recovered Asphalt Binders. The test for linearity was performed at 82°C for all the recovered binders. A binder is considered linear, and therefore capable of being tested using AASHTO MP1, if the G* at 12% shear strain is within 90% of the G* at 2% shear strain. Table 18 indicates results of linearity testing for one recovered binder sample, as a typical example.

All of the recovered binders indicated similar results to those shown in Table 18. Average results are shown in Table 19. All the recovered binders were linear.

Testing Time. This final response variable was intended to provide an indicator of the relative time required to complete the extraction and recovery process (without aggregate gradation). According to the technician performing the testing, the Centrifuge-Abson treatment required the least amount of time (approximately 4 hours), but was labor-intensive. The Centrifuge-Rotavapor treatment and SHRP-Rotavapor treatment required approximately the same amount of time (6 hours). Based on this analysis, there does not appear to be a significant advantage in selecting either of the Rotavapor recovery treatments as the preferred method. The Abson recovery method would be selected if time were the only consideration.

Extraction and Recovery Procedures. Based on the Phase I findings, then, the RAP binder for the binder effects study was extracted and recovered using the modified AASHTO TP2 procedure with an alternative n-propyl bromide solvent. The modified version of the AASHTO TP2 procedure used in this experiment can be summarized as follows:

1. A 1,000 – 1,100 g sample of RAP was obtained by sampling and quartering. This is an appropriate sample size to obtain approximately 50 – 60 g of recovered asphalt binder.
2. The RAP sample was dried to a constant mass using an oven operating at 110ºC. Weights were determined for the sample and filters used in the extraction and recovery procedures.
3. The RAP sample was placed in the extraction vessel and the lid was secured. Six hundred milliliters (600 ml) of n-propyl bromide solvent was added to the extraction

vessel. Nitrogen was introduced into the vessel at a rate of 1,000 ml/min. for one minute.

4. The extraction vessel containing the RAP and solvent was then placed on its side and rotated for five minutes.
5. The extraction vessel was placed vertically on a stand and connected to a recovery flask by a vacuum line. Nitrogen was introduced to the vessel at a rate of 400 ml/min. A vacuum (700 mm Hg) was applied to the vessel to draw the effluent into the first recovery flask. The vacuum was then switched to draw the effluent from the first recovery flask, through a 0.020-mm cartridge filter, into the second recovery flask. Finally, the vacuum was switched again to draw the effluent from the second recovery flask into the Rotavapor recovery flask.
6. Once the effluent was in the Rotavapor recovery flask, the primary distillation began. The distillation flask was maintained approximately 2/3 full at all times (700 mm Hg vacuum at 100 ± 2.5ºC).
7. Steps 3 – 6 were repeated, but 400 ml of solvent was used and the extraction vessel was rotated for ten minutes.
8. Steps 3 – 6 were again repeated, using 400 ml of solvent and 30 minutes rotational time, until the extract becomes a "light straw" color. At this point, primary distillation was continued until the distillation flask was approximately 1/3 full.
9. The effluent was then poured into centrifuge bottles. The bottles were centrifuged for 25 minutes at 3,600 rpm.
10. The centrifuged effluent was then poured back into the distillation flask. The Rotavapor oil bath temperature was increased to 174 ± 2.5ºC.
11. Distillation was continued until the condensation rate was less than one drip every 30 seconds. Nitrogen was then introduced into the flask at a rate of 1,000 ml/min. for 30 ± 1 minutes.

12. The recovered asphalt binder was then poured from the distillation flask into a container for testing.

Rationale for Modifications to TP2 and Subsequent Testing. During evaluation as part of the NCHRP 9-12 research, the Asphalt Institute research team identified two main problems with the use of AASHTO TP2 for RAP. First, because of the filtering system, the recovered aggregate was not suitable for gradation or other physical property testing. The borosilicate (glass wool) filter tended to clog and retain fines. Also, for mixtures with a higher percentage of fines (minus 0.075-mm), the filter system clogged more easily, thus extending the test procedure. This was considered a particular problem for milled RAP. Second, the solvents used in AASHTO TP2 are all toxic to some degree. It would be an improvement if an alternative, non-toxic (or less toxic) solvent could be identified.

To address the first concern (recovered aggregate), the filter system in TP2 was modified. The 8-micron (0.008-mm) filter and glass wool plug were removed from the inside of the vessel and replaced with a series of screens and spacers. A 2.00-mm (#10) mesh screen was placed on top as the first screen encountered by the aggregate. This was followed by a metal spacer, 0.3-mm (#50) mesh screen, a second metal spacer, 0.075-mm (#200) mesh screen, and finally a supporting 2.00-mm (#10) mesh screen. The effluent passing through the modified filter system could be expected to contain aggregate particles smaller than 0.075-mm.

Before recovery, the effluent was passed through a 20-micron (0.020-mm) cartridge filter. This filter replaced the 1-micron (0.001-mm) in-line filter. The advantage of the cartridge filter was that it provided four times the effective filter area (to account for excess fines) as a conventional in-line filter. The cartridge filter could also be weighed before the extraction process, dried to a constant mass, and weighed afterward to aid in asphalt content determination. The disadvantage was that any particles smaller than 20-microns (0.020-mm) would remain in the effluent before final centrifuge operations.

The second concern regarding the solvents was addressed by evaluating trichloroethylene, toluene/ethanol, and an alternative (n-propyl bromide) solvent in the TP2 procedure. Analysis of the data indicated that the TP2 procedure with the alternative (n-propyl bromide) solvent provided statistically the same physical property (high temperature binder stiffness as measured by the dynamic shear rheometer) results as the TP2 procedure with toluene/ethanol.

The modified version of AASHTO TP2 was selected, then, because:

- it provided comparable repeatability with the centrifuge extraction (AASHTO T164) and Rotavapor recovery (ASTM D5404) procedures
- it provided substantially better repeatability than the centrifuge extraction (AASHTO T164) and Abson recovery (AASHTO T170) procedures
- recovered binder stiffness ($G^*/\sin\delta$) was comparable between the Centrifuge-Rotavapor (AASHTO T164 and ASTM D5404) treatment and the TP2 treatment with the same solvents
- the modifications to the filter system allowed the aggregate to be recovered, thus permitting determination of asphalt binder content and aggregate gradation
- The experimental data indicated the following:
- The Abson recovery procedure appeared, as suggested by the SHRP research, to leave residual solvent in the recovered asphalt binder. This effect was more pronounced as the stiffness of the recovered asphalt binder increased.
- The repeatability of the Abson recovery procedure was poor. Data from high temperature shear stiffness ($G^*/\sin\delta$) tests indicated coefficients of variation from 38-69%.

- Either the modified version of AASHTO TP2 (SHRP extraction-recovery procedure) or the combination of centrifuge extraction (AASHTO T164) and Rotavapor recovery (ASTM D5404) procedures should be selected for recovering RAP asphalt binders.
- The n-propyl bromide solvent used in the research appears to provide comparable results to the "traditional" solvents (such as trichloroethylene and toluene/ethanol). This solvent can be listed as an acceptable alternate.

Recovered Binder Testing Procedures. Under Phase I, the MP1 test procedures were reviewed to determine if they were applicable to testing recovered RAP binder. Testing showed that the recovered binders were linear, up to fairly high percentages, say 50% RAP, and that, therefore, the MP1 tests were applicable.

One remaining concern, however, was whether the recovered RAP binder needs further aging in the RTFO and/or PAV. Testing conducted in Phase I indicated that the recovered asphalt binder might not need further aging before testing using the AASHTO MP1 tests. This finding is significant since further aging of recovered asphalt binders would necessitate additional recovery procedures and increased testing time. A sample of the data for one RAP (KY) from the Phase I testing is indicated in Table 20.

The data in Table 20 indicates that for most extraction/recovery procedures the RTFO-aged binder may have a high temperature stiffness that is approximately 1.5 to 1.75 times the original (unaged) stiffness. This difference may result in a three to five degree change in the estimated critical temperature of the recovered asphalt binder at high temperatures. The centrifuge/Abson extraction/recovery procedure has a much higher aging ratio. For this extraction/recovery procedure the RTFO-aged binder has a high temperature stiffness that is approximately eight times the original (unaged) stiffness. This increase in aging ratio is once again likely caused by incomplete solvent removal.

Further analysis of the data in Table 20 indicates that the intermediate temperature stiffness may increase by approximately 1.5 times (again, excepting the centrifuge/Abson procedure) from the unaged condition to the PAV-aged condition. The increase in stiffness drops to approximately 1.2 times from the RTFO-aged condition to the PAV-aged condition. The bending beam rheometer (BBR) stiffness and m-value also show little change from the RTFO to PAV aging conditions (approximately 5-7% change in values).

Based on the data from Task 5 and Table 20, the recommended practice is to perform RTFO aging on the recovered asphalt binder before testing. After this aging, AASHTO MP1 testing should be conducted.

DESCRIPTION OF TESTS AND RESULTS

Black Rock Study

The following describes the tests used to evaluate the three different cases in the black rock study and summarizes the test results.

Frequency Sweep Test at Constant Height (FS)

The Frequency Sweep at Constant Height (FS) test is conducted by applying a repeated shear load producing a strain of 0.005% in a horizontal direction while applying an axial stress to keep the specimen height constant. The frequency sweep test allows determination of the complex shear modulus (G*) and phase angle (δ) of a mixture at a wide range of frequencies from 0.01 Hz to 10Hz and at 4, 20 and 40°C (AASHTO TP7-94, *Standard Test Method for*

Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt (HMA) Using the Simple Shear Test (SST) Device, Procedure E). At 10 Hz and 40°C, a modulus (G*) value of about 35,000 to 50,000 psi or higher generally indicates a good mix while values below about 22,000 psi generally indicate poor performance. Values between 22,000 and 50,000 psi fall in a gray area and could be either good or bad. (These values are used by the Asphalt Institute as rough guidelines and were presented to the Mixture Expert Task Group in September 1997.)

In this study, the complex shear modulus and high temperature stiffness values (G* and G*/sinδ) were compared at the highest and lowest frequencies (10 and 0.01 Hz) for the three mixture cases. Tables 21 through 24 present the average complex shear modulus (G*) and high temperature stiffness (G*/sinδ) for all cases at 10 and 0.01Hz respectively. Figures 4 through 8 present some typical results in graphical format for a variety of frequencies, temperatures, RAP stiffnesses and RAP contents. These are intended as examples and are not all inclusive.

The tables show that, in almost all cases, the stiffness is lower at high temperatures, as expected. Stiffness also tends to increase for the higher RAP content in most instances, except for the black rock case (Case BR), where no RAP binder is included. In fact, in most instances, the stiffness values for the black rock case at 10 and 40% RAP are similar, especially when the PG 64-22 binder is used. This may be due to the facts that no RAP binder is included and the amount of RAP aggregate increases.

Similar trends are observed for stiffness (G*/sin δ), although the phase angle often behaves unexpectedly and affects the results. This type of anomaly has been observed in other FS testing.

Simple Shear at Constant Height (SS)

The Simple Shear at Constant Height (SS) test applies a single, controlled stress to the specimen while an axial load keeps the specimen height constant. The shear load ramps up at 70 kPa/sec to the specified shear load, which varies for different test temperatures. The load is then held constant for ten seconds. After ten seconds, the load ramps down at 25 kPa/sec. The maximum shear deformation is the primary data item of interest (AASHTO TP7-94 Procedure D).

In this study, the SS test was conducted on the same samples immediately after FS test at the same temperature (4, 20 and 40°C). For the mixture with 10% Connecticut RAP, the applied loads at different testing temperatures were the same, due to an incorrect default value in the program for the 20°C test file. The research team recognized the problem and for the rest of the study, the applied shear loads complied with the specification. Additional tests were conducted to be able to compare the results at non-standard loads. Tables 25 and 26 present the maximum shear deformations for all cases at 20 and 40°C respectively. Figures 9 through 12 illustrate some typical examples.

Trends indicated in Tables 25 and 26 largely conform to expectations. That is, the mixtures with the softer virgin binder tend to exhibit higher deformations. Larger deformations are also observed when testing at higher temperatures, as expected. The deformations of the black rock (BR) specimens at 10 and 40% RAP, for each individual RAP, vary relatively little, while the deformations of the actual practice (AP) and total blending (TB) specimens tend to decrease at higher RAP contents. This seems to demonstrate the expected stiffening effect of the RAP binder present in the actual practice and total blending specimens. The black rock case results are very consistent for the PG 64-22 at both 10 and 40% RAP for each RAP source. The results for the black rock case with the PG 52-34 tend to be somewhat more variable, perhaps showing a greater impact of the RAP aggregate with the softer virgin binder. The deformations of the actual practice and total blending specimens for a given RAP stiffness and testing conditions tend to be similar.

For the Arizona and Florida RAPs tested under two different loading conditions at 20°C, the higher load tends to produce the greater deformation, as expected. When the load increases nearly three times from 35 to 105 kPa, the deformations also tend to increase about three times. This is reasonable because the loading is still in the elastic range, even at the 105 kPa shear load.

Repeated Shear at Constant Height (RSCH)

In the Repeated Shear at Constant Height test (RSCH), a repeated, stress-controlled shear load is applied to the specimen while an axial stress is applied to keep the specimen height constant. The shear stress is applied in repeated haversine pulses. The load is applied for 0.1 second followed by a 0.6-second rest period. The test is typically run to 5000 cycles or 5% permanent shear strain. The plastic shear strain at 5000 cycles is the parameter of interest from this test (AASHTO TP7-94, Procedure C). Permanent shear strain of less than 1% is generally considered excellent, 1 to 2% is good, 2 to 3% is fair, 3 to 5% is questionable and more than 5% is poor, according to the guidelines used by the Asphalt Institute and others.

This test is normally conducted at an effective temperature for rutting based on the climate at the project location. In this study, it was decided to conduct the RSCH test at 58°C for all cases, but there were difficulties in testing samples prepared with the 52-34 binder. Therefore, samples with 64-22 and 52-34 binders were tested at 58 and 52°C respectively. Table 27 presents the shear strain for all cases. Figures 13 through 16 graphically illustrate some typical RSCH data.

The data summarized in Table 27 shows that the results of the RSCH test for a given RAP with a given virgin binder at the 10% addition rate tend to be similar. At the 10% level, the shear strains for a given binder tend to be much the same regardless of RAP source. The shear strains for the PG 52-34 tend to be higher than for the PG 64-22, as expected. The properties of the mixture seem to be controlled more by the virgin binder stiffness than the RAP.

When the RAP content increases to 40%, some differences start to emerge. The black rock samples (BR) tend to show somewhat higher shear strains at the 40% addition rate compared to the actual practice and total blending samples (AP and TB). Cases AP and TB, while exhibiting some variability, do tend to be closer to each other than to the black rock case. There is a sizeable amount of scatter in this data.

Indirect Tensile Creep and Strength Tests

In the indirect tensile creep test (ITC), a sample that has been cut to dimensions of 150 mm diameter by 50 mm height is loaded in static compression across its diametral plane. The load is held constant while the horizontal and vertical deformations of the sample are recorded over a period of time (in this case, 240 seconds). Creep compliance is then calculated using the load and resulting displacement of the specimen as a function of time. The creep test is normally performed at three temperatures (0, -10 and -20°C). Following ITC testing, indirect tensile strength (ITS) testing is performed at -10°C. ITS testing determines the fracture strength of a specimen by loading it at a constant deformation rate of 12.5 mm/min until a fracture is formed. Specimen dimensions and peak load are then used to calculate the fracture strength. The test procedures used for ITC and ITS testing are described in more detail in AASHTO TP9, *Standard Test Method for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device.*

For the black rock study, three specimens for each cell were compacted in the Superpave Gyratory Compactor to approximately 7% air voids. Each sample was aged for five days at 85°C before cutting and testing. This was done because thermal cracking is primarily a phenomenon of older pavements and a short-term aged sample may not accurately represent the behavior of an aged pavement. Indirect tensile creep (ITC) testing was conducted on each sample at 0, -10 and -20°C. Test results are presented here for the Connecticut and Arizona RAPs only, which were tested on an Interlaken IDT at the Asphalt Institute. Testing of the Florida RAP could not be completed due to recurrent problems with the Instron IDT at the North Central Superpave Center.

Tables 28 and 29 show the average tensile creep (at 60 seconds) and strength values for the mixtures with 10 and 40% RAP respectively. Some typical results are shown in Figures 17-22. The values represent an average of three test results, in most cases. At the 10% RAP level, the stiffnesses of the three different cases are similar though the black rock (BR) values tend to be somewhat lower than the other cases. The actual practice (AP) stiffness values tend to be between the black rock and total blending (Cases BR and TB) stiffness values, though occasionally actual practice (AP) shows the highest stiffness, especially with the PG 52-34 binder. Differences between all of the samples are relatively small at the 10% level, especially differences between the actual practice and total blending (AP and TB) specimens.

At the 40% level, the differences between the black rock case (BR) versus the other cases (AP and TB) become more apparent. Cases AP and TB tend to be very similar and the black rock case (BR) is much lower in stiffness. The difference between black rock versus the other two cases appears to be greater for the samples with the softer binder, although not dramatically so.

The strength values also seem to show a difference between the black rock and other cases at the 40% RAP level. The strength of the black rock case tends to be lowest and actual practice highest for each RAP-binder grade combination. The strengths of the actual practice and total blending specimens are similar. This trend is not as obvious at the 10% level.

An ANOVA analysis of the data (stiffness and strength results) for the 10% Arizona RAP samples shows that there is no statistical difference between the stiffness and strength values of the different cases. (The only exception is 10% Arizona RAP with PG 64-22, the black rock and actual practice cases (BR and AP) at -10°C.) This is not surprising since the 10% RAP samples actually contain very little RAP binder. It is therefore expected that the addition of RAP at this level will have very little effect on the mixture properties of the samples.

At the 40% RAP content, the Arizona blends start to show a more obvious trend. The 40% Arizona blends with PG 52-34 show actual practice (AP) stiffness values that are higher than those of either the black rock or total blending cases (BR or TB). The 40% Arizona blends with PG 64-22 show the same trend at 0 and -10°C, with black rock having the highest stiffness at -20°C. An ANOVA analysis of the data shows that for the PG 64-22 blends, all cases are statistically the same. However, visual observation of the data in Figure 19 shows that at 0 and -10°C, actual practice data more closely resembles that of total blending than of black rock. A t-test on the PG 52-34 data shows that the black rock and actual practice cases (BR and AP) are statistically different, while the actual practice and total blending cases (AP and TB) are statistically the same. When the PG 64-22 binder was used with 40% AZ RAP, the statistical analysis of stiffness showed that the cases are similar to each other except at 0°C, where they are all different from each other. Overall, though, the stiffness values imply that the PG 52-34 samples show behavior that is more similar to total blending than to black rock.

There is no noticeable trend for the strength data for these samples. The Arizona strength tests do show that the black rock and total blending cases (BR and TB) are similar for both binders, which is not an expected result.

An ANOVA analysis of the 10% Connecticut RAP blends with PG 64-22 stiffness data shows that all cases are statistically the same. The blends of 10% Connecticut RAP with PG 52-34 are also the same, except for the actual practice and total blending cases (AP and TB) at -

10°C. Strength values are also statistically the same. Again, this is not surprising due to the low level of RAP binder in the samples.

At 40% RAP content, the Connecticut RAP blends (both PG 64-22 and PG 52-34) show actual practice (AP) behavior that is similar to total blending (TB). A statistical analysis of the data for the PG 64-22 data shows that the actual practice case is most similar to the total blending case, although at -10°C, all cases were statistically the same. The PG 64-22 strength results were all statistically different. This is probably due to a large amount of scatter among the data. A t-test analysis on the PG 52-34 blends shows that the actual practice and total blending cases (AP and TB) are statistically the same and different from the black rock case (BR). The PG 52-34 strength results showed the same trend.

Effect of Aging

In this part of the black rock study, the effect of aging on the three mixture cases (total blending, real practice and black rock) was investigated. Blending of the new binder with the old, hardened RAP binder could take some time. It was thought that perhaps additional aging of the samples would provide more time for diffusion of the lighter fractions of the virgin binder into the hardened RAP binder film. If this slow diffusion happens to an appreciable extent, the actual practice (AP) sample results could move closer to the total blending (TB) results over time as the old and new binders blend. Therefore, long-term aged samples were tested with FS and SS tests, and results were compared to results of the same tests on samples that were not long-term aged (termed unaged for brevity, although short-term mix aging was done).

Only the Connecticut RAP was aged and tested for this part of the study. After long-term aging, samples are typically tested at 4 and 20°C because the primary concern with aged samples, as with the aged pavement they are supposed to represent, is cracking. Unaged samples are typically tested at 20 and 40°C; rutting is more of a concern for the younger pavements these samples are intended to represent. These test temperatures were used in this part of the study. The aged and unaged results can therefore be compared at 20°C, the common test temperature.

The long-term aging process used conformed to AASHTO PP2-94. In this method, the compacted gyratory samples were kept in an oven at 85 ± 3°C for 120 ±0.5 hours. Because the samples were compacted at low numbers of gyrations, to reach 7 ±1 %, some samples were not stable during the long-term aging process. Therefore, 150-mm diameter plastic molds were used to protect the samples during aging. Tables 30 to 33 present the complex shear modulus (at 10 and 0.01 Hz) for the 10 and 40% CT RAP specimens.

As expected, the modulus, G*, increased after aging in most cases. The G* of the mixture with 10% RAP and PG 52-34 virgin binder increased 4.5 times after aging. Some of the PG 64-22 mixture cases had aged modulus values that were close to the unaged modulus. Generally, the effect of aging was more significant for mixtures with PG 52-34 virgin binder than the mixtures with PG 64-22.

Similar conclusions were obtained from the SS test for aged and unaged Connecticut RAP. The maximum shear deformation decreased significantly after aging for the black rock and actual practice mixtures (Cases BR and AP) with 52-34 binder and 10% RAP (3.6 and 3.7 times). The maximum shear deformation did not change significantly when PG 64-22 was used as virgin binder for both RAP ratios.

Despite the changes in modulus and shear deformation, additional aging did not significantly change the comparisons of the various cases. Examination of the comparisons of the various cases shown in Appendix B, Tables B-2 and B-5, for the aged and unaged Connecticut RAP samples at 20°C, does not indicate a clear trend. The unaged data already indicates that the actual practice samples are not statistically different from the total blending samples in most cases. The statistical comparisons are nearly identical for the aged samples.

The results of testing the long-term aged specimens at 4°C, however, are rather interesting. At the 10% RAP level for both virgin binders, the results of the SS and the FS testing indicate all three cases are statistically the same. At the 40% RAP level, the SS and FS data clearly indicate that the actual practice samples are indistinguishable from the total blending samples, but are different from the black rock samples. This data appears to be very consistent, which may indicate that aging reduces the variability, or it may simply be a manifestation of a small sample size.

Overall Black Rock Findings

Observation of the data, for most comparisons, showed that at the 10% RAP ratio the three mixture cases were similar and for high RAP ratio (40%) the black rock case (BR) was different from the actual practice and total blending cases (AP and TB). There were, however, some results that did not show this trend. A statistical analysis was conducted to study the replicate results for each testing parameter. An analysis of mean was done, using the program SAS, to compare the three mixture cases for each parameter. Summaries of this analysis are presented in Appendix B, Tables B-1 through B-13, for the three RAPs. The mixture cases were compared at a 95% confidence level. These tables graphically show which cells are statistically the same by shading or placing a symbol in those cells that cannot be differentiated. These comparisons for all of the tests and conditions (except long-term aging of the CT samples) are summarized in Table 34. Table 34 shows the relationship of the actual practice samples to the other cases. In the table, “TB” indicates the actual practice samples are statistically the same as the total blending samples and “BR” indicates the actual practice samples are statistically the same as the black rock samples. An asterisk by TB indicates that, in that instance, the black rock case also equals the total blending case, but the actual practice case is different from the black rock case. An asterisk by BR has similar meaning. The notation “Same” indicates all three cases are the same and “Diff” indicates all three cases are different. “Both” means that the actual practice case is statistically the same as the black rock case and the total blending case, but the black rock and total blending cases are different from each other. Blank cells are inconclusive; this includes instances where the black rock and total blending cases are the same but are different from the actual practice case.

For mixtures with 10% RAP, there are 66 possible comparisons (2 binders x 3 RAPs x 11 test parameters). As shown in Table 34, there are 36 comparisons where the results of testing the three cases indicate that there is no significant difference between the black rock, actual practice and total blending cases (BR=AP=TB). There are nine comparisons that suggest actual practice is similar to total blending. Only six cases indicate that actual practice (AP) is similar to black rock (BR). The remaining cases are inconclusive. At the low RAP content, then, a preponderance of the comparisons shows no significant difference between the results.

When 40% RAP was used, the statistical analysis shows that actual practice (AP) is similar to total blending (TB) in 21 cases; only three cases suggest that actual practice (AP) is similar to black rock (BR). The three cases were the same in 11 comparisons. This means that, at the 40% RAP ratio, mixtures containing RAP are more similar to total blending than to black rock.

Also at the 40% RAP level, there are 12 cases where the three cases are all different from each other (BR≠AP≠TB). Ten of these cases occur with the PG 64-22 binder. This may, perhaps, indicate that the harder virgin binder does not blend as completely as the softer binder with any of the RAPs, which would conform to expectations. It is not likely that total blending occurs in all cases.

To ascertain that the observed behavior was not due to a variation in binder content, the research team measured the total asphalt content in retained samples of the three cases (black rock, actual practice and total blending). The question had to do with whether the total asphalt content was in fact the same or whether the black rock and total blending cases actually had a different (higher) binder content. Samples of all three cases were being burned off in the ignition oven to verify their asphalt contents. The data in Table 35 shows that the asphalt contents are quite consistent and that the actual practice samples do not have a lower asphalt content than the other two cases. In fact, the asphalt content appears to be slightly higher, which would tend to make the actual practice samples act more like black rock (less stiff) than like total blending (stiffer).

Binder Effects Study

Recovered RAP Binder Without Aging

Results for the virgin asphalt binders are indicated in Table 36. Also indicated in Table 36 are test results for the recovered RAP binders. The RAP binders were tested as if they were RTFO and PAV aged, as appropriate, although no additional aging was done. The blended binders were aged before testing according to AASHTO MP1.

Estimated Binder Properties of Blended Asphalt Binders. Two methods can be used to determine the blended binder test values. The first method, suggested by research conducted at the National Center for Asphalt Technology (NCAT) (2), involves determining binder test data for the virgin asphalt binder and the recovered RAP binder at the anticipated high temperature grade of the blended binder. For example, if a PG 64-22 asphalt binder was desired as the final grade, testing of the virgin asphalt binder and the recovered RAP binder would be conducted at 64°C.

The second blending procedure, suggested by research conducted at the Asphalt Institute (6), involves determining the critical temperature where the PG criteria is just achieved for the virgin asphalt binder and the recovered RAP binder.

Either procedure should be acceptable for blending according to the previous research. However, the use of critical temperatures has the advantage of testing asphalt binders at appropriate temperatures close to the expected limiting value. For example, to achieve a PG 64-xx grade asphalt binder in the final blend using a PG 52-34 virgin binder and the Arizona RAP both the virgin binder and the Arizona RAP would be tested at 64°C. The PG 52-34 asphalt binder would have an estimated stiffness ($G^*/\sin\delta$) of 0.27 kPa at 64°C. The recovered Arizona RAP binder would have an estimated stiffness ($G^*/\sin\delta$) of 32.01 kPa at 64°C.

Critical temperatures for the virgin and recovered RAP asphalt binders (unaged) are indicated in Table 36. The "Actual" performance grade and "MP1" performance grade of the binders are also included in Table 36.

In Table 36, the "Actual" high temperature performance grades of the asphalt binders are determined using the original $G^*/\sin\delta$ values only. This approach was used since the recovered RAP binders were not RTFO aged. It also matches the recommendations from the previous research conducted by NCAT that only one high temperature blending chart (Original $G^*/\sin\delta$) is necessary.

Another item of note is that the PG 52-34 asphalt binder grades as a PG 52-28 according to AASHTO MP1 testing conducted at the Asphalt Institute. Testing conducted by the supplier indicated that the asphalt binder was a PG 52-34.

The estimated critical temperatures of the blended asphalt binders were determined using the following equations:

Original	$G^*/\sin\delta$	$T_{HO} = T_{HO}(\text{Virgin}) + (\%RAP/100)*[T_{HO}(RAP) - T_{HO}(\text{Virgin})]$
RTFO	$G^*/\sin\delta$	$T_{HR} = T_{HR}(\text{Virgin}) + (\%RAP/100)*[T_{HR}(RAP) - T_{HR}(\text{Virgin})]$
PAV	$G^*\sin\delta$	$T_I = T_I(\text{Virgin}) + (\%RAP/100)*[T_I(RAP) - T_I(\text{Virgin})]$
PAV	BBR S	$T_S = T_S(\text{Virgin}) + (\%RAP/100)*[T_S(RAP) - T_S(\text{Virgin})]$
PAV	BBR m-value	$T_m = T_m(\text{Virgin}) + (\%RAP/100)*[T_m(RAP) - T_m(\text{Virgin})]$

where,

T_{HO} = Critical high temperature from Original $G^*/\sin\delta$ values

T_{HR} = Critical high temperature from RTFO $G^*/\sin\delta$ values

T_I = Critical intermediate temperature from PAV $G^*/\sin\delta$ values

T_S = Critical low temperature from BBR Stiffness values

T_m = Critical low temperature from BBR m-value

For example, the estimated blended binder critical temperatures of a PG 52-34 virgin asphalt binder blended with 20% Connecticut (CT) RAP are:

T_{HO} = 53.9 + (20/100)*(82.4 - 53.9) = 59.6°

T_{HR} = 54.6 + (20/100)*(75.8 - 54.6) = 58.8°

T_I = 11.5 + (20/100)*(25.1 - 11.5) = 14.2°

T_S = -23.7 + (20/100)*(-15.1 - (-23.7)) = -22.0°

T_m = -25.9 + (20/100)*(-14.4 - (-25.9)) = -23.6°

Based on these equations, the 20% CT RAP blended with the PG 52-34 virgin asphalt binder is estimated to have an actual performance grade of PG 58-32 and an MP1 grade of PG 58-28.

The estimated blended binder critical temperatures of the Florida, Connecticut and Arizona blends are indicated in Tables 37, 38 and 39, respectively.

Actual Binder Properties of Blended Asphalt Binders. After physically blending the virgin asphalt binder with the appropriate percentage of recovered RAP binder (10%, 20% or 40%), the blended asphalt binder was tested following the procedures in AASHTO MP1. Test results for the asphalt binders blended with the Florida RAP are presented in Table 40. Critical temperatures and performance grading information is presented in Table 41 for the Florida RAP blends. Binder properties and critical temperatures are likewise presented in Tables 42 and 43 for the Connecticut RAP blends and in Tables 44 and 45 for the Arizona RAP blends.

Several interesting observations can be made about the data in Tables 40 – 45. First, at the 10% RAP level, the blended asphalt binder had the same performance grade (AASHTO MP1) as the virgin asphalt binder with which the recovered RAP binder was blended. The actual high critical temperature of the blended asphalt binder was 1 – 4°C higher than the virgin asphalt binder. The actual low critical temperature of the blended asphalt binder was 0 – 2°C lower than the virgin asphalt binder.

At the 20% RAP level, all six blended asphalt binders had a high temperature performance grade (AASHTO MP1) that was one grade higher than the virgin asphalt binder. Five of the six blended asphalt binders had a low temperature performance grade (AASHTO MP1) that was the same as the virgin asphalt binder.

The data for the 10% and 20% RAP blends suggests that the practice recommended by the ETG (1) -- no change in binder grade for 15% RAP or less -- is appropriate. The change of one binder grade in high temperature stiffness for the 20% RAP blends also corroborates the 15% - 25% recommendation by the ETG.

At the 40% RAP level, half of the blended asphalt binders had a high temperature performance grade (AASHTO MP1) that was two grades higher than the virgin asphalt binder. For these blended binders, the low temperature performance grade (AASHTO MP1) was the same as the virgin asphalt binder. The 40% Florida RAP blended with the PG 64-22 asphalt binder had a high temperature performance grade (AASHTO MP1) that was only one grade higher than the virgin asphalt binder (without changing the low temperature grade).

The 40% Arizona RAP blended with the PG 52-34 asphalt binder had a high temperature performance grade (AASHTO MP1) that was three grades higher than the virgin asphalt binder, while the low temperature performance grade was one grade higher than the virgin asphalt binder. The 40% Arizona RAP blended with the PG 64-22 asphalt binder had a high temperature performance grade (AASHTO MP1) that was two grades higher than the virgin asphalt binder, while the low temperature performance grade was one grade higher than the virgin asphalt binder.

The inconsistent pattern of the 40% RAP blends – one to three grades higher on the high temperature performance grade with either no change or one grade higher on the low temperature performance grade – supports the recommendations of the ETG that blends using more than 25% RAP should follow blending chart recommendations. This appears particularly true as the RAP stiffness increases.

It is also interesting to note that the difference between low critical temperatures calculated using the BBR Stiffness and m-value appears to increase as the virgin asphalt binder stiffness increases or the RAP stiffness increases.

Comparison of Estimated and Actual Critical Temperatures. The estimated binder critical temperatures, described earlier, were determined assuming a linear relationship. That is, the critical temperature of a given RAP blend was linearly interpolated between the 0% RAP binder (or virgin asphalt binder) and 100% RAP binder. Tables 46 and 47 indicate the Estimated and Actual critical temperatures for the Original and RTFO DSR. Data in these tables determine the high temperature grade of the blended asphalt binder. The estimated critical temperatures here were calculated based on unaged RAP binder tested as if it had been RTFO aged.

Figures 23 – 25 illustrate the estimated and actual critical temperatures for the Original DSR for the Florida, Connecticut and Arizona RAP blends, respectively. Figures 26-28 illustrate the estimated and actual critical temperatures for the RTFO DSR for the Florida, Connecticut and Arizona RAP blends, respectively. Again, these estimates are based on testing the recovered RAP binders as if they were RTFO aged.

Analysis of the data in Table 46 indicates that the actual critical temperature is almost always higher than the estimated critical temperature for the Original high temperature stiffness (G*/sinδ). This means that the linear equation used for estimating the Original G*/sinδ critical temperatures is generally conservative – that is, the equation predicts a lower high critical temperature than the actual. The equation usually underestimates the actual critical temperature by approximately 1.5°C. The estimate is incorrect by as much as a half-grade (3.0°C) in only three of the eighteen cases. It is also interesting to note that this underestimation appears to be magnified as the RAP binder stiffness or percentage is increased.

Analysis of the data in Table 47 indicates that the actual critical temperature is almost always higher than the estimated critical temperature for the RTFO high temperature stiffness (G*/sinδ). This means that the linear equation used for estimating the RTFO G*/sinδ critical temperatures is generally conservative – that is, the equation consistently predicts a lower high critical temperature than the actual. The difference between estimated and actual values is much higher for the RTFO G*/sinδ critical temperatures than the Original G*/sinδ critical temperatures. The equation usually underestimates the actual critical temperature by approximately 2.5°C. The estimate is incorrect by as much as a half-grade (3.0°C) in eight of the eighteen cases. As with the Original G*/sinδ critical temperatures, it is interesting to note that this underestimation appears to be magnified as the blended binder stiffness or RAP percentage is increased.

Based on the data in Tables 46 and 47, it appears that the linear equations using the critical high temperatures of the virgin asphalt binder, ***unaged***-recovered RAP asphalt binder, and RAP percentage may not be the best for accurately determining the high critical temperature of a blended asphalt binder. The linear equation consistently underestimates the final blended critical high temperature by as much as a half-grade (3.0°C) in approximately 30% of all cases. The fact that the underestimation appears sensitive to binder stiffness and RAP percentage indicates that the response may be non-linear.

Table 48 indicates the Estimated (based on unaged RAP binder) and Actual critical temperatures for the intermediate temperature stiffness (PAV DSR G*sin δ). Data in this table can be used to determine the intermediate temperature grade of the blended asphalt binder.

Figures 29-31 illustrate the estimated and actual critical temperatures for the PAV DSR (G*sinδ) for the Florida, Connecticut, and Arizona RAP blends, respectively. These estimates are also based on tests of unaged RAP binder.

Analysis of the data in Table 48 indicates that the actual critical intermediate temperature may be either higher or lower than the estimated critical temperature for the PAV G*sinδ value. For the PG 52-34 blends, the equation usually overestimates the actual critical intermediate temperature. For the PG 64-22 blends, the equation usually underestimates the actual critical intermediate temperature. No apparent trend can be determined from the data, but the response is definitely non-linear as illustrated in Figures 29-31. The estimate is incorrect by as much as a half-grade (1.5°C) in eleven of the eighteen cases.

It is also interesting that the critical intermediate temperature of the Florida RAP (unaged) is lower than the critical intermediate temperature of the PG 64-22 asphalt binder. This would seem to indicate that blending the Florida RAP with the PG 64-22 asphalt binder would result in improved intermediate temperature properties compared to the virgin PG 64-22 binder. This anomaly is likely caused by the fact that the recovered RAP binders were not aged before testing to determine intermediate temperature grade. From the information in Table 29, not aging the recovered Florida RAP binder to the PAV-aged condition may have resulted in the intermediate temperature stiffness ($G^*\sin\delta$) having a value 75% of the actual. In turn, this lower stiffness would substantially increase the critical intermediate temperature of the recovered RAP binder.

Finally, it should be noted that five of the nine PG 64-22 blended binders have actual critical intermediate temperatures that are lower than the virgin asphalt binder (PG 64-22). Again, this would indicate that the blended asphalt binders (with up to 20% RAP) have better intermediate temperature properties than the virgin asphalt binder. Since the blended asphalt binders were PAV-aged, this anomaly is likely caused by testing error in the DSR.

Based on the data in Table 48**,** it appears that the linear equation using the critical intermediate temperatures of the virgin asphalt binder, ***unaged***-recovered RAP asphalt binder, and RAP percentage may not be the best for accurately determining the critical intermediate temperature of a blended asphalt binder. The linear equation either underestimates or overestimates the final blended critical intermediate temperature by as much as a half-grade (1.5°C) in more than 50% of all cases.

Tables 49 and 50 indicate the Estimated and Actual critical temperatures for the BBR Stiffness and m-value. Data in these tables can be used to determine the low temperature grade of the blended asphalt binder.

Figures 32 – 34 illustrate the estimated and actual critical temperatures for the BBR Stiffness for the Florida, Connecticut and Arizona RAP blends, respectively. Figures 35 – 37 illustrate the estimated and actual critical temperatures for the BBR m-value for the Florida, Connecticut and Arizona RAP blends, respectively. The estimates again are based on testing unaged RAP binder as if it were RTFO and PAV aged.

Analysis of the data in Table 49 indicates that the actual critical temperature is virtually the same as the estimated critical temperature for the BBR Stiffness in most cases. Only seven of eighteen comparisons indicate a difference greater than 0.5°C, and only one comparison is incorrect by as much as a half grade (3.0°C). The linear equation used for estimating the critical low temperature from BBR Stiffness is generally conservative (13 of 18 comparisons) – that is, the equation predicts a higher critical low temperature than the actual. For this parameter, the linear equation appears acceptable.

Analysis of the data in Table 50 indicates that the actual critical low temperature is always higher than the estimated critical low temperature for the BBR m-value. This means that the linear equation used for estimating the critical low temperature based on BBR m-value is not conservative – that is, the equation consistently predicts a lower critical low temperature than the actual. The equation usually overestimates the actual critical low temperature by approximately 2.0°C. The estimate is incorrect by as much as a half-grade (3.0°C) in four of the eighteen cases. It is interesting to note that this overestimation appears to be magnified as the RAP percentage is increased.

The data in Table 49 indicates that the linear equation using the critical low temperatures (determined by BBR Stiffness) of the virgin asphalt binder, ***unaged***-recovered RAP asphalt binder, and RAP percentage may be appropriate for accurately determining the critical low temperature (based on BBR Stiffness) of a blended asphalt binder. However, the data in Table 50 indicates that the linear equation using the critical low temperatures (determined by BBR m-value) of the virgin asphalt binder, ***unaged***-recovered RAP asphalt binder, and RAP percentage may not be appropriate for accurately determining the critical low temperature (based on BBR m-value) of a blended asphalt binder. The consistent error in m-value may be caused by the fact that no aging was performed on the recovered RAP asphalt binder prior to testing.

Based on all the data in Tables 46 –50 and Figures 23 – 37, it appeared that some aging of the recovered RAP asphalt binder may be necessary prior to testing. The research team hypothesized that the RTFO aging of the recovered RAP binder may be sufficient to eliminate much of the anomalous, non-linear behavior indicated previously.

Recovered RAP Binder – with RTFO Aging

The testing and analysis was then repeated including RTFO aging of the recovered RAP binder according to the protocols of AASHTO MP1. Results for the virgin asphalt binders and the recovered RAP binders after RTFO aging are indicated in Table 51.

Estimated Binder Properties of Blended Asphalt Binders. Critical temperatures for the virgin and recovered RAP asphalt binders (with RTFO aging) are indicated in Table 52. The “Actual” performance grade and “MP1” performance grade of the binders are also included in Table 52. A comparison of the critical temperatures for the unaged and RTFO-aged recovered RAP binders is presented in Table 53.

The data in Table 52 indicates that the RTFO aging appeared to significantly affect the intermediate and low temperature properties of the recovered RAP binders. The critical intermediate temperature increased as the RAP stiffness increased. Likewise, the critical low temperature became higher as the RAP stiffness increased.

A comparison of the critical temperatures and performance grades of the recovered RAP binders using two aging conditions (Table 53) indicated that the critical high temperature was still controlled by the Original DSR ($G^*/\sin\delta$) values. The critical intermediate temperature increased by 4.8°C to 6.4°C from the unaged to the RTFO-aged condition. The critical low temperature based on BBR Stiffness increased by 2.5 – 4.5°C from the unaged to the RTFO-aged condition. The critical low temperature based on BBR m-value increased by 4.4 – 8.1°C from the unaged to the RTFO-aged condition. These differences are illustrated in Figures 38-40.

As indicated in Figures 38 – 40, the magnitude of the difference in critical temperatures between the unaged and RTFO-aged RAP binders appears to increase as the RAP stiffness increases.

Based on the information in Table 52, the estimated critical temperatures of the blended asphalt binders were determined using the linear equations described earlier. The estimated blended binder critical temperatures (using RTFO-aged RAP binders) of the Florida, Connecticut and Arizona blends are indicated in Tables 54, 55 and 56, respectively.

Comparison of Estimated and Actual Critical Temperatures (RTFO-aged RAP Binders)

The actual critical temperatures of the Florida, Connecticut and Arizona RAP blends are presented in Tables 40 - 45. Table 57 indicates the Estimated and Actual critical temperatures for the RTFO DSR. The critical temperatures based on Original DSR data are provided in Table 46. Data from these two tables determine the high temperature grade of the blended asphalt binder. In Table 57, the Estimated values were determined using the linear equations and the critical temperatures of the virgin and recovered RAP asphalt binders after RTFO aging.

Figures 41 – 43 illustrate the estimated and actual critical temperatures for the RTFO DSR for the Florida, Connecticut and Arizona RAP blends, respectively, with RTFO aging of the recovered RAP binder.

Analysis of the data in Table 57 and Figures 41 - 43 indicates that the actual critical temperature is close to the estimated critical temperature for the RTFO G*/sinδ value, using

RTFO aging of the recovered RAP binders. In most cases (11 out of 18 comparisons) the equation results in estimated values that differ from the actual critical temperature by less than 1.0°C. Unlike the data in Table 47 based on unaged recovered RAP binder, the estimate is never incorrect by as much as a half-grade (3.0°C). The equation neither consistently underestimates (9 of 18 comparisons) nor overestimates (9 of 18 comparisons) the actual critical temperatures of the blended asphalt binders.

Based on the data in Tables 46 and 57, it appears that the linear equations using the critical high temperatures of the virgin asphalt binder, ***RTFO-aged*** recovered RAP asphalt binder, and RAP percentage may be appropriate for accurately determining the high critical temperature of a blended asphalt binder. RTFO aging of the recovered RAP binder appears to significantly improve the ability of the linear equations to accurately estimate the actual critical high temperature of the blended asphalt binders.

Table 58 indicates the Estimated and Actual critical temperatures for the PAV DSR (G*sinδ). Data in this table can be used to determine the intermediate temperature grade of the blended asphalt binder. In Table 58, the Estimated values were determined using the linear equations and the critical temperatures of the virgin asphalt binders (after PAV aging) and the recovered RAP asphalt binders (after RTFO aging).

Figures 44 – 46 illustrate the estimated and actual critical temperatures for the PAV DSR (G*sin δ) after RTFO-aging for the Florida, Connecticut and Arizona RAP blends, respectively.

Analysis of the data in Table 58 and Figures 44 – 46 indicates that the actual critical intermediate temperature is closer to the estimated critical intermediate temperature (PAV G*sinδ) for the PG 52-34 blends than the PG 64-22 blends. For the PG 52-34 blends, the equation indicates a critical temperature within one-half grade (1.5°C) of the actual critical intermediate temperature in six of nine comparisons. For the PG 64-22 blends, the equation usually indicates a critical temperature that is 2 –3°C warmer (more conservative) than the actual critical intermediate temperature. No apparent trend can be determined form the data, but the response still appears to be non-linear as illustrated in Figures 44 – 46.

Unlike the unaged recovered RAP binder (Figure 29), it should be noted that the critical intermediate temperature of the Florida RAP (RTFO-aged) is higher than the critical intermediate temperature of the PG 64-22 asphalt binder (Figure 44). This matches expectations better than the unaged recovered RAP binder. From the information in Table 20, it is still apparent that further aging (to PAV) would improve the predictive ability of the linear equations.

Based on the data in Table 58, it appears that the linear equation using the critical intermediate temperatures of the virgin asphalt binder, ***RTFO-aged*** recovered RAP asphalt binder, and RAP percentage may not be the best for accurately determining the critical intermediate temperature of a blended asphalt binder. Although the linear equation still differs from the final blended critical intermediate temperature by as much as a half-grade (1.5°C) in more than 50% of all cases, the effect of RTFO-aging of the recovered RAP binder appears to have improved the relationship for the PG 52-34 blends. In addition, in eight of the eleven instances when the estimated value differs from the actual value, the equation overestimates the actual critical temperature (i.e., the equation is conservative).

Tables 59 and 60 indicate the Estimated and Actual critical temperatures for the BBR Stiffness and m-value. Data in these tables can be used to determine the low temperature grade of the blended asphalt binder. In Tables 59 and 60, the estimated values were determined using the linear equations and the critical temperatures of the virgin asphalt binders (after PAV aging) and the recovered RAP asphalt binders (after RTFO aging).

Figures 47 – 49 illustrate the estimated and actual critical temperatures for the BBR Stiffness for the Florida, Connecticut and Arizona RAP blends, respectively. Figures 50 – 52 illustrate the estimated and actual critical temperatures for the BBR m-value for the Florida, Connecticut and Arizona RAP blends, respectively.

Analysis of the data in Table 59 indicates that the estimated critical low temperature for the BBR Stiffness using RTFO-aged recovered RAP binder did not match the actual critical low temperature as well as the original estimates (using recovered RAP binder with no aging). Unlike the original estimates (7 of 18 comparisons), sixteen of eighteen (16 of 18) comparisons indicate a difference greater than 0.5°C. However, like the original estimates only one comparison is incorrect by as much as a half grade (3.0°C). The linear equation used for estimating the critical low temperature from BBR Stiffness is conservative (17 of 18 comparisons) – that is, the equation predicts a higher critical low temperature than the actual. The linear equation appears acceptable, although more offset, for the RTFO-aged recovered RAP binder. Contrary to expectations, the RTFO-aging of the recovered RAP binder appeared to cause the estimates to be worse than the estimates based on unaged recovered RAP binder.

Analysis of the data in Table 60 indicates that the RTFO-aging of the recovered RAP binder appears to significantly improve the ability of the linear equations to estimate the actual critical low temperature based on the BBR m-value. The data in Table 50 (recovered RAP binder without aging) indicates that the equation used for estimating the critical low temperature based on BBR m-value consistently predicts a lower critical low temperature than the actual. The data in Table 60 maintain that trend, but not as consistently – six of eighteen comparisons indicate a higher critical low temperature than the actual. The magnitude of the difference between estimated and actual critical temperatures is also improved. The average difference between estimated and actual critical low temperature is approximately 0.5°C. The estimate is never incorrect by as much as a half-grade (3.0°C) and rarely incorrect by more than 1.0°C (4 of 18 comparisons).

The data in Tables 59 and 60 indicate that the linear equation using the critical low temperatures (determined by BBR Stiffness and m-value) of the virgin asphalt binder, ***RTFO-aged*** recovered RAP asphalt binder, and RAP percentage may be appropriate for accurately determining the critical low temperature (based on BBR Stiffness and/or m-value) of a blended asphalt binder. Curiously, RTFO-aging of the recovered RAP binder actually worsened the estimates for BBR Stiffness, but significantly improved the estimates for BBR m-value.

Based on the data in Tables 57 – 60 and Figures 41 – 52, it appears that RTFO aging of the recovered RAP asphalt binder may be necessary prior to testing. The estimated critical temperatures based on RTFO DSR and BBR m-value significantly improve using RTFO-aging of the recovered RAP binder. The estimated critical intermediate temperature based on PAV DSR improves somewhat by RTFO-aging of the recovered RAP binder. Only the estimated critical low temperature based on BBR Stiffness does not improve with RTFO-aging of the recovered RAP binder. However, since BBR m-value usually determines the low temperature grade of an asphalt binder, the improvement in BBR m-value appears more important than the BBR Stiffness.

Binder Grade Comparisons (Estimated versus Actual)

Using the linear equations described earlier with original (Table 46) and RTFO-aging (Tables 57 – 60) of the recovered RAP binder, the estimated blended binder grade can be compared with the actual blended binder grade. This data is presented in Table 61.

The data in Table 61 indicates that the estimated binder grades match the actual binder grades in 15 of 18 cases. In two of the three cases where the binder grades do not match, the estimates predicted a lower high temperature grade than indicated by the actual test results. In the other case (Arizona 20% RAP with PG 64-22 virgin asphalt binder), the low temperature grade was estimated to be a -22 grade. The actual critical temperature of that blend was -11.9°C, thereby making the blend a -16 grade rather than a -22 grade.

Mixture Effects Study

In studying the effect of the ratio of Reclaimed Asphalt Pavement (RAP) on mixture properties, the results of testing the actual practice (AP) samples from the black rock study were combined with the results of additional tests on similar samples made with 0, 20 and 40% RAP. This allowed studying the effect of RAP ratio at a wide range from 0 to 40%. In addition to the RSCH, FS, SS, ITC and ITS tests described earlier, beam fatigue tests were also performed on all cells in the experimental design.

Shear Test Results

Tables 62 to 67 present the average testing data for complex shear modulus and high temperature stiffness (G* and G*/sinδ) at different temperatures and loading frequencies for mixtures with different RAP ratios, different virgin binders and different RAP stiffnesses. Tables 68 to 70 present the maximum shear deformation from the SS test for all cases. Table 71 depicts the shear strain of samples from the RSCH test at 5000 loading cycles for all studied cases.

For the AZ RAP, the complex shear modulus from the FS test, shown in Table 62, increased with increasing RAP ratio at both testing temperatures (20 and 40°C). The rate of increase in modulus (G*) was lower for the 10 and 20% RAP ratio mixtures and it increased significantly for the high RAP ratio (40%). An exponential relationship was suitable for explaining the change in G* with RAP ratio. While the modulus increased, on average, eight times at 0.01 Hz, it increased just 2.5 times, on average, for testing at 10 Hz for both virgin binders. The stiffness (G*/sin δ) values, shown in Table 63, followed similar trends.

The complex shear modulus (Table 64) and high temperature stiffness (Table 65) for the FL RAP also increased with increasing RAP ratio in the mixtures. Although an exponential relationship was found to explain the change in G* and G*/sin δ with RAP ratio when PG 52-34 binder was added, the correlation was not very strong when PG 64-22 was used. The maximum increase in G* was only two times when a combination of hard new binder and high RAP ratio were used. Some scatter in the G* results with change in RAP ratio were observed when PG 64-22 was used.

The trends for the CT RAP were generally similar, as shown in Tables 66 and 67, except that there were cases where the values appeared to drop or remain nearly level as the RAP content increased from 20 to 40%. This was not true at all frequencies and temperatures.

The maximum shear deformation from the SS test for the AZ RAP decreased as the RAP ratio increased in the mixtures, as shown in Table 68. Again for most cases of testing loads and temperatures, an exponential relationship was observed. The maximum shear deformation dropped between three to ten times when the RAP ratio decreased from 0 to 40%.

The maximum shear deformation also tended to decrease exponentially with increasing RAP content for the FL RAP (Table 69) and CT RAP (Table 70). The change in this parameter was more significant for the FL mixtures with PG 52-34 binder.

Table 71 shows the change in shear strain from the RSCH test for all three RAP sources. The shear strain tended to decrease with increasing RAP content, but there was variability in the data. In some cases, the shear strain increased or did not change significantly. This may be due to variability in the data or to the balance between increasing binder stiffness and, possibly, decreasing aggregate shear resistance when higher percentages of RAP are used.

Overall, as RAP content increased complex shear modulus (G*) was found to increase exponentially and maximum shear deformation and shear strain were found to decrease.

Indirect Tensile Testing Results

Thermal Stress Analysis. In addition to providing low temperature stiffness and strength results, the low temperature indirect tension creep data can be analyzed using a procedure developed by Christensen to determine the mixture critical temperature (30). This procedure, essentially a modification of the SHRP models developed by Roque and others, uses compliance and Poisson's ratio data from the indirect tensile creep and strength tests to calculate the temperature where the thermal stress of the mixture exceeds the tensile strength.

PG 52-34 with Connecticut and Arizona RAP. Tables 72 and 73 and Figures 53 – 56 show the stiffness and tensile strength data for the PG 52-34 blends with Arizona and Connecticut RAP.

The trends shown for the PG 52-34 stiffness results match what would be expected for this type of testing. Stiffness values increase with decreasing temperature and with increasing RAP content. Stiffness values also increase when the stiffer Arizona RAP is used as opposed to the medium stiffness Connecticut RAP. As can be seen from the figures, stiffness values are fairly close between the two RAPs at 10% RAP content and at 20% RAP content for warmer temperatures, but start to diverge somewhere between 20 and 40% RAP content.

A statistical t-test analysis verifies that for both RAPs, the stiffness results for the 10% Arizona and Connecticut blends are statistically the same as the stiffness results for the PG 52-34 samples containing no RAP. The only exception is the Arizona blends at –10°C. When the RAP content is increased to 20%, the stiffness values are no longer statistically the same in most cases. The only exceptions are the Arizona blends at –20°C.

Strength results for the PG 52-34 blends do not show the same trends as the stiffness results. The Connecticut blend strengths are very similar, regardless of RAP content. There is only approximately 300kPa difference between the set of samples with no RAP and the set with 40% Connecticut RAP. The Arizona blends, while still similar, show more variation, ranging from 1,856 kPa at 10% RAP to 3,170 kPa at 40% RAP. The 10% Arizona RAP strength actually decreased from the strength of the no RAP set.

The Arizona RAP produced specimens that had greater stiffness than the Connecticut RAP blends did. The Arizona RAP was also a more variable material than the Connecticut RAP. Both of these factors could account for the behavior of the Arizona blend strengths.

The RAP blends were also analyzed using Christensen's low temperature cracking procedure to obtain mixture critical cracking temperatures for each blend. The results for the PG 52-34 blends are shown in Table 74. It is expected that the addition of a stiffer material will cause the low temperature properties of a mix to deteriorate, and that is shown by these results. At 0% RAP, the PG 52-34 mixture samples have a critical temperature of –28.1°C. For both RAPs, the critical temperature increases (i.e., the mix becomes less resistant to low temperature cracking) as the RAP content increases.

PG 64-22 with Connecticut and Arizona RAP. Tables 75 and 76 and Figures 57 – 60 show the stiffness and strength results for the Connecticut and Arizona blends with PG 64-22.

The PG 64-22 blends do not show the same trends as the PG 52-34 blends. The stiffness appears to decrease slightly at the 10% RAP level instead of increasing. At -20°C, the 40% RAP blends have lower stiffness than the 20% blends. The same happens with the 40% Arizona blend at -10°C.

A statistical t-test analysis shows that in almost all cases, the PG 64-22 with 10% RAP results are statistically equal to the PG 64-22 samples containing no RAP. At the 20% RAP level, the Arizona blends are statistically different from the 0% set and the Connecticut blends are statistically the same as the 0% set at -10 and -20°C. It is uncertain what caused the stiffness of the 40% blends at -20°C to decrease rather than increase. It is likely that this was caused by a testing error of some sort.

The PG 64-22 strength results are very similar to the PG 52-34 results. Strength values for the Arizona blends range from approximately 2,600 kPa to 3,300 kPa. Connecticut blend strengths range from 2,789 to 3,009 kPa. A t-test analysis of the data shows almost all of the RAP levels to have statistically different strength results, but in reality the strengths are very close.

Table 77 shows the mixture critical temperatures for the PG 64-22 blends.

The 40% Arizona critical temperature could not be calculated due to variability in the data files. The other results, with the exception of the 10% Connecticut blends, show the expected trend of increasing critical temperature with increasing RAP content.

Overall, the IDT testing showed that at low RAP contents, the creep stiffness of mixtures with up to about 10% RAP was essentially the same as for companion mixtures without RAP. As RAP content increases over 10% or so, the stiffness also increases. The mixture low critical temperatures also tended to increase (become warmer, or less negative) as RAP content increases. Strength values were relatively insensitive to RAP content.

Repeated Flexural Bending Testing

To evaluate the effect of RAP on the fatigue life of asphalt mixtures, beam fatigue testing was conducted. The underlying hypothesis was that the fatigue life of asphalt pavements will decrease with an increase in percentage of RAP of the stiffness of the RAP.

Beam fatigue testing was performed in accordance with *AASHTO TP8 Standard Test Method for Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending*. AASHTO TP8 requires a beam of asphalt with dimensions of 380mm-length, 50mm-height and 63mm-width. Smooth saw cut sides are necessary for clamping and attachment of the LVDT. The beam is placed in four-point loading with an LVDT mounted in the center of the beam at mid-height to measure the deflection. Testing is conducted at 20°C, with the beam conditioned at this temperature for two hours prior to testing. Loading is applied in a sinusoidal waveform in strain-controlled mode. At specified cycles the data acquisition system uses the deflection and the applied load applied to calculate and record the maximum tensile stress, maximum tensile strain, phase angle, stiffness and dissipated energy.

Beams were compacted in accordance with *ASTM 3202, Standard Practice for Preparation of Bituminous Specimens by Means of the California Kneading Compactor.* The pressures were reduced from ASTM 3202 in order to accommodate the high air voids desired for the beams. The beams were compacted to a height of 76mm in an 83mm wide mold to allow for saw cutting to the required height and width.

To simulate different pavement structural situations, beams were tested at high and low strain levels. AASHTO TP8 specifies a repeated sinusoidal loading at a frequency range of 5-10 Hz and an initial strain of 250 to 750 microstrains (με). A frequency of 10 Hz at 600με was chosen for the high strain and 10 Hz at 300με, half the strain, for the low strain beams. The 300 and 600με levels were chosen in order to stay within the specified range, and the low strain being one half of the high strain should be beneficial for data comparison. Upon running the beam made with PG 52-34 binder and zero percent RAP, the test ran for 344,000 cycles (9.5 hours) before the stiffness dropped 50%. A 9.5-hour test would allow only one beam per day so the high strain was adjusted to 750με. The 750με level cut the cycles to 162,000 (4.5 hours) which allowed the testing of one high strain beam during the day and testing of a low strain beam overnight. In the interest of time and the large number of beams in the test matrix the strain was adjusted to 800με, this is a minor change to AASHTO TP8 test protocol. The 800με reduced the test to 146,000 cycles (four hours). The PG 52 with 0% RAP was to be the softest mix tested, therefore, all other mix designs would reach failure criteria in fewer cycles.

Low strain beams typically do not drop 50% in stiffness in a reasonable amount of time. A cut off point of 500,000 cycles (14 hours) was established to allow the test to be done during the night and be ready for a high strain beam the next morning. Low strain was adjusted to 400με to keep the multiplier between the low and high strain at two. The 800με and 400με combination allowed two high strain beams to be run during the day and one low strain beam to be run over night.

The test matrix is shown in Table 78. The mix designs used for the beams were the same as used for the mixture effects study. Four beams in each cell represent two high-strain beams and two low-strain beams; the final two beams are two high-strain long-term oven aged (LTOA) beams.

The higher strain level (800 με) simulates a thin pavement with weak structure or poor subgrade. Low strain level testing is used to simulate thick pavements with sufficient structure and adequate subgrade.

All beams were short-term oven aged (STOA) according to SHRP test method M-007 as specified in the SHRP-A417 report (31). The SHRP report did not specify long-term aging for flexural beams, however, long-term aging was included in this study since fatigue effects are observed in aged pavements. Beams containing CT RAP were long-term oven aged (LTOA). In the interest of time the AZ RAP beams were not LTOA. The 9-12 team felt that simulated aging was appropriate due to fatigue relationship with aging. LTOA was performed to determine if oven aging had a significant effect on the results of the flexural beam fatigue test. In accordance with SHRP-A-417 (A) long-term aging was performed on the compacted beams at 85°C for 96 hours. After beams cooled to ambient temperature, the sides were saw cut to the proper dimensions for testing.

The response variables that were measured include the number of cycles to failure (N_f), dissipated energy, and the initial and final stiffnesses. Initial stiffness is defined as the measured stiffness after 50 cycles. The number of cycles to failure is defined as the number of cycles until the stiffness drops to 50 percent of initial stiffness. The dissipated energy is defined as the difference in the amount of energy required to deflect the beam at the beginning of the test and the amount required at the end of the test. The initial and final stiffnesses are calculated from the deflection and the load required to induce the deflection.

High Strain Comparisons. Tables 79-82 contain the data from the different combinations of short-term aged mix and RAP. Table 79 contains the data for PG 52-34 mix combined with the CT RAP tested at high strain. This combines the softer virgin mix with the medium stiffness RAP. Table 80 contains the data for PG 52-34 mix combined with AZ RAP and tested at high strain. This combination is the softer virgin mix combined with the stiffer RAP. Table 81 contains data for the PG 64-22 mix combined with CT RAP and tested at high strain. This combines the stiffer virgin mix with the softer RAP source. Table 82 contains PG 64-22 mix combined with AZ RAP and tested at high strain. This is a combination of the stiffer virgin mix and the stiffer RAP source. For certain combinations of binder and RAP, the cycles to failure varied considerably. The research team does not know the cause of this, however, it should be noted that the rest of the recorded values for these replicates are very similar.

Figures 61 and 62 illustrate the relationship between cycles to failure and the initial stiffness of the beams at different RAP ratios for the CT and AZ RAP. Figure 61 shows that as the stiffness increases the cycles to failure decreases. The curves on the PG 52-34 show that the virgin binder determines the relationship of cycles to failure vs. stiffness. The magnitude of the cycles vs. stiffness is determined by the stiffness of the RAP. Figure 62, cycles to failure vs. initial stiffness, does not show the same relationship. The researchers are not certain of the cause of this discontinuity, but theorize that the binder is the source. During the 9-12 project, the PG 64-22 binder was depleted and more was ordered. The supplier had reformulated the binder between the original and the new shipment of binder. The binder properties were similar to the original PG 64-22 binder, however the difference may be showing up in the mix effects.

Figures 63 and 64 show the relationship of the percentage of RAP vs. dissipated energy. The trend shows that the dissipated energy increases with an increase in RAP percentage. Since the addition of RAP will stiffen a mixture, this trend was expected and supports the hypothesis.

Low Strain Comparisons. Tables 83-86 contain the data for different combinations of mixture and RAP tested at low strain. The tests marked with 500,000+ indicate that test was stopped due to time constraints.

Figure 65 shows that the cycles vs. stiffness for the low strain follows the same trend as the cycles vs. initial stiffness for high strain. This trend is only shown for PG 64-22 mixture with Arizona RAP since it took the stiffest of all combinations for the failure criteria to be reached before the 500,000-cycle cutoff.

Figures 66 and 67 show the relationship of percent RAP vs. dissipated energy. It is important to note that there is no statistical difference between the values for 0% and 10% RAP. This would indicate that up to 10% of RAP may be added with no statistical effect on the performance of the mix. The graph for the mixture with PG 64-22 shows that the dissipated energy drops with increasing RAP content. The only explanation that the researchers can offer is the previously mentioned change in the PG 64-22 binder.

Long-Term Aged Comparisons. Tables 87 and 88 display the data from the high strain testing of the LTOA beams. Two of the tests were terminated due to machine malfunction and no data on those beams could be recovered. Long-term aging is not part of the beam fatigue protocol, however the 9-12 research team decided to pursue this data to study the relationship between aging and fatigue.

As expected the addition of RAP to an asphalt mixture increases the stiffness and the estimated fatigue life. The estimation of the fatigue life is based on a paper by Leahy (32) that determined the cycles to failure could be related to the equivalent single axle loads (ESALS). In Leahy's paper the cycles to failure were related to ESALS with the multiplication of an empirically determined shift factor (SF).

$N_{demand} = ESAL_{20C}/SF$

where:

N_{demand}=	design traffic demand (laboratory-equivalent repetitions of standard load),
$ESAL_{20C}$ =	design ESALs adjusted to a constant temperature of 20C (68F), and
SF =	empirically-determined shift factor.

The determination of the SF includes climatic and traffic conditions which are not being determined for this project. However, using Leahy's recommendation would indicate that a decrease in cycles to failure would decrease the fatigue life the same magnitude. In addition, the stiffness of the RAP does affect the stiffness and cycles to failure when higher percentages are added. The effects of adding a low percentage of RAP are not statistically different. These trends add to the support of the hypothesis.

Short Term Aged vs. Long Term Aged Comparisons. Comparisons of the short-term oven aged (STOA) and LTOA beams are shown in Figures 68 and 69. It is evident that there is a change in both stiffness and cycles to failure. Table 89 shows the ratio of the LTOA to STOA stiffness and cycles to failure. The highlighted section was not used due to the result being an outlier. With long-term aging the initial stiffness is raised approximately 30% and the cycles to failure drop 30-40%.

High Strain and Low Strain Comparison. Figure 70 shows the comparison of the high and low strain tests for the PG 52-34 mixtures with both RAPs. The low strain samples had a consistently higher stiffness than the high strain samples. The cycles to failure could not be compared for the different strain levels due to most of the low strain testing terminating due to time constraints instead of obtaining the failure criteria.

The results of this data support the hypothesis that the addition of RAP and the stiffness of RAP will decrease the life of an asphalt pavement if no adjustment is made to the virgin binder grade. This data supports previous Mixture Expert Task Group (Mix ETG) guidelines for the use of RAP (1).

As seen by the results, long-term aging of fatigue beams has a significant effect on the results of fatigue testing. While long-term aging of beams is not being recommended as a protocol at this time, further study of long-term aging and fatigue testing is suggested.

Mini Experiments

Plant vs. Lab Comparison

In this mini-experiment designed to assess the validity of the sample preparation techniques used in the study, one plant-produced mixture, from Connecticut, containing 20% RAP was compared to the same mixture recreated in the lab using the same raw materials. The sample preparation techniques used in the overall research project were used here to fabricate the lab mix. The concept behind this mini-experiment was to determine if the lab specimens used in this research effort had any semblance to plant-produced mixtures. If so, the credibility of the research findings would be strengthened. If not, those findings would be questionable. Mixtures were compared using the FS, SS and RSCH tests.

Tables 90 to 93 present the replicate and average results for the complex shear modulus stiffness (G*) and stiffness (G*/sinδ) at two testing temperatures (20 and 40°C) and at high and low loading frequencies (10 and 0.01 Hz) from the FS test. Tables 94 and 95 present the replicates and average maximum shear deformation (in) of lab and plant samples at two testing temperatures (20 and 40°C) from the SSCH test. Table 96 presents the shear strain of lab and plant samples at 5000 loading cycles from the RSCH tests.

Figure 71 depicts the average frequency sweep (FS) test results for laboratory and plant samples tested at 40°C and 10Hz. Similar results were obtained at 20°C and 0.01 Hz. Both parameters from this test, G* and G*/sinδ, from the laboratory and plant samples are similar. Statistical analysis (t-test) of the replicate results verified that there was not a significant difference between the lab and plant samples. Although the results at 20°C show that the plant mixtures had a slightly higher stiffness than the lab samples, the lab samples show somewhat higher stiffness than plant samples at 40°C. Because the difference was not statistically significant at either temperature, the slight stiffness difference could be related to other testing variables. The maximum difference between lab and plant samples for phase angle (δ) was less than 2 degrees.

Figure 72 shows the average simple shear (SS) test results for laboratory and plant samples at 20°C. As expected in a creep test, the shear deformation increased with time, and after releasing the load the deformation decreased. Part of the deformation remains in the sample (plastic deformation) and part is recovered (elastic deformation). Similar to the results on frequency sweep, the shear deformations for both lab and plant samples are similar. The maximum shear deformations for lab and plant samples were between 0.0044 and 0.0064in. The differences in average maximum shear deformations at 20 and 40°C were less than 0.0005 and 0.0007in respectively. Statistical analysis of the replicate maximum shear deformation showed that there was no significant difference between lab and plant samples.

Figure 73 presents the average repeated shear at constant height (RSCH) test results for lab and plant samples after 5000 loading cycles at 58°C. The difference in shear strain at 5000 loading cycles between lab and plant samples was 0.0003 or 0.03%. This value is not a significant difference between mixtures. Statistical analysis again verified this conclusion for replicate results for this test.

Effects of RAP Handling

To investigate the effects of different heating times and temperatures on the properties of RAP measured in the lab, those effects were evaluated based on changes in the intermediate temperature stiffness of the recovered binder properties, as outlined in Chapter 1. Tables 97 and 98 present the DSR results at 22 and 31°C on binders extracted from the RAPs after they were subjected to these different handling treatments. Each result is the average of at least two replicates. In case the individual test results differed more than 10% from their average, more replicate results were obtained.

Figures 74 and 75 present the change in complex shear modulus (G*) with aging times for both conditioning temperatures (110 and 150°C) for both binders evaluated. (Approximately 1-2kg of RAP was heated at a time.) These figures show that, in general, longer heating times and/or higher temperatures result in stiffer recovered RAP binders. Both figures also show the modulus for binder extracted from the RAP without aging, for comparison purposes.

A statistical analysis of the mean, using the SAS program, was performed to find the effect of the variables in this study. This analysis showed that for the Arizona RAP there was no significant difference in measured complex shear modulus (G*) for extracted binders following 2 hours of aging at 110°C, 2 hours at 150°C and 4 hours at 110°C. The modulus for binders after 4 hours aging at 150°C and 16 hours aging at 110 and 150°C also showed similar results, and there was no significant difference between those conditions. The modulus values for the three binder samples heated for longer times and higher temperatures were two times greater than the modulus values of the first mentioned group. This means that for the stiff RAP (AZ) handling the RAP in the lab at high temperature (150°C) and for more than 4 hours can significantly change the properties of the binder in RAP. The statistical analysis for results at 22 and 31°C led to similar conclusions.

For the extracted RAP binder from Florida, the 2 hours aging at 110 and 150°C were statistically the same. The complex shear modulus values for the other cases were two to three times greater than these cases. Therefore, for a soft RAP, such as that from Florida, aging for more than 2 hours regardless of temperature (110 or 150) changed the stiffness of the binder in the RAP.

The Florida data does show an anomaly in that the RAP heated for 16 hours at 110°C apparently has a lower modulus than the RAP heated for four hours at either temperature. This unexpected result may be due to an error in the recovery of the extracted RAP binder. The testing was repeated on retained samples of the recovered binder and results were verified. The recovery, however, was not repeated due to the time involved in aging more RAP for extraction.

These results show no appreciable change in the binder provided the heating time is held to no more than two hours. Four hours of heating at 110°C might be acceptable for some RAPs, but may result in stiffening of the binder. Therefore, it is preferable and more conservative to limit the heating time to two hours.

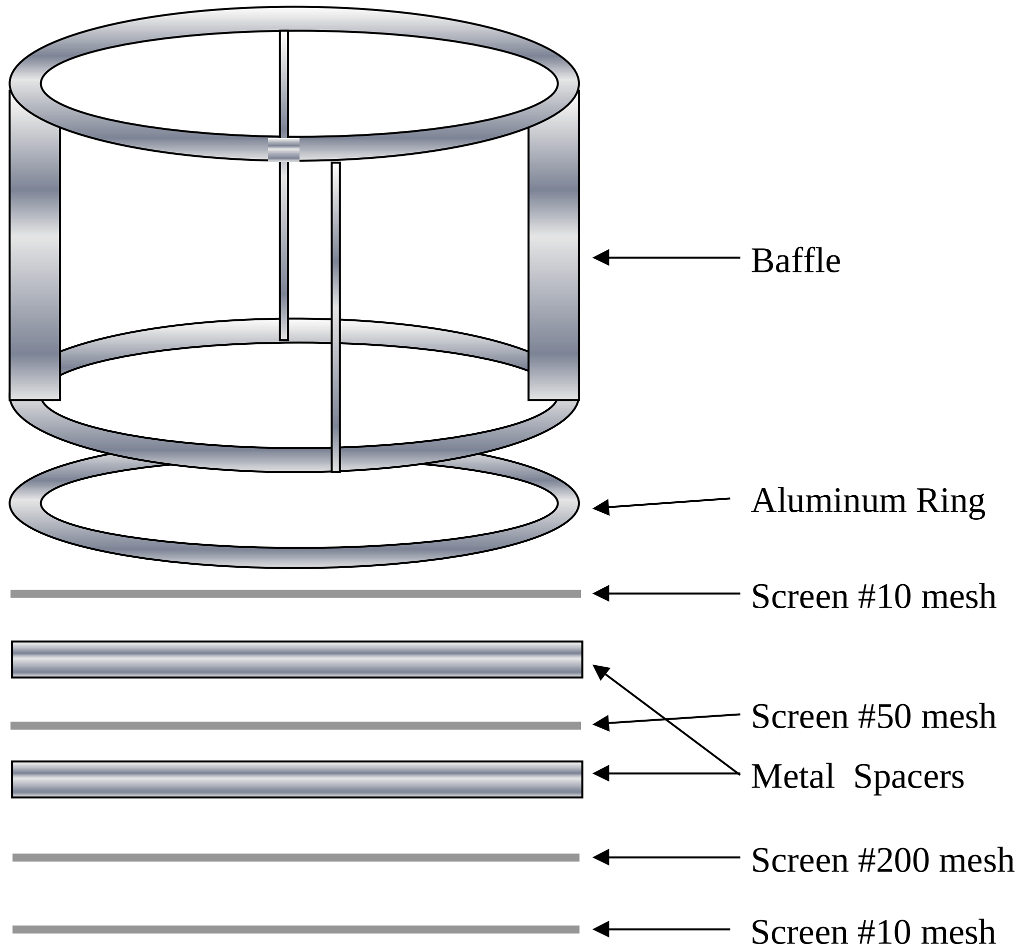

Figure 3. Modified Screen Configuration for AASHTO TP2

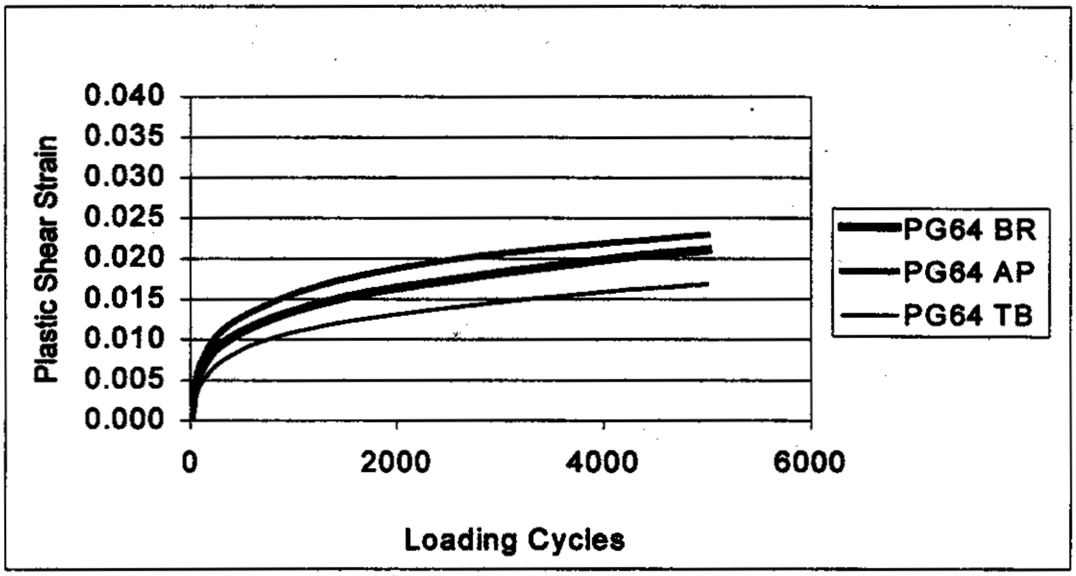

Figure 4. Frequency Sweep (FS) Results for 10% FL RAP at 40°C and 10 Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

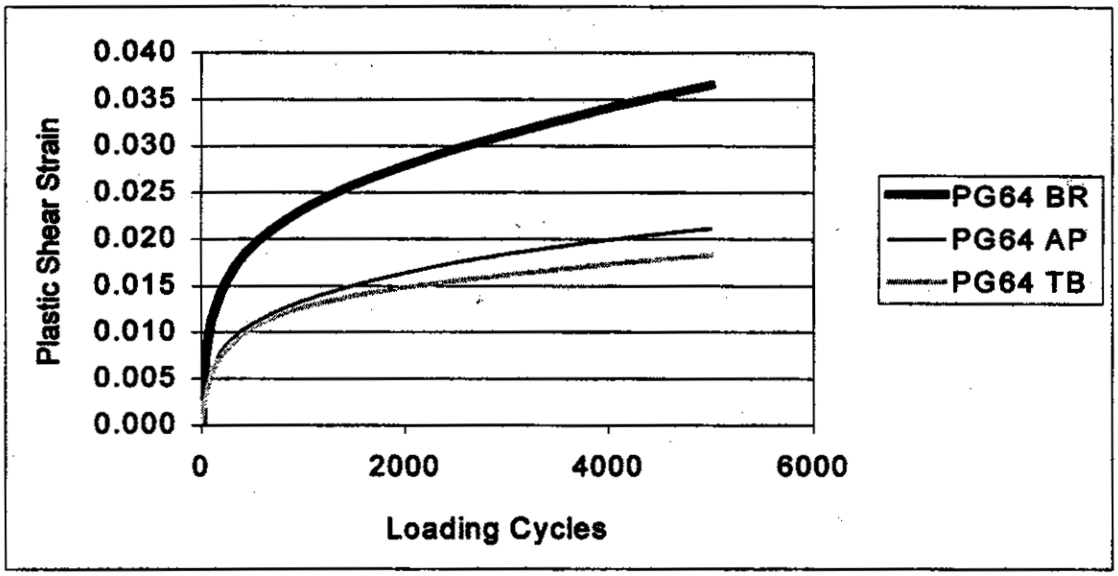

Figure 5. Frequency Sweep (FS) Results for 40% FL RAP at 40°C and 10 Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

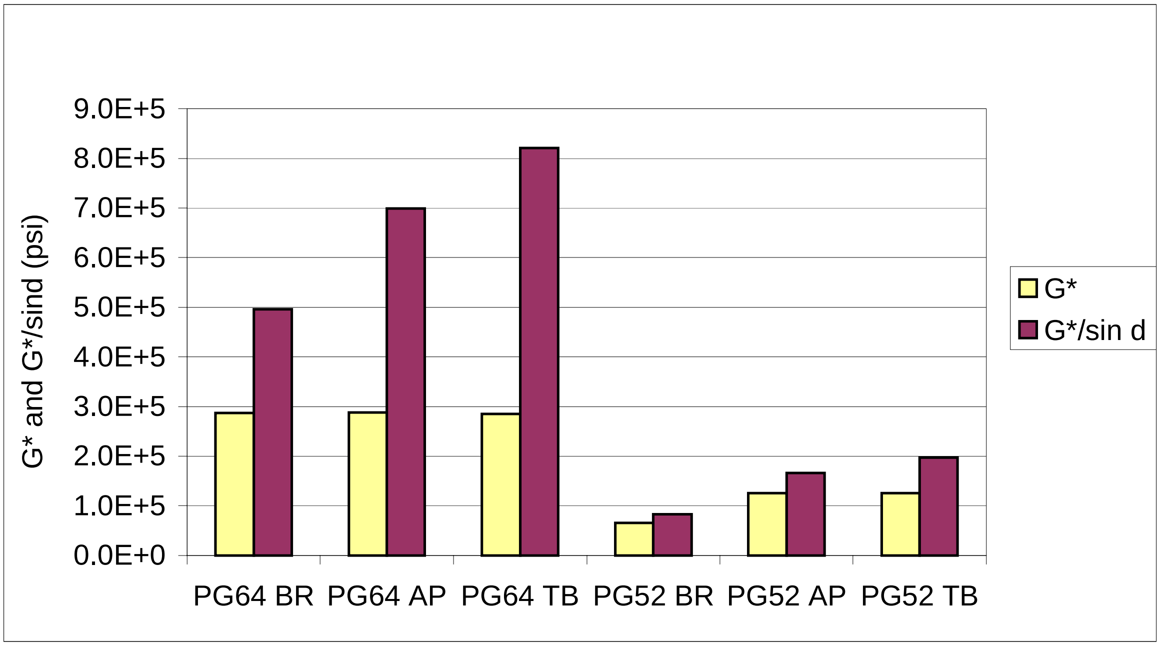

Figure 6. Frequency Sweep (FS) Results for 10% CT RAP (Unaged) at 20°C and 10Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

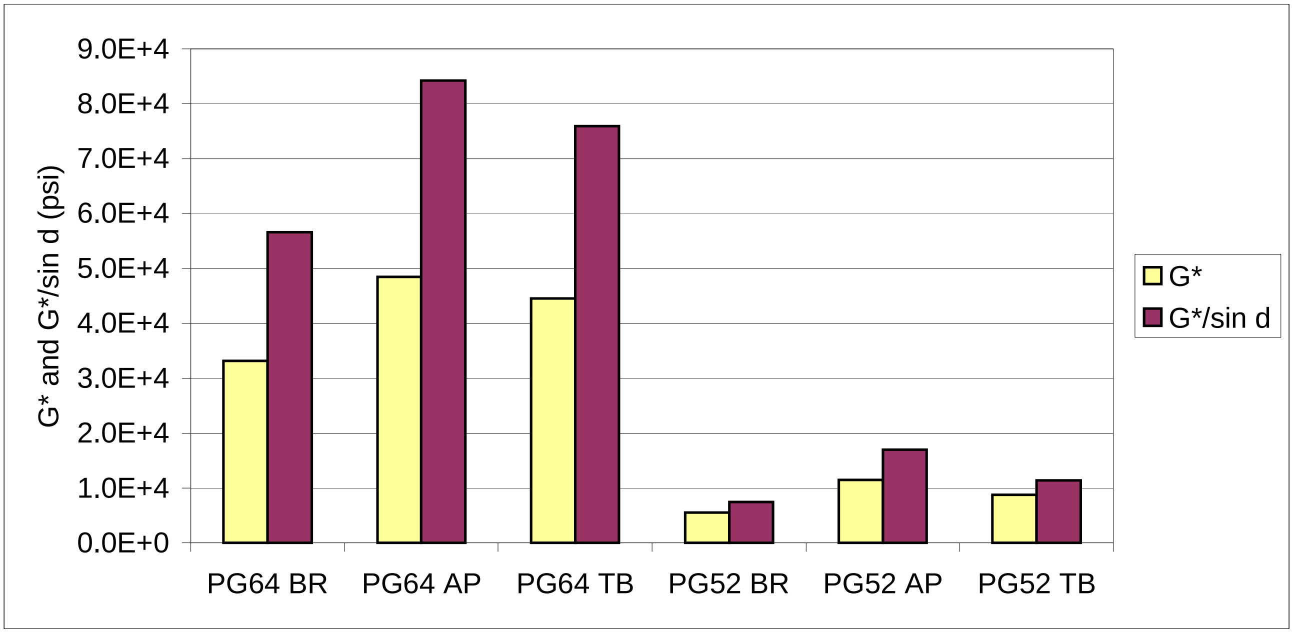

Figure 7. Frequency Sweep (FS) Results for 10% CT RAP (Aged) at 20°C and 0.01 Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

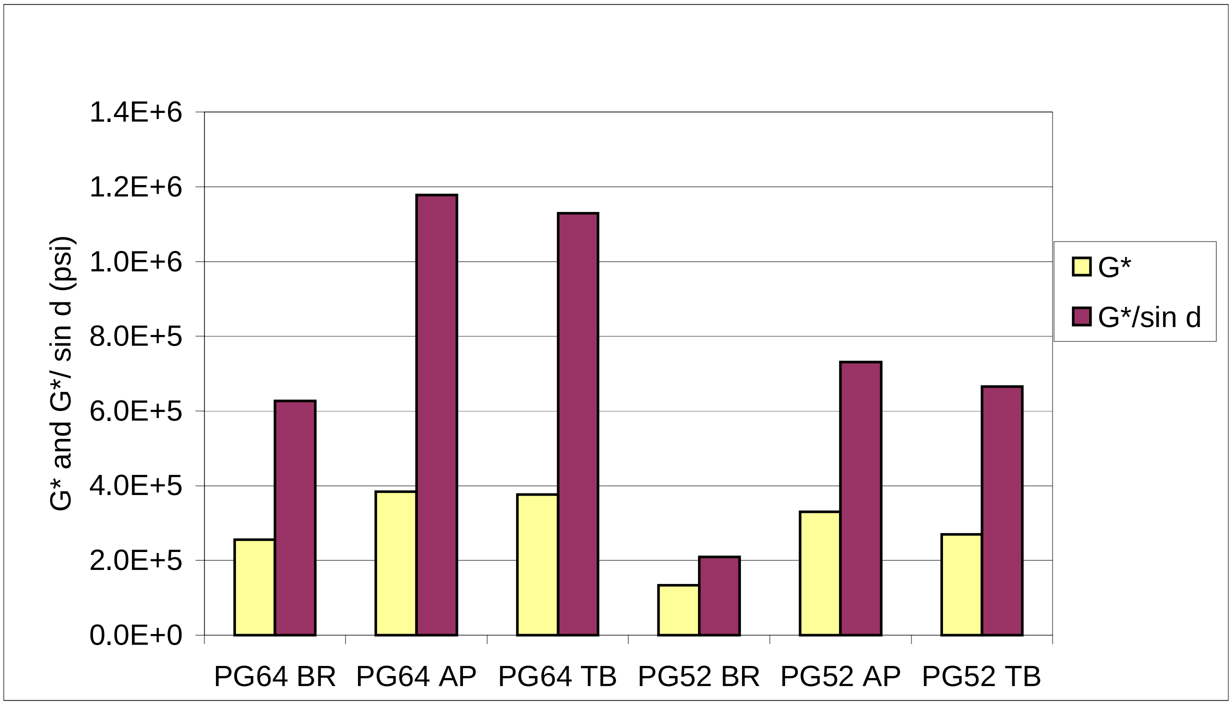

Figure 8. Frequency Sweep (FS) Results for 40% CT RAP (Aged) at 20°C and 10 Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

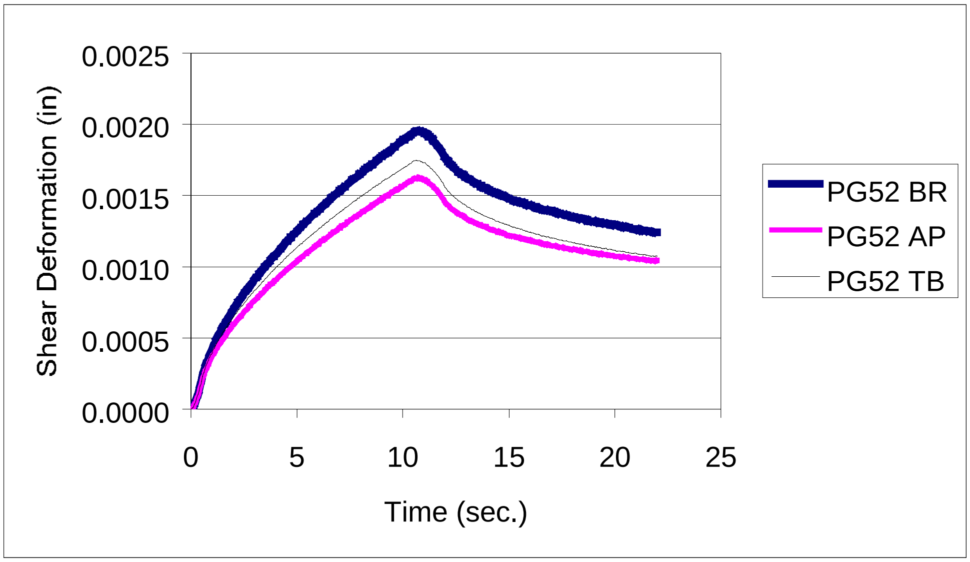

Figure 9. Simple Shear (SS) Deformation for 10% FL RAP with PG 52-34 at 20°C
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

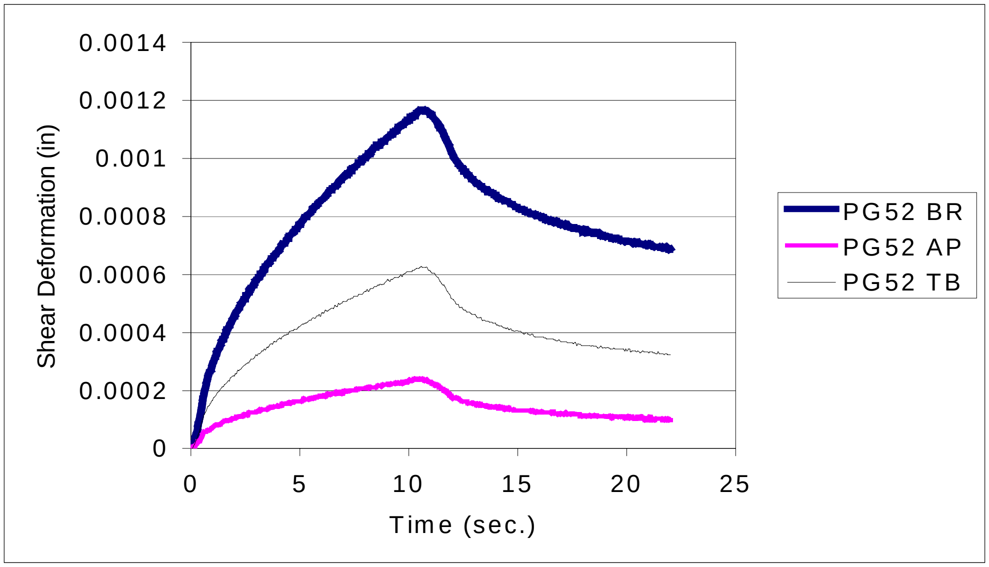

Figure 10. Simple Shear (SS) Deformation for 40% FL RAP with PG 52-34 at 20°C
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

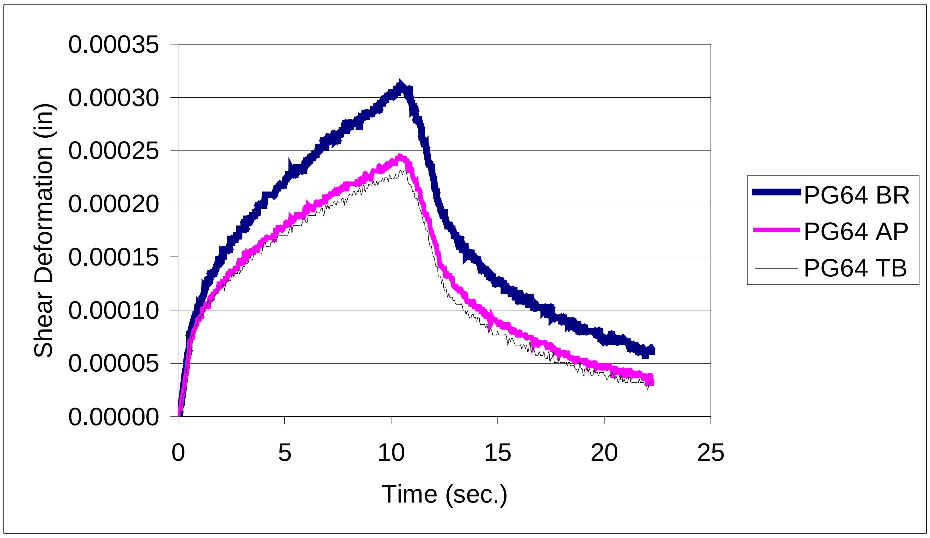

Figure 11. Simple Shear (SS) Deformation of 10% CT RAP (Aged) at 20°C
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

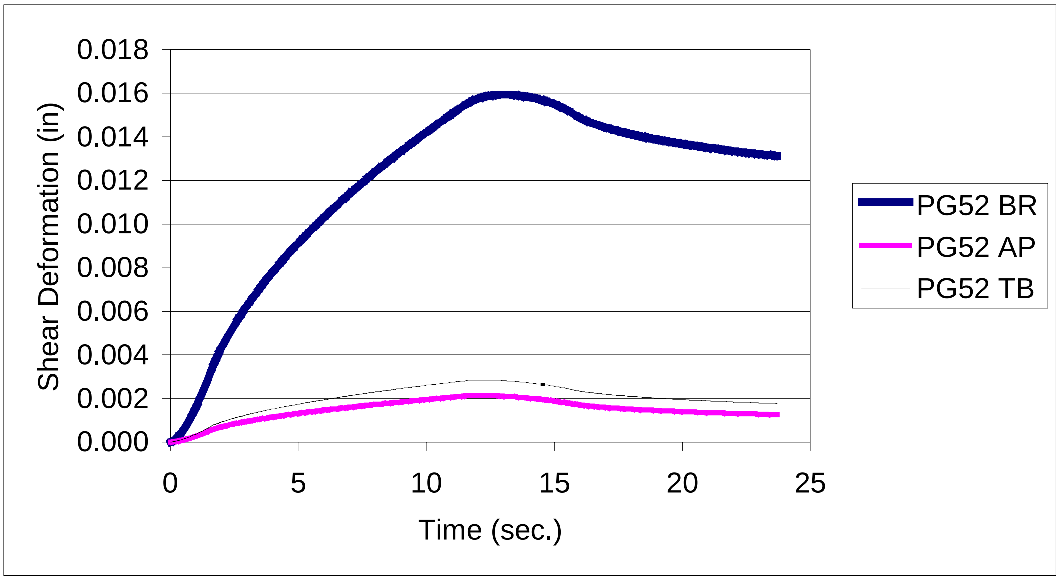

Figure 12. Simple Shear (SS) Deformation for 40% CT RAP with PG 52-34 at 20°C
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

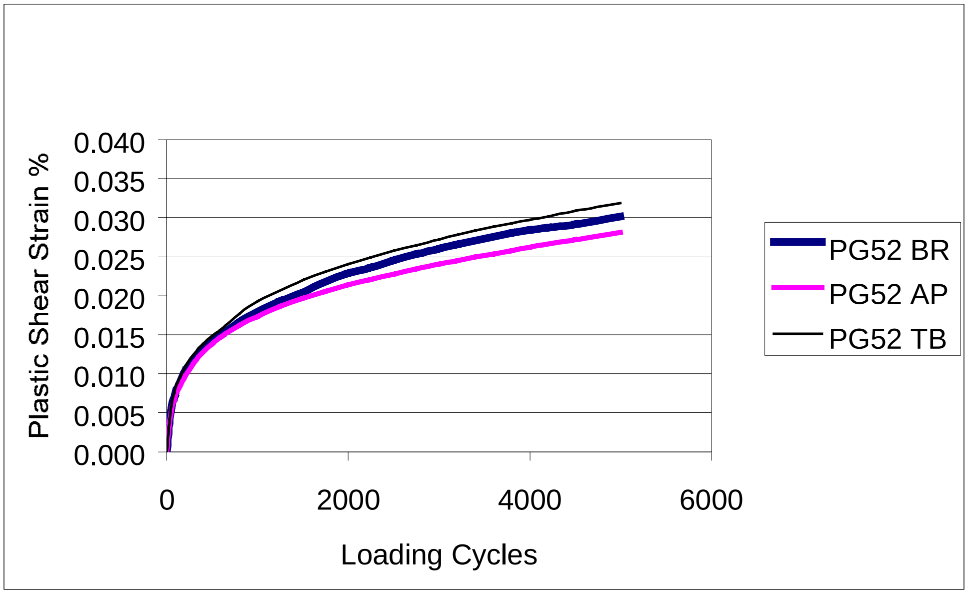

Figure 13. Repeated Shear (RSCH) Results for 10% CT RAP with PG 52-34
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

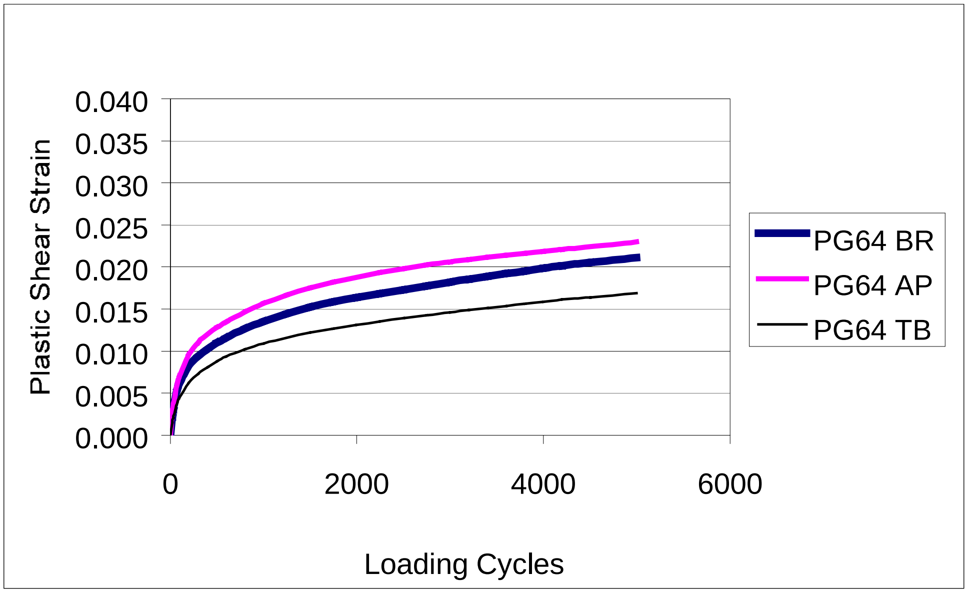

Figure 14. Repeated Shear (RSCH) Results for 10% AZ RAP with PG 64-22
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

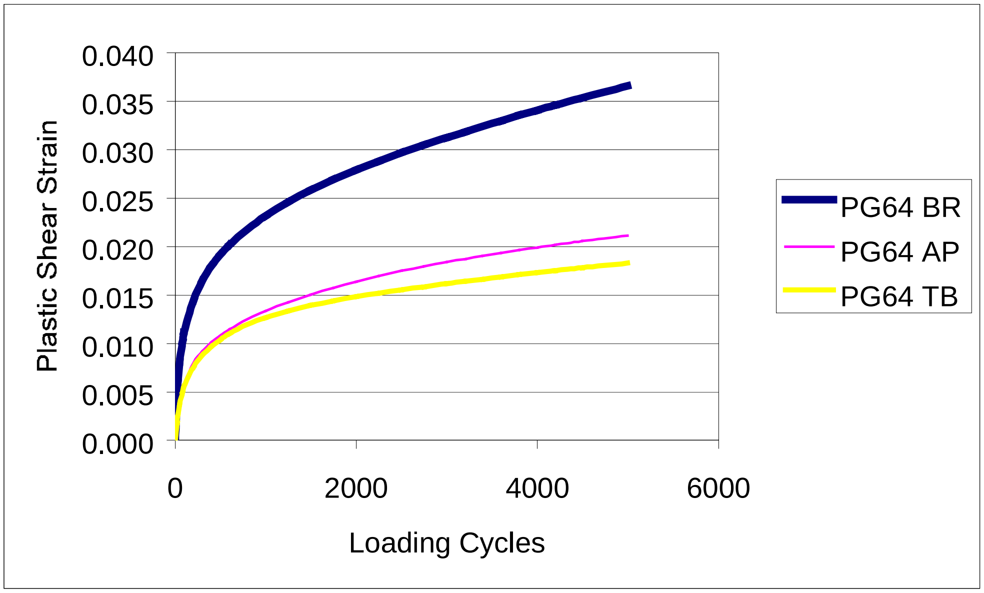

Figure 15. Repeated Shear (RSCH) Results for 40% CT RAP with PG 64-22
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

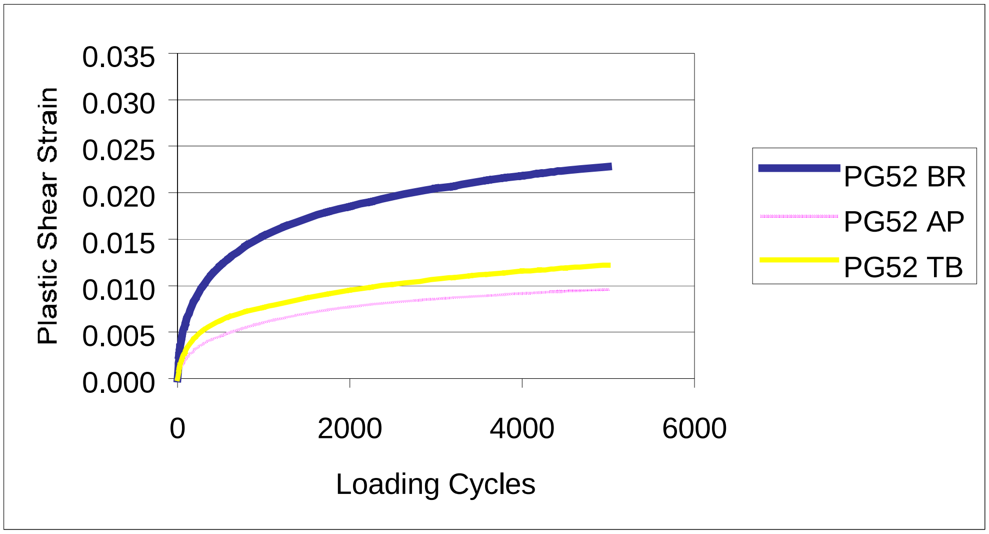

Figure 16. Repeated Shear (RSCH) Results for 40% AZ RAP with PG 52-34
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

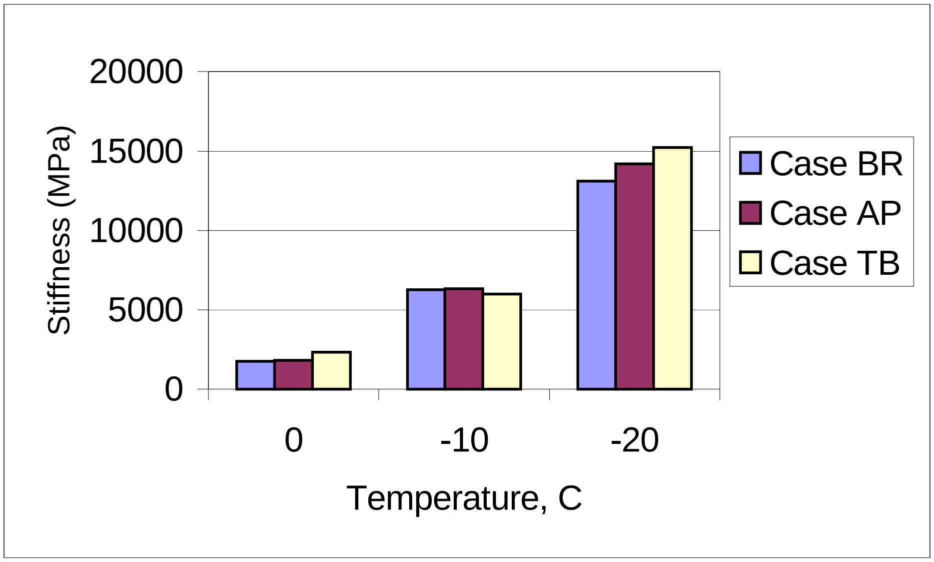

Figure 17. IDT Stiffness for 10% AZ RAP with PG 52-34

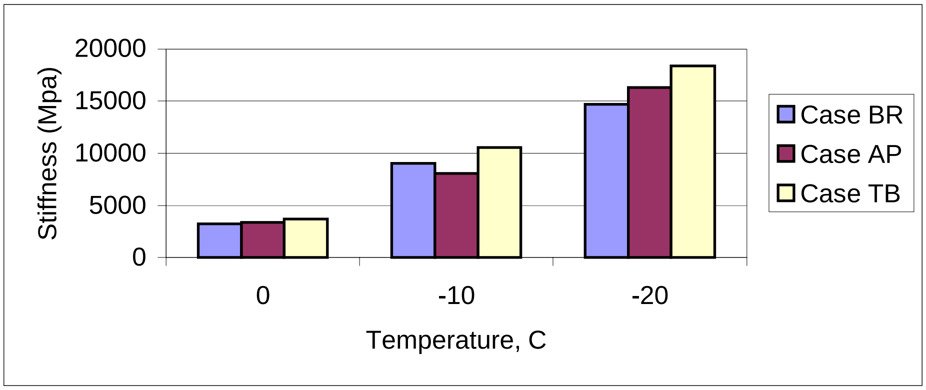

Figure 18. IDT Stiffness for 10% CT RAP with PG 64-22

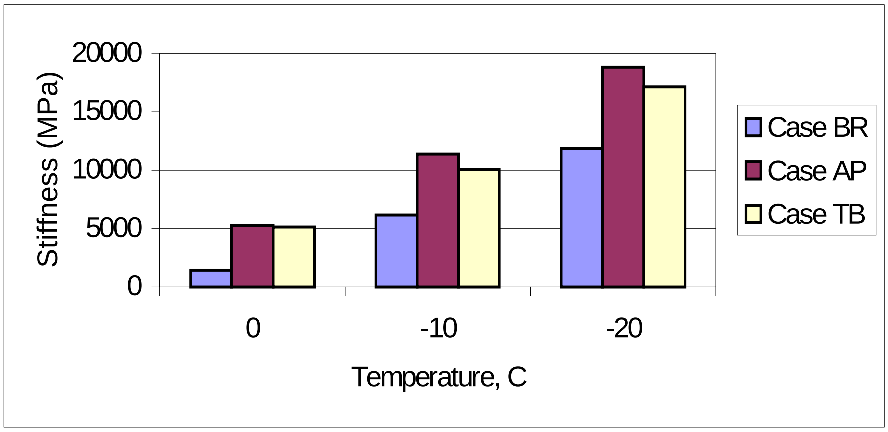

Figure 19. IDT Stiffness for 40% AZ RAP with PG 52-34

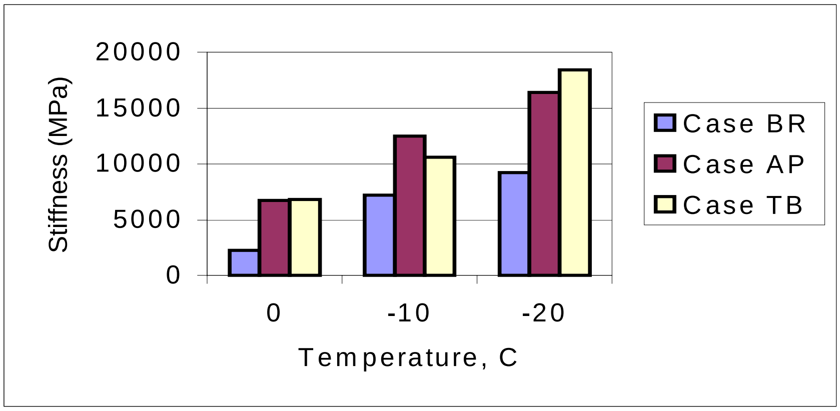

Figure 20. IDT Stiffness for 40% CT RAP with PG 64-22
Note: A = Black Rock, B = Actual Practice, C = Total Blending

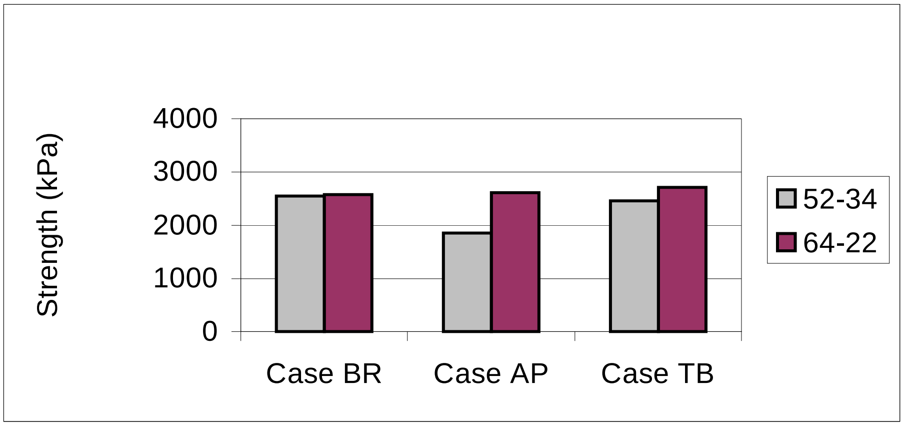

Figure 21. IDT Strength for 10% AZ RAP

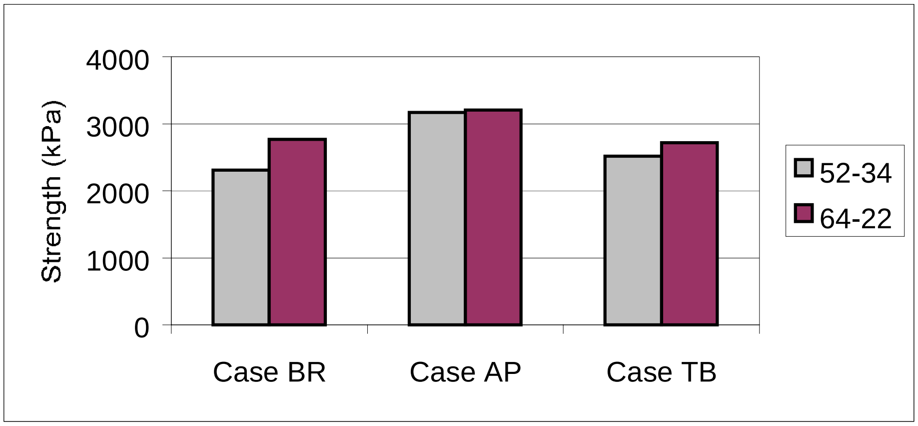

Figure 22. IDT Strength for 40% AZ RAP

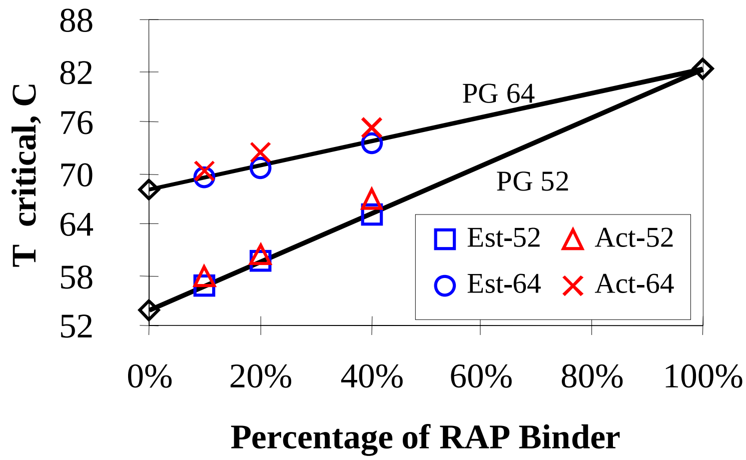

Figure 23. Critical Temperatures of Original DSR – Florida RAP Blends

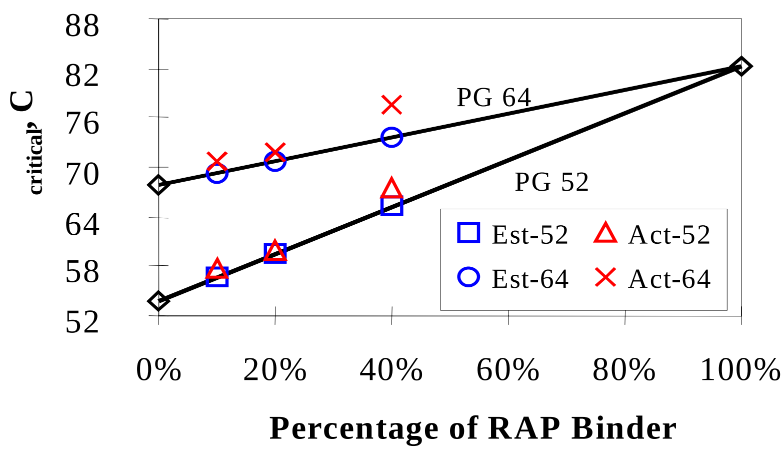

Figure 24. Critical Temperatures of Original DSR – Connecticut RAP Blends

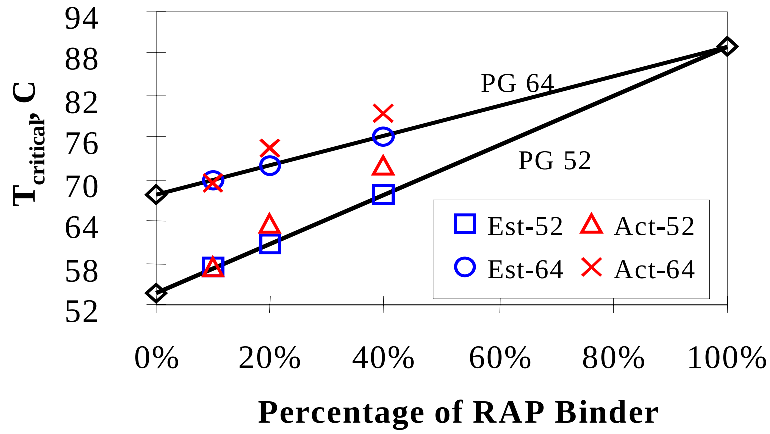

Figure 25. Critical Temperatures of Original DSR – Arizona RAP Blends

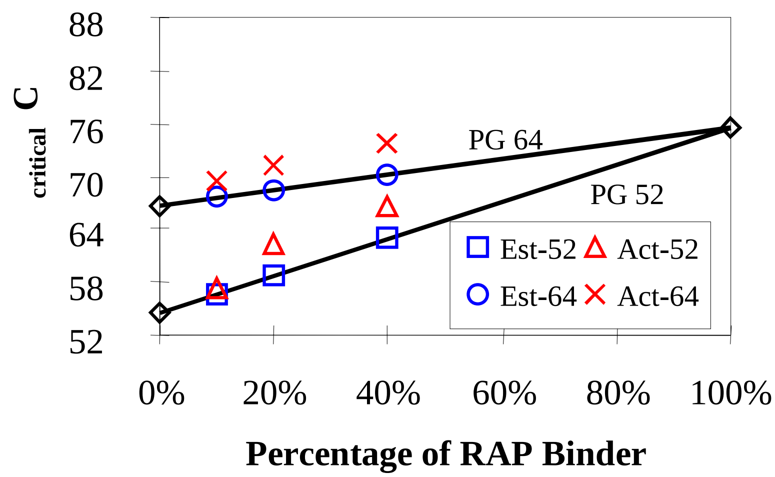

Figure 26. Critical Temperatures of RTFO DSR – Florida RAP Blends

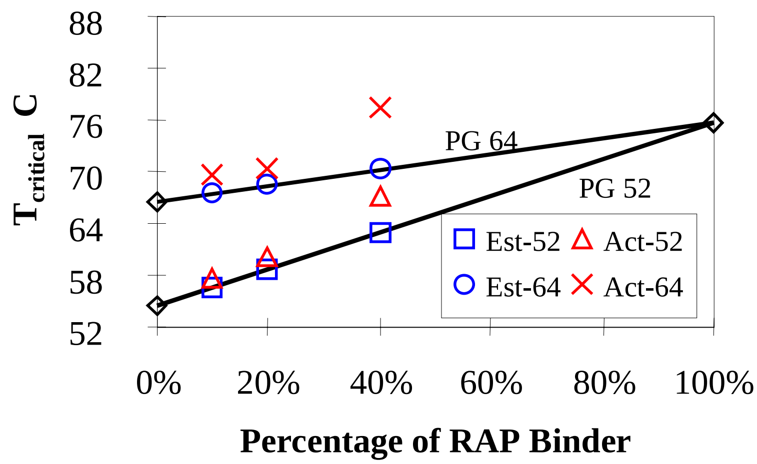

Figure 27. Critical Temperatures of RTFO DSR – Connecticut RAP Blends

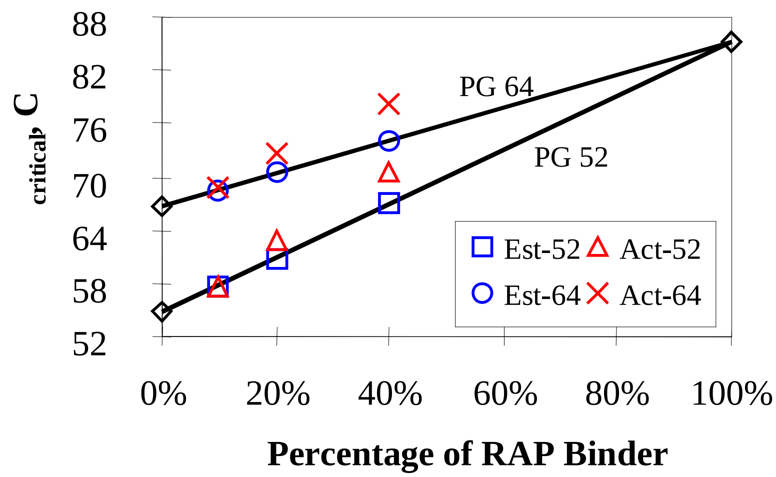

Figure 28. Critical Temperatures of RTFO DSR – Arizona RAP Blends

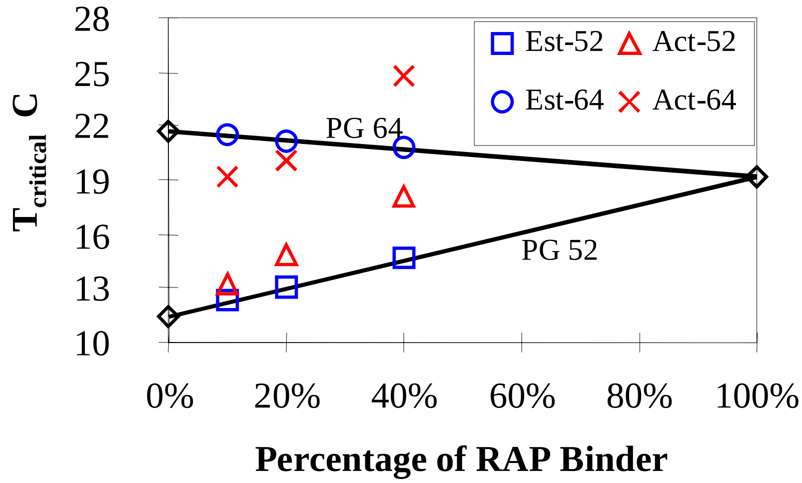

Figure 29. Critical Temperatures of PAV DSR – Florida RAP Blends

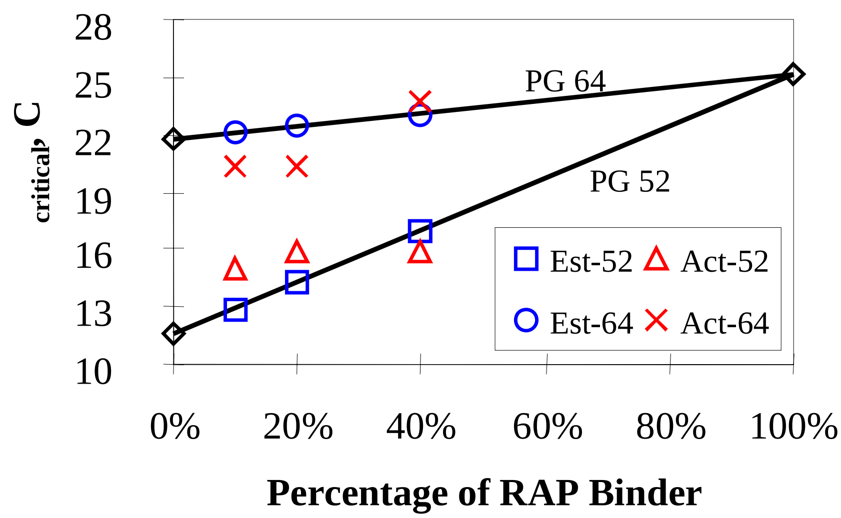

Figure 30. Critical Temperatures of PAV DSR – Connecticut RAP Blends

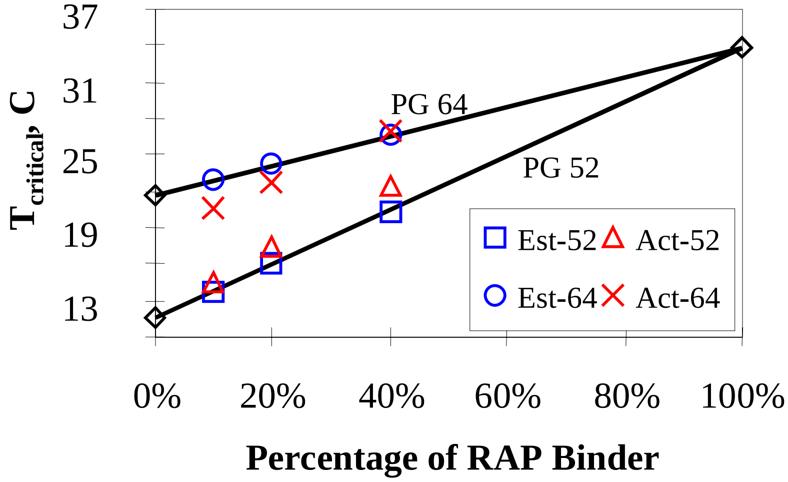

Figure 31. Critical Temperatures of PAV DSR – Arizona RAP Blends

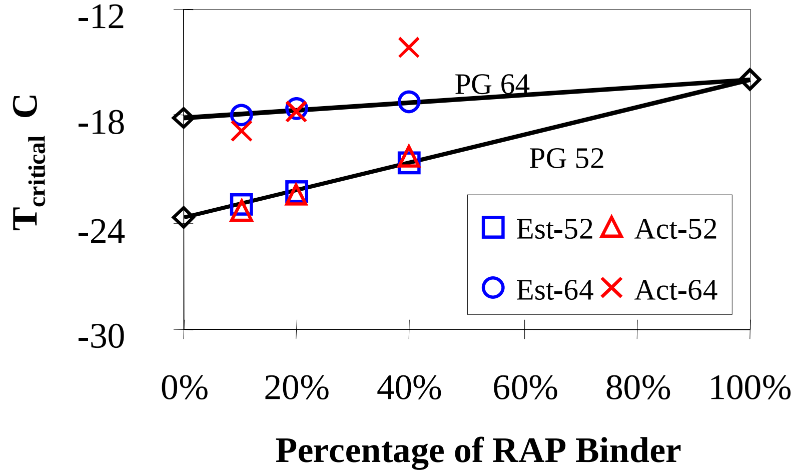

Figure 32. Critical Temperatures of BBR Stiffness – Florida RAP Blends

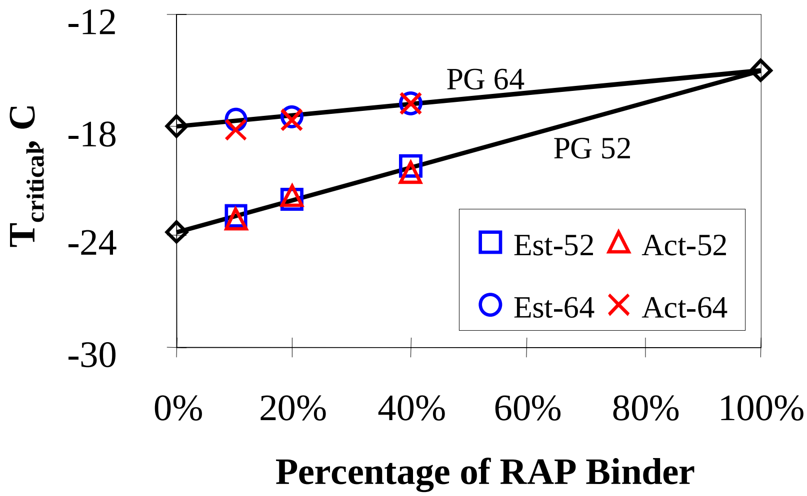

Figure 33. Critical Temperatures of BBR Stiffness – Connecticut RAP Blends

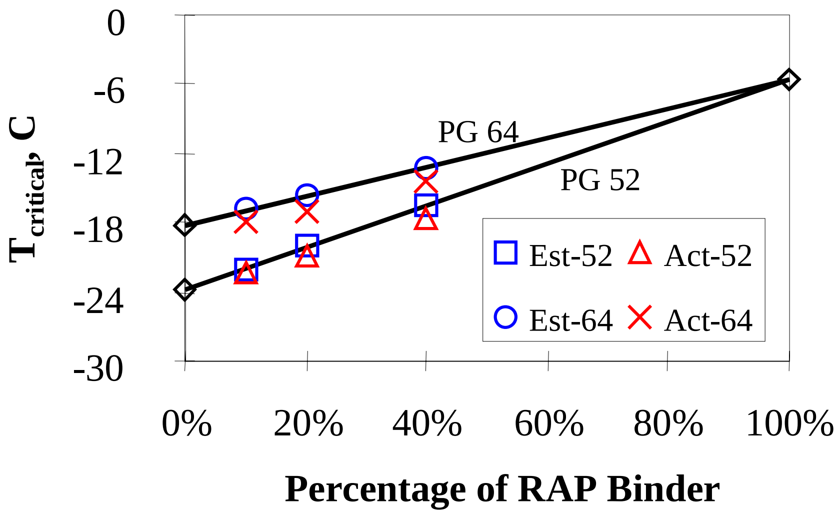

Figure 34. Critical Temperatures of BBR Stiffness – Arizona RAP Blends

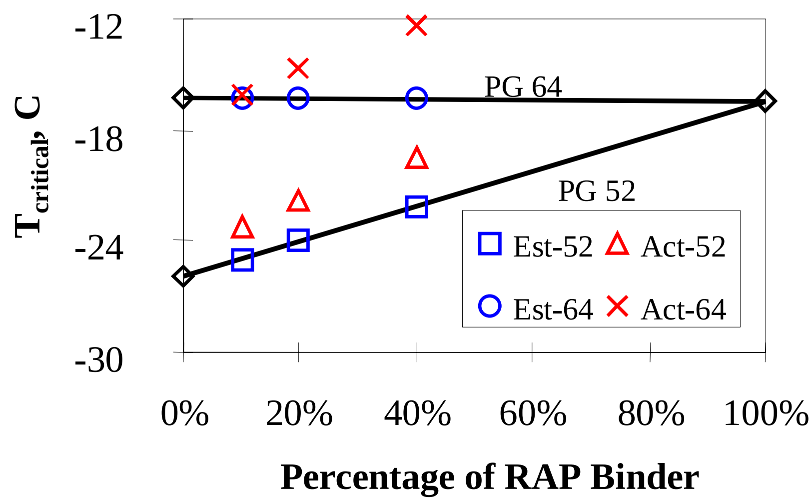

Figure 35. Critical Temperatures of BBR m-value – Florida RAP Blends

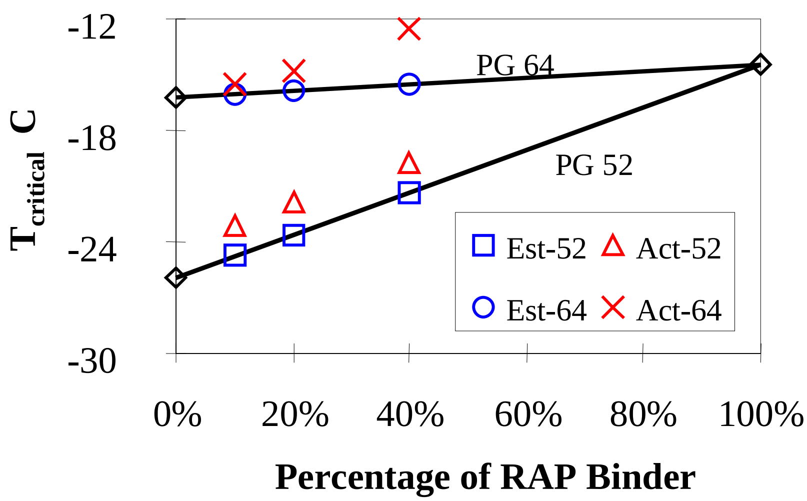

Figure 36. Critical Temperatures of BBR m-value – Connecticut RAP Blends

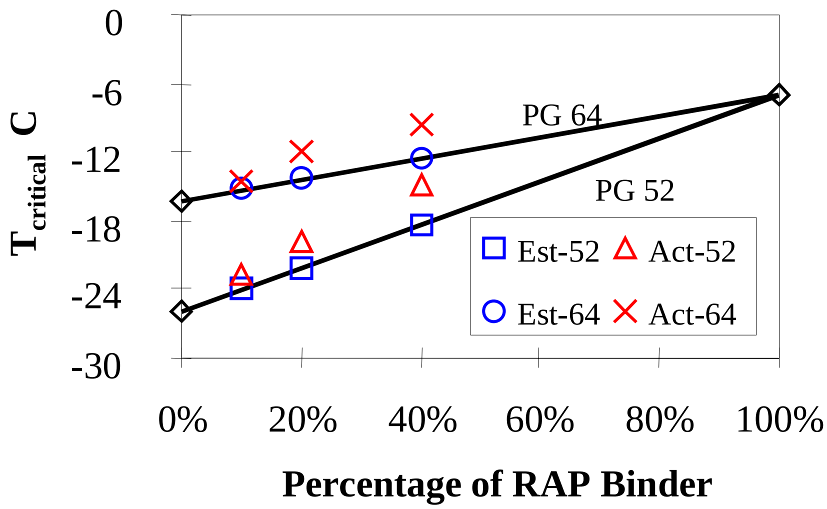

Figure 37. Critical Temperatures of BBR m-value – Arizona RAP Blends

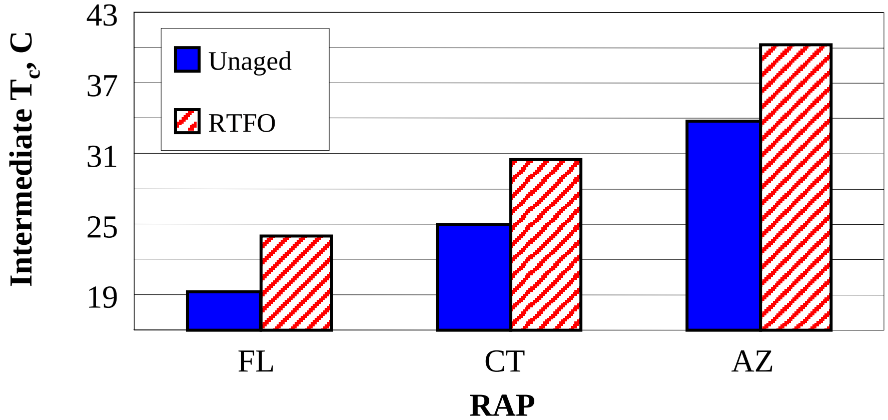

Figure 38. Comparison of Critical Intermediate Temperatures for Recovered RAP Binders after RTFO

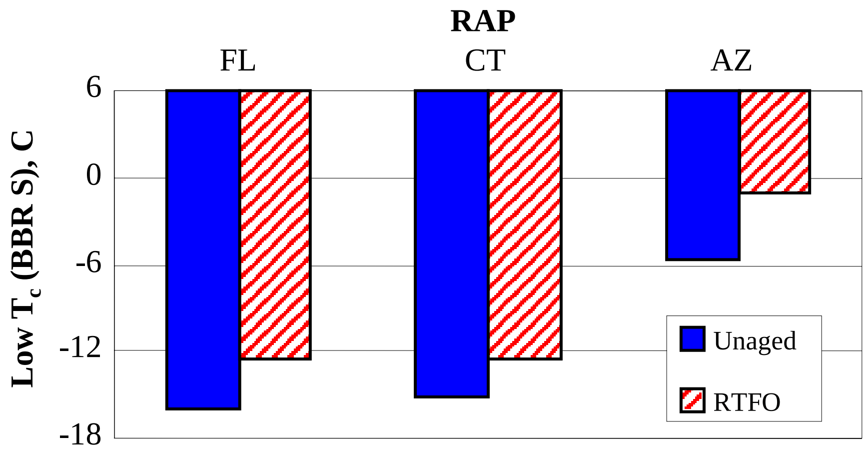

Figure 39. Comparison of Critical Low Temperatures (Stiffness) for Recovered RAP Binders after RTFO

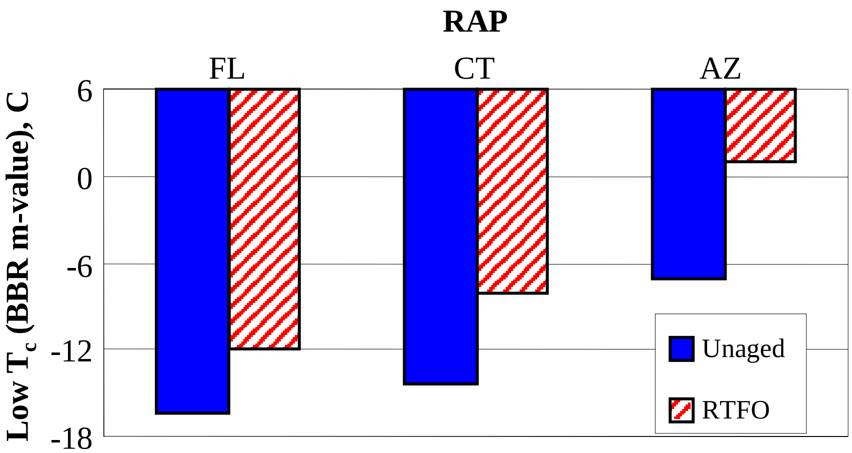

Figure 40. Comparison of Critical Low Temperatures (m-value) for Recovered RAP Binders after RTFO

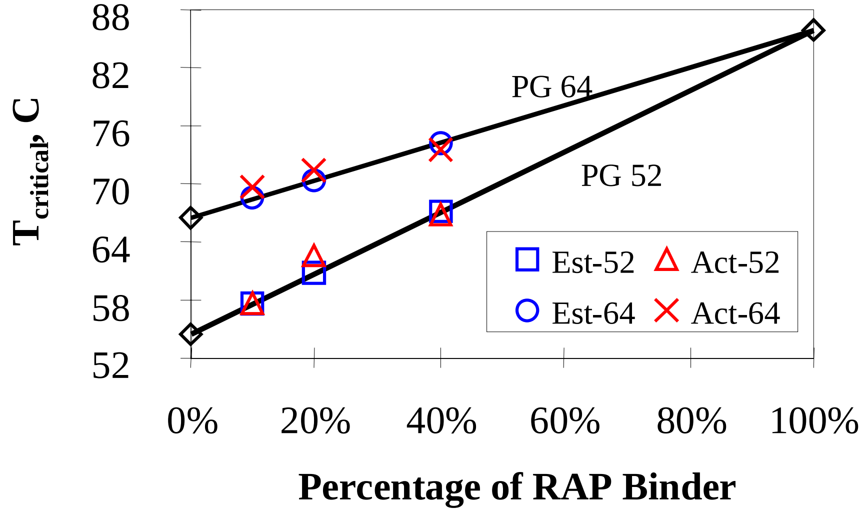

Figure 41. Critical Temperatures of RTFO DSR – Florida RAP Blends with RTFO

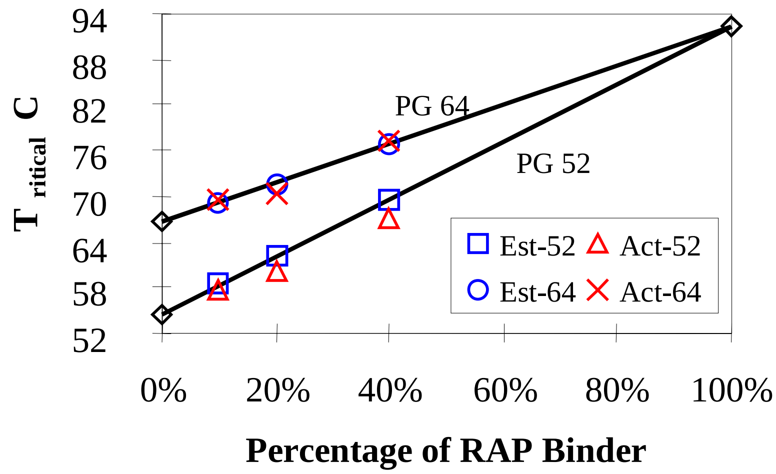

Figure 42. Critical Temperatures of RTFO DSR – Connecticut RAP Blends with RTFO

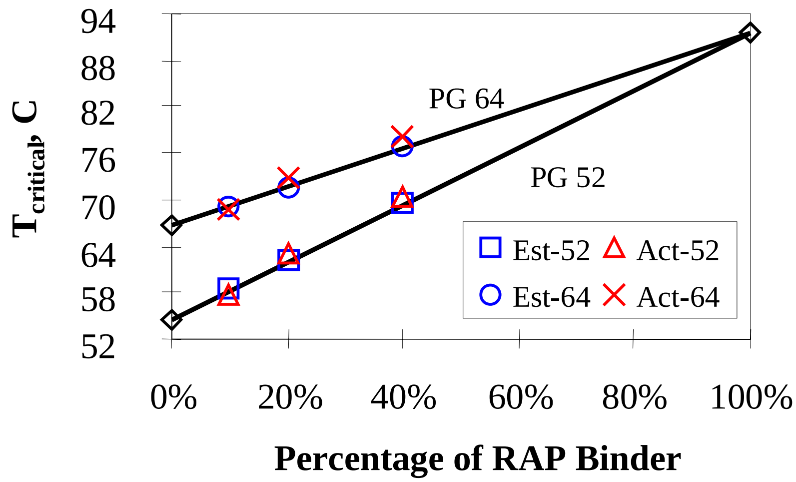

Figure 43. Critical Temperatures of RTFO DSR – Arizona RAP Blends with RTFO

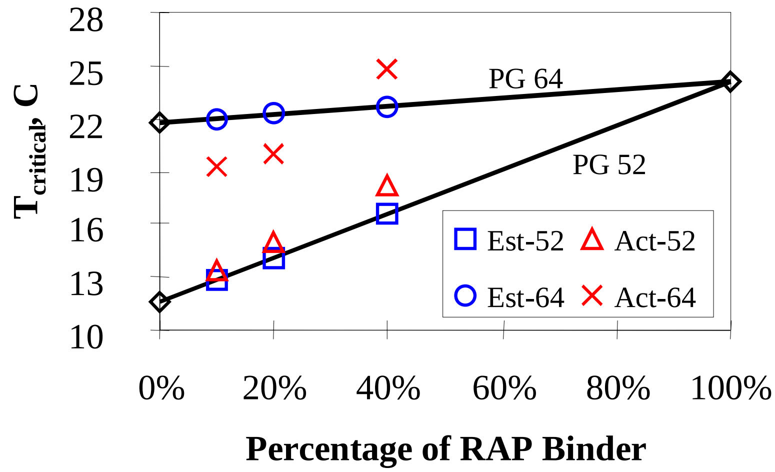

Figure 44. Critical Temperatures of PAV DSR – Florida RAP Blends with RTFO

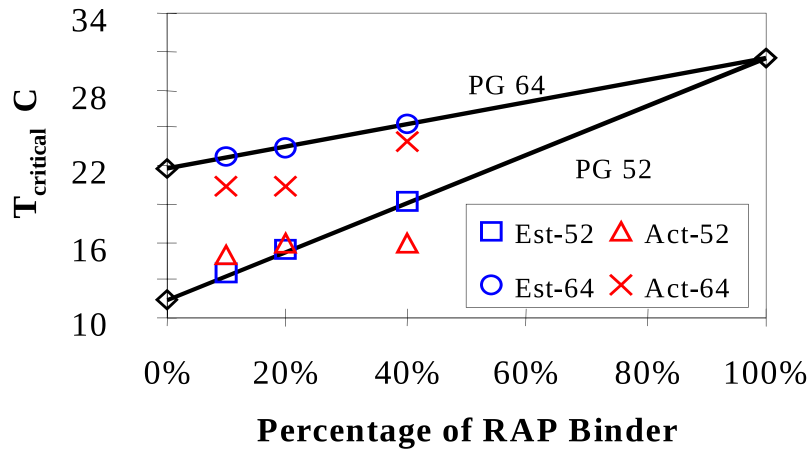

Figure 45. Critical Temperatures of PAV DSR – Connecticut RAP Blends with RTFO

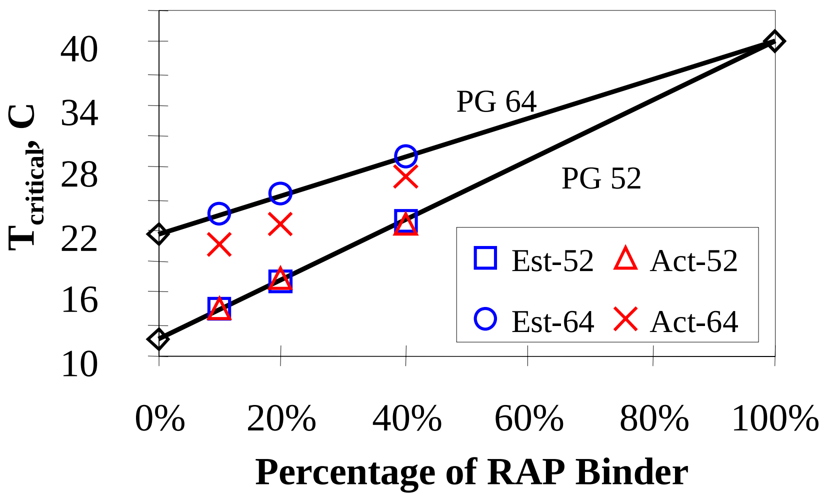

Figure 46. Critical Temperatures of PAV DSR – Arizona RAP Blends with RTFO

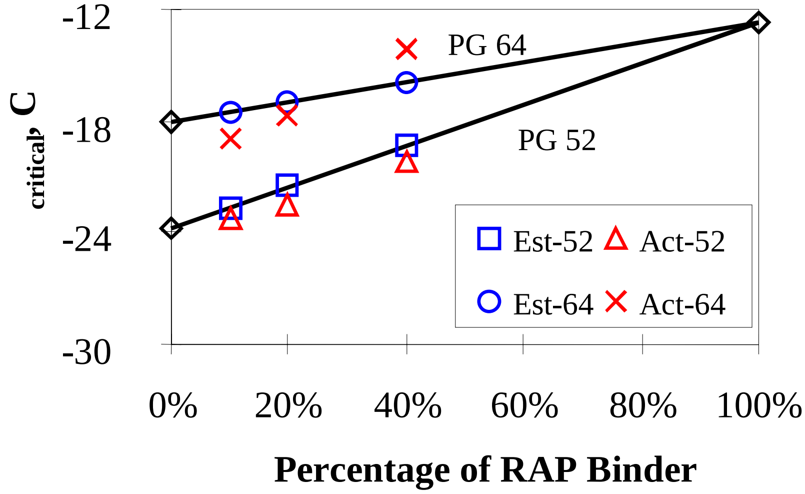

Figure 47. Critical Temperatures of BBR Stiffness – Florida RAP Blends with RTFO

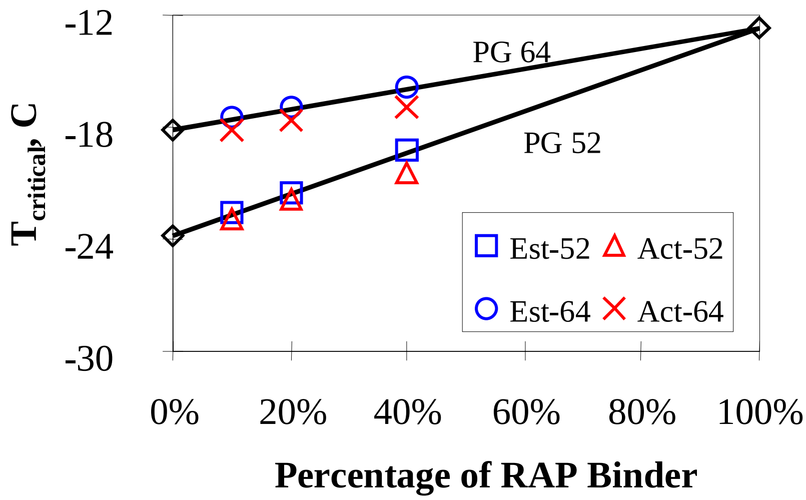

Figure 48. Critical Temperatures of BBR Stiffness – Connecticut RAP Blends with RTFO

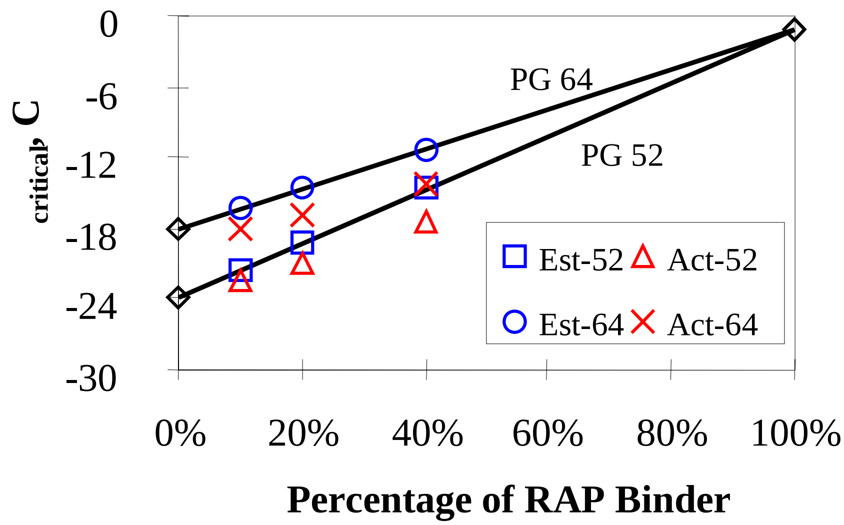

Figure 49. Critical Temperatures of BBR Stiffness – Arizona RAP Blends with RTFO

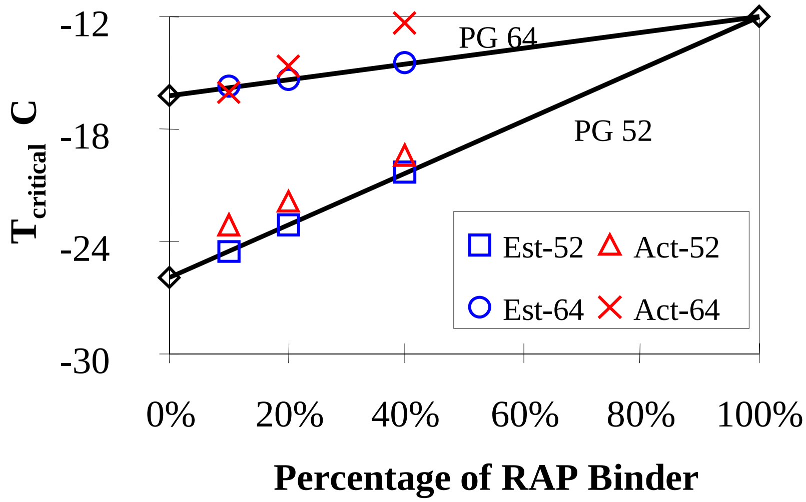

Figure 50. Critical Temperatures of BBR m-value – Florida RAP Blends with RTFO

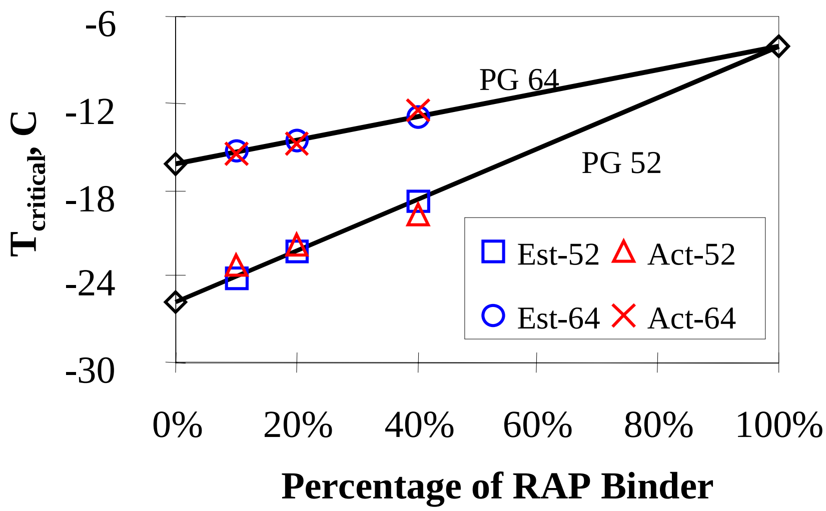

Figure 51. Critical Temperatures of BBR m-value – Connecticut RAP Blends with RTFO

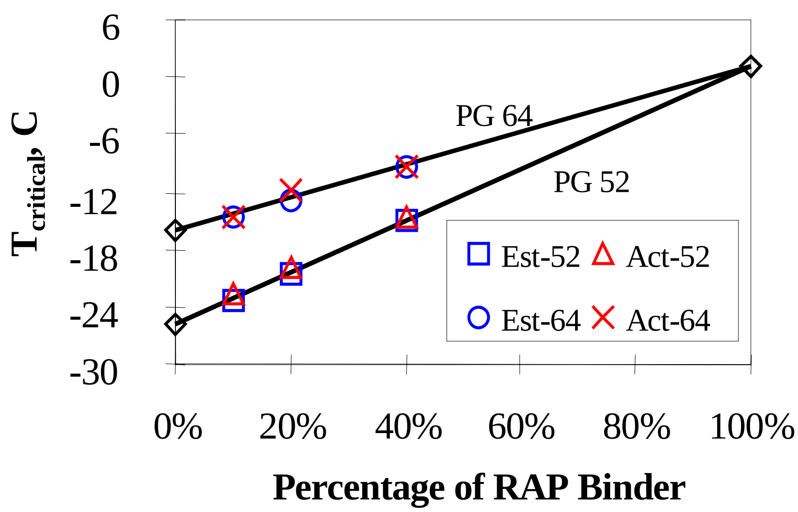

Figure 52. Critical Temperatures of BBR m-value – Arizona RAP Blends with RTFO

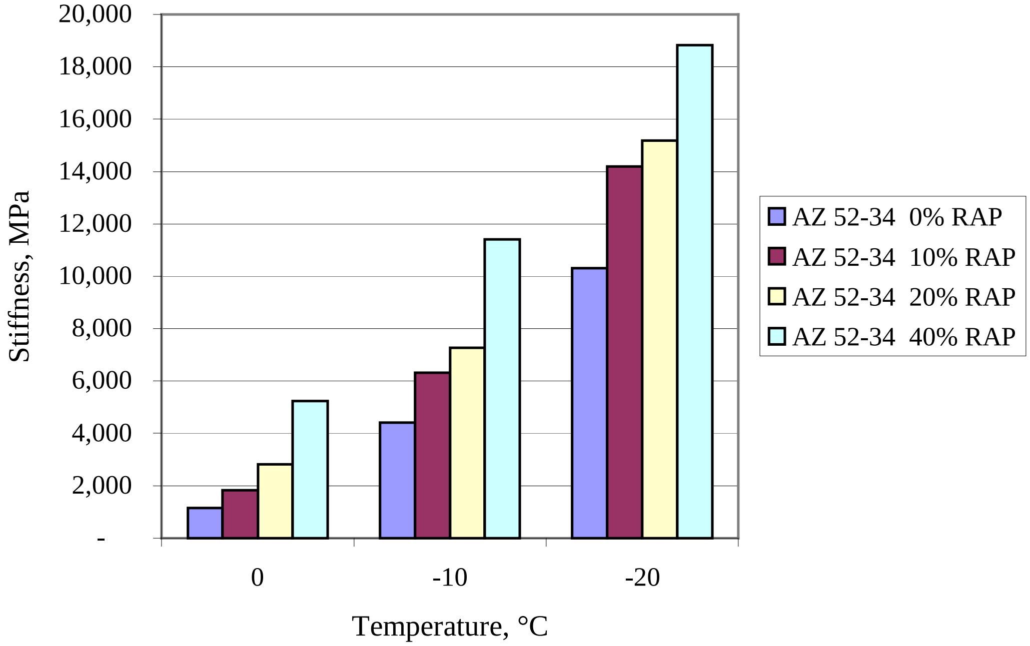

Figure 53. IDT Stiffness at 60 sec., Arizona RAP with PG 52-34

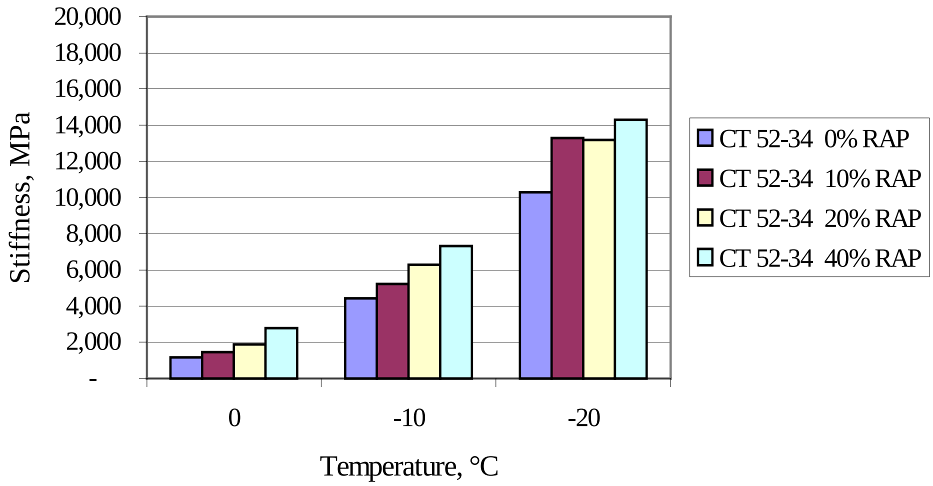

Figure 54. IDT Stiffness at 60 sec., Connecticut RAP with PG 52-34

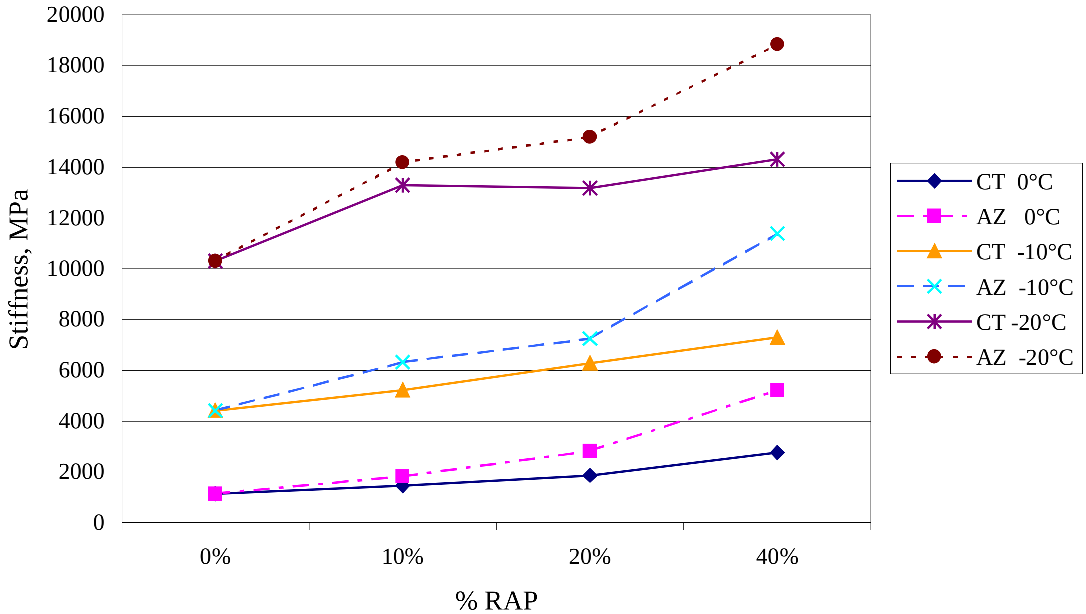

Figure 55. Comparison of IDT Stiffness for Arizona and Connecticut RAP with PG 52-34

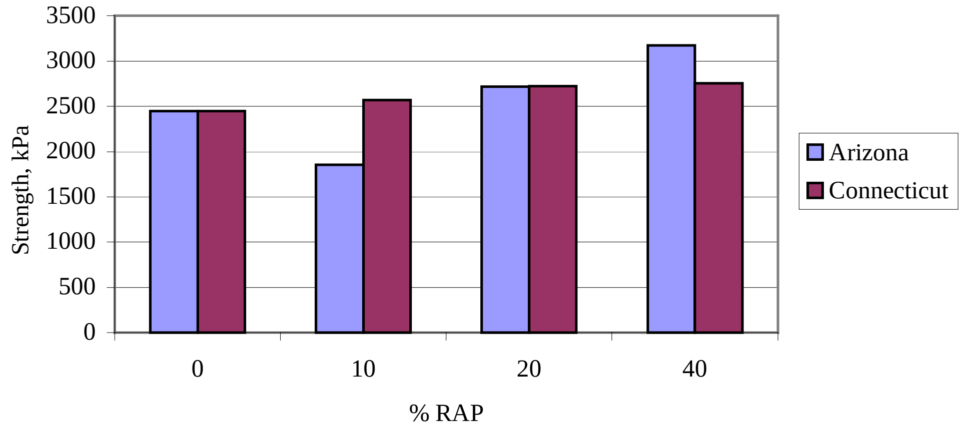

Figure 56. PG 52-34 IDT Strengths

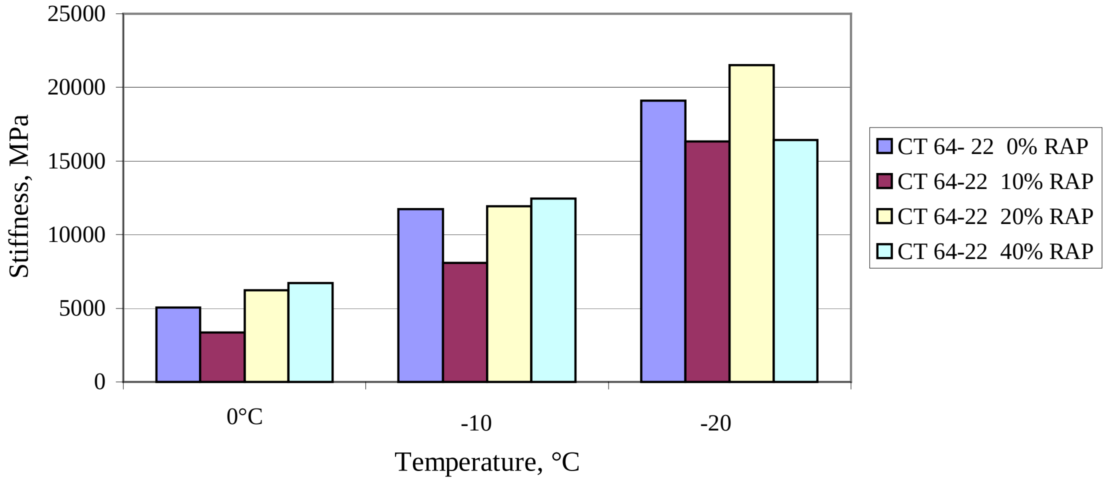

Figure 57. Connecticut RAP with PG 64-22, Stiffness

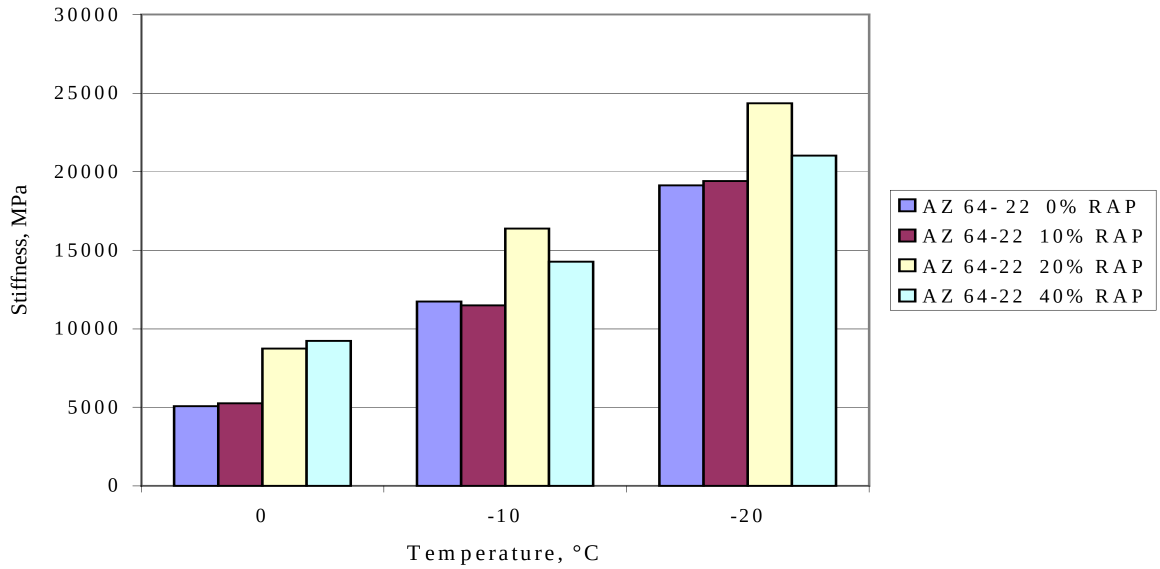

Figure 58. IDT Stiffness, MPa, PG 64-22 blends with Arizona RAP

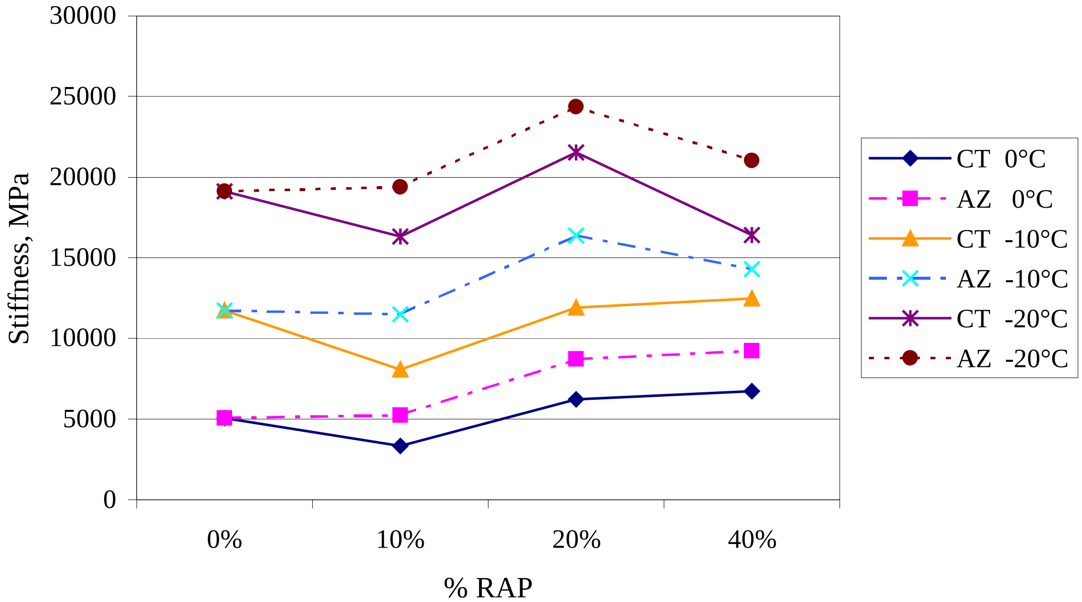

Figure 59. Comparison of IDT Stiffness for Arizona and Connecticut RAP with PG 64-22

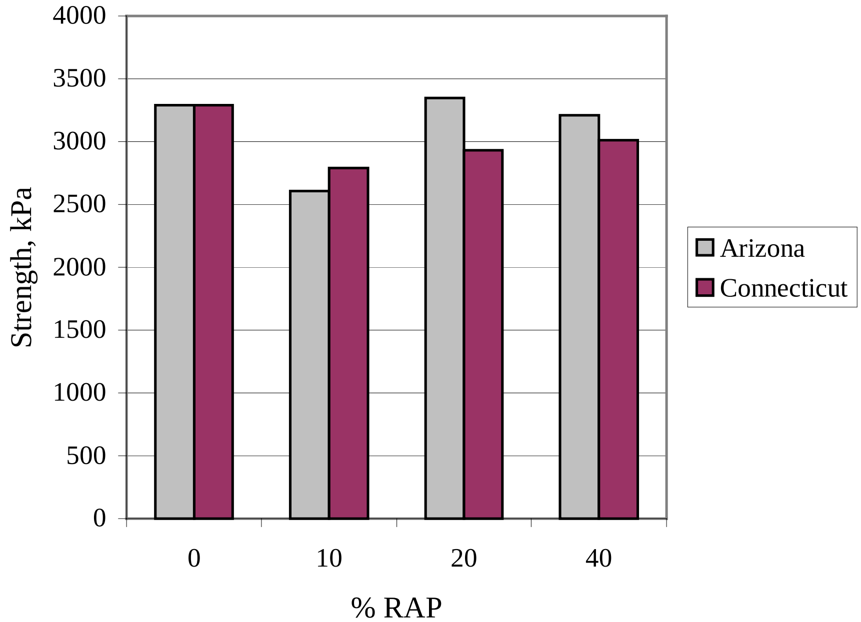

Figure 60. PG 64-22 IDT Strengths @ -10°C

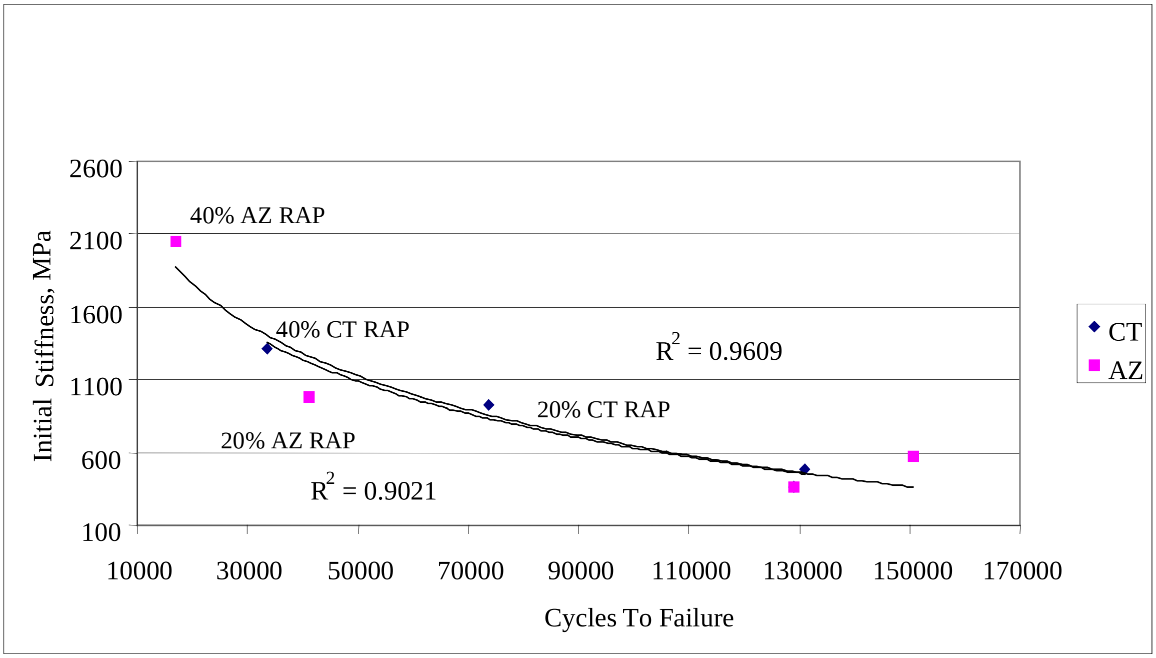

Figure 61. Beam Fatigue, Cycles vs. Stiffness High Strain, PG 52-34

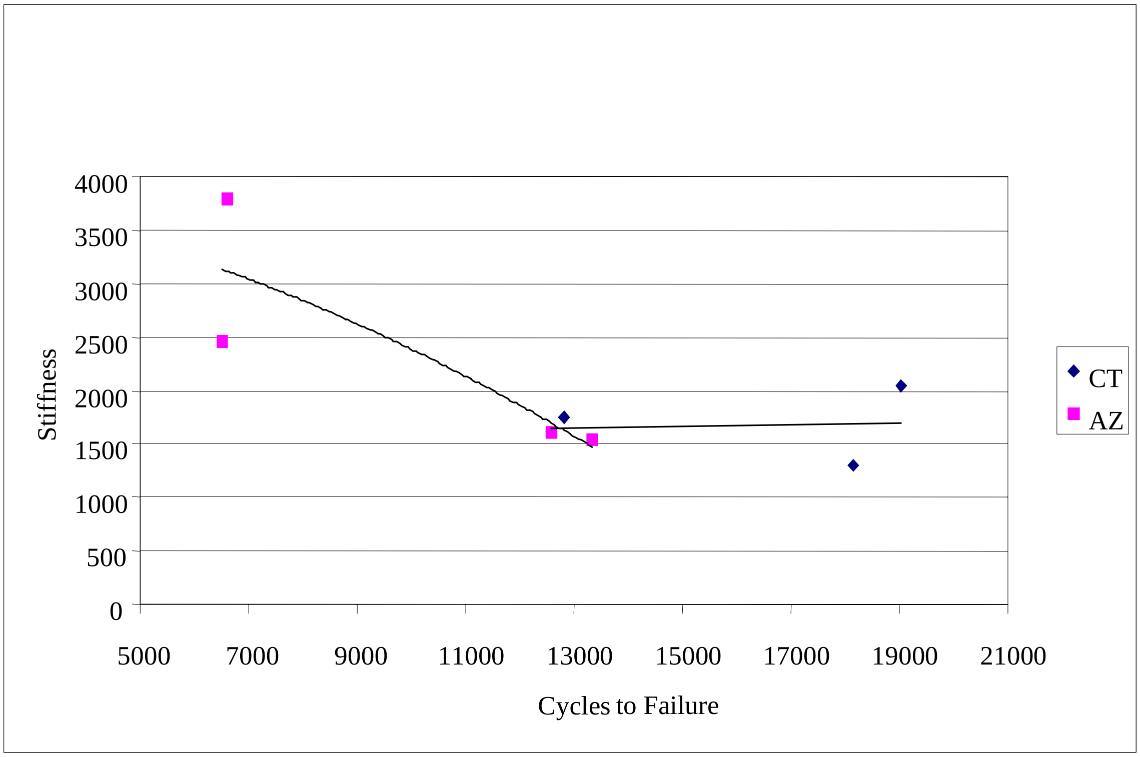

Figure 62. Beam Fatigue, Cycles vs. Stiffness High Strain, PG 64-22

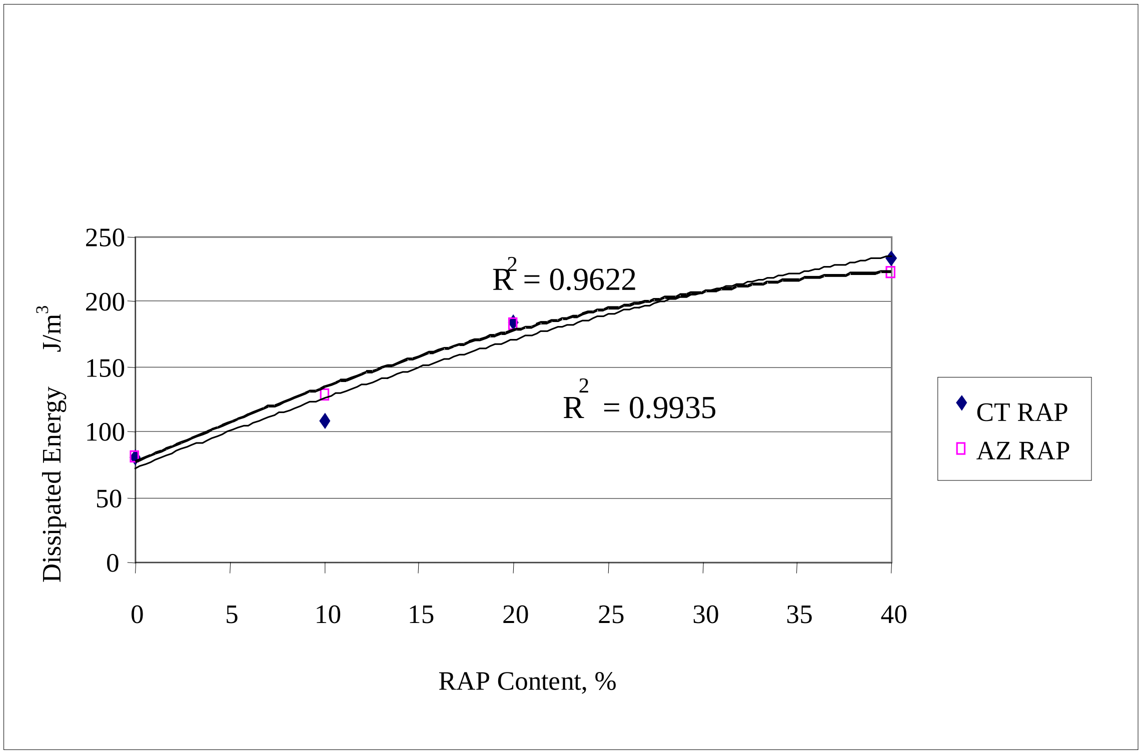

Figure 63. %RAP vs. Dissipated Energy, Beam Fatigue, High Strain, PG 52-34

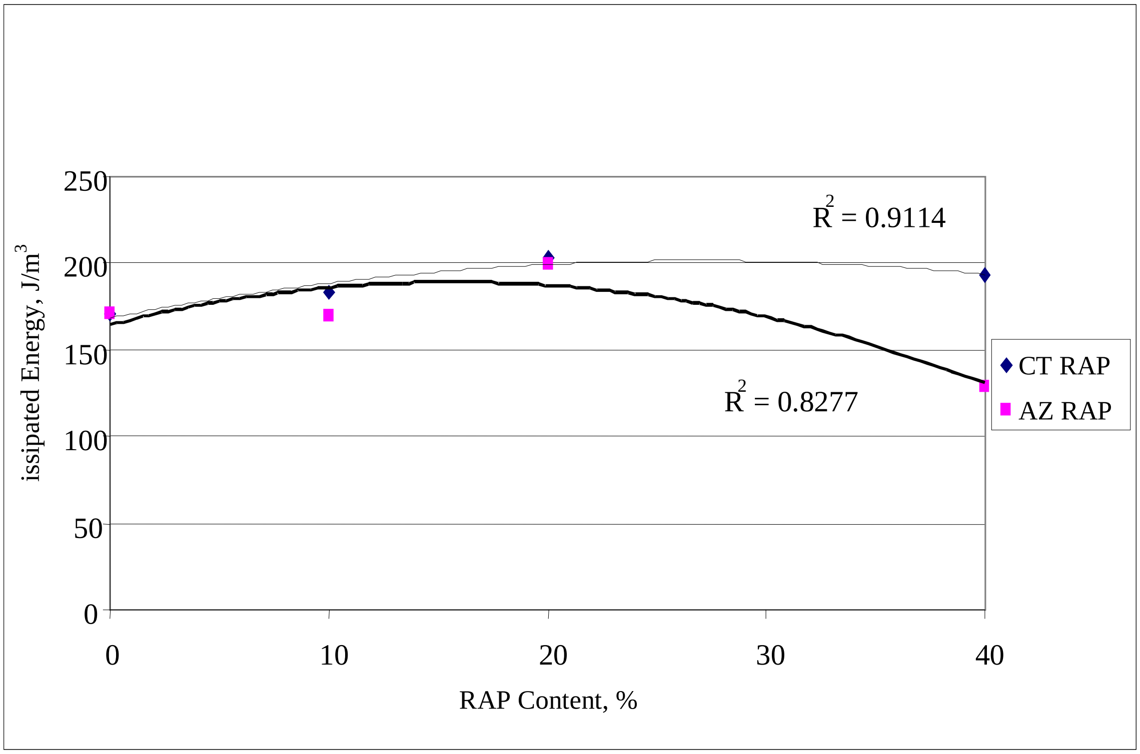

Figure 64. %RAP vs. Dissipated Energy, Beam Fatigue, High Strain, PG 64-22

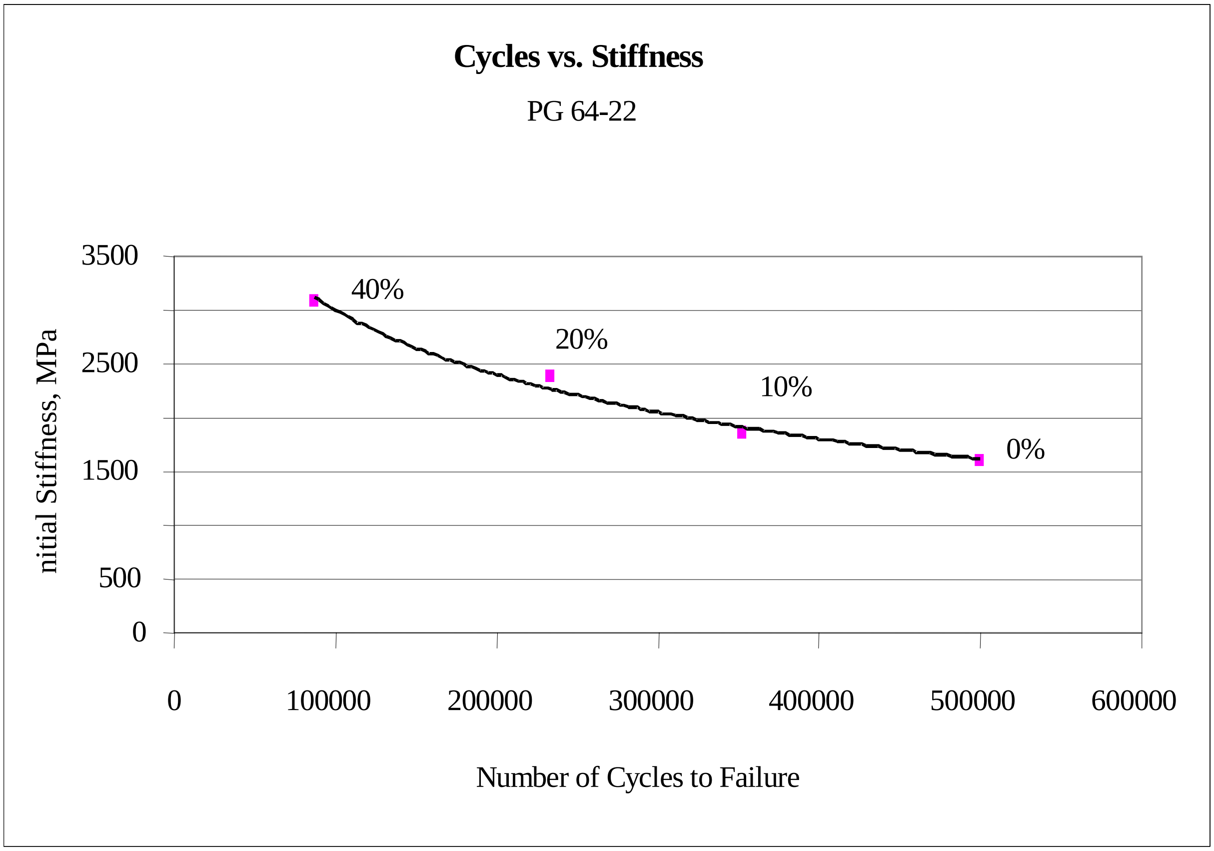

Figure 65. Beam Fatigue Cycles to Failure vs. Stiffness, PG 64-22, Low Strain

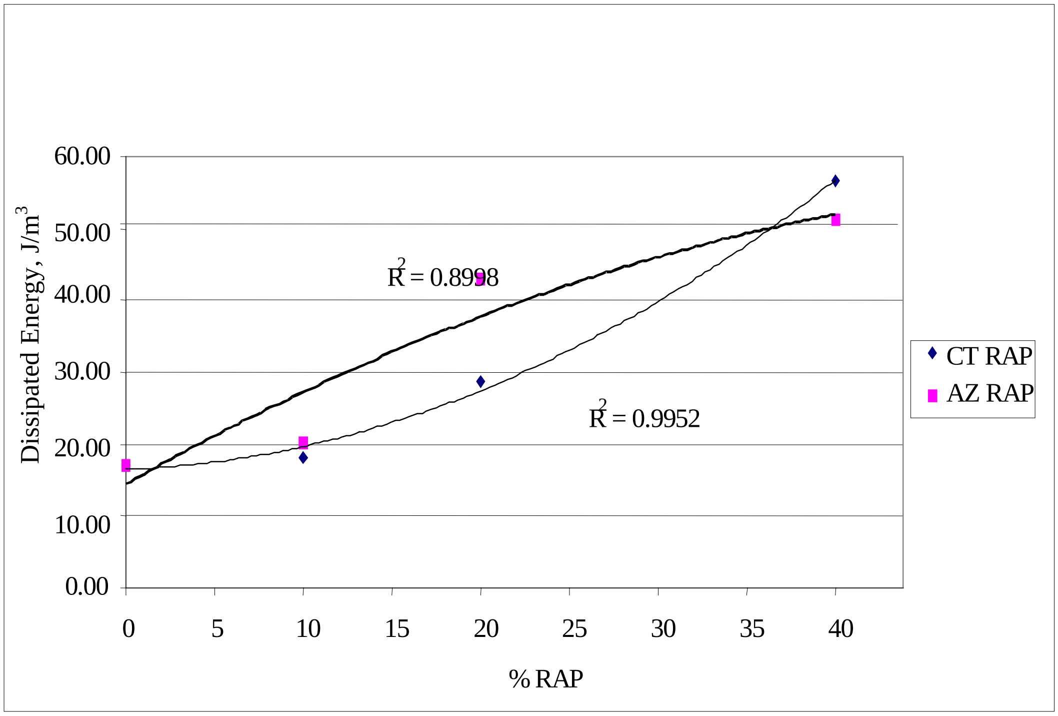

Figure 66. %RAP vs. Dissipated Energy, Beam Fatigue, Low Strain, PG 52-34

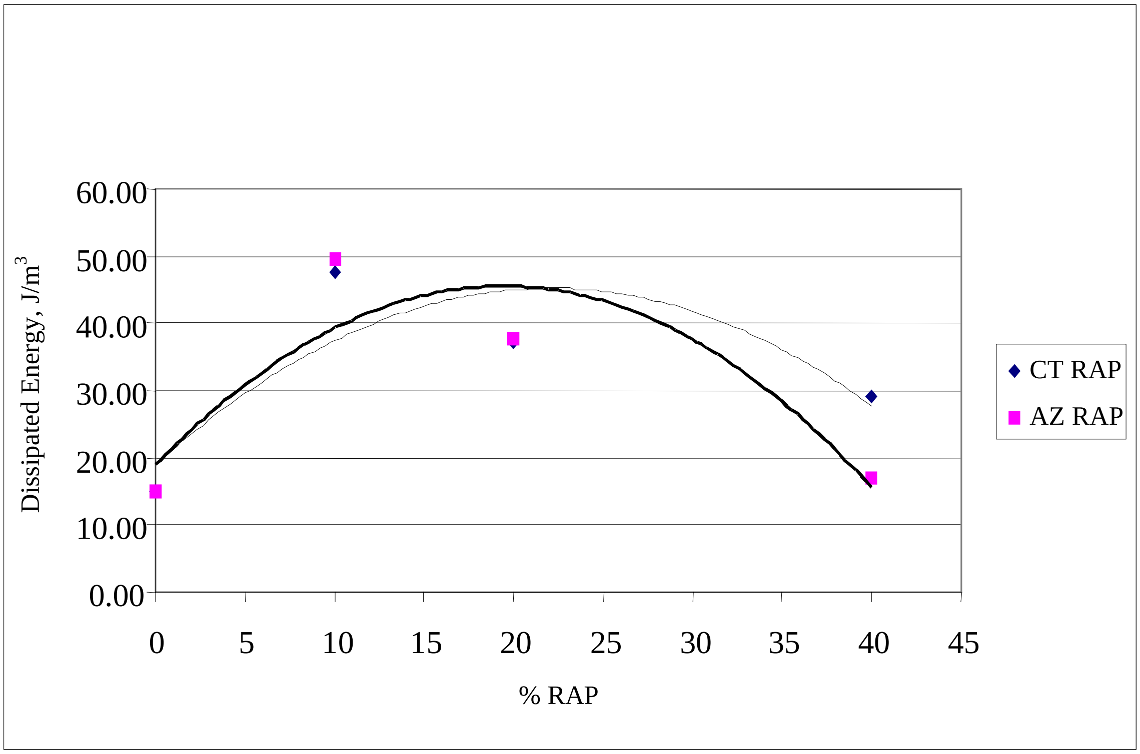

Figure 67. %RAP vs. Dissipated Energy, Beam Fatigue, Low Strain, PG 64-22

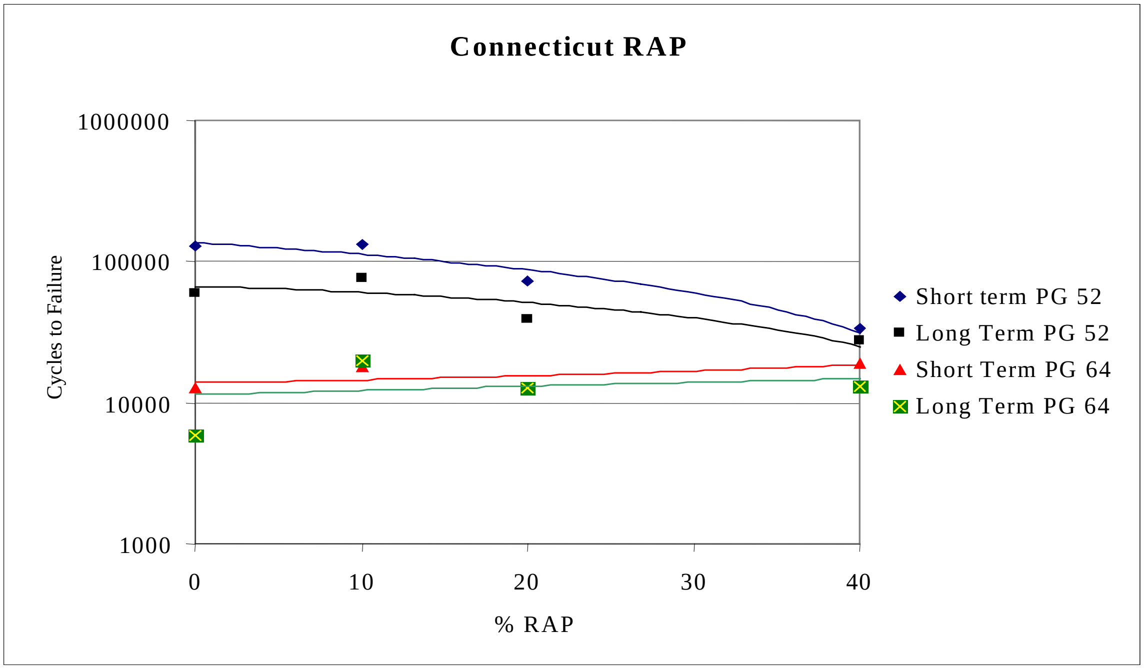

Figure 68. LTOA and STOA %RAP vs. Cycles to Failure in Beam Fatigue

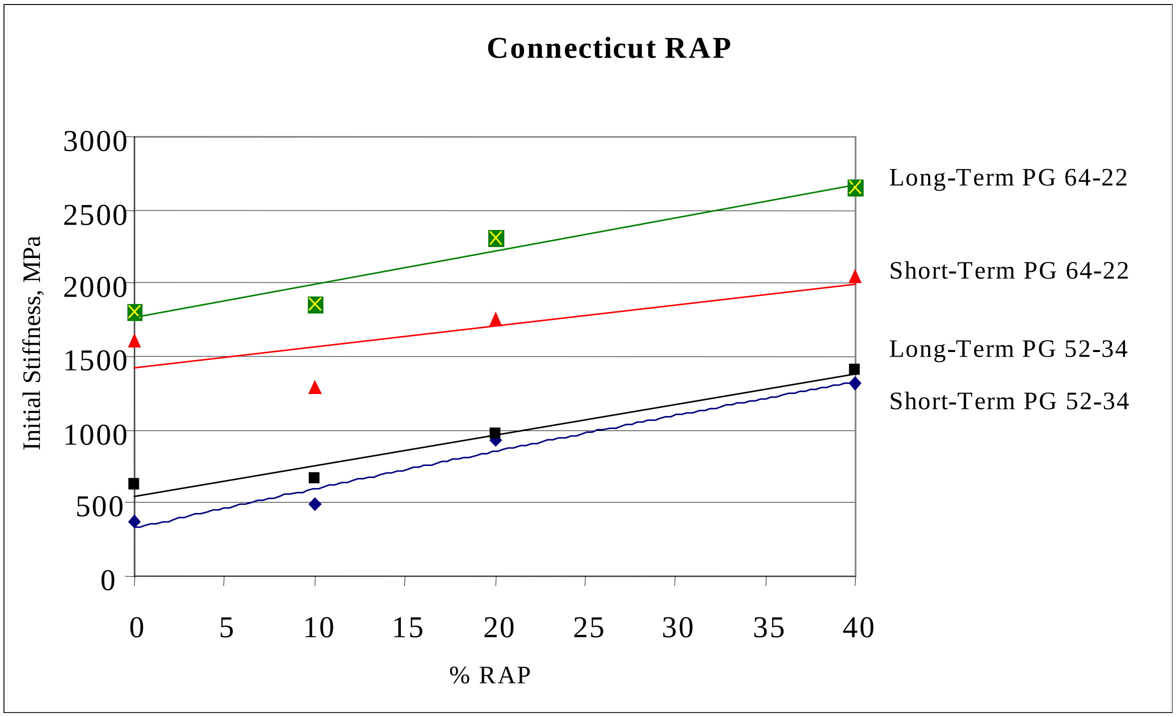

Figure 69. LTOA and STOA %RAP vs. Beam Fatigue Stiffness

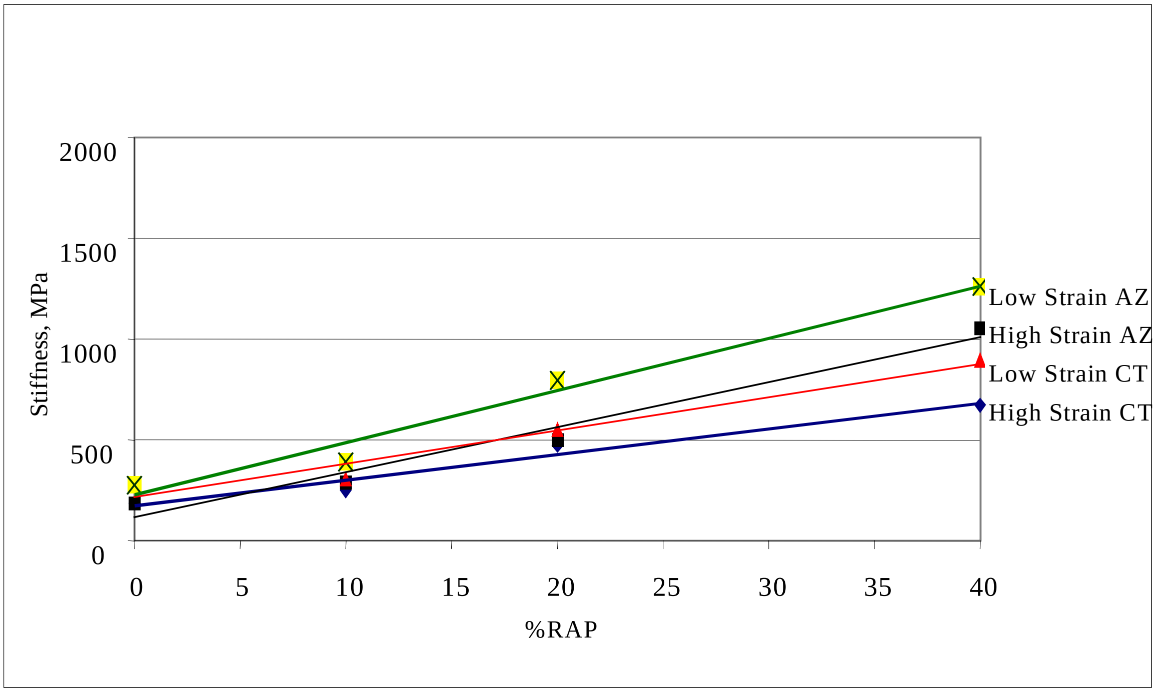

Figure 70. Comparison of High and Low Strain %RAP vs. Stiffness PG 52-34

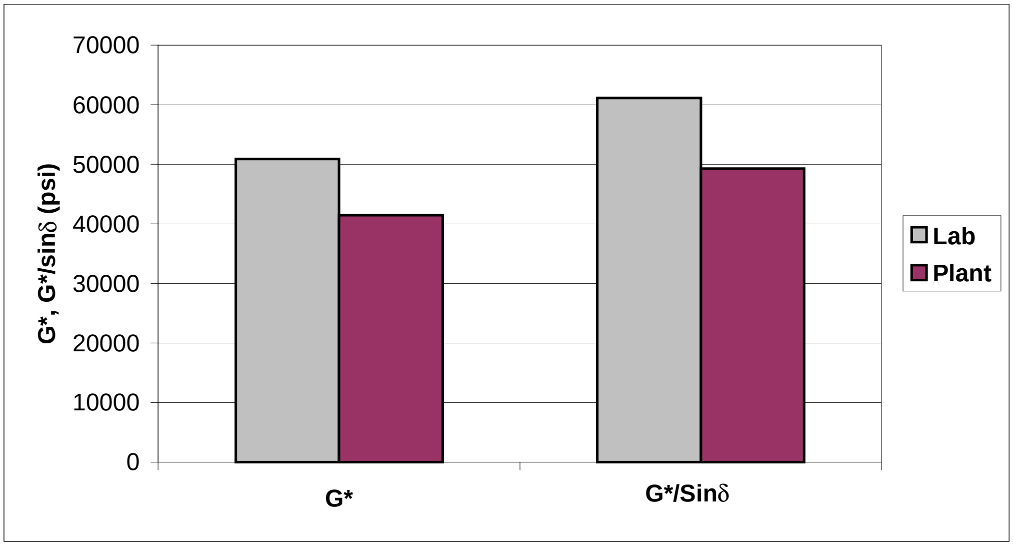

Figure 71. Frequency Sweep (FS) Results for Lab vs. Plant Mixtures (40°C, 10 Hz)

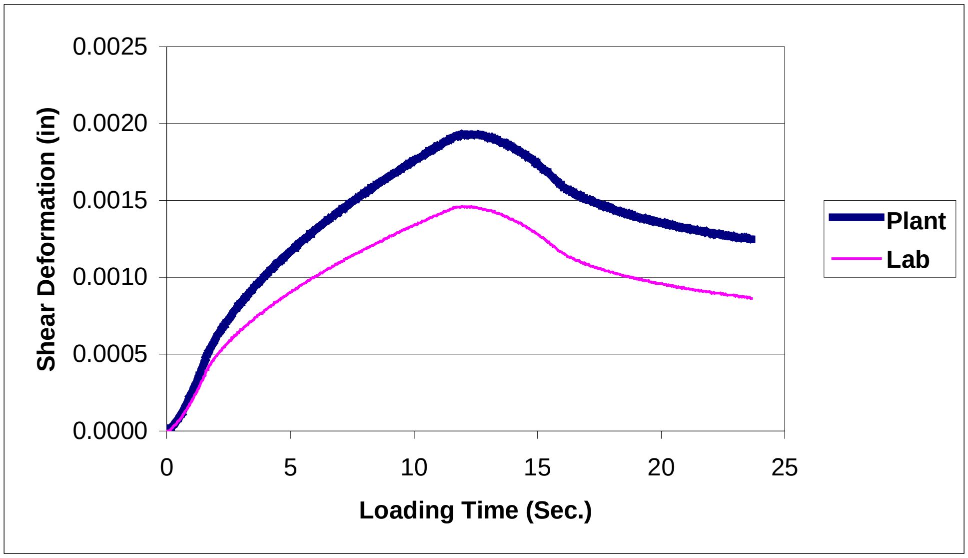

Figure 72. Average Simple Shear (SS) Results for Lab vs. Plant Mixtures (20°C)

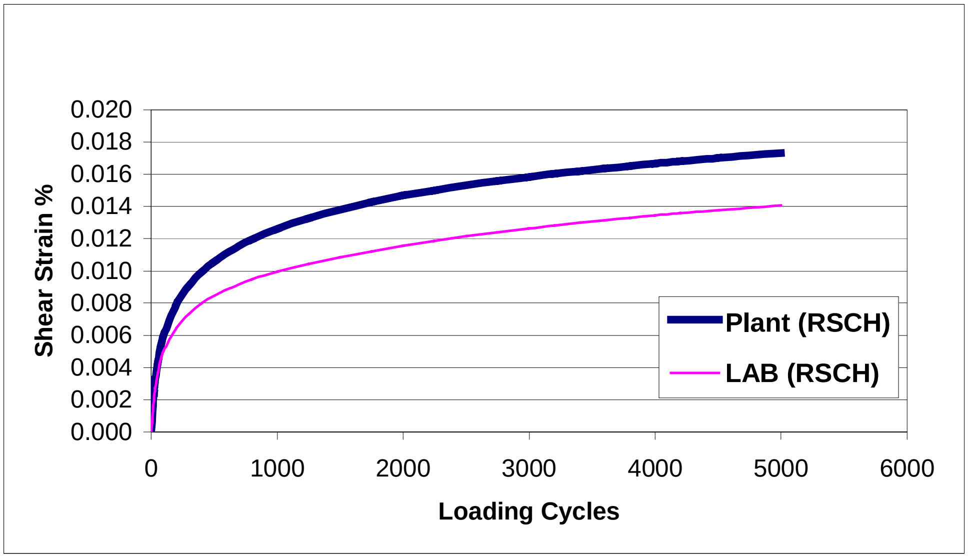

Figure 73. Average Repeated Shear (RSCH) Results for Lab vs. Plant Mixtures (58°C)

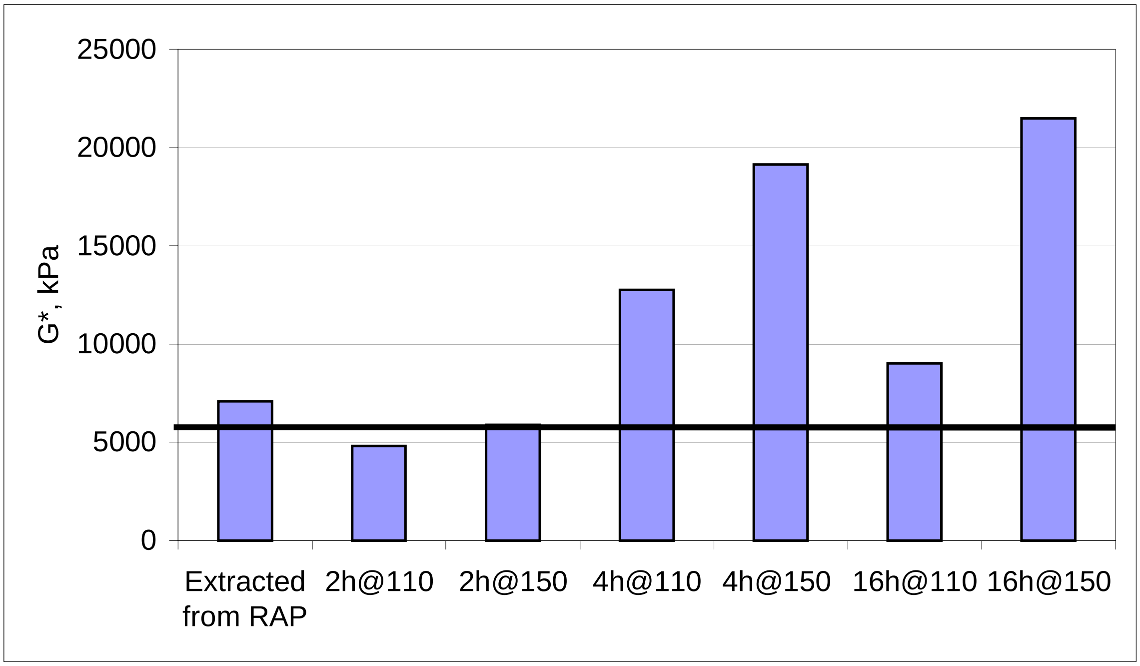

Figure 74. Florida RAP G* vs. Treatment (Tested at 22°C)

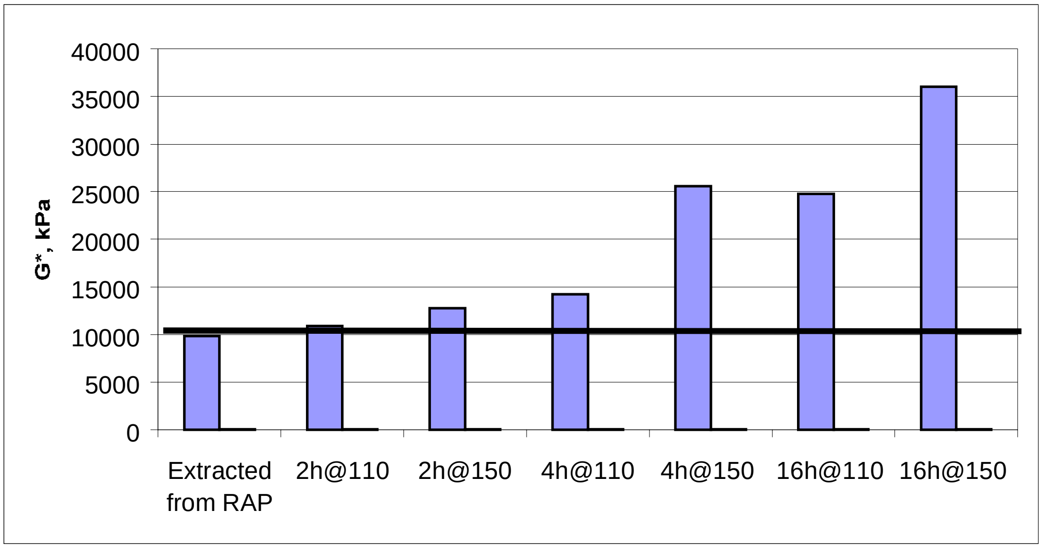

Figure 75. Arizona RAP G* vs. Treatment (Tested at 31°C)

Table 14. Tolerances Recommended in NCHRP 9-7

Property	Tolerance
Component Analysis	
%Asphalt Content: Solvent Extraction Nuclear Asphalt Content Gauge Ignition Oven	 ± 0.25 ± 0.18 ± 0.13
Gradation (% Passing):	
≥ 4.36 mm	± 3
2.36 mm – 0.15 mm	± 2
0.075 mm	± 0.7
G_{mm}	± 0.015
Volumetric Analysis	
%Air Voids @ N_{design}	± 1
%VMA @ N_{design}	± 1
%VFA @ N_{design}	± 5
G_{mb} @ N_{design}	± 0.022

Table 15. Asphalt Content Determinations

Extraction	Centrifuge	Centrifuge	SHRP	SHRP	SHRP
Recovery	Abson	Rotavapor	Rotavapor	Rotavapor	Rotovapor
Solvent	TCE	Tol/Eth	Tol/Eth	TCE	Alt
KY 1	5.09%	4.47%	4.93%	4.95%	4.85%
KY 2	5.13%	4.75%	4.62%	4.85%	4.85%
KY 3	5.06%	4.68%	4.61%	---	4.89%
KY Average	***5.09%***	***4.63%***	***4.72%***	***4.90%***	***4.86%***
KY Std. Dev.	***0.03%***	***0.14%***	***0.18%***	***0.07%***	***0.02%***
FL 1	5.53%	5.57%	5.30%	---	5.01%
FL 2	5.67%	5.26%	5.33%	---	5.01%
FL 3	5.59%	5.14%	5.25%	---	5.29%
FL Average	***5.60%***	***5.32%***	***5.29%***	**---**	***5.10%***
FL Std. Dev.	***0.07%***	***0.22%***	***0.04%***	**---**	***0.16%***

Table 16. Extracted RAP Gradation Averages

Extraction	Centr.	Centr.	SHRP	SHRP	Centr.	Centr.	SHRP	SHRP
Recovery	Abson	Rotavap	Rotavap	Rotavap	Abson	Rotavap	Rotavap	Rotavap
Solvent	TCE	Tol/Eth	Tol/Eth	NPB	TCE	Tol/Eth	Tol/Eth	NPB
Sieve,mm	KY	KY	KY	KY	FL	FL	FL	FL
25	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
19	100.0	99.2	99.2	99.1	100.0	100.0	100.0	100.0
12.5	97.2	96.7	97.0	95.1	99.8	99.7	99.6	99.3
9.5	93.7	92.3	93.9	92.5	98.8	98.8	99.2	98.5
4.75	72.4	71.1	73.1	73.1	84.4	84.3	85.1	82.2
2.36	53.8	53.5	54.8	55.4	66.2	66.6	67.9	62.9
1.18	40.9	41.2	42.0	42.7	56.1	56.6	57.9	53.6
0.6	30.1	31.0	31.9	32.1	45.9	46.1	48.0	44.8
0.3	18.8	20.3	21.7	21.1	32.5	32.4	34.9	32.9
0.15	13.1	14.8	16.4	15.6	19.8	19.4	22.7	21.2
0.075	10.6	12.3	14.1	13.4	12.9	12.4	16.0	15.0

Table 17. Average High Temperature Stiffness and Critical Temperature of Extracted RAP Binders

Extraction	Centr.	Centr.	SHRP	SHRP	SHRP	Centr.	Centr.	SHRP	SHRP
Recovery	Abson	Rotavap	Rotavap	Rotovap	Rotavap	Abson	Rotavap	Rotavap	Rotavap
Solvent	TCE	Tol/Eth	Tol/Eth	NPB	TCE	TCE	Tol/Eth	Tol/Eth	NPB
G*/sin δ	KY	KY	KY	KY	KY	FL	FL	FL	FL
64C	6.34	33.16	24.43	26.74	21.47	3.00	9.29	7.33	4.22
COV-64	69%	12%	11%	26.2%	14%	48%	20%	5%	20.6%
70C	2.98	13.84	10.13	11.12	9.02	1.43	3.96	3.18	1.85
COV-70	64%	11%	12%	24.0%	12%	44%	21%	5%	20.1%
76C	1.42	5.81	4.36	4.77	3.92	0.70	1.77	1.44	0.85
COV-76	60%	12%	13%	20.5%	10%	38%	20%	5%	23.0%
T_c	77.8	88.1	86.4	87.0	85.8	72.4	80.2	78.8	74.7
COV-T_c	5.6%	1.0%	1.2%	1.1%	0.5%	4.7%	1.8%	0.4%	2.3%

Table 18. Linearity of One Sample of Kentucky RAP (KY3) (Centrifuge-Rotovapor-Tol/Eth)

Strain, %	G*, kPa
2	2.62
4	2.61
6	2.58
8	2.57
10	2.56
12	2.54
14	2.55
16	2.55
18	2.54
20	2.52
22	2.50
24	2.50
26	2.51
28	2.50
30	2.50
$G^*_{12\%}$ / $G^*_{2\%}$	96.9%

Table 19. Linearity Tests (G* at 12%/G* at 2%)

Extraction	Recovery	Solvent	KY RAP	FL RAP
Centrifuge	Abson	TCE	97.19%	97.48%
	Rotovapor	Tol/Eth	97.01%	97.11%
Mod. SHRP	Rotovapor	Tol/Eth	97.98%	95.86%
		NPB	97.96%	96.63%

Table 20. Effect of Laboratory Aging on Recovered Asphalt Binder Properties

			ASTM D2172 D1856	ASTM D2172 D5404	AASHTO TP2	AASHTO TP2
Property	Temp., °C	Condition	TCE	Tol/Eth	Tol/Eth	NPB
G*/sinδ kPa	70	Unaged	3.69	12.82	10.86	11.84
		RTFO	30.01	22.80	18.90	17.44
		PAV	78.48	44.92	35.29	39.02
	Aging Ratio	RTFO/Unaged	8.13	1.78	1.74	1.47
G*/sinδ kPa	25	Unaged	2067	6779	6041	5606
		RTFO	8228	7915	6994	6895
		PAV	10,950	9565	8684	8130
	Aging Ratio	RTFO/Unaged	3.98	1.17	1.16	1.23
	Aging Ratio	PAV/Unaged	5.30	1.41	1.44	1.45
	Aging Ratio	PAV/RTFO	1.33	1.21	1.24	1.18
BBR, S MPa	-12	Unaged	122	254	252	222
		RTFO	284	289	249	240
		PAV	302	292	268	244
	Aging Ratio	RTFO/Unaged	2.33	1.14	0.99	1.08
	Aging Ratio	PAV/Unaged	2.48	1.15	1.06	1.10
	Aging Ratio	PAV/RTFO	1.06	1.01	1.08	1.02
BBR, m	-12	Unaged	0.349	0.282	0.293	0.295
		RTFO	0.268	0.275	0.283	0.279
		PAV	0.245	0.255	0.267	0.263
	Aging Ratio	RTFO/Unaged	0.77	0.98	0.97	0.95
	Aging Ratio	PAV/Unaged	0.70	0.90	0.91	0.89
	Aging Ratio	PAV/RTFO	0.91	0.93	0.94	0.94

Table 21. Average G* (psi) at 10Hz from Frequency Sweep Test for All Cases

RAP Stiffnesses	Virgin Binders	Mixture Cases	RAP Content 10%		RAP Content 40%	
			Temp. 20°C	Temp. 40°C	Temp. 20°C	Temp. 40°C
High (Arizona)	PG 52-34	BR	163590	18728	214328	15568
		AP	207100	26093	425350	89276
		TB	190389	31905	526319	74844
	PG 64-22	BR	512191	70405	424374	60218
		AP	343810	87518	587804	280917
		TB	383782	129394	486103	54440
Medium (Connecticut)	PG 52-34	BR	66060	7629	91072	10371
		AP	125057	11572	243924	38192
		TB	125163	18547	208019	31887
	PG 64-22	BR	287088	32146	211971	32790
		AP	288487	42691	339944	105318
		TB	284904	47793	312843	71972
Low (Florida)	PG 52-34	BR	165420	14172	194315	23902
		AP	200337	20471	439451	65095
		TB	168735	13569	268750	36783
	PG 64-22	BR	387755	58343	376133	63556
		AP	523579	62713	432870	95880
		TB	288056	43762	467425	89400

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 22. Average G*/sinδ (psi) at 10Hz from Frequency Sweep Test for All Cases

RAP Stiffnesses	Virgin Binders	Mixture Cases	RAP Content 10%		RAP Content 40%	
			Temp. 20°C	Temp. 40°C	Temp. 20°C	Temp. 40°C
High (Arizona)	PG 52-34	BR	266047.8	20854.2	402019.4	17063.7
		AP	392211.9	36843.8	1311344.1	122238.5
		TB	353658.7	38046.5	1877732.1	96984.9
	PG 64-22	BR	1051387.8	87743.7	1057816.6	71151.08
		AP	1134472.0	115548.3	2518479.7	598254.8
		TB	266047.8	213121.9	1482595.1	71478.0
Medium (Connecticut)	PG 52-34	BR	82301.02	8136.6	121787.8	8166.9
		AP	166590.5	14353.8	540376.1	49098.1
		TB	197190.8	21570.6	436421.1	39909.4
	PG 64-22	BR	496407.2	38789.9	492370.6	41763.4
		AP	699237.7	59991.5	1121183.0	191151.4
		TB	821202.7	58380.1	932604.6	110813.7
Low (Florida)	PG 52-34	BR	259636.6	15554.6	363980.2	27757.6
		AP	361920.8	23237.3	1193930.8	85918.4
		TB	269827.9	14793.2	600909.4	42898.4
	PG 64-22	BR	1052706	70296.7	1085352.8	78756.8
		AP	1411714	79073.8	1444640.4	133484.5
		TB	607205.3	52549.8	1269746.9	121955.4

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 23. Average of G* (psi) at 0.01 Hz from Frequency Sweep Test for All Cases

RAP Stiffnesses	Virgin Binders	Mixture Cases	RAP Content 10%		RAP Content 40%	
			Temp. 20°C	Temp. 40°C	Temp. 20°C	Temp. 40°C
High (Arizona)	PG 52-34	BR	5570.7	2253.7	9550.3	4917.7
		AP	10180.3	3143.7	49468.1	9557.3
		TB	7406.2	1194.7	100987.3	8061.3
	PG 64-22	BR	47657.3	6594.3	47700.1	15483.7
		AP	46531.1	2844.7	172032.2	16170.3
		TB	55094.7	5084.7	68055.7	5293.3
Medium (Connecticut)	PG 52-34	BR	1216.3	1184.5	2393.7	941.5
		AP	3624.0	519.5	19224.3	1437.5
		TB	4564.0	6145.0	12708.0	1242.7
	PG 64-22	BR	16561.7	1301.5	16693.3	1525.0
		AP	24364.7	1202.5	71765.0	6765.0
		TB	32108.5	10260.0	54680.0	3491.0
Low (Florida)	PG 52-34	BR	6029.6	701.0	11402.2	2535.4
		AP	14490.5	1099.2	50940.1	2236.4
		TB	5619.7	2649.0	17781.3	2163.4
	PG 64-22	BR	30885.2	1555.2	33634.2	3028.4
		AP	35303.1	1257.4	68462.1	3427.6
		TB	19510.1	5213.2	52511.7	4333.1

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 24. Average G*/sinδ (psi) at 0.01 Hz from Frequency Sweep Test for All Cases

RAP Stiffnesses	Virgin Binders	Mixture Cases	RAP Content 10%		RAP Content 40%	
			Temp. 20°C	Temp. 40°C	Temp. 20°C	Temp. 40°C
High (Arizona)	PG 52-34	BR	7014.3	2719.9	11788.9	8019.1
		AP	14157.3	6483.7	75685.9	13798.6
		TB	9388.7	1839.9	178546.8	11660.7
	PG 64-22	BR	67434.4	11209.2	71781.8	27314.4
		AP	72123.8	3706.3	362991.0	20528.6
		TB	91167.7	6314.1	103170.0	6235.9
Medium (Connecticut)	PG 52-34	BR	1793.4	1404.4	3301.7	1033.4
		AP	4543.7	564.4	28419.5	2296.6
		TB	5988.7	12940.7	17808.9	2061.7
	PG 64-22	BR	21715.4	1355.3	23781.5	2211.4
		AP	34101.6	1453.9	134117.7	10023.0
		TB	49540.9	17603.7	95729.8	4818.0
Low (Florida)	PG 52-34	BR	8502.1	1070.9	15967.8	4193.8
		AP	19892.3	2172.1	78217.6	5364.4
		TB	7891.4	3501.5	25752.1	2450.1
	PG 64-22	BR	41801.2	2187.7	45943.9	3307.9
		AP	45208.7	1527.4	109695.4	4098.4
		TB	25414.1	7058.7	76284.7	5094.0

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 25. Average Maximum Shear Deformation (in) at 20°C from Simple Shear Test for All Cases

RAP Stiffnesses	Virgin Binders	Mixture Cases	RAP Content 10%		RAP Content 40%	
			Temp. 20°C (35 kPa)	Temp. 20°C (105 kPa)	Temp. 20°C (35 kPa)	Temp. 20°C (105 kPa)
High (Arizona)	PG 52-34	BR	0.001567	0.005104	0.001612	0.005008
		AP	0.002172	0.003826	0.000157	0.000068
		TB	0.001304	0.004441	0.000125	0.000586
	PG 64-22	BR	0.000215	0.00074	0.000264	0.001073
		AP	0.000173	0.000692	0.000054	0.000186
		TB	0.000183	0.00065	0.000144	0.000522
Medium (Connecticut)	PG 52-34	BR	0.008305	NA	0.005299	0.01594
		AP	0.003227	NA	0.00058	0.00214
		TB	0.002001	NA	0.000082	0.002852
	PG 64-22	BR	0.00057	NA	0.00065	0.002381
		AP	0.000417	NA	0.000154	0.000532
		TB	0.000341	NA	0.000186	0.000702
Low (Florida)	PG 52-34	BR	0.001954	0.006171	0.001169	0.002514
		AP	0.001624	0.004806	0.00024	0.000827
		TB	0.001747	0.005923	0.000628	0.002076
	PG 64-22	BR	0.000327	0.001086	0.000308	0.001025
		AP	0.000339	0.001169	0.000147	0.000493
		TB	0.000269	0.000932	0.000183	0.000644

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending
NA = not available. Samples destroyed after testing with incorrect default load.

Table 26. Average Maximum Shear Deformation (in) at 40°C from Simple Shear Test for All Cases

RAP Stiffnesses	Virgin Binders	Mixture Cases	RAP Content 10%	RAP Content 40%
			Temp. 40°C	Temp. 40°C
High (Arizona)	PG 52-34	BR	0.022153	0.012883
		AP	0.014088	0.003417
		TB	0.013236	0.00422
	PG 64-22	BR	0.005197	0.006296
		AP	0.004242	0.000641
		TB	0.00215	0.002733
Medium (Connecticut)	PG 52-34	BR	0.09659	0.037415
		AP	0.016341	0.008734
		TB	NA	0.011249
	PG 64-22	BR	0.012976	0.010769
		AP	0.009215	0.002076
		TB	0.00325	0.003595
Low (Florida)	PG 52-34	BR	0.011781	0.01384
		AP	0.013101	0.00451
		TB	0.019155	0.00693
	PG 64-22	BR	0.009695	0.00703
		AP	0.008963	0.00366
		TB	0.011607	0.00383

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending
NA = Not available. Samples damaged during testing.

Table 27. Average Shear Strain from Repeated Shear at Constant Height Test for All Cases

RAP Stiffnesses	Cases	RAP Content 10%		RAP Content 40%	
		PG 52-34	PG 64-22	PG 52-34	PG 64-22
High (Arizona)	BR	0.02614	0.02109	0.02281	0.02014
	AP	0.02661	0.02295	0.00961	0.00706
	TB	0.02304	0.01686	0.01224	0.01125
Medium (Connecticut)	BR	0.03010	0.02221	0.03983*	0.03656
	AP	0.02811	0.028983	0.02930	0.01829
	TB	0.03185	0.02616	0.02671	0.02112
Low (Florida)	BR	0.027468	0.017813	0.044938	0.018967
	AP	0.01556	0.01508	0.01902	0.02028
	TB	0.027527	0.023973	0.023047	0.017623

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending
*Test value at 1247 load cycles.

Table 28. Average Indirect Tensile Creep and Strength (IDT) Test Mixture with 10% RAP

RAP Stiffnesses	Virgin Binders	Cases	Stiffness 0°C (MPa)	Stiffness -10°C (MPa)	Stiffness -20°C (MPa)	Strength -10°C (kPa)
High (Arizona)	PG 52-34	BR	1781	6272	13117	2547
		AP	1831	6326	14196	1856
		TB	2355	6022	15224	2458
	PG 64-22	BR	4347	8944	17461	2577
		AP	5243	11483	19400	2608
		TB	5292	11254	17532	2711
Medium (Connecticut)	PG 52-34	BR	1152	3456	10546	2166
		AP	1467	5229	13291	2568
		TB	1415	3836	10610	2545
	PG 64-22	BR	3262	9053	14673	2895
		AP	3357	8071	16305	2789
		TB	3719	10518	18363	3076

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 29. Average Indirect Tensile Creep and Strength (IDT) Test Mixture with 40% RAP

RAP Stiffnesses	Virgin Binders	Cases	Stiffness 0°C (MPa)	Stiffness -10°C (MPa)	Stiffness -20°C (MPa)	Strength -10°C (kPa)
High (Arizona)	PG 52-34	BR	1415	6180	11849	2308
		AP	5231	11395	18831	3170
		TB	5126	10092	17129	2518
	PG 64-22	BR	4744	11912	21451	2766
		AP	9226	14281	21023	3210
		TB	7026	12899	18861	2715
Medium (Connecticut)	PG 52-34	BR	673	2413	8092	1741
		AP	2766	7293	14303	2754
		TB	2683	6752	14989	2595
	PG 64-22	BR	2246	7164	9220	2123
		AP	6731	12477	16416	3009
		TB	6843	10576	18433	2532

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 30. Average of G* from Frequency Sweep Test for Aged and Unaged Samples with 10% Connecticut RAP at 10 Hz

Virgin Binder	Mixture Cases	G*(4°C-10Hz) (psi) Aged	G*(20°C-10Hz) (psi) Aged	G*(20°C-10Hz) (psi) Unaged
PG 52-34	BR	473405.3	141784.7	66060.2
	AP	472142.5	180255.3	125057.1
	TB	514363.0	199623.0	125163.0
PG 64-22	BR	570222.8	303975.0	287088.1
	AP	638731.5	341785.3	288487.4
	TB	573120.3	304277.7	284904.2

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 31. Average G* from Frequency Sweep Test for Aged and Unaged Samples with 10% Connecticut RAP at 0.01 Hz

Virgin Binder	Mixture Cases	G*(4°C-0.01Hz) (psi) Aged	G*(20°C-0.01Hz) (psi) Aged	G*(20°C-0.01Hz) (psi) Unaged
PG 52-34	BR	78523.3	5530.7	1216.3
	AP	88879.5	11517.5	3624.0
	TB	105079.7	8732.7	4564.0
PG 64-22	BR	188762.3	33180.8	16561.7
	AP	206103.7	48454.7	24364.7
	TB	202604.0	44589.3	32108.5

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 32. Average G* from Frequency Sweep Test for Aged and Unaged Samples with 40% Connecticut RAP at 10 Hz

Virgin Binder	Mixture Cases	G*(4°C-10Hz) (psi) Aged	G*(20°C-10Hz) (psi) Aged	G*(20°C-10Hz) (psi) Unaged
PG 52-34	BR	446780.0	132651.7	91072.7
	AP	734489.7	330743.7	243924.0
	TB	613428.7	270557.3	208019.0
PG 64-22	BR	548580.7	255768.3	211971.0
	AP	870869.3	384327.7	339944.5
	TB	844214.7	376932.0	312843.7

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 33. Average G* from Frequency Sweep Test for Aged and Unaged Samples with 40% Connecticut RAP at 0.01 Hz

Virgin Binder	Mixture Cases	G*(4°C-0.01Hz) (psi) Aged	G*(20°C-0.01Hz) (psi) Aged	G*(20°C-0.01Hz) (psi) Unaged
PG 52-34	BR	59659.7	4290.7	2393.7
	AP	205179.3	26982.7	19224.3
	TB	195495.0	26179.0	12708.0
PG 64-22	BR	202179.0	24600.7	16693.3
	AP	372691.7	66109.0	71765.0
	TB	383006.0	75480.0	54680.0

Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

Table 34. Relationship of Actual Practice Case (B) to Other Cases

RAP Content	Binder Grade	RAP Stiffness	FS (G*) at 20°C		FS (G*) at 40°C		SS (Def)		RSCH (Strain)	IDT Strength -10°C	IDT Creep		
			0.01 Hz	10 Hz	0.01 Hz	10 Hz	20°C	40°C			0°C	-10°C	-20°C
10%	PG52-34	High (AZ)	TB*	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
		Medium (CT)	**TB**	**TB**	**BR**	Both	Same		Same	Same	Same		Same
		Low (FL)	Same	Same	Same	Same	Same	Both	TB*				
	PG64-22	High (AZ)	Same	TB	Same	BR	Same	BR	Same	Same	Same	**TB**	**TB**
		Medium (CT)	TB	Same	BR	Both	TB		Same	Same	Same	Same	Same
		Low (FL)	Same	BR*	**BR***	Same	Same	Same	Same				
40%	PG52-34	High (AZ)	Both	Both	Same	TB	**BR**	**BR**	**TB**		**TB**	**TB**	**TB**
		Medium (CT)	Diff	TB	Same	Diff	**TB**	**Same**	Same	**TB**	**TB**	**TB**	**TB**
		Low (FL)			Same		**TB***	**TB**	**TB***				
	PG64-22	High (AZ)		TB*	**BR**		Diff	Diff	Diff		Diff	Same	Same
		Medium (CT)	Diff	TB		Diff	Diff	**TB**	**TB**	Diff	TB	Same	Both
		Low (FL)	Diff	Same	Same	TB*	Diff	TB	Same				

BR: Actual Practice = Black Rock, BR*: Actual Practice = Black Rock and Black Rock = Total Blending, but Actual Practice ≠ Total Blending
TB: Actual Practice = Total Blending, TB*: Actual Practice = Total Blending and Black Rock = Total Blending, but Actual Practice ≠ Black Rock
Same: Actual Practice = Black Rock = Total Blending
Diff: Black Rock ≠ Actual Practice ≠ Total Blending
Both: Actual Practice = Black Rock and Actual Practice = Total Blending, but Black Rock ≠ Total Blending
Blank cells are inconclusive.

Table 35. Variation in Asphalt Content in Black Rock Specimens

Virgin Binder	RAP Source	Black Rock Specimens	Actual Practice Specimens	Total Blending Specimens
PG 52-34	Florida	NA	NA	NA
	Connecticut	NA	5.04, 5.16	5.05
	Arizona	4.74	4.70, 5.29, 5.39	4.96, 5.22
PG 64-22	Florida	5.60	5.38	5.52
	Connecticut	NA	5.17, 5.36	NA
	Arizona	5.36	5.38, 5.03	5.03, 5.04

Table 36. Critical Temperatures and Performance Grades of Virgin and Recovered RAP Binders

		Virgin Binders		Recovered RAP Binders (Unaged)*		
Aging	Property	PG 52-34	PG 64-22	FL	CT	AZ
Original	DSR G*/sinδ	53.9	67.8	82.2	82.4	89.0
RTFO*	DSR G*/sinδ	54.6	66.6	75.4	75.8	85.3
PAV*	DSR G*sinδ	11.5	21.7	19.3	25.1	33.8
	BBR S	-23.7	-18.1	-15.9	-15.1	-5.6
	BBR m-value	-25.9	-16.2	-16.4	-14.4	-7.1
PG	Actual	PG 53-33	PG 66-26	PG 82-25	PG 82-24	PG 89-15
	MP1	PG 52-28	PG 64-22	PG 82-22	PG 82-22	PG 88-10

***** Recovered RAP binder tested as if RTFO and PAV aged.

Table 37. Estimated Critical Temperatures and Performance Grades of the Florida Blends

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	56.7	59.5	65.2	69.3	70.7	73.6
RTFO	DSR G*/sinδ	56.7	58.8	63.0	67.5	68.4	70.2
PAV	DSR G*sinδ	12.3	13.1	14.6	21.5	21.2	20.7
	BBR S	-23.0	-22.2	-20.6	-17.9	-17.7	-17.2
	BBR m-value	-24.9	-24.0	-22.1	-16.2	-16.2	-16.3
PG	Actual	PG 56-33	PG 58-32	PG 63-30	PG 67-26	PG 68-25	PG 70-26
	MP1	PG 52-28	PG 52-28	PG 58-28	PG 64-22	PG 64-22	PG 70-22

Table 38. Estimated Critical Temperatures and Performance Grades of the Connecticut Blends

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	56.7	59.6	65.3	69.3	70.7	73.7
RTFO	DSR G*/sinδ	56.7	58.9	63.1	67.5	68.5	70.3
PAV	DSR G*sinδ	12.8	14.2	16.9	22.1	22.4	23.1
	BBR S	-22.9	-22.0	-20.3	-17.8	-17.5	-16.9
	BBR m-value	-24.7	-23.6	-21.3	-16.0	-15.8	-15.5
PG	Actual	PG 56-32	PG 58-32	PG 63-30	PG 67-26	PG 68-25	PG 70-25
	MP1	PG 52-28	PG 58-28	PG 58-28	PG 64-22	PG 64-22	PG 70-22

Table 39. Estimated Critical Temperatures and Performance Grades of the Arizona Blends

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	57.4	60.9	67.9	70.0	72.1	76.3
RTFO	DSR G*/sinδ	57.7	60.8	66.9	68.5	70.4	74.1
PAV	DSR G*sinδ	13.8	16.0	20.5	23.0	24.2	26.6
	BBR S	-21.9	-20.1	-16.5	-16.8	-15.6	-13.1
	BBR m-value	-24.0	-22.1	-18.4	-15.3	-14.4	-12.6
PG	Actual	PG 57-31	PG 60-30	PG 66-26	PG 68-25	PG 70-24	PG 74-22
	MP1	PG 52-28	PG 58-28	PG 64-22	PG 64-22	PG 70-22	PG 70-22

Table 40. Measured Binder Properties of Florida Blended Binders

			PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	Temp C	10%	20%	40%	10%	20%	40%
Original	G*/sinδ kPa	52	2.17					
		58	0.99	1.33				
		64		0.63	1.40			
		70			0.67	1.01	1.34	1.92
		76				0.50	0.65	0.90
		82						
RTFO	G*/sinδ kPa	52	4.72					
		58	2.06	4.04				
		64		1.79	3.10	4.49		
		70			1.44	2.07	2.63	3.52
		76					1.22	1.60
		82						
PAV	G*sinδ kPa	13	5207	6352				
		16	3482	4356	6595			
		19			4489	5142	5549	
		22				3626	4122	6780
		25						4915
		28						
	BBR Stiffness MPa	-6						
		-12				131	140	237
		-18	143	183	232	269	312	465
		-24	333	355	456			
	BBR m-value	-6						
		-12				0.338	0.327	0.304
		-18	0.361	0.334	0.315	0.283	0.265	0.247
		-24	0.290	0.281	0.255			

Table 41. Measured Critical Temperatures and Performance Grades of the Florida Blended Binders

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	57.9	60.3	66.7	70.1	72.4	75.2
RTFO	DSR G*/sinδ	57.5	62.5	66.7	69.5	71.4	73.6
PAV	DSR G*sinδ	13.3	14.9	18.2	19.2	20.1	24.8
	BBR S	-23.3	-22.5	-20.3	-18.9	-17.7	-14.1
	BBR m-value	-23.2	-21.8	-19.5	-16.1	-14.6	-12.4
PG	Actual	PG 57-33	PG 60-31	PG 66-29	PG 69-26	PG 71-24	PG 73-22
	MP1	PG 52-28	PG 58-28	PG 64-28	PG 64-22	PG 70-22	PG 70-22

Table 42. Measured Binder Properties of Connecticut Blended Binders

			PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	Temp C	10%	20%	40%	10%	20%	40%
Original	G*/sinδ kPa	52	2.06	3.03				
		58	0.96	1.32				
		64		0.62	1.51			
		70			0.72	1.07	1.24	
		76				0.54	0.61	1.19
		82						0.58
RTFO	G*/sinδ kPa	52	4.78					
		58	2.13	2.90				
		64		1.32	3.21	4.46		
		70			1.52	2.07	2.28	
		76					1.08	2.62
		82						1.25
PAV	G*sinδ kPa	13	6525	7059	6082			
		16	4408	4878	4955			
		19				5845	5832	
		22				4101	4205	6065
		25				2846		4392
		28				1905		
	BBR Stiffness MPa	-6						
		-12				131	149	156
		-18	158	194	225	291	314	348
		-24	342	384	450			
	BBR m-value	-6						
		-12				0.326	0.323	0.304
		-18	0.355	0.340	0.317	0.281	0.274	0.257
		-24	0.291	0.278	0.261			

Table 43. Measured Critical Temperatures and Performance Grades of the Connecticut Blended Binders

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	57.7	60.1	67.3	70.6	71.8	77.5
RTFO	DSR G*/sinδ	57.8	60.1	67.0	69.5	70.3	77.4
PAV	DSR G*sinδ	15.0	15.8	15.9	20.4	20.4	23.8
	BBR S	-23.0	-21.8	-20.5	-18.2	-17.6	-16.9
	BBR m-value	-23.2	-21.9	-19.8	-15.5	-14.8	-12.5
PG	Actual	PG 57-33	PG 60-31	PG 67-29	PG 69-25	PG 70-24	PG 77-22
	MP1	PG 52-28	PG 58-28	PG 64-28	PG 64-22	PG 70-22	PG 76-22

Table 44. Measured Binder Properties of Arizona Blended Binders

			PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	Temp C	10%	20%	40%	10%	20%	40%
Original	G*/sinδ kPa	52	2.03					
		58	0.93	2.07				
		64		0.94	2.92	2.02		
		70			1.28	0.93	1.74	
		76			0.60		0.82	1.55
		82						0.73
RTFO	G*/sinδ kPa	52	4.79					
		58	2.07	4.36				
		64		1.91	5.42	3.99		
		70			2.36	1.84	3.16	
		76			1.06		1.45	2.95
		82						1.32
PAV	G*sinδ kpa	13	6150					
		16	4113	5936				
		19		4083		6041		
		22			5300	4161	5419	
		25			3664		3924	6223
		28						4500
	BBR Stiffness MPa	-6					80	115
		-12			166	148	165	230
		-18	171	209	314	298		
		-24	369	436				
	BBR m-value	-6					0.357	0.326
		-12			0.327	0.319	0.299	0.281
		-18	0.350	0.319	0.269	0.276		
		-24	0.287	0.260				

Table 45. Measured Critical Temperatures and Performance Grades of the Arizona Blended Binders

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	57.4	63.5	71.9	69.4	74.4	79.5
RTFO	DSR G*/sinδ	57.6	63.0	70.5	68.6	72.8	78.2
PAV	DSR G*sinδ	14.5	17.4	22.5	20.5	22.7	27.0
	BBR S	-22.4	-20.9	-17.6	-18.1	-17.0	-14.3
	BBR m-value	-22.8	-19.9	-14.8	-14.7	-11.9	-9.5
PG	Actual	PG 57-32	PG 63-29	PG 70-24	PG 68-24	PG 72-21	PG 78-19
	MP1	PG 52-28	PG 58-28	PG 70-22	PG 64-22	PG 70-16	PG 76-16

Table 46. Comparison of Estimated and Actual Critical High Temperatures – Original DSR

		PG 52-34 Blends			PG 64-22 Blends		
RAP	% RAP Binder	Estimated	Actual	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
FL	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	82.2	82.2	0.0	82.2	82.2	0.0
	10%	56.7	57.9	1.2	69.3	70.1	0.8
	20%	59.5	60.3	0.8	70.7	72.4	1.7
	40%	65.2	66.7	1.5	73.6	75.2	1.6
CT	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	82.4	82.4	0.0	82.4	82.4	0.0
	10%	56.7	57.7	1.0	69.3	70.6	1.3
	20%	59.6	60.1	0.5	70.7	71.8	1.1
	40%	65.3	67.3	2.0	73.7	77.5	3.8
AZ	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	89.0	89.0	0.0	89.0	89.0	0.0
	10%	57.4	57.4	0.0	70.0	69.4	-0.6
	20%	60.9	63.5	2.6	72.1	74.4	2.3
	40%	67.9	71.9	3.9	76.3	79.5	3.2

Table 47. Comparison of Estimated and Actual Critical High Temperatures – RTFO DSR (with no aging of RAP Binder)

		PG 52-34 Blends			PG 64-22 Blends		
RAP	% RAP Binder	Estimated	Actual	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
FL	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	75.4	75.4	0.0	75.4	75.4	0.0
	10%	56.7	57.5	0.8	67.5	69.5	2.0
	20%	58.8	62.5	3.7	68.4	71.4	3.0
	40%	63.0	66.7	3.7	70.2	73.6	3.4
CT	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	75.8	75.8	0.0	75.8	75.8	0.0
	10%	56.7	57.8	1.1	67.5	69.5	2.0
	20%	58.9	60.1	1.2	68.5	70.3	1.8
	40%	63.1	67.0	3.9	70.3	77.4	7.1
AZ	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	85.3	85.3	0.0	85.3	85.3	0.0
	10%	57.7	57.6	-0.1	68.5	68.6	0.1
	20%	60.8	63.0	2.2	70.4	72.8	2.4
	40%	66.9	70.5	3.6	74.1	78.2	4.1

Table 48. Comparison of Estimated and Actual Critical Intermediate Temperatures – PAV DSR

		PG 52-34 Blends			PG 64-22 Blends		
RAP	% RAP Binder	Estimated	Actual	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
FL	0% (Virgin)	11.5	11.5	0.0	21.7	21.7	0.0
	100%	19.3	19.3	0.0	19.3	19.3	0.0
	10%	12.3	13.3	1.0	21.5	19.2	-2.3
	20%	13.1	14.9	1.8	21.2	20.1	-1.1
	40%	14.6	18.2	3.6	20.7	24.8	4.1
CT	0% (Virgin)	11.5	11.5	0.0	21.7	21.7	0.0
	100%	25.1	25.1	0.0	25.1	25.1	0.0
	10%	12.9	15.0	2.1	22.1	20.4	-1.7
	20%	14.2	15.8	1.6	22.4	20.4	-2.0
	40%	16.9	15.9	-1.0	23.1	23.8	0.7
AZ	0% (Virgin)	11.5	11.5	0.0	21.7	21.7	0.0
	100%	33.8	33.8	0.0	33.8	33.8	0.0
	10%	13.8	14.5	0.7	23.0	20.5	-2.5
	20%	16.0	17.4	1.4	24.2	22.7	-1.5
	40%	20.5	22.5	2.0	26.6	27.0	0.4

Table 49. Comparison of Estimated and Actual Critical Low Temperatures – BBR Stiffness

		PG 52-34 Blends			PG 64-22 Blends		
RAP	% RAP Binder	Estimated	Actual	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
FL	0% (Virgin)	-23.7	-23.7	0.0	-18.1	-18.1	0.0
	100%	-15.9	-15.9	0.0	-15.9	-15.9	0.0
	10%	-23.0	-23.3	-0.3	-17.9	-18.9	-1.0
	20%	-22.2	-22.5	-0.3	-17.7	-17.7	0.0
	40%	-20.6	-20.3	0.3	-17.2	-14.1	3.1
CT	0% (Virgin)	-23.7	-23.7	0.0	-18.1	-18.1	0.0
	100%	-15.1	-15.1	0.0	-15.1	-15.1	0.0
	10%	-22.9	-23.0	-0.1	-17.8	-18.2	-0.4
	20%	-22.0	-21.8	0.2	-17.5	-17.6	-0.1
	40%	-20.3	-20.5	-0.2	-16.9	-16.9	0.0
AZ	0% (Virgin)	-23.7	-23.7	0.0	-18.1	-18.1	0.0
	100%	-5.6	-5.6	0.0	-5.6	-5.6	0.0
	10%	-21.9	-22.4	-0.5	-16.8	-18.1	-1.3
	20%	-20.1	-20.9	-0.8	-15.6	-17.0	-1.4
	40%	-16.5	-17.6	-1.1	-13.1	-14.3	-1.2

Table 50. Comparison of Estimated and Actual Critical Low Temperatures – BBR m-value

		PG 52-34 Blends			PG 64-22 Blends		
RAP	% RAP Binder	Estimated	Actual	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
FL	0% (Virgin)	-25.9	-25.9	0.0	-16.2	-16.2	0.0
	100%	-16.4	-16.4	0.0	-16.4	-16.4	0.0
	10%	-24.9	-23.2	1.7	-16.2	-16.1	0.1
	20%	-24.0	-21.8	2.2	-16.2	-14.6	1.6
	40%	-22.1	-19.5	2.6	-16.3	-12.4	3.9
CT	0% (Virgin)	-25.9	-25.9	0.0	-16.2	-16.2	0.0
	100%	-14.4	-14.4	0.0	-14.4	-14.4	0.0
	10%	-24.7	-23.2	1.5	-16.0	-15.5	0.5
	20%	-23.6	-21.9	1.7	-15.8	-14.8	1.0
	40%	-21.3	-19.8	1.5	-15.5	-12.5	3.0
AZ	0% (Virgin)	-25.9	-25.9	0.0	-16.2	-16.2	0.0
	100%	-7.1	-7.1	0.0	-7.1	-7.1	0.0
	10%	-24.0	-22.8	1.2	-15.3	-14.7	0.6
	20%	-22.1	-19.9	2.2	-14.4	-11.9	2.5
	40%	-18.4	-14.8	3.6	-12.6	-9.5	3.1

Table 51. Virgin and Recovered RAP Binders (with RTFO Aging)

			Virgin Binders		RAP Binders with RTFO Aging*		
Aging	Property	Temp, C	PG 52-34	PG 64-22	FL	CT	AZ
Original	G*/sinδ kPa	52	1.27				
		58	0.59				
		64		1.63			
		70		0.76			
		76			*2.06*[A]	*2.28*[A]	
		82			*1.02*[A]	*1.05*[A]	*2.65*[A]
		88				*0.52*[A]	*1.16*[A]
RTFO*	G*/sinδ kPa	52	3.13				
		58	1.40				
		64		3.09			
		70		1.42	15.97	38.01	
		76			7.38	17.59	
		82			3.50	8.20	9.35
		88			1.71	4.01	3.84
PAV*	G*sinδ kPa	10	6,226				
		13	4,045				
		16					
		19		6,984			
		22		4,846			
		25			6,486		
		28			4,492	6,531	
		31				4,699	
		34					
		37					
		40					5,103
		43					3,443
	BBR Stiffness MPa	6					129
		0					262
		-6				150	
		-12		120	280	281	
		-18	127	296	534		
		-24	312				
	BBR m-value	6					0.340
		0					0.292
		-6				0.320	
		-12		0.344	0.300	0.262	
		-18	0.388	0.281	0.234		
		-24	0.321				

[A] *Represents original, unaged value of recovered RAP binder.*

* Recovered RAP Binder aged in RTFO and tested as if RTFO and PAV aged according to MP1.

Table 52. Critical Temperatures and Performance Grades of Virgin and Recovered RAP Binders after RTFO

		Virgin Binders		Recovered RAP Binders (RTFO)*		
Aging	Property	PG 52-34	PG 64-22	FL	CT	AZ
Original	DSR G*/sinδ	53.9	67.8	82.2	82.4	89.0
RTFO*	DSR G*/sinδ	54.6	66.6	85.9	92.2	91.8
PAV*	DSR G*sinδ	11.5	21.7	24.1	30.4	40.2
	BBR S	-23.7	-18.1	-12.6	-12.6	-1.1
	BBR m-value	-25.9	-16.2	-12.0	-8.1	+1.0
PG	Actual	PG 53-33	PG 66-26	PG 82-22	PG 82-18	PG 89-9
	MP1	PG 52-28	PG 64-22	PG 82-22	PG 82-16	PG 88-4

* Recovered RAP Binder aged in RTFO and tested as if RTFO and PAV aged according to MP1.

Table 53. Comparison of Recovered RAP Binders Using Different Aging Conditions

		FL (Low)		CT (Medium)		AZ (High)	
Aging	Property	Unaged	RTFO*	Unaged	RTFO*	Unaged	RTFO*
Original	DSR G*/sinδ	82.2	82.2	82.4	82.4	89.0	89.0
RTFO*	DSR G*/sinδ	75.4	85.9	75.8	92.2	85.3	91.8
PAV*	DSR G*sinδ	19.3	24.1	25.1	30.4	33.8	40.2
	BBR S	-15.9	-12.6	-15.1	-12.6	-5.6	-1.1
	BBR m-value	-16.4	-12.0	-14.4	-8.1	-7.1	+1.0
PG	Actual	PG 82-25	PG 82-22	PG 82-24	PG 82-18	PG 89-15	PG 89-9
	MP1	PG 82-22	PG 82-22	PG 82-22	PG 82-16	PG 88-10	PG 88-4

* Recovered RAP Binder aged in RTFO tested as if RTFO and PAV aged according to MP1.

Table 54. Estimated Critical Temperatures and Performance Grades of the Florida Blends after RTFO

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	56.7	59.5	65.2	69.3	70.7	73.6
RTFO	DSR G*/sinδ	57.8	60.9	67.2	68.6	70.5	74.4
PAV	DSR G*sinδ	12.8	14.0	16.6	22.0	22.2	22.7
	BBR S	-22.6	-21.5	-19.3	-17.5	-17.0	-15.9
	BBR m-value	-24.5	-23.1	-20.3	-15.8	-15.4	-14.5
PG	Actual	PG 56-32	PG 59-31	PG 65-29	PG 68-25	PG 70-25	PG 73-24
	MP1	PG 52-28	PG 58-28	PG 64-28	PG 64-22	PG 70-22	PG 70-22

Table 55. Estimated Critical Temperatures and Performance Grades of the Connecticut Blends (with RTFO Aging of RAP Binder)

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	56.7	59.6	65.3	69.3	70.7	73.7
RTFO	DSR G*/sinδ	58.4	62.1	69.7	69.2	71.7	76.9
PAV	DSR G*sinδ	13.4	15.3	19.1	22.6	23.5	25.2
	BBR S	-22.6	-21.5	-19.3	-17.5	-17.0	-15.9
	BBR m-value	-24.1	-22.3	-18.8	-15.4	-14.6	-12.9
PG	Actual	PG 56-32	PG 59-31	PG 65-28	PG 69-25	PG 70-24	PG 73-22
	MP1	PG 52-28	PG 58-28	PG 64-28	PG 64-22	PG 70-22	PG 70-22

Table 56. Estimated Critical Temperatures and Performance Grades of the Arizona Blends (with RTFO Aging of RAP Binder)

		PG 52-34 Blends, % RAP Binder			PG 64-22 Blends, % RAP Binder		
Aging	Property	10%	20%	40%	10%	20%	40%
Original	DSR G*/sinδ	57.4	60.9	67.9	70.0	72.1	76.3
RTFO	DSR G*/sinδ	58.3	62.1	69.5	69.1	71.7	76.7
PAV	DSR G*sinδ	14.4	17.3	23.0	23.6	25.4	29.1
	BBR S	-21.5	-19.2	-14.7	-16.4	-14.7	-11.3
	BBR m-value	-23.2	-20.5	-15.1	-14.5	-12.8	-9.3
PG	Actual	PG 57-31	PG 60-29	PG 67-24	PG 69-24	PG 71-22	PG 76-19
	MP1	PG 52-28	PG 58-28	PG 64-22	PG 64-22	PG 70-22	PG 76-16

Table 57. Comparison of Estimated and Actual Critical Temperatures for RTFO DSR (with RFTO Aging of RAP Binder)

		PG 52-34 Blends			PG 64-22 Blends		
RAP	Blend	Estimated	Actual	$\Delta_{Act\text{-}Est}$	Estimated	Actual	$\Delta_{Act\text{-}Est}$
FL	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	85.9	85.9	0.0	85.9	85.9	0.0
	10%	57.8	57.5	-0.3	68.6	69.5	0.9
	20%	60.9	62.5	1.6	70.5	71.4	0.9
	40%	67.2	66.7	-0.5	74.4	73.6	-0.8
CT	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	92.2	92.2	0.0	92.2	92.2	0.0
	10%	58.4	57.8	-0.6	69.2	69.5	0.3
	20%	62.1	60.1	-2.0	71.7	70.3	-1.4
	40%	69.7	67.0	-2.7	76.9	77.4	0.5
AZ	0% (Virgin)	53.9	53.9	0.0	67.8	67.8	0.0
	100%	91.8	91.8	0.0	91.8	91.8	0.0
	10%	58.3	57.6	-0.7	69.1	68.6	-0.5
	20%	62.1	63.0	0.9	71.7	72.8	1.1
	40%	69.5	70.5	1.0	76.7	78.2	1.5

Table 58. Comparison of Estimated and Actual Critical Temperatures for PAV DSR (with RTFO Aging of RAP Binder)

		PG 52-34 Blends			PG 64-22 Blends		
RAP	Blend	Estimated	Actual	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
FL	0% (Virgin)	11.5	11.5	0.0	21.7	21.7	0.0
	100%	24.1	24.1	0.0	24.1	24.1	0.0
	10%	12.8	13.3	0.5	22.0	19.2	-2.8
	20%	14.0	14.9	0.9	22.2	20.1	-2.1
	40%	16.6	18.2	1.6	22.7	24.8	2.1
CT	0% (Virgin)	11.5	11.5	0.0	21.7	21.7	0.0
	100%	30.4	30.4	0.0	30.4	30.4	0.0
	10%	13.4	15.0	1.6	22.6	20.4	-2.2
	20%	15.3	15.8	0.5	23.5	20.4	-3.1
	40%	19.1	15.9	-3.2	25.2	23.8	-1.4
AZ	0% (Virgin)	11.5	11.5	0.0	21.7	21.7	0.0
	100%	40.2	40.2	0.0	40.2	40.2	0.0
	10%	14.4	14.5	0.1	23.6	20.5	-3.1
	20%	17.3	17.4	0.1	25.4	22.7	-2.7
	40%	23.0	22.5	-0.5	29.1	27.0	-2.1

Table 59. Comparison of Estimated and Actual Critical Temperatures for BBR Stiffness (with RTFO Aging of RAP Binder)

		PG 52-34 Blends			PG 64-22 Blends		
RAP	Blend	Estimated	Actual	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
FL	0% (Virgin)	-23.7	-23.7	0.0	-18.1	-18.1	0.0
	100%	-12.6	-12.6	0.0	-12.6	-12.6	0.0
	10%	-22.6	-23.3	-0.7	-17.5	-18.9	-1.4
	20%	-21.5	-22.5	-1.0	-17.0	-17.7	-0.7
	40%	-19.3	-20.3	-1.0	-15.9	-14.1	1.8
CT	0% (Virgin)	-23.7	-23.7	0.0	-18.1	-18.1	0.0
	100%	-12.6	-12.6	0.0	-12.6	-12.6	0.0
	10%	-22.6	-23.0	-0.4	-17.5	-18.2	-0.7
	20%	-21.5	-21.8	-0.3	-17.0	-17.6	-0.6
	40%	-19.3	-20.5	-1.2	-15.9	-16.9	-1.0
AZ	0% (Virgin)	-23.7	-23.7	0.0	-18.1	-18.1	0.0
	100%	-1.1	-1.1	0.0	-1.1	-1.1	0.0
	10%	-21.5	-22.4	-0.9	-16.4	-18.1	-1.7
	20%	-19.2	-20.9	-1.7	-14.7	-17.0	-2.3
	40%	-14.7	-17.6	-2.9	-11.3	-14.3	-3.0

Table 60. Comparison of Estimated and Actual Critical Temperatures for BBR m-value (with RTFO Aging of RAP Binder)

		PG 52-34 Blends			PG 64-22 Blends		
RAP	Blend	Estimated	Actual	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
FL	0% (Virgin)	-25.9	-25.9	0.0	-16.2	-16.2	0.0
	100%	-12.0	-12.0	0.0	-12.0	-12.0	0.0
	10%	-24.5	-23.2	1.3	-15.8	-16.1	-0.3
	20%	-23.1	-21.8	1.3	-15.4	-14.6	0.8
	40%	-20.3	-19.5	0.8	-14.5	-12.4	2.1
CT	0% (Virgin)	-25.9	-25.9	0.0	-16.2	-16.2	0.0
	100%	-8.1	-8.1	0.0	-8.1	-8.1	0.0
	10%	-24.1	-23.2	0.9	-15.4	-15.5	-0.1
	20%	-22.3	-21.9	0.4	-14.6	-14.8	-0.2
	40%	-18.8	-19.8	-1.0	-12.9	-12.5	0.4
AZ	0% (Virgin)	-25.9	-25.9	0.0	-16.2	-16.2	0.0
	100%	1.0	1.0	0.0	1.0	1.0	0.0
	10%	-23.2	-22.8	0.4	-14.5	-14.7	-0.2
	20%	-20.5	-19.9	0.6	-12.8	-11.9	0.9
	40%	-15.1	-14.8	0.3	-9.3	-9.5	-0.2

Table 61. Comparisons of Estimated and Actual Blended Binder Grades

		PG 52-34 Blends		PG 64-22 Blends	
RAP	Blend	Estimated	Actual	Estimated	Actual
FL	0% (Virgin)		PG 52-28*		PG 64-22
	100%		PG 82-22		PG 82-22
	10%	PG 52-28	PG 52-28	PG 64-22	PG 64-22
	20%	PG 58-28	PG 58-28	PG 70-22	PG 70-22
	40%	PG 64-28	PG 64-28	PG 70-22	PG 70-22
CT	0% (Virgin)		PG 52-28*		PG 64-22
	100%		PG 82-16		PG 82-16
	10%	PG 52-28	PG 52-28	PG 64-22	PG 64-22
	20%	PG 58-28	PG 58-28	PG 70-22	PG 70-22
	40%	PG 64-28	PG 64-28	*PG 70-22*	*PG 76-22*
AZ	0% (Virgin)		PG 52-28*		PG 64-22
	100%		PG 88-4		PG 88-4
	10%	PG 52-28	PG 52-28	PG 64-22	PG 64-22
	20%	PG 58-28	PG 58-28	*PG 70-22*	*PG 70-16*
	40%	*PG 64-22*	*PG 70-22*	PG 76-16	**PG 76-16**

* Manufacturer graded as PG 52-34, Asphalt Institute tested as PG 52-28.

Table 62. Effect of RAP Ratio on Complex Shear Modulus (G*, psi) for Arizona RAP

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Frequency)			
		20°C		40°C	
		10Hz	0.01Hz	10Hz	0.01Hz
52-34	0	212322	10032	34390	1046
	10	207100	10180	26093	3143
	20	309090	23211	54011	1700
	40	425350	49468	89276	9557
64-22	0	395637	37203	105683	2178
	10	343809	46531	87518	2844
	20	474536	81998	154467	4878
	40	587804	172032	280917	16170

Table 63. Effect of RAP Ratio on Stiffness (G*/sinδ, psi) for Arizona RAP

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Frequency)			
		20°C		40°C	
		10Hz	0.01Hz	10Hz	0.01Hz
52-34	0	375813.1	12890.6	39021.7	1289.7
	10	389726.3	13987.9	35166.9	6192.6
	20	720598.5	33413.5	69110.2	2287.6
	40	1286933.4	74508.3	117581.2	12800.0
64-22	0	1099001.4	50540.9	136961.7	3129.7
	10	1050703.5	70501.3	114414.4	3649.3
	20	1595750.2	127566.2	248133.9	6190.3
	40	2517951.1	362869.2	594469.5	20327.5

Table 64. Effect of RAP Ratio on Complex Shear Modulus (G*, psi) for Florida RAP

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Frequency)			
		20°C		40°C	
		10Hz	0.01Hz	10Hz	0.01Hz
52-34	0	212322	10032	34390	1046
	10	200337	14490	20471	1099
	20	290918	13226	38425	968
	40	439451	50940	65095	2236
64-22	0	395637	37203	105683	2178
	10	523579	35303	62713	1257
	20	483636	63287	124663	4344
	40	432870	68462	95880	3427

Table 65. Effect of RAP Ratio on Stiffness ($G^*/\sin\delta$, psi) for Florida RAP

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Frequency)			
		20°C		40°C	
		10Hz	0.01Hz	10Hz	0.01Hz
52-34	0	375813.1	12890.6	39021.7	1289.7
	10	362016.7	19877.4	23228.1	2198.0
	20	545939.1	18084.3	46132.8	1051.6
	40	1193756.3	77645.5	85862.1	3027.9
64-22	0	1099001.4	50540.9	136961.7	3129.7
	10	1409866.3	45235.3	79048.0	1534.5
	20	1540279.0	92796.4	185231.3	5303.0
	40	1480546.8	108787.2	133514.1	4086.2

Table 66. Effect of RAP Ratio on Complex Shear Modulus (G*, psi) for Connecticut RAP (unaged)

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Frequency)			
		20°C		40°C	
		10Hz	0.01Hz	10Hz	0.01Hz
52-34	0	212322	10032	34391	1046
	10	125057	3624	12955	1202
	20	291333	23347	55457	2622
	40	243924	19244	38192	1437
64-22	0	395637	37203	105683	2178
	10	288487	24364	42691	519
	20	469899	56367	133185	3164
	40	339944	71765	105318	6765

Table 67. Effect of RAP Ratio on Stiffness $G^*/\sin\delta$ (psi) for Connecticut RAP (unaged)

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Frequency)			
		20°C		40°C	
		10Hz	0.01Hz	10Hz	0.01Hz
52-34	0	375813.1	12890.6	39022.9	1289.7
	10	166462.1	4543.7	14353.2	1453.3
	20	664580.7	35586.7	71767.3	3918.5
	40	540998.3	28430.6	49074.6	2293.3
64-22	0	1099001.4	50540.9	136961.7	3129.7
	10	698339.2	34100.7	59957.1	563.8
	20	1360849.8	81143.5	210276.3	3910.9
	40	1118115.2	133933.2	191320.0	10013.5

Table 68. Effect of RAP Ratio on Maximum Shear Deformation (in) for Arizona RAP

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Load)		
		20°C		40°C
		35 kPa	105 kPa	35 kPa
52-34	0	0.000913	0.003148	0.020123
	10	0.002172	0.003826	0.014088
	20	0.000484	0.001711	0.008122
	40	0.000157	0.000680	0.003417
64-22	0	0.000183	0.000968	0.006373
	10	0.000173	0.000692	0.004242
	20	0.000138	0.000465	0.002464
	40	0.000054	0.000185	0.000641

Table 69. Effect of RAP Ratio on Maximum Shear Deformation (in) for Florida RAP

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Load)		
		20°C		40°C
		35 kPa	105 kPa	35 kPa
52-34	0	0.000913	0.003148	0.020123
	10	0.001624	0.004806	0.013101
	20	0.000839	0.002832	0.010740
	40	0.000240	0.008270	0.004511
64-22	0	0.000183	0.000968	0.006373
	10	0.000339	0.001169	0.008963
	20	0.000173	0.000590	0.002868
	40	0.000147	0.000493	0.003660

Table 70. Effect of RAP Ratio on Maximum Shear Deformation (in) for Connecticut RAP (unaged)

Virgin Binder	RAP Ratio (%)	Test Conditions (Temperature and Load)		
		20°C		40°C
		35 kPa	105 kPa	35 kPa
52-34	0	0.000913	0.000315	0.020123
	10	NA	NA	0.016341
	20	0.000513	0.001797	0.006652
	40	0.000580	0.002140	0.008734
64-22	0	0.000183	0.000968	0.006373
	10	NA	NA	0.009215
	20	0.000189	0.000634	0.003348
	40	0.000154	0.000532	0.002076

Table 71. Effect of RAP Ratio on Shear Strain at 5000 Loading Cycles

RAP Stiffnesses	RAP Ratio (%)	Virgin Binder Grade	
		PG 52-34	PG 64-22
High (Arizona)	0	0.00037*	0.01700
	10	0.02661	0.02295
	20	0.020433	0.017285
	40	0.009607	0.00706
Medium (Connecticut)	0	0.00037*	0.01700
	10	0.028107	0.028983
	20	0.018043	0.00023
	40	0.029303	0.018293
Low (Florida)	0	0.00037*	0.01700
	10	0.01556	0.01508
	20	0.02747	0.01885
	40	0.01902	0.02028

* Shear Strain at 4200 loading cycles

Table 72. IDT Stiffness (MPa) at 60 sec using PG 52-34

		Stiffness (MPa)	
% RAP	Temperature, °C	AZ	CT
0%	0	1,142	1,142
	-10	4,415	4,415
	-20	10,298	10,298
10%	0	1,831	1,467
	-10	6,326	5,229
	-20	14,196	13,291
20%	0	2,823	1,869
	-10	7,255	6,275
	-20	15,183	13,171
40%	0	5,231	2,766
	-10	11,395	7,293
	-20	18,831	14,303

Table 73. PG 52-34 Strength, kPa

% RAP	CT	AZ
0	2,444	2,444
10	2,568	1,856
20	2,720	2,719
40	2,754	3,170

Table 74. Mixture IDT Critical Temperatures for PG 52-34 Blends

	Mixture Critical Temperature, °C	
% RAP	AZ	CT
0	-28.1	-28.1
10	-21.4	-24.7
20	-15.8	-20.4
40	-6.9	-17.0

Table 75. PG 64-22 IDT Stiffness @ 60 sec, MPa

		Stiffness, MPa	
% RAP	Temperature, °C	AZ	CT
0%	0	5,076	5,076
	-10	11,736	11,736
	-20	19,113	19,113
10%	0	5,243	3,357
	-10	11,483	8,071
	-20	19,400	16,305
20%	0	8,727	6,228
	-10	16,385	11,908
	-20	24,365	21,536
40%	0	9,226	6,731
	-10	14,281	12,477
	-20	21,033	16,416

Table 76. PG 64-22 IDT Strengths @ -10°C, kPa

	Strength, kPa	
% RAP	CT	AZ
0	3,290	3,290
10	2,789	2,608
20	2,930	3,349
40	3,009	3,210

Table 77. Mixture Critical Temperatures for PG 64-22 Blends

	Mixture Critical Temperature, °C	
% RAP	AZ	CT
0	-8.2	-8.2
10	-2.9	-11.6
20	5.7	-0.1
40	*	4.7

*Could not be calculated due to variability.

Table 78. Beam Fatigue Test Matrix

RAP Stiffness	RAP Content	Virgin Binder	
		PG 52-34	PG 64-22
No RAP	0	X	X
Connecticut	10	X	X
	20	X	X
	40	X	X
Arizona	10	X	X
	20	X	X
	40	X	X
Florida	10	X	X
	20	X	X
	40	X	X

Table 79. PG 52-34 Combined with Connecticut RAP High Strain

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m³ Initial	Energy J/m³ Final	Dissipated Energy, J/m³
52-34 with 0% RAP	800	112,032	366	185	56.89	60.91	166.51	86.98	79.53
	800	146,180	367	186	56.8	60.5	166.75	86.72	80.03
52-34 with 10% CT RAP	800	88,063	520	263	53.40	56.51	235.39	118.14	117.25
	800	174,179	458	232	53.81	56.94	203.05	103.91	99.14
52-34 with 20% CT RAP	800	60,854	784	401	49.10	54.00	343.42	176.64	166.78
	800	86,680	1078	545	39.91	40.89	396.42	194.08	202.34
52-34 with 40% CT RAP	800	31,159	1273	649	41.88	47.76	500.97	275.03	225.94
	800	35,907	1352	692	42.16	48.15	539.73	299.28	240.45

Table 80. PG 52-34 Combined with Arizona RAP High Strain

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m^3 Initial	Energy J/m^3 Final	Dissipated Energy, J/m^3
52-34 with 0% RAP	800	112,032	366	185	56.89	60.91	166.51	86.98	79.53
	800	146,180	367	186	56.8	60.5	166.75	86.72	80.03
52-34 with 10% AZ RAP	800	145,321	534	271	52.52	56.66	238.55	121.84	116.71
	800	155,738	612	306	51.36	55.25	276.24	136.73	139.51
52-34 with 20% AZ RAP	800	35,045	958	490	44.38	49.85	390.58	207.42	183.16
	800	47,473	994	509	43.25	49.39	397.63	214.21	183.42
52-34 with 40% AZ RAP	800	10,459	2025	1038	31.77	39.73	601.14	381.72	219.42
	800	23,325	2082	1066	32.22	40.54	626.1	400.03	226.07

Table 81. PG 64-22 Combined with Connecticut RAP High Strain

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m^3 Initial	Energy J/m^3 Final	Dissipated Energy, J/m^3
64-22 with 0% RAP	800	12,432	1719	859	34.91	43.57	529.56	379.2	150.36
	800	12,746	1503	752	35.92	44.04	480.65	290	190.65
64-22 with 10% CT RAP	800	22,992	1370	699	35.15	41.13	449.16	261.74	187.42
	800	13,336	1212	619	36.22	41.31	406.59	228.29	178.3
64-22 with 20% CT RAP	800	13,337	1898	970	32.72	39.57	572.57	355.93	216.64
	800	12,307	1595	816	33.23	39.92	489.02	299.17	189.85
64-22 with 40% CT RAP	800	19,397	2065	1055	30.72	40.26	583.97	393.85	190.12
	800	18,688	2011	1031	31.49	40.58	585.43	389.69	195.74

Table 82. PG 64-22 Combined with Arizona RAP High Strain

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m³ Initial	Energy J/m³ Final	Dissipated Energy, J/m³
64-22 with 0% RAP	800	12,432	1719	859	34.91	43.57	529.56	379.2	150.36
	800	12,746	1503	752	35.92	44.04	480.65	290	190.65
64-22 with 10% AZ RAP	800	11,564	1563	782	33.68	39.15	455.09	283.53	171.56
	800	15,100	1515	758	34.05	40.7	452.42	284	168.42
64-22 with 20% AZ RAP	800	8,407	2496	1279	27.06	34.45	612.36	418.04	194.32
	800	4,646	2436	1248	27.61	34.36	607.35	403.19	204.16
64-22 with 40% AZ RAP	800	8,010	3920	1991	19.48	26.9	581.54	474.45	107.09
	800	5,205	3681	1869	21.1	27.83	618.24	467.71	150.53

Table 83. PG 52-34 Combined with Connecticut RAP Low Strain

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m³ Initial	Energy J/m³ Final	Dissipated Energy, J/m³
52-34 with 0% RAP	400	500000+	411	276	54.12	56.92	47.53	32.33	15.2
	400	500000+	454	275	52.96	56.66	51.03	31.99	19.04
52-34 with 10% CT RAP	400	500000+	510	318	50.82	53.93	56.24	36.00	20.24
	400	500000+	439	290	49.40	52.98	47.81	32.04	15.77
52-34 with 20% CT RAP	400	500000+	834	548	45.80	49.90	84.89	59.76	25.13
	400	500,008	923	550	45.47	49.89	92.27	59.94	32.33
52-34 with 40% CT RAP LTOA	400	343,818	1526	769	37.42	43.30	132.07	75.38	56.69
	400	500000+	1745	1017	37.42	42.41	154.01	97.66	56.35

Table 84. PG 52-34 Combined with Arizona RAP Low Strain

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m^3 Initial	Energy J/m^3 Final	Dissipated Energy, J/m^3
52-34 with 0% RAP	400	500000+	411	276	54.12	56.92	47.53	32.33	15.2
	400	500000+	454	275	52.96	56.66	51.03	31.99	19.04
52-34 with 10% AZ RAP	400	500000+	559	399	49.76	49.37	61.17	42.53	18.64
	400	500000+	594	380	48.78	52.42	64.13	42.27	21.86
52-34 with 20% AZ RAP	400	500000+	1588	889	41.71	46.9	147.15	89.75	57.4
	400	500000+	1139	700	39.68	44.18	98.66	69.97	28.69
52-34 with 40% AZ RAP	400	250,403	2495	1258	27.11	33.47	142.52	90.79	51.73
	400	307,228	2495	1263	26.64	33.88	143.42	92.86	50.56

Table 85. PG 64-22 Combined with Connecticut RAP Low Strain

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m³ Initial	Energy J/m³ Final	Dissipated Energy, J/m³
64-22 with 0% RAP	400	500000+	1002	640	35.04	40.46	76.17	58.45	17.72
	400	500000+	1026	714	34.73	39.47	76.36	63.93	12.43
64-22 with 10% CT RAP	400	211,418	1709	855	30.86	33.77	111.18	57.82	53.36
	400	464,265	1493	753	32.22	36.81	105.28	63.20	42.08
64-22 with 20% CT RAP	400	500,000	2183	932	27.61	31.90	123.21	62.45	60.76
	400	500,000	1352	1070	31.90	34.97	89.32	75.59	13.73
64-22 with 40% CT RAP	400	500000+	2258	1194	27.28	34.33	131.95	89.98	41.97
	400	160,848	709	527	44.25	48.02	72.33	56.21	16.12

Table 86. PG 64-22 Combined with Arizona RAP Low Strain

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m³ Initial	Energy J/m³ Final	Dissipated Energy, J/m³
64-22 with 0% RAP	400	500000+	1002	640	35.04	40.46	76.17	58.45	17.72
	400	500000+	1026	714	34.73	39.47	76.36	63.93	12.43
64-22 with 10% AZ RAP	400	295,048	1966	988	29.7	34.56	125.18	69.67	55.51
	400	410,107	1740	876	30.29	35.04	110.12	66.38	43.74
64-22 with 20% AZ RAP	400	295,151	2710	1366	24.04	29.94	124.52	85.61	38.91
	400	171,247	2066	1153	26.27	31.04	108.2	71.56	36.64
64-22 with 40% AZ RAP	400	157,044	3387	1694	18.67	24.02	100.12	84	16.12
	400	17,137	2769	1385	19.97	25.75	95.01	77.34	17.67

Table 87. Beam Fatigue Results, PG 52-34 Combined with Connecticut RAP LTOA

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m^3 Initial	Energy J/m^3 Final	Dissipated Energy, J/m^3
52-34 with 0% RAP LTOA	800	*	*	*	*	*	*	*	*
	800	60,421	618	318	48.88	54.06	268.01	138.4	129.61
52-34 with 10% CT RAP LTOA	800	83,001	688	352	46.86	51.01	289.23	149.86	139.37
	800	71,051	628	322	46.94	52.09	267.81	138.71	129.1
52-34 with 20% CT RAP LTOA	800	38,239	959	490	40.83	47.42	370.35	207.04	163.31
	800	40,000	970	474	40.74	46.37	357.45	180.63	176.82
52-34 with 40% CT RAP LTOA	800	30,000	1479	763	35.45	43.14	464.87	294.20	170.67
	800	24,666	1323	682	35.85	42.99	421.53	257.81	163.72

* Not available. Equipment malfunction.

Table 88. Beam Fatigue Results, PG 64-22 Combined with Connecticut RAP LTOA

Specimen ID	Strain Level, με	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, °	Phase angle Final, °	Energy J/m³ Initial	Energy J/m³ Final	Dissipated Energy, J/m³
64-22 with 0% RAP LTOA	800	4,692	1844	951	31.87	37.61	489.84	318.68	171.16
	800	7,135	1773	907	31.36	38.16	455.49	310.71	144.78
64-22 with 10% CT RAP LTOA	800	19,840	1510	755	32.36	38.76	419.27	275.47	143.8
	800	*	*	*	*	*	*	*	*
64-22 with 20% CT RAP LTOA	800	10,090	2391	1228	28.12	35.76	609.99	416.13	193.86
	800	15,152	2240	1120	27.44	34.71	488.02	317.00	171.02
64-22 with 40% CT RAP LTOA	800	11,030	2894	1447	24.59	32.00	512.46	466.60	45.86
	800	15,294	2414	1207	25.13	32.73	458.16	367.38	90.78

***** Not available. Equipment malfunction

Table 89. Comparison of LTOA and STOA Beam Fatigue Tests

Virgin Binder	RAP Ratio, %	Initial Stiffness, MPa				Cycles to Failure			
		STOA	LTOA	LTOA/STOA	Average	STOA	LTOA	LTOA/STOA	Average
PG 52-34	0	367	618	1.69	1.28	129106	60421	0.47	0.60
	10	489	658	1.35		131121	77026	0.59	
	20	931	964.5	1.04		73767	39119.5	0.53	
	40	1313	1401	1.07		33533	27333	0.82	
PG 64-22	0	1611	1809	1.12	1.30	12589	5914	0.47	0.72
	10	1291	1854	1.44		18164	72223	3.98	
	20	1747	2316	1.33		12822	12621	0.98	
	40	2038	2654	1.30		19043	13162	0.69	

Table 90. Plant vs. Lab Frequency Sweep (FS) Test Results at 20°C and 10Hz

Sample No.	Lab Modulus Stiffness		Plant Modulus Stiffness	
	(G*) 20°C-10Hz	(G*/sin δ) 20°C-10Hz	(G*) 20°C-10Hz	(G*/sin δ) 20°C-10Hz
1	326100	881955	375432	1072028
2	259992	606134	414633	956127
3	324502	847965	303009	667435
4	270934	759476	243704	550034
5	316475	743284	277454	839461
Average	**299601**	**767763**	**322846**	**817017**

Table 91. Plant vs. Lab Frequency Sweep (FS) Test Results at 20°C and 0.01Hz

Sample No.	Lab Modulus Stiffness		Plant Modulus Stiffness	
	(G*) 20°C-0.01Hz	(G*/sin δ) 20°C-0.01Hz	(G*) 20°C-0.01Hz	(G*/sin δ) 20°C-0.01Hz
1	34383	48968	30504	45676
2	29715	43408	24847	32579
3	22368	34026	23208	31733
4	23832	33822	13170	19168
5	27646	41078	24777	37616
Average	**27589**	**40260**	**23301**	**33354**

Table 92. Plant vs. Lab Frequency Sweep (FS) Test Results at 40°C and 10Hz

Sample No.	Lab Modulus Stiffness		Plant Modulus Stiffness	
	(G*) 40°C-10Hz	(G*/sin δ) 40°C-10Hz	(G*) 40°C-10Hz	(G*/sin δ) 40°C-10Hz
1	41727	47755	52648	64750
2	50936	59424	41353	49477
3	51584	61437	30559	35995
4	44417	51340	47668	56394
5	58883	77668	35069	39905
6	57604	69159	NA	NA
Average	**50859**	**61131**	**41459**	**49304**

NA = Not Available

Table 93. Plant vs. Lab Frequency Sweep (FS) Test Results at 40°C and 0.01Hz

Sample No.	Lab Modulus Stiffness		Plant Modulus Stiffness	
	(G*) 40°C-0.01Hz	(G*/sin δ) 40°C-0.01Hz	(G*) 40°C-0.01Hz	(G*/sin δ) 40°C-0.01Hz
1	3435	3672	4275	7153
2	2442	2712	2988	4154
3	5603	7952	1776	2242
4	3994	5252	3469	5154
5	3667	4338	1907	2354
6	5319	6371	NA	NA
Average	**4077**	**5050**	**2883**	**4211**

NA = Not Available

Table 94. Simple Shear (SS) Test Results at 20 and 40°C for Lab Samples

Sample No.	Lab		
	Max. Shear Def.(in) 20°C-35 kPa	Max. Shear Def.(in) 20°C-105 kPa	Max. Shear Def.(in) 40°C-35 kPa
1	0.001192	0.000337	0.005863
2	0.001346	0.000394	0.006190
3	0.001874	0.000548	0.004758
4	0.001644	0.000490	0.004431
5	0.001259	0.000385	0.004931
Average	**0.001461**	**0.000429**	**0.005261**

Table 95. Simple Shear (SS) Test Results at 20 and 40°C for Plant Samples

Sample No.	Plant		
	Max. Shear Def. (in) 20°C-35 kPa	Max. Shear Def.(in) 20°C-105 kPa	Max. Shear Def.(in) 40°C-35 kPa
1	0.001673	0.000519	0.006488
2	0.001586	0.000452	0.005787
3	0.001490	0.000461	0.006459
4	0.002970	0.000856	0.005527
5	0.001951	0.000586	0.005469
Average	**0.001932**	**0.000575**	**0.005944**

Table 96. RSCH Test Results at 58°C

Sample No.	Plant Shear Strain, %	Lab Shear Strain, %
1	0.02141	0.01060
2	0.01994	0.01133
3	0.02176	0.01719
4	0.01404	0.01764
5	0.01297	0.01115
6	0.01378	0.01649
Average	**0.017317**	**0.014067**

Table 97. DSR Results for Extracted Binder Tested at 22°C

RAP Stiffness	Heating Temp. °C	Heating Time (Hours)					
		2		4		16	
		G* (psi)	δ (°)	G* (psi)	δ (°)	G* (psi)	δ (°)
Low (Florida)	110	4804400	48.3	12769000	40.3	9024150	43.3
	150	5885150	47.6	19142000	32.9	21480500	27.4
High Arizona)	110	34268000	33.9	38444000	30.1	37472000	33.1
	150	39412000	32.4	60294500	25.2	73266000	26.4

Table 98. DSR Results for Extracted Binders Tested at 31°C

RAP Stiffness	Heating Temp. °C	Heating Time (Hours)					
		2		4		16	
		G* (psi)	δ (°)	G* (psi)	δ (°)	G* (psi)	δ (°)
Low (Florida)	110	1677600	54.7	3457833	49.1	2532750	51.5
	150	1554450	54.8	6948933	40.0	9199000	31.4
High (Arizona)	110	10892500	44.0	14224500	39.4	12288500	42.8
	150	12752000	43.1	25596000	32.5	36027000	26.4