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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, Hϕ, 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.

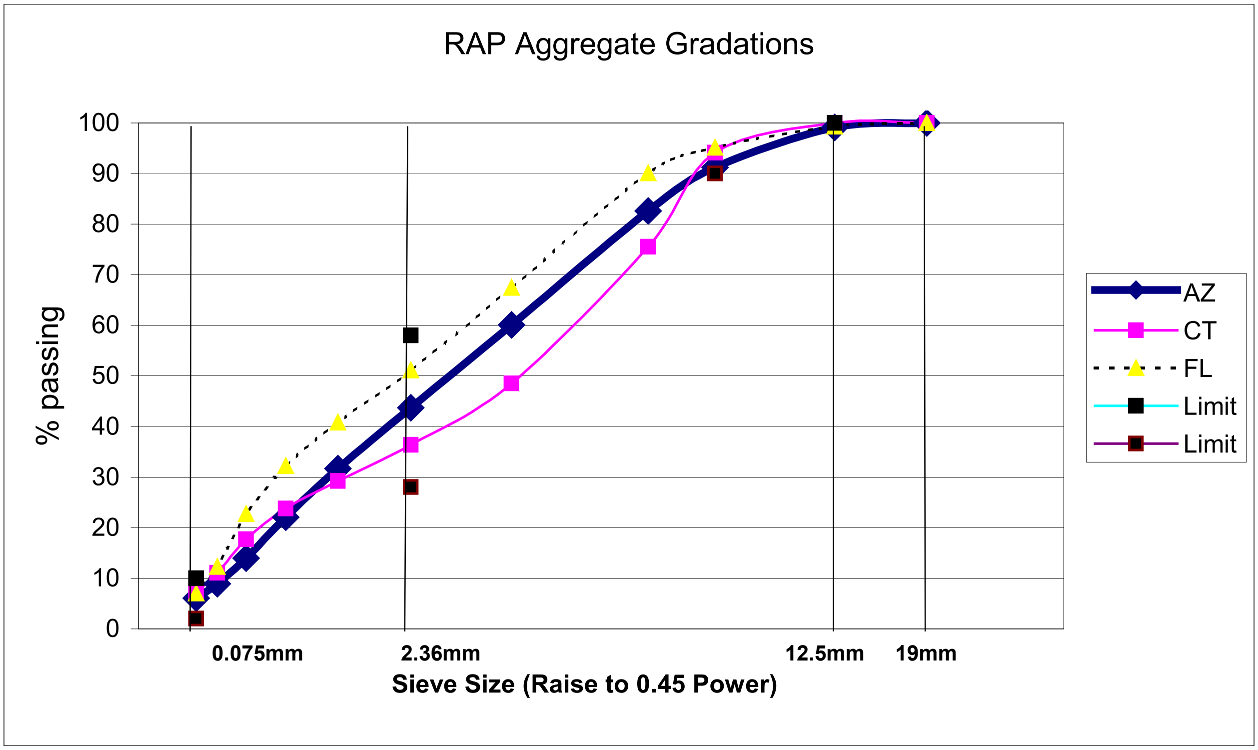

Figure 1. RAP Aggregate Gradations

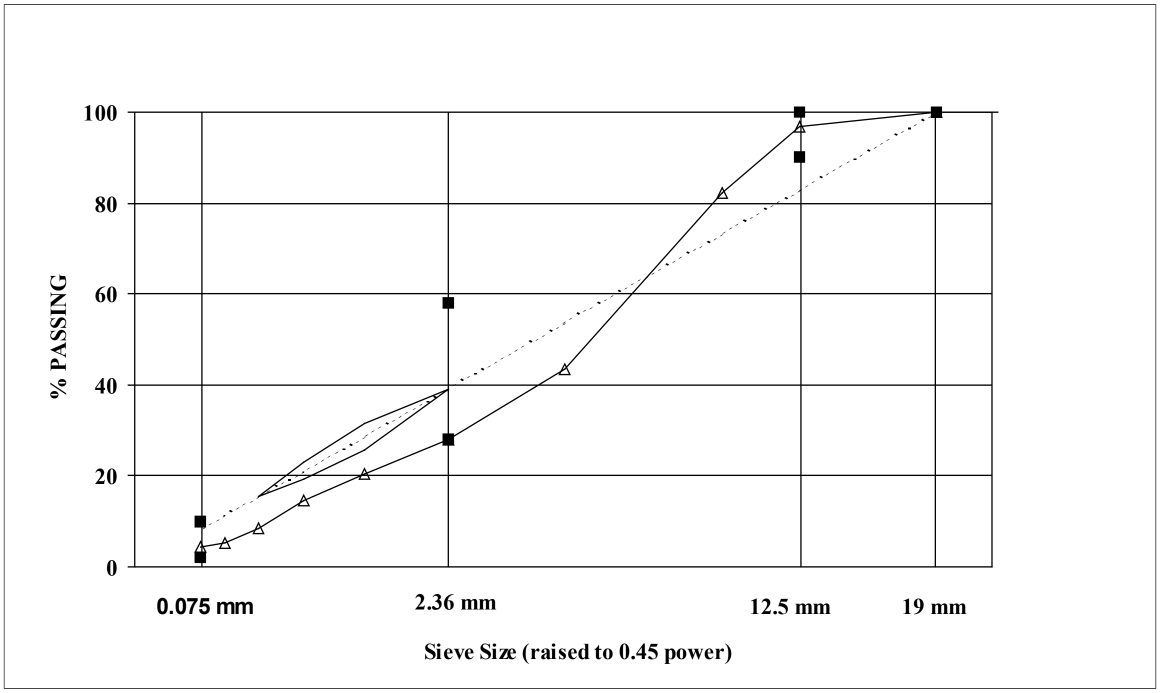

Figure 2. Design Gradation

Table 1. Virgin and Recovered RAP Binders

Aging	Property	Temp, C	Virgin Binders: PG 52-34	Virgin Binders: PG 64-22	RAP Binders - Unaged*: FL	RAP Binders - Unaged*: CT	RAP Binders - Unaged*: 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

			Mixture Cases		
Virgin AC	RAP Stiffness	RAP %	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°C
	Simple Shear at Constant Height*	4 and 20°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°C
	Simple Shear at Constant Height	20 and 40°C
	Repeated Shear at Constant Height	52 and 58°C

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

Table 8. Binder Effects Experiment

RAP Stiffness	% of RAP Binder	Virgin Asphalt 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^{o}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 ($G^*/\sin\delta$). This means that the linear equation used for estimating the Original $G^*/\sin\delta$ 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 ($G^*/\sin\delta$). This means that the linear equation used for estimating the RTFO $G^*/\sin\delta$ 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 $G^*/\sin\delta$ critical temperatures than the Original $G^*/\sin\delta$ 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 $G^*/\sin\delta$ 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*sinδ) 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 $G^*/\sin\delta$ 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 ($G^*/\sin\delta$) 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 $G^*/\sin\delta$, 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.

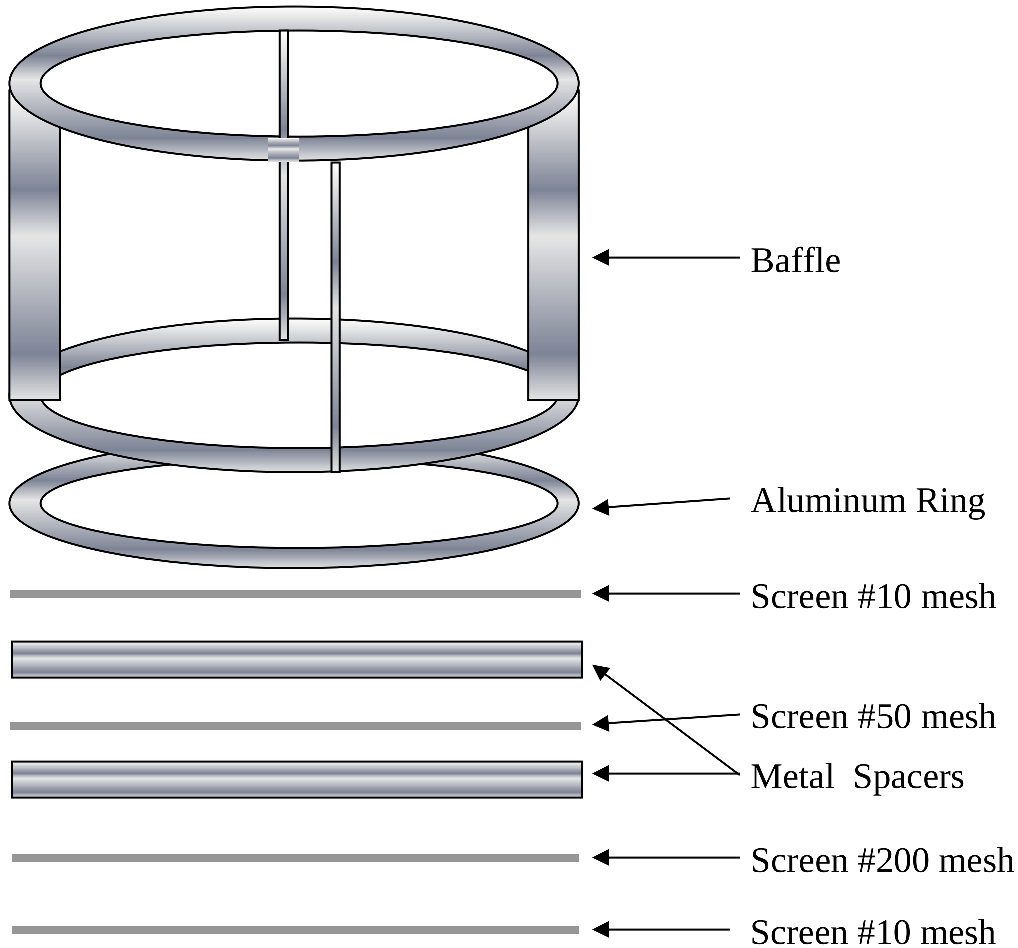

Figure 3. Modified Screen Configuration for AASHTO TP2

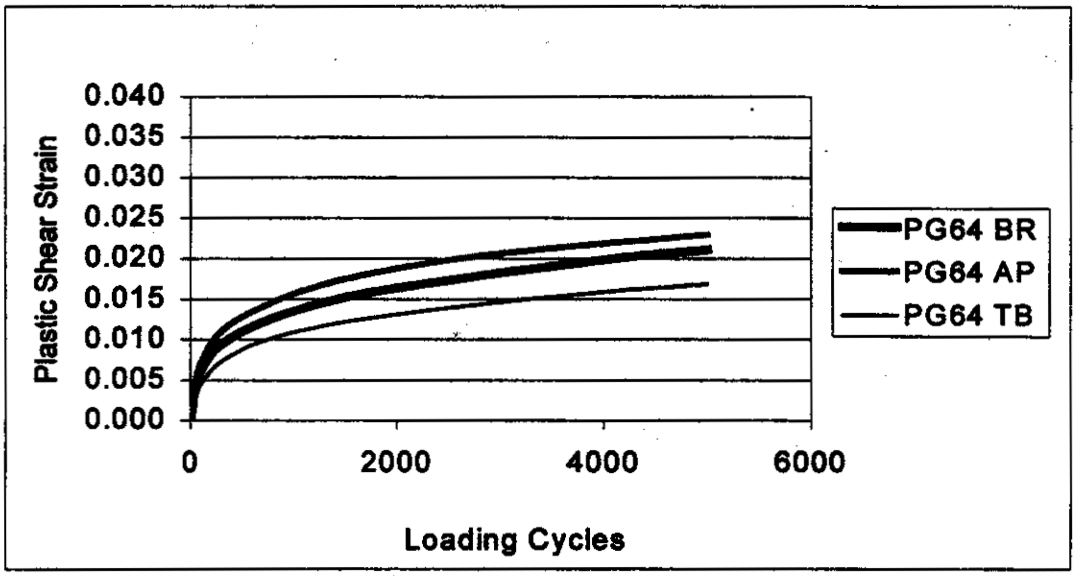

Figure 4. Frequency Sweep (FS) Results for 10% FL RAP at 40°C and 10 Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

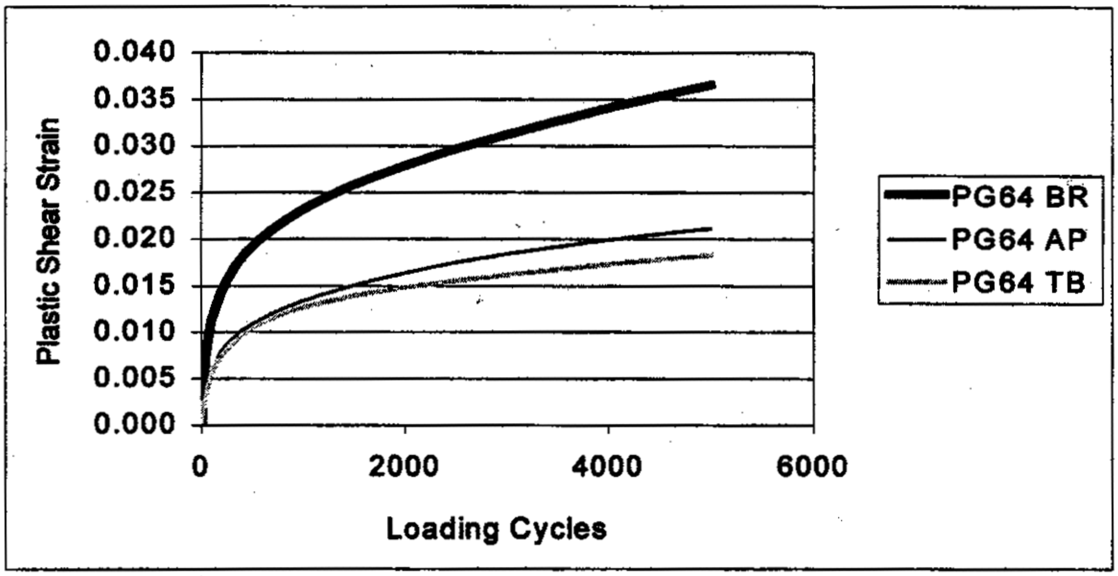

Figure 5. Frequency Sweep (FS) Results for 40% FL RAP at 40°C and 10 Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

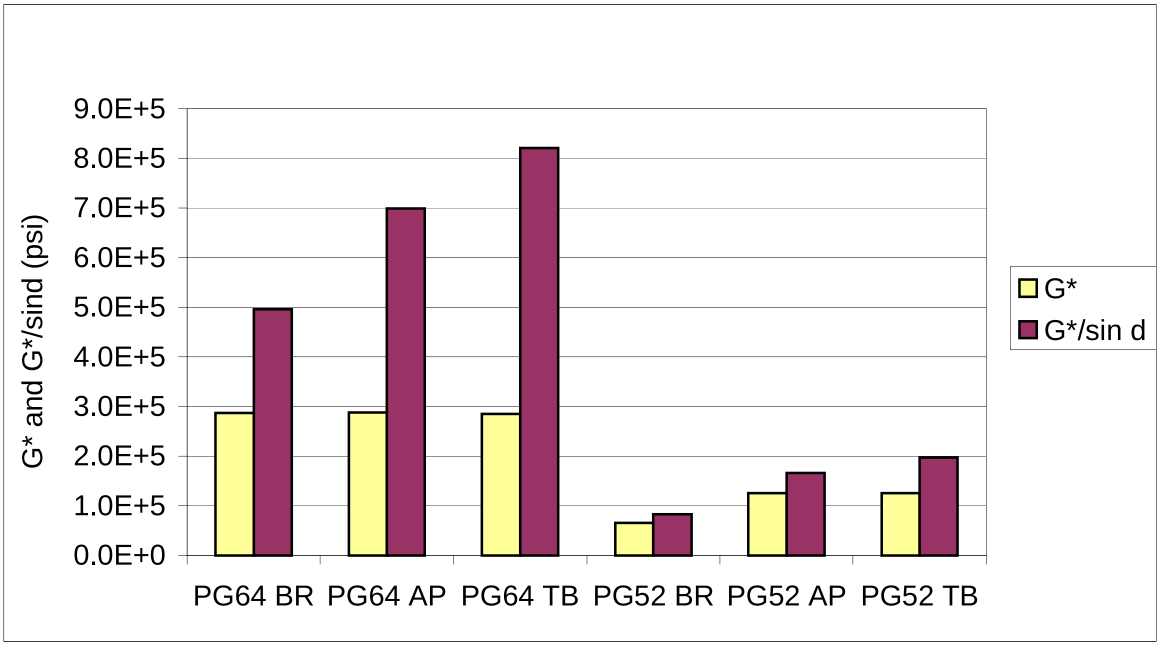

Figure 6. Frequency Sweep (FS) Results for 10% CT RAP (Unaged) at 20°C and 10Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

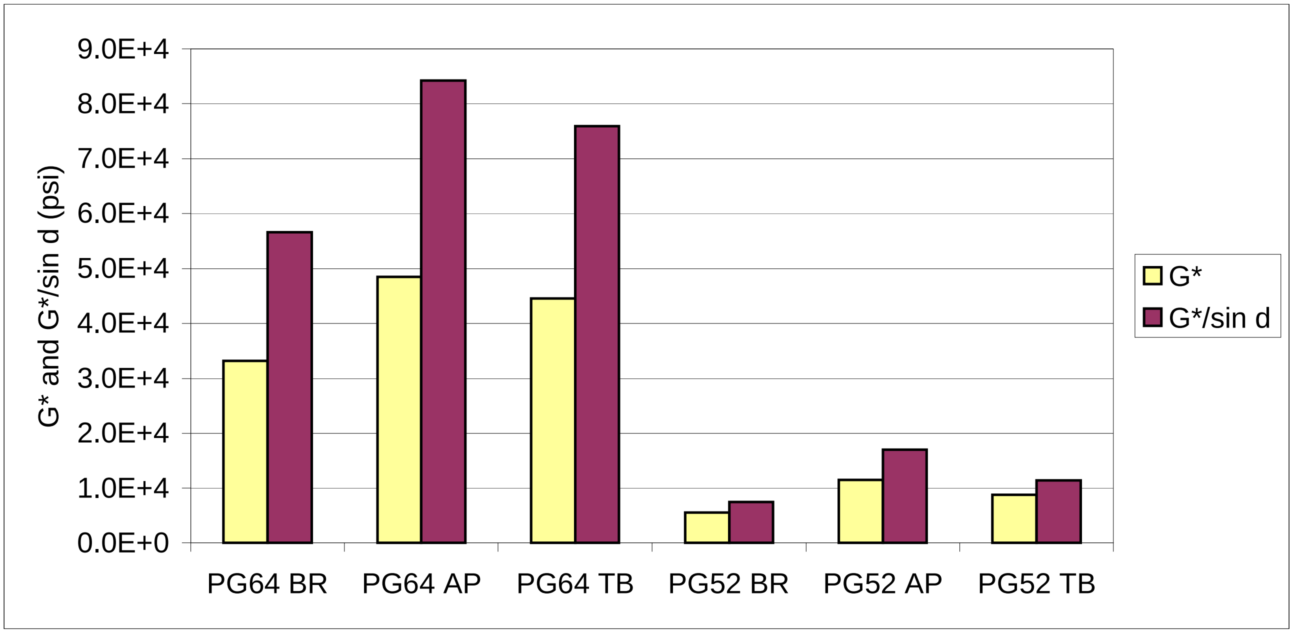

Figure 7. Frequency Sweep (FS) Results for 10% CT RAP (Aged) at 20°C and 0.01 Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

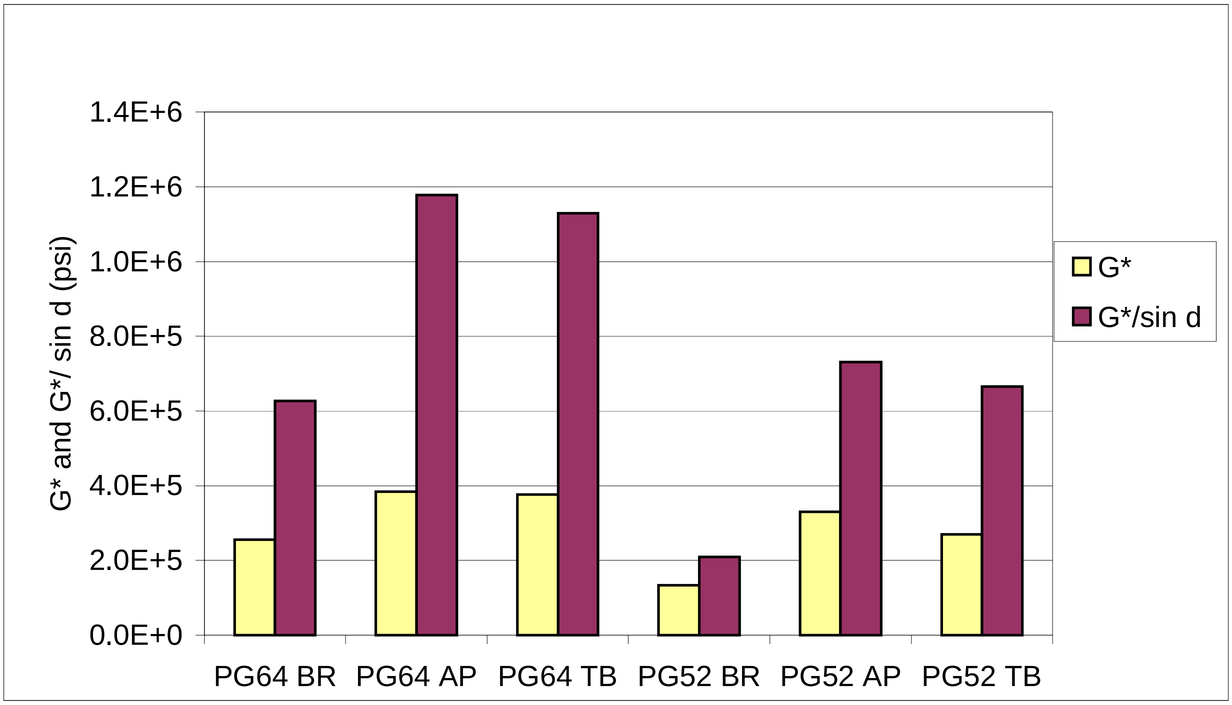

Figure 8. Frequency Sweep (FS) Results for 40% CT RAP (Aged) at 20°C and 10 Hz
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

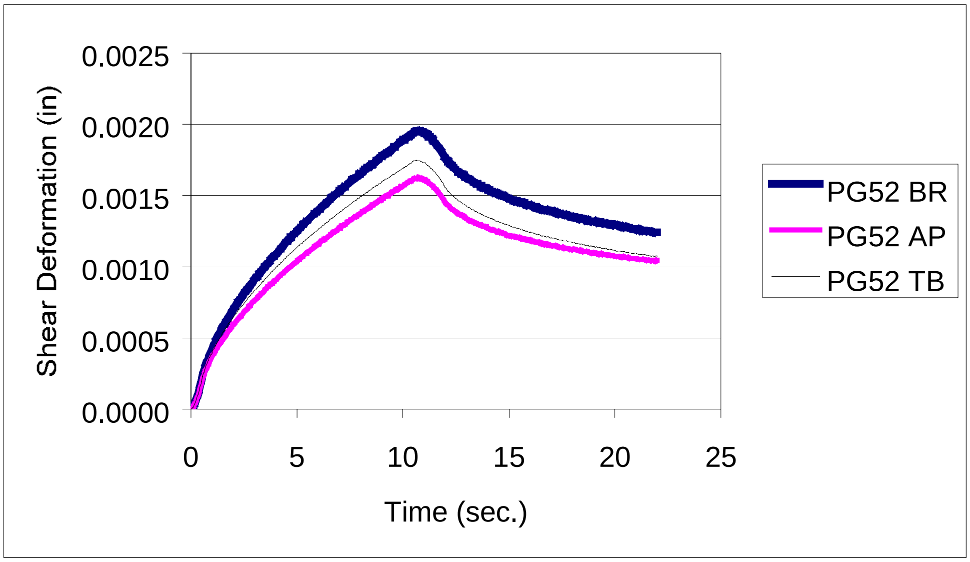

Figure 9. Simple Shear (SS) Deformation for 10% FL RAP with PG 52-34 at 20°C
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

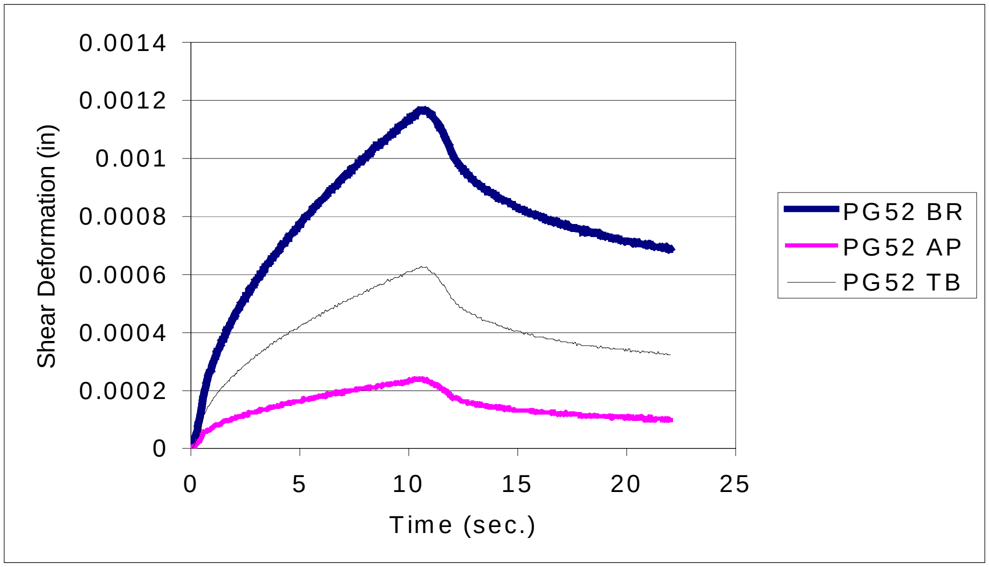

Figure 10. Simple Shear (SS) Deformation for 40% FL RAP with PG 52-34 at 20°C
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

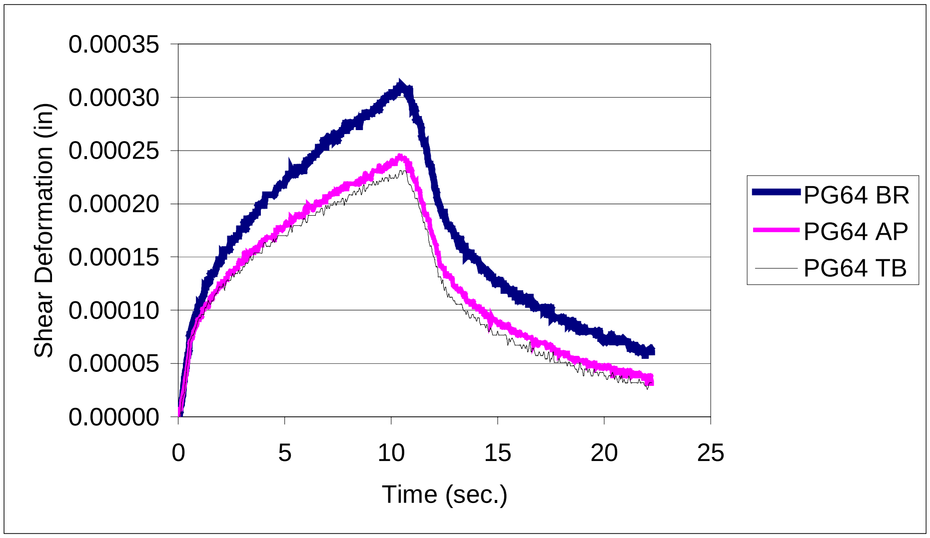

Figure 11. Simple Shear (SS) Deformation of 10% CT RAP (Aged) at 20°C
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

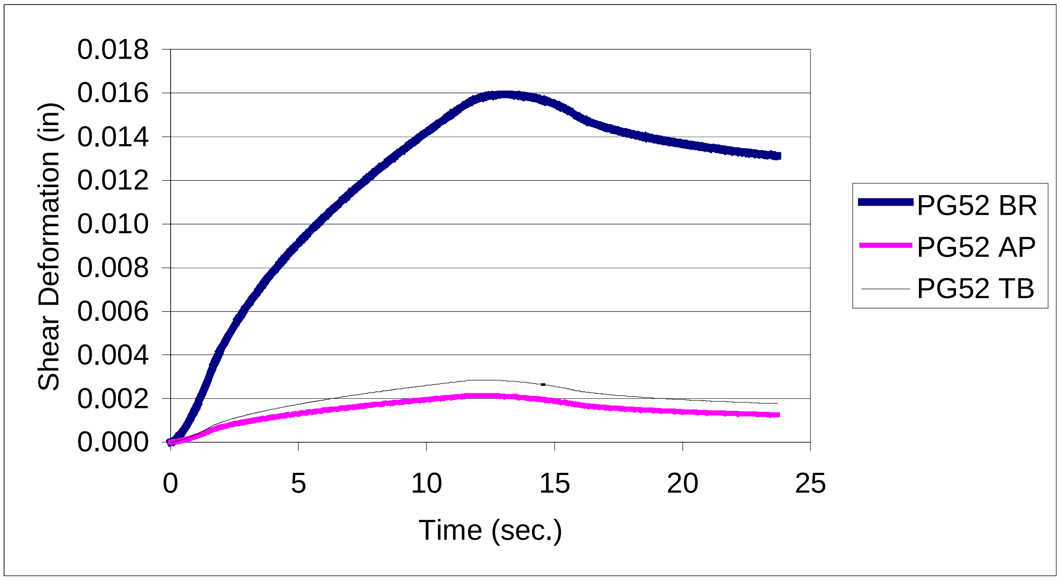

Figure 12. Simple Shear (SS) Deformation for 40% CT RAP with PG 52-34 at 20°C
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

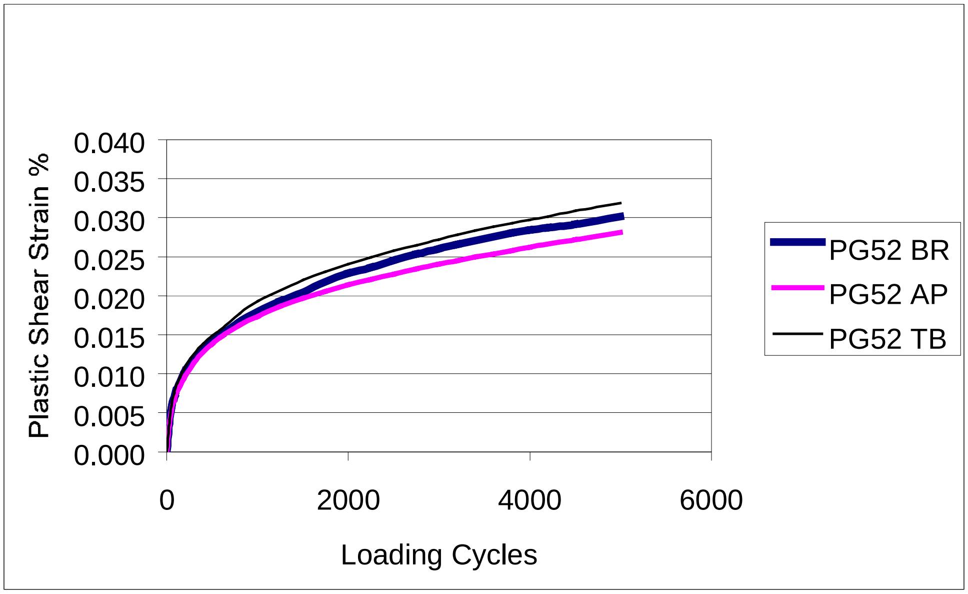

Figure 13. Repeated Shear (RSCH) Results for 10% CT RAP with PG 52-34
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

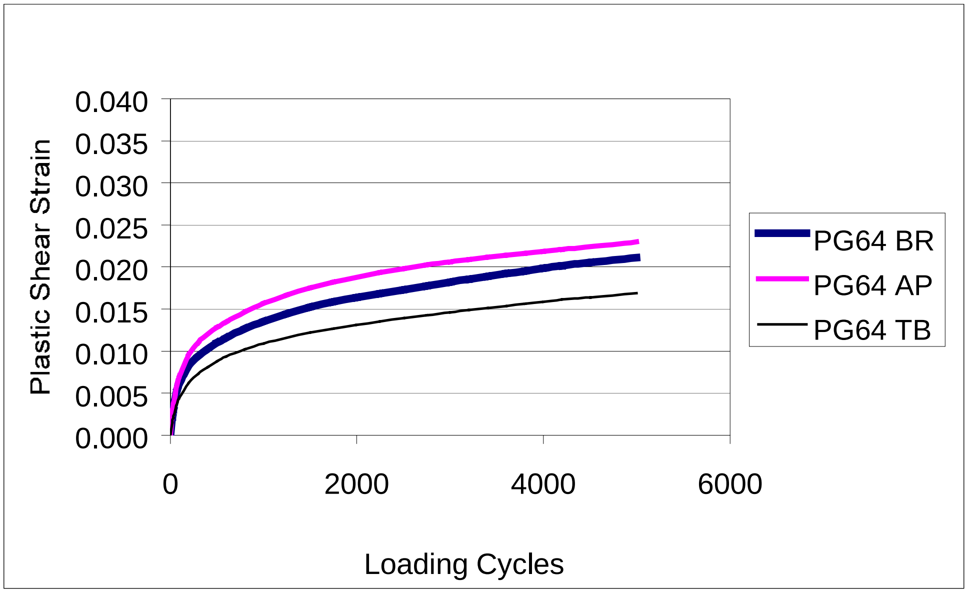

Figure 14. Repeated Shear (RSCH) Results for 10% AZ RAP with PG 64-22
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

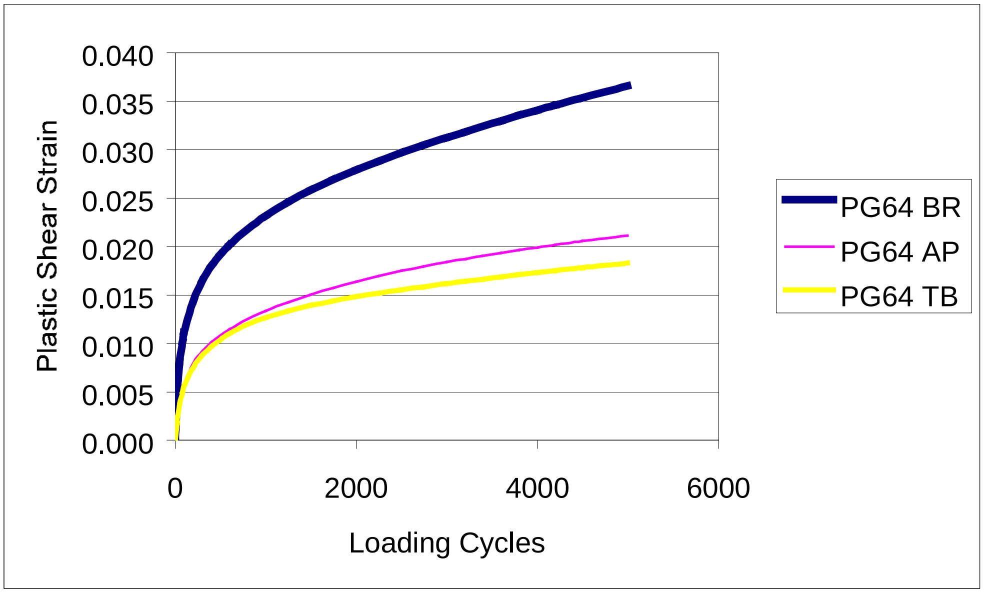

Figure 15. Repeated Shear (RSCH) Results for 40% CT RAP with PG 64-22
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

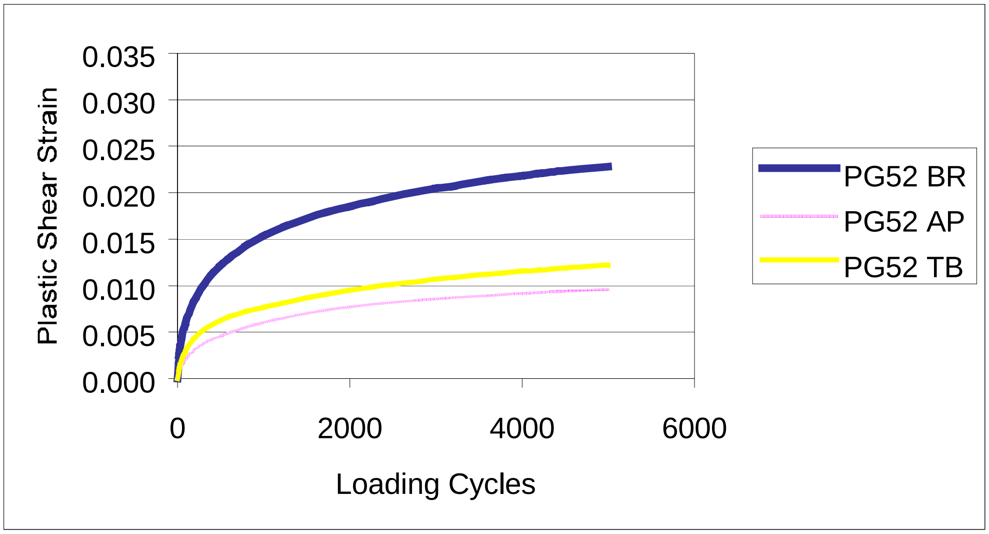

Figure 16. Repeated Shear (RSCH) Results for 40% AZ RAP with PG 52-34
Note: BR = Black Rock, AP = Actual Practice, TB = Total Blending

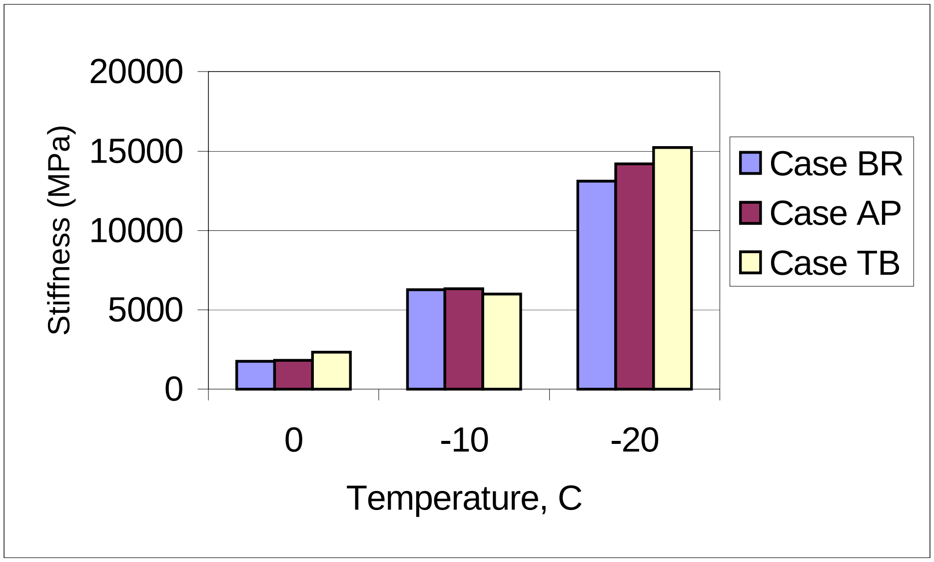

Figure 17. IDT Stiffness for 10% AZ RAP with PG 52-34

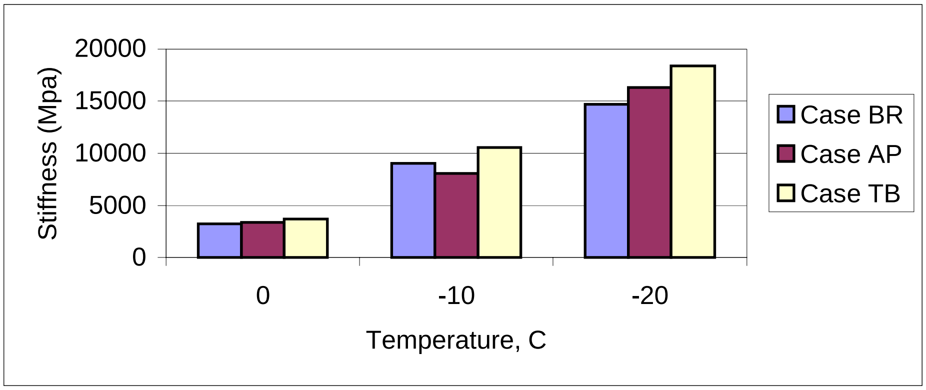

Figure 18. IDT Stiffness for 10% CT RAP with PG 64-22

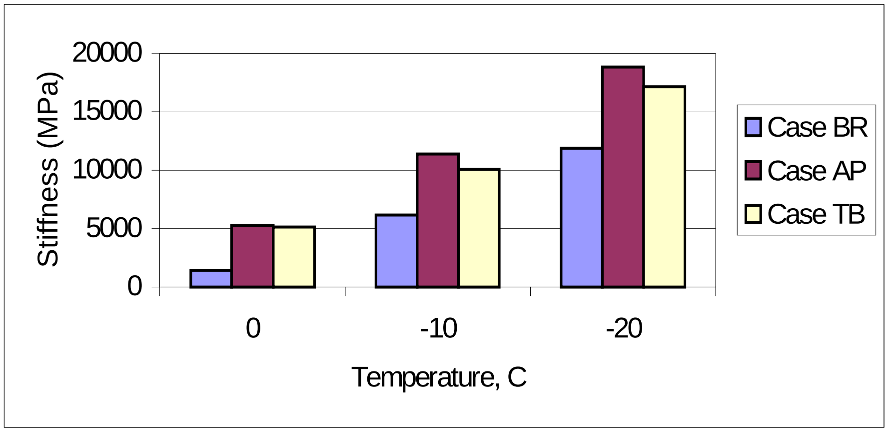

Figure 19. IDT Stiffness for 40% AZ RAP with PG 52-34

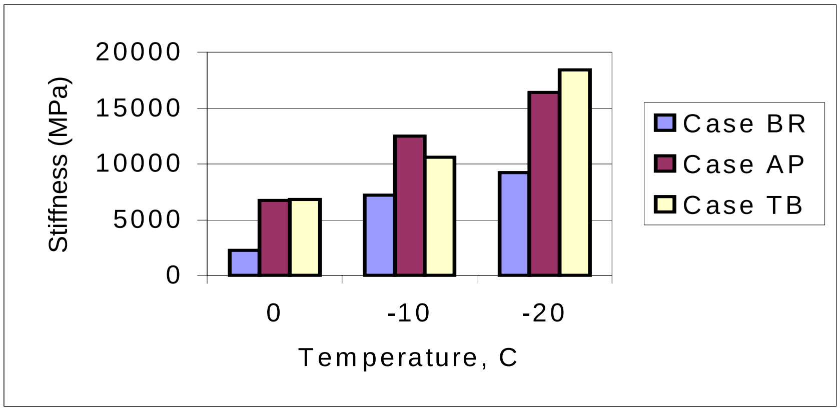

Figure 20. IDT Stiffness for 40% CT RAP with PG 64-22
Note: A = Black Rock, B = Actual Practice, C = Total Blending

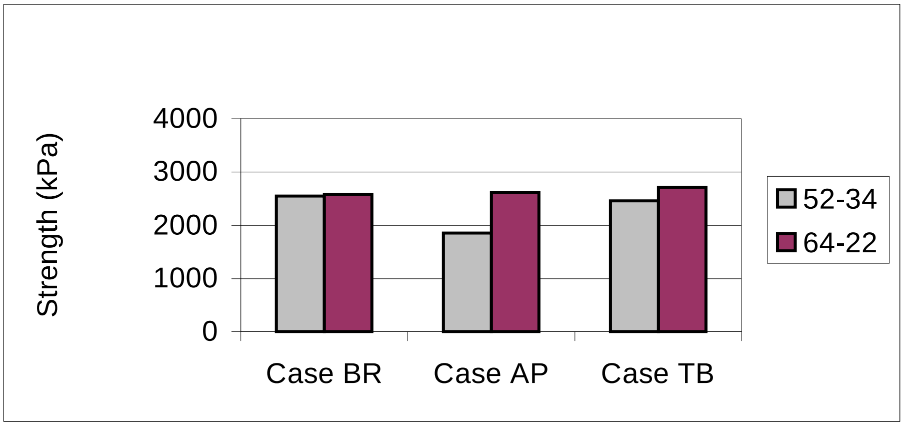

Figure 21. IDT Strength for 10% AZ RAP

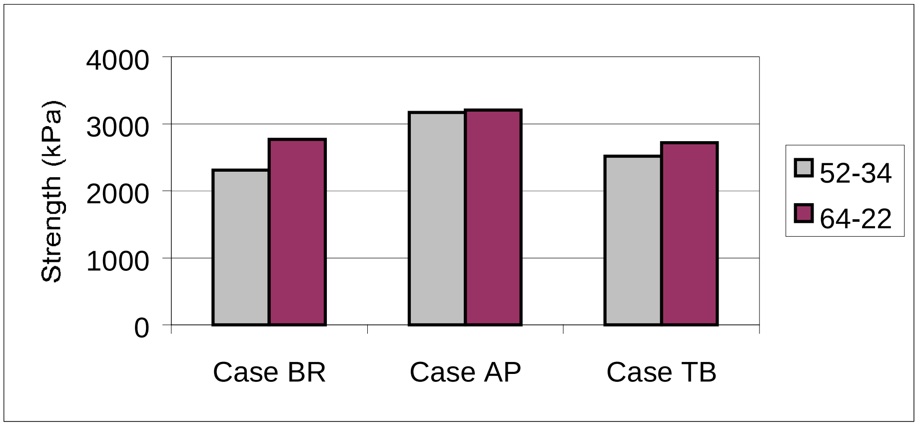

Figure 22. IDT Strength for 40% AZ RAP

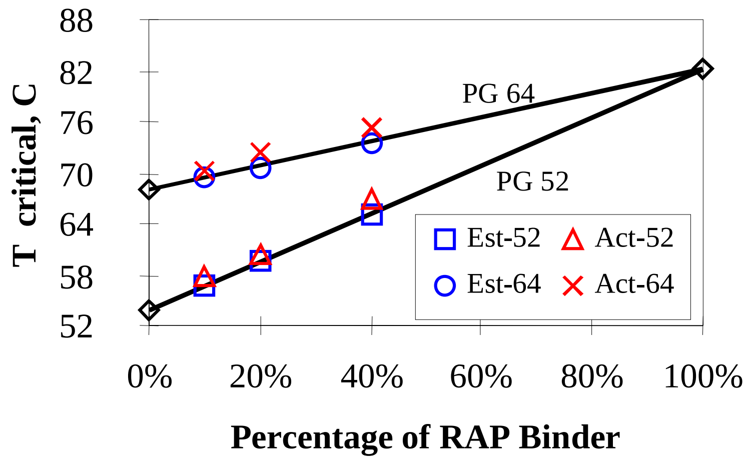

Figure 23. Critical Temperatures of Original DSR – Florida RAP Blends

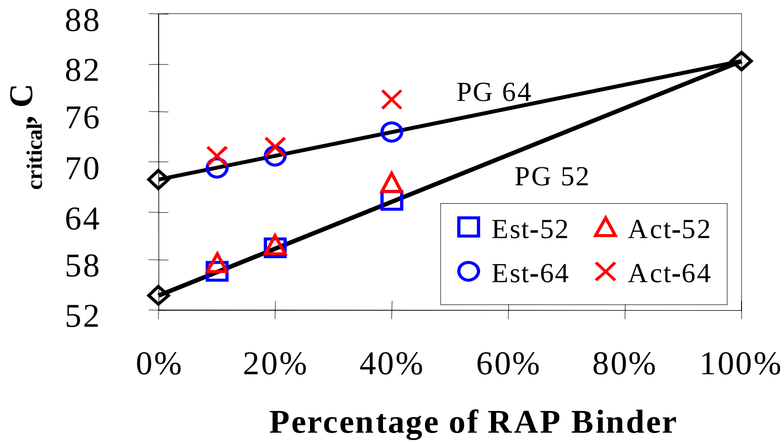

Figure 24. Critical Temperatures of Original DSR – Connecticut RAP Blends

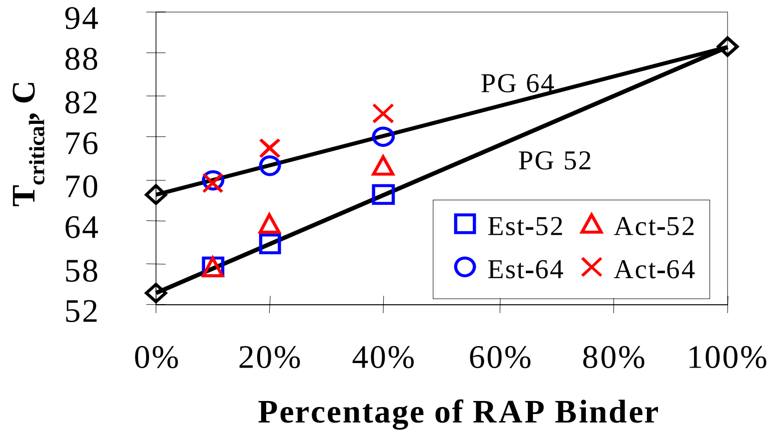

Figure 25. Critical Temperatures of Original DSR – Arizona RAP Blends

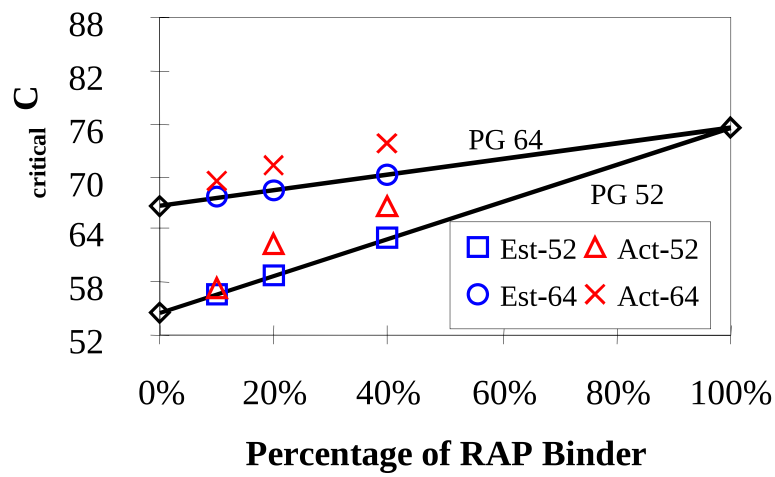

Figure 26. Critical Temperatures of RTFO DSR – Florida RAP Blends

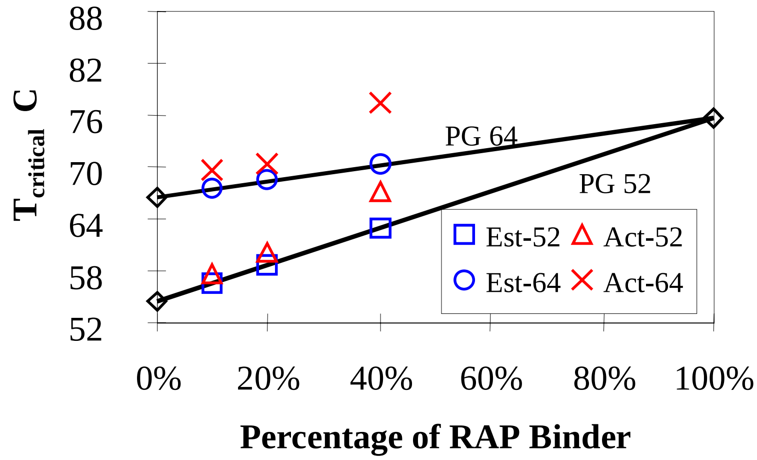

Figure 27. Critical Temperatures of RTFO DSR – Connecticut RAP Blends

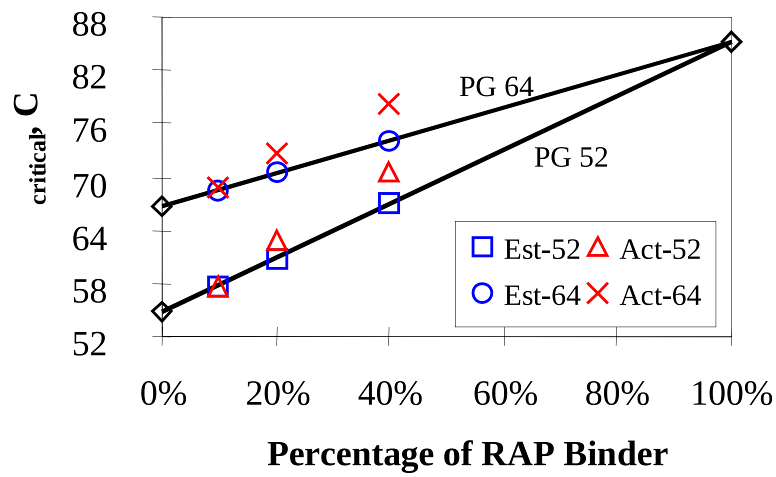

Figure 28. Critical Temperatures of RTFO DSR – Arizona RAP Blends

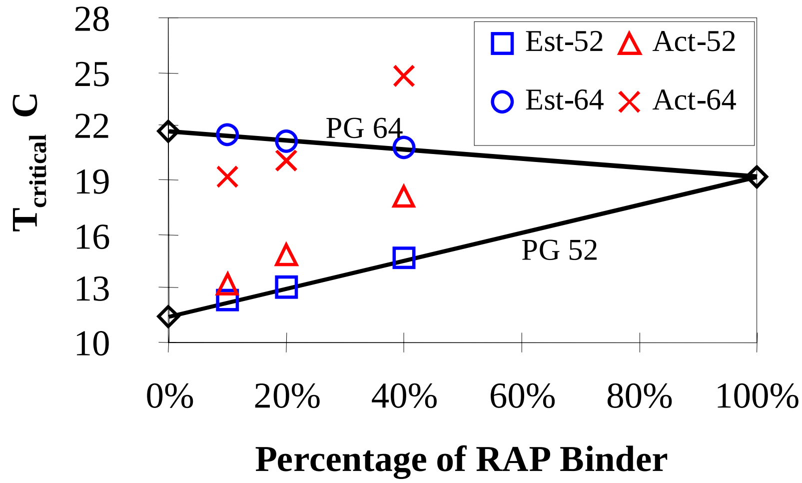

Figure 29. Critical Temperatures of PAV DSR – Florida RAP Blends

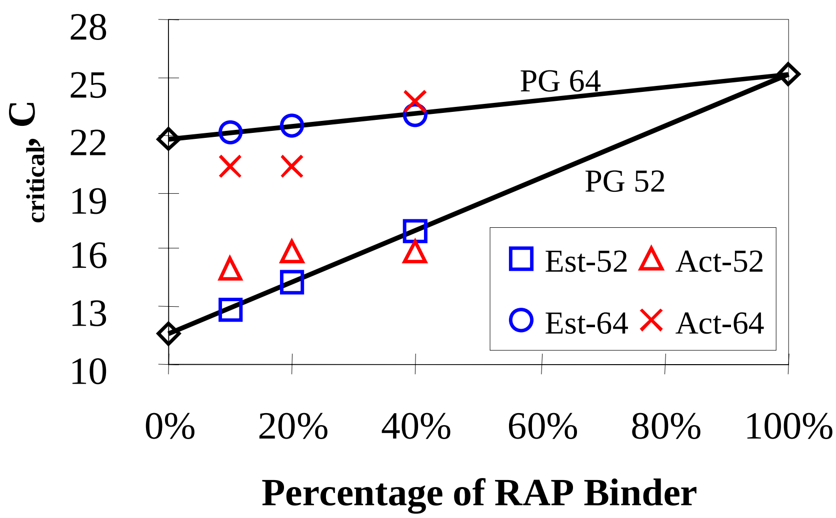

Figure 30. Critical Temperatures of PAV DSR – Connecticut RAP Blends

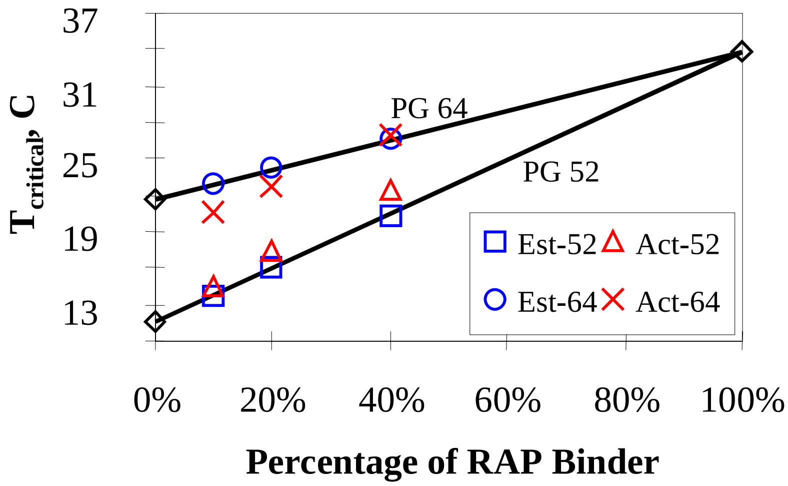

Figure 31. Critical Temperatures of PAV DSR – Arizona RAP Blends

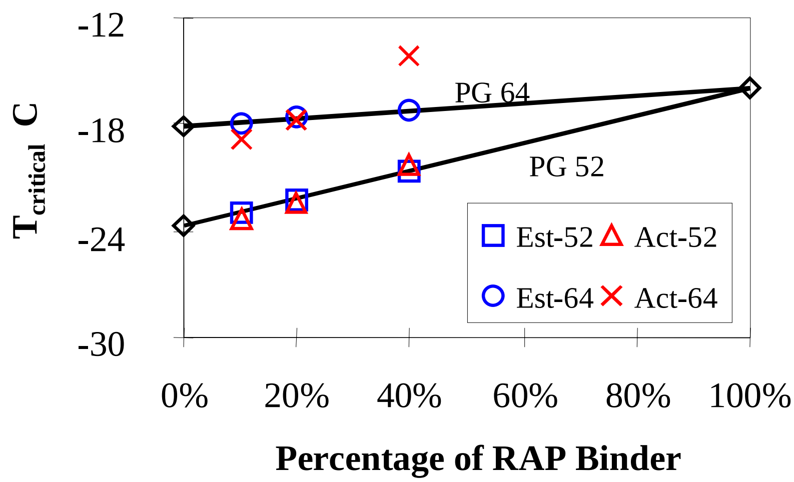

Figure 32. Critical Temperatures of BBR Stiffness – Florida RAP Blends

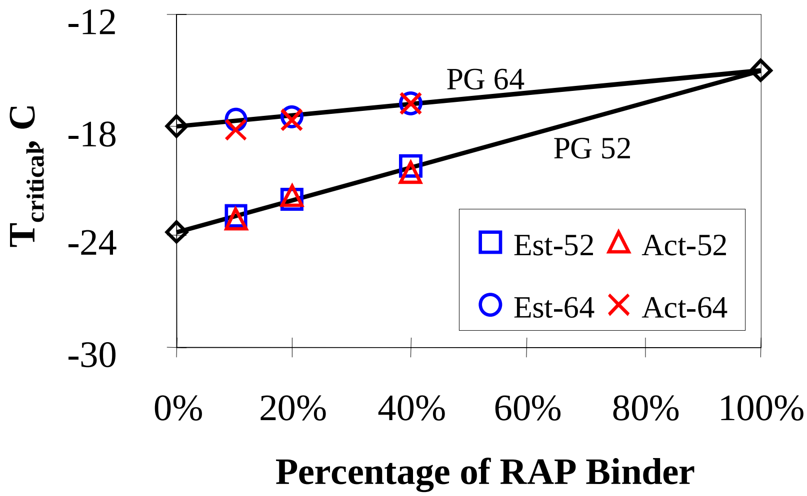

Figure 33. Critical Temperatures of BBR Stiffness – Connecticut RAP Blends

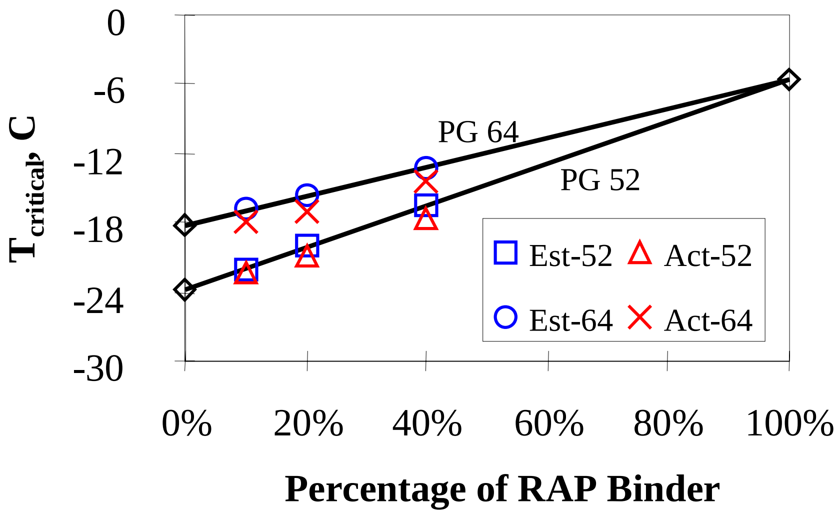

Figure 34. Critical Temperatures of BBR Stiffness – Arizona RAP Blends

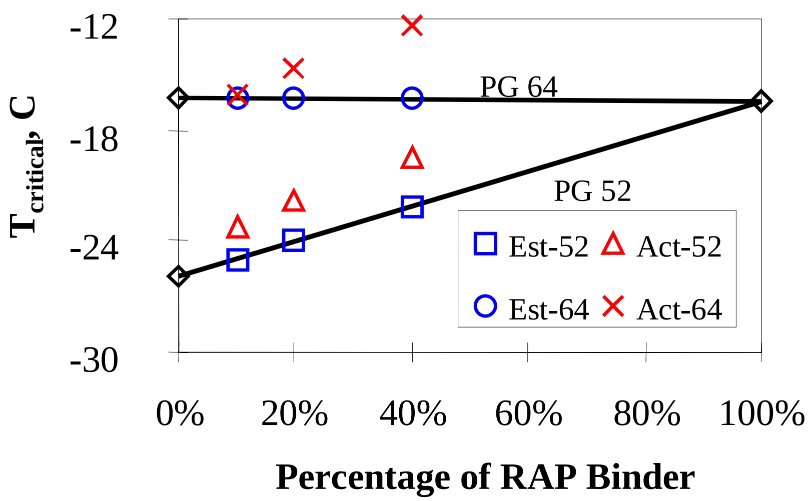

Figure 35. Critical Temperatures of BBR m-value – Florida RAP Blends

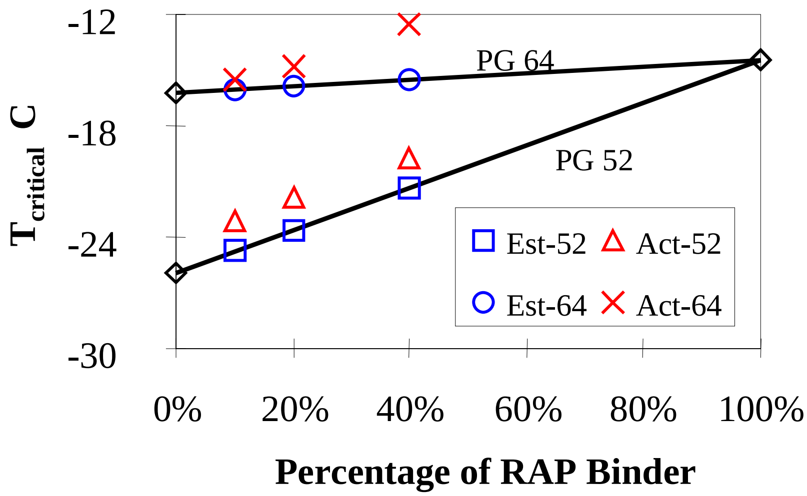

Figure 36. Critical Temperatures of BBR m-value – Connecticut RAP Blends

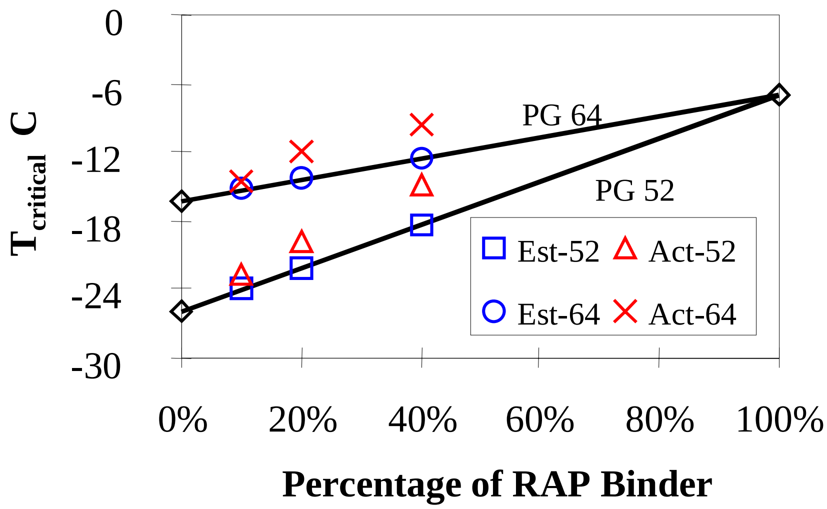

Figure 37. Critical Temperatures of BBR m-value – Arizona RAP Blends

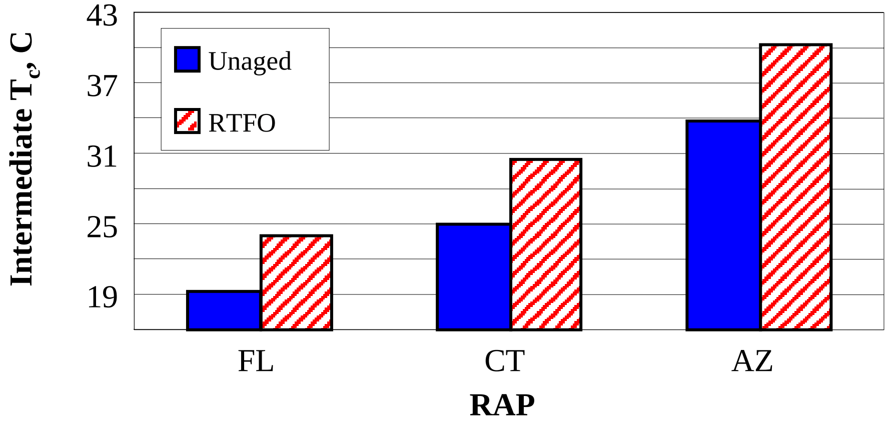

Figure 38. Comparison of Critical Intermediate Temperatures for Recovered RAP Binders after RTFO

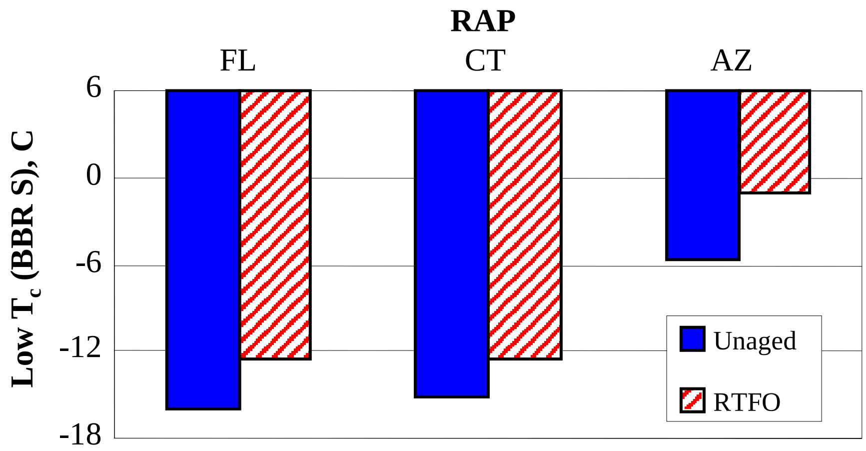

Figure 39. Comparison of Critical Low Temperatures (Stiffness) for Recovered RAP Binders after RTFO

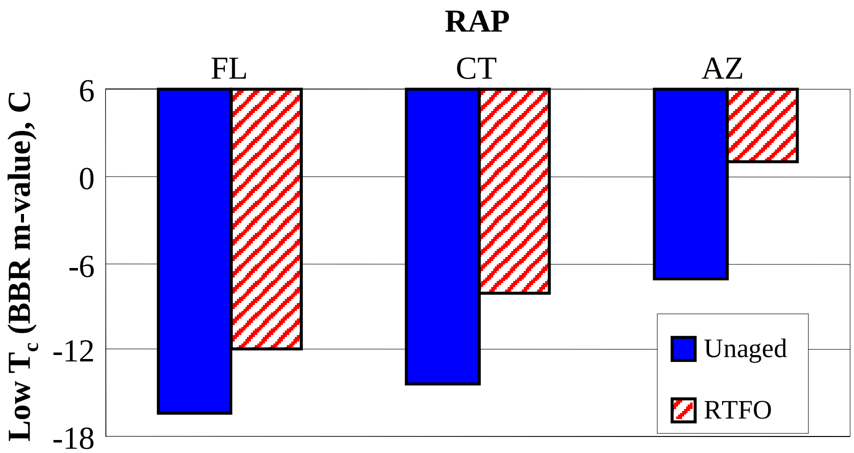

Figure 40. Comparison of Critical Low Temperatures (m-value) for Recovered RAP Binders after RTFO

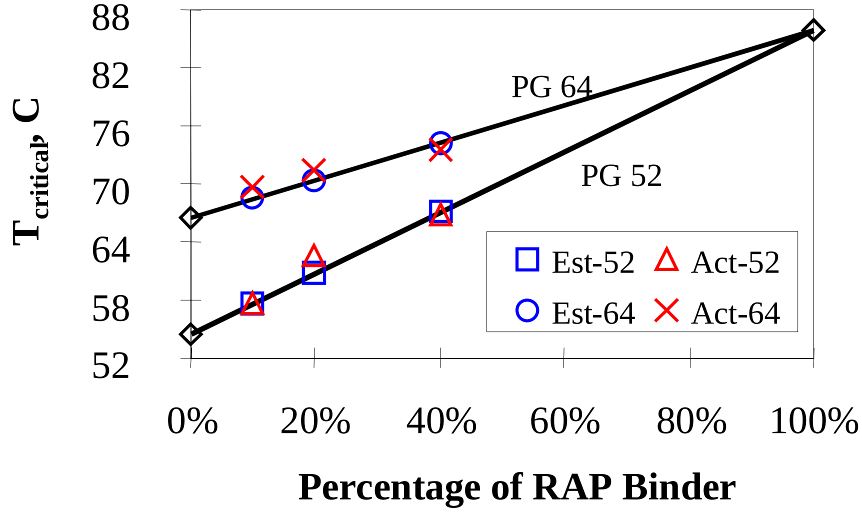

Figure 41. Critical Temperatures of RTFO DSR – Florida RAP Blends with RTFO

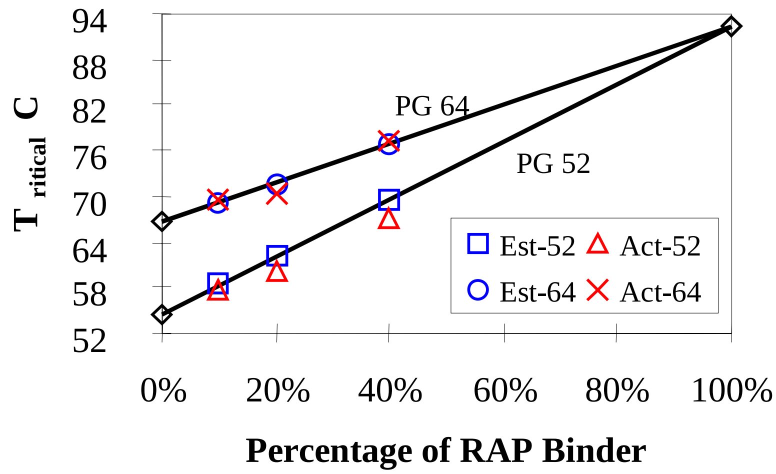

Figure 42. Critical Temperatures of RTFO DSR – Connecticut RAP Blends with RTFO

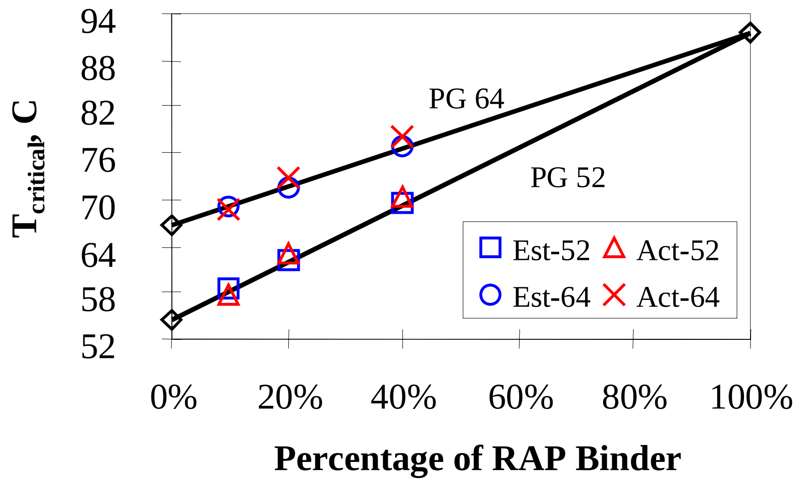

Figure 43. Critical Temperatures of RTFO DSR – Arizona RAP Blends with RTFO

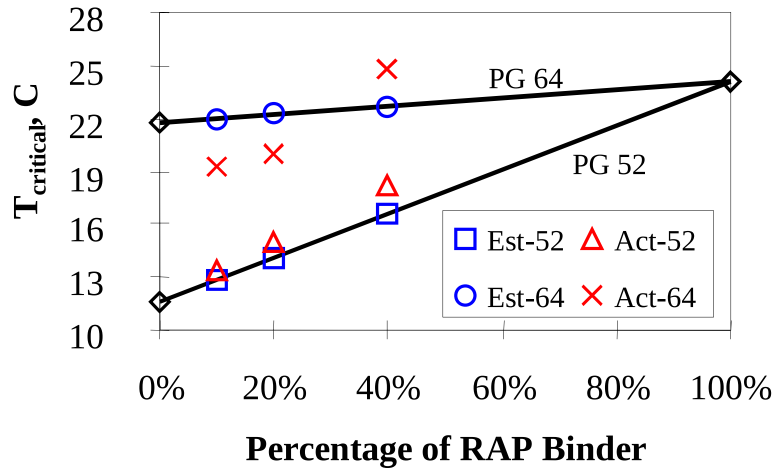

Figure 44. Critical Temperatures of PAV DSR – Florida RAP Blends with RTFO

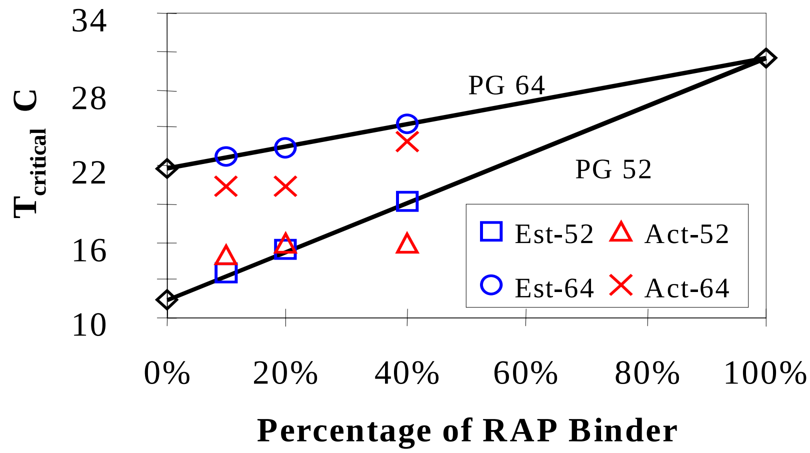

Figure 45. Critical Temperatures of PAV DSR – Connecticut RAP Blends with RTFO

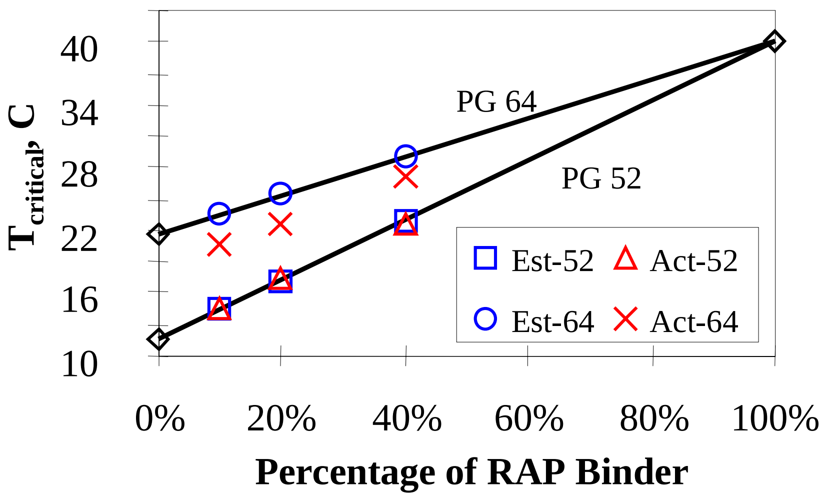

Figure 46. Critical Temperatures of PAV DSR – Arizona RAP Blends with RTFO

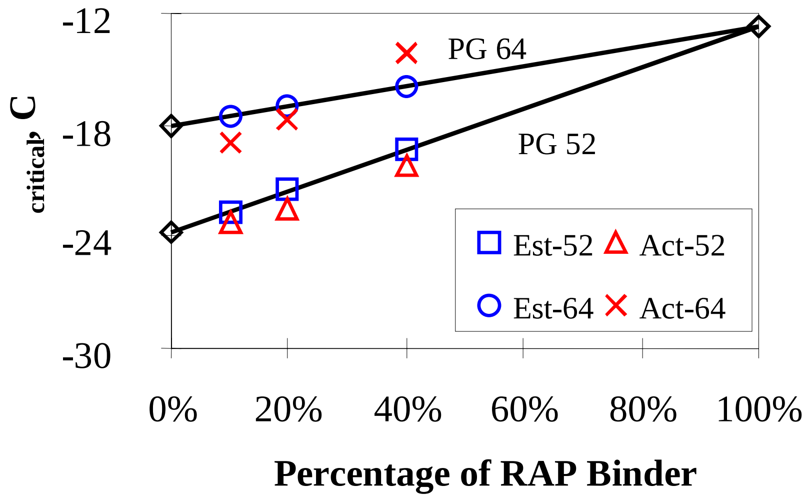

Figure 47. Critical Temperatures of BBR Stiffness – Florida RAP Blends with RTFO

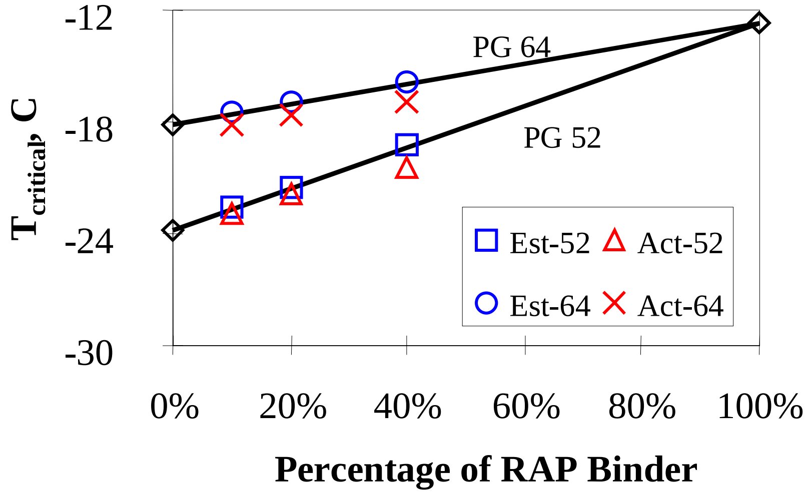

Figure 48. Critical Temperatures of BBR Stiffness – Connecticut RAP Blends with RTFO

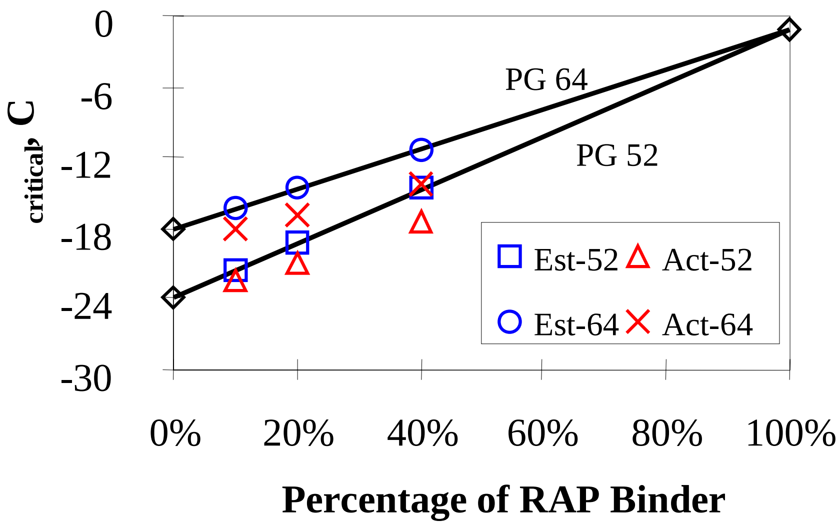

Figure 49. Critical Temperatures of BBR Stiffness – Arizona RAP Blends with RTFO

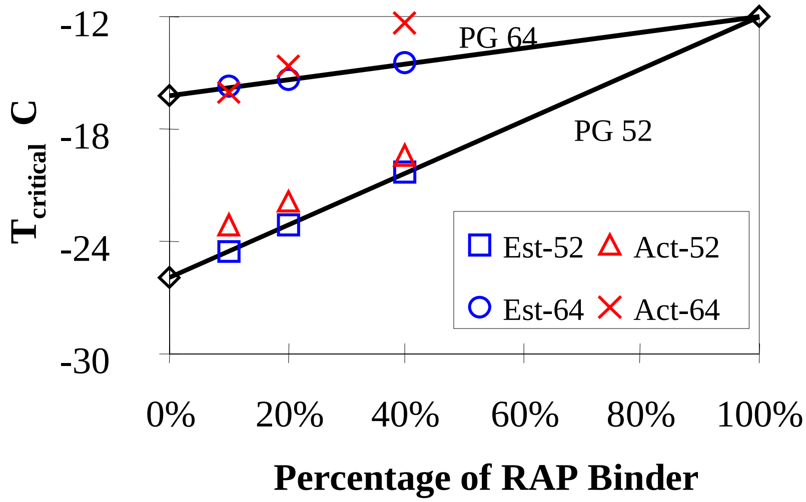

Figure 50. Critical Temperatures of BBR m-value – Florida RAP Blends with RTFO

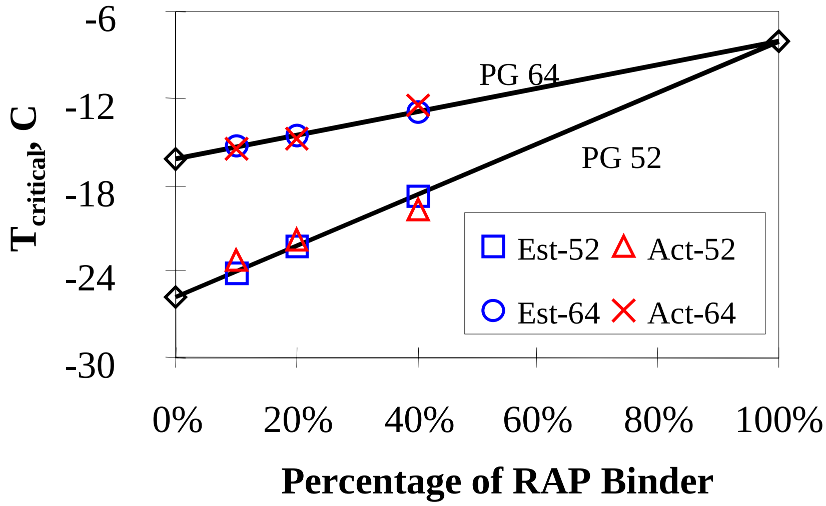

Figure 51. Critical Temperatures of BBR m-value – Connecticut RAP Blends with RTFO

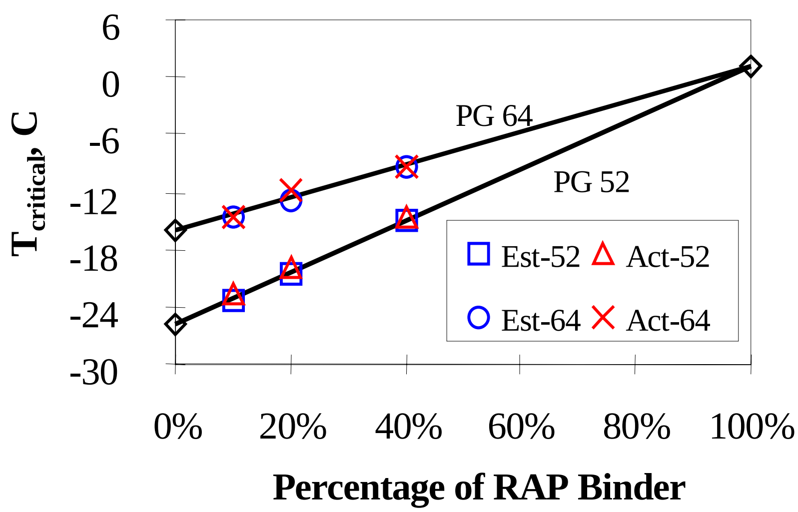

Figure 52. Critical Temperatures of BBR m-value – Arizona RAP Blends with RTFO

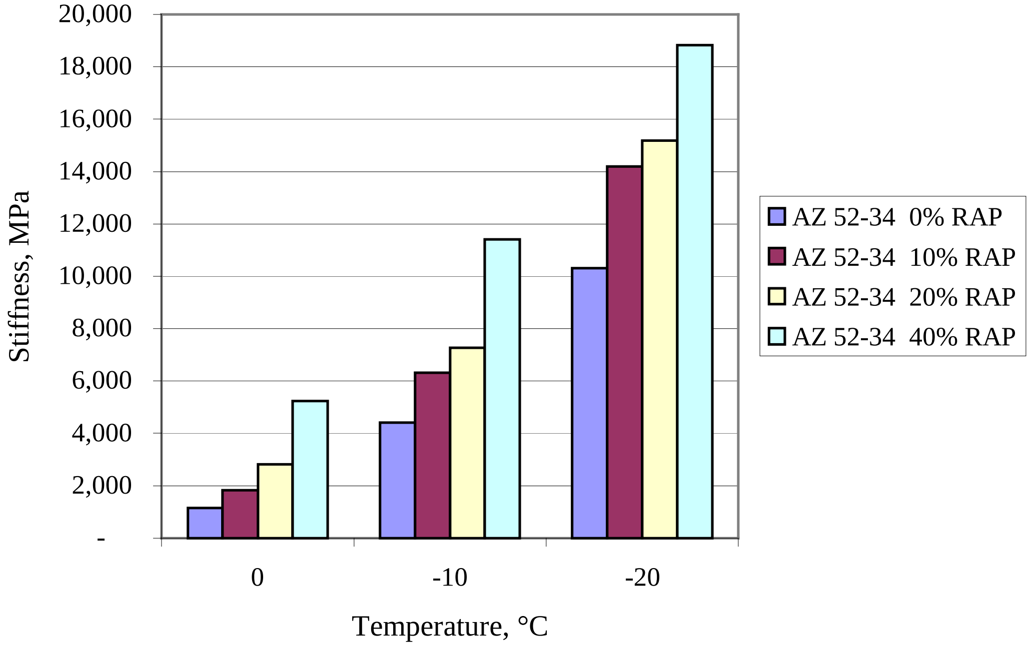

Figure 53. IDT Stiffness at 60 sec., Arizona RAP with PG 52-34

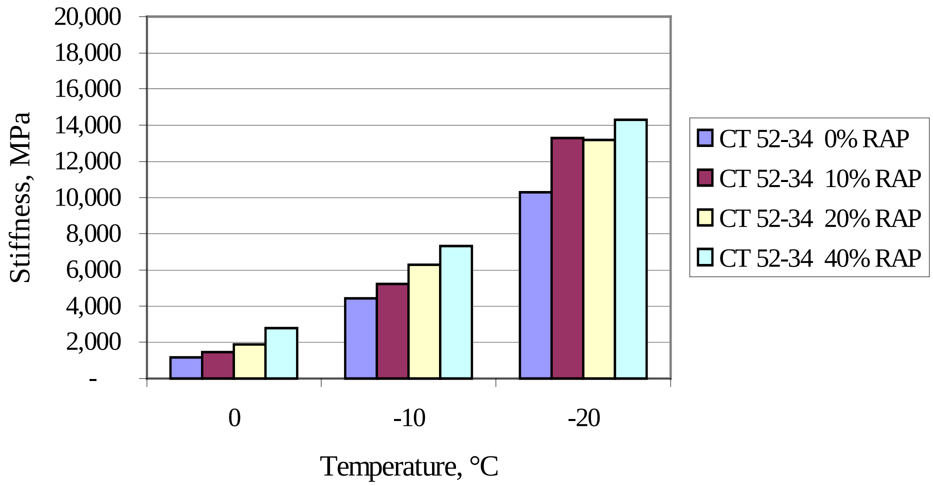

Figure 54. IDT Stiffness at 60 sec., Connecticut RAP with PG 52-34

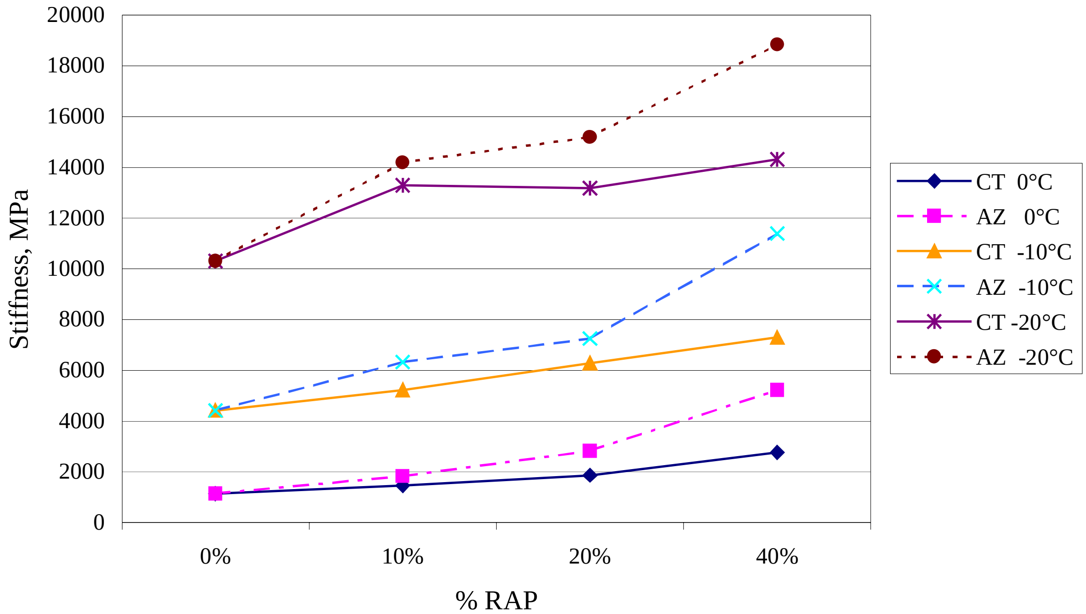

Figure 55. Comparison of IDT Stiffness for Arizona and Connecticut RAP with PG 52-34

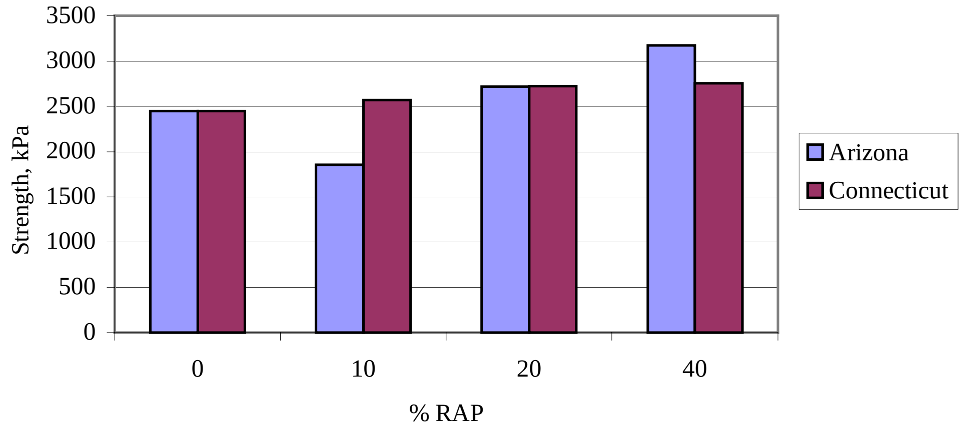

Figure 56. PG 52-34 IDT Strengths

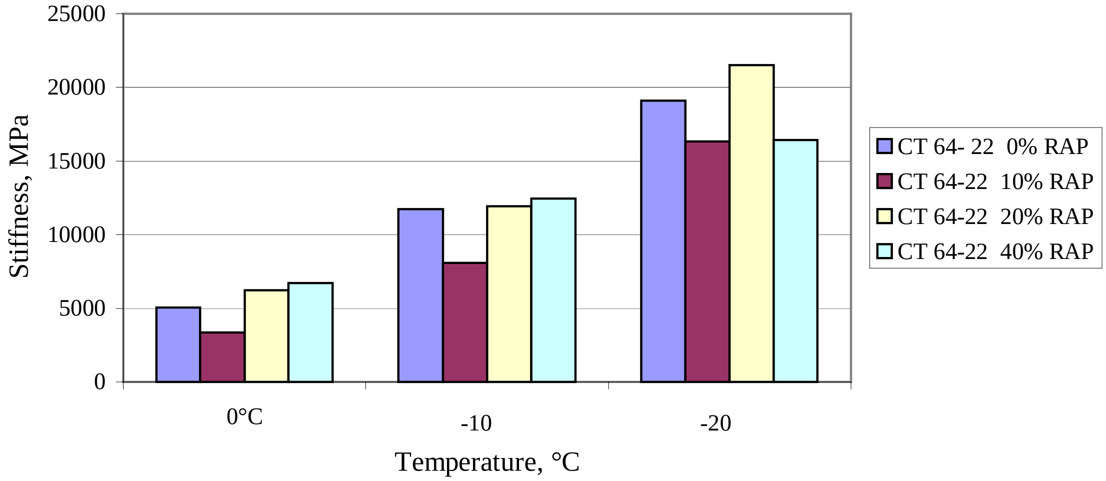

Figure 57. Connecticut RAP with PG 64-22, Stiffness

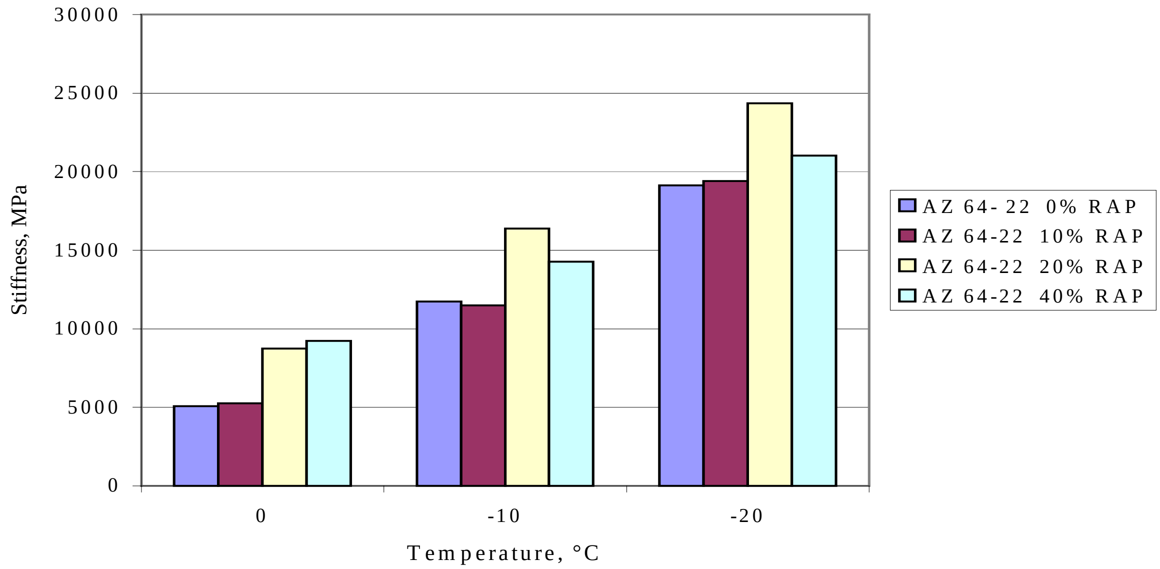

Figure 58. IDT Stiffness, MPa, PG 64-22 blends with Arizona RAP

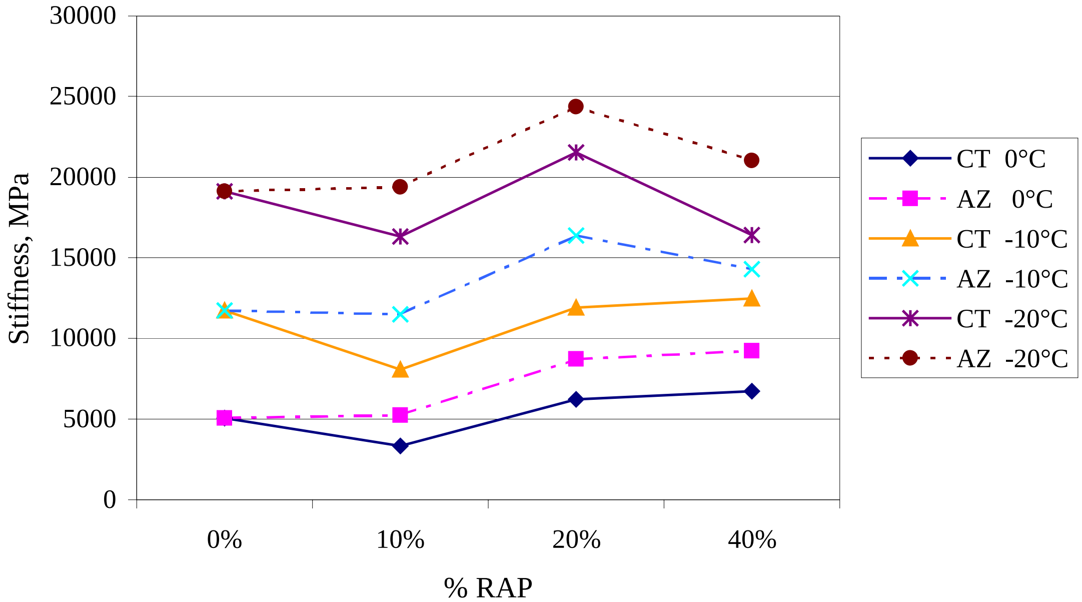

Figure 59. Comparison of IDT Stiffness for Arizona and Connecticut RAP with PG 64-22

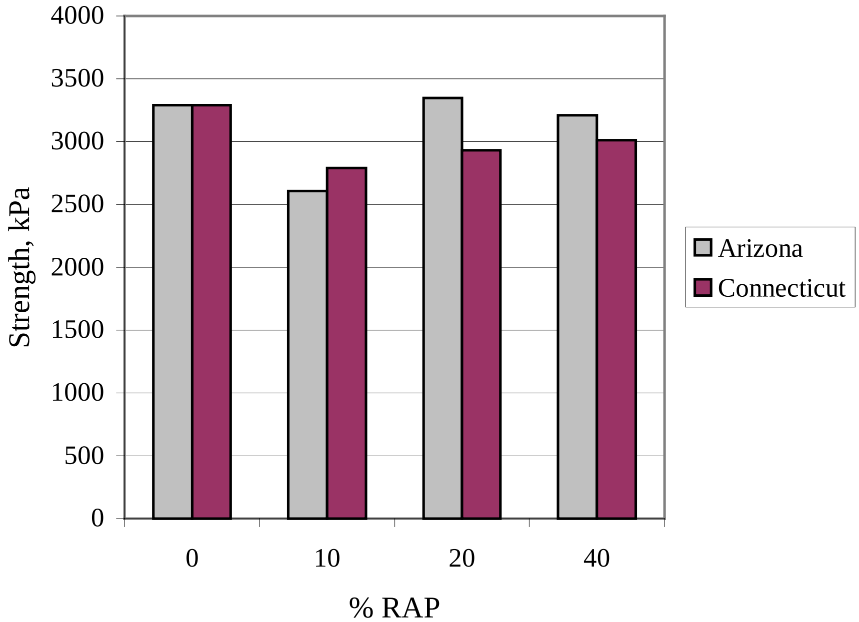

Figure 60. PG 64-22 IDT Strengths @ -10°C

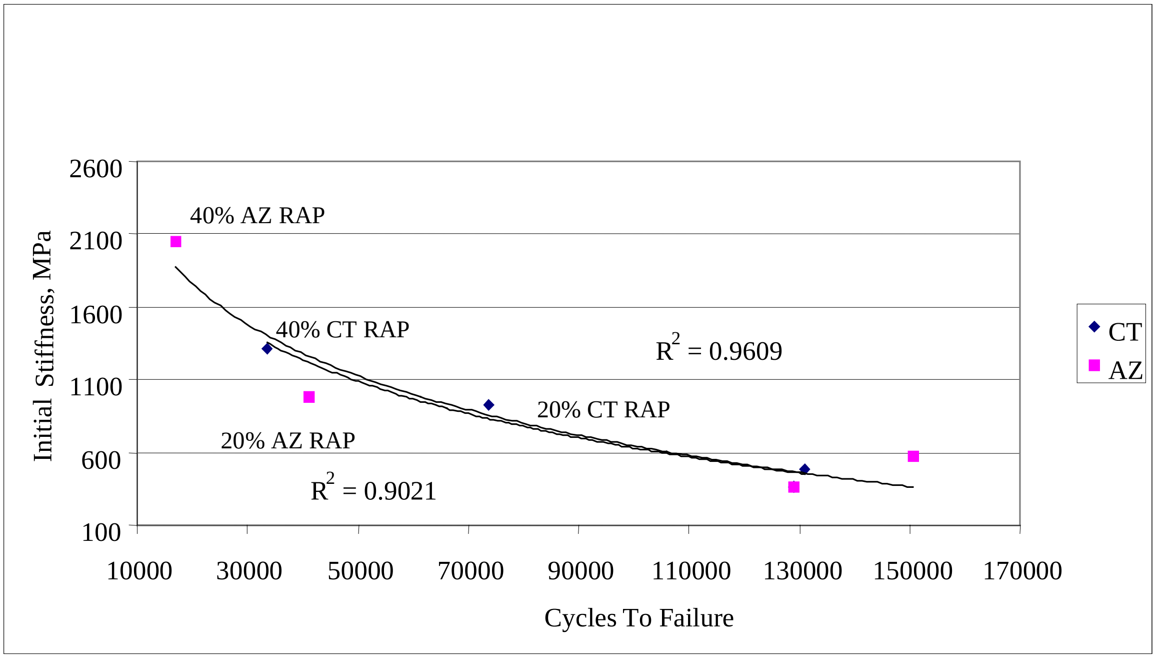

Figure 61. Beam Fatigue, Cycles vs. Stiffness High Strain, PG 52-34

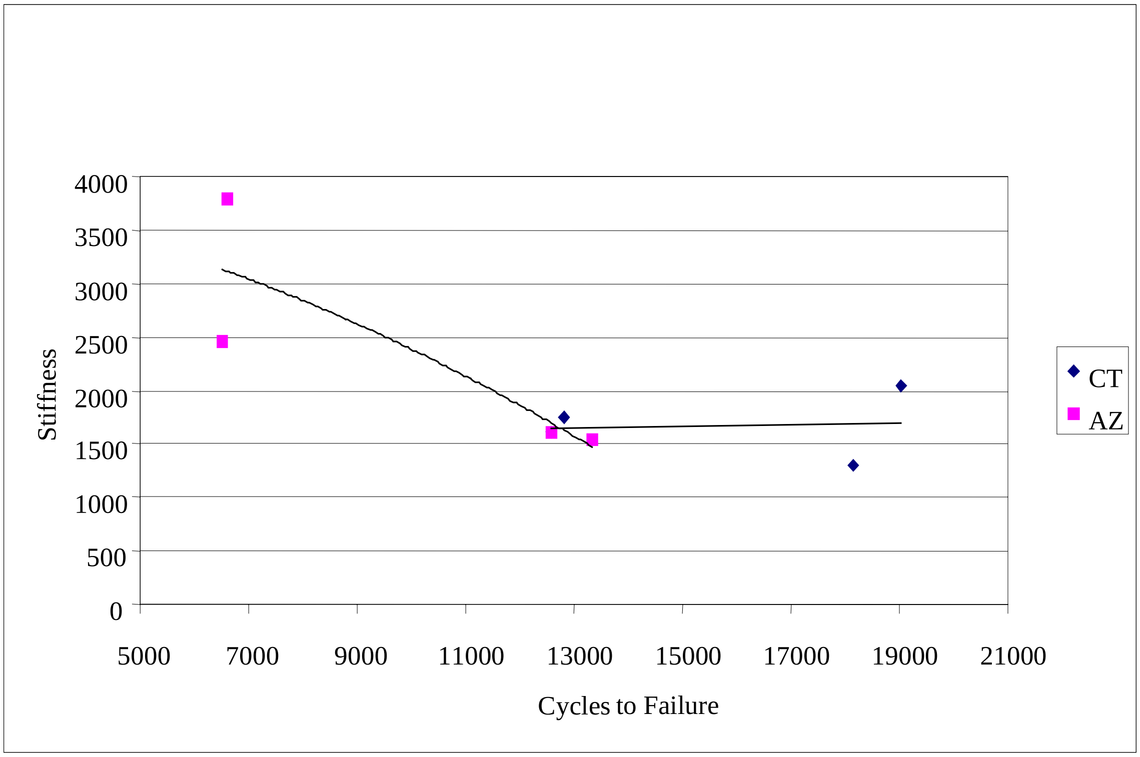

Figure 62. Beam Fatigue, Cycles vs. Stiffness High Strain, PG 64-22

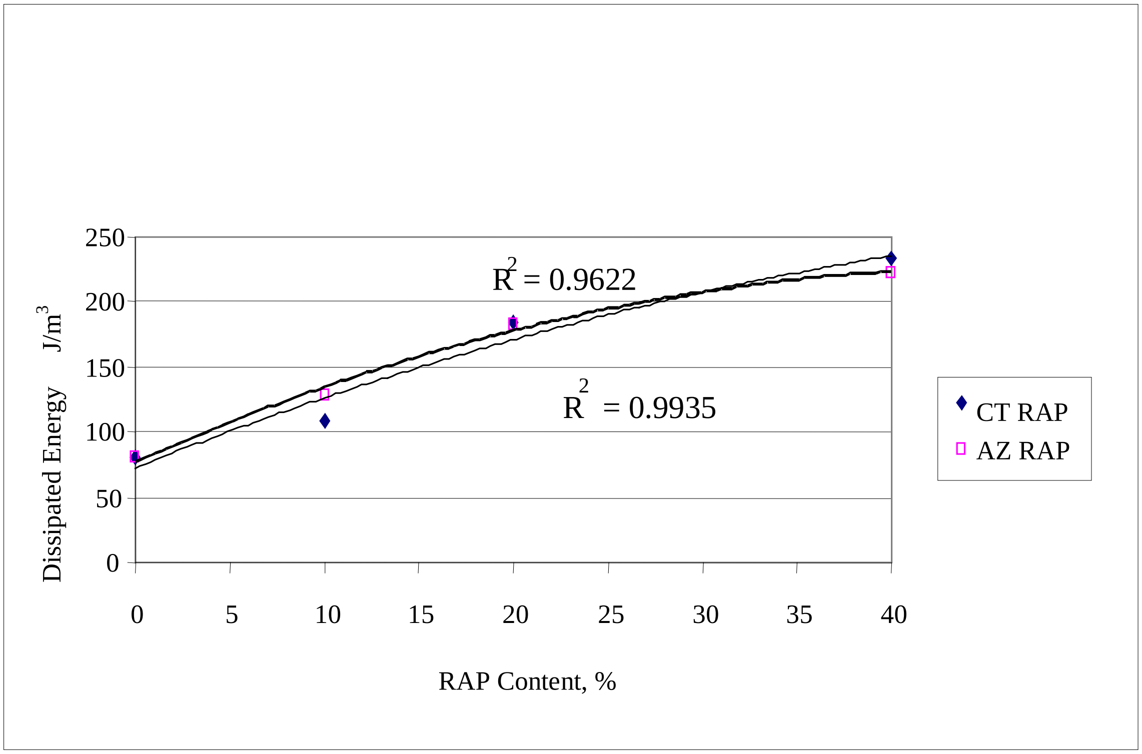

Figure 63. %RAP vs. Dissipated Energy, Beam Fatigue, High Strain, PG 52-34

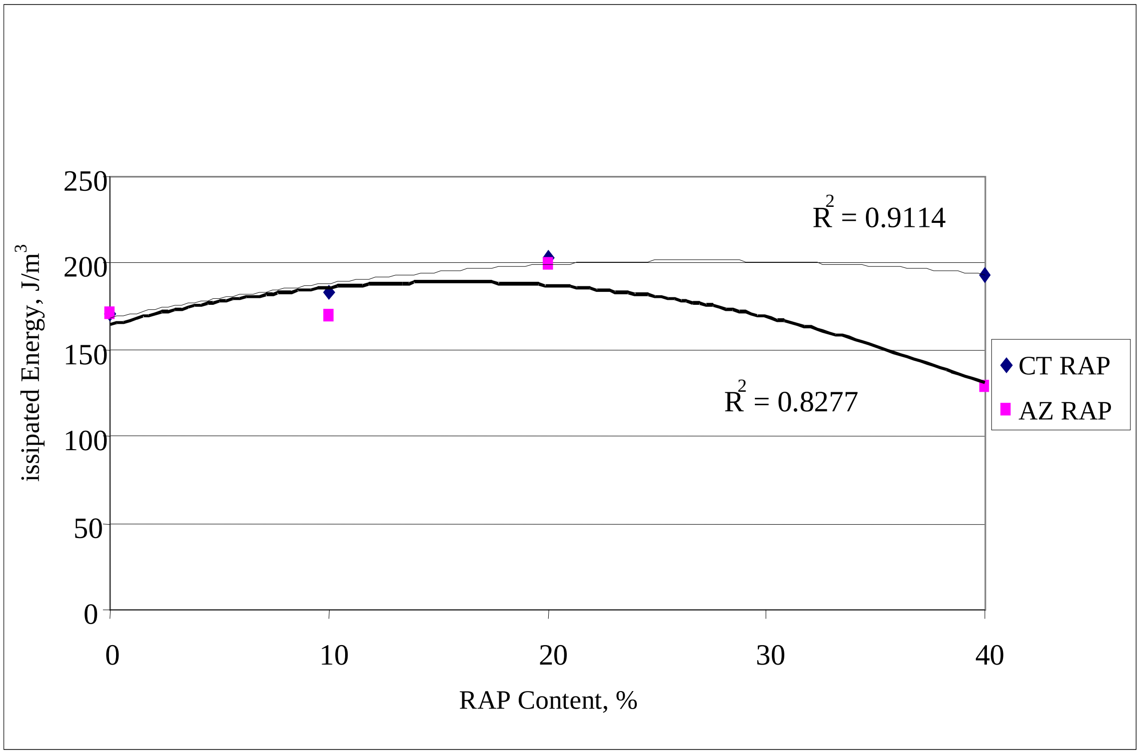

Figure 64. %RAP vs. Dissipated Energy, Beam Fatigue, High Strain, PG 64-22

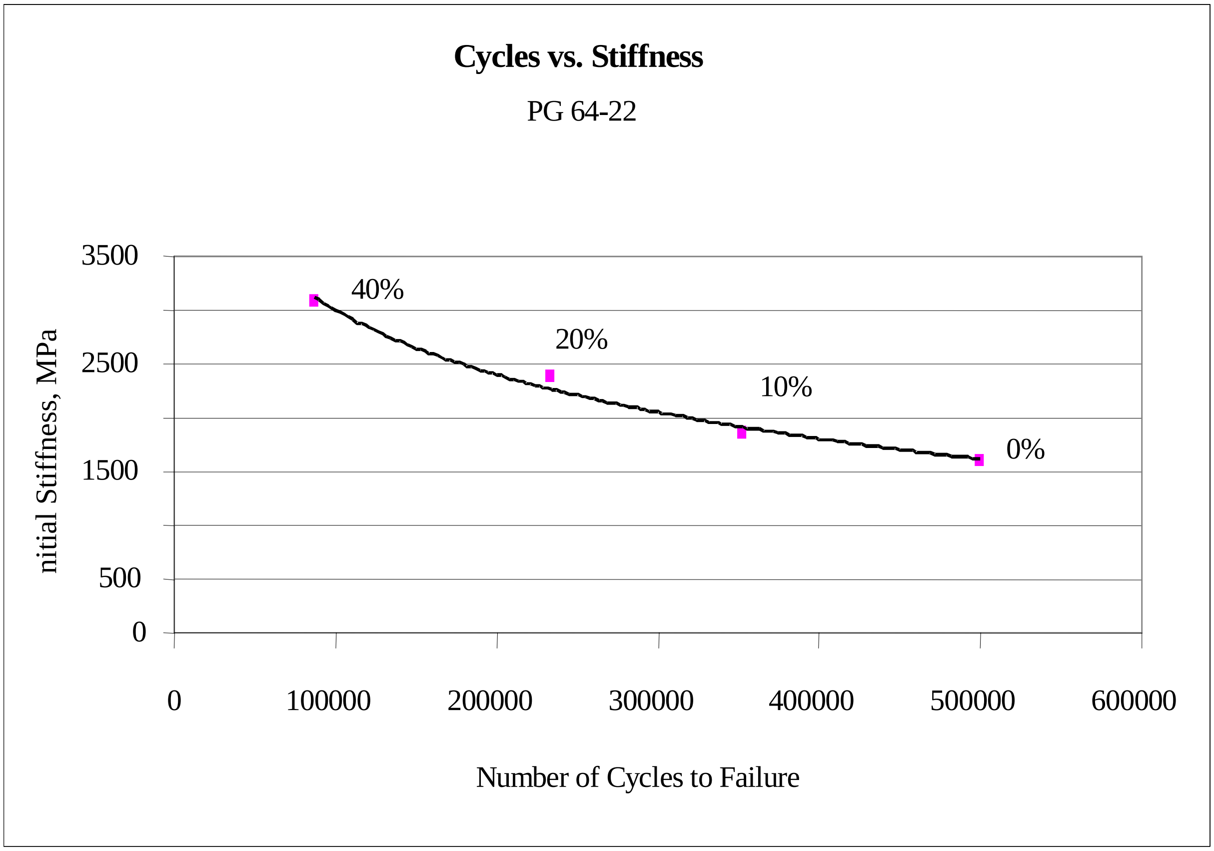

Figure 65. Beam Fatigue Cycles to Failure vs. Stiffness, PG 64-22, Low Strain

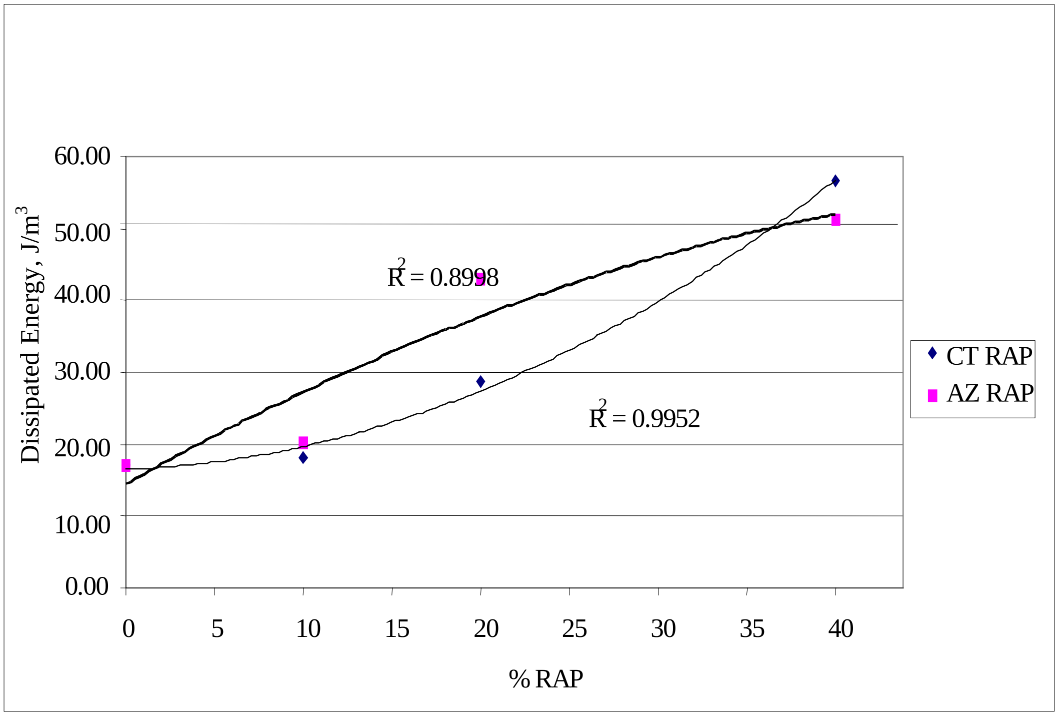

Figure 66. %RAP vs. Dissipated Energy, Beam Fatigue, Low Strain, PG 52-34

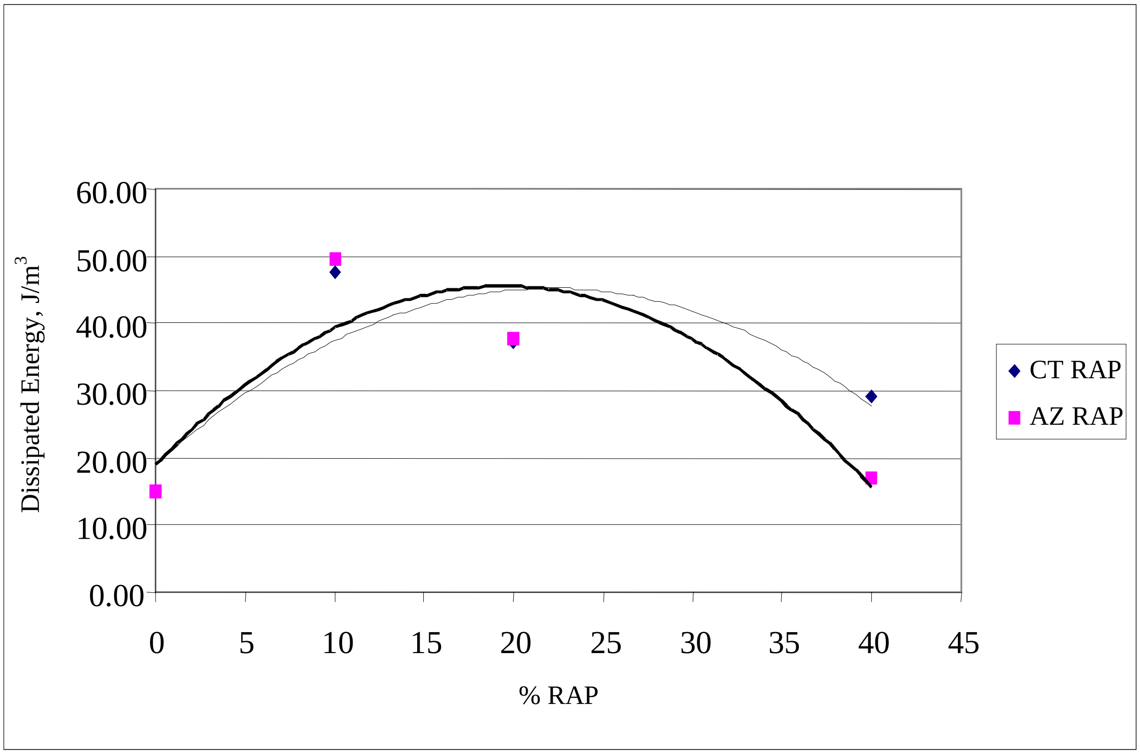

Figure 67. %RAP vs. Dissipated Energy, Beam Fatigue, Low Strain, PG 64-22

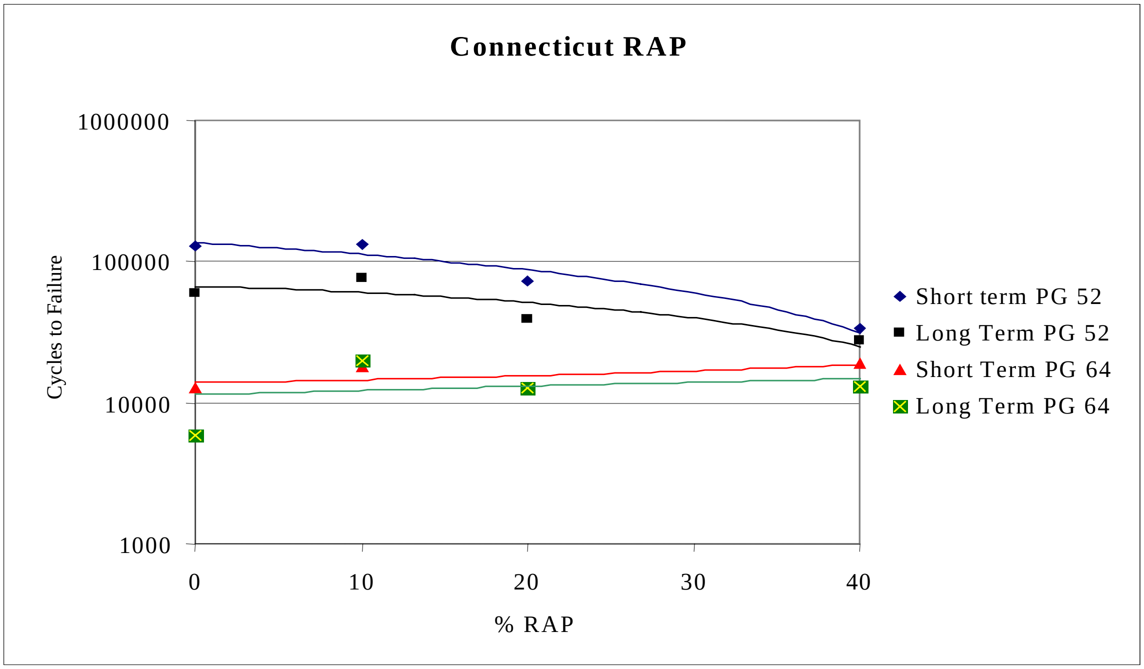

Figure 68. LTOA and STOA %RAP vs. Cycles to Failure in Beam Fatigue

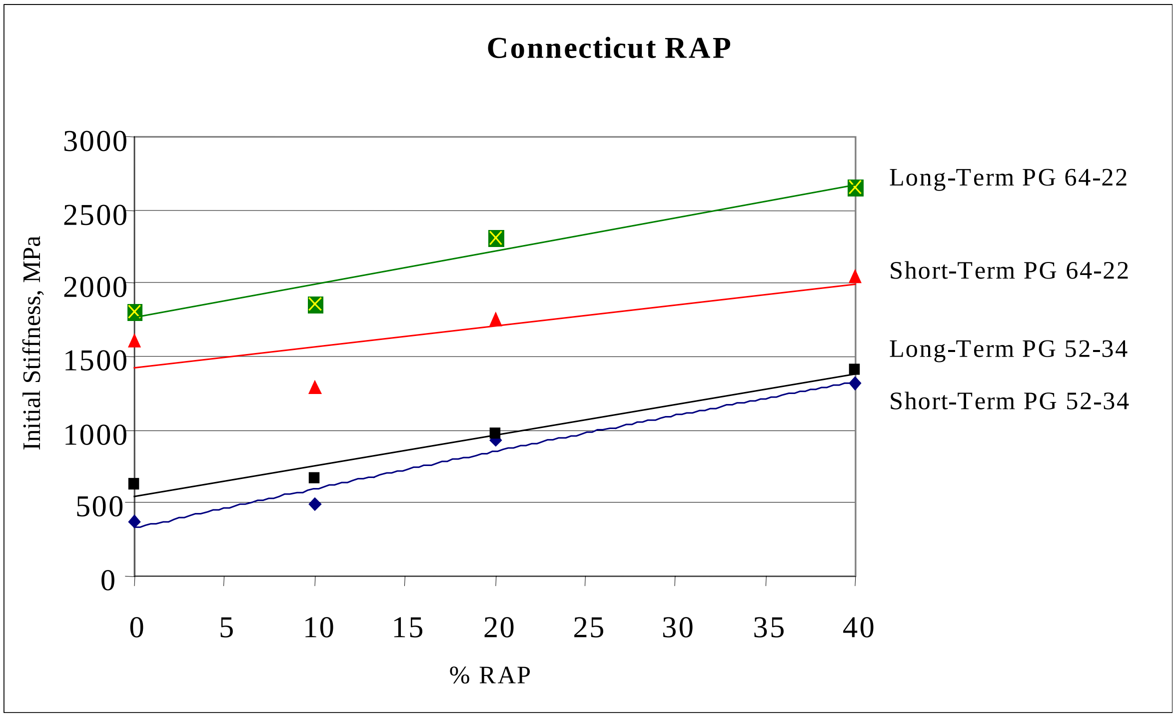

Figure 69. LTOA and STOA %RAP vs. Beam Fatigue Stiffness

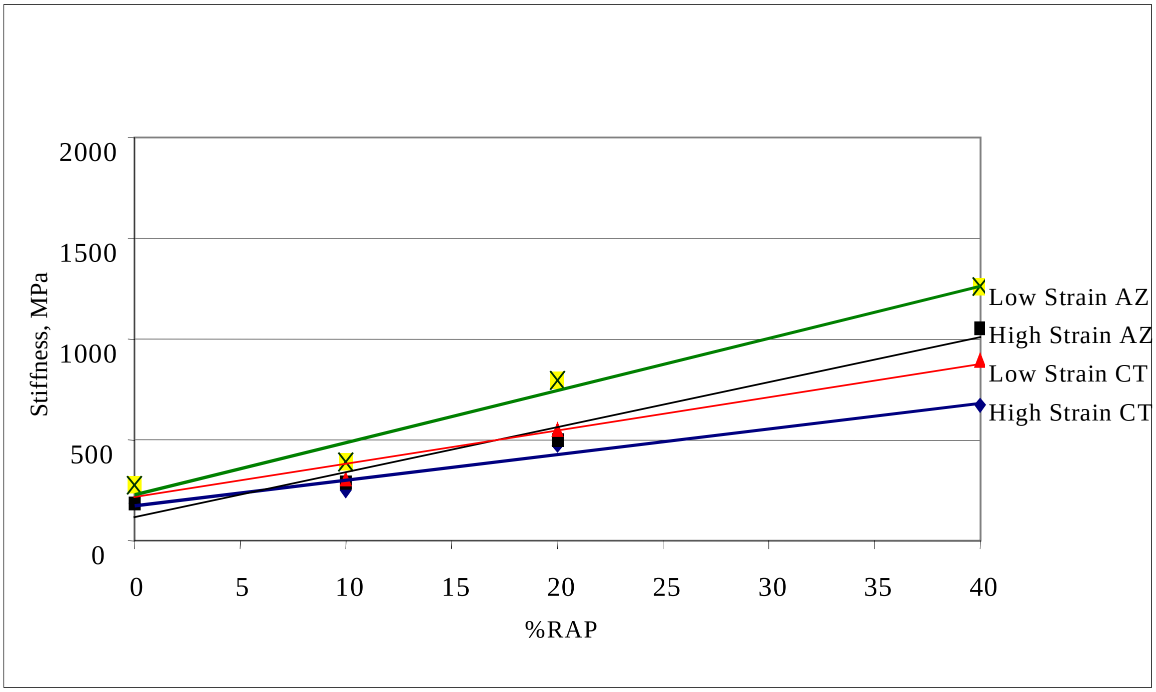

Figure 70. Comparison of High and Low Strain %RAP vs. Stiffness PG 52-34

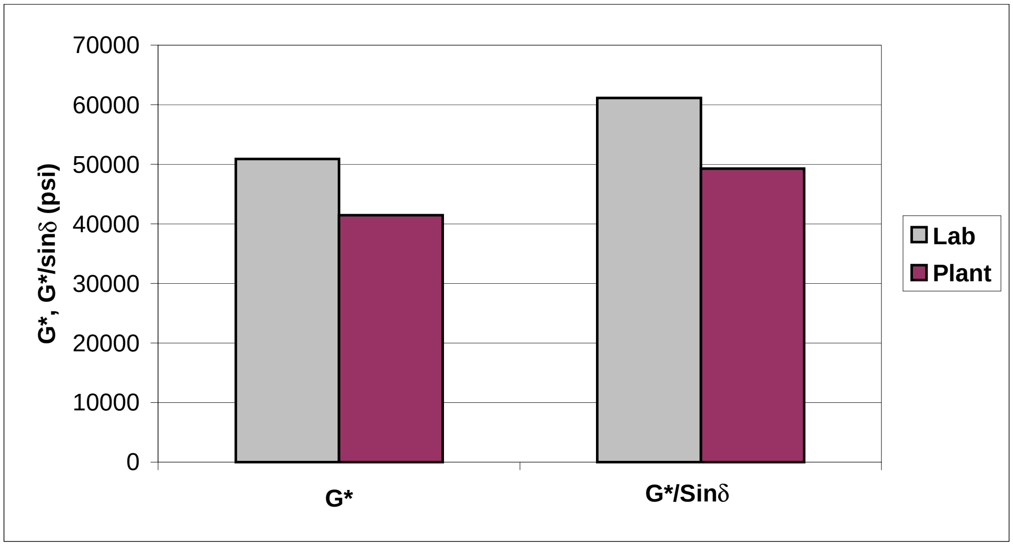

Figure 71. Frequency Sweep (FS) Results for Lab vs. Plant Mixtures (40°C, 10 Hz)

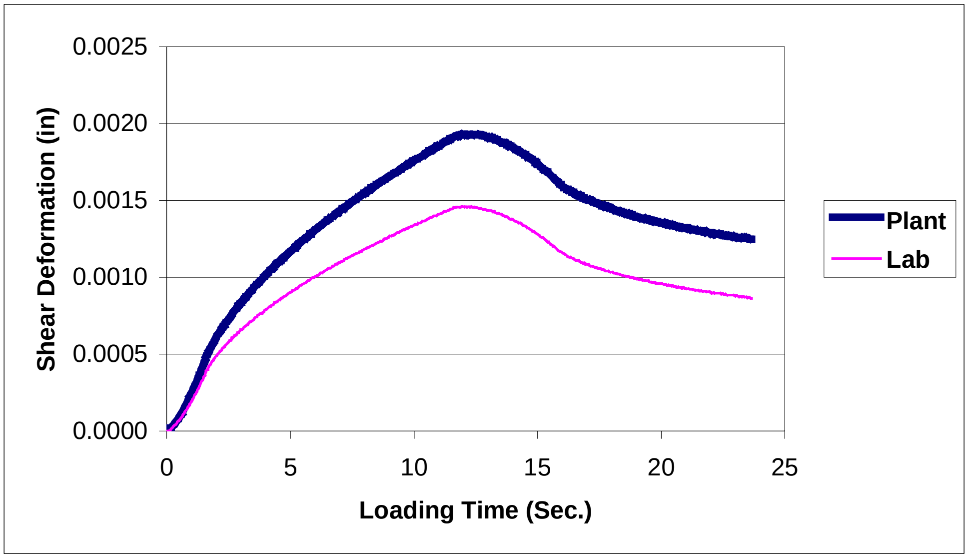

Figure 72. Average Simple Shear (SS) Results for Lab vs. Plant Mixtures (20°C)

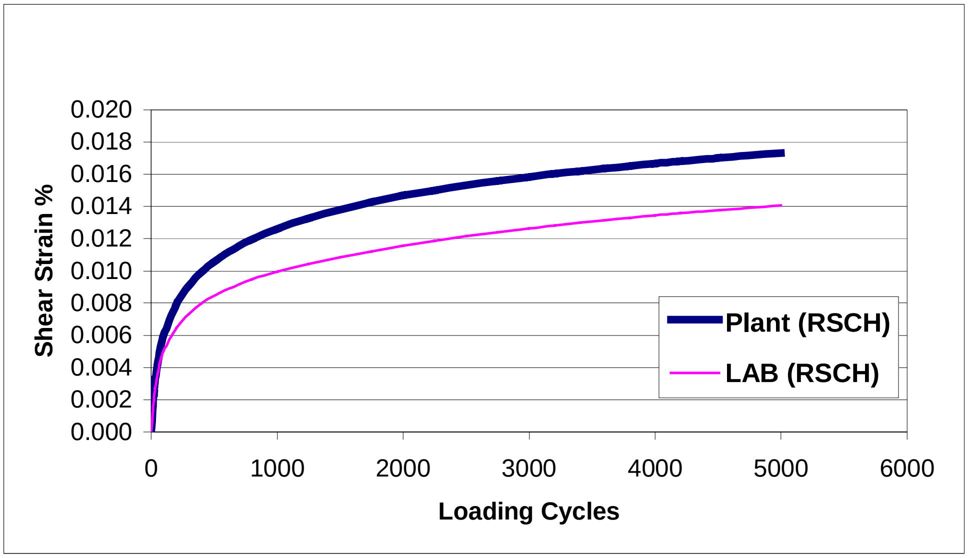

Figure 73. Average Repeated Shear (RSCH) Results for Lab vs. Plant Mixtures (58°C)

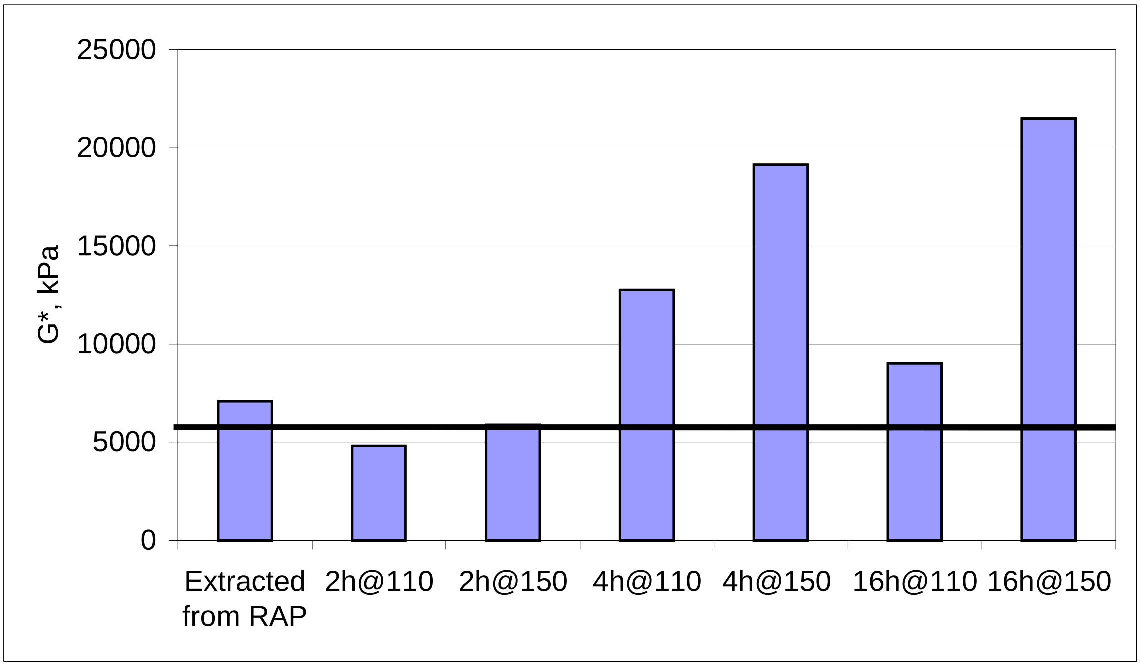

Figure 74. Florida RAP G* vs. Treatment (Tested at 22°C)

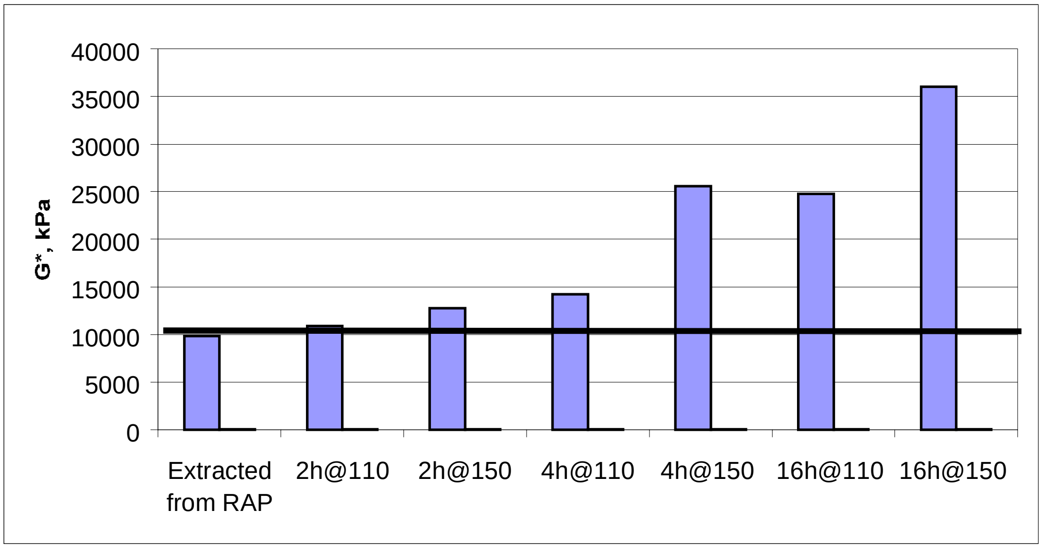

Figure 75. Arizona RAP G* vs. Treatment (Tested at 31°C)

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

Aging	Property	Temp C	PG 52-34 Blends, % RAP Binder 10%	PG 52-34 Blends, % RAP Binder 20%	PG 52-34 Blends, % RAP Binder 40%	PG 64-22 Blends, % RAP Binder 10%	PG 64-22 Blends, % RAP Binder 20%	PG 64-22 Blends, % RAP Binder 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	$G^*/\sin\delta$ 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	$G^*/\sin\delta$ 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	$G^*\sin\delta$ 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	$\Delta_{Act\text{-}Est}$	Estimated	Actual	$\Delta_{Act\text{-}Est}$
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	$\Delta_{Act\text{-}Est}$	Estimated	Actual	$\Delta_{Act\text{-}Est}$
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	$\Delta_{Act-Est}$	Estimated	Actual	$\Delta_{Act-Est}$
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	$\Delta_{Act\text{-}Est}$	Estimated	Actual	$\Delta_{Act\text{-}Est}$
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*/sinδ, 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*/sinδ (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/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% 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, $\mu\varepsilon$	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% 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/m^3 Initial	Energy J/m^3 Final	Dissipated Energy, J/m^3
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, $\mu\varepsilon$	Total No. of Cycles	Initial Stiffness MPa	Final Stiffness MPa	Phase angle Initial, ^{o}	Phase angle Final, ^{o}	Energy J/m ^{3} Initial	Energy J/m ^{3} Final	Dissipated Energy, J/m^{3}
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/m³ Initial	Energy J/m³ Final	Dissipated Energy, J/m³
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/m^3 Initial	Energy J/m^3 Final	Dissipated Energy, J/m^3
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

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATIONS

SUMMARY OF BINDER EXTRACTION REVIEW

Existing extraction and recovery procedures were evaluated to determine their accuracy, precision, speed and ease when testing RAP. Different, existing solvents were also evaluated in the extraction/recovery process. The various combinations of extraction procedure, recovery procedure and solvent type were evaluated to determine how readily mixture component analysis (asphalt content and gradation) could be performed. The physical properties of the recovered binder were also determined to test the treatment's precision.

Based on the testing completed, it does not appear that the Abson recovery procedure is acceptable for determination of RAP properties. Coefficients of variation were very high for the RAP samples tested (38-69%). The stiffness of the recovered binder was also lowest for this treatment.

The Centrifuge-Rotavapor-Toluene/Ethanol and modified SHRP-Rotavapor-Toluene/Ethanol treatments were similar in many ways. Both treatments exhibited comparable precision (CV = 12%) and time of testing (six hours). The stiffness of the recovered binder was slightly different for the two treatments. Of the two, the Centrifuge-Rotavapor-Toluene/Ethanol treatment exhibited the highest stiffness. The gradations of the material extracted using the SHRP-Rotavapor-Toluene/Ethanol treatments were slightly finer than the other treatments. This was expected since the SHRP extraction procedure appears to remove more fines from the effluent than the Centrifuge extraction procedure. The retention of fines in the recovered binder may be causing the binder stiffness to be higher for the Centrifuge-Rotavapor-Toluene/Ethanol treatment. Likewise, the additional fines removed are likely causing the change in gradation for the SHRP-Rotavapor-Toluene/Ethanol treatment. Based on the results of the testing completed, it appears that the SHRP extraction and recovery (Rotavapor) procedure is the best choice. The SHRP extraction and recovery procedures are detailed in AASHTO TP2 with the modifications noted earlier. It appears that this extraction and recovery procedure is:

1. More repeatable than the Centrifuge-Abson procedure, and equally repeatable compared to the Centrifuge-Rotavapor procedure,
2. Equally time-consuming as the Centrifuge-Rotavapor procedure, but slightly more time-consuming than the Centrifuge-Abson procedure (six hours compared to four hours), and
3. Comparable in asphalt content determination and gradation to the Centrifuge-Abson and Centrifuge-Rotavapor procedures.

Of all the parameters, accuracy is the most difficult to define. It appears that the modified SHRP-Rotavapor procedure removes more residual solvent than the Centrifuge-Abson procedure and more fines than the Centrifuge-Abson or Centrifuge-Rotavapor procedures. These two factors would suggest that the SHRP-Rotavapor procedure provides a more accurate representation of the RAP binder properties.

Because of the concern with the toxicity of extraction solvents, it is attractive to use alternative solvents, such as the n-propyl bromide solvent. The testing here indicated higher variability in the properties of binders recovered with the alternative solvent, but the variability was still much improved over that of the Centrifuge-Abson procedure.

The binder test methods themselves were found to be applicable to testing the recovered binder. (The recovered binders tested under Task 4 were linear.)

RAP Binder Blending Procedure

Based on the experimental data, blending of RAP binders can be accomplished by knowing the desired final grade (critical temperatures) of the blended binder physical properties (and critical temperatures) of the recovered RAP binder and one of the following two variables:

1. Physical properties (and critical temperatures) of virgin asphalt binder, or
2. Percentage of RAP in the mixture

The following steps should be followed to determine the physical properties and critical temperatures of the RAP binder. These are illustrated through flow charts in Appendix C.

1. The RAP binder should be recovered using the modified AASHTO TP2 method (described previously) with an appropriate solvent (either a toluene/ethanol combination or an n-propyl bromide solvent have been determined to be acceptable). At least 50 g of recovered RAP binder are needed for testing.
2. Perform binder classification testing using the tests in AASHTO MP1. Rotational viscosity, flash point and mass loss tests are not needed.
   2.1 Perform original DSR testing on the recovered RAP binder to determine the critical high temperature, T_c(High), based on original DSR values where $G^*/\sin\delta = 1.00$ kPa. Calculate the critical high temperature as follows:

2.1.1 Determine the slope of the Stiffness-Temperature curve as the change in $\Delta Log(G^*/\sin\delta) / \Delta T$.

2.1.2 Determine T_c(High) to the nearest 0.1°C using the following equation:

$$T_c(High) = \left(\frac{Log(1.00) - Log(G_1)}{a} \right) + T_1$$

where,

G_1 is the $G^*/\sin\delta$ value at a specific temperature, T_1

a is the slope of the Stiffness-temperature curve described in 2.1.1

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the $G^*/\sin\delta$ *value closest to the criterion (1.00 kPa) to minimize extrapolation errors.*

3. Perform RTFO aging on the remaining RAP binder.

4. Perform RTFO DSR testing on the RTFO-aged recovered RAP binder to determine the critical high temperature (based on RTFO DSR). Calculate the critical high temperature (based on RTFO DSR) as follows:

4.1 Determine the slope of the Stiffness-Temperature curve as the change in $\Delta Log(G^*/\sin\delta)/\Delta T$.

4.2 Determine T_c(High), based on RTFO DSR, to the nearest 0.1°C using the following equation:

$$T_c(High) = \left(\frac{Log(2.20) - Log(G_1)}{a} \right) + T_1$$

where,

G_1 is the G*/sinδ value at a specific temperature, T_1

a is the slope of the Stiffness-temperature curve described in 4.1

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the G*/sinδ *value closest to the criterion (2.20 kPa) to minimize extrapolation errors.*

5. Determine the critical high temperature of the recovered RAP binder as the lowest of the Original DSR and RTFO DSR critical temperatures. Determine the high temperature performance grade of the recovered RAP binder based on this single critical high temperature.

6. Perform intermediate temperature DSR testing on the RTFO-aged recovered RAP binder to determine the critical intermediate temperature, T_c(Int), based on PAV DSR.

   6.1 Determine the slope of the Stiffness-Temperature curve as ΔLog(G*sin δ)/ΔT.

   6.2 Determine T_c(Int) to the nearest 0.1°C using the following equation:

$$T_c(Int) = \left(\frac{Log(5000) - Log(G_1)}{a} \right) + T_1$$

where,

G_1 is the G*sin δ value at a specific temperature, T_1

a is the slope of the Stiffness-temperature curve described in 6.1

*Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the G*sin δ value closest to the criterion (5,000 kPa) to minimize extrapolation errors.*

7. Perform BBR testing on the RTFO-aged recovered RAP binder to determine the critical low temperature, $T_c(S)$ or $T_c(m)$, based on BBR Stiffness or m-value.

7.1 Determine the slope of the Stiffness-Temperature curve as ΔLog(S)/ΔT.

7.2 Determine $T_c(S)$ to the nearest 0.1°C using the following equation:

$$T_c(S) = \left(\frac{Log(300) - Log(S_1)}{a} \right) + T_1$$

where,

S_1 is the S-value at a specific temperature, T_1

a is the slope of the Stiffness-temperature curve described in 7.1

Note: Although any temperature (T_1) and the corresponding stiffness (S_1) can be selected, it is advisable to use the S- value closest to the criterion (300 MPa) to minimize extrapolation errors.

7.3 Determine the slope of the m-value-Temperature curve as Δm-value/ΔT.

7.4 Determine $T_c(m)$ to the nearest 0.1°C using the following equation:

$$T_c(m) = \left(\frac{0.300 - m_1}{a} \right) + T_1$$

where,

m_1 is the m-value at a specific temperature, T_1

a is the slope of the curve described in 7.3

Note: *Although any temperature (T_1) and the corresponding m-value (m_1) can be selected, it is advisable to use the m- value closest to the criterion (0.300) to minimize extrapolation errors.*

7.5 Select the higher (less negative) of the two low critical temperatures $T_c(S)$ and $T_c(m)$ to represent the low critical temperature for the recovered asphalt binder, $T_c(Low)$. Determine the low temperature performance grade of the recovered RAP binder based on this single critical low temperature.

Once the physical properties and critical temperatures of the recovered RAP binder are known, two blending approaches may be used. In one approach (designated Method A) the asphalt technologist knows the percentage of RAP that will be used in an asphalt mixture and needs to determine an appropriate virgin asphalt binder for blending. In the second approach (Method B) the asphalt technologist seeks to determine the maximum percentage of RAP that can be used in an asphalt mixture while still using the same virgin asphalt binder grade. Both approaches assume that the specifying agency will specify the performance grade of the blended binder. (These methods are also shown as flow charts in Appendix C and are described in detail for technicians in the companion Technicians' Manual (Appendix E).)

METHOD A – Blending at a Known RAP Percentage (Virgin Binder Grade Unknown)

If the final blended binder grade, desired percentage of RAP and recovered RAP properties are known, then the properties of an appropriate virgin asphalt binder grade can be determined. Consider the following example:

- The specifying agency requires a blended binder grade of PG 64-22 or better.
- The RAP percentage in the mixture is 30%.
- The recovered RAP properties are as indicated in Table 99.

By rearranging the equations described earlier, the critical temperatures of the virgin asphalt binder can be determined:

$$T_{Virgin} = \frac{T_{Blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)}$$

where: T_{Virgin} = critical temperature of the virgin asphalt binder

T_{Blend} = critical temperature of the blended asphalt binder (final desired)

%RAP = percentage of RAP expressed as a decimal (i.e., 0.30 for 30%)

T_{RAP} = critical temperature of recovered RAP binder

Using these equations for the high, intermediate and low critical temperatures, the properties of the virgin asphalt binder needed to satisfy the assumptions could be determined. These values are indicated in Table 100 and Figures 76 – 78.

As indicated in Table 100 and Figure 76, the minimum high temperature grade of the virgin asphalt binder should be 54.3°C to satisfy the requirements of the blended grade (PG 64-

22) using the RAP in Table 99 at 30%. This means that a PG 58-xx grade would be needed to ensure that the minimum required value of 54.3°C would be achieved.

Table 100 and Figure 77 indicate that the minimum low temperature grade of the virgin asphalt binder should be –26.4°C (-16.4°C -10°C factor in AASHTO MP1) to satisfy the requirements of the blended grade (PG 64-22) using the RAP in Table 99 at 30%. This means that a PG xx-28 grade would be needed to ensure that the minimum required value of –26.4°C would be achieved.

From Table 100 and Figures 76 and 77, a PG 58-28 asphalt binder would be selected as the virgin asphalt binder for use in a mixture using 30% of the RAP described in Table 99. To meet the intermediate temperature grade (G*sin δ) in Figure 78, the virgin asphalt binder would need to have a critical intermediate temperature no higher than 22.6°C. Since the maximum critical intermediate temperature for a PG 58-28 binder is 19°C, the selected binder should easily meet all blended binder requirements.

It should be noted that the actual high temperature grade required for the virgin asphalt binder is 54.3°C. It is possible that a PG 52-28 binder could be used, provided that the actual high temperature was at least 54.3°C. However, material variability (RAP or virgin binder) and testing variability (Recovery and DSR testing) make this choice questionable.

METHOD B – Blending with a Known Virgin Binder Grade (RAP Percentage Unknown)

If the final blended binder grade, virgin asphalt binder grade and recovered RAP properties are known, then the allowable RAP content can be determined. Consider the following example:

- The specifying agency requires a blended binder grade of PG 64-22 or better.

- The virgin binder grade is a PG 58-28 (critical temperatures in Table 101).
- The recovered RAP is a PG 82-10 (critical temperatures in Table 101).

By rearranging the equations described earlier, the percentage of RAP can be determined:

$$\%RAP = \frac{T_{Blend} - T_{Virgin}}{T_{RAP} - T_{Virgin}}$$

where: T_{Virgin} = critical temperature of the virgin asphalt binder

T_{Blend} = critical temperature of the blended asphalt binder (final desired)

%RAP = percentage of RAP expressed as a decimal (i.e., 0.30 for 30%)

T_{RAP} = critical temperature of recovered RAP binder

Using these equations for the high, intermediate and low critical temperatures, the percentage of RAP needed to satisfy the assumptions can be determined. These values are indicated in Table 102 and Figures 79 – 81.

As indicated in Table 102 and Figure 79 a percentage of RAP between 14% and 36% should satisfy the high temperature requirements of the blended grade (PG 64-22) using the RAP and virgin asphalt binders in Table 101. Note that to achieve the minimum PG 64-xx grade, the percentage of RAP is rounded up. To achieve a maximum PG 64-xx grade (that is, a PG 70-xx grade is not desired), the percentage of RAP is rounded down.

Table 102 and Figure 80 indicate that a RAP percentage between 6% and 40% should satisfy the low temperature requirements of the blended grade (PG 64-22) using the RAP and virgin asphalt binders in Table 101. Note that to achieve the minimum PG xx-22 grade, the percentage of RAP is rounded down. To achieve a maximum PG xx-22 grade (that is, a PG xx-28 grade is not desired), the percentage of RAP is rounded up.

From Table 102 and Figures 79 and 80, a RAP percentage between 14% and 36% would satisfy all the requirements of a blended PG 64-22 binder. If the maximum high temperature grade was not a concern, the RAP percentage could be increased to 40% without changing the desired low temperature grade of the blended asphalt binder.

To meet the intermediate temperature grade (G*sin δ) in Figure 81, the RAP percentage would need to be less than 66%.

Testing Reliability Issues

Variability in test results typically can come from one of three sources: materials, sampling and testing. Often, variability in testing is attributed to the material being tested when, in reality, sampling or testing errors may have contributed to the variability in the test results.

Good sampling practices can effectively minimize variability in test results caused by sampling. Adherence to the proper test methods may minimize testing variability, but it still will be present. If sampling variability can be reduced by good sampling practices and testing variability can be properly accounted for, then material variability can be quantified.

Testing of recovered RAP asphalt binders can occur in either the recovery procedure or in the binder test procedure (i.e., DSR, BBR tests). Variability due to the combined effects of the recovery procedure and high temperature DSR testing is indicated in Table 103 for two RAPs tested in the first phase of this research project.

The data in Table 103 indicates that the test results from three separate recoveries indicated a change in the critical high temperature by as much as 2.1°C. The d2s limit defining the acceptable range of two test results (95% confidence limit) was 2.5°C for the Kentucky RAP and 0.7°C for the Florida RAP.

Applying a tolerance of 2.5°C to the critical high temperature of the RAP binder in Tables 99 and 101 changes it from 86.6°C to 84.1°C. The effect on the blending would change the virgin binder critical high temperature from 54.3°C to 55.4°C in Method A – a change of approximately 1°C, but no change in the virgin binder grade. The effect on blending would also change the minimum RAP percentage from 14% to 15% in Method B. In either instance, because the RAP is being blended with virgin asphalt binder at percentages of (typically) 40% or less, variability in test results due to the recovery procedure and subsequent testing is decreased.

It should be noted that Table 103 provides an indication of single laboratory testing variability associated with the modified AASHTO TP2 procedure. Since this is a new procedure, multi-laboratory variability has not been determined. It should also be noted that no low temperature variability (single laboratory) was determined from the two RAP sources.

Other sources (33) describe multi-laboratory testing variability associated with the Superpave binder tests. This information is readily available from the AASHTO Material Reference Laboratory Program. However, this testing variability is based on samples that are typically taken from the asphalt binder tanks, not recovered from an asphalt mixture sample. It is expected that the testing variability will increase as the binder is subjected to the recovery procedure.

Until testing variability can be sufficiently established for recovered asphalt binders, the user agency may wish to add a factor of safety to ensure that the final blended asphalt binder grade is achieved. Based on the 2.5°C change in the critical high temperature of the recovered RAP binder (Kentucky), an increase/decrease of no more than 2.0°C in the critical temperatures of the desired binder grade should be sufficient. Therefore, an agency requiring a PG 64-22 blended asphalt binder would fix the critical high temperature at 66°C instead of 64°C. The critical low temperature of the blended binder would be -14°C rather than -12°C. These adjustments may or may not result in a change in the virgin asphalt binder grade required or the percentage of RAP used in the mixture.

Discussion of AASHTO MP1A Blending

At the time of this experiment, the critical low temperature of an asphalt binder was determined principally from the BBR Stiffness and m-value. Blending equations were determined during the experiment to accommodate estimations of BBR Stiffness and m-value of blended asphalt binders.

Recently, however, a research team involved with the Asphalt Binders Expert Task Group developed a new procedure for determining the critical low temperature of an asphalt binder (34). This procedure uses BBR data to generate a thermal stress curve, and uses direct tension data to determine failure stress at one or more temperatures. The point at which the failure stress intersects the thermal stress curve is the critical low temperature of the asphalt binder. This procedure was forwarded to AASHTO as an alternate to the performance graded asphalt binder specification. It has been designated as AASHTO MP-1A.

The equipment, procedure and analysis software have only recently been finalized. Consequently there was no time in the research to examine the concept of low temperature blending charts using the alternate method of determining critical low temperature (AASHTO MP-1A). However, a separate research effort being conducted at the Asphalt Institute as part of the FHWA's National Asphalt Training Center II contract is examining the concept of low temperature blending using the MP-1A procedure. That final report should supplement the findings of this research.

BINDER EFFECTS STUDY

Analysis of Effect of RAP on Binder Grade

The binder effects study indicated that the binder grade changed as RAP percentage increased, but the high temperature grade changed more rapidly than the low temperature grade. For low temperatures the temperature difference between the original (virgin) binder and the RAP blends is indicated in Table 104 below. The data is also graphically represented in Figures 82 and 83.

Table 104 and Figure 82 indicate that the Arizona RAP has a greater influence than the Florida and Connecticut RAP on the low temperature grade of the blended asphalt binder. This was expected since the Arizona RAP had an actual low temperature grade 10°C warmer than the Florida and Connecticut RAP.

Table 104 and Figure 83 indicate that at 10% RAP the average low temperature grade of the blended asphalt binder changes by less than 1.0°C. At 20% RAP, the average low temperature grade of the blended asphalt binder changes by approximately 2.5°C. Figure 83 also indicates that the PG 52 asphalt binder is slightly more affected by the RAP than the PG 64 asphalt binder.

For high temperatures the temperature difference between the original (virgin) binder and the RAP blends is indicated in Table 105. The data is also graphically represented in Figures 84 and 85.

Table 105 and Figure 84 indicate that, as with the low temperature grade, the Arizona RAP has a greater influence than the Florida and Connecticut RAP on the high temperature grade of the blended asphalt binder.

Table 105 and Figure 85 indicate that at 10% RAP the average high temperature grade of the blended asphalt binder changes by approximately 3.0°C. At 20% RAP, the average high temperature grade of the blended asphalt binder changes by approximately 5-7°C. Figure 85 also indicates that the PG 52 asphalt binder is slightly more affected by the RAP than the PG 64 asphalt binder.

The slopes of the lines in Figures 83 and 85 indicate that the percentage of RAP has twice the effect on the high temperature grade of the asphalt binder as it does on the low temperature grade. This can also be seen in Table 106 where the change in temperature is calculated for various RAP percentages corresponding to the limits in the Mix ETG recommended tiers and the binder effects experiment. Table 107 indicates the percentage of RAP required to cause a specified change in critical temperature.

Table 106 indicates that following the ETG guidelines, 0-14% RAP could have changes of 1.6°C in the low temperature grade and 4.2°C in the high temperature grade of the blended asphalt binder. Assuming the virgin asphalt binder is produced with some "margin" on the low temperature and high temperature grade, the final blended grade should be substantially the same as the virgin asphalt binder grade. *(The binder grade "margin" assumes that an asphalt binder is produced approximately 2°C from the minimum critical temperature. In other words, a PG 64-22 asphalt binder would be produced with actual critical temperatures of 66°C and -24°C.)*

Assuming the 2°C margin indicated above, the 15% RAP limit before a change in binder grade is required appears reasonable. A virgin asphalt binder with more "margin" may allow a higher percentage of RAP before a grade change is required. For example, a mixture using a PG 64-22 with a 4°C margin on the low temperature grade (i.e., a PG 64-26 binder) could use 25% RAP without a change in the virgin asphalt binder grade. Conversely, a virgin asphalt binder with less "margin" may allow a lower percentage of RAP before a grade change is required.

The data in Tables 104 and 105 suggest that the Arizona RAP has a greater effect than the Florida and Connecticut RAP on the blended asphalt binder grade. This appears to be particularly true for the low temperature grade (Table 104) where it appears that the Arizona RAP changes the low temperature grade twice as fast as the Florida and Connecticut RAP. Separating the RAP stiffness into two groups yields the data in Tables 108 and 109. Tables 110 and 111 indicate the percentage of RAP required to cause a specified change in critical temperature.

The data in Tables 107, 110 and 111 indicate that, in general, the ETG recommendations are appropriate. A 2°C change in the critical low temperature is caused by the addition of 16.7% RAP. A 3°C change in the critical low temperature is caused by the addition of 24.2% RAP. When the RAP stiffness increases (Table 110, Arizona RAP), the RAP percentages are 11.0% and 16.0% to create a change in the critical low temperatures of 2°C and 3°C, respectively. When the RAP stiffness decreases (Table 110, Florida and Connecticut RAP), the RAP percentages are 22.7% and 32.8% to create a change in the critical low temperatures of 2°C and 3°C, respectively. This data suggests that the ETG recommendations can also be modified depending on the low temperature stiffness of the recovered RAP binders. A possible modification to the recommendations could be made based on the data in Tables 107 and 110. That modification is shown in Table 112. Table 112 is used to select binder grades in the accompanying proposed AASHTO specification revisions (Appendix F), Guidelines (Appendix D) and Technicians' Manual (Appendix E).

BLACK ROCK STUDY

The black rock study offers compelling evidence that blending does occur between the old, hardened RAP binder and the virgin added binder. At low RAP contents, certainly 10% or less, there is not enough RAP present to significantly change the mixture properties. At 40% RAP, however, the effects were significant. At the higher RAP content, samples representing actual practice more closely resembled samples representing total blending than those representing black rock. This confirms both the concept of blending charts and the establishment of a tiered approach to RAP usage. At low RAP contents, no changes are necessary, but as the RAP content increases, the need to use a blending chart does also.

It does not seem reasonable that total blending would actually happen in the field. Findings from this research, however, strongly suggest that actual practice achieves a situation much closer to total blending than to no blending (black rock).

The application of these findings to current practice would support continuation of a tiered approach to RAP usage.

MIXTURE EFFECTS STUDY

The mixture effects study looked at RAP contents ranging from 0 to 40%. Shear testing, indirect tensile testing and beam fatigue were used to analyze the effects of increasing the RAP content on the mixture properties.

The shear testing indicated that the complex shear modulus of the mixtures increased exponentially with RAP content, in most cases. Deformation decreased as the RAP content increased and shear strain decreased as RAP ratio increased. All of these changes indicate the stiffening effect of the RAP on the mixture properties. The effects become especially significant between 20 and 40% RAP.

Indirect tensile testing supports these findings as well. Increasing the RAP content increases the low temperature stiffness of the mix. The samples with 10% RAP were typically similar to the control samples (0% RAP). At higher RAP contents, the effects of the RAP become significant.

Beam fatigue testing reveals similar conclusions. As the RAP content increases, beam fatigue life, as measured by cycles to failure, decreases. Again there was no significant effect of the RAP at the 10% level, but higher percentages of RAP became more significant. The beams made with softer binder exhibited greater fatigue life, as expected. This supports the concept of using a softer virgin binder with higher proportions of RAP.

These results combined suggest that mixtures with higher percentages of RAP can be expected to be stiffer and therefore more resistant to permanent deformation. This increased stiffness, however, can lead to a decrease in low temperature and fatigue cracking resistance, *unless compensated for by changes in the binder properties.*

These findings also correlate well with the results of the black rock study and the binder effects study in support of a tiered approach to the use of RAP. All of these studies suggest strongly that there is indeed a threshold level of RAP below which the effects of the RAP are insignificant. This is clearly the case at 10% RAP. At the 20% RAP level, effects were sometimes significant, but not always. At the 40% level, the effects of the RAP were quite apparent, in most cases. This suggests that an upper limit for the threshold of between 15 and 20% would be reasonable.

While a tiered approach is not novel or innovative, it is practical. Its use allows for the relatively easy implementation of low levels of RAP. If the economics of using RAP justify further expense at the mix design phase, additional testing and/or adjustments to the binder grade can be performed to take into account the increased effects of the RAP at higher addition rates.

PLANT VS. LAB COMPARISON

The plant vs. lab mini-experiment was done to ensure that the laboratory approach used in this study had some validity. If the results of the lab-prepared testing differed greatly from the results of testing plant-produced mix with the same components, applying these laboratory findings to actual projects would be questionable. Only one RAP and its plant-mix were investigated in this mini-experiment.

The results of this limited study indicate that the laboratory approach for preparing samples was representative of plant-produced mix. The plant-produced mixes tended to be slightly stiffer than the lab mixes, but not significantly stiffer. This can increase the confidence level when applying the results of this research project to actual construction.

EFFECTS OF RAP HANDLING

The findings of the mini-experiment on the effects of time and temperature on RAP properties support the conventional recommendations to limit heating time and temperature. Heating the RAP for long periods of time at high temperatures (16 hours at 150°C) resulted in changes in the binder properties, which could lead to changes in mixture properties. For some RAP-virgin binder combinations, however, heating for long time periods at relatively low temperatures had no detrimental effect.

This was not an exhaustive study, by any means. It was also limited by the use of binder test results as surrogates for extensive mixture testing, due to concerns about mix testing variability masking the effects of heating. Nonetheless, the findings do concur with other recommendations that RAP be heated at low temperatures (110°C) for short periods of time (5).

If circumstances require longer heating times, comparisons should be made of mixes heated for long periods versus those heated for recommended times to determine if any detrimental changes occurred. Comparisons of the volumetric properties of multiple samples could be used on a project by project, or material by material, basis to demonstrate the effects of prolonged heating. This may be preferable to the binder testing done here since few contractors have access to binder equipment, though they do have access to a gyratory compactor.

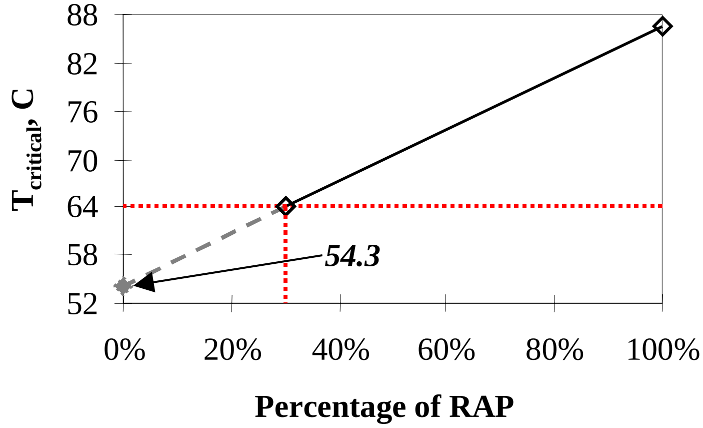

Figure 76. High Temperature Blending Chart (RAP Percentage Known)

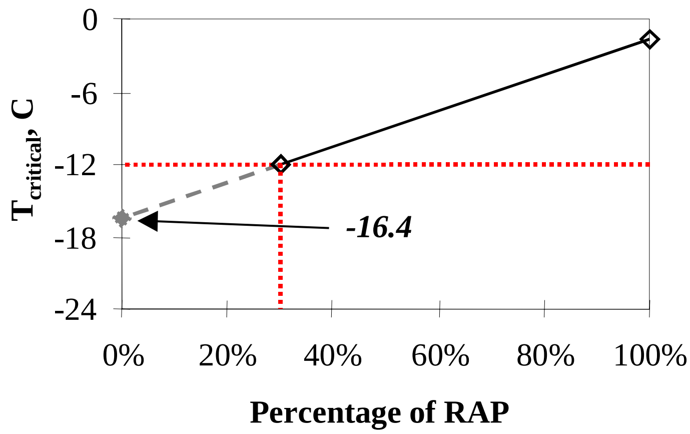

Figure 77. Low Temperature Blending Chart (RAP Percentage Known)

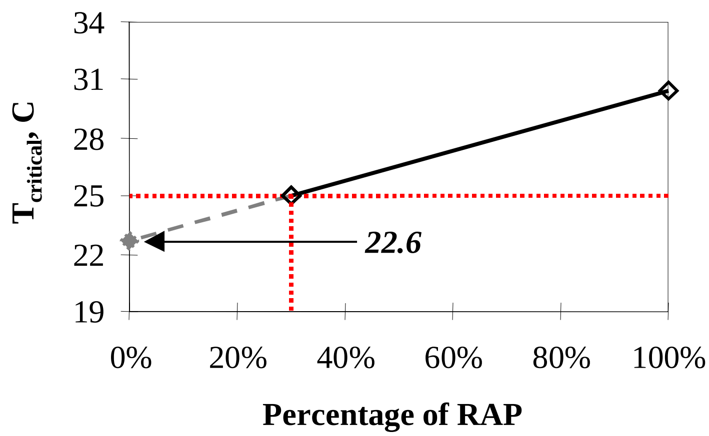

Figure 78. Intermediate Temperature Blending Chart (RAP Percentage Known)

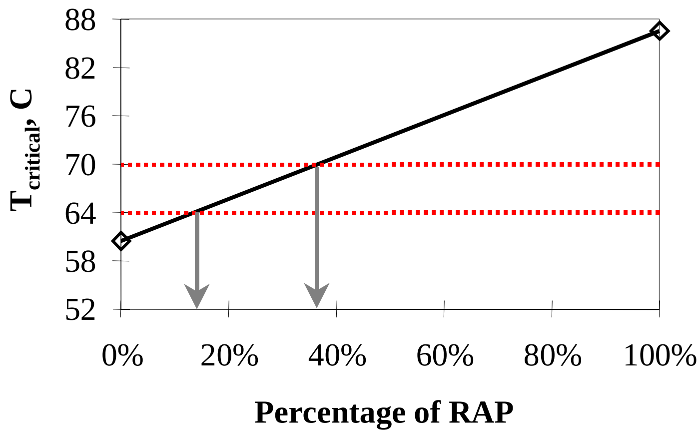

Figure 79. High Temperature Blending Chart (RAP Percentage Unknown)

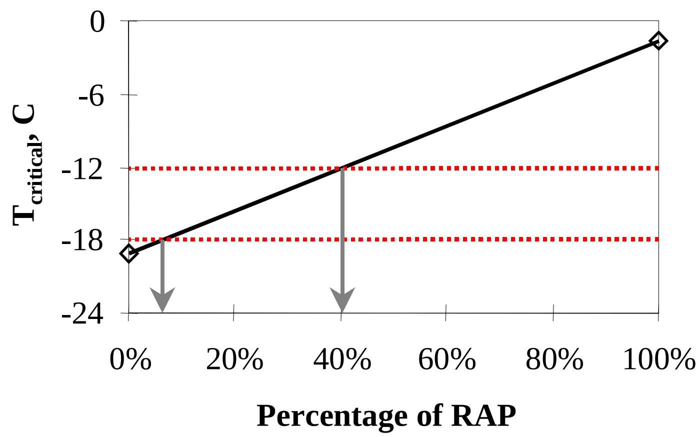

Figure 80. Low Temperature Blending Chart (RAP Percentage Unknown)

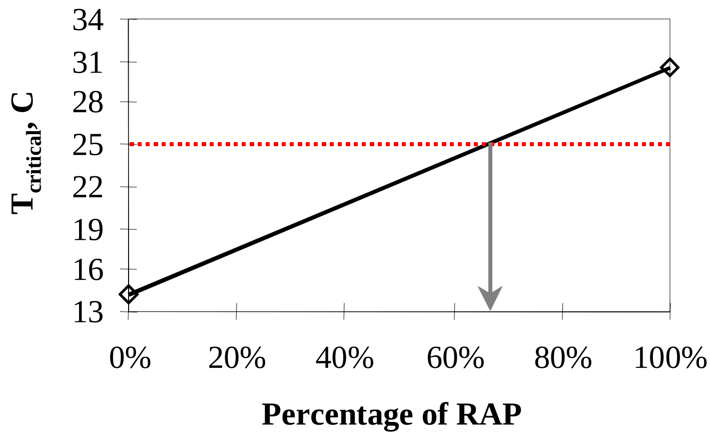

Figure 81. Intermediate Temperature Blending Chart (RAP Percentage Unknown)

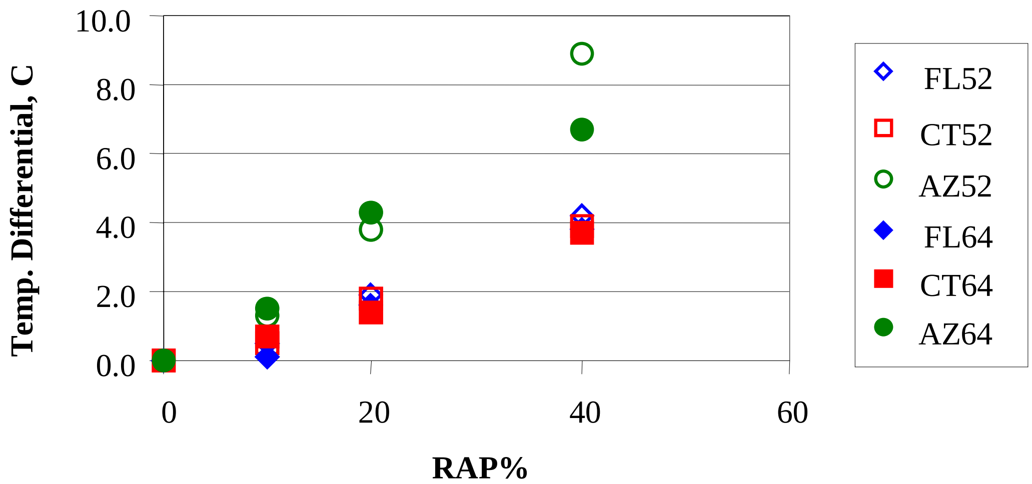

Figure 82. Individual Change in Low Temperature Grade with Addition of RAP

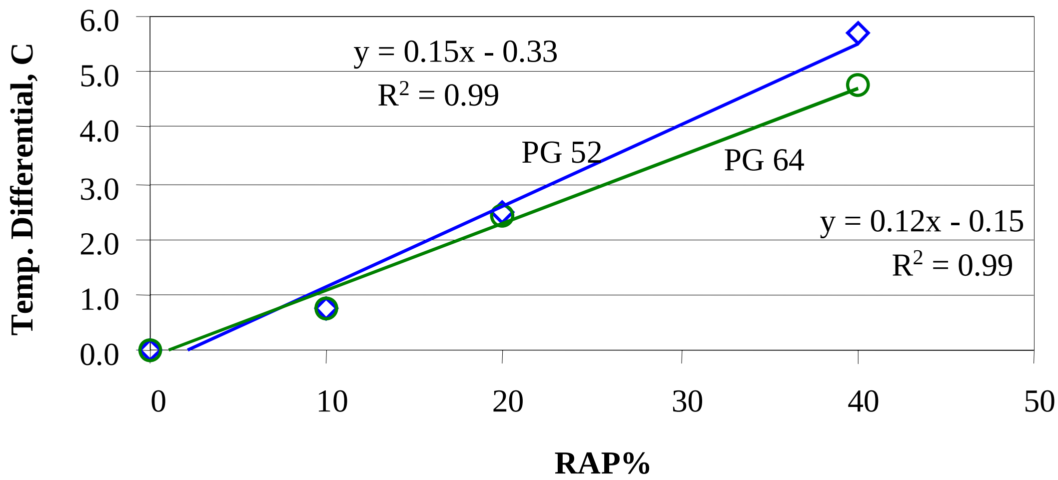

Figure 83. Average Change in Low Temperature Grade with Addition of RAP

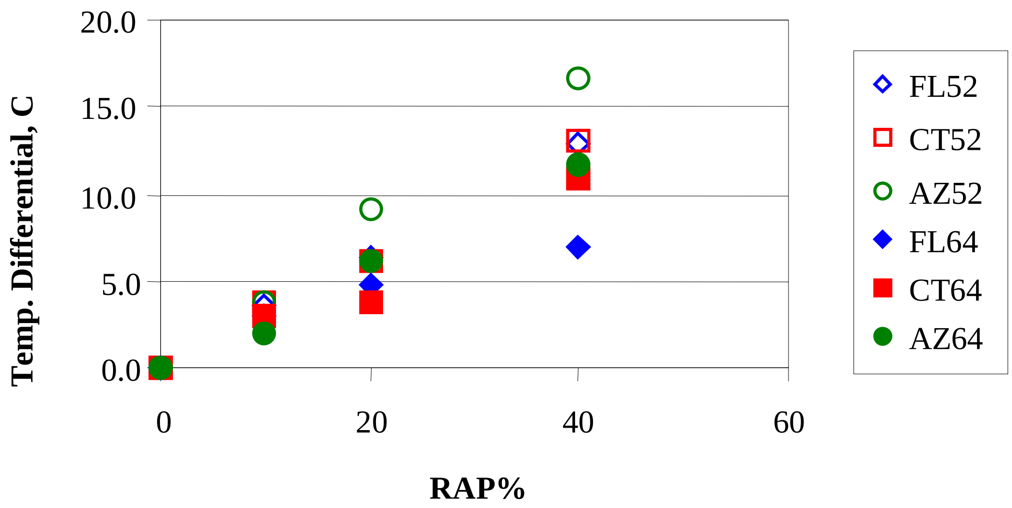

Figure 84. Individual Change in High Temperature Grade with Addition of RAP

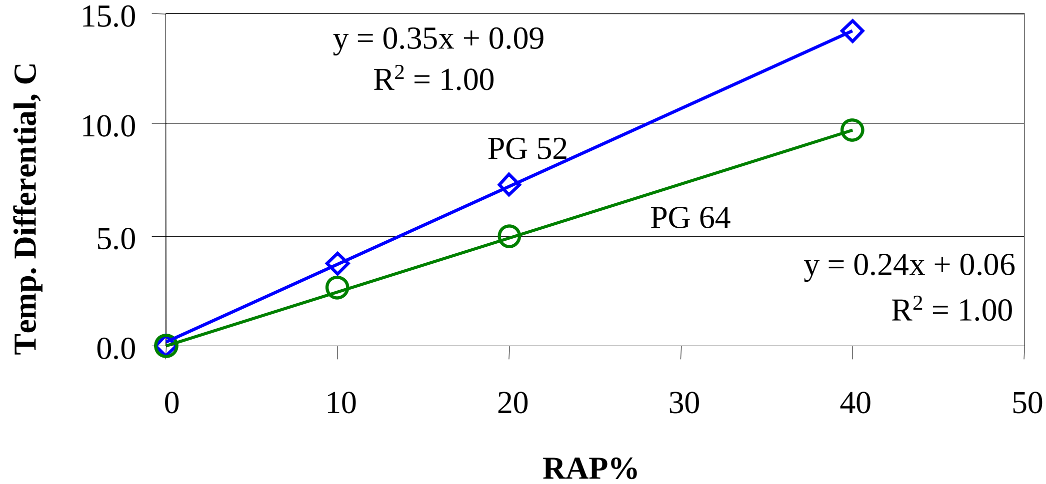

Figure 85. Average Change in High Temperature Grade with Addition of RAP

Table 99. Critical Temperatures of Recovered RAP Binder

Aging	Property	Critical Temperature, °C	
Original	DSR G*/sinδ	High	**86.6**
RTFO	DSR G*/sinδ	High	88.7
PAV	DSR G*sinδ BBR S BBR m-value	Intermediate Low Low	**30.5** -4.5 **-1.7**
	PG	Actual MP1	PG 86-11 PG 82-10

Table 100. Estimated Critical Temperatures of Virgin Asphalt Binder

Aging	Property	Critical Temperature, °C	
Original	DSR G*/sinδ	High	**54.3**
RTFO	DSR G*/sinδ	High	53.4
PAV	DSR G*sinδ BBR S BBR m-value	Intermediate Low Low	**22.6** -15.2 **-16.4**
	PG	Actual MP1	PG 54-26 PG 58-28

Table 101. Critical Temperatures of Virgin and Recovered RAP Binders

Aging	Property	Critical Temperature, °C		
		Temp. Range	Virgin Binder	RAP Binder
Original	DSR G*/sinδ	High	**60.5**	**86.6**
RTFO	DSR G*/sinδ	High	61.0	88.7
PAV	DSR G*/sinδ	Intermediate	**14.2**	**30.5**
	BBR S	Low	-22.2	-4.5
	BBR m-value	Low	**-19.0**	**-1.7**
	PG	Actual	PG 60-29	PG 86-11
		MP1	PG 58-28	PG 82-10

Table 102. Estimated Percentage of RAP to Achieve Final Blended Grade

Aging	Property	Temp.	**Percentage of RAP to Achieve:** PG 64-22	**Percentage of RAP to Achieve:** PG 70-28
Original	DSR G*/sinδ	High	**13.4%**	**36.4%**
RTFO	DSR G*/sinδ	High	10.8%	32.5%
PAV	DSR G*sinδ	Intermediate	**66.3%**	**---**
	BBR S	Low	57.6%	23.7%
	BBR m-value	Low	**40.5%**	**5.8%**

Table 103. Testing Variability of Modified AASHTO TP2 Method (with Toluene/Ethanol)

	G*/sinδ, kPa							
	Kentucky				**Florida**			
	64ºC	70ºC	76ºC	**T_c**	64ºC	70ºC	76ºC	**T_c**
Rep 1	21.76	9.23	4.06	**86.0**	7.10	3.10	1.42	**78.6**
Rep 2	24.24	9.60	4.01	**85.3**	7.11	3.07	1.39	**78.4**
Rep 3	27.30	11.55	5.01	**87.4**	7.79	3.37	1.51	**79.0**
Average	24.43	10.13	4.36	**86.2**	7.33	3.18	1.44	**78.7**
σ (1s)	2.27	1.02	0.46	**0.9**	0.32	0.13	0.05	**0.2**
CV (1s%)	9%	10%	11%	**1%**	4%	4%	4%	**0.3%**
d2s	6.41	2.88	1.30	**2.5**	0.91	0.38	0.14	**0.7**
d2s%	26%	28%	30%	**3%**	12%	12%	10%	**1%**

Table 104. Change in Low Temperature Grade of Virgin Asphalt Binder with Addition of RAP

		Change in Critical Low Temperature , °C			
		0% RAP	10% RAP	20% RAP	40% RAP
PG 52-34	FL	0.0	+0.5	+1.9	+4.2
	CT	0.0	+0.5	+1.8	+3.9
	AZ	0.0	+1.3	+3.8	+8.9
	Average	**0.0**	**+0.8**	**+2.5**	**+5.7**
PG 64-22	FL	0.0	+0.1	+1.6	+3.8
	CT	0.0	+0.7	+1.4	+3.7
	AZ	0.0	+1.5	+4.3	+6.7
	Average	**0.0**	**+0.8**	**+2.4**	**+4.7**

Table 105. Change in High Temperature Grade of Virgin Asphalt Binder with Addition of RAP

		Change in Critical High Temperature, °C			
		0% RAP	10% RAP	20% RAP	40% RAP
PG 52-34	FL	0.0	+3.6	+6.4	+12.8
	CT	0.0	+3.8	+6.2	+13.1
	AZ	0.0	+3.7	+9.1	+16.6
	Average	**0.0**	**+3.7**	**+7.2**	**+14.2**
PG 64-22	FL	0.0	+2.9	+4.8	+7.0
	CT	0.0	+2.9	+3.7	+10.8
	AZ	0.0	+2.0	+6.2	+11.6
	Average	**0.0**	**+2.6**	**+4.9**	**+9.8**

Table 106. Change in Critical Temperature with Addition of RAP (Average of All RAPs)

	Low Temperature, °C			High Temperature, °C		
RAP	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
14%	+1.8	+1.5	**+1.6**	+5.0	+3.4	**+4.2**
15%	+1.9	+1.7	**+1.8**	+5.3	+3.7	**+4.5**
25%	+3.4	+2.9	**+3.2**	+8.8	+6.1	**+7.5**
26%	+3.6	+3.0	**+3.3**	+9.2	+6.3	**+7.7**
40%	+5.7	+4.7	**+5.2**	+14.1	+9.7	**+11.9**

Table 107. Percentage of RAP to Cause Change in Critical Temperature (Average of All RAP)

	Low Temperature, %RAP			High Temperature, %RAP		
Temp., °C	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
2.0	15.5	17.9	**16.7**	5.5	8.1	**6.8**
3.0	22.2	26.3	**24.2**	8.3	12.3	**10.3**
4.0	28.9	34.6	**31.7**	11.2	16.4	**13.8**
6.0	42.2	51.3	**46.7**	16.9	24.8	**20.9**

Table 108. Change in Critical Low Temperature with Addition of RAP

	Florida, Connecticut RAP (PG xx-22)			Arizona RAP (PG xx-10)		
RAP	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
14%	+1.2	+1.0	**+1.1**	+2.7	+2.5	**+2.6**
15%	+1.3	+1.1	**+1.2**	+3.0	+2.7	**+2.8**
25%	+2.4	+2.1	**+2.2**	+5.3	+4.4	**+4.8**
26%	+2.5	+2.2	**+2.4**	+5.5	+4.5	**+5.0**
40%	+4.0	+3.5	**+3.8**	+8.7	+6.9	**+7.8**

Table 109. Change in Critical High Temperature with Addition of RAP

	Florida, Connecticut RAP (PG xx-22)			Arizona RAP (PG xx-10)		
RAP	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
14%	+4.6	+3.2	**+3.9**	+5.9	+3.9	**+4.9**
15%	+5.0	+3.5	**+4.2**	+6.3	+4.2	**+5.2**
25%	+8.2	+5.6	**+6.9**	+10.5	+7.2	**+8.8**
26%	+8.5	+5.8	**+7.2**	+10.9	+7.5	**+9.2**
40%	+13.0	+8.8	**+10.9**	+16.8	+11.7	**+14.2**

Table 110. Percentage of RAP to Cause Change in Critical Low Temperature

	Florida, Connecticut RAP (PG xx-22)			Arizona RAP (PG xx-10)		
Temp., °C	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
2.0	21.3	24.1	**22.7**	10.9	11.1	**11.0**
3.0	30.9	34.6	**32.8**	15.2	16.9	**16.0**
4.0	40.4	45.2	**42.8**	19.6	22.8	**21.2**
6.0	59.4	66.2	**62.8**	28.3	34.6	**31.4**

Table 111. Percentage of RAP to Cause Change in Critical High Temperature

	Florida, Connecticut RAP (PG xx-22)			Arizona RAP (PG xx-10)		
Temp., °C	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
2.0	5.8	8.2	**7.0**	4.8	7.6	**6.2**
3.0	8.9	12.9	**10.9**	7.2	10.9	**9.0**
4.0	12.0	17.5	**14.8**	9.6	14.3	**12.0**
6.0	18.3	26.8	**22.6**	14.3	20.9	**17.6**

Table 112. Binder Selection Guidelines for RAP Mixtures

	RAP Percentage		
	Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	**PG xx-22 or lower**	**PG xx-16**	**PG xx-10 or higher**
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (i.e., select a PG 58-28 if a PG 64-22 would normally be used)	20 – 30%	15 – 25%	10 – 15%
Follow recommendations from blending charts	>30%	>25%	>15%

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

BINDER EFFECTS STUDY

The following conclusions and recommendations can be made from this research:

1. The modified AASHTO TP2 procedure, using either a combination of toluene (85%) and ethanol (15%) or an n-propyl bromide as solvent, is the preferred recovery procedure for RAP because of the repeatability and accuracy of the test results.
2. After recovery, the RAP binder should be tested in the DSR to determine the critical high temperature where the high temperature stiffness ($G^*/\sin\delta$) of the unaged recovered RAP binder is 1.00 kPa.
3. The remaining recovered RAP binder should be RTFO-aged prior to further testing. No PAV aging of the recovered RAP binder is necessary.
4. After RTFO-aging, the RAP binder should be tested in the DSR to determine the critical high temperature where the high temperature stiffness ($G^*\sin\delta$) of the RTFO-aged recovered RAP binder is 2.20 kPa. The RAP binder should also be tested in the DSR to determine the critical intermediate temperature where the stiffness ($G^*\sin\delta$) of the RTFO-aged recovered RAP binder is 5,000 kPa. The RAP binder should also be tested in the BBR to determine the critical low temperature where either the BBR Stiffness of the RTFO-aged recovered RAP binder is 300 MPa or the BBR m-value is 0.300.
5. Linear blending equations using critical temperatures appear to be appropriate for estimating the properties of the blended asphalt binder. Detailed procedures using these linear equations are provided in the accompanying Technicians' manual.

6. The critical temperatures (and performance grade) of the virgin asphalt binder can be determined from the linear blending equations if: (a) the percentage of RAP is known; (b) the critical temperatures of the recovered RAP binder are known; and (c) the critical temperatures of the desired blended binder are known.
7. The percentage of RAP to be used in a mixture can be determined from the linear blending equations if: (a) the critical temperatures of the virgin asphalt binder are known; (b) the critical temperatures of the recovered RAP binder are known; and (c) the critical temperatures of the desired blended binder are known.
8. The critical temperatures (and performance grade) of the blended asphalt binder can be determined from the linear blending equations if: (a) the percentage of RAP is known; (b) the critical temperatures of the recovered RAP binder are known; and (c) the critical temperatures of the virgin asphalt binder are known.
9. The RAP percentages suggested by the Asphalt Mixtures Expert Task Group [1] appear to be substantially correct. Based on the research findings, the ETG recommendations appear to represent a "middle ground." One possible refinement to the recommendations would also consider the stiffness of the RAP binder. Depending on the low temperature stiffness of the RAP, percentages of up to 20%, depending on the RAP binder stiffness, can be used without change to the virgin asphalt binder grade. RAP percentages greater than 15 to 30%, again depending on the RAP stiffness, can be used by following the blending equations and charts. RAP percentages between these extremes can be used by decreasing the high and low temperature grade of the virgin asphalt binder by one grade (i.e., using a PG 58-28 instead of a PG 64-22).
10. Blends containing 40% RAP were successfully tested in the research. At this high level, however, some non-linearity begins to appear in the blending equations. Users should exercise caution in the use of the linear blending equations (or charts) for percentages of RAP greater than 40%.

11. Testing variability was discussed, but insufficient data was available from this research to provide a systematic method of properly accounting for testing variability. Users should be cognizant of the variability in test results caused by the recovery and binder testing procedures. Further research in this area is warranted.
12. Blending using the new procedure for determining the critical low temperature of an asphalt binder, based on thermal stress curves developed from the BBR test and failure stress determined from the direct tension test, was discussed. Further research in this area is warranted to determine how to adjust the low temperature equations for determining blended asphalt binder properties.

BLACK ROCK STUDY

Based on experimental design, testing, and analyzing the data in this study the following conclusions can be drawn:

1. RAP does not act as a black rock. Test results have shown that mixtures containing RAP have properties much closer to those of the total blending case; at high RAP levels a significant amount of partial blending is occurring. Therefore, using blending charts in the design of mixtures containing RAP is a valid approach.
2. The Superpave performance tests, including shear tests and indirect tensile tests, were able to differentiate between black rock and two other mixtures cases (total blending and standard practice) at a high RAP ratio (40%), providing statistically valid evidence that RAP is not a black rock.
3. For all three shear tests, there was no significant difference among mixture cases at the low RAP ratio (10%) but there was a significant difference between the black rock case and the

other mixture cases at the high RAP ratio (40%). At low RAP contents, there is not enough hardened RAP binder present to change the mix properties.

4. Indirect tensile testing also supported this conclusion. The 10% RAP blends did not indicate a significant difference between the cases. At the 40% level, however, there was a noticeable difference between the actual practice and total blending cases versus the black rock case. At the higher percentages of RAP, the low temperature properties show behavior that approaches total blending.
5. The findings of this research project strongly suggest that the Mixtures ETG recommendation of a 15% threshold, below which no change in binder grade is required, appears reasonable. It is only at higher RAP levels that statistically significant differences between the mixture cases were measured. This limit could perhaps be raised to 20%, depending on the stiffness of the recovered RAP binder. A selection chart based on recovered RAP grade is offered.

MIXTURE EFFECTS STUDY

Evaluation of various RAP contents from 0 to 40% leads to the following conclusions.

1. The complex shear modulus of mixtures increased exponentially with RAP content in most cases.
2. Addition of a high stiffness RAP will create a mixture that is stiffer than a mixture made with a medium stiffness RAP.
3. Shear deformation and accumulated shear strain generally decreased as RAP content increased.
4. Low temperature mixture stiffness values increased with increasing RAP content.
5. Increasing RAP content or RAP stiffness decreases a mixture's resistance to low temperature

cracking, if no adjustments are made in the virgin binder grade.

6. The addition of up to 10% RAP into an asphalt mixture will not significantly affect the high or low temperature stiffness of the mixture. The addition of over 20% RAP does have a significant effect on the stiffness.
7. Increasing RAP content has very little effect on low temperature tensile strength of a mix.
8. As RAP content increased, beam fatigue life, measured by cycles to failure, decreased when no adjustments were made to the virgin binder grade.
9. Beams made with softer binder generally exhibited longer fatigue life.

MINI-EXPERIMENTS

Plant vs. Lab Comparison

1. No significant difference was found between samples of plant-produced HMA and specimens prepared in the laboratory using the protocols of this study.
2. The procedures used in this project do a reasonably good job of replicating field practice.
3. The conclusions of this project should be applicable to actual plant-produced mixtures.

Effects of RAP Handling

1. No significant changes occurred in the binder properties of RAP that was heated for 2 hours at either 110 or 150°C.
2. Higher temperatures and longer heating times could bring about changes in the RAP binder properties.

3. To reduce the possibility of changing the RAP binder properties and, possibly, the resulting mixture properties, the time of heating RAP in the laboratory should be limited to 2 hours or less at 150°C or less.

OVERALL CONCLUSIONS

The results of the black rock, binder effects and mixture effects studies all point to a threshold level of RAP of between 10 and 20%. At the 10% level, the effects of the RAP were not significant. At the 20% level, the effects were sometimes significant and at 40% the effects were usually significant. A 15% level may be a reasonable middle ground, although there is evidence to support raising this level to 20%, especially if changes are made in the binder stiffness. Changing the virgin binder grade based on the recovered RAP stiffness would counteract some of the apparently detrimental effects of RAP on fatigue and low temperature properties, both of which are largely binder dependent. Procedures based on the combined results of the different parts of this research are offered in the companion Guidelines for specifying agencies (Appendix D) and Manual for technicians (Appendix E). Suggestions for moving the results of this research are given in Appendix F, the Implementation Plan.

SUGGESTED RESEARCH

There are a number of questions remaining about the use of RAP in the Superpave system that will require more research to resolve. The following topics are among those questions.

Field verification of the findings of this project is needed. The test site in Connecticut is an excellent starting point, since the binder and RAP from that project have been extensively tested. The actual mixtures used in this research do not correspond to the field mixtures, however, since a common virgin aggregate and virgin binders were used for the purposes of this lab evaluation. Additional projects incorporating RAP and control sections without RAP should be placed in the field and monitored over time. Incorporation of differing percentages of RAP in the mixtures would help to verify the three-tiered approach recommended by the Mixtures Expert Task Group and largely verified here. This additional testing and evaluation may also help to verify the effect of RAP stiffness on binder grade selection and the validity of a table such as that suggested in Table 112.

Additional testing is needed in multiple laboratories to establish the variability of recovered RAP binder properties after extraction using the modified SHRP extraction and recovery procedures recommended in this research. Ruggedness and precision and bias testing is also needed.

The issue of recycling modified binders remains a question regardless of the mix design system used. Modified binders have been used for long enough now that pavements incorporating those binders are or soon will be in need of rehabilitation. How will RAP with a modified binder behave when added to a new mix, especially if that new mix also includes a modifier? Will compatibility issues become a concern? This study did not include binder modifiers in either the RAP materials or the virgin binders.

The effect of recycling agents was also not investigated during this research; it was determined to be beyond the scope of the project. The effect of these agents should be investigated. Perhaps an approach similar to that used in the black rock study could be used to assess the effects of rejuvenators. If recycling agents do act as rejuvenators, they would presumably make RAP act even less like a black rock and more like total blending. This effect should be considered when selecting the amount of RAP to incorporate or when selecting the virgin binder grade.

Lastly, a test method that can evaluate any mixture based on fundamental engineering properties should be developed and used to evaluate all mixtures, including those containing RAP. If the industry had a true performance test, the establishment of tiers and recommendations on changes in binder grade would be irrelevant. Any mixture could be designed and evaluated for its long-term performance. This is a lofty goal but should be an ultimate goal.

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APPENDIX A
ANNOTATED BIBLIOGRAPHY

Review of Current Practice: Literature Review (Task 1)

Literature searches on Reclaimed Asphalt Pavement, extraction and testing procedures were conducted through the Purdue Technical Information Service (TIS). TIS searched the following databases for information: Transportation Research Information Service (TRIS), Scisearch, EI Compendex, Pascal, NTIS, Energy Science & Technology JICST-Eplus, McGraw-Hill Publications, Inspec, Fluidex, Inside Conferences, Wilson Applied Science & Technology Abstracts, RAPRA Rubber & Plastics, Apilit, General Science Fulltext, API Encompass: News, Federal Research in Progress, Conference Papers Index, Geobase, Spin, Georef, Chemical Engineering & Biotechnology Abstracts, Mechanical Engineering Abstracts, Geoarchive, Abstracts in New Technologies & Engineering, Metadex, Tulsa (Petroleum Abstracts), Engineered Materials Abstracts, Ceramic Abstracts, World Translations Index, Materials Business File, Polymer Online, Meteorological & Geophysical Abstracts, and World Surface Coatings Abstracts.

The initial search for the key words "reclaimed" or "recycle" or "extract" and "asphalt" or "bituminous" or "pavement" or "binder" revealed over 3,000 items. The search criteria were then narrowed and the search was limited to items published in English in the years 1990 through 1997. It was felt that this time period was reasonable since the Superpave test methods to be analyzed in this study were not developed prior to 1990. Many changes have occurred in test methods and extraction/recovery procedures since that time. This search still resulted in 1,082 items. Summaries of the most relevant documents are provided below in different categories.

Extraction and Recovery Methods

Solvent Removal from Asphalt

B.L. Burr, R.R. Davison, C.L. Glover and J.A. Bullin. Transportation Research Record, No. 1269, Transportation Research Board, Washington, D.C. (1990) pp. 1-8.

This study compared the Abson and Rotavapor recovery methods at different temperatures for several asphalt viscosities. Trichloroethylene was used and solvent concentrations were measured after recovery using gel permeation chromatography.

Neither method was found to remove solvent adequately, though more solvent was removed at higher temperatures or with longer recovery periods. The Abson method was found to remove less solvent for high viscosity binders. The solvent hardened the asphalt; greater hardening was observed with longer exposure periods and higher temperatures. The Abson method was found to leave enough solvent in the recovered binder to produce significant softening, as measured by changes in the viscosity. More solvent could be recovered through longer recovery times and higher temperatures, but this would result in greater solvent hardening. The rotavapor method was found to remove more solvent, but was less repeatable than the Abson method.

Hardening was also observed, to a lesser extent, when volatile fractions of the asphalt were lost. Asphalts that had been aged through the Rolling Thin Film Oven (RTFO) did not exhibit this hardening, presumably because the volatiles were lost during aging.

Evaluation of Solvents for Extraction of Residual Asphalt from Aggregates

C.A. Cipione, R.R. Davison, B.L. Burr, C.J. Glover and J.A. Bullin. Transportation Research Record, No. 1323**,** Transportation Research Board, Washington, D.C. (1991) pp. 47-52.

The research compared the use of various solvents for removing asphalt from aggregates. The addition of alcohol to the solvent was also investigated. Several experiments were performed. The experiments compared the ability of different solvents to remove residual material. The different extraction methods and aggregate sources were compared for their effectiveness. The experiments also investigated the effect of moisture on the ability of solvents to remove residual asphalt, as well as the effects of adding different amounts of alcohol to the solvents.

The results of the experiments indicated that ASTM D-2172 Method A modified by using trichloroethylene (TCE)/ethanol was best at removing residual asphalt. It also suggested that moisture did not have a significant effect on the solvent. The study on the addition of alcohol to solvents showed that TCE with 15% ethanol was most effective in asphalt removal, and agitation increased the efficiency further. When the same amount of solvent was used, the TCE system removed significantly more hard-to-remove material than the toluene system did. It was also concluded that TCE/ethanol and pyridine are comparable in solvent power for hard-to-remove material, but seemed to remove different material preferentially. The authors also indicate that no solvent removes asphalt completely. Furthermore, the material that is easier to remove is probably better for predicting cracking.

Asphalt Hardening in Extraction Solvents

B.L. Burr, R.R. Davison, H.B. Jemison, C.J. Glover and J.A. Bullin. <u>Transportation Research Record</u>, No. 1323, Transportation Research Board, Washington, D.C. (1991) pp. 70-76.

This research investigated the effects of light, oxygen and temperature on the hardening of asphalt in solvents. The object was to quantify the amount of hardening with respect to time of exposure, temperature and concentration of dissolved asphalt. The experiment was performed on various solvents and asphalts. Some solutions were deoxygenated by bubbling with CO_2 or N_2, some had oxygen bubbled through to attain CO_2 saturation, and some solvents were direct from the bottle. Dark, low hood light and strong fluorescent light were used. Recoveries were conducted using the rotavapor apparatus at either near room temperature under vacuum or at higher temperatures under atmospheric pressure. The solvents tested were TCE, $CHCL_2$, CH_2CH_2, TCE/ethanol, toluene, and CCL_4. The solutions in different conditions were observed using gel permeation chromatography (GPC).

From the results, it seemed that prehardened asphalt still hardened in solvent at about the same rate as tank asphalt. Some oxygen-containing samples hardened considerably, and light seemed to accelerate hardening. In the TCE/ethanol sample, there was a gradual increase in hardening with decreasing asphalt concentration. The results appear to indicate that solvent hardening occurs to about the same degree in most solvents. The hardening is more rapid at the beginning, and then slows as time passes. One conclusion is that extracting at room temperature and completing the recovery process as quickly as possible can minimize solvent hardening.

New Apparatus and Procedure for the Extraction and Recovery of Asphalt Binder from Pavement Mixtures

B.L. Burr, C.J. Glover, R.R. Davison and J.A. Bullin. <u>Transportation Research Record</u>, No. 1391, Transportation Research Board, Washington, D.C. (1993) pp. 20-29.

This research was focused on presenting the SHRP extraction and recovery method and comparing it with modified versions of two commonly used procedures. The methods studied are the SHRP extraction method, and modified version of ASTM D-2172 A and ASTM D-2172 B. The modification in Method A was the substitution of toluene for trichloroethylene (TCE), with ethanol added in later washes; and the difference in Method B was that the solvents were varied for some experiments. It was recognized during the research that because properties of asphalt change when mixed with aggregates, there is no way of knowing the properties that the extracted asphalt is supposed to possess, i.e. "the 'correct' result is never known."

The results showed that the SHRP method and Modified Method A produced similar results and precision, while the Modified Method B extraction results were less reproducible with respect to average viscosities. Modified Method B had a low asphalt removal efficiency, leaving large amounts of asphalt on the aggregates. The SHRP method was slightly more efficient in removing asphalt compared to the Modified Method A. The authors concluded that the SHRP and Modified Method A procedures were able to provide better asphalt samples that have nearly unchanged properties. However, there are other considerations, such as the requirement of considerable operator attention and lab space.

Aging of Asphalt on Paved Roads- Characterization of Asphalt Extracted from the Wearing Courses of the Belgrade-Nis Highway

M. Smiljanic, J. Stefanovic, Hans-J. Neumann, I. Rahimaian and J. Jovanovic. Journal: Erdol and Kohl, Vol. 46, No. 6, Hamburg, Germany. (1993) pp. 238-244.

This paper presents the findings of tests to characterize asphalt binders extracted from eight paved road samples from different parts of Belgrade. These samples were related to different levels of roadway distress. The goal of the research was to correlate properties in aged asphalt with the damage on the road.

In this research, the penetration, softening point, Fraas breaking point and number average molecular weight were determined. Elemental analysis and thermal analysis were performed. The asphaltene content was also determined. Thermogravimetry was used as the method for measuring the accelerated aging of asphalt. The test was performed at 250^{o}C, as opposed to 165^{o}C for conventional methods.

The conclusions drawn from the research include the confirmation that aging of asphalt is a hardening process involving an increase in softening point and Fraas point and decrease in penetration. The more damage there is in the pavement, the greater the changes in the properties of the asphalt. Thermal analysis of the samples also showed that there is less oxidation susceptibility where the roads are better preserved.

Recycling Agents and Blended Binders

Evaluating Recycled Asphalt Binders by the Thin-Film Oven Test

A. Samy Noureldin and Leonard E. Wood. Transportation Research Record, No. 1269, Transportation Research Board, Washington, D.C. (1990) pp. 20-25.

In this research, long-term performance was evaluated, and the homogeneity, incompatibility and hardening rate in hot-mix-recycled bituminous pavement were identified. The effects of artificial laboratory aging on a virgin binder and three rejuvenated binders were determined.

The binder used was an AC-20, and the recycled binders were restored to the AC-20 classification range. The experiment examined the effects of binder type (virgin and three recycled binders restored using different agents) and time of exposure in the thin film oven test (TFOT) (0, 2, 5 and 10 hrs). During the preparation of samples, actual field conditions were simulated, so virgin aggregate was added to the RAP followed by the rejuvenator, except Mobilsol-30, which was added before the virgin aggregate.

The findings indicated that rejuvenated binders might have different aging behaviors than virgin binders of the same consistency. Penetration and viscosity measurements on a rejuvenated binder were not adequate to ensure long-term performance. The results indicated additional criteria and test conditions need to be developed to ensure success of hot-mix-recycled pavement. The TFOT was identified as a good tool to determine the hardening rate, possible nonhomogeneity and incompatibility that may occur with a rejuvenated binder. It was noted that in order to ensure good-quality recycled asphalt pavement with acceptable performance, careful selection and testing of a recycling agent is essential.

Viscosity Mixing Rules for Asphalt Recycling

J.M. Chaffin, R.R. Davidson, C.J. Glover and J.A. Bullin. Transportation Research Record, No. 1507, Transportation Research Board, Washington, D.C. (1995) pp. 78-85.

Forty-seven blends of aged asphalts and softening agents were blended at multiple levels of aged material content. It was found that for 45 of the blends, the relationship between viscosity of the blends at 60°C and the proportion of aged material can be described using the Grunberg model. Blends using low-viscosity asphalts as softening agents exhibited significantly different behavior from blends using commercial recycling agents. The low-viscosity asphalt softening agents had viscous interaction parameters close to or greater than zero. All of the blends using commercial recycling agents had interaction parameters less than zero. The value of the interaction parameter is a strong function of the viscosity difference between the aged asphalt and recycling agent. A normalized Grunberg model was developed to eliminate this dependency. An average normalized interaction parameter can be used to generate a "universal" mixing rule for commercial-type recycling agents.

Viscoelastic Characterization of Blended Binders

Hamid R. Soleymani. Ph.D. Dissertation, University of Saskatchewan, Saskatoon, Canada (September 1997) 223 pp.

Research was conducted to study the properties of laboratory-aged binders blended with two soft asphalt cements and two recycling agents. The main objective of this research was to characterize the blended binders with PG testing parameters (G^*, δ, S and m-value). The other objective of this research was to investigate the temperature and loading time dependencies of blended binders with their master curves. The relationships between master curve parameters of blended binder with proportion of recycling agent were studied. The master curve parameters, rheological index (R) and crossover frequency (ω_c), were based on the SHRP A-002A model for asphalt cement, which suggested a hyperbolic equation for the master curve of asphalt cements. The blended binders were characterized at a wide range of temperatures from -30 to 70°C. All blended binders were tested with the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR).

Based on the results of this research, a linear relationship was shown to be adequate for prediction of PG testing parameters (log G*, δ, log S, and m-value). Two methods were proposed for the selection of soft asphalt cements/recycling agents in recycled mixtures. The first method was based on a linear relationship for PG binder performance criteria (G*/sinδ, G*sinδ, S and m-value). The second method was based on a linear relationship of the critical temperatures, the temperatures at which the PG criteria were just satisfied. The relationship of master curve parameters (R and ω_c) of the blended binders was studied. A linear relationship was accurate enough for prediction of these parameters of blended binders with the proportion of recycling agents in the blends. The temperature dependency of shift factors was studied based on defining temperature (T_d) from the William, Landel and Ferry (WLF) Equation. The defining temperature decreased as the proportion of recycling agent in the blend decreased and the binders aged.

The results of this study can be used for selection of asphalt cement/recycling agent to rejuvenate the aged asphalt cement in RAP. In addition, results can be used for producing a specific PG asphalt cement by blending different asphalt cements.

Effect of Composition on Asphalt Recycling Agent Performance

G.D. Peterson, R.R. Davison, C.J. Glover and J.A. Bullin. Transportation Research Record, No. 1436, Transportation Research Board, Washington, D.C. (1994) pp. 38-46.

The purpose of this research was to find out the types of materials suitable for use as asphalt recycling agents. Experiments were performed for re-blended asphalts with different components mixed in controlled amounts and artificially aged. Tank asphalts were hardened by bubbling oxygen though molten asphalt, then aging in the Pressurized Oxygen Vessel (POV). The factors to be studied were the effect of oil on aging of aromatic fractions; effect of metals and asphaltenes on aging; and effect of oils, waxes, and asphaltenes on re-blended asphalt aging. The zero shear complex viscosity, measured in the dynamic shear rheometer, and carbonyl area, which indicates amount of oxidation, were measured for aged and unaged blends.

The results from the experiments showed that asphaltenes had practically no effect on the oxidation rate, but did increase hardening rate. Aged material containing high amounts of asphaltenes, when recycled, had increased hardening susceptibility, but better temperature susceptibility. Highly aromatic recycling agents produced pavements that were superior to the original pavement. Small amounts of wax had no effect, but waxes and saturates unquestionably affect the ductility negatively.

An Integrated Approach for Determining Additive Requirements in Hot Mix Recycling

V.P. Sevas, A.C. Edler, M.A. Ferreria and E.J. Van Assen. Sixth International Conference on Structural Design of Asphalt Pavements, Vol. 1, Ann Arbor, Michigan. (1987) pp. 23-33.

An integrated approach including chemical composition and fluxing power methods was used for selection of the type and amount of recycling agent for hot asphalt recycling.

In chemical composition, first an open column chromotography method was used to fractionate aged bitumens and recycling agents, but because of the time consumed and large sample sizes required, the High Performance Liquid Chromatography (HPLC) method was used instead. In this study, ten recycling agents, seven new bitumens and three aged asphalt cements were fractionated by HPLC, and the chemical fractions including asphaltenes, saturate and aromatic + resins were determined.

To determine the physical requirements for a recycling agent, the fluxing power method was used. In this method, the penetration of blended binders with differing amounts of recycling agent was measured and the slope of fluxing lines were obtained. The steeper the slope of the fluxing lines the greater the fluxing power of the agent for restoring aged extracted binders. Chemical composition data were used in conjunction with fluxing power requirements to design and produce laboratory and field recycled mixes.

Design of Recycled Asphalt Pavements and Selection of Modifiers

R.L. Dunning and R.L. Mendenhald. American Society for Testing and Materials, <u>Recycling of Bituminous Pavements</u>, STP 662, ASTM, Philadelphia, PA (1977) pp. 35-46.

The purpose of this paper is to discuss the design of recycled asphalt pavement with emphasize on the criteria required to reconstitute an aged asphalt. Recommended specification requirements for a modified binder include a flash point of 200°C, a viscosity range of 90 to 300 cP at 60°C, and a composition of at least 9 percent polar compounds and 60 percent aromatic compounds.

The amount of modifier required to soften an asphalt to a predetermined viscosity may be calculated within limits by using equations based upon plots of log-log (viscosity) versus log[559.7-(%modifier)] and log-log(viscosity) versus [559.7+2 (%modifier)].

Practical Aspects of Reconstituting Deteriorated Bituminous Pavements

D.D. Davidson, William Cenessa and S.J. Escobar. American Society for Testing and Materials, STP 662, <u>Recycling of Bituminous Pavements</u>, ASTM, Philadelphia, PA (1977) pp. 16-34.

The objective of this paper was to provide practical guidelines, which can be used to reconstitute deteriorated asphalt pavements. Two elements involved in recycled mix design, including restoration of durability and desirable consistency to the aged asphalt and determination of the proper mix design, were studied in this research.

In the first element, some physical and chemical specifications were proposed for reclaiming agents. These specifications include viscosity, flash point, volatility, compatibility, chemical composition and specific gravity. For recycled mix design, various steps were suggested through this research:

- Basic properties of the pavement to be recycled must be determined.
- The Asphalt Institute formula was shown to be adequate for determining the asphalt demand of the aggregate.
- Recycling Agent may be selected.
- Viscosity or penetration blending graphs should be used for checking the amount of recycling agent in the recycling pavement.

Design Approaches for Mixtures Containing RAP

Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP) Superpave Mixture Expert Task Group. Federal Highway Administration, Washington, D.C. (1997) 5 pp.

This guideline is the result of an FHWA Superpave Mixture Expert Task Group activity to make specific recommendations for inclusion of RAP into Superpave mixture design procedures.

This guideline suggests that, in the design of Superpave mixtures with RAP, aggregate in the RAP be handled as aggregate and asphalt binder in the RAP be considered as part of the blended asphalt binder. All aggregate requirements for the aggregate blend (virgin and RAP) must be satisfied. For adjusting the asphalt binder grade, this guideline divided the design of mixtures containing RAP into three tiers as follows:

1) ≤ 15% RAP by weight of total mixture

   The asphalt binder grade for the mixture is selected for the environmental and traffic conditions as required for a mixture with all virgin materials. No grade adjustment is made to compensate for the stiffness of the asphalt binder in the RAP.

2) 16% to 25% RAP by weight of total mixture

   The selected binder grade for the new asphalt binder is one grade lower than the grade required for a virgin asphalt binder at both the high and low temperatures.

3) > 25% RAP by weight of total mixture

   The binder grade for the new asphalt binder is selected using an appropriate blending chart for high and low temperatures.

Designing Recycled Hot Mix Asphalt Mixtures Using Superpave Technology

Prithvi S. Kandhal and Kee Y. Foo. Progress of Superpave (Superior Performing Asphalt Pavement): Evaluation and Implementation, STP 1322, American Society for Testing and Materials, West Conschocken, PA (1997).

This research project was undertaken to develop a procedure for selecting the Performance Grade (PG) of virgin asphalt binder to be used in recycled mixtures. Three aged asphalt binders recovered from reclaimed asphalt pavement (RAP) and three performance grade (PG) binders, PG 64-22, PG 58-22 and PG 52-28, were physically blended in different proportions to obtain various recycled binders. The recycled binders were subjected to a temperature sweep using the dynamic shear rheometer near high pavement service temperatures (that is, measuring $G^*/\sin\delta$ or rutting factor at various temperatures) to determine their high temperature grade and near the intermediate service temperatures (that is, measuring G*sinδ or fatigue factor at various temperatures) to determine their intermediate temperature grade.

It was concluded that the construction of a "temperature sweep" blending chart is very time consuming. It involves conducting a temperature sweep on both aged asphalt binder in the RAP as well as the proposed virgin asphalt binder to determine the temperature at which G*/sinδ equals 1.0 kPa. The inconvenience of running temperature sweep tests can be eliminated by constructing a "specific grade" blending chart. In this blending chart, the Y-axis is a log-log scale (similar to viscosity or penetration blending charts). The information needed to construct a "specific grade" blending chart is the G*/sinδ of both the aged asphalt binder and the virgin asphalt binder at the high pavement service temperature.

Preliminary Mixture Design Procedure for Recycled Asphalt Materials

T.W. Kennedy and Ignacio Perez. American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA (1977) pp. 47-67.

This paper summarizes the findings of a study to evaluate the strength, fatigue and elastic characteristics of recycled asphalt pavement materials and to develop a preliminary mixture design procedure. Mixtures with different types and amounts of additives for three recycling projects in Texas were evaluated. The primary methods of evaluation were the static and repeated-load indirect tension tests.

Estimates of tensile strength, resilient elastic and fatigue characteristics of recycled mixtures were obtained. The necessary steps for the design of recycled asphalt mixtures have been subdivided into three categories; general, preliminary design and final design. Some recommended values for the indirect tensile test were proposed for recycled mixtures.

Some other findings of this study were:

- The engineering properties of the recycled mixtures evaluated in this study generally were slightly better than those of conventional mixtures.
- Satisfactory mixtures can be obtained with recycled mixtures.

Development of Low-Temperature Blending Charts for Recycled Asphalt Binders Using the Superpave Binder Specification Parameters

Hussain Bahia, Robert Peterson and David Ross. Development of Low Temperature Blending Charts for Recycled Asphalt Binders Using the Superpave Binder Specification Parameters, FHWA Report DTFH-61-95-C-00055, National Asphalt Training Center II Project (1996).

This study was initiated by the FHWA to establish guidelines for selecting Performance Graded asphalts for mixtures containing RAP material. This report summarizes the results of an experiment at the Asphalt Institute and also refers to another study carried out by the Transportation Center of the University of Saskatchewan, Canada (Soleymani).

Comparing a linear and non-linear model for prediction of PG parameters of blended binders showed that a linear model can be used for this purpose. Two alternative methods have been recommended based on the results of the mentioned studies. These methods differ in the concept used to define a blending chart. The first is based on the concept of limiting temperature. The second is based on testing at the testing temperatures appropriate for the target grade (design grade).

Black Rock Issue

Modifier Influence in the Characterization of Hot-Mix Recycled Material

Samuel H. Carpenter and John Wolosick. Transportation Research Record 777, Transportation Research Board, Washington, D.C. (1980) pp. 15-21.

This paper investigates the influence of the recycling agent diffusion process on the recycled mixture. A recycled material with 2.6-mm penetration at 25°C was used in this study. A standard modifier (Paxole 1009) was chosen to rejuvenate the aged mixture. Two sets of material were tested. The rejuvenated samples were made by blending the modifier into the extracted asphalt cement and the combination was added to aggregate recovered from the original Reclaimed Asphalt Pavement (RAP). The recycled samples were prepared by adding the same proportion of modifier to the recycled material without extraction of the asphalt cement from the RAP. Two series of material were characterized with resilient modulus, creep compliance and Marshall stability. The test data support a softening effect caused by the diffusion of the modifier into the old asphalt cement.

In a validation study, the asphalt cements of recycled samples were recovered in two different stages at an appreciable time following mixing; these were characterized as inner and outer layers. The outer and inner layers were not of the same consistency, but they approached the same consistency after more than 60 days following mixing. Therefore, the diffusion process must be recognized and accounted for in the prediction of lab and in field performance.

Test for Efficiency of Mixing of Recycled Asphalt Paving Mixtures

Teh-Chang Lee, Ronald Terrel, and Joe Mahoney. Transportation Research Record 911, Transportation Research Board, Washington, D.C. (1983) pp. 51-60.

The main objective of this research was to develop a technique and necessary test equipment needed to establish the ability of a mixing operation to produce an intimate mixture consisting of Reclaimed Asphalt Pavement, modifying agent and new asphalt.

The researchers examined the resilient modulus, as a classical engineering testing method, for determining the efficiency and time dependency of recycling agents in recycled mixtures. They concluded that the resilient modulus test appears to be sensitive enough to the recycling agent content but not sensitive enough to detect small changes in the mixture. Therefore, the researchers used a dye chemistry technique for this purpose.

In the dye chemistry technique, a small amount of dye chemical was added with the recycling agent and then developed dye in the mixture was detected by visual examination or by using other measuring methods. The investigators found that the dye chemistry method provides additional insight into how a recycling agent disperses with time. Standard laboratory samples were prepared and maintained at room temperature for 1, 5, 10 and 30 days and up to 6 months after compaction of samples. The laboratory and field dye chemistry results showed that the diffusion of a recycling agent through a mix is a function of mixing time and the potential of further dispersion of a recycling agent with time is only local.

Rejuvenator Diffusion in Binder Film for Hot-Mix Recycled Asphalt Pavement

Ahmad Samy Noureldin and Leonard E. Wood. Transportation Research Record 1115, Transportation Research Board, Washington, D.C. (1987) pp. 51-61.

The objective of this study was to determine the extent to which certain types of rejuvenators diffuse into the hardened asphalt film coating the aggregate and effect of its properties during a specific period of time.

A partial extraction technique that had the effect of dividing the asphalt film into microlayers was used. The recovered binders from each microlayer were characterized by means of consistency tests. In this study, one RAP, one new aggregate and three types of recycling agents (AC-2.5, AE-150 and Mobilsol-30) were selected. In the stage extraction method, the amount of solvent for extraction of binder in recycled mixtures was added to mix in increments of 200, 200, 300 and 700 ml in order to extract the asphalt film in four stages. Some findings from this study are as below:

- Stage extraction of the hard asphalt film from the RAP indicated a non-uniform consistency distribution. The outer microlayer of binder film was the hardest, the second microlayer was less hardened and the third layer appeared to retain its original consistency.
- Stage extraction of binder rejuvenated by recycling agents without addition of virgin aggregate indicated that the rejuvenators are most effective at softening the hardened binder on the outer two microlayers of the asphalt film.

Laboratory and Field Performance of Recycled Asphalt Pavements

Mixture Properties of Recycled Central Plant Materials

J.A. Epps, D.N. Little, R.J. O'Neal and B.M. Galling. "Mixture Properties of Recycled Central Plant Materials," American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA 1997, pp. 68-103.

The objectives of this research were to:

a.) define the material properties of central plant recycled mixes in Texas,

b.) compare properties of these recycled mixes with conventional paving mixtures normally used in Texas,

c.) evaluate the performance of the pavements containing central plant recycled mixes, and

d.) compare the performance of pavement constructed with recycled and conventional paving mixtures.

Hveem, Marshall, resilient modulus, indirect tensile, direct tensile and water sensitivity properties were reported for recycled mixtures compacted both in the laboratory and under normal field procedures. The material properties of central plant recycled mixes indicated that, through proper mixture design, these mixtures can meet conventional design criteria. The short-term performance evaluation of the recycled pavement, based on Serviceability Index and Pavement Rating Score, indicated that they showed satisfactory performance.

Laboratory Performance of Recycled Asphalt Concrete

R.L. Terrel and D.R. Fritchen. American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA (1977) pp. 104-122.

This research used a practical laboratory test system for evaluating the performance of recycled asphalt pavement. One old asphalt pavement was selected for this study. The amounts of two different recycling agents to be used were determined with viscosity blending charts, and the laboratory samples were prepared. The laboratory recycled samples were conditioned in freeze-thaw. The performance of the laboratory samples was determined by measuring the resilient modulus (M_r).

The addition of both types of rejuvenating agent softened the old mixes in terms of decreasing the modulus. The results of this research also indicated that the performance of recycled asphalt concrete pavement is comparable to the performance of standard new asphalt concrete pavements.

Recycling Old Asphaltic Pavement with Sulfur

W.C. McBee, T.A. Sullivan, and Don Saybk. American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA (1977) pp. 123-141.

In this study, the feasibility of using sulfur to soften or reduce the viscosity of the oxidized asphalt binder in old asphaltic pavements was demonstrated. On a laboratory scale, three sources of RAP were investigated. With all three materials, mixes incorporating the addition of 1.25 weight percent sulfur (16 to 26 weight percent of the binder) to the reclaimed asphalt material were designed.

The laboratory testing results showed that recycled mixtures softened with sulfur plus additional asphalt had higher than normal stiffness values, which means greater fatigue life for the recycled mixtures. A series of constant-stress amplitude flexural fatigue tests showed that recycling by the addition of asphalt-paxale, sulfur-asphalt or sulfur alone can provide a pavement material with fatigue behavior equal or superior to that of a typical asphaltic concrete system.

Durability of Recycled Asphalt Concrete Surface Mixes

Osama Abdulshafi, Bozena Kedzierski, and Michael G. Fitch. Ohio Department of Transportation, Columbus, OH (1997) 109 pp.

This study was designed to evaluate the durability of HMA surface mixtures produced in the state of Ohio that contain varied amounts of RAP and included evaluations of both the binders and the mixtures. The binder evaluation included determination of the viscosity and infrared spectroscopy characteristics of laboratory aged samples; virgin, RAP and blended virgin plus RAP samples were analyzed. Uncompacted mixture samples containing 0, 10, 20 and 30% RAP were oven-aged until the recovered binder properties (Abson process) matched those from standard binder aging methods. Specimens were then prepared from these mixtures by Marshall compaction and analyzed for bulk specific gravity, theoretical maximum specific gravity, resilient modulus, AASHTO T-283 moisture sensitivity, indirect tensile strength and indirect tensile creep modulus.

Infrared spectroscopy indicated that the RTFO and PAV procedures produced aged binders that differ in chemical composition from those recovered from oven-aged mixtures. The results also indicated that the aged RAP binder does not completely blend with the virgin asphalt cement. Mixtures containing RAP showed an increase in the resilient modulus, increase in indirect tensile strength and increase in indirect creep modulus as the percentage of RAP increased. The mixtures containing RAP also showed slight improvement in the resistance to moisture damage. A procedure for the selection of the percent RAP was recommended.

Five-Year Experience of Low-Temperature Performance of Recycled Hot Mix

K.K. Tam, P. Joseph, and D.F. Lynch. Transportation Research Record, No. 1362, Transportation Research Board, Washington, D.C. (1992) pp. 56-65.

This research looked into the thermal cracking of recycled hot-mix (RHM) and confirmed the belief that RHM is less resistant to thermal cracking than non-recycled mixes. The results were obtained through laboratory and field evaluation. The research also compared the use of two types of results as methods of evaluation. The thermal cracking properties of the mixes were analyzed using the limiting mix stiffness and pavement fracture temperature criteria. RHM specimens were produced from plant mixes and individual mix components in the laboratory. These RHM mixtures covered different recycling ratios. Penetration grade asphalt cements (85/100 to 300/400) were used in the RAP mixtures.

The research showed that the Fracture Temperature (FT) criteria correlated well with field data and are more suitable and reliable for evaluating low temperature performance of hot mixes than limiting stiffness. It also correlated well with recovered penetration values and followed the expected trends of behaviors. The limiting stiffness method needs to be examined further and modified accordingly before it can be used for predicting low temperature behavior. The research also showed that RHMs are more prone to thermal cracking than conventional mixes. In order to minimize low temperature cracking and obtain better accuracy of predicting fracture temperature, recycling ratios should be limited to 50/50, an appropriate virgin asphalt cement should be selected for a desirable recovered mix penetration, the fracture temperature method should be used for mix evaluation, and more data needs to be obtained to support the use of laboratory samples for prediction or evaluation of low temperature performance in the field, both for RHM and conventional mixes.

Laboratory Evaluation of Recycled Asphalt Pavement Using Nondestructive Tests

A. Samy Noureldin and Leonard E. Wood. Transportation Research Record, No. 1269, Transportation Research Board, Washington, D.C. (1990) pp. 92-100.

This research was focused on characterizing the performance of recycled hot-mix asphalt pavement compared to virgin mix using pulse velocity, resilient modulus and Marshall stability tests. The binder in the RAP was restored to an AC-20 designation using three different agents. The percentage rejuvenator used was determined using the Asphalt Institute curves, and was verified by extraction, recovery and testing. The salvaged and virgin aggregates were combined to a fixed gradation, and mixes containing 5.5, 6, and 6.5% asphalt were prepared.

The test results show that the virgin mixture stiffness and strength values were generally higher than those of recycled mixtures. AE-150 may not be a good rejuvenator as the stiffness and strength values of the recycled mixture with AE-150 were very low. Pulse velocity test parameters were not sensitive to binder content or binder type present in mixtures. Resilient modulus test results were sensitive to both, and can be used for the design of asphalt mixtures and the evaluation of recycling agent used. The Marshall stability test was adequate for identifying binders with potential for producing high stability mixtures, and pulse velocity and modulus of elasticity measurement could be used for pavement thickness design considering their low variability.

Recyclability of Moisture Damaged Flexible Pavements

Serji N. Amirkhanian and Bill Williams. Journal of Materials in Civil Engineering, Vol. 5, No. 4, American Society of Civil Engineering, New York (1993) pp. 510-530.

The objective of this research was to evaluate asphalt concrete mixtures, which had been damaged by moisture, using test data from lab-prepared Marshall specimens. Also evaluated in this study were the South Carolina Department of Highways and Public Transportation (SCDHPT) procedures using RAP from field cores to design recycled mix instead of using milled RAP from actual paving.

The mix design for the virgin specimens was prepared using the Marshall method with an optimum asphalt content of 5.25%. The SCDHPT Marshall mix design was used for the recycled Marshall specimens. Hydrated lime and liquid antistrip agents were used. Some specimens were partially vacuum saturated according to the Root-Tunnicliff moisture-conditioning test. All specimens, wet and dry, were tested for resilient modulus and indirect tensile strength. A visual stripping rating was also performed on the moisture-conditioned specimens.

Statistical analysis of the results showed that the indirect tensile strength ratios and resilient moduli ratios of moisture-damaged asphalt concrete samples were significantly higher than those of virgin materials. The tensile strength ratio and resilient modulus ratios were higher for virgin materials, but not significantly. There were no significant differences in the specimens containing milled RAP and cored RAP. It was also found that antistripping agents were effective in recycled concrete mixtures. The results indicated that mixes containing up to 15% RAP are not more susceptible to moisture damage than virgin mixes and that the reuse of moisture-damaged RAP mixtures does not necessarily increase the risk of moisture damage for the new pavement.

Performance of Recycled Hot-Mix Asphalt Mixtures in Georgia

Prithvi S. Kandhal, Shridhar S. Rao, Donald E. Watson, and Brad Young. Transportation Research Record, No. 1507, Transportation Research Board, Washington, D.C. (1995) pp. 67-77.

The purpose of this research was to evaluate the performance of recycled pavements and compare them to virgin asphalt pavements. Field projects in Georgia were selected for the first part of this research such that the recycled and virgin sections used the same virgin aggregates in the mixture, were produced by the same HMA plant, were placed and compacted by the same equipment and crew, and were subjected to the same traffic and environment. The extraction of aged asphalt from the mixtures was done using the ASTM D2172 Method A procedure using trichloroethylene (TCE), while the recovery process was that recommended by SHRP. Tests performed on the recovered asphalt included viscosity at 60°C, penetration at 25°C, and dynamic shear rheometer (DSR) at 64°C and 22°C. Tests conducted on the cores were air void content, resilient modulus at 25°C and indirect tensile test at 25°C. Mix from cores of the virgin and recycled pavements was reheated and recompacted in the Corps of Engineers gyratory to determine the gyratory stability index (GSI), gyratory elasto-plastic index (GEPI) and roller pressure.

The results of the first part of the research showed that the pavement sections were performing satisfactorily, and there were no significant differences between the properties of the virgin and recycled sections in terms of air voids or resilient modulus measured on cores as well air voids, GSI and confined dynamic creep modulus for the recompacted mixes. There were significant differences in the indirect tensile strength, GEPI and roller pressure values. Recovered binder test results showed no significant differences for viscosity, penetration, rutting factor ($G^*/\sin\delta$) or fatigue factor ($G^*\sin\delta$).

The second part of the research involved studying projects with only recycled wearing courses and projects with only virgin wearing courses. Measurements taken from these projects included rut depth, cracking and density. Asphalts recovered from the cores were tested for penetration at 25°C and viscosity at 60°C.

The results of the second part of the research showed that there were no significant differences in the properties of virgin and recycled pavements in terms of rutting, cracking or density. The overall performance of the virgin and recycled pavements was comparable based on visual inspection. The conclusion of the research was that recycled pavements generally perform as well as virgin pavements, implying that the current Georgia DOT specifications, procedures and quality control are satisfactory.

Behavior of Recycled Asphalt Pavements at Low Temperatures

M. Sargious and N. Mushule. "Behaviour of Recycled Asphalt Pavements at Low Temperatures." Canadian Journal of Civil Engineering, Vol. 18, National Research Council of Canada, Ottawa (1991) pp. 428-435.

In this study, a mixture containing 45.2% reclaimed asphalt pavement and 54.8% virgin materials was compared to a 100% virgin mixture designed to meet the same initial properties. Laboratory properties including resilient modulus, modulus of elasticity, coefficient of thermal expansion, thermal conductivity and specific heat were compared in what is termed the experimental analysis. A finite element computer program called FETAB was used in the theoretical analysis to analyze the performance of the recycled and virgin mixtures if they were used in a variety of thicknesses and over different subgrades. The program considers the influence of mixture properties as well as pavement properties to determine the thermal stresses that would build up in various pavement cross sections due to a change in temperature from 20 to -40^{o}C.

In both the theoretical and experimental analyses, the recycled mixture/pavement was found to perform better than the virgin control in terms of low-temperature cracking. This may have been due to the fact that a softer asphalt (400/500) was used in the recycled mixture than in the control (150/200). The recycled mixture also had a higher coefficient of thermal conductivity, higher tensile strength and lower coefficient of thermal contraction. The authors noted that further research was needed.

The Mechanical Properties of Recycled Asphalt Mixes

A.F. Stock and S.J. Sulaiman. Highways and Transportation, Vol. 42, No. 3, Journal of the Institution of Highways and Transportation, London (1995) pp. 19-24.

This paper presents the results of a program of mechanical tests designed to evaluate mixes, mix design approach, and quality of recycled mixes. The tests were performed on mixes containing increasing amounts of recycled asphalt up to 70%. Tests performed were the Marshall stability and flow, dynamic stiffness and flexural strength. During the preparation of the samples, the recycled material was heated at temperatures limited to 100°C so as to avoid binder run-off. The hot mix was placed in a large mold and compacted. The compacted samples were then cut into manageable pieces from which cores and test samples were cut. This ensured that the samples were provided from one batch of mix.

The results from the Marshall test showed that there was no significant difference in the stabilities of the mixes with varying proportions of RAP up to 50%. The mix with 70% RAP showed significantly higher stability. The differences in flow were also not significant. This implied that the mixing and compaction technique used produced samples with uniform density and mechanical properties. There were also no significant differences in the dynamic stiffness of mixes with up to 70% RAP, for a range of temperatures from -5°C to 25°C, and for loading rates between 0.1 and 10 Hz. The RAP also does not influence the flexural strength for temperatures in that range. The strain at failure increased with RAP content, but was not likely to lead to premature failure.

Performance of Recycled Asphalt Concrete Overlays in Southwestern Arizona

Mustaque Hossain, Dwight G. Metcalf, and Larry A. Scofield. Transportation Research Record, No. 1427, Transportation Research Board, Washington, D.C. (1993) pp. 30-37.

The research studied recycled asphalt concrete overlays as a rehabilitation strategy. Eight test sections were observed for roughness, frictional properties and cracking. Overlays containing 50/50 blends of virgin and recycled materials and all virgin materials were placed in two thicknesses, 51mm and 102 mm. The thinner overlays were constructed over existing surfaces and over milled surfaces (mill and replace). The test sections were in a dry, no-freeze zone.

In this research, roughness and frictional characteristics were used to indicate present serviceability. Roughness was measured by the Mays ride meter, and frictional characteristics were measured using the Mu meter. The structural pavement performance was evaluated using visual distress survey (PAVER) and falling weight deflectometer. Rut depth, bulk density and air voids were also measured.

The research concluded that the overlays performed satisfactorily throughout their service lives. The recycled pavements performed as well as the virgin pavements. The thicker overlays performed better in terms of cracking, but showed more rutting, due to densification. The mill and replace strategy did not provide increased life, but for those pavements, the recycled mix performed better than the virgin mix. Pavements of both thicknesses required rehabilitation after ten years of service.

Evaluation of Recycled Projects for Performance

Harold R. Paul. Asphalt Paving Technology, Vol. 65, Journal of the Association of Asphalt Paving Technologists, St. Paul, Minnesota (1996) pp. 231-254.

This report summarizes a performance evaluation comparing recycled and conventional projects over a five-year period. Five recycled pavement sections were paired with virgin pavements constructed during the same time period by the same contractor, if possible, and with similar mix designs, cross sections and traffic. RAP contents ranged from 20 to 50%.

The pavement performance was analyzed in terms of serviceability, Pavement Condition Rating, (PCR) and structural strength (Dynaflect). Cores were analyzed to determine specific gravity, asphalt content and recovered binder properties (penetration, viscosity and ductility).

The findings indicate that the recycled pavements performed as well as conventional pavements from six to nine years after construction. No significant differences were found between the recycled and virgin pavements as measured by PCR or upper pavement strength (excluding subgrade differences). The recovered binders revealed no significant difference in penetration, viscosity or ductility.

Recycling of Asphalt Mixtures Containing Crumb Rubber

B.E. Ruth, M. Tia, G. Jonsson, and J.C. Setze. Florida Department of Transportation, Report No. FL/DOT/MO/D510717, Tallahassee, FL (1997) 221 pp.

This study was conducted to evaluate the effects of recycling asphalt mixtures that contain Crumb Rubber Modifier. The study is reviewed here due to its use of a procedure to simulate a recycled mixture by oven-aging it in the laboratory. Mixtures were evaluated using various percentages of RAP with three different sizes of CRM at three different concentrations of rubber. Mixtures were prepared meeting a typical Florida DOT gradation modified to represent a milled mixture. The mixtures, which contained the CRM modifier, were aged for 14 days in a convection oven at 85^{o}C to simulate field aging. The artificial RAP was then combined with additional aggregate and asphalt to produce mixtures, which were then evaluated in terms of Rice densities and GTM compaction-densification tests.

Among other results, the study found that there was no statistical difference between mixtures with and without CRM in terms of compacted mixture properties. The inclusion of RAP with age-hardened CRM did not significantly influence the shear resistance of one type of mixture, but did affect the air void content, due to significant increases in the Rice density. This increase in the Rice density was concluded to be due to binder absorption and a possible loss of volatiles.

Field Validation of Laboratory Aging Procedures for Asphalt Aggregate Mixtures

C.A. Bell, M.J. Fellin and A. Weider. Asphalt Paving Technology, Vol. 63, Journal of the Association of Asphalt Paving Technologists, St. Paul, Minnesota (1994) pp. 45-80.

This paper summarizes the work to validate the short-term and long-term oven aging techniques developed under SHRP to simulate aging during the construction process and during field service. Field samples were used during this study to compare to laboratory-produced samples of the original construction materials that were intended to simulate actual aging behaviors. The diametral resilient modulus was used to evaluate the effects of different aging times and handling procedures.

The results presented in this study support the conclusion that oven aging for four hours at 135°C is representative of the type of aging that occurs during mixing and placement. Two days of oven aging at 85°C represents aging typical of up to five years, and four days at 85°C appears to simulate up to 15 years for Wet-No Freeze and seven years in Dry-Freeze climates.

Guidelines for Wet-Freeze and Dry-No Freeze could not be developed because of a lack of suitable projects with samples of the original materials that were sufficiently old. Oven aging at 85°C was considered more reliable than aging at 100°C because aging at the higher temperature can damage the samples.

Evaluation of Fatigue Properties of Recycled Asphalt Concrete

Elton R. Brown. Sixth International Conference on Structural Design of Asphalt Pavements, Vol. 1, Ann Arbor, Michigan. (1987) pp. 305-322.

In this study, samples of aged asphalt concrete were obtained from three locations. These samples were blended with new aggregate and new asphalt materials to produce six different recycled mixtures. The flexural fatigue properties of recycled samples, two conventional mixtures and blends of recycled mixture and new material were evaluated.

Test results indicate that recycled mixtures can be designed to perform as well as conventional mixtures when tested in flexural fatigue. The properties of blended asphalt binders in the recycled mixture should be similar to the properties of a new asphalt binder to provide satisfactory results.

Recycled mixtures performed better than conventional mixtures in fatigue when analyzed for a thin layer of asphalt concrete placed over a base course; however, the conventional mixtures performed better than the recycled mixtures when the data were analyzed for thick layers such as full depth asphalt concrete.

Fundamental Properties of Recycled Asphalt Mixes

V. P. Servas, M.A. Ferreira, and P.C. Curtayne. Sixth International Conference on Structural Design of Asphalt Pavements, Vol. 1, Ann Arbor, Michigan. (1987) pp. 455-465.

This study has two sections; a laboratory based evaluation of recycled base mixes and the use of a heavy vehicle simulator test to determine the behavior of recycled asphalt base layers. A laboratory study was carried out to determine the properties of asphalt mixes composed of different proportions of reclaimed material, meeting the design criteria of conventional mixes. It was found that the proportion of reclaimed material had no effect on permanent deformation and fatigue resistance. This study took no account of either the durability characteristics of recycled mixes or the effect of recycling additives.

The heavy vehicle simulator was used to test recycled asphalt base layers. The results of this accelerated testing suggested that the field behavior of recycled base mixes is comparable to that of conventional asphalt.

Pavement Recycling Executive Summary and Report

U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-SA-95-060, Washington, D.C. (1996) 119 pp.

The FHWA initiated a project in mid-1992 to assess the current state-of-practice of recycled HMA production. The scope of this project included site visits to 17 State highway agencies (SHAs), with at least two SHAs in each FHWA region. Field contacts included discussions with design, research, and construction individuals from SHAs, contractors, and industry. This report summarizes the state-of-practice for the use, materials mix design, structure design, construction and performance of recycled HMA pavement.

Based on this report, it was estimated that 45 million tons of RAP are generated annually with approximately 33 percent of the RAP being reused in HMA productions. There are practical limitations on the amount of RAP that can be incorporated into a recycled HMA. Some of these limitations include plant technology and the amount of fine material in the RAP. However, some specifications or special provisions provide further limitations on RAP usage. These limitations are an obstacle that limits recycled HMA production. In most cases, restrictions were based on past projects that did not perform well. However, it was found that there was limited research or analysis to explain the poor performance. Other agencies placed limitations on RAP based on their judgment. Some of the reasons for low limits of RAP in specifications cited include:

- The RAP variability was perceived to be too high to use in HMA production, or recycled HMA production is too variable.
- Blending soft asphalt cement or rejuvenating agent with salvaged binder can be accomplished in the laboratory. Some engineers, however, do not believe that blending occurs during production and placement.
- The quality of recycled HMA has not been proven through performance evaluation. Pavement performance evaluations conducted by the Washington State DOT and updated with their PMS system show that recycled HMA performs as well as conventional HMA. Most of the SHAs indicated that recycled HMA performance is equivalent to conventional HMA when the recycled HMA meets mixture requirements of conventional HMA.

Some other conclusions from this study are:

- The major obstacle to increased RAP usage is limitations placed in standard specification, supplemental specifications and special provisions.

- Those SHAs that perform an evaluation of RAP and report its composition in plans, specifications and estimates generally permit greater percentages of RAP in all HMA mixtures.
- As with poor-performing conventional HMA, poor recycled HMA performance can be related to poor mixture design procedures or use of control and acceptance procedures that do little to ensure the quality of the recycled HMA.
- The recycled HMA mixture design procedure outlined in the Asphalt Institute's Manual Series No. 2 and No. 20 is a technically viable method for establishing ingredient properties of a recycled mixture.
- To minimize the amount of recovery and testing performance, up to 15 percent RAP in all mixtures could be permitted without changing to softer grade asphalt cement. With a RAP content of more than 15 percent, the selection of the new type of asphalt cement or recycling agent added to recycled HMA should be based on a viscosity blending chart or equivalent procedure or formula.
- Additional training should be provided to increase the awareness of proper mixture design and analysis, product equipment and handling procedures, performance evaluation and quality control plans.
- Research needs include the use of RAP with modified asphalt cements and use of RAP in the Superpave binder specifications and mixture design and analysis system.

Production Variability Analysis of Hot-Mixed Asphalt Concrete Containing Reclaimed Asphalt Pavement

Mansour Solaimanian and Thomas W. Kennedy. University of Texas at Austin, Department of Civil Engineering, Research Report #2828-1F, Austin, TX (1995).

This study was to evaluate the production and construction variability of HMAC containing high quantities of RAP material, including an analysis of the variability in RAP stockpiles and variability of plant-produced HMA with 20 to 50% RAP. The researchers found that projects with high percentages of RAP showed greater variability than HMA without RAP. The variability affected asphalt content and gradation determinations more than density. Variability in the RAP material was manifested in variability in the plant-produced mix; that is, projects with more variation in RAP asphalt content or stiffness showed more variability in the asphalt content and stiffness of the plant-mix as well.

The Quality of Random RAP: Separating Fact from Superstition

Robert M. Nady. Focus on HMAT, Summer 1997, Vol. 2, No. 2, National Asphalt Pavement Association, Lanham, MD pp. 14-17.

This paper reports on an evaluation of the variability of milled RAP versus unclassified (stockpiled random) RAP in Iowa. RAP from both sources is found to be quite uniform in terms of gradation and asphalt content. There were differences between the two types, such as the generally finer gradation noted for the milled RAP. Explanations for the uniformity of a given source are offered and include consistency of the historical state gradation specifications, routine quality control testing, and RAP processing equipment.

APPENDIX B
STATISTICAL ANALYSIS OF BLACK ROCK DATA

Table B-1. Summary of Comparison of Means, Frequency Sweep, Complex Shear Modulus
RAP Source: Florida

Binder Type	RAP Content	Aging	Test Temp.,°C	Frequency Hz	Mix Case			Significance
					A	B	C	
PG 52-34	10%	N	20	0.01				A=B=C
PG 52-34	10%	N	20	10				A=B=C
PG 52-34	10%	N	40	0.01				A=B=C
PG 52-34	10%	N	40	10				A=B=C
PG 64-22	10%	N	20	0.01				A=B=C
PG 64-22	10%	N	20	10	*	*		A=B, A=C, B≠C
PG 64-22	10%	N	40	0.01	*		*	A=B, A=C, B≠C
PG 64-22	10%	N	40	10				A=B=C
PG 52-34	40%	N	20	0.01				A≠B, B≠C, A=C
PG 52-34	40%	N	20	10				A≠B, B≠C, A=C
PG 52-34	40%	N	40	0.01				A=B=C
PG 52-34	40%	N	40	10				A≠B, B≠C, A=C
PG 64-22	40%	N	20	0.01				A≠B≠C
PG 64-22	40%	N	20	10				A=B=C
PG 64-22	40%	N	40	0.01				A=B=C
PG 64-22	40%	N	40	10		*	*	A=C, B=C, A≠B

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-2. Summary of Comparison of Means, Frequency Sweep Data, Complex Shear Models
RAP Source: Connecticut

Binder Type	RAP Content	Aging	Test Temp.,°C	Frequency Hz	Mix Case A	Mix Case B	Mix Case C	Significance
PG 52-34	10%	L	4	0.01				A=B=C
PG 52-34	10%	L	4	10				A=B=C
PG 52-34	10%	L	20	0.01	*		*	A=C, B=C, A≠B
PG 52-34	10%	L	20	10		*	*	A=B, B=C, A≠C
PG 52-34	10%	N	20	0.01				A≠B, A≠C, B=C
PG 52-34	10%	N	20	10				A≠B, A≠C, B=C
PG 52-34	10%	N	40	0.01				A=B, A≠C, B≠C
PG 52-34	10%	N	40	10		*	*	A=B, B=C, A≠C
PG 64-22	10%	L	4	0.01				A=B=C
PG 64-22	10%	L	4	10				A=B=C
PG 64-22	10%	L	20	0.01	*		*	A=C, B=C, A≠B
PG 64-22	10%	L	20	10				A=B=C
PG 64-22	10%	N	20	0.01				A≠B, A≠C, B=C
PG 64-22	10%	N	20	10				A=B=C
PG 64-22	10%	N	40	0.01				A=B, A≠C, B≠C
PG 64-22	10%	N	40	10	*	*		A=B, B=C, A≠C
PG 52-34	40%	L	4	0.01				A≠B, A≠C, B=C
PG 52-34	40%	L	4	10	*		*	A=C, B=C, A≠B
PG 52-34	40%	L	20	0.01				A≠B, A≠C, B=C
PG 52-34	40%	L	20	10				A≠B, A≠C, B=C
PG 52-34	40%	N	20	0.01				A≠B≠C
PG 52-34	40%	N	20	10				A≠B, A≠C, B=C
PG 52-34	40%	N	40	0.01				A=B=C
PG 52-34	40%	N	40	10				A≠B≠C
PG 64-22	40%	L	4	0.01				A≠B, A≠C, B=C
PG 64-22	40%	L	4	10				A≠B, A≠C, B=C
PG 64-22	40%	L	20	0.01				A≠B≠C
PG 64-22	40%	L	20	10				A=B=C
PG 64-22	40%	N	20	0.01				A≠B≠C
PG 64-22	40%	N	20	10				A≠B, A≠C, B=C
PG 64-22	40%	N	40	0.01				A≠B, B≠C, A=C
PG 64-22	40%	N	40	10				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-3. Summary of Comparison of Means, Frequency Sweep Data, Complex Shear Modulus
RAP Source: Arizona

Binder Type	RAP Content	Aging	Test Temp.,°C	Frequency Hz	Mix Case			Significance
					A	B	C	
PG 52-34	10%	N	20	0.01		*	*	A≠B, B=C, A=C
PG 52-34	10%	N	20	10				A=B=C
PG 52-34	10%	N	40	0.01				A=B=C
PG 52-34	10%	N	40	10				A=B=C
PG 64-22	10%	N	20	0.01				A=B=C
PG 64-22	10%	N	20	10				A≠B, B=C, A≠C
PG 64-22	10%	N	40	0.01				A=B=C
PG 64-22	10%	N	40	10				A=B, A≠C, B≠C
PG 52-34	40%	N	20	0.01		*	*	A=B, B=C, A≠C
PG 52-34	40%	N	20	10		*	*	A=B, B=C, A≠C
PG 52-34	40%	N	40	0.01				A=B=C
PG 52-34	40%	N	40	10				A≠B, B=C, A≠C
PG 64-22	40%	N	20	0.01				A≠B, A=C, B≠C
PG 64-22	40%	N	20	10	*		*	A≠B, B=C, A=C
PG 64-22	40%	N	40	0.01				A=B, B≠C, A≠C
PG 64-22	40%	N	40	10				A≠B, A=C, B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-4. Summary of Comparison of Means, Simple Shear Test, Maximum Shear Deformation
RAP Source: Florida

Binder Type	RAP Content	Aging	Test Temp.,°C	Mix Case A	Mix Case B	Mix Case C	Significance
PG 52-34	10%	N/A	20				A=B=C
PG 52-34	10%	N/A	40		*	*	A=B, B=C, A≠C
PG 64-22	10%	N/A	20				A=B=C
PG 64-22	10%	N/A	40				A=B=C
PG 52-34	40%	N/A	20		*	*	A≠B, A=C, B=C
PG 52-34	40%	N/A	40		*	*	A≠B, A≠C, B=C
PG 64-22	40%	N/A	20				A≠B≠C
PG 64-22	40%	N/A	40				A≠B, A≠C, B=C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-5. Summary of Comparison of Means, Simple Shear Data, Maximum Shear Deformation
RAP Source: Connecticut

Binder Type	RAP Content	Aging	Test Temp, °C	Mix Case			Significance
				A	B	C	
52-34	10	L	4				A=B=C
52-34	10	L	20				A=B=C
52-34	10	N	40			NA	A=B
52-34	10	N	20				A=B=C
64-22	10	L	4				A=B=C
64-22	10	L	20				A≠B, B=C,A≠C
64-22	10	N	20				A≠B, B=C,A≠C
64-22	10	N	40			NA	A=B
52-34	40	L	4				A≠B, B=C,A≠C
52-34	40	L	20				A≠B, B=C,A≠C
52-34	40	N	20				A≠B, B=C,A≠C
52-34	40	N	40				A=B=C
64-22	40	L	4				A≠B, B=C,A≠C
64-22	40	L	20				A≠B, B=C,A≠C
64-22	40	N	20				A≠B≠C
64-22	40	N	40				A≠B, B=C,A≠C

* Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-6. Summary of Comparison of Means, Simple Shear Data,
Maximum Shear Deformation

RAP Source: Arizona

Binder Type	**RAP Content**	**Aging**	**Test Temp.,°C**	**Mix Case**			**Significance**
				A	**B**	**C**	
PG 52-34	10%	N	20				A=B=C
PG 52-34	10%	N	40				A=B=C
PG 64-22	10%	N	20				A=B=C
PG 64-22	10%	N	40				A=B, A≠C, B≠C
PG 52-34	40%	N	20				A≠B, A≠C, B=C
PG 52-34	40%	N	40				A≠B, A≠C, B=C
PG 64-22	40%	N	20				A≠B≠C
PG 64-22	40%	N	40				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-7. Summary of Comparison of Means, Repeated Shear at Constant Height, Shear Strain
RAP Source: Florida

Binder Type	RAP Content	Aging	Test Temp.,°C	Mix Case			Significance
				A	B	C	
PG 52-34	10%	N	52		*	*	A≠B, A=C, B=C
PG 64-22	10%	N	58				A=B=C
PG 52-34	40%	N	52		*	*	A≠B, A=C, B=C,
PG 64-22	40%	N	58				A=B=C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-8. Summary of Comparison of Means,Repeated Shear at Constant Height Data, Shear
RAP Source: Connecticut

Binder Type	RAP Content	Test Temp, °C	Mix Case			Significance
			A	B	C	
52-34	10	52				A=B=C
64-22	10	58				A=B=C
52-34	40	52				A=B=C
64-22	40	58				A≠B,B=C, A≠C

* Cases with same symbol or shading are not significantly different at a 5% confidence level
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-9. Summary of Comparison of Means, Repeated Shear at Constant Height, Shear Strain
RAP Source: Arizona

Binder Type	**RAP Content**	**Aging**	**Test Temp.,°C**	**Mix Case**			**Significance**
				A	**B**	**C**	
PG 52-34	10%	N	52				A=B=C
PG 64-22	10%	N	58				A=B=C
PG 52-34	40%	N	52				A≠B, B=C, A≠C
PG 64-22	40%	N	58				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-10. Summary of Comparison of Means, Indirect Tensile Strength, Stiffness
RAP Source: Connecticut

Binder Type	**RAP Content**	**Test Temp.,°C**	**Mix Case**			**Significance**
			A	**B**	**C**	
PG 52-34	10%	-20				A=B=C
PG 52-34	10%	-10				A=C, A≠B, B≠C
PG 52-34	10%	0				A=B=C
PG 64-22	10%	-20				A=B=C
PG 64-22	10%	-10				A=B=C
PG 64-22	10%	0				A=B=C
PG 52-34	40%	-20				A≠B, A≠C, B=C
PG 52-34	40%	-10				A≠B, A≠C, B=C
PG 52-34	40%	0				A≠B, A≠C, B=C
PG 64-22	40%	-20		*	*	A=B, B=C, A≠C
PG 64-22	40%	-10				A=B=C
PG 64-22	40%	0				A≠B,A≠C, B=C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-11. Summary of Comparison of Means, Indirect Tensile Strength, Stiffness
RAP Source: Arizona

Binder Type	RAP Content	Test Temp.,°C	Mix Case			Significance
			A	B	C	
PG 52-34	10%	-20				A=B=C
PG 52-34	10%	-10				A=B=C
PG 52-34	10%	0				A=B=C
PG 64-22	10%	-20		*	*	A≠B, A=C, B=C
PG 64-22	10%	-10				A≠B, A≠C, B=C
PG 64-22	10%	0				A=B=C
PG 52-34	40%	-20				A≠B, A≠C, B=C
PG 52-34	40%	-10				A≠B, A≠C, B=C
PG 52-34	40%	0				A≠B, A≠C, B=C
PG 64-22	40%	-20				A=B=C
PG 64-22	40%	-10				A=B=C
PG 64-22	40%	0				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-12. Summary of Comparison of Means, Indirect Tensile Strength, Strength
RAP Source: Connecticut

Binder Type	RAP Content	Test Temp.,°C	Mix Case			Significance
			A	B	C	
PG 52-34	10%	-10				A=B=C
PG 64-22	10%	-10				A=B=C
PG 52-34	40%	-10				A≠B, A≠C, B=C
PG 64-22	40%	-10				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-13. Summary of Comparison of Means, Indirect Tensile Strength, Strength
RAP Source: Arizona

Binder Type	RAP Content	Test Temp.,°C	Mix Case			Significance
			A	B	C	
PG 52-34	10%	-10				A=B=C
PG 64-22	10%	-10				A=B=C
PG 52-34	40%	-10				A≠B, B≠C, A=C
PG 64-22	40%	-10				A≠B, B≠C, A=C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

APPENDIX C
FLOW CHARTS SHOWING DEVELOPMENT OF BLENDING CHARTS

Figure C1. Method A - Blending at a Known RAP Percentage (Virgin Binder Grade Unknown)

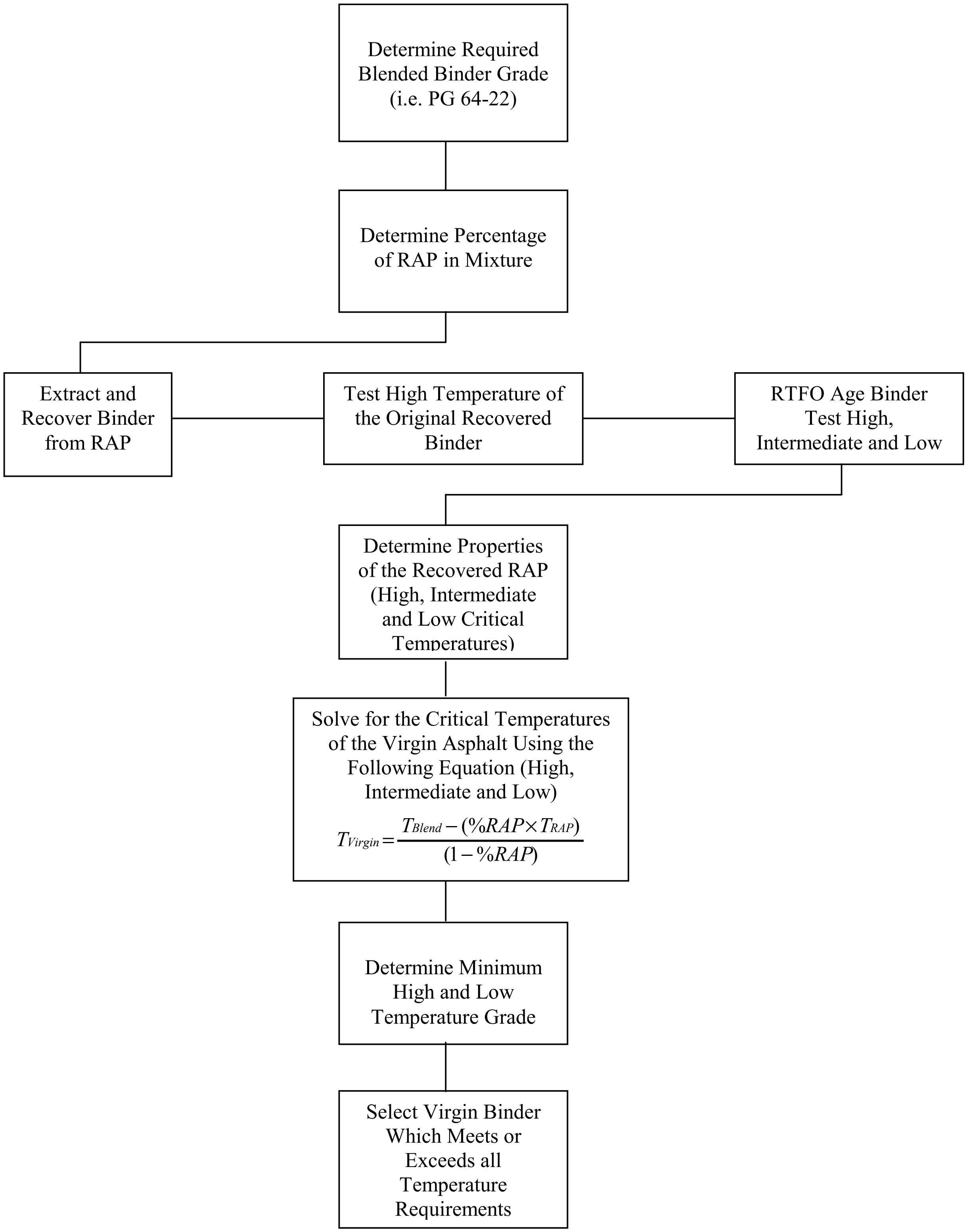
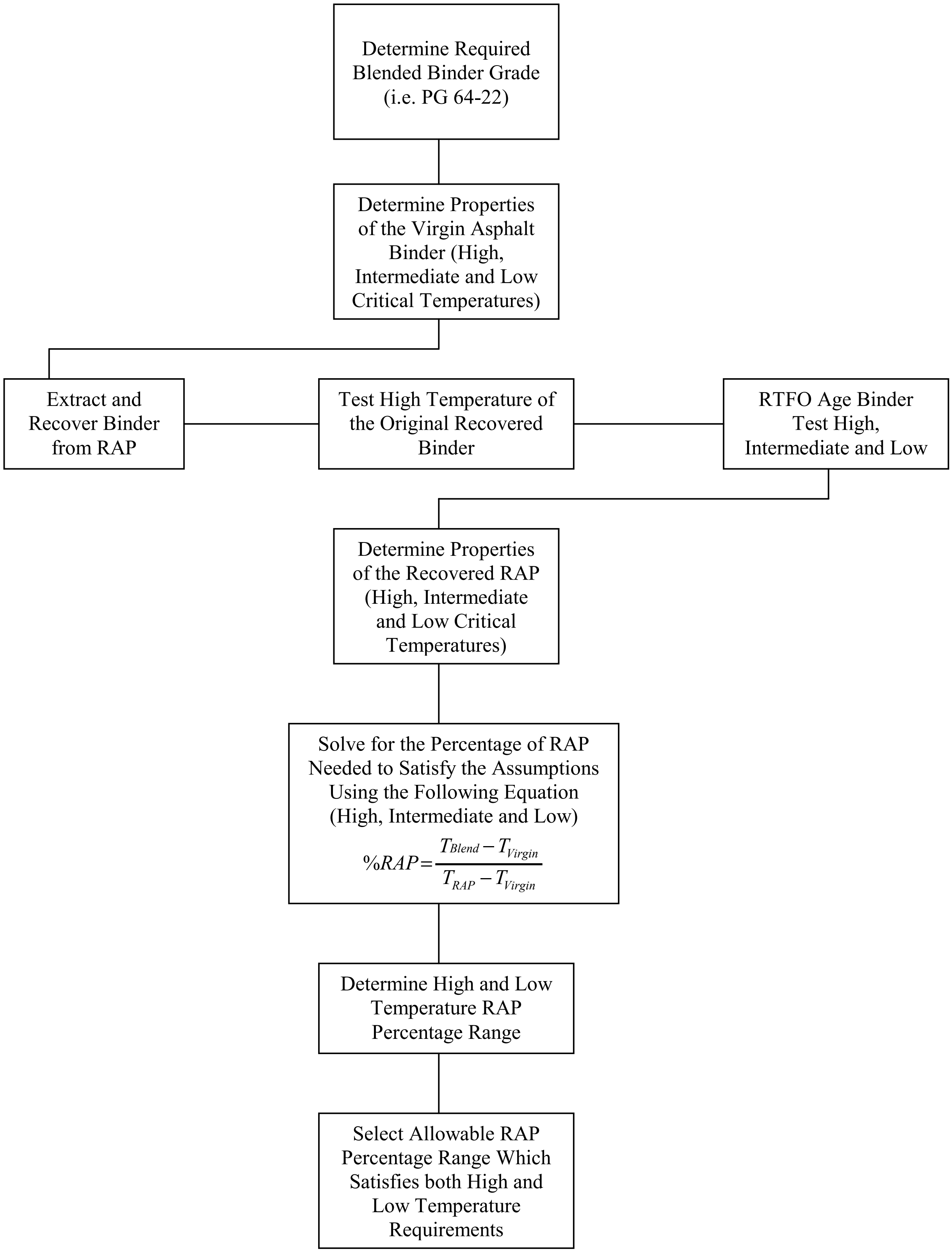


Figure C2. Method B – Blending with a Known Virgin Binder (RAP Percentage Unknown)



Appendix D is published as *NCHRP Research Results Digest 253,* "Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Guidelines."

Appendix E is published as *NCHRP Report 452,* "Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual."

APPENDIX F

USE OF RAP IN SUPERPAVE: IMPLEMENTATION PLAN

Use of RAP in Superpave:
Implementation Plan

Prepared for
National Cooperative Research Program
Transportation Research Board
National Research Council

North Central Superpave Center
West Lafayette, Indiana
and
Asphalt Institute
Lexington, Kentucky

May 2000

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INTRODUCTION

Reclaimed Asphalt Pavement (RAP) has been widely and successfully used in the past when producing new asphalt pavements. The findings of NCHRP 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*, should allow the beneficial use of RAP to be continued as states and other specifying agencies implement the Superpave system. The objectives of this 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. The products of the research include proposed revisions to applicable AASHTO standards, a manual for technicians and guidelines for specifying agencies.

Summary of 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. The “black rock” case was simulated by extracting the binder from a RAP mixture then blending the recovered RAP aggregate in the proper proportions with virgin aggregate and 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” cases were fabricated by extracting and recovering the RAP binder and blending it into the virgin binder, then combining the blended binder with the RAP and virgin 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 difference between the three different blending cases at low RAP contents. 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.

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 or an n-propyl bromide solvent.

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, up to as high as 30% RAP depending on the recovered RAP binder grade, 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 remaining MP1 tests at high, 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. 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.) Since PAV aging is not necessary, the testing process is shortened by approximately one day.

The binder effects study also supports the tiered usage concept. At low RAP contents, the effects of the 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 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 required.

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 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 at higher RAP contents. 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 (with no change in binder grade) 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.

The significance of these results is that the concept of using a softer virgin binder for 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 used or which virgin binder to use.

The RAP aggregate properties 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. The mixtures being recycled presumably met specifications when constructed, so certain minimum aggregate properties and mixture properties were met. 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 RAP binder 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 and developing blending charts, and designing a RAP mixture under the Superpave system; a manual for laboratory and field technicians; guidelines for the use of specifying agencies; and this implementation plan for moving these results into practice.

Applicability of Findings to Highway Practice

Many of the findings of NCHRP 9-12 largely confirm past practices. One example of this is the concept of a tiered approach to the use of RAP. Many states previously allowed the use of up to 15-20% RAP without a change in the binder grade. The findings of the black rock, binder effects and mixture effects studies all support the existence of a threshold level of RAP usage, in the range of 10 to 20% RAP, below which the RAP has a negligible effect on binder or mixture properties. Depending on typical RAP stiffnesses, agencies should be able to continue using RAP up to the threshold level without changing the binder grade.

Agencies also used to adjust the binder grade for higher RAP contents, either by using a softer grade of binder or by constructing blending charts to determine which binder or how much RAP to use. Both of these approaches are predicated on the assumption that blending occurs between the new binder and the hardened RAP binder. The findings of the black rock study demonstrate that blending does occur to an appreciable extent. So again, this approach to using RAP can be continued with Superpave mixtures.

There are, however, some changes that should be made in current practice as a result of this research project. An improved method for extracting and recovering the RAP binder, or any asphalt binder for that matter, was refined and validated in this project. Revisions have been proposed to AASHTO TP2, *Standard Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures,* to reflect this improved technique.

The interim guidance on the use of RAP in Superpave mixtures, issued by the Superpave Mixtures Expert Task Group, has also been largely confirmed with slight revisions. The major revision is a more detailed chart for binder grade selection that takes into account the stiffness of the RAP binder.

The findings of the project are directly applicable to highway practice. Many of the findings, since they confirm current practice, are in essence already implemented. This project will lend support and increase the confidence level of the specifying agencies. Other findings can be easily implemented through revisions to existing AASHTO specifications. There should be no major barriers to implementation of these findings.

IMPLEMENTATION SUGGESTIONS

As mentioned earlier, implementation of many of the findings of this research will be greatly facilitated by the fact that current practice is largely confirmed. It is, nonetheless, important to communicate these findings widely so that they can be implemented through AASHTO and agency specifications. It is also prudent to monitor some projects including RAP to confirm the laboratory results in a field setting. The following suggestions should help to disseminate information about the findings of NCHRP 9-12 to help ensure wide implementation and secure the benefits of using RAP in Superpave mixtures.

Communication of Results

There are many avenues available to communicate the results of this research effort. In order to ensure that all interested parties get the necessary information, it is recommended to use every possible medium. There is also a high level of interest in this topic, which justifies a broad distribution of information.

Revisions of AASHTO Specifications

The most meaningful method to implement changes in highway practice is through official, approved changes to the AASHTO specifications. Most agencies adopt these standards, although some agencies make customized modifications to suit their particular circumstances.

Proposed revisions to the following standards have been developed as a result of this research effort:

- TP2, *Standard Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*
- MP2, *Standard Specification for Superpave™ Volumetric Mix Design*
- PP28, *Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)*

These proposed revisions, as shown in Appendix A, will be presented to the appropriate Expert Task Group for their review and approval. The Superpave Binder Expert Task Group is expected to be primarily interested in the revisions to TP2, while the Mixture and Aggregates ETG is expected to be primarily interested in MP2 and PP28. The research team will attempt request time on the agenda for the next meetings of these two groups following the project panel's approval of the final report and associated documents. The Mixture and Aggregates Expert Task Group was briefed on the preliminary findings of the project at their meeting in March 2000.

Once the Expert Task Groups are satisfied with the proposed revisions, it is anticipated they will forward the revisions to AASHTO for balloting by the states and eventual inclusion in the specifications. At every step in the process, the supporting data will be reviewed and further revisions may be approved.

Revisions of Training Courses

There are currently a number of training programs in use around the country dealing with hot mix asphalt design. These courses should be modified to include the use of RAP in Superpave Mixtures. A set of slides that could be included is attached in Appendix B.

The courses that should be revised include the following:

- NHI 13150, *Asphalt Pavement Recycling for State and Local Governments*
- NHI 13151, *Superpave for Senior Managers*
- NHI 13153, *Superpave Fundamentals*
- FHWA, *Hot Mix Asphalt for the Undergraduate*
- NATC Superpave Mix Design course (used by most Superpave Centers, Asphalt Institute and others)

The suggested revisions will be communicated to NHI for possible inclusion in the first three courses, for which they are responsible. NHI is moving towards providing courses to instructors and others in electronic format, which may facilitate incorporation of the suggested changes. The two Superpave courses were recently revised. Additional revisions may be needed to add RAP. These changes may be accommodated in the course materials as additional handouts or addenda pending further revision of the course materials.

Changes to the FHWA and NATC courses can be implemented by distributing them through FHWA, the Superpave Centers and the Asphalt Institute. The FHWA course is posted on the Internet for free downloading. The additional information on RAP can also be posted on various sites as discussed below. The Superpave Centers are generally familiar with the states, universities and others doing Superpave training in their respective regions. The Centers can distribute the proposed course revisions within their regions.

Written and Electronic Communication

There are numerous outlets for written and electronic communication of the findings and implementation suggestions. The research team is directly involved in many of these and has routine contact with others. For example, most of the Superpave Centers have websites and newsletters. The newsletters are jointly produced and include both regional and national segments. The NCSC can ensure that summaries of the findings of this project are published in the national newsletter insert. Each regional segment could also include a discussion of the regional impacts of or reactions to the use of RAP in Superpave mixtures. For example, each region could survey their states and summarize the current extent of RAP usage in Superpave and/or other HMA mixtures. Detailed summaries and downloadable training presentations could be posted on each center's website (or linked to the NCSC site). The Asphalt Institute and FHWA also have websites that could post the information.

The South Central Superpave Center maintains a Superpave Newsgroup with a very wide and active audience. This group could be informed of the existence of web postings dealing with the use of RAP in Superpave. This is likely to promote a large number of hits and possibly discussion of the findings.

Other written means of communication include the *FHWA Superpave Implementation Update, FOCUS Newsletter* and trade publications. NAPA has included articles on RAP in *Focus on HMAT*. The Asphalt Institute publishes *Asphalt* magazine; their readers would be interested in RAP. The research team has already been contacted by ASCE for a possible article and is frequently contacted by local media. A news release could be prepared and distributed through the Purdue University News Service and/or Schools of Engineering publications office for wider, more general audiences.

Presentations

Due to the high level of interest in this project, several presentations of interim findings have already been made. (In each case, it has been noted that the presentations offered preliminary findings and conclusions that were not yet final or approved.) Presentations on various aspects of the project have been made at the following meetings:

- Superpave: Today and Tomorrow, April 1998
- Minnesota Asphalt Conference, November 1998.
- Transportation Research Board, January 1999.
- Rocky Mountain Asphalt Conference and Equipment Show, February 1999.
- MatCong 5, Fifth Materials Engineering Congress, May 1999.
- Asphalt Paving Association of Iowa Summer Meeting, July 1999.
- Missouri Asphalt Conference, November 1999.
- Asphalt Pavement Association of Indiana, December 1999.
- Transportation Research Board Annual Meeting, January 2000.
- North Central Asphalt User-Producer Group Meeting, January 2000.
- Association of Asphalt Paving Technologists, March 2000.
- Superpave Mixtures and Aggregate Expert Task Group, March 2000.
- International Center for Aggregate Research Meeting, April 2000.

The research team welcomes the opportunity to make presentations at other appropriate meetings. One abstract has been accepted by the Canadian Technical Asphalt Association for presentation at their next meeting. Other appropriate forums for similar presentations include the Mixture and Aggregates Expert Task Group and Binder Expert Task Group, TRB asphalt committees, state asphalt pavement association meetings, user-producer group meetings, etc.

Field Test Sections

Need and Benefits

Recycled mixtures have performed as well as virgin mixtures when using conventional penetration or viscosity graded asphalts in properly designed Marshall or Hveem mixtures. The research conducted under NCHRP 9-12 indicates that recycled mixtures designed under the Superpave system will also perform at least as well as virgin mixtures. Because of the long, successful history of RAP usage, the need for intensive field validation of the research findings is somewhat lessened. Nonetheless, field validation would be a prudent course of action. Implementation of RAP in Superpave mixtures can proceed without this field validation due to the long history of RAP usage. The field trials, however, would be useful for possible further refinement of the recommendations based on this research project.

The Superpave system itself is still evolving. It is reasonable to expect that the guidelines for RAP usage in the Superpave system will have to evolve accordingly. Field trials can provide the basis to support further refinements to the system.

Suggested Evaluation Criteria

Superpave mixtures incorporating RAP should be compared to virgin Superpave mixtures. The evaluation should focus on long term performance of the mixtures, including measurements of rutting, low temperature cracking, fatigue cracking, moisture damage and other distresses.

The findings of NCHRP 9-12 indicate that when high percentages of RAP are used with stiffer RAPs, the virgin binder grade needs to be adjusted to "soften" the resulting blend. The recommended tiers, then, vary depending on the RAP binder stiffness and the proposed RAP content. If no adjustment is made in the virgin binder grade, the resistance to rutting is likely to be improved (by a stiffer mixture), but the low temperature and fatigue cracking resistance will likely be decreased. When a softer virgin binder is used to compensate for the RAP binder stiffness, the rutting resistance may be decreased but the cracking resistance should be improved. Field trials that measure the performance of the recycled mixtures in terms of both rutting and cracking will help to ensure that a proper balance has been struck between rutting and cracking resistance.

The ideal field trial would include test sections with various RAP contents and virgin binders compared to a control section with no RAP. The traffic volume should be consistent throughout the test sections. A fairly high traffic volume is desirable in order to truly test the rutting performance.

Suggested Mechanism for Follow-Up

Pavement test sections included in the Long Term Pavement Performance studies will be assured of continued monitoring. Both Connecticut and Indiana have SPS-9 sections with RAP. The Connecticut project was the source of the medium stiffness RAP used in this research. The Indiana project provided RAP material that is currently being evaluated by the NCSC under a regional pooled fund project using techniques similar to those used in NCHRP 9-12.

Individual states will also likely construct their own test sections. Due to the high level of interest in this topic, sharing of field data should be encouraged. The regional user-producer groups and Superpave Centers may be able to facilitate this sharing. Both the user-producer groups and the Superpave Centers have interest in the continued evaluation and refinement of the Superpave system. Some user-producer groups, such as the Rocky Mountain group, have developed, or are trying to develop, regional databases to track the performance of Superpave pavements. These databases could be used to follow-up on applicable test sections.

Reporting of Long Term Performance

Reporting of long term performance of Superpave mixtures with and without RAP will likely be most effective on the regional level through the user-producer groups or the Superpave Centers. Through the coordination between the Superpave Centers, this regional information can be shared and disseminated nationally. There may also be a need in the future for a national review of Superpave RAP mixture performance similar to the review of SMA mixtures done by NCAT.

BENEFITS OF IMPLEMENTATION

Hot mix asphalt mixtures with RAP have performed well in the past in properly designed mixtures. The benefits of using RAP include the following:

- 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
- not reusing RAP could cause disposal problems and increased costs.

Historically these benefits have helped to make reclaimed asphalt pavement one the most widely recycled materials. An FHWA study [1] shows that 80% of the asphalt pavement removed every year is recycled. Only about 60% of aluminum cans, 37% of plastic soft drink bottles and 31% of glass beverage bottles are recycled. RAP would not be used to such a great extent if it did not perform well at an economical price.

This study will allow that high level of RAP reuse to continue as agencies move to the Superpave system for routine HMA mixture design.

REFERENCE

1. Federal Highway Administration, "A Study of the Use of Recycled Paving Material." Report No. FHWA-RD-93-147 (1993).

APPENDIX F: APPENDIX A, Proposed AASHTO Specification Revisions

Proposed Revisions to
Standard Specification for
Superpave Volumetric Mix Design

AASHTO Designation: MP2-00[1, 2]

1. Scope

1.1 This specification for Superpave volumetric mix design uses aggregate and mixture properties to produce a hot-mix asphalt (HMA) job-mix formula.

1.2 This standard specifies minimum quality requirements for binder, aggregate, and HMA for Superpave volumetric mix designs.

1.3 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards:

- T11 Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing
- T27 Sieve Analysis of Fine and Coarse Aggregates
- T176 Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test
- T283 Resistance of Compacted Bituminous Mixture to Moisture Induced Damage
- T304 Uncompacted Void Content of Fine Aggregate
- MP1 Specification for Performance Graded Asphalt Binder
- PP28 Superpave Volumetric Design for HMA
- TP4 Preparing and Determining the Density of Hot-Mix Asphalt Specimens by Means of the Superpave Gyratory Compactor

2.2 ASTM Standards:

- D5821 Determining the Percentage of Fractured Particles in Coarse Aggregate
- D4791 Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate

2.3 Other References:

"LTPP Seasonal Asphalt Concrete Pavement Temperature Models, FHWA-RD-97-103," September, 1998.

3. Terminology

3.1 HMA - Hot-Mix Asphalt

3.2 Design ESALs - Design equivalent (80kN) single-axle loads

> Discussion - Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period. For pavements designed for more or less than 20 years, determine the design ESALs for 20 years when using this standard.

3.3 Air voids (V_a) - The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture (Note 1).

> Note 1 - Term defined in the Asphalt Institute Manual MS-2, "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types."

3.4 Voids in the Mineral Aggregate (VMA) - The volume of the intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective binder content,

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[1] This standard is based on SHRP Product M001.

[2] Approved in December 1995, this provisional standard was first published in June 1996.

expressed as a percent of the total volume of the specimen (Note 1).

3.5 Voids Filled With Asphalt (VFA) - The percentage of the VMA filled with binder (the effective binder volume divided by the VMA).

3.6 Dust-to-Binder Ratio ($P_{0.075}/P_{be}$) - By mass, the ratio between the percent of aggregate passing the 0.075 mm (#200) sieve ($P_{0.075}$) and the effective binder content (P_{be}).

3.7 Nominal Maximum Aggregate Size - One size larger than the first sieve that retains more than 10 percent aggregate (Note 2).

3.8 Maximum Aggregate Size - One size larger than the nominal maximum aggregate size (Note 2).

Note 2 - The definitions given in Subsections 3.7 and 3.8 apply to Superpave mixes only and differ from the definitions published in other AASHTO standards.

3.9 Reclaimed Asphalt Pavement (RAP) - removed and/or processed pavement materials containing asphalt binder and aggregate

4. Significance and Use - This standard may be used to select and evaluate materials for Superpave volumetric mix designs.

5. Binder Requirements

5.1 The binder shall be a performance-graded (PG) binder, meeting the requirements of MP1, which is appropriate for the climate and traffic-loading conditions at the site of the paving project or as specified by the contract documents.

5.1.1 Determine the mean and the standard deviation of the yearly, 7-day-average, maximum pavement temperature, measured 20 mm below the pavement surface, and the mean and the standard deviation of the yearly, 1-day-minimum pavement temperature, measured at the pavement surface, at the site of the paving project. These temperatures can be determined by use of the LTPPBind software or be supplied by the specifying agency. If the LTPPBind software is used, the LTPP high and low temperature models should be selected in the software when determining the binder grade. Often, actual site data is not available, and representative data from the nearest weather station will have to be used.

5.1.2 Select the design reliability for the high and low temperature performance desired. The design reliability required is established by agency policy.

Note 3 - The selection of design reliability may be influenced by the initial cost of the materials and the subsequent maintenance costs.

5.1.3 Using the pavement temperature data determined, select the minimum required PG binder that satisfies the required design reliability.

5.2 If traffic speed or the design ESALs warrant, increase the high temperature grade by the number of grade equivalents indicated in Table 1 to account for the anticipated traffic conditions at the project site.

5.3 If RAP is to be used in the mixture, adjust the binder grade selected in 5.1.3 and 5.2 according to Table 2 to account for the RAP binder stiffness and amount. Procedures for developing a blending chart are included in the Appendix.

6. Combined Aggregate Requirements

6.1 Size Requirements

6.1.1 Nominal Maximum Size - The combined aggregate shall have a nominal maximum aggregate size of 9.5 to 19.0 mm for HMA surface course and 19.0 to 37.5 mm for HMA subsurface courses.

6.1.2 Gradation Control Points - The combined aggregate shall conform to the gradation requirements specified in Table 3~~2~~ when tested according to T11 and T27.

6.1.3 Gradation Restricted Zones - It is recommended that the selected combined aggregate gradation does not pass through the restricted zones specified in Table 4~~3~~. See Figure 1 for an example of a graph showing the gradation control points and the restricted zone.

6.2 Coarse Aggregate Angularity Requirements - The aggregate shall meet the coarse aggregate angularity requirements, specified in Table 5~~4~~, measured according to D5821.

6.3 Fine Aggregate Angularity Requirements - The aggregate shall meet the uncompacted void content of fine aggregate requirements, specified in Table 5~~4~~, measured according to T304, Method A.

6.4 Sand Equivalent Requirements - The aggregate shall meet the sand equivalent (clay content) requirements, specified in Table 5~~4~~, measured according to T176.

6.5 Flat-and-Elongated Requirements - The aggregate shall meet the flat-and-elongated requirements, specified in Table 5~~4~~, measured according to D4791, with the exception that the material passing the 9.5 mm sieve and retained on the 4.75 mm sieve shall be included. The aggregate shall be measured using the ratio of 5:1, comparing the length (longest dimension) to the thickness (smallest dimension) of the aggregate particles.

6.6 When RAP is used in the mixture, the RAP aggregate shall be extracted from the RAP using a solvent extraction or ignition oven as specified by the Agency. The RAP aggregate shall be included in determinations of gradation, coarse aggregate angularity, fine aggregate angularity and flat-and-elongated requirements. The sand equivalent requirements shall be waived for the RAP aggregate but shall apply to the remainder of the aggregate blend.

7. HMA Design Requirements

7.1 The binder and aggregate in the HMA shall conform to the requirements of Sections 5 and 6.

7.2 The HMA design, when compacted in accordance with TP4, shall meet the relative density, VMA, VFA, and dust-to-binder ratio requirements specified in Table 6~~5~~. The initial, design, and maximum number of gyrations are specified in PP28.

7.3 The HMA design, when compacted according to TP4 at 7 $\pm$ 1.0 percent air voids and tested in accordance with T283 shall have a tensile strength ratio of at least 0.80.

Table 1 - Binder Selection on the Basis of Traffic Speed and Traffic Level

Design ESALs[1] (million)	Adjustment to the High Temperature Grade of the Binder[5]		
	Traffic Load Rate		
	Standing[2]	Slow[3]	Standard[4]
< 0.3	-[(6)]	-	-
0.3 to < 3	2	1	-
3 to < 10	2	1	-
10 to < 30	2	1	-[(6)]
≥ 30	2	1	1

(1) The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.
(2) Standing Traffic - where the average traffic speed is less than 20 km/h.
(3) Slow Traffic - where the average traffic speed ranges from 20 to 70 km/h.
(4) Standard Traffic - where the average traffic speed is greater than 70 km/h.
(5) Increase the high temperature grade by the number of grade equivalents indicated (one grade is equivalent to 6 °C). Use the low temperature grade as determined in Section 5.
(6) Consideration should be given to increasing the high temperature grade by one grade equivalent.

Note 4 - Practically, PG binders stiffer than PG 82-XX should be avoided. In cases where the required adjustment to the high temperature binder grade would result in a grade higher than a PG 82, consideration should be given to specifying a PG 82-XX and increasing the design ESALs by one level (e.g., 10 to < 30 million increased to ≥ 30 million).

Table 2 - Binder Selection Guidelines for RAP Mixtures

Recommended Virgin Asphalt Binder Grade	RAP Percentage		
	Recovered RAP Grade		
	PG xx-22 or lower	PG xx-16	PG xx-10 or higher
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (i.e., select a PG 58-28 if a PG 64-22 would normally be used.	20 - 30%	15 - 25%	10 - 15%
Follow recommendations from blending charts	>30%	>25%	>15%

Table 3~~2~~ - Aggregate Gradation Control Points

	Nominal Maximum Aggregate Size - Control Point (Percent Passing)									
	37.5 mm		25.0 mm		19.0 mm		12.5 mm		9.5 mm	
Sieve Size	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
50.0 mm	100	--	--	--	--	--	--	--	--	--
37.5 mm	90	100	100	--	--	--	--	--	--	--
25.0 mm	--	90	90	100	100	--	--	--	--	--
19.0 mm	--	--	--	90	90	100	100	--	--	--
12.5 mm	--	--	--	--	--	90	90	100	100	--
9.5 mm	--	--	--	--	--	--	--	90	90	100
4.75 mm	--	--	--	--	--	--	--	--	--	90
2.36 mm	15	41	19	45	23	49	28	58	32	67
0.075 mm	0	6	1	7	2	8	2	10	2	10

Table 4~~3~~ - Boundaries of Aggregate Restricted Zone

Sieve Size Within Restricted Zone	Minimum and Maximum Boundaries by Sieve Size for Nominal Maximum Aggregate Size (Minimum and Maximum Percent Passing)									
	37.5 mm		25.0 mm		19.0 mm		12.5 mm		9.5 mm	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
0.300 mm	10.0	10.0	11.4	11.4	13.7	13.7	15.5	15.5	18.7	18.7
0.600 mm	11.7	15.7	13.6	17.6	16.7	20.7	19.1	23.1	23.5	27.5
1.18 mm	15.5	21.5	18.1	24.1	22.3	28.3	25.6	31.6	31.6	37.6
2.36 mm	23.3	27.3	26.8	30.8	34.6	34.6	39.1	39.1	47.2	47.2
4.75 mm	34.7	34.7	39.5	39.5	--	--	--	--	--	--

Table 5~~4~~ - Superpave Aggregate Consensus Property Requirements

Design ESALs[1] (million)	Coarse Aggregate Angularity (Percent), minimum		Uncompacted Void Content of Fine Aggregate (Percent), minimum		Sand Equivalent (Percent), minimum	Flat and Elongated (Percent), maximum
	≤ 100 mm	> 100 mm	≤ 100 mm	> 100 mm		
< 0.3	55/-	-/-	-	-	40	-
0.3 to < 3	75/-	50/-	40	40	40	10
3 to < 10	85/80[2]	60/-	45	40	45	
10 to < 30	95/90	80/75	45	40	45	
≥ 30	100/100	100/100	45	45	50	

1 The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

2 85/80 denotes that 85 % of the coarse aggregate has one fractured face and 80 % has two or more fractured faces.

Note 5 - If less than 25% of a construction lift is within 100 mm of the surface, the lift may be considered to be below 100 mm for mixture design purposes.

Table 65 - Superpave HMA Design Requirements

Design ESALs[1] (million)	Required Relative Density (% of Theoretical Maximum Specific Gravity)			Voids in the Mineral Aggregate (Percent), minimum					Voids Filled With Asphalt Range (Percent)	Dust-to-Binder Ratio Range
				Nominal Maximum Aggregate Size, mm						
	$N_{initial}$	N_{design}	N_{max}	37.5	25.0	19.0	12.5	9.5		
< 0.3	≤ 91.5								70 - 80[(3)]	
0.3 to < 3	≤ 90.5								65 - 78	
3 to < 10										
10 to < 30	≤ 89.0	96.0	≤ 98.0	11.0	12.0	13.0	14.0	15.0	65 - 75[(2)]	0.6 - 1.2
≥ 30										

(1) Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

(2) For 9.5-mm nominal maximum size mixtures, the specified VFA range shall be 73 to 76% for design traffic levels ≥ 3 million ESALs.

(3) For 25.0-mm nominal maximum size mixtures, the specified lower limit of the VFA shall be 67% for design traffic levels < 0.3 million ESALs.

(4) For 37.5-mm nominal maximum size mixtures, the specified lower limit of the VFA shall be 64% for all design traffic levels.

Note 6 - If the aggregate gradation passes beneath the boundaries of the aggregate restricted zone specified in Table 3, the dust-to-binder ratio range may be increased from 0.6 - 1.2 to 0.8 - 1.6 at the agency's discretion.

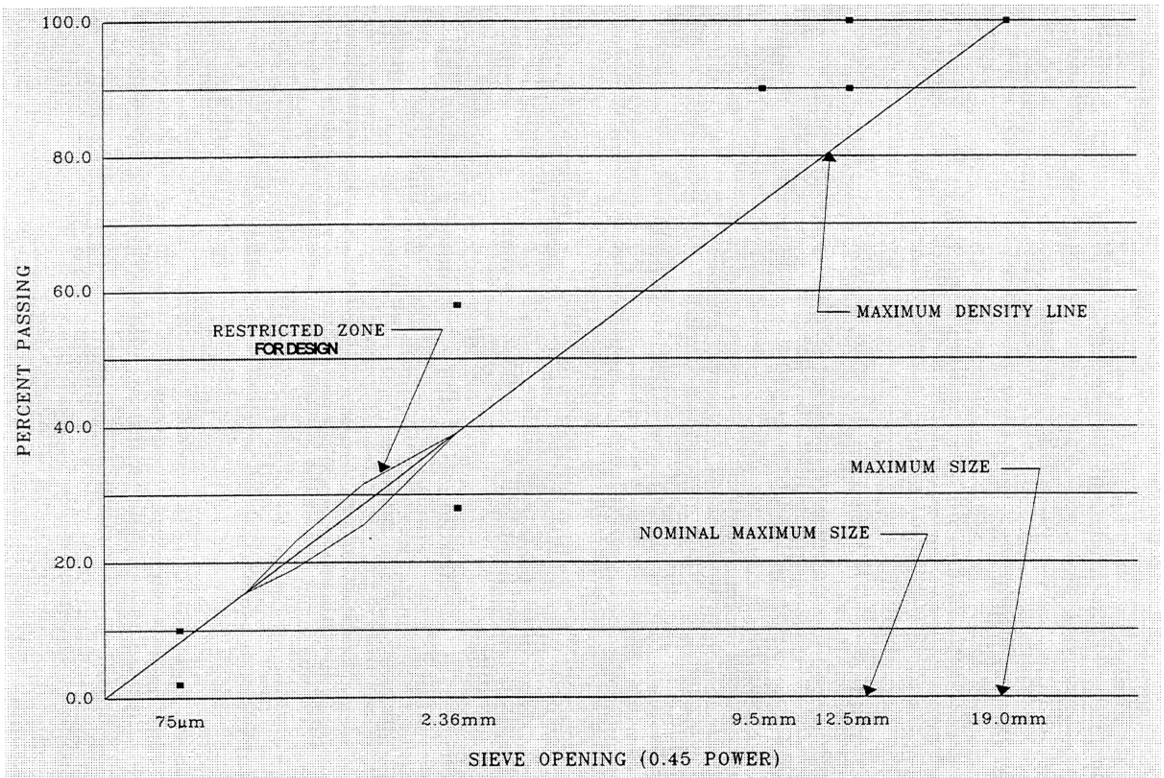

Figure 1: Superpave Gradation Control Points and Restricted Zone for a 12.5 mm Nominal Maximum Size Aggregate Gradation

MP2

F-A-1

APPENDIX X1

(non-mandatory information)

Blending of RAP binders can be accomplished by knowing the desired final grade (critical temperature) of the blended binder, the physical properties (and critical temperatures) of the recovered RAP binder and either the physical properties (and critical temperatures) of the virgin asphalt binder or the desired percentage of RAP in the mixture.

X1 Determine the physical properties and critical temperatures of the RAP binder.

X1.1 Recover the RAP binder using the AASHTO TP2 method (revised 6/00) with an appropriate solvent. At least 50 g of recovered RAP binder are needed for testing. Perform binder classification testing using the tests in AASHTO MP1. Rotational viscosity, flash point and mass loss tests are not required.

X1.2 Perform original DSR testing on the recovered RAP binder to determine the critical high temperature, T_c(High), based on original DSR values where $G^*/\sin\delta = 1.00$ kPa. Calculate the critical high temperature as follows.

X1.2.1 Determine the slope of the Stiffness-Temperature curve, a, as $a = \Delta\log(G^*/\sin\delta)/\Delta T$.

X1.2.2 Determine T_c(High) to the nearest 0.1°C using the following equation:

$$T_c(High) = \left(\frac{Log(1.00) - Log(G_1)}{a}\right) + T_1$$

where,

G_1 = the $G^*/\sin\delta$ value at a specific temperature T_1

a = the slope as described in X1.2..1

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the $G^*/\sin\delta$ value closest to the criterion (1.00 kPa) to minimize extrapolation errors.

X1.3 Perform RTFO aging on the remaining binder.

X1.4 Perform RTFO DSR testing on the RTFO-aged recovered binder to determine the critical high temperature (based on RTFO DSR). Calculate the critical high temperature (RTFO DSR) as follows:

X1.4.1 Determine the slope of the Stiffness-Temperature curve, a, as $a = \Delta\log(G^*/\sin\delta)/\Delta T$.

X1.4.2 Determine T_c(High), based on RTFO DSR, to the nearest 0.1°C using the following equation:

$$T_c(High) = \left(\frac{Log(2.20) - Log(G_1)}{a}\right) + T_1$$

where,

G_1 = the $G^*/\sin\delta$ value at a specific temperature T_1

a = the slope as described in X1.4.1

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the $G^*/\sin\delta$ value closest to the criterion (2.20 kPa) to minimize extrapolation errors.

X1.5 Determine the critical high temperature of the recovered RAP binder as the lowest of the Original DSR and RTFO DSR critical temperatures. Determine the high temperature performance grade of the recovered RAP binder based on this single critical high temperature.

X1.6 Perform intermediate temperature DSR testing on the RTFO-aged recovered RAP binder to determine the critical intermediate temperature T_c(Int), as if the RAP binder were PAV aged.

X1.6.1 Determine the slope of the Stiffness-Temperature curve, a, as $a = \Delta\log(G^*\sin\delta)/\Delta T$.

X1.6.2 Determine T_c(Int) to the nearest 0.1°C using the following equation:

$$T_c(Int) = \left(\frac{Log(5000) - Log(G_1)}{a}\right) + T_1$$

where,

G_1 = the $G^*\sin\delta$ value at a specific temperature T_1

a = the slope as described in X1.6.1

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the $G^*\sin\delta$ value closest to the criterion (5000 kPa) to minimize extrapolation errors.

X1.7 Perform BBR testing on the RTFO-aged recovered RAP binder to determine the critical low temperature, T_c(S) or T_c(m), based on BBR Stiffness or m-value.

X1.7.1 Determine the slope of the Stiffness-Temperature curve as $\Delta\log(S)/\Delta T$

X1.7.2 Determine $T_c(S)$ to the nearest 0.1°C using the following equation:

$$T_c(S) = \left(\frac{Log(300) - Log(S_1)}{a}\right) + T_1$$

where,

S_1 = the S-value at a specific temperature T_1
a = the slope as described in X1.7.1

Note: Although any temperature (T_1) and the corresponding stiffness (S_1) can be selected, it is advisable to use the S value closest to the criterion (300 MPa) to minimize extrapolation errors.

X1.7.3 Determine the slope of the m-value-Temperature curve as Δm-value/ΔT

X1.7.4 Determine $T_c(m)$ to the nearest 0.1°C using the following equation:

$$T_c(m) = \left(\frac{0.300 - m_1}{a}\right) + T_1$$

where,

m_1 = the m-value at a specific temperature T_1
a = the slope as described in X1.7.3

Note: Although any temperature (T_1) and the corresponding m-value (m_1) can be selected, it is advisable to use the m-value closest to the criterion (0.300) to minimize extrapolation errors.

X1.7.5 Select the higher of the two low critical temperatures, $T_c(S)$ or $T_c(m)$, to represent the low critical temperature for the recovered asphalt binder, T_c(Low). Determine the low temperature performance grade of the recovered RAP binder based on this single critical low temperature.

X1.8 Once the physical properties and critical temperatures of the recovered RAP binder are known, proceed with blending at a known RAP percentage or with a known virgin binder grade.

X2. Blending at a Known RAP Percentage

X2.1 If the desired final blended binder grade, the desired percentage of RAP and the recovered RAP binder properties are known, then the required properties of an appropriate virgin binder grade can be determined.

X2.1.1 Determine the critical temperatures of the virgin asphalt binder at high, intermediate and low properties as:

$$T_{Virgin} = \frac{T_{Blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)}$$

where:

T_{virgin} = critical temperature of virgin asphalt binder (high, intermediate or low)
T_{Blend} = critical temperature of blended asphalt binder (final desired) (high, intermediate or low)
%RAP = percentage of RAP expressed as a decimal
T_{RAP} = critical temperature of recovered RAP binder (high, intermediate or low)

Using this equation for the high, intermediate and low critical temperatures respectively, the properties of the virgin asphalt needed can be determined.

X3 Blending with a Known Virgin Binder

X3.1 If the final blended binder grade, virgin asphalt binder grade and recovered RAP properties are known, then the allowable RAP percentage can be determined.

X3.1.1 Determine the allowable RAP percentage as:

$$\%RAP = \frac{T_{Blend} - T_{Virgin}}{T_{RAP} - T_{Virgin}}$$

where:

T_{Virgin} = critical temperature of the virgin asphalt binder (high, intermediate or low)
T_{Blend} = critical temperature of the blended asphalt binder (high, intermediate or low)
T_{RAP} = critical temperature of the recovered RAP binder (high, intermediate or low)

Using this equation for the high, intermediate and low critical temperatures respectively, the allowable RAP percentage that will satisfy all temperatures can be determined.

F-A-11

Suggested Revisions to
Standard Practice for Superpave
Volumetric Design for Hot-Mix Asphalt (HMA)

AASHTO Designation: PP28-00[1, 2]

1. Scope

1.1 This standard for mix design evaluation uses aggregate and mixture properties to produce a hot-mix asphalt (HMA) job-mix formula. The mix design is based on the volumetric properties of the HMA in terms of the air voids, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA).

1.2 This standard may also be used to provide a preliminary selection of mix parameters as a starting point for mix analysis and performance prediction analyses which primarily use TP7 and TP9.

1.3 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards:

T2	Sampling of Aggregates
T11	Materials Finer Than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing
T27	Sieve Analysis of Fine and Coarse Aggregates
T84	Specific Gravity and Absorption of Fine Aggregate
T85	Specific Gravity and Absorption of Coarse Aggregate
T100	Specific Gravity of Soils
T166	Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens
T209	Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
T228	Specific Gravity of Semi-Solid Bituminous Materials
T248	Reducing Samples of Aggregate to Testing Size
T275	Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens
T283	Resistance of Compacted Bituminous Mixture to Moisture Induced Damage
MP1	Performance Graded Asphalt Binder
MP2	Superpave Volumetric Mix Design
PP2	Mixture Conditioning of Hot-Mix Asphalt (HMA)
TP4	Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor
TP7	Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot-Mix Asphalt (HMA) Using the Simple Shear Test (SST) Device
TP9	Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device

3. Terminology

3.1 HMA - Hot-Mix Asphalt

3.2 Design ESALs - Design equivalent (80kN) single-axle loads

Discussion - Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period. For pavements designed for more or less than 20 years, determine the design ESALs for 20 years when using this standard.

3.3 Air voids (V_a) - The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as

[1] This standard is based on SHRP Product M001.

[2] Approved in December 1995, this provisional standard was first published in June 1996.

a percent of the bulk volume of the compacted paving mixture (Note 1).

Note 1 - Term defined in Asphalt Institute Manual MS-2, "Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types."

3.4 Voids in the Mineral Aggregate (VMA) - The volume of the intergranular void space between the aggregate particles of a compacted paving mixture that includes the air voids and the effective binder content, expressed as a percent of the total volume of the specimen (Note 1).

3.5 Absorbed binder volume (V_{ba}) - The volume of binder absorbed into the aggregate (equal to the difference in aggregate volume when calculated with the bulk specific gravity and effective specific gravity).

3.6 Binder content (P_b) - The percent by mass of binder in the total mixture including binder and aggregate.

3.7 Effective binder volume (V_{be}) - The volume of binder which is not absorbed into the aggregate.

3.8 Voids Filled With Asphalt (VFA) - The percentage of the VMA filled with binder (the effective binder volume divided by the VMA).

3.9 Dust-to-Binder Ratio ($P_{0.075}/P_{be}$) - By mass, ratio between percent passing the 0.075 mm (# 200) sieve ($P_{0.075}$) and the effective binder content (P_{be}).

3.10 Nominal Maximum Aggregate Size - One size larger than the first sieve that retains more than 10 percent aggregate (Note 2).

3.11 Maximum Aggregate Size - One size larger than the nominal maximum aggregate size (Note 2).

Note 2 - The definitions given in Subsections 3.10 and 3.11 apply to Superpave mixes only and differ from the definitions published in other AASHTO standards.

3.12 Reclaimed Asphalt Pavement (RAP) - removed and/or processed pavement material containing asphalt binder and aggregate.

4. Summary of the Practice

4.1 Materials Selection - Binder and aggregate and RAP stockpiles are selected that meet the environmental and traffic requirements applicable to the paving project. The bulk specific gravity of all aggregates proposed for blending and the specific gravity of the binder are determined.

Note 3 - If RAP is used, the bulk specific gravity of the RAP aggregate may be estimated by determining the G_{mm} of the RAP mixture and using an assumed asphalt absorption for the RAP aggregate to calculate the RAP aggregate bulk specific gravity, if the absorption can be estimated with confidence. The RAP aggregate effective specific gravity may be used in lieu of the bulk specific gravity at the discretion of the Agency. The use of the effective specific gravity may introduce an error into the combined aggregate bulk specific gravity and subsequent VMA calculations. The Agency may choose to specify adjustments to the VMA requirements to account for this error based on experience with their local aggregates.

4.2 Design Aggregate Structure - At least three trial aggregate gradations from selected aggregate stockpiles are blended. For each trial gradation, an initial trial binder content is determined, and at least two specimens are compacted in accordance with TP4. A design aggregate structure and an estimated design binder content are selected on the basis of satisfactory conformance of a trial gradation meeting the requirements given in MP2 for V_a, VMA, VFA, dust-to-binder ratio at N_{design}, and relative density at N_{intial}.

4.3 Design Binder Content Selection - Replicate specimens are compacted in accordance with TP4 at the estimated design binder content and at the estimated design binder content $\pm$ 0.5 percent and + 1.0 percent. The design binder content is selected on the basis of satisfactory conformance with the requirements of MP2 for V_a, VMA, VFA, and dust-to-binder ratio at N_{des}, and the relative density at N_{ini} and N_{max}.

4.4 Evaluating Moisture Susceptibility - The moisture susceptibility of the design aggregate structure is evaluated at the design binder content: the mixture is conditioned according to the mixture conditioning for the volumetric mixture design procedure in PP2, compacted to 7 $\pm$ 1.0 percent air voids in accordance with TP4, and evaluated according to T283. The design shall meet the tensile strength ratio requirement of MP2.

5. Significance and Use - The procedure described in this practice is used to produce HMA which satisfies Superpave HMA volumetric mix design requirements.

6. Preparing Aggregate Trial Blend Gradations

6.1 Select a binder in accordance with the requirements of MP2.

6.2 Determine the specific gravity of the binder according to T228.

6.3 Obtain samples of aggregates proposed to be used for the project from the aggregate stockpiles in accordance with T2.

> Note 4~~3~~ - Each stockpile usually contains a given size of an aggregate fraction. Most projects employ 3 to 5 stockpiles to generate a combined gradation conforming to the job-mix formula and MP2.

6.4 Reduce the samples of aggregate fractions according to T248 to samples of the size specified in T27.

6.5 Wash and grade each aggregate sample according to T11 and T27.

6.6 Determine the bulk and apparent specific gravity for each coarse and fine aggregate fraction in accordance with T85 and T84, respectively, and determine the specific gravity of the mineral filler in accordance with T100.

6.7 Blend the aggregate fractions using Equation 1:

$$P = Aa + Bb + Cc, \quad etc. \tag{1}$$

where:

P = the percentage of material passing a given sieve for the combined aggregates A, B, C, etc.;

A, B, C, etc. = the percentage of material passing a given sieve for aggregates A, B, C, etc.; and

a, b, c, etc. = the proportions of aggregates A, B, C, etc. used in the combination, and where the total = 1.00.

6.8 Prepare a minimum of three aggregate trial blends; plot the gradation of each trial blend on a 0.45-power gradation analysis chart, and confirm that each trial blend meets MP2 gradation controls (see Tables 2 and 3 of MP2). Gradation control is based on four control sieve sizes: the sieve for the maximum aggregate size, the sieve for the nominal maximum aggregate size, the 4.75 or 2.36 mm sieve, and the 0.075 mm sieve. An example of three acceptable trial blends in the form of a gradation plot is given in Figure 1.

6.9 Obtain a test specimen from each of the trial blends according to T248, and conduct the quality tests specified in Section 6 of MP2 to confirm that the aggregate in the trial blends meets the minimum quality requirements specified in MP2.

> Note 5~~4~~ - The designer has an option of performing the quality tests on each stockpile instead of the trial aggregate blend. The test results from each stockpile can be used to estimate the results for a given combination of materials.

7. Determining an Initial Trial Binder Content for Each Trial Aggregate Gradation - Designers can either use their experience with the materials or the procedure given in Appendix X1 to determine an initial trial binder content for each aggregate trial blend.

> Note 6 - When using RAP, the initial trial asphalt content should be reduced by an amount equal to that provided by the RAP.

8. Compacting Specimens of Each Trial Gradation

8.1 Prepare replicate mixtures (Note 7~~5~~) at the initial trial binder content for each of the chosen aggregate trial blends. From Table 1, determine the number of gyrations based on the design ESALs for the project.

> Note- 7~~5~~ - At least two replicate specimens are required, but three or more may be prepared if desired. Generally, 4500 to 4700 g of aggregate is usually sufficient for each compacted specimen with a height of 110 to 120 mm for aggregates with combined bulk specific gravities of 2.55 - 2.70, respectively.

8.2 Condition the mixtures according to PP2, and compact the specimens to N_{design} gyrations in accordance with TP4. Record the specimen height to the nearest 0.1 mm after each revolution.

8.3 Determine the bulk specific gravity (G_{mb})of each of the compacted specimens in accordance with T166 or T275 as appropriate.

8.4 Determine the theoretical maximum specific gravity (G_{mm}) according to T209 of separate samples representing each of these combinations that have been mixed and conditioned to the same extent as the compacted specimens.

Note 8~~6~~ - The maximum specific gravity for each trial mixture shall be based on the average of at least two tests.

9. Evaluating Compacted Trial Mixtures

9.1 Determine the volumetric requirements for the trial mixtures in accordance with MP2.

9.2 Calculate V_a and VMA at N_{design} for each trial mixture using Equations 2 and 3:

$$V_a = 100x\left(1-\left(\frac{G_{mb}}{G_{mm}}\right)\right) \qquad (2)$$

$$VMA = 100x\left(1-\frac{G_{mb}P_s}{G_{sb}}\right) \qquad (3)$$

where:

G_{mb} = the bulk specific gravity of the extruded specimen;
G_{mm} = the theoretical maximum specific gravity of the mixture;
P_s = the percent of aggregate in the mix; and
G_{sb} = the bulk specific gravity of the combined aggregate.

Note 9~~7~~ - Although the initial trial binder content was estimated for a design air void content of 4.0 percent, the actual air void content of the compacted specimen is unlikely to be exactly 4.0 percent. Therefore, the change in binder content needed to obtain a 4.0 percent air void content, and the change in VMA caused by this change in binder content, is estimated. These calculations permit the evaluation of VMA and VFA of each trial aggregate gradation at the same design air void content, 4.0 percent.

9.3 Estimate the volumetric properties at 4.0 percent air voids for each compacted specimen.

9.3.1 Determine the difference in average air void content at N_{design} (ΔV_a) of each aggregate trial blend from the design level of 4.0 percent using Equation 4:

$$\Delta V_a = 4.0 - V_a \qquad (4)$$

where:

V_a = air void content of the aggregate trial blend at N_{design} gyrations.

9.3.2 Estimate the change in binder content (ΔP_b) needed to change the air void content to 4.0 percent using Equation 5:

$$\Delta P_b = -0.4\left(\Delta V_a\right) \qquad (5)$$

9.3.3 Estimate the change in VMA (ΔVMA) caused by the change in the air void content (ΔV_a) determined in Section 9.3.1 for each aggregate trial blend, using Equation 6 or 7.

$$\Delta VMA = 0.2(\Delta V_a) \qquad (6) \qquad \text{If } V_a > 4.0$$

$$\Delta VMA = -0.1(\Delta V_a) \qquad (7) \qquad \text{If } V_a < 4.0$$

Note 10~~8~~ - A change in binder content affects the VMA through a change in the bulk specific gravity of the compacted specimen (G_{mb}).

9.3.4 Calculate the VMA for each aggregate trial blend at N_{design} gyrations and 4.0 percent air voids using Equation 8:

$$VMA_{design} = VMA_{trial} + \Delta VMA \qquad (8)$$

where:

VMA_{design} = the VMA estimated at a design air void content of 4.0 percent; and
VMA_{trial} = the VMA determined at the initial trial binder content.

9.3.5 Using the values of ΔV_a determined in Section 9.3.1 and Equation 9, estimate the relative density of each specimen at $N_{initial}$ when the design air void content is adjusted to 4.0 percent at N_{design}:

$$\%Gmm_{initial} = 100\,x\left(\frac{G_{mb}h_d}{G_{mm}h_i}\right) - \Delta\,V_a \qquad (9)$$

where:

- $\%Gmm_{initial}$ = relative density at $N_{initial}$ gyrations at the adjusted design binder content;
- h_d = height of the specimen after N_{design} gyrations, from the Superpave gyratory compactor, mm; and
- h_i = height of the specimen after $N_{initial}$ gyrations, from the Superpave gyratory compactor, mm.

9.3.6 Estimate the percent of effective binder (Pbe_{est}) and calculate the dust-to-binder ratio ($P_{0.075}/P_{be}$) for each trial blend using equations 10 and 11:

$$be_{est} = -\,(Ps \times Gb)\,\frac{(Gse - Gsb)}{(Gse \times Gsb)} + Pb_{est}(1$$

where:

- Pbe_{est} = the estimated effective binder content;
- P_s = the aggregate content;
- G_b = specific gravity of the binder;
- G_{se} = the effective specific gravity of the aggregate;
- G_{sb} = the bulk specific gravity of the combined aggregate; and
- Pb_{est} = the estimated binder content.

$$P_{0.075} / P_{be} = \frac{P_{0.075}}{Pbe_{est}} \qquad (11)$$

where:

- $P_{0.075}$ = the percent passing the 0.075 mm sieve.

9.3.7 Compare the estimated volumetric properties from each aggregate trial blend at the adjusted design binder content with the criteria specified in MP2. Select, as the design aggregate structure, that aggregate trial blend that best satisfies the criteria.

Note 11~~9~~ - Table 2 presents an example of the selection of a design aggregate structure from three aggregate trial blends.

Note 12~~0~~ -- Many aggregate trial blends will fail the VMA criterion. Generally, the $\%Gmm_{initial}$ criterion will be met if the VMA criterion is satisfied. Subsection 12.1 gives a procedure for the adjustment of VMA.

Note 13~~1~~ -- If the trial aggregate gradations have been chosen to cover the entire range of the gradation controls, then the only remaining solution is to make adjustments to the aggregate production or to introduce aggregates from a new source. The aggregates which fail to meet the required criteria will not produce a quality mix and should not be used. One or more of the aggregate stockpiles should be replaced with another material which produces a stronger structure. For example, a quarry stone can replace a crushed gravel, or crushed fines can replace natural fines.

10. Selecting the Design Binder Content

10.1 Prepare replicate mixtures (Note 7~~5~~) containing the selected design aggregate structure at each of the following four binder contents: (1) the estimated design binder content, P_b(design); (2) 0.5 percent below P_b(design); (3) 0.5 percent above P_b(design); and (4) 1.0 percent above P_b(design).

10.1.1 From Table 1, determine the number of gyrations based on the design ESALs for the project.

10.2 Condition the mixtures according to PP2, and compact the specimens to N_{design} gyrations according to TP4. Record the specimen height to the nearest 0.1 mm after each revolution.

10.3 Determine the bulk specific gravity of each of the compacted specimens in accordance with T166 or T275 as appropriate.

10.4 Determine the theoretical maximum specific gravity (G_{mm}) according to T209, of each of the four mixtures using companion samples which have been conditioned to the same extent as the compacted specimens (Note 8~~6~~).

10.5 Determine the design binder content which produces a target air void content (V_a) of 4.0 percent at N_{design} gyrations using the following steps:

10.5.1 Calculate V_a, VMA, and VFA at N_{design} using Equations 2, 3 and 12:

$$VFA = 100\,x\left(\frac{VMA - V_a}{VMA}\right) \qquad (12)$$

10.5.2 Calculate the dust-to-binder ratio, using equation 13.

$$P_{0.075} \;/\; P_{be} = \frac{P_{0.075}}{P_{be}} \qquad (13)$$

where:

P_{be} = the effective binder content.

10.5.3 For each of the four mixtures, determine the average corrected specimen relative densities at $N_{initial}$ ($\%Gmm_{initial}$), using Equation 14.

$$\%Gmm_{\,initial} = 100\,x\left(\frac{G_{mb}h_d}{G_{mm}h_i}\right) \qquad (14)$$

10.5.4 Plot the average V_a, VMA, VFA, and relative density at N_{design} for replicate specimens versus binder content.

> Note 14~~2~~ - All plots are generated automatically by the Superpave software. Figure 2 presents a sample data set and the associated plots.

10.5.5 By graphical or mathematical interpolation (Figure 2), determine the binder content to the nearest 0.1 percent at which the target V_a is equal to 4.0 percent. This is the design binder content (P_b) at N_{design}.

10.5.6 By interpolation (Figure 2), verify that the volumetric requirements specified in MP2 are met at the design binder content.

10.6 Compare the calculated percent of maximum relative density with the design criteria at $N_{initial}$ by interpolation, if necessary. This interpolation can be accomplished by the following procedure.

10.6.1 Prepare a densification curve for each mixture by plotting the measured relative density at x gyrations, $\%Gmm_x$, versus the logarithm of the number of gyrations (see Figure 3).

10.6.2 Examine a plot of air void content versus binder content. Determine the difference in air voids between 4.0 percent and the air void content at the nearest, lower binder content. Determine the air void content at the nearest, lower binder content at its data point, not on the line of best fit. Designate the difference in air void content as ΔV_a.

10.6.3 Using Equation 14, determine the average corrected specimen relative densities at $N_{initial}$ ($\%Gmm_{initial}$). Confirm that $\%Gmm_{initial}$ satisfies the design requirements in MP2 at the design binder content.

10.7 Prepare replicate (Note 7~~5~~) specimens composed of the design aggregate structure at the design binder content to confirm that $\%Gmm_{max}$ satisfies the design requirements in MP2.

10.7.1 Condition the mixtures according to PP2, and compact the specimens according to TP4 to the maximum number of gyrations, N_{max}, from Table 1.

10.7.2 Determine the average specimen relative density at N_{max}, $\%Gmm_{max}$, by using Equation 15, and confirm that $\%Gmm_{max}$ satisfies the volumetric requirement in MP2.

$$\%Gmm_{\max} = 100\frac{G_{mb}}{G_{mm}} \qquad (15)$$

where:

$\%Gmm_{max}$ = relative density at N_{max} gyrations at the design binder content.

11. Evaluating Moisture Susceptibility

11.1 Prepare six mixture specimens (nine are needed if freeze-thaw testing is required) composed of the design aggregate structure at the design binder content. Condition the mixtures in accordance with PP2, and compact the specimens to 7 ± 1.0 percent air voids in accordance with TP4.

11.2 Test the specimens and calculate the tensile strength ratio in accordance with T283.

11.3 If the tensile strength ratio is less than 0.80, as required in MP2, remedial action such as the use of anti-strip agents is required to improve the moisture susceptibility of the mix. When remedial agents are used to modify the binder, retest the mix to assure compliance with the 0.80 minimum requirement.

12. Adjusting the Mixture to Meet Properties

12.1 Adjusting VMA - If a change in the design aggregate skeleton is required to meet the specified VMA, there are three likely options: (1) change the gradation (Note 15~~3~~); (2) reduce the minus 0.075 mm fraction (Note 16~~4~~); or (3) change the surface texture and/or shape of one or more of the aggregate fractions (Note 17~~5~~).

Note 15~~3~~ - Changing gradation may not be an option if the aggregate trial blend analysis includes the full spectrum of the gradation control area.

Note 16~~4~~ - Reducing the percent passing the 0.075 mm sieve of the mix will typically increase the VMA. If the percent passing the 0.075 mm sieve is already low, this is not a viable option.

Note 17~~5~~ - This option will require further processing of existing materials or a change in aggregate sources.

12.2 Adjusting VFA - The lower limit of the VFA range should always be met at 4.0 percent air voids if the VMA meets the requirements. If the upper limit of the VFA is exceeded, then the VMA is substantially above the minimum required. If so, redesign the mixture to reduce the VMA. Actions to consider for redesign include: (1) changing to a gradation that is closer to the maximum density line; (2) increasing the minus 0.075 mm fraction, if room is available within the specification control points; or (3) changing the surface texture and shape of the aggregates by incorporating material with better packing characteristics, e.g., less thin, elongated aggregate particles.

12.3 Adjusting the Tensile Strength Ratio - The tensile strength ratio can be increased by: (1) adding chemical anti-strip agents to the binder to promote adhesion in the presence of water; or (2) adding hydrated lime to the mix.

13. Report

13.1 The report shall include the identification of the project number, traffic level, and mix design number.

13.2 The report shall include information on the design aggregate structure including the source of aggregate, kind of aggregate, source and amount of RAP, required quality characteristics, and gradation.

13.3 The report shall contain information about the design binder including the source of binder and the performance grade.

13.4 The report shall contain information about the HMA including the percent of binder in the mix; the relative density; the number of initial, design, and maximum gyrations; and the VMA, VFA, V_{be}, V_{ba}, V_a, and dust-to-binder ratio.

14. Keywords - HMA mix design; volumetric mix design; Superpave.

Appendix X1
Calculating an Initial Trial Binder Content for Each Aggregate Trial Blend
(Non-Mandatory Information)

X1.1 Calculate the bulk and apparent specific gravities of the combined aggregate in each trial blend using the specific gravity data for the aggregate fractions obtained in Subsection 6.6 and Equations X1.1 and X1.2:

$$G_{sb} = \frac{P_1 + P_2 + \ldots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \ldots + \frac{P_n}{G_n}} \quad \textbf{(X1.1)}$$

$$G_{sa} = \frac{P_1 + P_2 + \ldots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \ldots + \frac{P_n}{G_n}} \quad \textbf{(X1.2)}$$

where:

G_{sb} = the bulk specific gravity for the combined aggregate;
G_{sa} = the apparent specific gravity for the combined aggregate;
P_1, P_2, P_n = the percentages by mass of aggregates 1, 2, n; and
G_1, G_2, G_n = the bulk specific gravities (Eq. X1.1) or apparent specific gravities (Eq. X1.2) of aggregates 1, 2, n.

X1.2 Estimate the effective specific gravity of the combined aggregate in the aggregate trial blend using Equation X1.3:

$$G_{se} = G_{sb} + 0.8\ (G_{sa} - G_{sb}) \quad \textbf{(X1.3)}$$

where:

G_{se} = the effective specific gravity of the combined aggregate;
G_{sb} = the bulk specific gravity of the combined aggregate; and
G_{sa} = the apparent specific gravity of the combined aggregate.

Note X1.1 - The multiplier, 0.8, can be changed at the discretion of the designer. Absorptive aggregates may require values closer to 0.6 or 0.5.

Note X1.2 - The Superpave mix design system includes a mixture conditioning step before the compaction of all specimens; this conditioning generally permits binder absorption to proceed to completion. Therefore, the effective specific gravity of Superpave mixtures will tend to be close to the apparent specific gravity in contrast to other design methods where the effective specific gravity generally will lie near the midpoint between the bulk and apparent specific gravities.

X1.3 Estimate the volume of binder absorbed into the aggregate, V_{ba}, using Equations X1.4 and X1.5:

$$V_{ba} = W_s \left(\frac{1}{G_{sb}} - \frac{1}{G_{se}} \right) \quad \textbf{(X1.4)}$$

where W_s, the mass of aggregate in 1 cm^3 of mix, g, is calculated as:

$$W_s = \frac{P_s\ (1 - V_a)}{\frac{P_b}{G_b} + \frac{P_s}{G_{se}}} \quad \textbf{(X1.5)}$$

and where:

P_b = the mass percent of binder, in decimal equivalent, assumed to be 0.05;
P_s = the mass percent of aggregate, in decimal equivalent, assumed to be 0.95;
G_b = the specific gravity of the binder; and
V_a = the volume of air voids, assumed to be 0.04 cm^3 in 1 cm^3 of mix.

Note X1.3 - This estimate calculates the volume of binder absorbed into the aggregate, V_{ba}, and subsequently, the initial, trial binder content at a target air void content of 4.0 percent.

X1.4 Estimate the volume of effective binder using Equation X1.6:

$$V_{be} = 0.176 - [0.0675 \log(S_n)] \quad \textbf{(X1.6)}$$

where:

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V_{be} = the volume of effective binder, cm^3; and
S_n = the nominal maximum sieve size of the largest aggregate in the aggregate trial blend, mm.

Note X1.4 - This regression equation is derived from an empirical relationship between: (1) VMA and V_{be} when the air void content, V_a, is equal to 4.0 percent: V_{be} = VMA - P_a = VMA - 4.0; and (2) the relationship between VMA and the nominal maximum sieve size of the aggregate in MP2.

X1.5 Calculate the estimated initial trial binder (P_{bi}) content for the aggregate trial blend gradation using Equation X1.7:

$$P_{bi} = 100\,x\left(\frac{G_b(V_{be} + V_{ba})}{(G_b(V_{be} + V_{ba})) + W_s}\right) \quad \text{(X1.7)}$$

where:

P_{bi} = the estimated initial trial binder content, percent by weight of total mix.

Table 1 - Superpave Gyratory Compaction Effort

Design ESALs[1] (million)	Compaction Parameters			Typical Roadway Application[2]
	$N_{initial}$	N_{design}	N_{max}	
< 0.3	6	50	75	Applications include roadways with very light traffic volumes such as local roads, county roads, and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate, or interstate. Special purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to < 3	7	75	115	Applications include many collector roads or access streets. Medium-trafficked city streets and the majority of county roadways may be applicable to this level.
3 to < 30	8	100	160	Applications include many two-lane, multilane, divided, and partially or completely controlled access roadways. Among these are medium to highly trafficked city streets, many state routes, US highways, and some rural Interstates.
≥ 30	9	125	205	Applications include the vast majority of the US Interstate system, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level.

(1) The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

(2) As defined by A Policy on Geometric Design of Highways and Streets, 1994, AASHTO.

Note 18~~6~~ - When specified by the agency and the top of the design layer is ≥ 100 mm from the pavement surface and the estimated design traffic level is ≥ 0.3 million ESALs, decrease the estimated design traffic level by one, unless the mixture will be exposed to significant mainline construction traffic prior to being overlaid. If less than 25% of a construction lift is within 100 mm of the surface, the lift may be considered to be below 100 mm for mixture design purposes.

Note 19~~7~~ - When the estimated design traffic level is between 3 to <10 million ESALs, the agency may, at its discretion, specify $N_{initial}$ at 7, N_{design} at 75, and N_{max} at 115.

Table 2 - Selection of a Design Aggregate Structure (Example)

Volumetric Property	Trial Mixture (19.0 mm nominal maximum aggregate) 20-Year Project Design ESALs = 5 million			Criteria
	1	2	3	
	At the initial trial binder content			
P_b (trial)	4.4	4.4	4.4	
$\%Gmm_{initial}$ (trial)	88.1	87.8	87.1	
$\%Gmm_{design}$ (trial)	95.9	95.3	94.7	
V_a at N_{design}	4.1	4.7	5.3	4.0
VMA_{trial}	12.9	13.4	13.9	
	Adjustments to reach design binder content (V_a = 4.0% at N_{design})			
ΔV_a	-0.1	-0.7	-1.3	
ΔP_b	0.0	0.3	0.5	
ΔVMA	0.0	-0.1	-0.3	
	At the estimated design binder content (V_a = 4.0% at N_{design})			
Estimated P_b (design)	4.4	4.7	4.9	
VMA (design)	12.9	13.3	13.6	≥ 13.0
$\%Gmm_{initial}$ (design)	88.2	88.5	88.4	≤ 89.0

Notes: The top portion of this table presents measured densities and volumetric properties for specimens prepared for each aggregate trial blend at the initial trial binder content.

None of the specimens had an air void content of exactly 4.0 percent. Therefore, the procedures described in Section 9 must be applied to: 1) estimate the design binder content at which V_a = 4.0 percent, and 2) obtain adjusted VMA and relative density values at this estimated binder content.

The middle portion of this table presents the change in binder content (ΔP_b) and VMA (ΔVMA) that occurs when the air void content (V_a) is adjusted to 4.0 percent for each aggregate trial blend.

A comparison of the VMA and densities at the estimated design binder content to the criteria in the last column shows that aggregate trial blend #1 does not have sufficient VMA (12.9 % versus a requirement of ≥13.0 %). Trial blend #2 exceeds the criterion for relative density at $N_{initial}$ gyrations (89.5 % versus a requirement of ≤ 89.0 %). Trial #3 meets the requirements for relative density and VMA and, in this example, is selected as the design aggregate structure.

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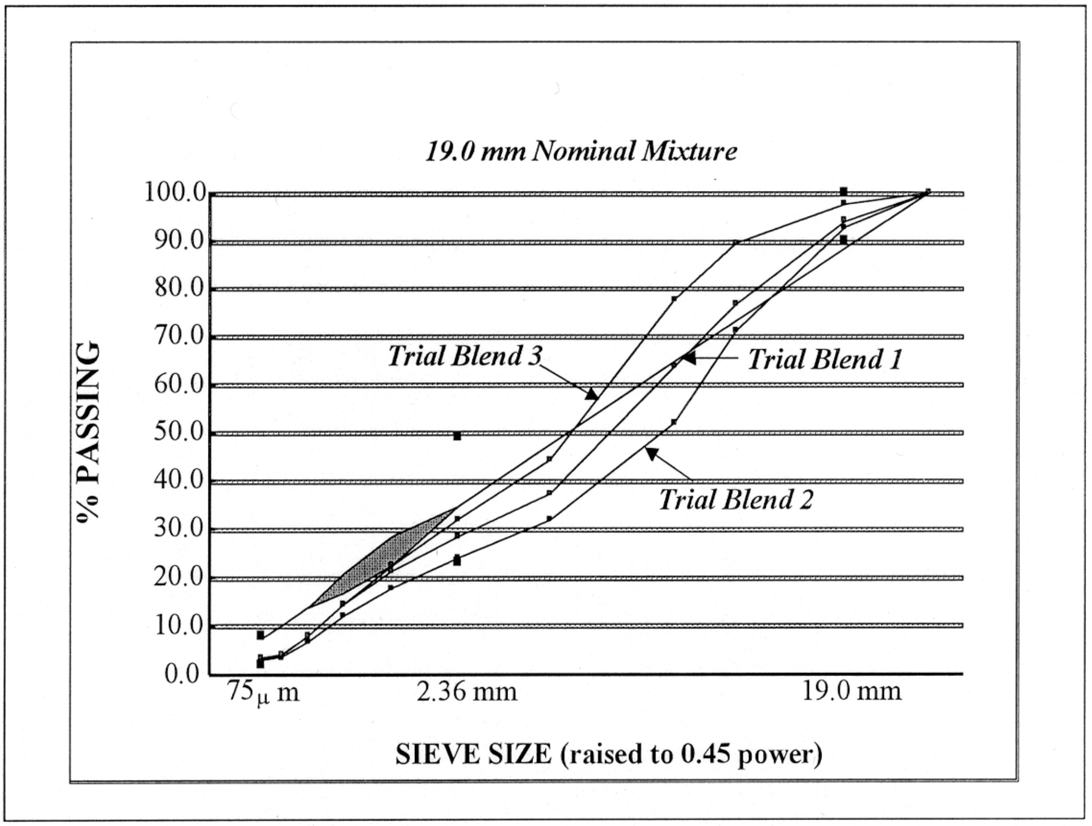
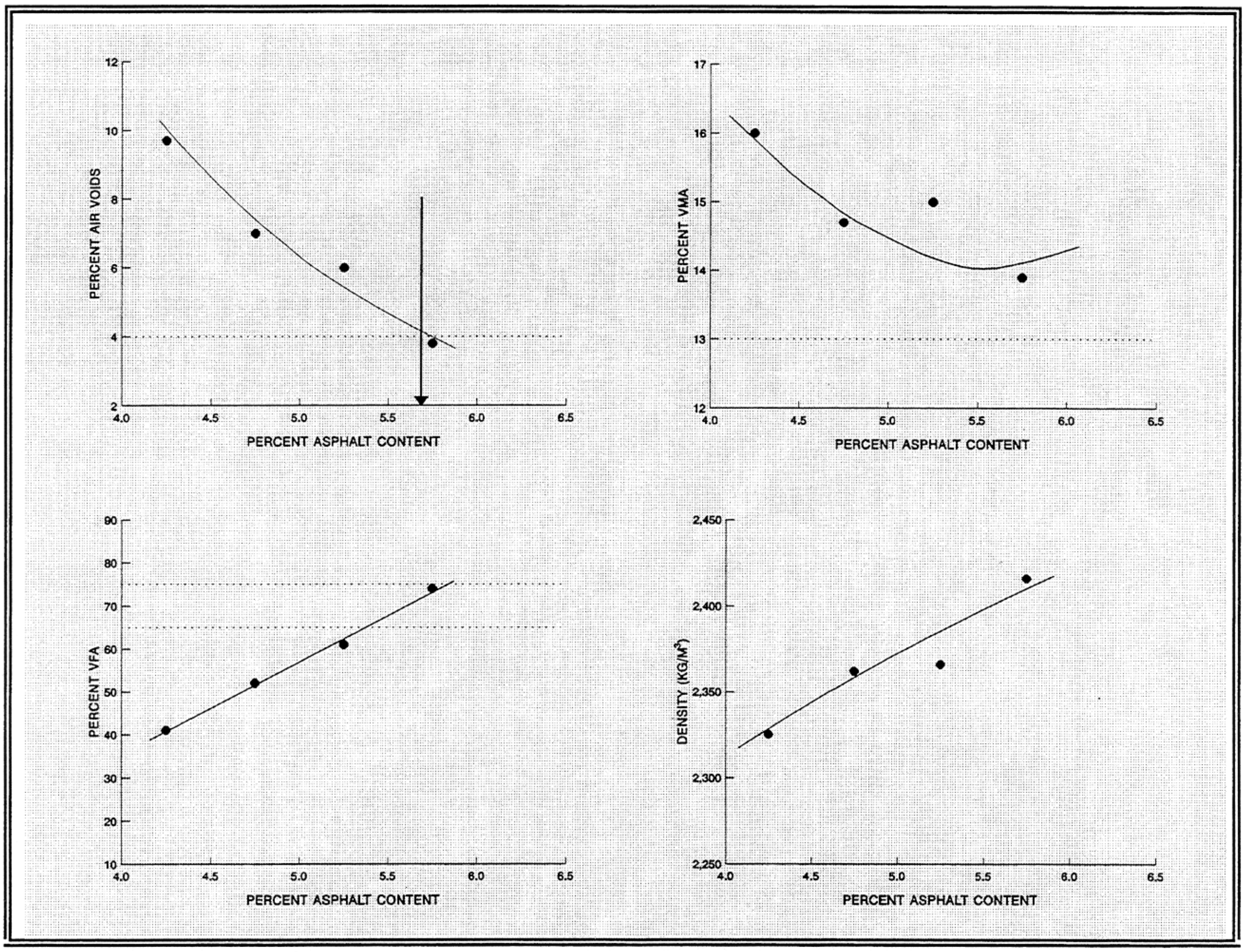


Figure 1 - Evaluation of the Gradations of Three Trial Blends (Example)



P_b (%)	V_a (%)	VMA (%)	VFA (%)	Density at N_{des} (kg/m^3)
4.3	9.5	15.9	40.3	2320
4.8	7.0	14.7	52.4	2366
5.3	6.0	14.9	59.5	2372
5.8	3.7	13.9	73.5	2412

In this example, the estimated design binder content is 4.8 percent; the minimum VMA requirement for the design aggregate structure (19.0 mm nominal maximum size) is 13.0 percent, and the VFA requirement is 65 to 75 percent.

Entering the plot of percent air voids versus percent binder content at 4.0 percent air voids, the design binder content is determined as 5.7 percent.

Entering the plots of percent VMA versus percent binder content and percent VFA versus percent binder content at 5.7 percent binder content, the mix meets the VMA and VFA requirements.

Figure 2 - Sample Volumetric Design Data at N_{des}

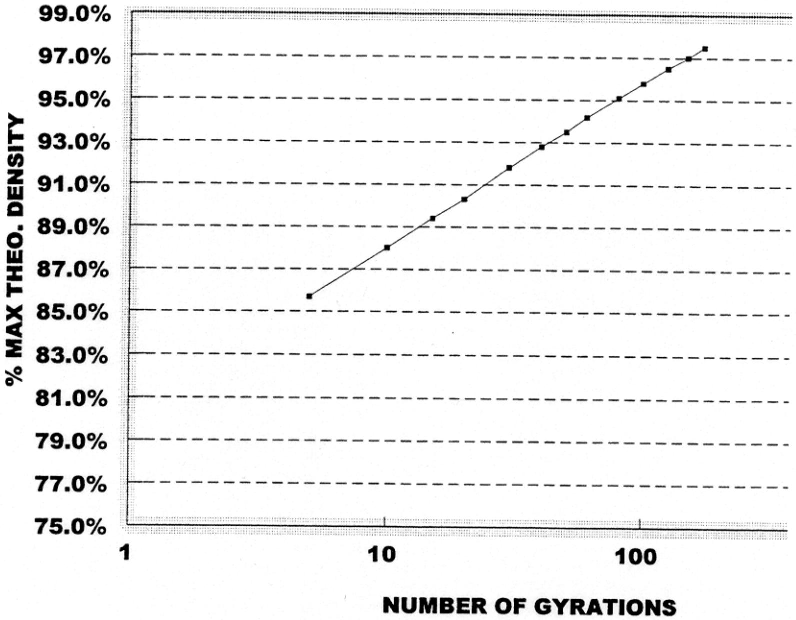


Figure 3 - Sample Densification Curve

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Proposed Revisions to
Standard Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Hot Mix Asphalt (HMA)

AASHTO Designation TP2-94[1, 2] (Reapproved 1996)

1. Scope

1.1 This standard describes a procedure for the extraction and recovery of asphalt binder from ~~hot mix~~ asphalt mixtures (both hot mix asphalt (HMA) and reclaimed asphalt pavement (RAP)) ~~samples~~ which has a minimal e~~a~~ffect on the physical and chemical properties of the asphalt binder recovered. It is intended for use when the physical or chemical properties or both of the recovered asphalt binder are to be determined. It can also be used to determine the quantity of asphalt binder in the HMA or RAP. Recovered aggregate may be used for sieve analysis.

1.2 This method is applicable to HMA sampled from the pavement, RAP sampled from the pavement or stockpile, HMA plant production, or laboratory fabricated HMA.

~~1.3 This method is not suitable for sieve analysis of recovered aggregate, since the aggregate undergoes prolonged grinding in the extraction device that will affect the aggregate gradation.~~

1.3~~4~~ This procedure may involve hazardous materials, operations and equipment. This procedure does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards

M231	Specification for Standard Masses and Balances Used in the Testing of Highway Materials
T110	Moisture or Volatile Distillates in Bituminous Pavement Mixtures
T168	Method of Sampling Bituminous Paving Mixtures

2.2 ASTM Standards

D5361	Sampling Compacted Bituminous Mixtures for Laboratory Testing

3. Terminology

3.1 asphalt binder - an asphalt-based cement that is produced from petroleum residue either with or without the addition of non-particulate organic modifiers

4. Summary of Method - The ~~HMA sample~~ asphalt mixture is repeatedly washed and filtered with solvent ~~toluene and toluene with 15 percent ethanol~~ in an extraction/filtration apparatus. Each filtrate is distilled under vacuum in a rotary evaporator with the asphalt remaining in the flask. After recovery of the final filtrate, the solution is concentrated to about 300 mL and centrifuged to remove aggregate fines. The decanted solution is distilled under vacuum to remove the extraction solvents. Nitrogen gas is introduced during the final phase of distillation to drive off any remaining traces of solvents. The quantity of asphalt binder in the asphalt mixture~~HMA~~ is calculated (optional) and the recovered asphalt (distillation residue) sample is subjected to further physical and chemical testing as required. The recovered aggregate can then be used for sieve analysis, if desired.

5. Significance and Use - This method is used for obtaining recovered asphalt binder residue samples from asphalt mixture~~HMA~~ samples for further physical and chemical analyses, and for optional calculation of asphalt binder content ~~in HMA samples~~.

[1] This standard is based on SHRP Product 1004.
[2] Approved in October 1994, this provisional standard was first published in March 1995.

6. Apparatus

6.1 Extraction Vessel - The extraction vessel shall be a device as shown in Figure 1, and shall have a 130-mm long piece of 150-mm I.D. Schedule 80 aluminum pipe or Schedule 80, grade 304 stainless steel pipe (Figure 2) with removable top and bottom 13-mm thick aluminum or stainless steel plates. The top plate (Figure 3) shall have a mixing motor mount and 19-mm port for adding solvent. The bottom plate (Figure 4) shall be equipped with a quick connect fitting. Four 100-mm by 25-mm baffles (Figure 5) shall be mounted in the extraction vessel followed by ~~a 2.00-mm stainless steel screen, glass wool plug, 0.203-μm filter, and 2.00-mm stainless steel backup screen.~~ 3-mm aluminum ring, 2-mm (#10) mesh screen, spacer (Figure 6), 0.3-mm (#50) mesh screen, another spacer, 0.075-mm (#200) mesh screen, then another 2-mm (#10) mesh screen, as shown in Figure 1.

> Note 1 - Vessel available through Pass Industries Ph# (606)881-0205 has proven acceptable for these requirements.

6.2- In-line~~Fine~~ filter - The in-line~~fine~~ filter apparatus shall be a cartridge type with 20-μm retention and at least 820-cm^3 effective filter area. The filter apparatus shall be able to be removed from the system to accommodate weighing before and after procedure. The filter shall be capable of withstanding heat up to 135°C without degradation in order to accommodate oven drying of the filter apparatus.~~as shown in Figure 6, shall consist of a top and bottom (Figure 7), each fabricated from 13-mm diameter aluminum plate, which hold a 0.025-μm (1 micron) woven polypropylene filter and a 2.00-mm (#10) stainless steel backup screen.~~

> Note 2 - Whatman Polycap™ 75 HD Catalog number 6703-7521 or equivalent is a suitable filter.

6.3 ~~Suction flask, 500 mL~~Two (2) filtrate flasks with tubulation, 1000mL

6.4 Round bottom flask~~s~~, 1000 mL and cork stand~~s~~

6.5 Gas flowmeter, capable of indicating a gas flow up to 1000 mL/minute

6.6 Rotary evaporator device, ~~Buchi Rotavapor RE-111A,~~ with transfer and purge tubes, capable of holding a recovery flask in oil at a 15 degree angle and rotating at 40 r/min

> Note 3 - The Buchi Rotavapor RE-120 has proven acceptable for these requirements.

6.7 Hot oil bath, capable of heating oil to 180°C

6.8 Single speed mixing motor, 150 W (1/5 hp), 30 r/min

6.9 Centrifuge, batch unit capable of exerting a minimum centrifugal force of 770 times gravity

6.10 Wide-mouth centrifuge bottles, 250 mL.

6.11 Oven, capable of maintaining a temperature of 110 ± 5°C

6.12 Balance, of suitable capacity meeting the requirements of M231 for Class G2 balances

6.13 Thermometer, having a range of ~~-2~~30 to 300°C

6.14 Utilities - Vacuum source and cooling water source.

6.15 Scale (optional) - having a capacity of 12 kg or more, sensitive to 0.1 g or less, and accurate within 0.1% of the test load at any point within the range of use for this test. Within any 100-g range of test load, a difference between readings shall be accurate within 0.1 g.

7. Materials and Reagents

7.1 6-mm diameter polypropylene tubing -- varying length, for transferring solution throughout the procedure~~ -- 430-mm long, for the rotavapor transfer tube -- 585-mm long, for the rotavapor purge tube~~

> Note 4~~1~~ - To avoid contamination of the sample due to solvent degradation of the tubing, do not substitute Nalgene or rubber tubing for the polypropylene tubing specified.

7.2 Copper tubing, of an amount and size adequate to connect the apparatus as shown in Figure~~s~~ ~~6-8 or 9~~.

> ~~Note 2 - The quantity of copper tubing needed will be dependent upon the space used to set up the apparatus.~~

~~7.3 Woven Polypropylene Filter Cloths - coarse filter cloth made from 2 by 2 twill weave monofilament woven polypropylene having a~~

~~0.203-μm (8 micron) or 0.0142 m3/minute (5 CFM) rating and fine filter cloth made from oxford weave multifilament woven polypropylene, having a 0.025 to 0.051-μm (1-2 micron) or 0.00142 m3/minute (0.5 CFM) rating~~

~~7.4 Glass Wool, borosilicate~~

~~7.5 Stainless steel screen, 2.00 mm (#10)~~

~~7.6 Toluene, reagent grade~~

~~7.7 Ethanol, absolute~~

7.3 Solvent

7.3.1 n-Propyl Bromide

7.3.2 or, Trichloroethylene, reagent grade

7.3.3 or, Toluene, reagent grade. If using Toluene, combine with Ethanol, absolute, in proportions of 85% Toluene and 15% Ethanol after the third wash (in section 12.2)

7.8 Nitrogen gas, at least 99.95 percent pure, in a pressurized tank, with a pressure-reducing regulator valve

8. Hazards - Use solvents only under a fume hood or with an effective surface exhaust system in a well-ventilated area and observe the manufacturer's recommended safety precautions when using compressed nitrogen.

9. Sampling - Obtain asphalt mixture~~HMA~~ samples in accordance with T168. When sampling from a compacted roadway, remove specimens from the roadway in accordance with ASTM D5361. When sampling RAP, refer to ASTM D75 for aggregate sampling.

10. Preparation of Apparatus

10.1 Preparing the Extraction Vessel - Install the baffles piece and other internal parts in the order shown in Figure 1.~~place the metal screen downstream of the baffle. Cut several pieces of glass wool and pack them in the space between the screen and the downstream end of the extraction vessel. Place the gaskets, filter and aluminum end piece on extraction vessel, as shown in Figure 1.~~ Tightly and evenly fasten the bottom~~end~~ piece (with quick connect) of the vessel with wing nuts or hexagonal nuts.

10.2 Preparing the Rotary Evaporator - Turn on the cooling water. Turn on the oil bath and set the temperature to 100 ± 2.5°C. Place six 3-mm glass boiling beads in a 1000 mL round bottom flask. Attach this~~e~~ recovery flask to the rotary evaporator and immerse approximately 38 mm of the flask into the oil bath. Set the angle of the recovery flask from the horizontal to the bath at 15 degrees. Set the flask rotation at 40 r/min. Clamp the empty condensate flask onto the condenser. Attach the transfer tube inside the neck of the rotary evaporator. ~~Apply a vacuum of 93.3 ± 0.7 kPa (700 ± 5 mm Hg) to the rotary evaporator.~~ Attach the filtrate transfer line to the external fitting on neck of rotary evaporator.

11. Standardization

11.1 At least every six months, verify the calibration of the oil bath temperature detector by using a certified mercury in glass thermometer of suitable range that is accurate to ± 0.2°C. Immerse the thermometer in the oil bath close to the thermal detector and compare the temperature indicated by the certified thermometer to the temperature setting for the oil bath. If the temperature indicated by the thermal detector does not agree with the certified thermometer within ± 0.5°C, perform additional calibration or maintenance.

11.2 At least every six months, use a mercury manometer or other certified pressure measurement device to verify calibration of the vacuum indicator. If the vacuum indicator and the certified pressure measurement device do not agree within ± 0.1 kPa, perform additional calibration or maintenance~~maintainance~~.

11.3 At least every six months, verify the rotational velocity of the rotary evaporator.

11.4 At least every six months, verify the flow rate of the nitrogen flow meter.

12. Procedure

12.1 Sample Preparation

12.1.1 If a sample of ~~HMA~~asphalt mixture is not sufficiently soft to separate with a spatula or trowel, place the sample in a large, flat pan and warm it in a oven at 110 ± 5°C only until it can be handled or mixed.

12.1.2 Split or quarter the loose asphalt mixture~~HMA~~ sample until an amount of the~~HMA~~ sample that will yield approximately 50 to 60 g of extracted asphalt binder is obtained (typically approximately 1000g of asphalt mixture). ~~If the asphalt binder content is to be determined, record the mass of the HMA sample obtained and recovery flask to the nearest 0.1 g. If more than approximately 60 g is required for testing, use multiple extractions and recoveries.~~

> Note 5~~3~~ - This procedure works best when recovering~~for quantities of asphalt binder~~ less than 60 g of asphalt binder. Therefore, if the asphalt binder content of the mix is already known, then the mass of the original~~HMA~~ sample required is that which yields about 50 to 60 g of asphalt binder.

> Note 6~~4~~ - The maximum aggregate size in the test specimen will affect the calculated asphalt content. If the calculated results from this standard are used to represent the asphalt content in the asphalt mixture~~HMA~~ from which the sample was obtained, use a minimum mass of test specimens for calculations that will ensure that inclusion or removal of one maximum size particle will not change the calculated asphalt content by more than 0.05 percent. This may require testing multiple test specimens.

12.1.3 If the asphalt binder content is to be determined, obtain a separate test specimen from the asphalt mixture~~HMA~~ sample, determine the moisture content in accordance with T110 and record the mass percent of water in the test specimen.

12.2 Extraction and Filtration

12.2.1 Place the asphalt mixture~~HMA~~ sample in the extraction vessel. Put the gasket and the upstream end piece on the vessel and fasten the wing nuts tightly and evenly, creating a secure seal.

12.2.2 Charge 600 mL of solvent~~toluene~~ through the 19-mm port on the upstream end of the extractor. Blanket the interior of the extraction vessel by injecting nitrogen through the upstream port at a rate of 1000 mL/min for 1 minute. Close the port with the threaded plug. Attach the extractor to the motor. Start the motor and mix for 5 ± 1 minutes at 30 r/min. Turn off the motor.

12.2.3 Remove the extractor, place it on a stand and attach the quick connect fitting to the first filtrate receiving flask. Make sure the filtrate transfer line is closed. Remove the upstream port plug and blanket the extractor with nitrogen at a rate of 400 mL/min while drawing the asphalt/solvent solution into the first flask~~filtering~~. Apply 93.3 ± 0.7 kPa (700 ± 5 mm Hg) vacuum to the first filtrate receiving flask to draw the material from the vessel. Continue drawing the solution into the first flask until there is no noticeable amount of solution exiting the vessel. ~~Filter until the filtrate flow rate is below 10 mL/min.~~ Turn off the vacuum.

12.2.4~~3.1~~ Filtering through the in-line cartridge filter~~If using the fine filter~~, switch the vacuum to the~~a~~ second filtrate receiving flask and apply 93.3 ± 0.7 kPa (700 ± 5 mm Hg) vacuum. Filter until there is no noticeable amount of solution remaining in the first flask or the filter.~~the filtrate flow rate is below 10 mL/min.~~ Turn off the vacuum.

12.2.5~~4~~ After filtration, open the filtrate transfer valve on the second receiving flask and allow the solution to flow from the filtrate receiving flask to the recovery flask. Continue the transfer until the filtrate receiving flask is empty or the recovery flask is about 2/3 full, then, begin the primary distillation.

12.2.6~~5~~ After the distillation is started, d~~D~~isconnect the extractor from the quick connect fitting. Repeat the extraction procedure. For the second ~~and third~~ washe~~s~~ use 400 ± 10 mL of ~~toluene~~solvent and mix/rotate for 10 ± 1 minutes. For all subsequent washes (Note 7~~5~~), use 400 ± 10 mL of~~toluene with 15 volume percent ethanol~~ solvent and mix for 30 to 35 minutes. ~~In addition, mix the second wash for ten ± 1 minutes and all subsequent washes for a minimum of 30 minutes.~~

> Note 7~~5~~ - ~~It is suggested that a~~After the third wash, the condensate from the primary distillation step may be used for the extraction solvent. Recycling solvent in this manner allows the entire procedure to use approximately 1500 mL solvent~~toluene~~.

12.2.7~~6~~ Proceed to the final recovery step (12.4) ~~if~~ when the filtrate flowing through the transfer tube, after a 30 minute wash, is a light brown color. A minimum of three washes is required.

12.3 Primary Distillation

12.3.1 Close the filtrate transfer valve line and distill solvent at 100 ± 2.5°C (oil bath temperature) and 93.3 ± 0.7 kPa (700 ± 5 mm Hg) vacuum.

12.3.2 If after the primary distillation step the condensate flask is over half full, empty the flask. Save this solvent for use in subsequent washes (Note 7~~5~~). After primary distillation of each filtrate, maintain vacuum, temperature, flask rotation, and cooling water. Repeat the primary distillation after each filtration (Note 8~~6~~).

> Note 8~~6~~ - It is important to concentrate the asphalt in the recovery flask after each wash and at a low temperature. This minimizes the temperature and the time spent in dilute solution and, therefore, minimizes asphalt hardening in solvent.

~~12.3.3 If desired, after primary distillation of the first three filtrates, remove the recovery flask (which should contain only small amounts of solvent) and set it aside. Replace it with another 1000 mL round bottom flask containing six 3-mm diameter glass boiling beads. Carry out the remaining primary distillations using the new recovery flask. Pour the contents of the current recovery flask into the original recovery flask. Attach the original recovery flask to the rotary evaporator.~~

12.4 Final Extraction and Recovery

12.4.1 Distill the contents of the recovery flask until it is about 1/3 full.

12.4.2– Turn off the vacuum, then clean and d~~D~~isconnect the recovery flask and pour the contents into the centrifuge bottles using a funnel and screen to prevent the boiling beads from entering the bottles. Fill the bottles so that their masses are equal. Wash any remaining residue from the recovery flask into the centrifuge bottles. Increase the oil bath temperature to 174 ± 2.5°C. Centrifuge the bottles at 3600 r/min for 25 minutes.

12.4.3– Empty the centrifuge bottles back into the recovery flask ~~Decant the asphalt binder solvent solution into the recovery flask~~ and add six 3-mm diameter glass boiling beads. Re-a~~A~~ttach the flask to the rotary evaporator. Disconnect the transfer tube from the rotary evaporator and replace it with the gas purge tube. Disconnect the filtrate transfer line from the external rotary evaporator neck fitting and replace it with the nitrogen gas line. Apply 93.3 ± 0.7 kPa (700 mm Hg) vacuum. Lower the flask approximately 38 mm into the oil bath.

12.4.4 Distill the solvent.

12.4.5 When the condensation rate falls below 1 drop every 30 seconds, introduce nitrogen gas at a rate of 1000 mL/minute. Maintain the gas flow, vacuum and bath temperature for 30 ± 1 minutes to reduce the residual solvent concentration to near zero. Complete removal of residual solvent is very important for obtaining accurate asphalt properties.

12.4.6 Shut down the oil bath, flask rotation, vacuum, gas flow, and cooling water. Remove the evaporating flask. If the asphalt binder content is to be determined, determine and record the mass of the recovered asphalt binder to the nearest 0.1 g. Pour the asphalt into a sample tin using a screen to prevent the boiling beads- from entering the tin.

~~13. Calculations (Optional)~~

~~13.1 Calculate the percent asphalt binder in the HMA using the following formula:~~

~~a = [w3 /(w1 - w2)](100)~~

~~where:~~

~~w2 = (w1)(wpercent/100)~~

~~and where:~~

~~a = percent asphalt in the test specimen~~
~~w1 = mass of test specimen in grams~~
~~w2 = mass of water in test specimen in grams~~
~~wpercent = mass percent of water~~
~~w3 = mass of asphalt in test specimen in grams~~

13. Determination of Asphalt Binder Content (Optional)

13.1 When a determination of asphalt binder content is desired, use the following procedure:

Before section 12.2.1:

- determine mass of mixture sample
- determine mass of cartridge filter
- determine mass of centrifuge bottles

After section 12.4.3:

- dry centrifuge bottles, in-line filter and opened

vessel (including inserts) to constant mass
- determine mass of fine material in centrifuge bottles (dry - original)
- determine mass of fine material in filter (dry - original)
- determine mass of all aggregate material in vessel (scrape/brush all screens, etc.)

Asphalt content % =

$$\frac{\text{Original sample} - (\text{Recovered aggr} + \Delta\text{Bottles} + \Delta\text{filter})}{\text{Original sample}}$$

14. Report

14.1 Report the source of the test sample.

14.2 Report the following, if the asphalt binder content is to be determined:

14.2.1 the mass of test specimen to the nearest gram,

14.2.2 the mass percent of water in the companion test specimen to the nearest 0.01 percent,

14.2.3 the mass of asphalt binder in the test specimen to the nearest gram,

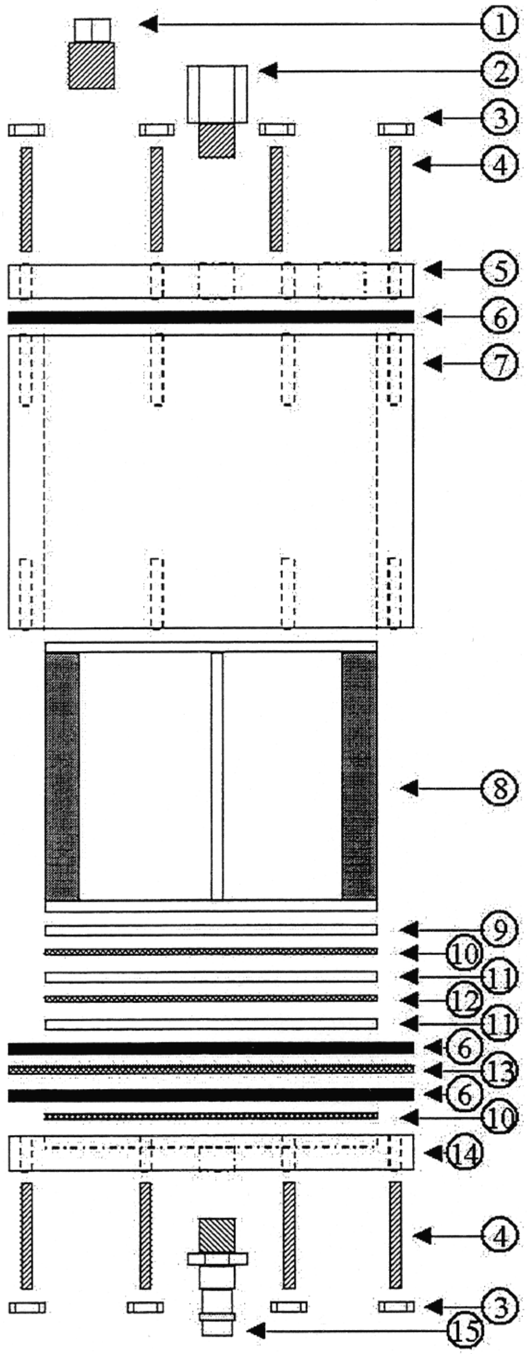
14.2.4 the percent asphalt binder in the test sample to the nearest 0.01 percent,

15. Precision and Bias

15.1 Precision - The research required to develop precision values has not been conducted.

15.2 Bias - The research required to establish the bias of this method has not been conducted.

16. Key Words - extraction, recovery, asphalt binder, rotary evaporator



1- 1- ISO 12RT (3/4 in. NPT) plug

2- ISO 8RT (1/2 in. NPT) fitting with I.D. hole for motor shaft

3- 12 M5 x 0.5 nuts

4- 12 M5 x 0.5 x 50 mm studs

5- extraction vessel top

6- 3 Viton gaskets 3 mm thick, 16 mm width with holes to fit over studs

7- extraction vessel housing

8- aluminum baffle

9- aluminum ring 3 mm thick 148 mm O. D., 10 mm width

10- stainless steel #10 screen

11- metal spacers

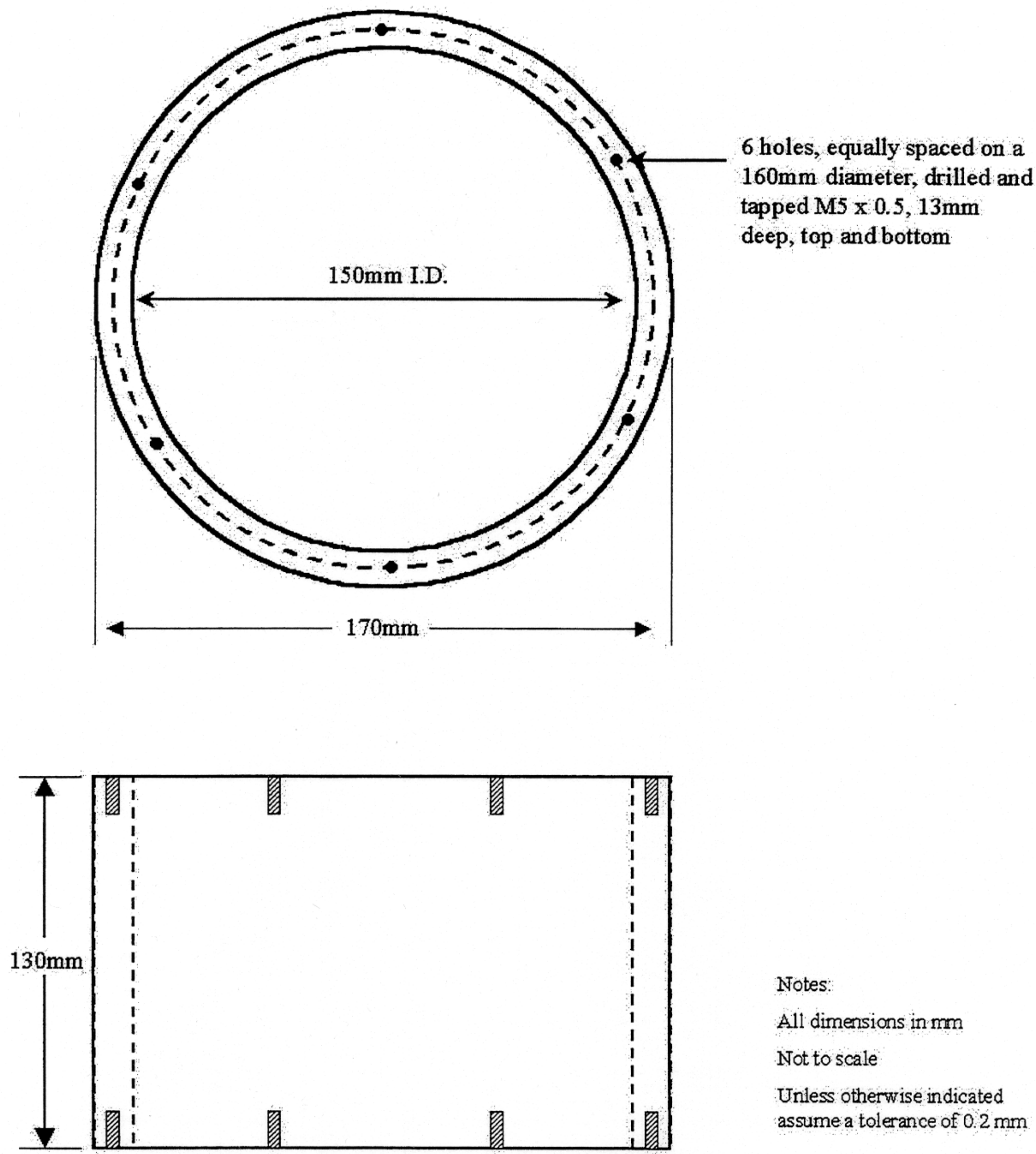
12- # 50 screen

13- # 200 screen

14- extraction vessel bottom

15- ISO 4RT (1/4 in. NPT) quick connect fitting

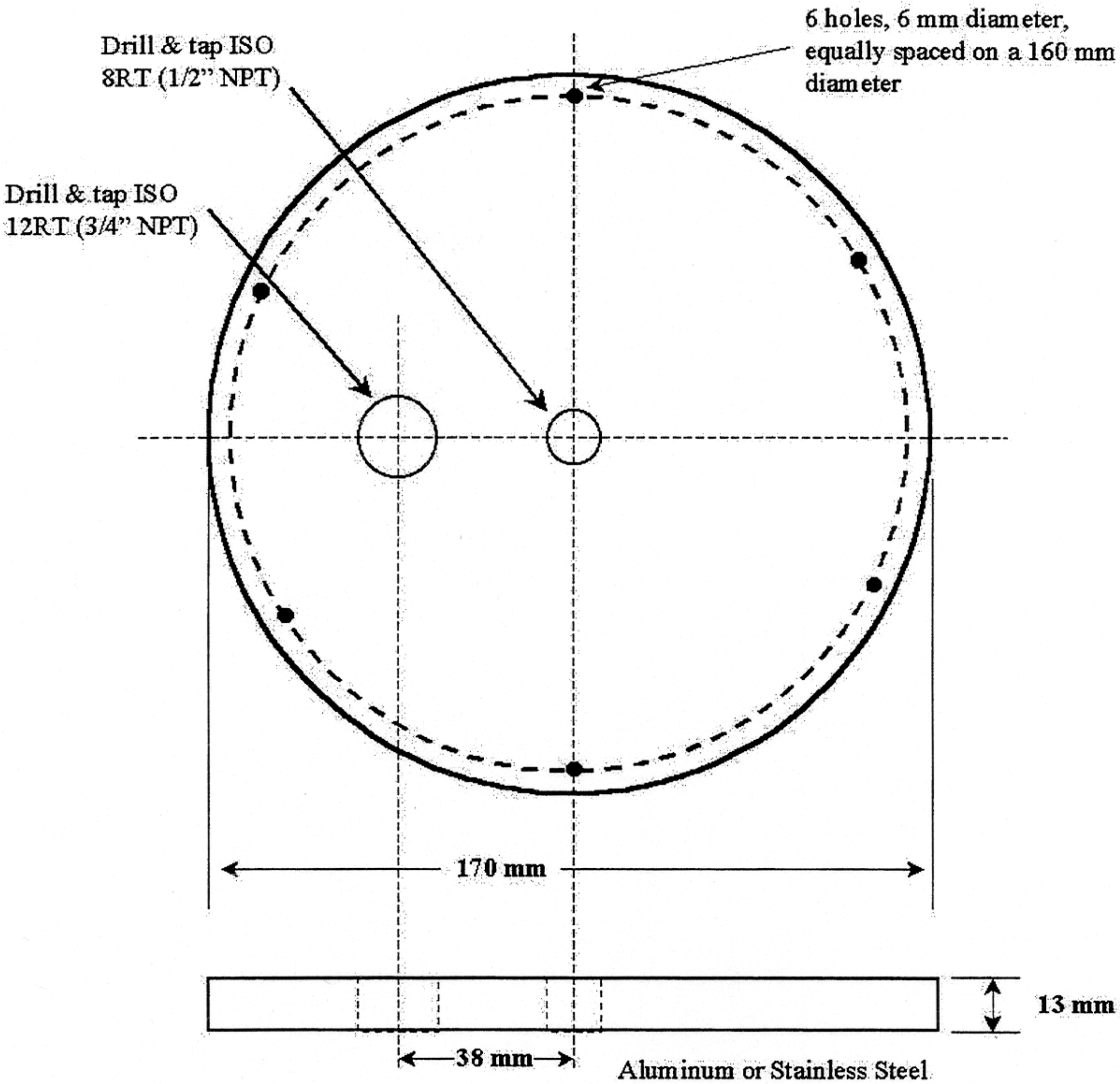
Figure 1- Extraction Vessel



Schedule 80 Aluminum or Schedule 80 Stainless Steel, Grade 304

Figure 2- Extraction Vessel Housing

F-A-33



Notes:

All dimensions in mm

Not to scale

Unless otherwise indicated
assume a tolerance of 0.2 mm

Figure 3- Extraction Vessel Top Plate

F-A-34

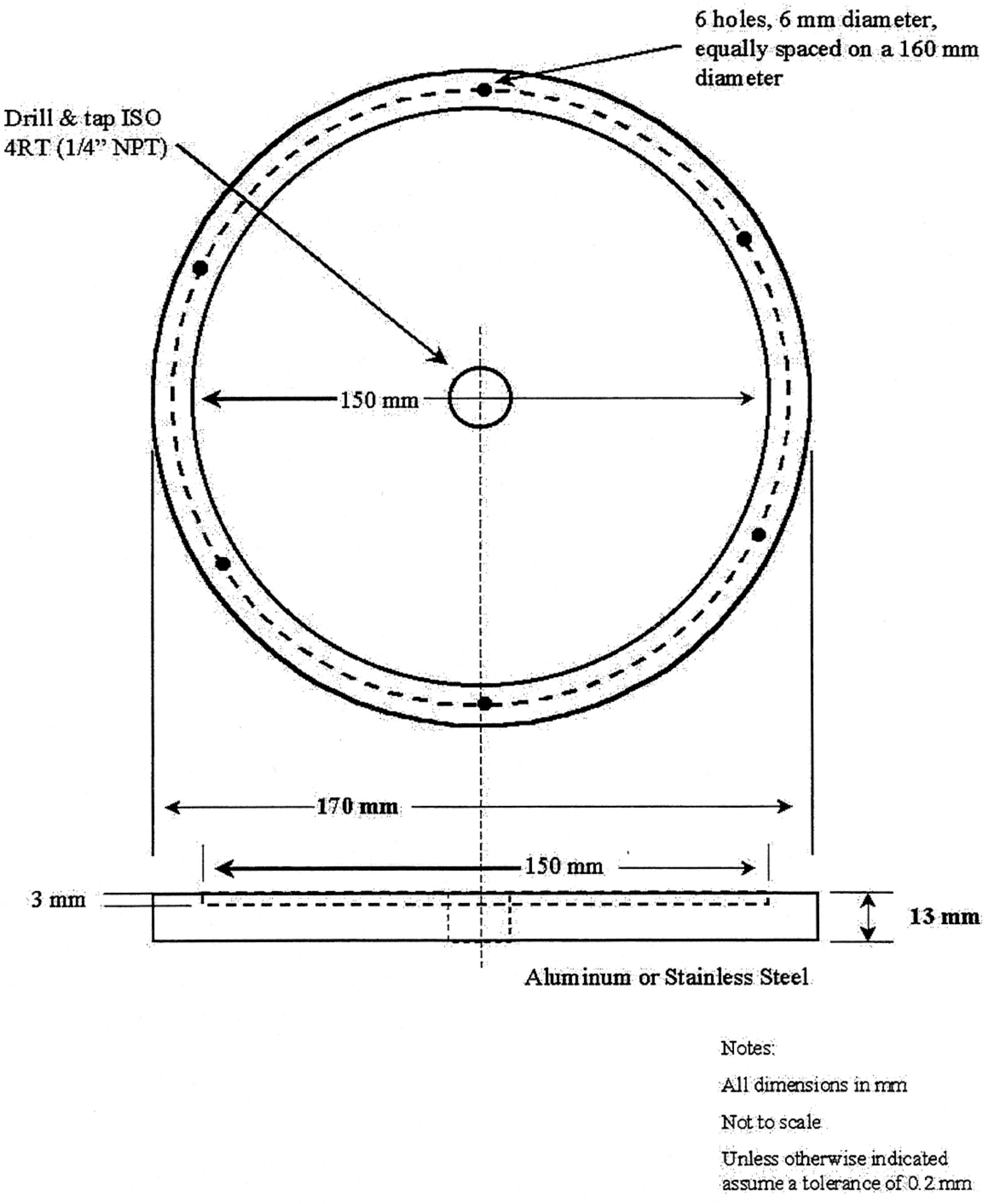


Figure 4- Extraction Vessel Bottom Plate

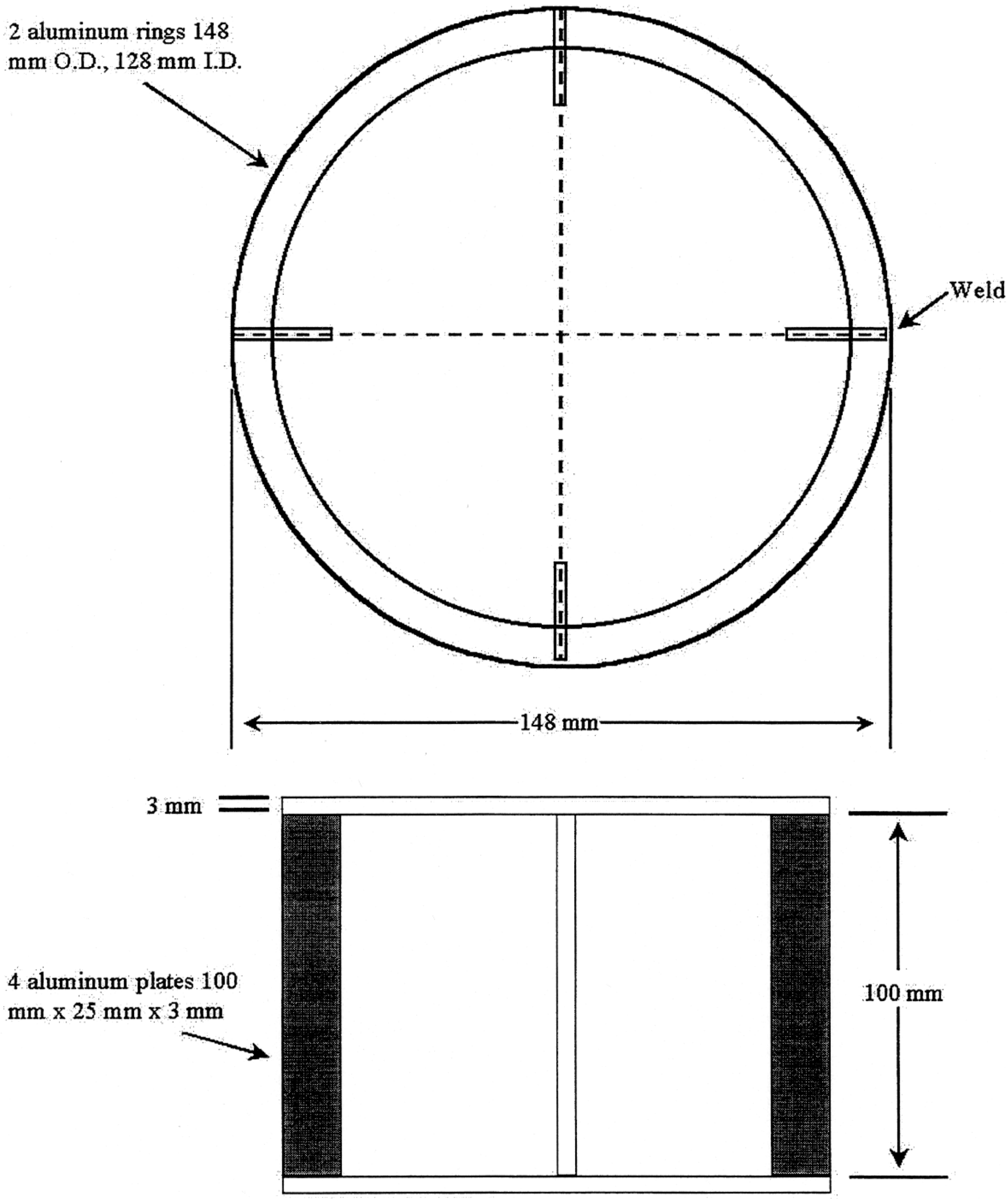


Figure 5- Extraction Vessel Baffle

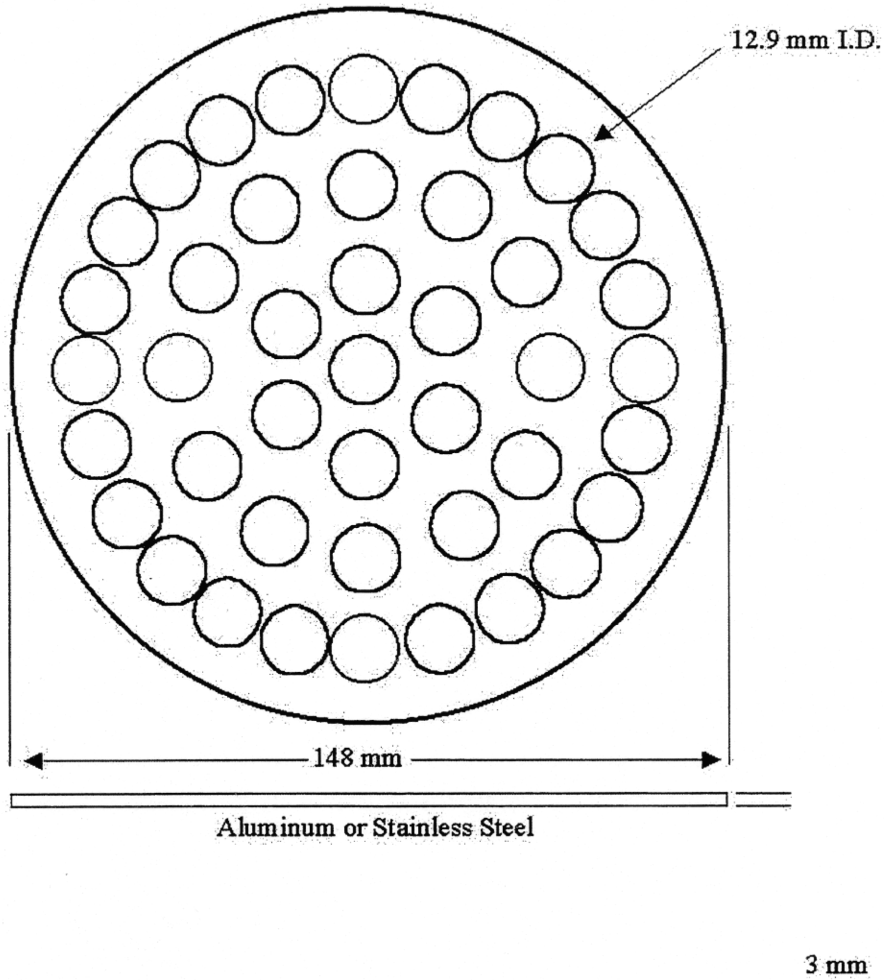


Figure 6- Extraction Vessel Spacer

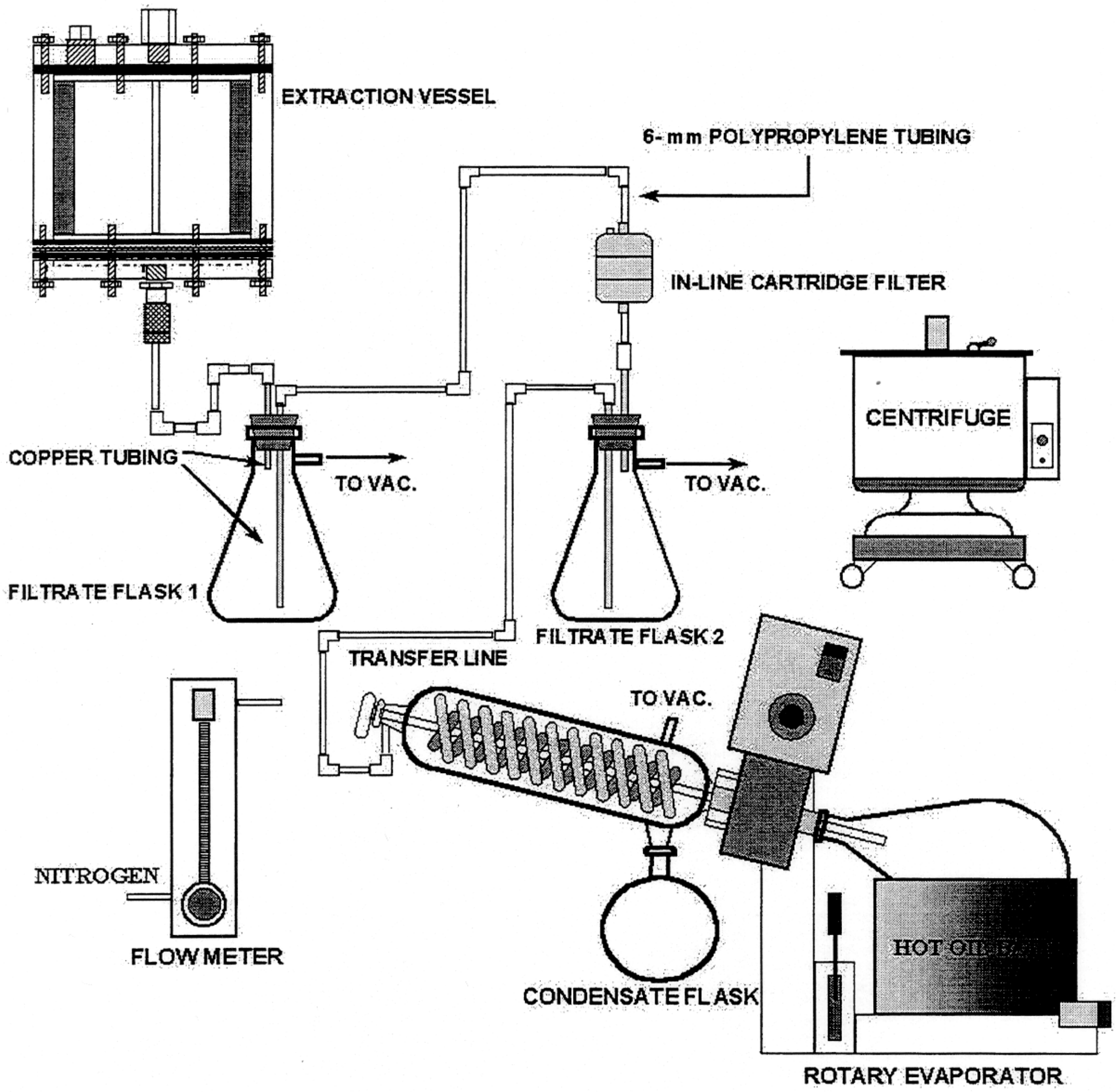
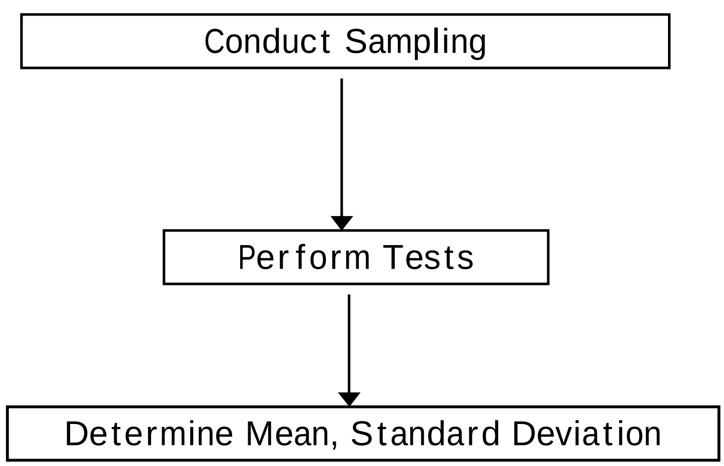


Figure 7- Extraction and Recovery Apparatus

APPENDIX F: APPENDIX B, Suggested Training Material Additions

Superpave Mixtures
with RAP



Evaluation of RAP

- Asphalt Content
- Aggregate Gradation
- Aggregate Properties
  - Consensus properties
- Binder Properties
  - RAP binder stiffness influences how much RAP can be used with minimal testing

RAP Aggregate Evaluation

- Extract and test
  - Gradation
  - Coarse aggregate angularity
  - Fine aggregate angularity
  - Flat and elongated particles
- Include in evaluation of consensus properties of trial blends
  - Evaluate sand equivalent on virgin aggregates only

RAP Binder Evaluation

- If using high percentages of RAP - see binder grade selection table
- Extract and recover binder according to AASHTO TP2 (revised)
- Determine high, intermediate and low critical temperatures for recovered RAP binder

Possible Binder Grade Selection Table

	RAP Percentage Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	**PG xx-22 or lower**	**PG xx-16**	**PG xx-10 or higher**
No change	<20%	<15%	<10%
One grade softer than normal (i.e., PG 58-28 instead of PG 64-22)	20 – 30%	15 – 25%	10 – 15%
Follow recommendations from blending charts	>30%	>25%	>15%

Steps in Mix Design (Superpave)

Gradation, Asphalt Content and Low Temperature Grade of Extracted Binder from RAP

Gradation of New Aggregate

Determine Combined Gradation in Recycled Mix

Steps in Mix Design (Superpave) (continued)

Determine Approximate Asphalt Demand of Combined Aggregate

Determine Virgin Binder Grade

Estimate initial trial binder content (Reduce added binder due to amount of RAP binder present)

Steps in Mix Design (Superpave) (continued)

Compact Trial Mixes with Superpave Gyratory Compactor

↓

Evaluate Mixtures and Select Job Mix Formula

Selection of PG Grade for New Binder

As shown on Table

- Tier 1, no change in binder grade.
- Tier 2, drop high and low grades by 6º.
- Tier 3, use blending charts.
- Tiers determined by low temperature stiffness of the RAP binder (may be estimated based on local experience)

Constructing a Blending Chart

- Use critical temperatures
- Determine Appropriate Grade of New Binder (Method A), or
- Determine Maximum and Minimum Amounts of RAP (Method B)

Data Needed for Blending Chart

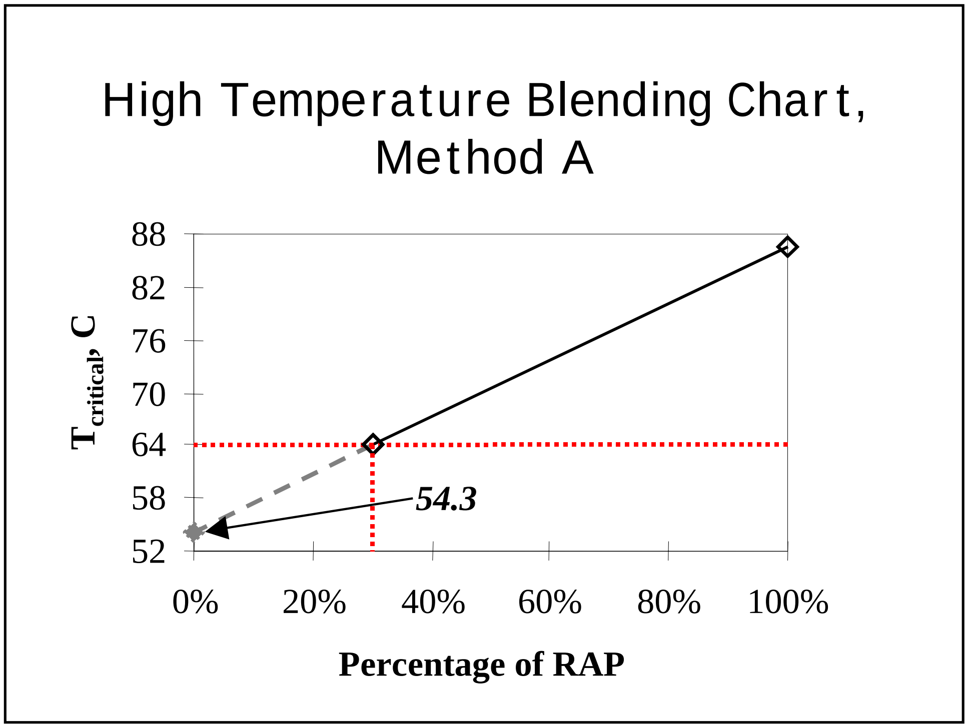
- Target PG Grade
- Critical high, intermediate and low temperatures of recovered RAP binder
- And either
  - Critical high, intermediate and low temperatures of new (virgin) binder, or
  - Desired RAP content

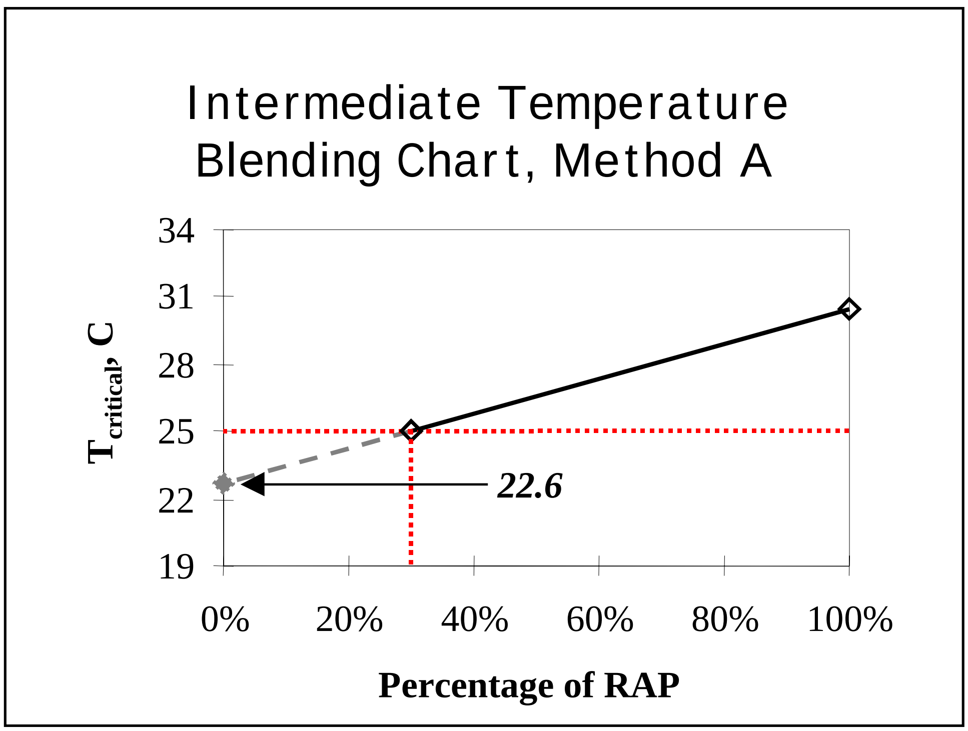
Example of Method A - Blending at Known RAP Content

- Desired Final Binder Grade = PG64-22 or better
- Desired RAP Content = 30%
- Recovered RAP Properties Measured

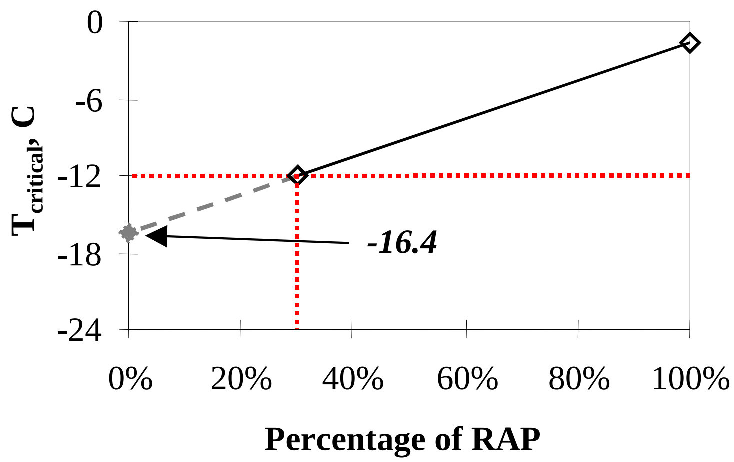
Critical Temperatures of Recovered RAP Binder

Property	Critical Temperature, C	
DSR $G^*/\sin\delta$	High	**86.6**
DSR $G^*/\sin\delta$	High	88.7
DSR $G^*\sin\delta$	Intermed.	**30.5**
BBR S	Low	-4.5
BBR m-value	Low	**-1.7**
PG	Actual	PG 86-11
	MP1	PG 82-10


High Temperature Blending Chart, Method A
88
82
76
70
64
58
52
$T_{critical}$, C
54.3
0%
20%
40%
60%
80%
100%
Percentage of RAP


Intermediate Temperature Blending Chart, Method A
34
31
28
25
22
19
$T_{critical}$, C
22.6
0%
20%
40%
60%
80%
100%
Percentage of RAP

Low Temperature Blending Chart, Method A



Estimated Critical Temperatures Needed of Virgin Binder

Property	Critical Temperature, C	
DSR G*/sinδ	High	**54.3**
DSR G*/sinδ	High	53.4
DSR G*sinδ	Intermed.	**22.6**
BBR S	Low	-15.2
BBR m-value	Low	**-16.4**
PG	Actual	PG 54-26
	MP1	PG 58-28

Use PG58-28 for the virgin binder

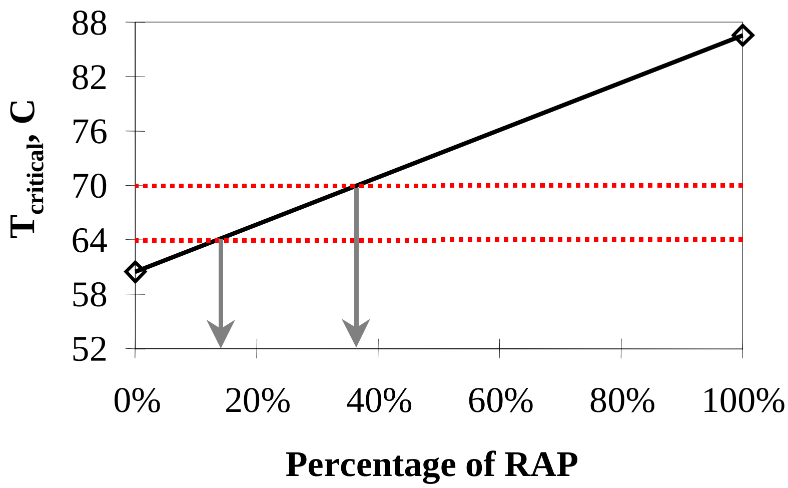
Example of Method B - Blending with Known Virgin Binder

- Desired Final Binder Grade = PG64-22 or better
- Virgin binder grade is PG58-28
- Recovered RAP is a PG82-10
- Critical temperatures of virgin and RAP binders are determined.

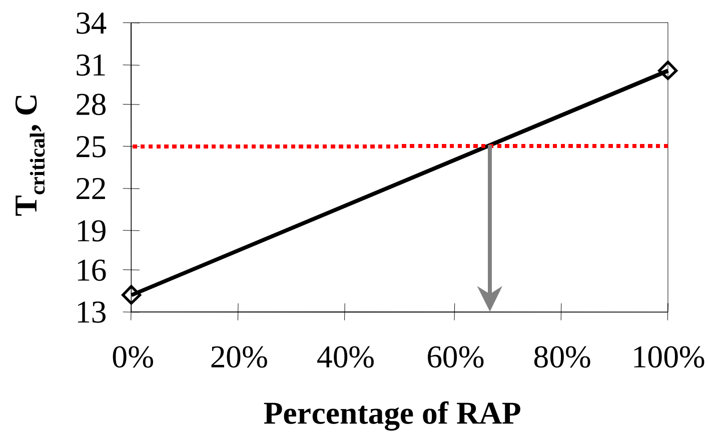
Virgin and RAP Binder Critical Temperatures

	Critical Temperature, C		
Property	Temp. Range	Virgin Binder	RAP Binder
DSR G*/sin δ	High	**60.5**	**86.6**
DSR G*/sin δ	High	61.0	88.7
DSR G*sin δ	Intermediate	**14.2**	**30.5**
BBR S	Low	-22.2	-4.5
BBR m-value	Low	**-19.0**	**-1.7**
PG	Actual	PG 60-29	PG 86-11
	MP1	PG 58-28	PG 82-10

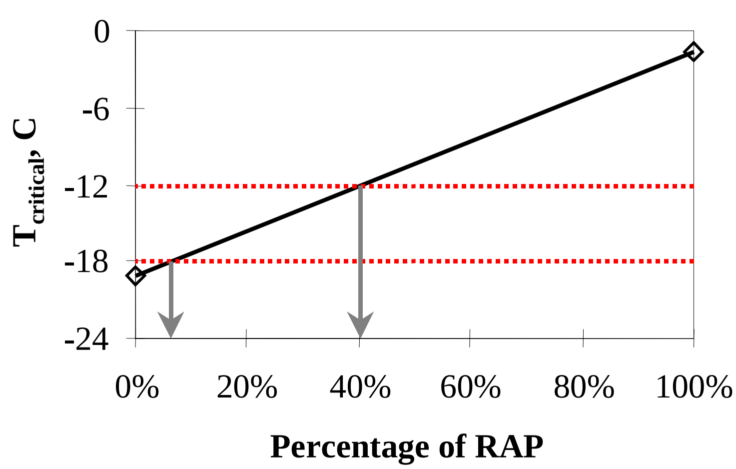
High Temperature Blending Chart, Method B



Intermediate Temperature Blending Chart, Method B



Low Temperature Blending Chart, Method B



Estimated RAP Content to Achieve Final Blended Grade

		Percentage of RAP to Achieve:	
Property	Temperature	PG 64-22	PG 70-28
DSR G*/sinδ	High	**13.4%**	**36.4%**
DSR G*/sinδ	High	10.8%	32.5%
DSR G*sinδ	Intermediate	**66.3%**	**- - -**
BBR S	Low	57.6%	23.7%
BBR m-value	Low	**40.5%**	**5.8%**

RAP Content

- To achieve PG64-22, use between 14 and 36% RAP.

Summary

- Include RAP aggregate in gradation and determination of consensus properties of trial and final blends.
- Evaluate RAP binder properties if RAP is very hard or high percentages are used.
- Adjust virgin binder grade by decreasing grade or constructing blending charts, depending on RAP stiffness and content.

APPENDIX G
PROPOSED PROCEDURE FOR DETERMINING THE ASPHALT BINDER GRADE RECOVERED FROM HMA

Although not a direct product of the research under NCHRP 9-12, the panel asked the research team to consider a possible extension of this work to suggest a procedure for verifying the grade of an asphalt binder in a sample of HMA. The following produce is, then, a suggestion based on previous research under SHRP, some of the work under NCHRP 9-12, and experience with HMA. This procedure is not supported by any data generated during NCHRP 9-12.

Proposed Procedure for Determining the Asphalt Binder Grade Recovered from HMA

R. Michael Anderson, Asphalt Institute

This procedure outlines the steps necessary to determine the performance grade of an asphalt binder recovered from a sample of hot mix asphalt (HMA) containing RAP. This procedure may be used to determine if the recovered binder grade matches design expectations. To account for testing variability and validate the binder grade, it is recommended that two recoveries and associated binder testing be performed on each sample.

1. Sample the HMA in accordance with appropriate sampling procedures. Obtain a sample size of approximately 8,000 grams.

2. Discharge the sample onto a splitting board and split into quarters.

3. If performing centrifuge extraction (ASTM D2172) followed by Rotavapor recovery (ASTM D5404), select opposite quarters for testing.

4. If performing the modified SHRP extraction-recovery procedure (AASHTO TP2), select opposite quarters and combine. Quarter the combined sample, and select opposite quarters for testing.

> Note: Research conducted during SHRP and validated during the NCHRP 9-12 study indicated that sample sizes substantially larger than 1000 grams may alter the recovered asphalt binder properties. Therefore, a sample size of 900 – 1100 grams is recommended when conducting testing using AASHTO TP2.

5. Perform the selected extraction-recovery procedure and recover the asphalt binder from one of the sample quarters.

6. Perform testing to grade the asphalt binder in accordance with AASHTO MP1 with the following exceptions: (a) rotational viscosity, flash point, and original DSR testing is not required; and (b) rolling thin film oven (RTFO) aging is not required – the recovered asphalt binder sample should be treated as if it already had been subjected to RTFO-aging.

> Note: RTFO aging is intended to simulate the oxidation and volatilization of an asphalt binder during HMA production and construction. Some asphalt technologists also consider that the RTFO simulates 1-2 years of in-place aging. Some asphalt technologists also theorize that the aging process that occurs in a drum-mix plant is different than the process in a batch plant. As a result, the RTFO procedure may not adequately simulate the actual post-production, recovered stiffness of an asphalt binder.
>
> It is recommended that agencies wishing to verify the recovered asphalt binder grade of a mixture containing RAP first experiment with the determination of the asphalt binder grade of a conventional (non-RAP) mixture to determine the expected change in stiffness caused during the mixture production.
>
> For example, an asphalt binder sample obtained from the Contractor's tanks indicates an original stiffness of 1.22 kPa and an RTFO stiffness of 2.44 kPa at 64ºC. After recovery from a mixture sample, the asphalt binder stiffness at 64ºC (no RTFO aging) was determined to be 2.10 kPa (86% of the RTFO data). Based on this information, the agency may decide to adjust the specification limits for recovered asphalt binder from a minimum of 2.20 kPa to a minimum of 1.90 kPa (86% of the specification limit).

7. PAV aging should be performed prior to performing intermediate and/or low temperature binder tests.

8. To validate the recovery procedure and test results, it is recommended (although not required) to repeat Steps 5-7.

9. Report the results from the two individual tests in addition to the average test values.