



FINAL REPORT FOR RMRC PROJECT 66

Project Title: Design System for HMA Containing a High Percentage of RAS Material

Principal Investigator: Hussain U. Bahia - UW - Madison

Other Investigators: Daniel Swiertz – UW - Madison

Affiliation: Dept. of Civil & Environmental Engineering, University of Wisconsin Madison

Start Date: 1 January 2009

End Date: 31 December 2011

Project Objective

The primary objective of this research is to develop and validate a simple design system for hot mix asphalt (HMA) containing a high percentage of reclaimed asphalt shingles (RAS). More specifically:

1. Develop a test method to quantify the contribution of RAS binder to the HMA blended binder properties without the use of chemical solvents to extract the asphalt binder from the RAS.
2. Determine the effect of combining RAS and reclaimed asphalt pavement (RAP) on blended binder properties.
3. Create an analysis tool, or spreadsheet, that will allow users to estimate the effect of varying levels of RAS binder on the blended binder.

CONTENTS

LIST OF TABLES	III
LIST OF FIGURES	III
1. INTRODUCTION	1
1.1 PURPOSE AND SIGNIFICANCE OF RESEARCH	1
1.2 RESEARCH OBJECTIVES	2
1.3 REPORT STRUCTURE.....	3
2. LITERATURE REVIEW	3
2.1 ASPHALT BINDER AGING CHARACTERISTICS.....	3
2.2 STATE-OF-PRACTICE IN HIGH RAS CONTENT MIXTURE DESIGN.....	6
2.2.1 RAS Processing and Re-Use	6
2.2.2 Binder Extraction and Blending Charts.....	7
2.2.3 Non-Solvent Based Methods	11
2.3 PROPOSED RAS BINDER ANALYSIS METHOD	13
3. MATERIALS AND METHODS.....	15
3.1 RAS/RAP BINDER ANALYSIS METHOD	15
3.1.1 Materials Preparation.....	15
3.1.2 Analysis Procedure and Output.....	18
Continuous Grade Analysis.....	18
Binder Workability (Viscosity) Analysis.....	21
3.2 VERIFICATION OF THE PROCEDURE.....	22
3.2.1 Design of Verification Experiment	23
3.2.2 Verification Results.....	25
3.3 RAS AND RAP SOURCE DESCRIPTION.....	26
4. RESULTS AND ANALYSIS.....	26
4.1 EVALUATION OF THE IGNITION OVEN FOR USE IN OBTAINING RAS AGGREGATES.....	26
4.2 EFFECT OF RAS BINDER ON LOW TEMPERATURE BLENDED BINDER PROPERTIES.....	28
4.3 EFFECT OF RAS BINDER ON INTERMEDIATE AND HIGH TEMPERATURE BLENDED BINDER PROPERTIES	29
4.4 EFFECT OF RAS BINDER ON BLENDED BINDER WORKABILITY	30
4.5 EFFECT OF BLENDING RAP AND RAS	31
5. SUMMARY OF FINDINGS AND RECOMMENDATIONS	32
6. REFERENCES	33

APPENDIX A: MORTAR MIX DESIGN EQUATIONS	36
--	-----------

APPENDIX B: TESTING METHODS AND CONDITIONS	38
---	-----------

List of Tables

Table 1. Typical RAS Composition (Adapted from Krivit, 2007).....	7
Table 2. Required Test Specimens for Characterization Procedure.....	17
Table 3. Mortar Procedure Verification Results	25
Table 4. RAS Source Information	26
Table 5. Effect of Ignition Oven on RAS Gradation.....	27
Table 6. Effect of Ignition Oven on Low Temperature Analysis Results	28
Table 7. RAS Grade Change Rate Sensitivity: Low Temperature.....	29
Table 8. RAS Grade Change Rate Sensitivity: Intermediate and High Temperature	30
Table 9. Effect of RAS and RAP on the Mixing and Compaction Temperature Change Profile	30

List of Figures

Figure 1. Time-dependent aging behavior of asphalt binder; notice the drastic decrease in the binder viscosity index over time as a result of a reduced oxidation rate. Figure from Read & Whiteoak, 2003. ...	5
Figure 2. Asphalt binder rheological response to aging. Notice that the master curves are distorted and translated as a result of aging.	6
Figure 3. Blending at a known RAP content and unknown virgin binder grade (Zofka et al., 2004).	9
Figure 4. Blending at a known virgin binder grade (Zofka et al., 2004).	10
Figure 5. Typical RAS and RAP materials used in the mortar preparation.	16
Figure 6. Mortar preparation procedure.	17
Figure 7. Low temperature continuous grading of asphalt binder.	18
Figure 8. Determination of PAV-aged fresh binder stiffness shift from mortar testing.	20
Figure 9. Continuous grade change profile output.	21
Figure 10. Mixing and compaction temperature change profile.	22
Figure 11. Artificial ‘RAP’ Preparation.....	23
Figure 12. Typical artificial ‘RAP’ material	24
Figure 13. Effect of RAP + RAS system on low temperature continuous grade.....	32

1. Introduction

1.1 Purpose and Significance of Research

Demand for asphalt binders for use in paving applications is expected to increase steadily as a result of more federal and state spending dollars being recently allocated to road construction. Forecasted demand for paving asphalt worldwide is expected to rise 2.1% annually through 2013 with the roofing sector asphalt demand growing even faster. The annual global market for asphalt products is approximately 97 million metric tons (Fredonia Group, 2010). As a bi-product of refining petroleum and due to the manufacturing and construction costs associated with building new asphalt pavements, costs incurred by contractors during construction are also steadily rising. To combat these rising costs, and in an effort to conserve resources while still maintaining pavement performance, the use of reclaimed asphalt material as a major component of new Hot Mix Asphalt (HMA) has gained widespread popularity.

The use of Reclaimed Asphalt Shingles (RAS) and Reclaimed Asphalt Pavement (RAP) have been found to be both environmentally sound and economical for use in pavement mixtures, and as a result reclaimed asphalt has become the most recycled material in the United States, with as much as 80% of the total asphalt removed annually being reused in some form according to the FHWA (AASHTO, 2011). It is estimated that approximately 11 million tons of reclaimed asphalt shingles are available annually, either from manufacturers' scrap or construction waste (EPA, 2010). RAS and RAP usage can help offset the rising asphalt construction costs associated with binder and mix design prices. Environmentally, the use of recycled (reclaimed) material reduces construction waste and conserves natural resources.

Most importantly, mixes that properly account for reclaimed asphalt materials in the mix design demonstrate equivalent performance characteristics compared to traditional hot mixes (McDaniel, 2000). Despite several findings that confirm this statement, RAS usage among state agencies and contractors remains relatively low. Fewer than 20 states accept the usage of RAS in new pavement layers, with fewer still drafting standard specifications. States that do allow RAS in pavement layers generally do so in limited amounts and in some instances allow RAS to be used in binder courses only. Several states limit the maximum percentage of RAS by weight of the mixture to 5 percent, a number reflecting a number of studies that indicated mixes containing up to 5 percent RAS by weight performed equivalent to HMA without RAS material (Shingle Recycling.org, 2010; Krivit, 2007). The current Wisconsin Department of Transportation specification limits the *binder replacement* percentage by RAS material to 15 percent in surface courses and 20 percent in binder courses.

The primary concern with utilizing higher percentages of RAS materials in HMA is the effect of the

blending, if any, that occurs between the aged binder within the RAS material and the virgin binder on the effective binder properties. RAS binder is heavily oxidized during production and, similar to the RAP binder, continues to age-harden over time, resulting in a stiffer binder with less ability to relax stress compared to the virgin binder. Scholz reported that binder extracted from mixes containing RAS materials demonstrated a higher performance grade compared with binder extracted from mixes without RAS, validating the concept that not only does the RAS binder blend with the virgin binder, the effect of the blending can be significant (Scholz, 2010). Mixtures that do not properly account for the blending that can occur between the RAS and virgin binder may then be prone to distresses caused by overly stiff binder (or similarly binder with reduced stress relaxation capabilities), such as thermal and fatigue cracking.

The possibility of poor pavement performance when using high percentages of RAS and RAP and the reluctance of state agencies to allow higher percentages of RAP and RAS is partially caused by the current design systems. The blending chart system developed by AASHTO for high percentage RAS and RAP mixes relies on binder extraction and determination of the physical reclaimed binder properties. The reclaimed binder properties are then combined with the virgin binder properties in a blending chart. The most commonly used method in retrieving RAS and RAP binder properties is with the use of chemical solvents to extract and recover the asphalt binder (AASHTO T164 / ASTM D 2172). However, it is well documented that these solvents may alter the recovered binder properties significantly. Many contractors are not properly equipped to perform extraction tests using these solvents due to more stringent environmental regulations and cost restrictions, leading many designers to be unwilling (or unable) to utilize higher percentages of RAS and RAP mixes (Copeland, 2009).

1.2 Research Objectives

This research was completed in coordination with the Asphalt Research Consortium (ARC) Work Element E2b and this report is intended to compliment the results of that research. The limited use of higher percentages of RAS (and RAP) material in new HMA mixes is a direct consequence of the lack of understanding that exists with regard to the effect of the blending that occurs between the virgin binder and the RAS and/or RAP binder. A binder characterization procedure that can estimate the extent and effect of this binder blending without the use of chemical solvents is needed to better understand how RAS and RAP influences blended binder properties. The specific objectives of this research are:

- Develop a test method to quantify the contribution of RAS binder to the HMA blended binder properties without the use of chemical solvents to extract the asphalt binder from the RAS.

- Determine the effect of combining RAS and reclaimed asphalt pavement (RAP) on blended binder properties.
- Create an analysis tool, or spreadsheet, that will allow users to estimate the effect of varying levels of RAS binder on the blended binder.

This research was completed in coordination with the Asphalt Research Consortium (ARC) Work Element E2b and this report is intended to compliment the results of that research. The research will continue under the ARC project which is expected to end in December 2013.

1.3 Report Structure

This report is divided into five sections including the introduction. Section two includes a literature review of the effects of binder aging on rheological properties and current high percentage RAS mix design methods. The proposed analysis procedure is also introduced. Section three provides a detailed explanation of the analysis procedure and the materials used in this study. Section four presents the most relevant results from this study. Finally, a summary of the research and conclusions is given in section five.

2. Literature Review

The literature review includes a summary of the effects of binder aging on the rheological response of blended binder. A summary of the current extraction and blending chart system is then presented. Several non-solvent based procedures that have been proposed to characterize RAP materials are reviewed, and may offer promise in characterizing RAS materials as well. Finally, the proposed binder characterization method is introduced.

2.1 Asphalt Binder Aging Characteristics

Asphalt binder is unique as a construction material in that its physical material properties change over time and between regions as a result ambient conditions and material aging. The magnitude of the change in rheological response of a particular asphalt binder will most likely differ from another asphalt binder from another source. That is to say, aging characteristics for asphalt are source specific (Bahia and Anderson, 1995). It can be assumed, then, that the properties of one recycled binder will be different from another; blending at an equal percentage with the same virgin binder will likely demonstrate different results, in terms of rheological response of the blended binder. To that end, is it important to understand the effects of binder aging in order to better comprehend the effects on binder performance that occur as a

result of the blending that occurs between RAS and RAP materials and virgin binders.

A more complete understanding of asphalt binder aging first requires a definition of aging in this context. Aging is identified as the time-dependent change in binder physical properties as a result of changes in chemical composition. Four aging mechanisms are generally agreed upon by which asphalt ages in service: volatilization, oxidation, steric hardening, and physical hardening (Bahia & Anderson, 1995; Read & Whiteoak, 2003). Steric and physical hardening, however, are not caused by compositional changes in the binder, but rather by structural (molecular rearrangement) changes (Read & Whiteoak, 2003). Steric and physical hardening are therefore reversible with the addition of heat or mechanical work. As such, only oxidation and volatilization, which are compositional changes and are irreversible, will be further considered as mechanisms of in service aging.

Binder Oxidation

Asphalt binder is an organic substance, and like many organic substances, it will react with atmospheric oxygen. Oxidation refers to the change in mechanical properties of the asphalt binder as a result of the reaction of atmospheric oxygen with certain molecular compounds within the binder. Although oxidation occurs at all pavement temperatures and all stages of the service life of asphalt, it is the primary mechanism associated with long term, in service aging of asphalt cement. Oxidation can also occur as a result of direct exposure to UV radiation, which may be significant in the case of RAS. In roofing applications, asphalt will react with UV light in a process called photo-oxidation, which causes a similar effect to the rheological properties of binder when compared to 'traditional' oxidation. When asphalt binder is exposed to oxygen, polar sites containing oxygen are formed, and the propensity for self assembly increases. As micelles of high molecular weight are formed, the viscosity of the binder increases. Oxidation also increases the number of polar hydroxyl, carbonyl and carboxylic groups in the pavement, making the pavement harder and stiffer. The oxidation rate of asphalt binder is known to decrease over time as the rate of association of these complex molecules is inhibited by the increased viscosity of the pavement, as shown in Figure 1 (Bahia & Anderson, 1995; Read & Whiteoak, 2003).

Binder Volatilization

Volatilization is the loss of smaller molecules within the asphalt binder as their boiling point is exceeded. Volatilization is generally associated with the high temperatures experienced during the binder application phase of construction, representative of the high slope region in Figure 1. Generally, emissions of volatiles begin at approximately 150 °C, with the amount of volatiles doubling with each 10 to 12 °C increase in temperature. Volatilization causes asphalt constituents (aromatics) to evaporate, creating stiffer and more viscous asphalt (Read & Whiteoak, 2003). Volatilization is always accompanied

by oxidation reactions, which also contribute to stiffening the pavement.

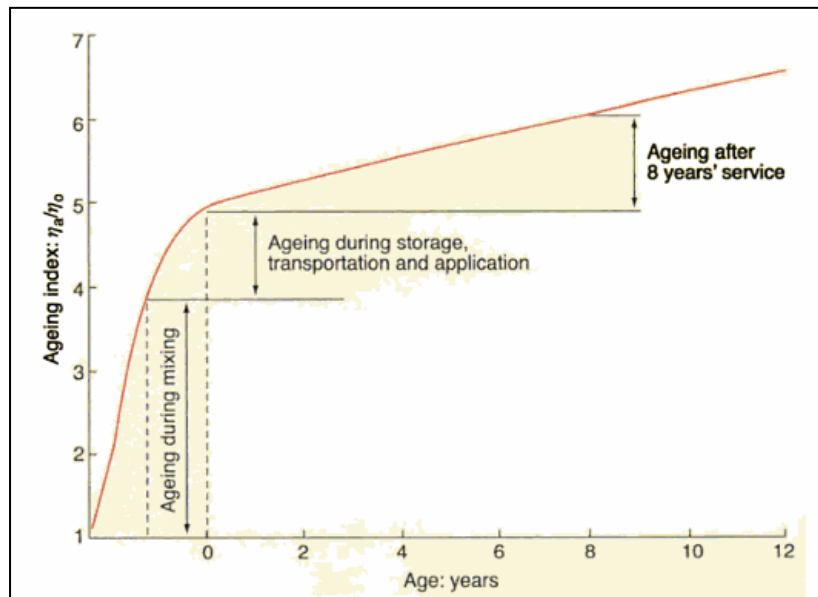


Figure 1. Time-dependent aging behavior of asphalt binder; notice the drastic decrease in the binder viscosity index over time as a result of a reduced oxidation rate. Figure from Read & Whiteoak, 2003.

Rheological Implications of Binder Aging

Volatilization and oxidative aging produces larger, more polar molecules, which in turn affect the rheological response of asphalt binder. Aging changes the time-temperature dependencies of asphalt binder, which is known to be viscoelastic. It is well documented that binder aging results in distortions of the material rheological master curves, implying a major change in rheological type as a result of chemical and micro-structural changes. Figure 2 demonstrates the rheological master curve distortion due to aging in laboratory. Figure 2 compares the complex modulus (G^*) and $\tan \delta$ values for asphalt binders aged for varying lengths of time and temperature (Bahia & Anderson, 1995; Bahia et al., 2009).

As a result of the trends shown in Figure 2, aging binder will cause an increase in the material complex modulus, and a decrease in the loss tangent. The complex modulus is proportional to asphalt stiffness; as a result of aging the asphalt layer will become less deformable, creating more stresses per unit strain. Performance-wise, this is not detrimental to rutting or other plastic deformation resistance, but is seen as detrimental for fatigue and thermal cracking at intermediate and low temperatures, respectively. Thermal cracking is further enhanced with the drop in loss tangent, which is proportional to the capacity of asphalt to relax stresses (m -value). The increase in complex modulus allows for more stresses to build up within the pavement during heating and cooling cycles, while the decrease in loss

tangent does not allow these stresses to dissipate, creating thermal cracks. However, the drop in loss tangent allows for a decrease in the ratio of energy stored to energy dissipated, hence the pavement becomes more elastic. This is beneficial for rutting resistance (Bahia & Anderson, 1995; Bahia et al., 2009).

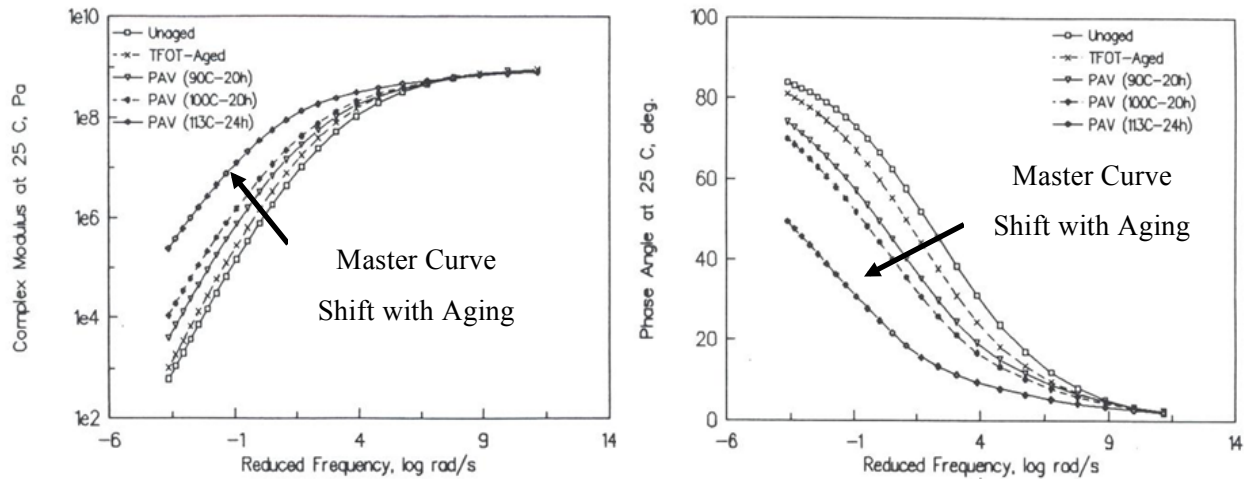


Figure 2. Asphalt binder rheological response to aging. Notice that the master curves are distorted and translated as a result of aging.

2.2 State-of-Practice in High RAS Content Mixture Design

2.2.1 RAS Processing and Re-Use

RAS is commonly referred to with the heading of manufacturers' or tear-off. Both manufacturers' and tear-off asphalt shingles are part of the same larger subset of recycled construction and demolition materials; they only differ in source, homogeneity, and possibly quality. Manufacturers' shingles are generated from the high quality industrial scrap from shingle manufacturing processes. Enough manufacturers' shingles can often be generated from one manufacturing plant to sustain an entire recycling operation, hence the homogeneity of the RAS material. Historically, shingle recycling efforts and specifications made by state governments focused on manufacturers' shingles due to their high quality and availability and the strict quality control specifications within the asphalt industry. In contrast, tear-off shingles, shingles obtained from demolition or re-roofing applications, may contain many sources and qualities of material. However, as a direct result of the cost savings associated with including RAS material in new hot mixes, and the already well developed manufacturers' shingles market, usage of tear off shingles has begun to grow in popularity and new state specifications for quality control and usage are already being investigated (Krivit, 2007).

Design considerations regarding RAS are difficult to specify because asphalt shingles are highly variable and may contain many different combinations of materials. In addition to heavily oxidized asphalt cement, asphalt shingles also contain hard mineral aggregates, fibrous organic felt or fiberglass threads, adhesives, and other fillers. Table 1 displays typical material composition for asphalt shingles. Each material may significantly alter pavement performance at high percentage, thus any design system must account for all material properties.

Table 1. Typical RAS Composition (Adapted from Krivit, 2007)

Material	Percentage by Weight
Coating Filler (Limestone or fly ash)	32 % to 42%
Granules (rocks and coal slag)	28% to 42%
Asphalt Cement	16% to 25%
Dust (limestone and silica sand)	3% to 6%
Roofing Mat (fiberglass, organic thread)	2% to 15%
Adhesive (asphalt based)	0.2% to 2%

Shingles are processed in a similar manner to RAP materials. Shingles are ground up and screened for deleterious materials. Typically materials are sorted using a half inch screen. Materials retained on the screen are not used in HMA, but rather used in applications for base course materials. Materials passing the half inch screen are sent to stockpiles for incorporation into HMA. RAS is incorporated into HMA in a similar fashion to RAP; the gradation of the material and total asphalt content are used to calculate the effective mixture gradation and binder replacement values, respectively.

2.2.2 Binder Extraction and Blending Charts

Chemical Extraction and Recovery Methods and Effects

Traditional approaches to determine the effect of the reclaimed asphalt material on the blended binder properties of the mixture rely on the physical determination of the reclaimed binder properties. To date, solvent extraction and recovery is the only method that physically separates the binder from aggregates in reclaimed materials for characterization. Of the many methods that utilize chemical solvents outlined in the AASHTO and ASTM standards, three primary extraction methods exist: centrifuge extraction, reflux extraction, and vacuum extraction. Most popular today are the centrifuge methods and reflux methods due primarily to simplicity of conducting the extraction. Each method utilizes one of several different solvents, each differing in ability to both dissolve the asphalt binder and ability of the dissolved asphalt to be recovered from the solvent. Examples of common solvents include trichloroethylene (TCE), toluene,

or methylene chloride. After the binder is extracted from the RAP or RAS, two methods exist to recover dissolved binder from the solvent: the Abson recovery method (ASTM D1856-95a (2003)/AASHTO T 170-00), and the rotary evaporator method (Kondrath, 2009).

Solvent extraction and recovery has long been criticized for altering the extracted binder properties, however. Binder hardening is an often-cited result of solvent extraction. Hardening is predominately associated with high temperature extraction, common in the reflux method, but may be unavoidable regardless of test method when using solvent extraction (Kondrath, 2009; Stroup-Gardiner & Nelson, 2000). SHRP research demonstrated that hardening appears to occur with all commonly used solvents, and is especially prominent when heavily chlorinated solvents are used, and is even present using low temperature extraction processes (Stroup-Gardiner & Nelson, 2000; Burr et al., 1991).

After the binder has been extracted from the reclaimed material, it must be recovered from the solvent solution for characterization. Research has indicated that even 0.5 percent residual solvent can cause a 50 percent decrease in viscosity (Peterson et al., 2000). Just as in the extraction process, excess heat can age the binder, causing greater stiffness. SHRP research has demonstrated that the physical properties of asphalt binders removed via the Abson recovery method varied greatly, as much as 42 percent for absolute viscosity. The rotary evaporator method, although less labor intensive, involves the use of high temperatures, resulting in binder aging (Kondrath, 2009; Stroup-Gardiner & Nelson, 2000; Peterson et al., 2000).

All of the above side effects associated with chemical solvent extraction and recovery are present in both RAP and RAS binder extraction, but the problems are more significant for RAS materials. RAS stockpiles may differ widely in composition regionally as well as within single sources due to different manufacturing processes in the case of scrap RAS. Extraneous materials within RAS sources make chemical extraction difficult. Experience has demonstrated that the extraction filters and the outlet for the extraction vessel clogged easily even after multiple chemical washings. In addition, the extraction produced a “straw-colored” effluent that resulted in a subjective completion time for the extraction process. The extraction process for the RAS was lengthy due to the above problems, and took roughly 2-3 days (Scholz, 2010).

Binder Blending Charts

For high percentage RAS and RAP design, reclaimed binder properties are to be determined after extraction and recovery, and these properties are used in blending charts to produce a mix with a designated PG grade. Blending charts are used today for high percentages of RAP, RAS or any combination of the two using the same general method, but will be demonstrated here for RAP alone. Blending charts can be used in two distinct scenarios: a virgin binder grade is selected and the appropriate

amount of RAP to be included in the mix is determined, or a percentage of RAP is designated, and the virgin binder grade is determined (McDaniel & Anderson, 2001).

To construct a blending chart using Superpave specifications, the desired final binder grade and physical properties of the recovered binder are needed along with either the physical properties of the virgin binder or percentage of RAP to be included in the mixture. To determine physical properties, recovered binder is tested in the DSR and BBR to determine the RAP binder PG grade. The virgin binder is also tested in the same manner. Two charts are then constructed, one for low temperature properties, and one for high and intermediate properties (McDaniel & Anderson, 2001). The two scenarios are outlined below in Figure 3 and Figure 4.

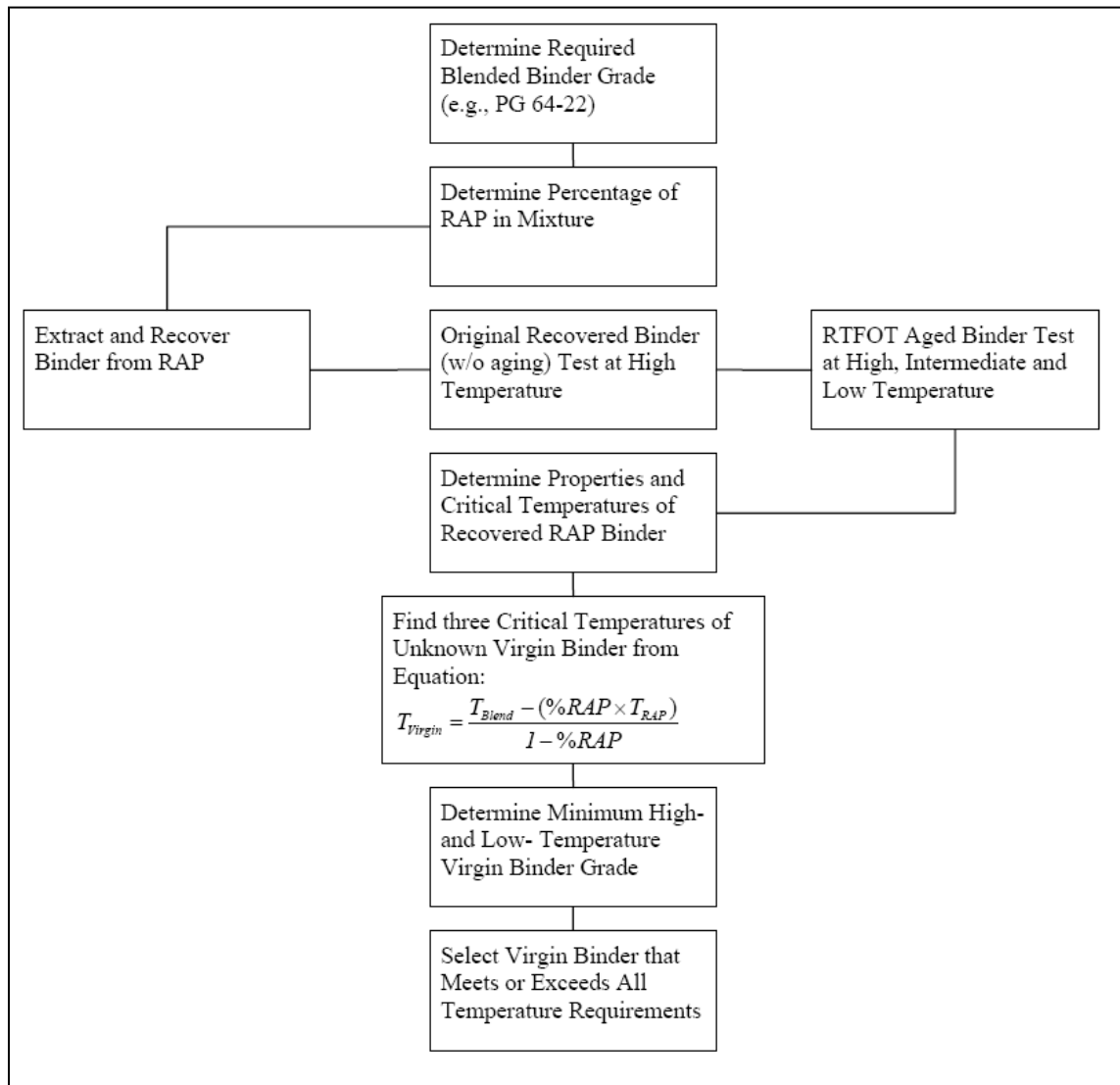


Figure 3. Blending at a known RAP content and unknown virgin binder grade (Zofka et al., 2004).

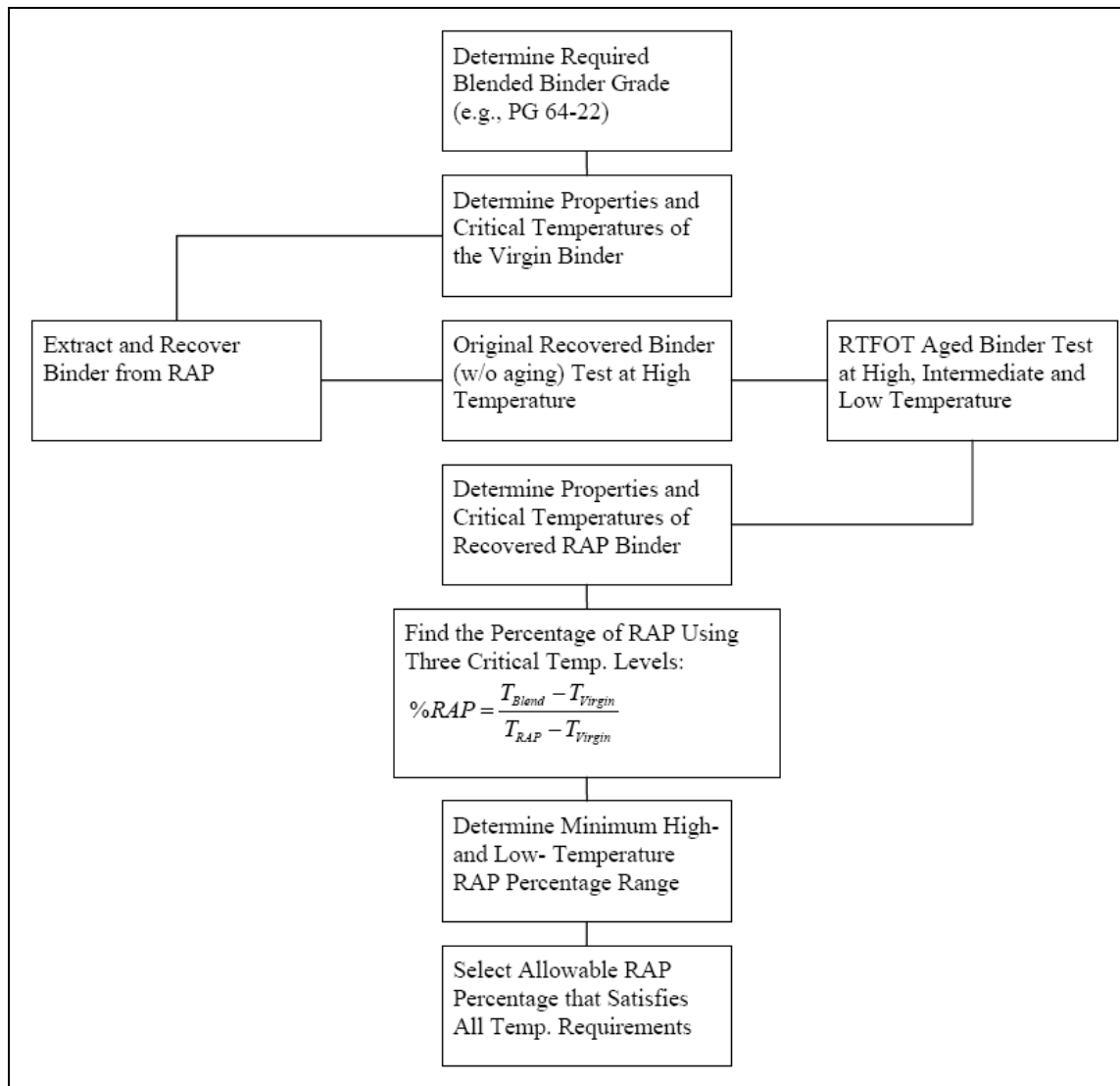


Figure 4. Blending at a known virgin binder grade (Zofka et al., 2004).

Blending charts have the obvious disadvantage of being a very time consuming method of classification in addition to their complexity. Superpave specification recommends using both original and rolling thin film oven (RTFO) blending charts at high temperature, however the original binder chart is often the only chart constructed due to time constraints. Further, blending charts are a quantity based design tool, and fail to capture actual blended binder properties. Also, the process of extraction and recovery along with constructing blending charts is very costly, as the time commitment and level of complexity is relatively high.

2.2.3 Non-Solvent Based Methods

Due to the many disadvantages to using the above mentioned systems for RAP and RAS characterization, analysis methods that circumvent the use of chemical extraction are desirable. Several methods have been developed to address this need. These methods are outline below.

Carter (2004)

The purpose of this study was to develop and validate indirect tension stress relaxation tests on compacted samples to determine the asphalt binder properties. Then, the effect of adding RAP to the mixes in terms of stress relaxation can be evaluated. To accomplish the objectives, the author performed stress relaxation tests on compacted specimens containing binder alone and on HMA mixes for comparison. To evaluate RAP mixes, gyratory compacted samples containing 0, 15, 25, 50 and 100 percent RAP were tested at 5 °C and 22 °C. The research indicated that the indirect tension stress relaxation test is a good indicator of binder properties, and testing at one intermediate temperature can be sufficient to evaluate the effect of RAP in HMA mixes.

Importantly, this study recognized the non-linearity between binder stiffness and percent RAP in a mix in high percentage design. Specifically, the author suggests a linear relationship between percentage of RAP and mix modulus only between zero and 50 percent RAP, with asymptotic behavior between 50 and 100 percent RAP. This is in contrast to the traditional blending chart assumption of linearity between RAP percent and modulus. The author recommends high percentage RAP mixes be used primarily in lower lifts during construction based on their seeming inability to relax with time.

Using this testing regime has limitations for high percentage RAP mixture design. The authors recommend the procedure as a quality control tool, as opposed to a design guide, as no model was proposed regarding the information presented and high percentage design. The testing requires fairly complex, time consuming procedures including preparation of gyratory specimens. The test temperatures fail to capture the entire pavement in service temperature range needed for accurate mix design. In rigor, low, intermediate and high temperature testing would be required for a full analysis.

Zofka et al. (2005)

The goal of this study was to determine whether thin beams cut from mixture specimens tested in the BBR could provide reasonable mixture stiffness values. Mixture specimens were tested in indirect tension to check the BBR stiffness accuracy. Then by back calculation using the Hirsch model, binder stiffness could be determined from mixture stiffness. To further validate this approach, extracted binder stiffness

was measured. The estimated stiffness could then be used in blending charts in lieu of binder stiffness obtained using solvents. In all, six mix designs with two different asphalt grades and varying asphalt contents were used in the project to simulate Minnesota Department of Transportation specifications. Although limited testing was conducted, “reasonable” values for stiffness were documented by the author, prompting further study.

Variability within and between individual mixes was evident in the research. Samples are cut from gyratory specimens in four steps, producing approximately seven rectangular beams. The beams, however, varied in thickness from about 6 mm to 9 mm. Further, the beams were manually sawn from gyratory specimens, and may have varied in thickness in individual specimens. Failure to accommodate the change in thickness can lead to error in estimating stiffness, as the BBR uses standard dimensioned beams unless otherwise specified in calculating stiffness.

Although a promising approach to RAP design, this method has the obvious disadvantage of time and labor constraint. Sample preparation involves creating a mix design for gyratory specimens, and cutting said specimens according to a four step procedure. Samples for this study were professionally cut, indicating complexity in the cutting process. The calculations were altered for variability in the beam dimensions, adding complexity in the back calculation step. Verification of this test used the indirect tension test, a complex, destructive test method.

Ma et al. (2009)

The proposed analysis method presented in this thesis is an advancement of the method developed in Ma et al. The author was involved with testing and development of the Ma et al. procedure. Ma et al. attempted to isolate RAP binder low temperature properties using beam theory and back calculation techniques derived from mortar testing in the BBR. The procedure was based on the hypotheses that if two mortar samples are prepared with identical gradation and total binder content, with one mortar sample containing a known percentage of RAP binder and the other with no RAP binder, any difference in properties between the mortar samples can be attributed to the RAP binder. By limiting the percentage of RAP binder in the mortar sample to a known amount, properties of the RAP binder-fresh binder blend can be estimated. From this blend, RAP binder properties alone can be estimated.

The procedure presented in Ma et al requires the BBR testing of one fresh binder aged in the PAV and two PAV aged mortar samples. From the testing results, the stiffness (or m-value) of the PAV aged fresh binder is directly measured, while the PAV aged fresh binder – RAP binder blend can be estimated using the relationship between mortar-binder testing results. If the RAP binder percentage is controlled to a certain percentage, and the relationship between fresh binder and mortar is known, the properties of the blended binder can be estimated. A relationship between blended binder properties and percent RAP

binder can then be created, allowing for an extrapolation to 100 percent RAP binder. This calculation technique allows the user to input any percentage of RAP binder, and find the correlating blended binder properties. For example, if it is desired to have a blended binder that passes a certain low temperature performance grade, input the limiting parameter values at that testing temperature and extract the percentage of RAP allowed.

Testing at two target low temperatures allows for the estimation of RAP binder properties at any low PG temperature, along with an estimation of RAP binder continuous grade. Users can then select any target PG temperature and determine the maximum allowable RAP binder replacement allowed to maintain the desired grade.

An extensive verification procedure was completed for the analysis procedure and was presented to the Asphalt Research Consortium (Asphalt Research Consortium – Quarterly Report, 2010). It was concluded that the analysis procedure fails to consistently estimate the true RAP binder properties, and especially RAP binder m-value. This trend was verified using two artificial RAP sources and two virgin binder grades, combined in three separate cases. One possible reason for the discrepancy between results was the extrapolation from the blended binder (generally containing 15 percent RAP binder) to 100 percent RAP binder, as any minor inconsistency in the blended binder would only be amplified when extrapolated. The other possible reason is the incomplete blending of the aged and fresh binder. The verification results pressed the need for a more refined analysis procedure, especially one that encompasses all temperature ranges in specification and has the ability to incorporate RAS.

At the time of this writing no studies have been found that attempt to isolate RAS binder properties for use in mixture design. It is suspected, however, that the above mentioned analysis procedures could be used similarly with RAS materials either in place of or alongside the RAP materials.

2.3 Proposed RAS Binder Analysis Method

Based on the findings in the literature and the current state-of-practice, there is a need for an unbiased, cost-effective, and simple procedure for characterizing the effect of RAS and RAP materials on blended binder properties. The procedure should eliminate the need for chemical extraction and recovery and produce results that are readily accessible in terms of commonly used binder properties (such as performance grade). All critical service temperatures should also be considered for completeness. This sub-section provides a summary of the proposed testing method, while a more detailed description of the test method will follow in Section 3.

The proposed complete characterization procedure includes two main parts: a binder continuous (true) grading analysis, and a binder workability (high temperature viscosity) analysis. Continuous

grading systems are analogous to the Superpave performance grading (PG) system except that instead of grade levels spanning a specified temperature range, unbroken temperature numbering is applied. For example, while the high temperature continuous grade of a binder could be measured as 61 °C, the corresponding Superpave PG would be 58 °C. The limiting parameter values remain the same (i.e. the low temperature stiffness is still limited to a maximum of 300 MPa etc). Using a continuous grade system, greater clarity is achieved in the characterization procedure, while the Superpave PG can be applied after analysis.

The workability (viscosity) analysis procedure is based on standard viscosity – temperature susceptibility (VTS) profiles for asphalt binder, as defined in ASTM D 2493 Standard Viscosity – Temperature Chart for Asphalts. The appropriate viscosity limits can then be applied to the VTS profiles and the mixing and compaction temperatures can be back-calculated (Asphalt Institute, 2001). The product of this analysis is the estimated change in mixing or compaction temperature from the fresh binder caused by the addition of RAS or RAP materials to the mix.

Both the continuous grading analysis and the binder workability analysis procedure require testing three samples at each critical temperature. These samples include one fresh binder and two mortar samples. The mortar samples are comprised of a single aggregate source (the RAS or RAP aggregate) the fresh binder. It is generally accepted that if the constituent properties (aggregate source and gradation, total binder content etc) of a mixture are kept constant between two mixes, the mechanical properties, such as stiffness will depend on the binder. Therefore, if the two mortar samples are prepared with identical gradation and identical total asphalt content, using the same constituents, but one mortar sample contains a percentage of reclaimed binder (replacing an identical percentage of fresh binder), then any difference in properties between the mortar samples can be directly attributed to the percentage of reclaimed binder. If the properties of the fresh binder (also used for making the mortar samples) are also known, then the change in properties of the fresh binder due to blending with the reclaimed binder can be isolated. That is to say, if the continuous grade of the fresh binder is known, the mortar testing will allow for the estimation of the resulting continuous grade of the fresh binder-reclaimed binder blend (the blended binder).

This testing approach offers several advantages over current characterization methods. First, eliminating solvents from the testing removes any potential bias they may cause. The blending that occurs in the mortar samples is also a more reasonable simulation of what happens in the field, as the RAS material is directly blended with the fresh binder at temperatures similar to those used in the mixing plant. This helps to alleviate the concerns associated with incomplete blending, as the blending we achieve in the laboratory, complete or incomplete, will be a simulation of the blending that occurs in the field.

3. Materials and Methods

This section will provide a detailed explanation of the RAS/RAP binder characterization system developed in this research as well as the associated test methods and procedure output. An explanation of the methods used for procedure verification will then be summarized. Finally, the materials used in this study will then be presented.

3.1 RAS/RAP Binder Analysis Method

3.1.1 Materials Preparation

Preparation of the required mortar and binder samples for analysis is based off of the work presented by Ma et al (2010), with critical modifications. Preparation of two mortar materials and one fresh binder material is required. To avoid confusion, the preparation procedure presented below will focus on RAS materials, but the preparation and testing is identical whether RAP, RAS or any combination of RAP and RAS is used. The following steps are taken to prepare the materials:

- (1) Bulk RAS material is dried and sieved, and materials passing sieve #50 but retained on sieve #100 sieve (called here R_{100}) are collected. Figure 5 displays pictures of typical bulk and sieved RAS and RAP material. The R_{100} material is split into two batches:
 - a. Batch 1: This batch of R_{100} RAS is burned in the ignition oven to estimate the asphalt binder content following ASTM D6307-05 procedure. Experience has shown that for complete analysis, at least 150 grams of material (split among 3-4 oven pans) should be burned.
 - b. Batch 2: Mix approximately 150 g sample of this unburned R_{100} material with RTFO-aged fresh binder to create RTFO mortar that is designated as “A Mortar”. The amount of RTFO binder needed depends on the workability of the mortar; the mortar needs to be workable enough to cast BBR and DSR samples. Experience has shown that a total mortar binder content (RAP binder + RTFO binder) of 30 percent by weight is appropriate as a starting point for the mortar sample, with 35-40 percent total binder by weight being near optimum.

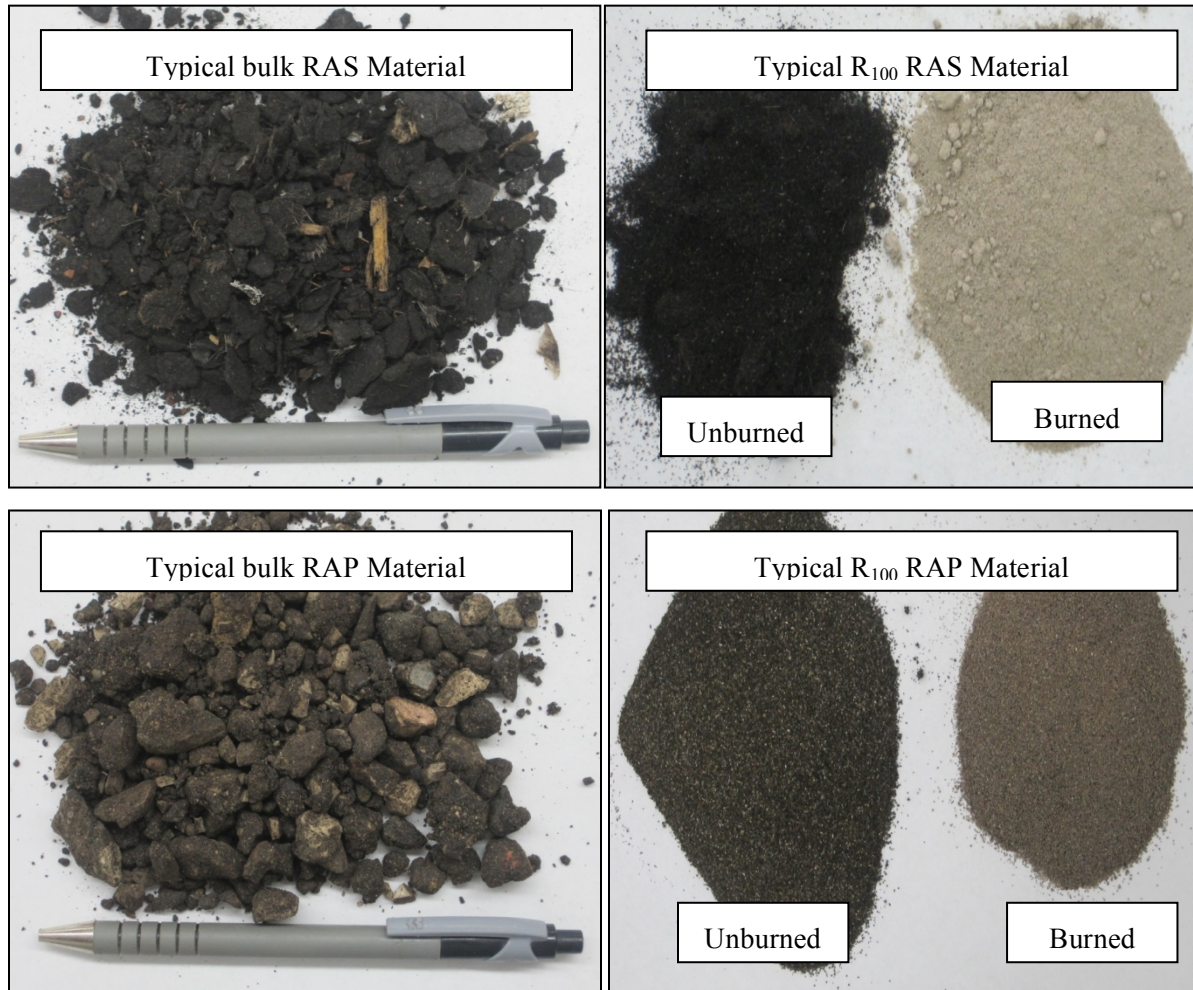


Figure 5. Typical RAS and RAP materials used in the mortar preparation.

- (2) Burned R₁₀₀ aggregates from batch (1) are mixed with RTFO aged fresh binder at the same *total* binder content as the RTFO-RAP Mortar prepared in (1)-b. Approximately 150 g of the burned aggregates makes a good starting point. This mortar is denoted as RTFO-B Mortar. Mortar design binder content calculations can be found in Appendix A.
- (3) Age the RTFO-A and RTFO-B mortars in the pressure aging vessel (PAV) for *24 hours* at 100 °C. The amount of mortar in each PAV pan is determined so that 50 grams total of binder is present in the pan. For example, if the total binder content of the mortars is 40 percent, the amount of mortar in each PAV pan will be $50\text{g} / (0.40 \text{ binder content}) = 125 \text{g mortar}$. The required PAV aging time and the amount of mortar per pan used in this step was verified in Ma et al (2010). Aging the RTFO aged fresh binder in the PAV follows standard procedure, 50 grams of binder aged for 20 hours at 100 °C.
- (4) The PAV-B mortar and the PAV-A Mortar, along with the PAV aged binder are cast into separate BBR beams and tested at two target low temperatures.

(5) Steps (1)-b and (2) are repeated using unaged fresh binder in place of RTFO fresh binder to create fresh-A mortar and fresh-B mortar. These samples will be used for DSR testing at high temperatures, hence require less material to mix (approximately 40g of R₁₀₀ is usually sufficient). These mortars are usually prepared at the same total binder content used in steps (1)-b and (2).

The mortar preparation procedure is summarized in the following graphic.

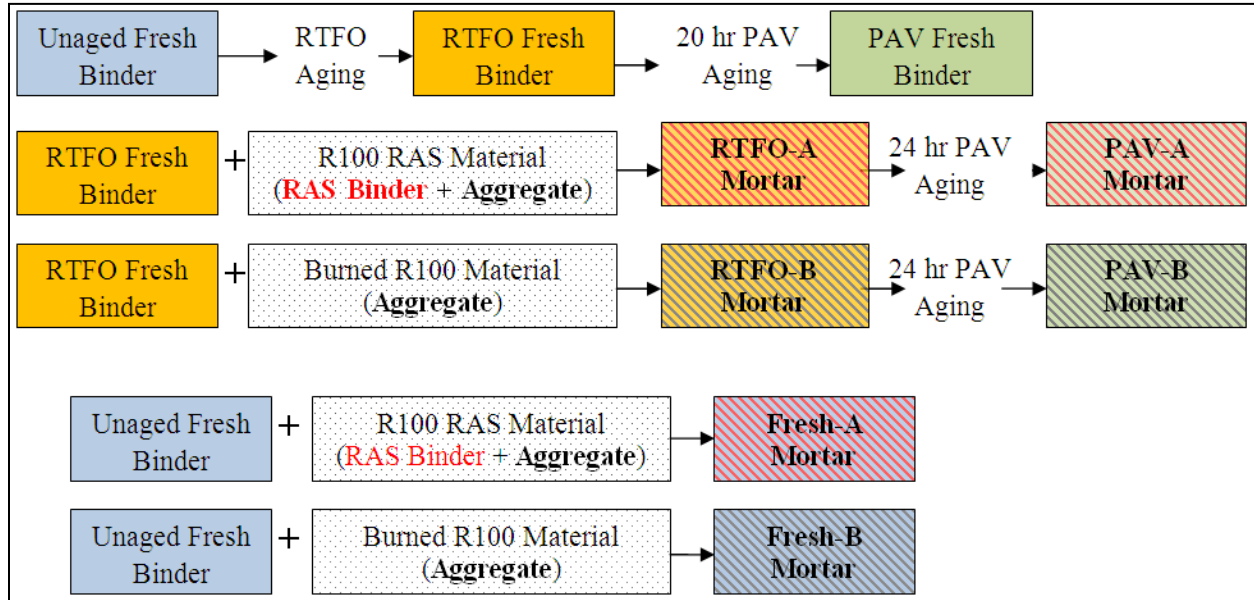


Figure 6. Mortar preparation procedure.

The test samples required for a complete analysis (continuous grading and binder viscosity) procedure are summarized in Table 2. The corresponding test methods and testing conditions are explained in detail in Appendix B.

Table 2. Required Test Specimens for Characterization Procedure

Low Temperature: BBR		Intermediate Temperature: DSR		High Temperature: DSR		Mixing and Compaction: DSR	
Binder Samples	Mortar Samples	Binder Samples	Mortar Samples	Binder Samples	Mortar Samples	Binder Samples	Mortar Samples
PAV	PAV A PAV B	PAV	PAV A PAV B	Fresh RTFO	Fresh A Fresh B RTFO A RTFO B	Fresh	Fresh A Fresh B

3.1.2 Analysis Procedure and Output

Continuous Grade Analysis

In a traditional continuous grading characterization procedure, a binder is tested at two target PG temperatures and a limiting parameter value is applied to the parameter – temperature profile to determine the corresponding asphalt binder continuous grade. Figure 7 demonstrates this concept for asphalt binder for low temperature (BBR); the same procedure applies at all temperature ranges with the only change being the test temperatures and limiting parameters ($G^* \sin(\delta)$ and $G^* / \sin(\delta)$ are the limiting parameters used at intermediate, and high temperatures, respectively). Note that the continuous grade is taken as the limiting temperature (higher) at which either stiffness or m-value reaches the specified limit first.

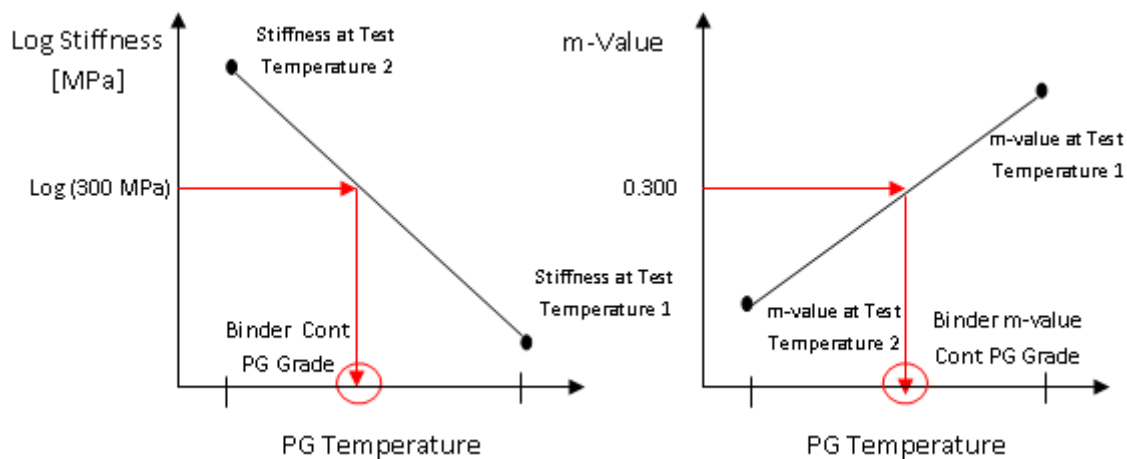


Figure 7. Low temperature continuous grading of asphalt binder.

The analytical procedure is based on the assumption that the effect of reclaimed binder on the continuous grading curve for the original fresh binder at low temperature will simply be a shift in stiffness and m-value (the stiffness of the reclaimed binder-fresh binder blend will be higher than the fresh binder stiffness, whereas the m-value will be lower for the reclaimed binder-fresh binder blend), resulting in a continuous grade change. The magnitude of the grade shift is determined from the mortar testing results at two target temperatures. If the only difference between the PAV-A and PAV-B mortars is the percentage of reclaimed binder in PAV-A mortar, then any difference in performance parameter between the mortars can be attributed solely to the reclaimed binder. If the shift between the PAV-A and PAV-B performance parameter remains nearly constant at all practical testing times (60 seconds in the case of low temperature) and the two testing temperatures, the same shift at the critical time 60 seconds can be applied to the PAV-aged fresh binder at each testing temperature. Figure 8 illustrates this concept at low

temperature for stiffness. The stiffness is first reported at 60 seconds for the PAV-A and PAV-B mortars at each temperature. Then, the stiffness 60 seconds for the PAV-A mortar is divided by the stiffness at 60 seconds for the PAV-B mortar, resulting in the T1 shift value for stiffness. The same procedure is completed at testing temperature T2. The shift factors for T1 and T2 are averaged and applied to the PAV-aged fresh binder stiffness. The shift is applied by simply multiplying the PAV-aged fresh binder stiffness by the shift factor. It is important to note that at low temperature, the shift factor for stiffness is computed independent of, but simultaneously with the shift factor for m-value, and likewise applied to the fresh binder parameter values independently and simultaneously. The limiting continuous grade caused by either the m-value or stiffness limits of the shifted continuous grading curves is taken as the predicted blended binder continuous grade.

Two important notes regarding the shift factor: first, the shift factor will be different for each recycled material – fresh binder pairing, that is, each binder analysis procedure will produce different shift values. As well, the shift at low temperature is not necessarily the same shift the shift at intermediate and high temperature, and must be calculated for every instance. Second, the shift values between the A-Mortar and B-Mortar was verified for each analysis described herein, as well as by analyzing approximately 30 RAP/RAS – fresh binder combinations tested by the research team determine whether a constant shift in properties was appropriate. A more in-depth description of the analytical procedure at low temperature can be found in Swiertz et al. (2011), while the intermediate and high temperature analysis is described in detail in Swiertz & Bahia (2011).

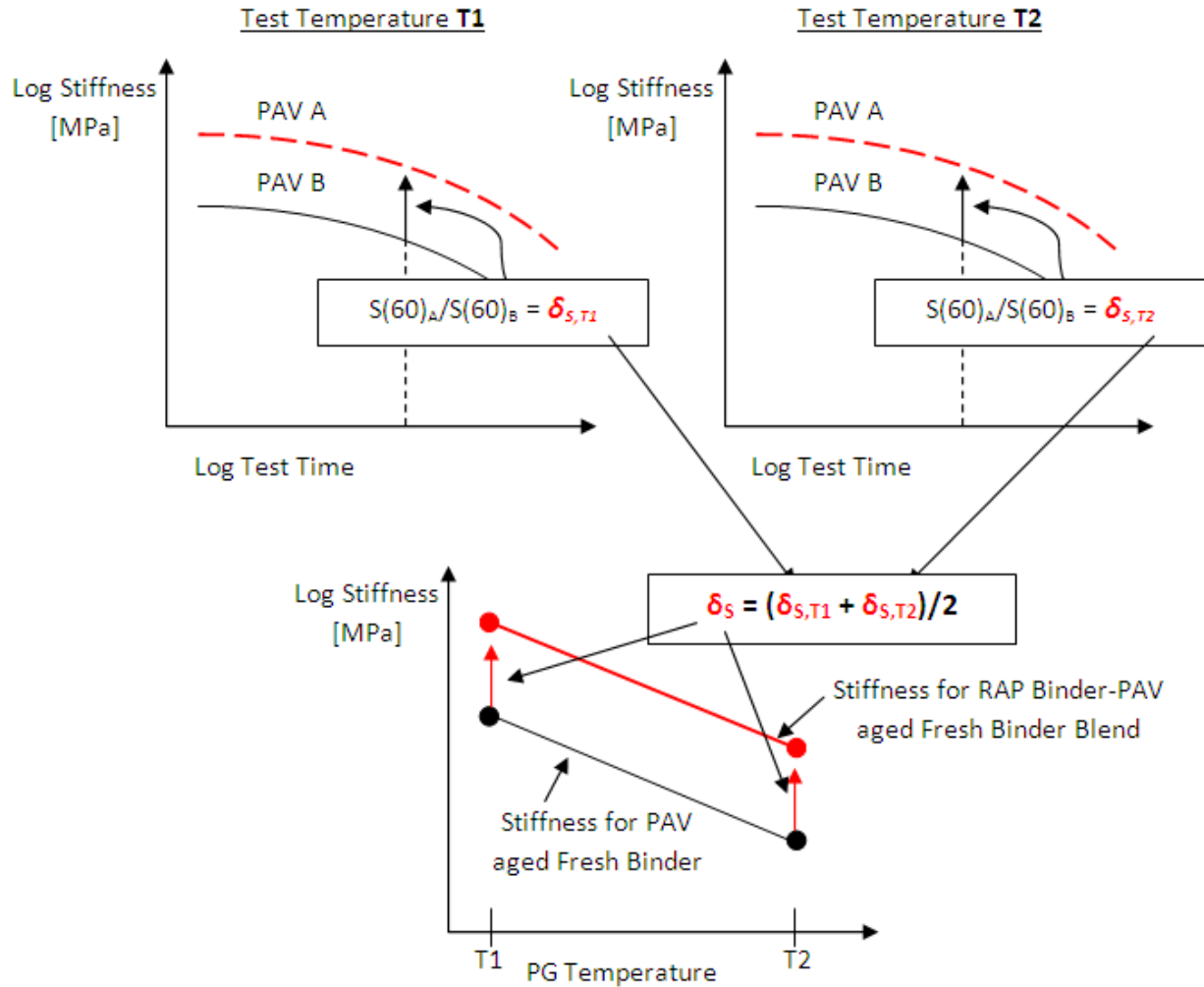


Figure 8. Determination of PAV-aged fresh binder stiffness shift from mortar testing.

From the predicted blended binder continuous grade, along with the fresh binder continuous grade, a relationship between PG temperature change and percent reclaimed binder can be estimated (Figure 9). The maximum continuous grade estimation range, denoted with a solid line in the figure, is dependent on the mixing conditions described in Appendix A. The binder replacement-continuous grade trend as shown is extended beyond the testing percentage into what is denoted as the “extrapolation range”, shown in the figure as the dotted line. The extrapolation range is assumed to be linear, following the same slope as the estimation range. The data from this range is not used for calculations in this study. A useful parameter for comparing the effects of different RAS/RAP source – fresh binder combinations is calculated as the inverse of the slope of the continuous grade estimation range. This parameter is referred to herein as the ‘Grade Change Rate’ and has units of °C/%RAS Binder Replacement. A similar parameter often used in the literature is the binder grade ‘Improvement Rate’, which has the same units. The calculation for the grade change rate is shown below.

$$\text{Grade Change Rate} \left(\frac{^{\circ}\text{C}}{\% \text{RAS Binder}} \right) =$$

$$\frac{|\text{Estimated Blended Binder Continuous Grade} - \text{Measured Blended Binder Continuous Grade}|}{\text{Percent Binder Replacement}}$$

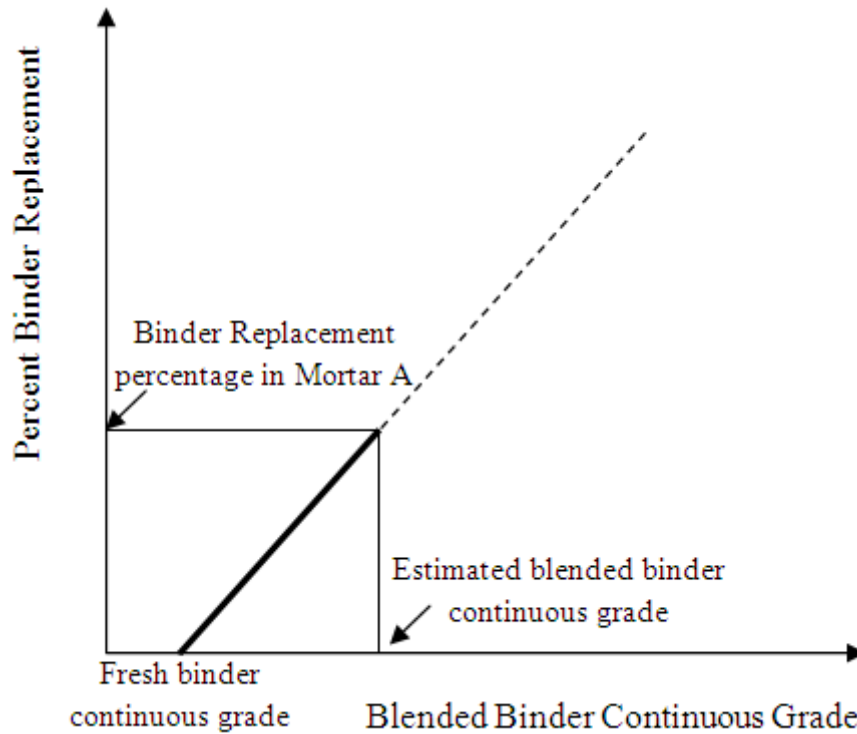


Figure 9. Continuous grade change profile output.

Binder Workability (Viscosity) Analysis

The proposed blended binder viscosity analysis procedure utilizes standard Superpave DSR testing conditions to capture the sample viscosity – temperature susceptibility (VTS) profile. Samples are tested at two test temperatures, 76°C and 94°C with standard 25 mm parallel plate geometry in strain controlled oscillation at 10 radians/second using 2 percent applied strain. For each temperature, complex viscosity η^* is recorded to produce a VTS profile. The blended binder viscosity analysis procedure follows the continuous grading analysis procedure with the response parameter being η^* . This process is described below.

Similar to the continuous grading procedure, the ratio between the A-Mortar and B-Mortar viscosity at each test temperature is taken as the effect of adding an amount of RAS binder (binder replacement) to the fresh binder. The ratio between the A-Mortar and B-Mortar viscosity will generally increase with

increasing test temperatures for a given binder replacement level. RAS binder is less temperature susceptible (lower VTS slope) than fresh binder, so this trend is logical and expected. The ratio of the A-Mortar and B-Mortar samples is multiplied by the fresh binder viscosity at each temperature and the result is the estimated blended binder VTS profile. The VTS profiles for the blended binder and fresh binder are used to estimate the effect of the RAP or RAS on the estimated mixing and compacting temperatures of the HMA. Per the Asphalt Institute Superpave Mix Design Manual, the optimal binder viscosity ranges for mixing or compacting HMA are 0.17 ± 0.02 Pa-sec and 0.28 ± 0.03 Pa-sec, respectively (Asphalt Institute, 2001). These optimum ranges are applied to the blended binder and fresh binder VTS profiles, and the estimated mixing and compaction temperature for the blended binder mix can be calculated. Testing multiple binder replacement levels for each fresh binder source allows users to create a mixing (or compacting) temperature change profile, shown below in Figure 10. The slope of this profile allows for the estimation of the change in mixing and compaction temperature for a selected binder replacement level and offers insight into the degree of blending that may occur at specific temperatures.

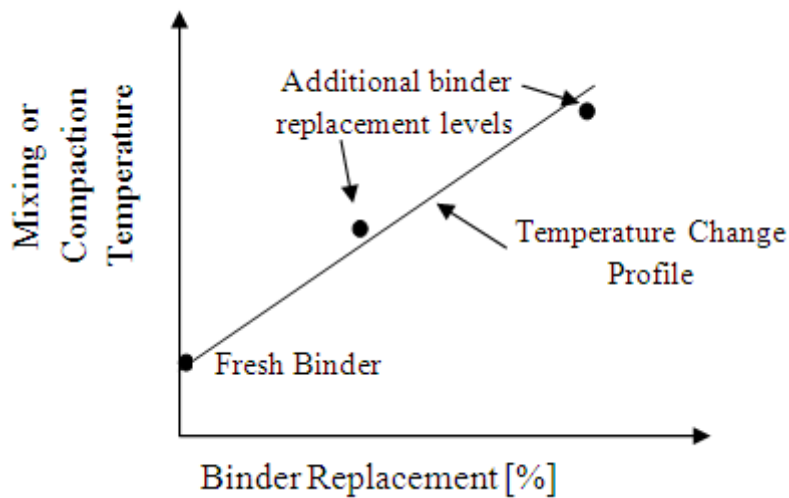


Figure 10. Mixing and compaction temperature change profile.

3.2 Verification of the Procedure

A simple verification experiment was completed to assess the ability of the proposed characterization procedure to capture the blended binder properties at all critical temperature ranges of the PG grading system. The experiment addressed three primary objectives:

- Confirm the estimated blended binder continuous grade produced from the mortar testing procedure against the actual blended binder continuous grade produced by actual binder blends.

- Confirm the estimated blended binder viscosity from the mortar testing procedure by producing physical binder blends.
- Isolate the effect, if any, of the ignition oven on the burned RAP and RAS aggregates in terms of mortar testing results.

3.2.1 Design of Verification Experiment

The verification procedure utilizes artificial RAP materials (although denoted as artificial ‘RAP’, the fundamental methodology of the verification procedure can be assumed to be identical when applied to RAP or RAS) with known binder properties tested in the proposed analysis procedure as A Mortar and compares the estimated blended binder properties to the known blended binder properties following a three step process:

- Three artificial ‘RAP’ sources were produced by mixing burned R₁₀₀ aggregate material with binder aged for 40 hours in the PAV (two complete PAV aging cycles) at asphalt contents similar to what is commonly observed in R₁₀₀ RAP. Two PAV cycles were selected for binder aging in order to simulate asphalt binder near the end of its service life in a pavement. Figure 11 demonstrates the artificial RAP preparation procedure.

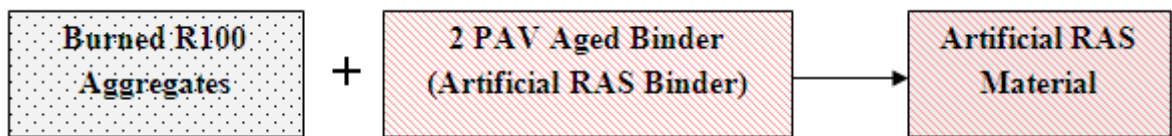


Figure 11. Artificial ‘RAP’ Preparation

Figure 12 shows a typical finished artificial RAP material in comparison to a typical field RAP material. In total, three artificial RAP sources were produced:

- Artificial RAP A₁: 40 hr PAV aged PG 64-22-a binder + R₁₀₀ aggregate from Reno, Nevada mixed at 10.5% total asphalt content.
- Artificial RAP A₂: 40 hr PAV aged PG 64-22-b binder + R₁₀₀ aggregate from Reno, Nevada mixed at 10.5% total asphalt content.
- Artificial RAP B: 40 hr PAV aged PG 58-28 binder + R₁₀₀ aggregate from Wisconsin mixed at 7.4% total asphalt content.

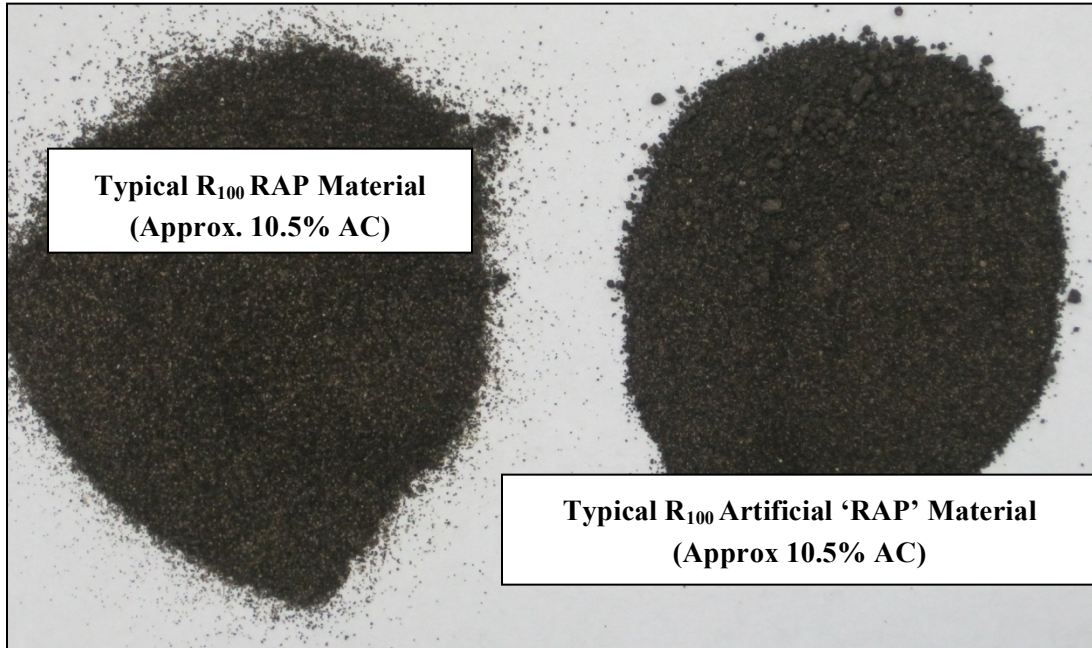


Figure 12. Typical artificial 'RAP' material

- (b) The artificial 'RAP' materials were prepared according to Section 3.3.1 and tested at low, intermediate and high temperatures treating the artificial 'RAP' as a standard R₁₀₀ RAP or RAS material. The result is an estimate of the artificial 'RAP' binder-fresh binder continuous grade or viscosity. The burned aggregates used for creating B-Mortar are the same as those used for creating the artificial 'RAP' material.

The binder replacement content was held at either 15 percent (Cases I, II, III) or 25 percent (Case IV) unless otherwise specified to represent typical RAP and RAS binder testing, respectively. Four cases were tested:

<i>Artificial 'RAP'</i> _{A1} + PG 64 – 22 – <i>a fresh binder</i>	Case I
<i>Artificial 'RAP'</i> _B + PG 58 – 28 <i>fresh binder</i>	Case II
<i>Artificial 'RAP'</i> _{A1} + PG 58 – 28 <i>fresh binder</i>	Case III
<i>Artificial 'RAP'</i> _{A2} + PG 64 – 22 – <i>b fresh binder</i>	Case IV

- (c) Results from (b) were verified against physically blended binder containing 15 percent (25 percent for the Case IV) artificial 'RAP' binder + 85 percent (75 percent for the Case IV) fresh

binder aged according to the testing at either low, intermediate, or high temperature. No mortars are tested in this step.

3.2.2 Verification Results

Complete verification results and explanations can be found in Swiertz et al (2011) and Swiertz & Bahia (2011) for low temperatures and intermediate and high temperatures, respectively. It was observed that the proposed mortar testing procedure could estimate the actual blended binder true grade within 2.5 °C for low and intermediate temperatures for all cases. At high temperature, the proposed procedure was capable of estimating the continuous grade of blended binder within 6 °C, but this difference could be reduced significantly by applying alternate testing geometries in the DSR or by increasing the total binder content in the mortar. For the high temperature viscosity testing, only Case I and Case II were tested and the average percent difference between the estimated blended binder viscosity and the measured blended binder viscosity was within 6.3 percent. The verification results are summarized in Table 3.

Table 3. Mortar Procedure Verification Results

Continuous Grade Verification	
Critical Temperature Range	Max Difference in Continuous Grade ¹ [°C]
Low	2.44
Intermediate	2.42
High	5.96
High Temperature Viscosity Verification	
Critical Temperature Range	Average Percent Difference in Viscosity ² [%]
High	6.3

¹Max absolute difference between proposed mortar procedure estimated blended binder continuous grade and the measured physical blended binder continuous grade for the four cases tested.

²Absolute value of the difference between the estimated blended binder viscosity and the measured blended binder viscosity divided by the average of the measurement, averaged for two verification cases.

Based on the verification results, the researchers feel the mortar preparation and testing procedure is acceptable at low and intermediate temperatures, and should be used with discretion at high temperatures (both for continuous grade analysis and high temperature viscosity).

3.3 RAS and RAP Source Description

RAS sources used for this study were limited to the region surrounding Dane County, Wisconsin. The sources were sampled over a one year period. Sampling intervals were selected to correspond with the typical start and end of a typical southern Wisconsin construction season in order to isolate the effect of stockpile turnover and the requirement for project specific testing in the mortar approach. Two area contractors supplied RAS materials for characterization. Care was taken to assure that the contractors' stockpiles were supplied from an independent source of RAS materials. Although more RAS sources would have made this study more robust, it was noted that several contractors obtain RAS materials from the same source, limiting the number of unique RAS sources obtainable during this study. A description and sampling time for the RAS sources is provided in Table 4.

Table 4. RAS Source Information

RAS Source	Stockpile Location	Sampling Date
K-1	South - Central Wisconsin	August, 2009
K-2	South - Central Wisconsin	May, 2010
K-3	South - Central Wisconsin	August, 2010
L	South - Eastern Wisconsin	August, 2010

An extensive RAP characterization study was coincidentally completed with the RAS study reported herein. The results are articulated in Swiertz et al. (2011) and Swiertz & Bahia (2011). In general, the conclusions applied to the RAS materials can similarly be applied to RAP materials with regard to source sensitivity, binder source sensitivity and effects of modification.

4. Results and Analysis

This section includes a summary of results of evaluating the proposed mortar procedure testing on the specified RAS materials. The result of a useful application of this procedure for blending RAP and RAS stockpiles is also discussed in this section.

4.1 Evaluation of the Ignition Oven for Use in Obtaining RAS Aggregates

An important assumption made in this procedure is the effects of the ignition oven on the aggregate gradation and the subsequent effect on the final analysis results are negligible. It is critical to verify the assumption.

Effect of the Ignition Oven on Aggregate Gradation

A primary role of the ignition oven is to provide burned RAS aggregates to blend in the B-Mortar materials. It is known that the ignition oven may cause aggregate breakdown and a subsequent change in the final gradation. However, it is unclear as to the extent of this breakdown on the R₁₀₀ RAS materials used in the proposed procedure. RAS sources K-1, K-2, and L were sieved and the R₁₀₀ materials were burned according to ASTM D6307-05 – Standard Test Method for Asphalt Content of Hot Mix Asphalt by Ignition Method. The post-ignition oven aggregates were then subjected to another sieve analysis to determine the percent passing the #100 (there was zero percent passing the #100 sieve before the ignition oven test). The results of the analysis are shown in Table 5.

Table 5. Effect of Ignition Oven on RAS Gradation

RAS Source	AC Content ¹ [% by weight]	Percent Passing #100 [%]
K-1	29.27	42.45
K-2	32.26	65.07
L	37.92	60.45

¹AC content is determined by absolute mass loss during burning but for RAS materials may represent loss of asphalt cement, fibrous materials, wood particles, and other extraneous materials.

As can be seen in Table 5, the assumption that using the ignition oven has a negligible effect on the RAS gradation is incorrect. It is shown that for two of the three cases, there is more than 40% passing the #100 sieve which indicates the material has degraded during the burning process. Second, the asphalt contents determined by the ignition oven are not concurrent with the typical values listed in Table 1, and are in fact much higher. This, however, was expected because the ignition oven burns away the extraneous materials (felts, mats, fibers, etc) that are known to be included with the asphalt cement in shingles. Results in Table 5 also show that the sampling interval can drastically change the material properties of the RAS stockpile; although a similar ‘AC’ content was shown for K-1 and K-2, the percent passing after burning are significantly different, suggesting a change to the material properties in the stockpile in the six month sampling period.

Effect of Gradation Change on Analysis Results

To determine whether the change in aggregate physical properties/gradation due to using the ignition oven will affect the analysis result of the proposed mortar testing procedure, a two step process was followed:

- A-Mortar was created as usual: using unburned R₁₀₀ RAS material at a design binder replacement value.
- Two B-Mortar materials were created; the first contained only the R₁₀₀ burned aggregates after the ignition oven test (the passing #100 aggregates were discarded), while the second B-Mortar contained the bulk aggregates from the ignition oven test (not sieved after burning). The total asphalt content of both B-Mortars was identical, and was identical to the A-Mortar per the mortar design guidelines.

The mortar samples were tested at low temperature only, as concerns with incorporating RAS materials are most focused on low temperature properties. RAS source K-2 was selected as it demonstrated the most significant aggregate breakdown. The results of the analysis expressed in terms of continuous grade temperatures (Temperatures at which PG requirement is satisfied) are shown in Table 6. The material breakdown caused by the ignition oven does not appear to significantly influence the analysis results at low temperature PG grade testing.

Table 6. Effect of Ignition Oven on Low Temperature Analysis Results

B-Mortar	RAS Binder [%]	Total Mortar AC [%]	Binder Continuous Grade		Grade Change Rate [°C /% RAS]
			Fresh Binder	Blended Binder	
Bulk Aggregates	40.19	54.23	-30.38	-13.72	0.41
R100 Aggregates	40.19	54.23	-30.38	-13.63	0.42

In addition to the findings summarized in Table 6, a simple t-test was used to verify the findings. Stiffness and m-value results for the B-Mortar were compared at an $\alpha = 0.05$ significance level. Resulting p-values for the four comparisons (B-Mortar stiffness and m-value at two temperatures each) were all larger than 0.1, suggesting the means are not statistically different. It can thus be concluded that the ignition oven, although causing sample breakdown and most likely bias in calculating the AC content, is suitable in providing B-Mortar aggregates for use in the proposed procedure.

4.2 Effect of RAS Binder on Low Temperature Blended Binder Properties

The RAS sources shown in Table 4 were tested in the proposed analysis procedure at low temperature and the grade change rates for each source and sampling time was calculated. In order to create an even comparison between RAS sources, the fresh binder used to blend the mortars was kept the same. It was demonstrated by the authors (Swiertz et al. (2011) and Swiertz & Bahia (2011)) that the grade change rate

of RAP materials was highly dependent on the source of the fresh binder as well as the source of RAP, and it is hypothesized the same is true for RAS materials. Table 7 summarizes these testing results.

Table 7. RAS Grade Change Rate Sensitivity: Low Temperature

RAS Source	RAS Binder Replacement [%]	Fresh Binder PG	Continuous Grade [°C]		Grade Change Rate [°C/%RAS Binder Replacement]
			Fresh Binder	Blended Binder	
K-1	20		-30.4	-23.4	0.35
K-2	40.2	58-28	-30.4	-14.4	0.40
K-3	40.2		-30.4	-13.7	0.41
L	40.1		-30.4	-12.4	0.45
				Average	0.40
				Std. Dev.	0.04

Comparing the results presented in Table 7 with calculated RAP grade change rates shows some interesting trends. Swiertz & Bahia (2011) demonstrated that for 18 RAP source – fresh binder combinations, the average grade change rate was 0.26, with a standard deviation of 0.15, suggesting that the higher average change rate for the RAS samples is significant, and is expected. RAS materials are known to use stiffer, air-blown binder. Also, it is observed that the standard deviation between the RAS sources is also much lower than the RAP sources, possibly as a result of more uniform manufacturing processes (similar binder grades) in the RAS materials.

4.3 Effect of RAS Binder on Intermediate and High Temperature Blended Binder Properties

A similar study was conducted to estimate effects on binder properties at intermediate and high temperatures using in the grading system. Due to material limitations and concerns regarding the DSR verification results, only RAS source K-1 was tested in these temperature ranges. A 20 percent binder replacement level was used for both intermediate and high temperature testing. The results of this study are shown in Table 8.

Table 8. RAS Grade Change Rate Sensitivity: Intermediate and High Temperature

Temperature Range	RAS Source	Fresh Binder PG	Continuous Grade [°C]		Grade Change Rate [°C/%RAS Binder Replacement]
			Fresh Binder	Blended Binder	
Intermediate	K-1	58-28	17.7	21	0.17
High	K-1		59.3	63.2	0.20

Interestingly, the grade change rates shown in Table 8 are consistent with the K-1 source grade change rates found at low temperature. More RAS sources will be needed to verify if this trend is ubiquitous. As expected, the grade change rates for the K-1 RAS material are higher than the grade change rates found for most RAP materials, as expected.

4.4 Effect of RAS Binder on Blended Binder Workability

The K-1 RAS source was also tested in the proposed blended binder viscosity analysis procedure. Three RAS binder replacement levels (20, 35, and 50 percent) were selected for analysis with the same PG 58-28 fresh binder used for the low, intermediate, and high temperature testing. The results are shown in Table 9 along with a typical RAP source for comparison. The results indicate that the influence of RAS binder on the viscosity of the blended binder is more pronounced when compared to the RAP material; it is more than twice the influence on equi-viscous temperature change rate due to blended RAP binder with the same fresh binder. This is in agreement with the results of the continuous grade analysis for RAS and RAP materials, and is in agreement with findings in existing literature.

Table 9. Effect of RAS and RAP on the Mixing and Compaction Temperature Change Profile

RAP/RAS Source	Fresh Binder PG	Temperature Change Profile [°C/%RAP or %RAS]	
		Mixing Temperature	Compaction Temperature
Wi (RAP)	58-28	0.34	0.34
K-3 (RAS)		0.92	0.87

The significance of the results presented in Table 9 are important to consider as they confirm the notion that if the K-1 RAS source is blended at an identical mixing temperature as the RAP source, the RAS binder (as a percent of the available RAS binder) is expected to produce very different effects on

the virgin binder. This is important to consider in calculating the effective binder content of mixes. The effect of blending RAS and RAP together will be discussed in a later section, but these results may provide insight into an error that may occur in calculating the total binder content.

4.5 Effect of Blending RAP and RAS

A useful application of the proposed analysis procedure is application to RAP and RAS blends. In practice, RAP and RAS are often used together to achieve potential cost savings due to less need for fresh binders. In most HMA specifications, the combined binder replacement produced by RAP and RAS is limited to a maximum percentage. This design system does not consider that the contribution of the RAS binder could be very different from RAP binder on the blended binder properties. Depending on the ratio of RAS to RAP, the current system could either be overly conservative or it may also be overly lenient in allowing too much RAS and RAP. The proposed analysis procedure can be used to help resolve this issue and further calculate the optimum blend of RAS to RAP to conserve a certain level of binder performance.

To apply this concept to the proposed procedure, testing can result in an estimate of the grade change rate for RAP alone, and RAS alone. A simple weighted linear combination of the RAP and RAS separately is used to provide an estimate of the combined grade change rate of the RAP + RAS system. Any arbitrary blend of RAP and RAS materials can then be created and tested in the proposed procedure to validate the prediction. If the measured grade change rate for the trial RAP + RAS blend matches the predicted grade change rate by linear combination, the procedure can be used to optimize RAP+RAS blends to meet a certain binder criteria.

This hypothesis was tested in two combinations in which each RAP/RAS source and fresh binder source was unique. The RAP alone and RAS alone blends were first tested for each combination. Two trial blends were created for each combination in order to verify the predicted linear combination. The total binder replacement (RAP + RAS) was held at approximately 12 percent for one blend and approximately 25 percent for the second. It was found that for all four trial blends, the predicted blended binder continuous grade and the measured blended binder continuous grade were within 2.7 °C, indicating a linear combination of RAP and RAS is sufficient in predicting the effect of RAP + RAS systems on the blended binder continuous grade within the binder replacement levels tested.

An example output for one of the RAP + RAS scenarios is shown below in Figure 13. The horizontal and vertical axes represent the percent binder replacement for RAP and for RAS, respectively. The key to the right represents the resulting low temperature continuous grade of the blended binder.

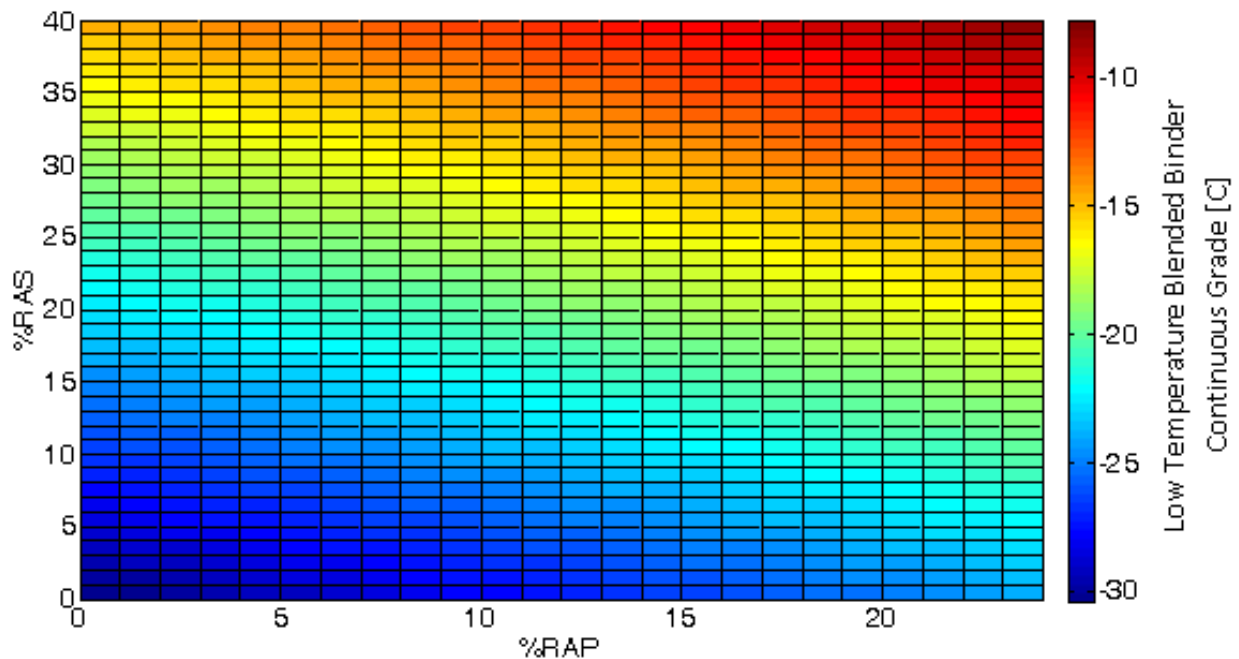


Figure 13. Effect of RAP + RAS system on low temperature continuous grade

5. Summary of Findings and Recommendations

This study presented a new method for characterizing the effect of RAS and RAP materials on fresh binder properties without the use of chemical extraction. The results from using the method shows promise in optimizing RAP and RAS binder replacement levels in HMA mixtures to conserve a desired blended binder performance level. The main findings of this study can be listed as follows:

- The results of the verification study indicate the procedure is capable of estimating the low and intermediate temperature blended binder continuous grade to within 2.5 °C of the actual value based on four unique cases. Verification at high temperature produced continuous grade estimates within 6 °C of the actual blended binder continuous grade, but modifications to the testing geometry and mortar design reduced this difference significantly.
- The effect of RAS materials on the blended binder continuous grade at all critical temperatures is dependent on the RAS source, particularly at high RAS binder replacement levels.
- The effect of ‘stockpile turnover’ for a single RAS source on the blended binder continuous grade was clearly demonstrated, indicating a need for project specific sampling.
- The analysis procedure was capable of demonstrating the effect of RAS materials on the required mixing and compaction temperatures to achieve desired mixture workability.

- The continuous grading procedure was applied to RAS and RAP blends. It is shown that the cumulative effect of RAP and RAS on the blended binder continuous grade is additive. This trend can be used to predict the blended binder continuous grade for any combination (optimization) of RAS and RAP binder replacement. A simple blending chart in the form of a surface plot can be used to demonstrate the blending possibilities.

Limitations of this Study

It is important that this study is limited in scope and thus the findings are subject to several limitations and practical implications. RAS sources used in this study were limited to specific geographic locations, South-central and South-eastern Wisconsin, and do not represent an adequate geographical sampling. A larger sampling set is needed to verify these findings. Conclusions regarding source sensitivity need to be treated with care. Manufacturing and processing of RAS materials may differ in other areas of the country, resulting in more variability in the testing data. Overall, the analysis procedure presented in this report is less material dependent when compared to mixture testing and binder extraction, and can be completed in any lab capable of performing simple binder testing with limited training. Most importantly, the results are readily applicable to the mixture design process and the procedure can be used to as either a quality control or optimization tool for high RAS and RAP mixes.

6. References

AASHTO T164 Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA). (2010). AASHTO.

AASHTO T 170 Standard Method of Test for Recovery of Asphalt Binder from Solution by Abson Method. (2010). AASHTO.

AASHTO. Best Practices Guide: Center for Environmental Excellence. AASHTO, 2011. Retrieved from: http://environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/detailed_toc.aspx.

AI. *Superpave Mix Design*, Superpave series No. 2 (SP-2), Asphalt Institute, Third Edition, Lexington, KY, 2001.

ASTM D1856 - 09 Standard Test Method for Recovery of Asphalt From Solution by Abson Method. (2009). ASTM.

ASTM D2172 - 05 Standard Test Methods for Quantitative Extraction of Bitumen From Bituminous Paving Mixtures. (2005). ASTM.

- ASTM D6307 - Standard Test Method for Asphalt Content of Hot Mix Asphalt by Ignition Method. (Reapproved 2010). ASTM.
- Bahia, H., & Anderson, D. (1995). The Pressure Aging Vessel (PAV): A test to Simulate Rheological Changes Due to Field Aging. *Physical Properties of Asphalt Cement Binders: ASTM STP 1241* , 67-89.
- Bahia, H., Mangiafico, S., & Bautista, E. (2009). Rheological Properties of Bitumen in RAP - How to Account for it in Recycled Asphalt Mixtures. *Recycling and Stabilization Conference*. University of Wisconsin - Madison.
- Burr, B., Davison, R., Jemison, H., Glover, C., & Bullin, J. (1991). Asphalt Hardening in Extraction Solvents. *Transportation Research Record* , No. 1323 pp 70-76.
- Carter, A. (2004). *Development of a Non-Solvent Based Test Method for Evaluation of Reclaimed Asphalt Pavement Mixes*. Dissertation.
- Copeland, A. (2009). *Reclaimed Asphalt Pavement in Asphalt Mixtures: State-of-the-Practice*. FHWA Office of Infrastructure Research.
- Environmental Protection Agency. *From Roofs to Roads: Recycling Asphalt Roofing Shingles into Paving Materials*. EPA, 2010. Retrieved from: http://www.epa.gov/osw/consERVE/rrr/imr/cdm/pubs/roof_br.pdf
- Fredonia Group. World Asphalt to 2013 – Market Research, Market Share, Market Size, Sales, Demand Forecast, Market Leaders, Company Profiles, Industry Trends. Fredonia Group. April, 2010. Retrieved from: <http://www.fredoniagroup.com/World-Asphalt.html>
- Kondrath, E. (2009). *Reclaimed Asphalt Pavement in Hot Mix Asphalt* . New Jersey Department of Transportation.
- Krivit, D. (2007). *Recycling Tear Off Shingles: Best Practices Guide*. The Construction Materials Recycling Association.
- Ma, T., Mahmoud, E., & Bahia, H. (2010). Development of Testing Procedure for the Estimation of RAP Binder Low Temperature Properties Without Extraction. *Transportation Research Record*, No. 2179 pp 58-65.
- McDaniel, R., & Anderson, R. (2001). *Recommended use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*. NCHRP Report 452.
- McDaniel, R., Soleymani, H., Anderson, M., Turner, P., & Peterson, R. (2000). *Recommended use of Reclaimed Asphalt Pavement in Superpave Mix Design Method*. NCHRP Project 9-12.
- Peterson, R., Soleymani, H., Anderson, R., & McDaniel, R. (2000). Recovery and Testing of RAP Binders from Recycled Asphalt Pavements . *Association of Asphalt Paving Technologies* , Vol. 69 pp. 72.
- Read, J., & Whiteoak, D. (2003). *The Shell Bitumen Handbook: Fifth Edition*. London: Thomas Telford.

Scholz, T. (2010). *Preliminary Investigation of RAP and RAS in HMA*. Salem: Oregon Department of Transportation.

Shinglerecycling.org. (2009). Retrieved September 2010, from Shingle Recycling: shinglerecycling.org

Stroup-Gardiner, M., & Nelson, J. (2000). *Use of Normal Propyl Bromide Solvents for Extraction and Recovery of Asphalt Cements*. NCAT.

Swiertz, D., Bahia, H. (2011) Test Method to Quantify the Effect of RAP and RAS on Blended Binder Properties without Binder Extraction. In *Canadian Technical Asphalt Association (CTAA) Proceedings*, Quebec City, Quebec. Vol. 56, pp. 43-60.

Swiertz, D., Mahmoud, E., Bahia, H. (2011) Estimating the Effect of RAP and RAS on Fresh Binder Low Temperature Properties without Extraction and Recovery. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2208, pp. 48-55.

Zofka, A., Marasteanu, M., Clyne, T., Li, X., & Hoffmann, O. (2004). *Development of Simple Asphalt Test for Determination of RAP Blending Charts*. Minnesota Department of Transportation.

Zofka, A., Marasteanu, M., Li, X., Clyne, T., & McGraw, J. (2005). Simple Method to Obtain Asphalt Binders Low Temperature from Asphalt Mixture Properties . *Journal of the Association of Asphalt Paving Technologists* , Vol. 74.

Appendix A: Mortar Mix Design Equations

After a RAP or RAS material has been sieved and the R_{100} material collected, samples are burned in the ignition oven to determine the total asphalt content. The following equations are also valid for RAS materials and RAP/RAS material blends, with the only adjustment being the R_{100} asphalt content. The total asphalt content AC_{total} and percent binder replacement AC_{RAP} are calculated internally from Equations a and b, respectively.

$$AC_{total-A Mortar} = \left[\frac{(RAP_S * R100_{AC}) + RTFO}{RAP_S + RTFO} \right] * 100$$

a.

$$AC_{RAP} = \left[\frac{RAP_S * R100_{AC}}{(RAP_S * R100_{AC}) + RTFO} \right] * 100$$

b.

Where,

$AC_{total-A Mortar}$: RTFO-A Mortar total asphalt content [%]

AC_{RAP} : Percent RAP binder replacement [%]

RAP_S : Sieved R_{100} RAP material quantity [g]

$R100_{AC}$: R_{100} RAP asphalt content [%]

$RTFO$: RTFO aged fresh binder quantity [g]

Note that the AC_{RAP} is the maximum reclaimed binder replacement estimation value. After the A Mortar calculations have been made, the B Mortar can be mixed. Here, the user will only control the quantity of burned R_{100} material, as the binder quantity is controlled based on AC_{total} from above. The RTFO-A Mortar and RTFO-B Mortar have the same total binder content; the amount of RTFO aged fresh binder required in the RTFO-B Mortar for this to be true is then:

$$RTFO = \frac{AC_{total-A Mortar} * RAP_B}{1 - AC_{total-A Mortar}}$$

c.

Where,

RAP_B : Burned R_{100} RAP material [g]

The RTFO-B Mortar total binder content $AC_{total-B Mortar}$ can then be expressed as

$$AC_{total-B Mortar} = \left(\frac{RTFO}{RAP_B + RTFO} \right) * 100$$

And

$$AC_{total-B\ Mortar} = AC_{total-A\ Mortar}$$

d.

Note that for Equation d to be true, the quantity of RTFO aged fresh binder required for the RTFO-B Mortar will be greater than the quantity used in the RTFO-A Mortar as the RTFO-A Mortar contains RTFO aged fresh binder along with RAP binder whereas the RTFO-B Mortar only contains RTFO aged fresh binder.

The RTFO-mortars are aged in the PAV to create PAV-mortars. So to this point the RTFO-mortars and PAV-mortars have been completed, along with the fresh binder, RTFO aged fresh binder, and PAV aged fresh binder. Recall that high temperature testing also requires testing Fresh-mortar samples. The above preparation formula is also applicable to Fresh-mortar preparation, where RTFO aged fresh binder is simply replaced with unaged fresh binder. The user only needs to specify RAP material quantities (RAP_S and RAP_B) and the fresh binder quantity is automatically updated. RAP_S and RAP_B are typically approximately 30-40 grams as the high temperature testing samples do not require much material. The following equations are used:

$$Fresh_{A\ Mortar} = \left[\frac{(AC_{total-A\ Mortar} * RAP_S) - (RAP_S * R100_{AC})}{1 - AC_{total-A\ Mortar}} \right]$$

And

$$Fresh_{B\ Mortar} = \left(\frac{AC_{total-A\ Mortar} * RAP_B}{1 - AC_{total-A\ Mortar}} \right)$$

e.

Where

Fresh_{A Mortar}: Required unaged fresh binder for Fresh-A Mortar [g]

Fresh_{B Mortar}: Required unaged fresh binder for Fresh-B Mortar [g]

Appendix B: Testing Methods and Conditions

In general the proposed analysis procedure uses standard Superpave test methods with only minor modifications. This section outlines the test methods recommended at low, intermediate and high temperatures and any modifications made to the method.

Low Temperature – BBR

Preparation of specimens for testing in the BBR for low temperature characterization follows standard procedure with slight modification. To accommodate the stiffer, more viscous mortar samples, BBR mold clamps are used to secure the ends of the beam while being molded and trimmed. Figure B1 below shows the BBR molds ready for casting. Notice also that polyethylene thread seal tape is used on the side beams of the mold to provide a non-stick surface. Traditionally, plastic strips are used to provide the same non-stick surface. Plastic strips will provide equal performance as the thread seal tape, however it was found the tape was more efficient to apply and is more economical for this study. Silicone BBR molds were not experimented with. Beams are cast and trimmed according to standard procedure.

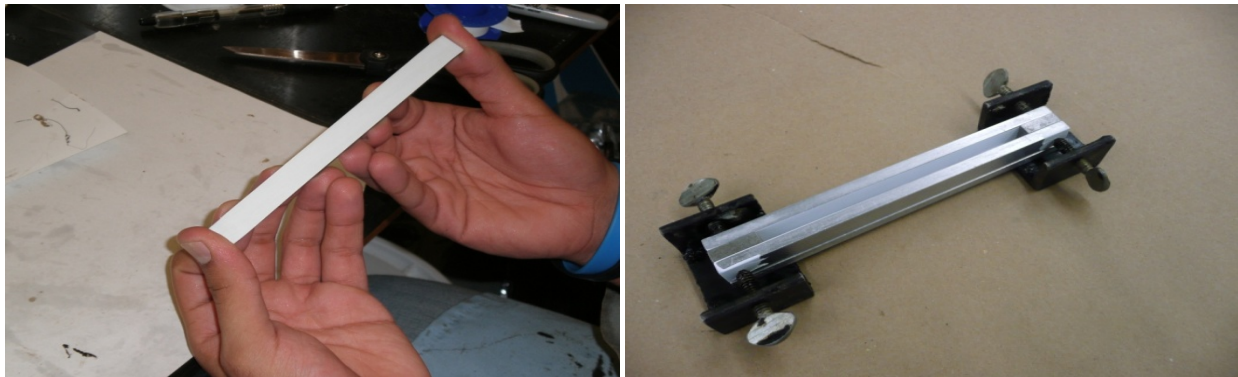


Figure B1. Left: side bar with thread seal tape. Right: view of BBR mold showing the optional side clamps.

Figure B2 below shows the de-molded binder and mortar beams required for a complete low temperature analysis procedure. Notice that the mortar samples are dimensioned the same as the binder samples, and are uniform. Recall that the material preparation section calls for increasing the mortar asphalt content until the beams are easily cast into the BBR molds; for reference the mortar samples in the figure are about 35 percent total asphalt content.

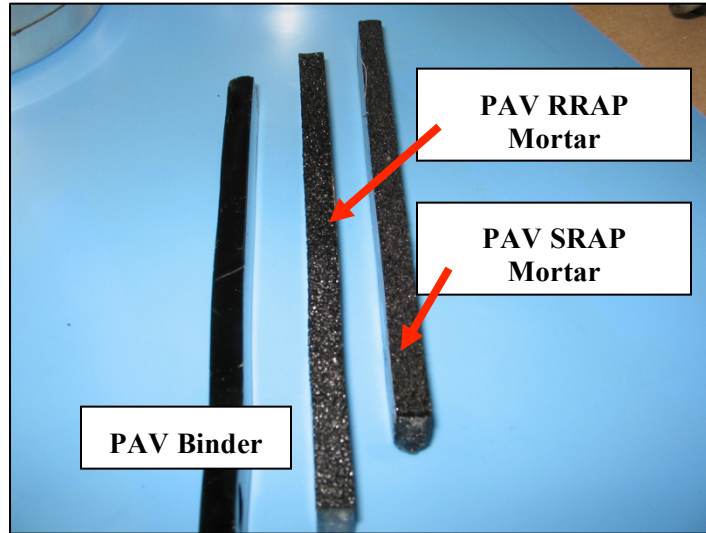


Figure B2. Typical BBR specimens for low Temperature classification.

The BBR test will be carried out at two temperatures as determined by the fresh binder grade and using a load proportional to the testing temperature. Generally, the PG grade and plus one grade is selected for testing. For example a PG 64 - 22 binder would be tested at -6 °C and -12 °C for low temperature analysis, as the addition of reclaimed binder is expected to be detrimental to the low temperature grade. Hence, testing at the PG grade plus one grade, will allow the continuous grade to be interpolated from the data. The testing loads are adjusted using the air bearing to allow for adequate deflection in the mortar samples. The standard load of 980 mN was determined to be too small to provide adequate deflection (as per the binder standard) in the mortar samples. Table B1 displays the recommended load for BBR testing.

Table B1. BBR Test Loads (Values in mN)

Test Temperature [C]	PAV Binder	PAV Mastic
0	980	980
-6	980	1980
-12	980	2980
-18	980	3980
-24	980	4980

Intermediate and High Temperature - DSR

Intermediate and high temperature samples are tested in the DSR according to standard procedure

with minor modifications. Again, the testing temperatures are dictated by the fresh binder performance grade. At high temperature the testing temperatures are selected to be the fresh binder high PG and plus one grade. As an example, a PG 64-22 binder will be tested at 64 °C and 70 °C, as the addition of reclaimed material is expected to increase the high PG. At intermediate temperature, the testing temperatures are generally determined to be the fresh binder corresponding intermediate grade and plus one grade. So with the PG 64-22, the testing temperatures would be 25 °C and 28 °C.

The test procedure at intermediate temperature follows a standard binder grading test at two temperatures. Both mortar and binder samples are cast in 8 mm silicone molds, and the test is completed with the 8 mm parallel plate geometry utilizing a 2 mm test gap setting and 1 percent applied strain. The complex modulus (G^*) and phase angle (δ) are measured to compute the necessary fatigue characterization $G^*\sin(\delta)$ value at 10 rad/sec. Most modern DSRs can directly display this value.

The high temperature procedure follows a standard binder grading procedure at two temperatures. The mortar and binder samples are cast in 25 mm molds and the test is completed with the 25 mm parallel plate geometry utilizing a 1mm test gap setting and applying 10 percent strain to the sample. The complex modulus (G^*) and phase angle (δ) are measured to compute the necessary fatigue characterization $G^*/\sin(\delta)$ value at 10 rad/sec. As noted in the verification section, a 2 mm testing gap may provide more accurate results at high temperature, but with some forewarning. It is also important to note that the user should monitor the torque and measured parameter values if possible as the mortar samples may exceed the machine limits for these values. If that is the case, higher temperatures could be used, or the mortar samples could be mixed again at higher total asphalt content. The same solution can be applied if the DSR exceeds normal force limits while reaching the trimming and testing gap.